

**Design, Realization and Analysis of the Quality Assurance
of the Strip Sensors for the ATLAS ITk Experiment**

Èric Bach Marquès

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for the ATLAS ITk Experiment**

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Abstract

The current ATLAS Inner Detector at CERN will be upgraded to the new Inner Tracker (ITk) to meet the demands of the High-Luminosity Large Hadron Collider (HL-LHC), which requires detectors capable of withstanding harsh radiation conditions. To achieve this, a new generation of silicon strip sensors has been developed to enhance detector robustness and long-term stability.

The objectives of this thesis are to develop, implement, and validate a comprehensive Quality Assurance (QA) framework for ITk strip sensor production, to systematically analyze production results, and to conduct targeted investigations beyond nominal operating conditions.

Chapter 1 provides an overview of the physical principles and technological design of n-on-p silicon strip sensors, including their operating principles and key technological elements. It discusses the behavior of essential electrical parameters, such as leakage current, full depletion voltage (V_{FD}), inter-strip resistance (R_{int}) and capacitance (C_{int}), and charge collection efficiency (CCE), and their evolution under radiation-induced bulk and surface damage. An overview of the ATLAS ITk is also presented, including the design and main characteristics of the ATLAS18 strip sensors.

In Chapter 2, Quality Assurance (QA) and Quality Control (QC) are described as key components of quality management in any production process. This work focuses on the QA of ITk strip sensor production, aiming to ensure that sensor quality requirements are consistently met. To this end, specially designed test devices were monitored throughout more than five years of production: Testchips, containing multiple test structures for key parameter analysis; MD8 diodes, used to extract leakage current and capacitance-voltage characteristics; and Mini sensors, which reproduce the Main sensor design at a reduced scale. These QA devices were distributed to various collaborating institutions for proton, neutron, gamma, and gamma + neutron irradiations at fluences and doses representative of those expected in the ITk, and were subsequently used for electrical testing, with IMB-CNM serving as the primary pre-irradiation test site.

Chapter 3 describes the IMB-CNM facilities and measurement setups used for pre-irradiation Testchip and MD8 measurements, together with the parameter extraction methods corresponding to each test structure. Python scripts were primarily developed to extract test parameters, perform local data analysis, upload results to the collaborative

production database (PDB), and report global results for a comprehensive analysis of production parameters.

Chapter 4 discusses the QA results from the ITk strip sensor production, which constitutes a central part of this thesis, as all pre- and post-irradiation results are carefully analyzed. Distribution and time-evolution plots enable continuous monitoring and detailed studies of observed trends throughout the entire production. This analysis provides insight into the behavior of key parameters during production, as well as the effects of irradiation induced by different particles up to target fluences and doses of 1.6×10^{15} neq/cm² and 66 Mrad, respectively. In addition, parameter-to-parameter correlations are studied for parameters exhibiting unusual behavior, particularly those with expected dependencies, such as parameters associated with the p-stop structure. Finally, anomalies and incidents identified during production are presented together with the corresponding mitigation decisions.

In Chapter 5, four additional studies investigate the physics of strip sensors beyond nominal operation: the characteristics of different p-stop implantation processes and the post-irradiation effects of p-stop on silicon strip sensors; the influence of material setup and irradiation angle on high-energy proton exposures; the performance of strip sensors irradiated to extreme fluences (up to 1×10^{18} neq/cm²); and the variability among wafers and batches extracted from silicon ingots.

Overall, this thesis delivers an end-to-end QA framework, validated through large-scale production and extended experimental studies, ensuring that the ITk strip sensors meet the stringent performance requirements of the HL-LHC upgrade.

Contents

Acknowledgments	i
Abstract	iii
Contents	v
1 Introduction	1
1.1 Fundamentals of Strip Sensors	1
1.1.1 Silicon Properties as a Semiconductor	1
1.1.2 PN Junction	5
1.1.3 The Strip Sensor	7
1.2 Strip Sensor Technology	7
1.2.1 Strip Formation and Operating Principles	7
1.2.2 Strip Sensor Functionality	9
1.3 Basic Properties and Radiation Effects of Silicon Strip Sensors	13
1.3.1 Basic Electrical Properties	14
1.3.2 Radiation Effects	19
1.4 Inner Tracker (ITk) Sensors	26
1.4.1 Inner Tracker	26
1.4.2 ITk Strip Sensor Specifications	34
1.4.3 Wafer Layout	43
1.5 State of the Art and Open Questions at the Start of This Work	50
2 Quality Assurance (QA)	53
2.1 Quality Assurance vs. Quality Control	53
2.1.1 Quality Assurance	53
2.1.2 Quality Control	54
2.2 Designed Test Structures	55
2.2.1 Testchip&MD8	56
2.2.2 Mini&MD8	70
2.3 Production Flow	71
2.4 Irradiations	74
2.4.1 Protons	76
2.4.2 Neutrons	77

2.4.3	Gamma Rays	77
2.4.4	Gamma + Neutrons	78
2.5	Original Contributions of This Thesis to the Quality Assurance of ITk Strip Sensors	78
3	Tests	83
3.1	Measurement Setups and Equipment	83
3.1.1	Automatic Tests	86
3.1.2	Manual Tests	89
3.2	Tests Made at IMB-CNM	92
3.2.1	Testcarta	93
3.2.2	CBR_IV	94
3.2.3	CCPL_C and CCPL_IV	97
3.2.4	CFLD_CV	98
3.2.5	CFLD-P_CV	101
3.2.6	INT_C	103
3.2.7	INT_IV	105
3.2.8	PTP_IV	107
3.2.9	RBIAS_IV	109
3.2.10	MD8_CV	110
3.2.11	MD8_IV	112
3.3	Database and Scripts	113
3.3.1	Extraction Algorithms	114
3.3.2	Upload Scripts	117
3.3.3	Reporting Scripts	124
3.3.4	Additional Scripts	127
4	Results of the Quality Assurance during Production of the ATLAS ITk Strip Sensors	131
4.1	Parameter Distribution and Time Evolution	131
4.1.1	Implant Resistance per Unit Length (R-I) and Implant Effective Linewidth ($W_{\text{EFF-I}}$)	133
4.1.2	Metal Resistance per Unit Length (R-M) and Metal Effective Linewidth ($W_{\text{EFF-M}}$)	135
4.1.3	Coupling Capacitance (C_{coupl})	137
4.1.4	Coupling Oxide Current at 100 V ($I_{\text{CCPL-100V}}$)	138
4.1.5	Oxide Capacitance (C_{ox}) and Oxide Thickness (t_{ox})	139
4.1.6	Flat-Band Voltage (V_{FB})	140
4.1.7	P-Stop Oxide Capacitance ($C_{\text{ox-P}}$) and P-Stop Oxide Thickness ($t_{\text{ox-P}}$)	142
4.1.8	Threshold Voltage (V_T)	142

4.1.9	Slope of the MOS Capacitor C–V Curve from Accumulation to Depletion (S_{REF})	143
4.1.10	Inter-Strip Capacitance (C_{int})	144
4.1.11	Inter-Strip Resistance (R_{int})	146
4.1.12	Punch-Through Voltage (V_{PT})	147
4.1.13	Bias Resistance (R_{bias})	149
4.1.14	Full Depletion Voltage (V_{FD})	152
4.1.15	Leakage Current at 500 V ($I_{500\text{V}}$) and Breakdown Voltage (V_{BD}) . .	154
4.1.16	Charge Collection Efficiency at 500 V ($\text{CCE}_{500\text{V}}$)	155
4.1.17	Summary of QA Trends and Physical/Technological Insights . . .	157
4.2	Parameter Correlations	159
4.2.1	V_T vs. V_{FB} (Pre-Irradiated)	160
4.2.2	V_{PT} vs. S_{REF} (Pre-Irradiated)	160
4.2.3	$I_{500\text{V}}$ vs. V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. .	162
4.2.4	$\text{CCE}_{500\text{V}}$ Irradiated with Bham Protons vs. V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$	162
4.2.5	V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ vs. Pre-Irradiated V_{FD}	163
4.3	Incidences During Production	164
4.3.1	Low P-Stop Implantation	165
4.3.2	Tests of Capacitances	175
4.3.3	Low Flat-Band Voltage	177
4.3.4	QA Batch Rejections	181
5	Additional Studies	183
5.1	Low P-Stop Implantation	183
5.1.1	Origin of the Problem	183
5.1.2	Experiments Made	184
5.1.3	Results	190
5.2	Study of 24 GeV Proton Damage as a Function of Fluence on Testchips and Mini Sensors	198
5.2.1	Origin of the Problem	198
5.2.2	Experiments Made	199
5.2.3	Results	205
5.3	Study of Extreme Fluence Irradiations	219
5.3.1	Origin of the Problem	219
5.3.2	Experiment Made	220
5.3.3	Results	220
5.4	Investigation of the Relationship Between Ingots and Batches	223
5.4.1	Origin of the Problem	223

5.4.2	Experiment Made	224
5.4.3	Results	224
Bibliography		237
List of Publications		247
List of Conferences		249

List of Figures

1.1	(a) Unit cell of the silicon crystalline structure, (b) tetrahedral building block in the diamond cubic lattice, (c) and schematic two-dimensional representation of the tetra-covalent bonds (right) [1, 2].	2
1.2	Two-dimensional silicon crystal lattice with an electron-hole pair formed after the breaking of a covalent bond at position A (left), and diagram of silicon electron energy with respect to lattice spacing (5.43 Å in crystalline silicon at room temperature) (right) [2].	2
1.3	Two-dimensional crystal lattices with (a) a substitutional impurity and (b) an interstitial impurity, respectively [1].	4
1.4	Schematic energy band gaps for (a) intrinsic, (b) p-type, and (c) n-type semiconductors.	5
1.5	Drawings and energy band diagrams of (a) separated n-type and p-type regions, and (b) after forming a pn junction in thermal equilibrium [2]. .	6
1.6	Schematic drawing of a transversal section of the silicon bulk showing a particle crossing perpendicular to the surface (left) and a particle crossing at an angle (right) [12].	9
1.7	Schematic 3D drawing of an n-on-p strip silicon sensor used in CMS HL-LHC experiments [4]. The bottom-left inset shows a simplified cross-sectional view of the sensor. Adapted from [2].	10
1.8	Strip isolation mechanisms used in n-on-p detectors: (a) Strips with no isolation, (b) strips isolated with p-stop, (c) strips isolated with p-spray, (d) strips isolated with a combined p-stop and p-spray effect, and (e) field-plate isolation. Adapted from [4].	12
1.9	Schematics of sensor biasing methods: polysilicon resistor (left), the punch-through effect (center), and FOXFET transistor (right). Adapted from [4].	13
1.10	I-V characteristics of a pn junction [31].	15
1.11	Avalanche breakdown voltage plotted over a wide range of impurity concentrations (10^{14} – 10^{18} cm ⁻³) for Si, GaAs ⟨100⟩, and GaP semiconductor materials. The dashed line indicates the impurity concentration above which the tunneling effect dominates [32].	16

1.12	Recoil-atom path and resulting defects (displaced atoms and clusters) after receiving 50 keV, approximately the kinetic energy transferred by a 1 MeV neutron [31–33].	21
1.13	Displacement damage $D(E)$ in silicon normalized to 95 MeV·mb as a function of particle energy for neutrons, protons, pions, and electrons. The inset enlarges the higher-energy region [13].	21
1.14	Energy-level positions of defects in the silicon band gap acting as (a) charged defects, (b) generation-recombination centers, or (c) trapping centers [36].	22
1.15	Evolution of depletion voltage—and N_{eff} —with fluence, showing type inversion at sufficiently high fluence. Adapted from [13].	23
1.16	Power dissipation vs. silicon temperature, showing thermal runaway above a critical temperature [4].	23
1.17	Difference in effective doping concentration N_{eff} vs. annealing time at 60°C [13, 36].	26
1.18	Schematic representation of the LHC and its four experimental detectors [44].	27
1.19	Schematic of the CERN accelerator complex [49, 51].	28
1.20	Timeline of LHC operations and planned upgrades [57].	29
1.21	Computer-generated image of the ATLAS Inner Detector [58].	29
1.22	Computer-generated image of the new ATLAS Inner Tracker [51, 59].	30
1.23	3D rendering of Pixel (green) and Strip (blue) systems in the ATLAS Inner Tracker (ITk), with labeled longitudinal distances starting at $z = 0$ [64].	31
1.24	Schematic layout of the ITk active detector elements in one quadrant of the detector. Horizontal and vertical lines correspond to Barrel and Endcap layers, respectively. Pixel layers are colored in red, and Strip layers in blue [51].	31
1.25	2D schematic layout of the ITk with expected fluence distribution (left) and TID distribution (right) [51].	32
1.26	3D rendering of Barrel Pixel and Strip systems in the ATLAS Inner Tracker (ITk), with labeled radius starting at $R = 0$ [64].	33
1.27	Computer-generated images of the Barrel stave (bottom) and the Endcap petal (upper right). In both cases, modules are mounted on rigid carbon-fiber supports. The End-of-Substructure (EoS) card at one end of each petal or stave interfaces with out-of-detector electronics. The inset shows the sensor and other elements (hybrids, ABCStar ASICs, HCCStar chips, Powerboard, and wire-bonds) mounted in a module [51].	34
1.28	Strip sensor designs in 6-inch silicon wafers for the ATLAS ITk [61, 66].	36

1.29	Schematic layout of the square SS sensor, showing the dimensions of all design features. Fiducial marks are indicated at the bottom of the image [67].	38
1.30	Parameters defining the stereo angle of Endcap sensors [67].	40
1.31	Wafer layout design of the LS (left) and R0 (right) sensors. Design visualized and exported from KLayout.	44
1.32	Layout of the upper-left quadrant of the LS Main sensor with its principal technological structures (implants of strips and p-stops not shown). Design visualized and exported from KLayout.	44
1.33	Dimensioned Testchip&MD8 and Mini&MD8 layout pieces corresponding to LS/SS (left) and R1 (right) wafers.	45
1.34	QA devices: ATLAS Testchip LS/SS (left), MD8 diode (center), and Mini sensor (right). Design visualized and exported from KLayout.	45
1.35	Schematics of the eight sensor wafer designs (SS, LS, R0, R1, R2, R3, R4, and R5) used in the ATLAS ITk. Positions of diced QA pieces circled in yellow (one Testchip&MD8 and one Mini&MD8 per wafer).	46
1.36	Testchip layouts from R0, R1, R2, R3, R4, and R5 Endcap wafers. Different interdigitated structures appear in each Testchip [11].	48
1.37	Miniature sensor layouts and their dimensions: Mini_LS, Mini_SS and Mini. Design visualized and exported from KLayout.	49
1.38	Monitor Diode layouts and their dimensions: MD8, MD4, MD2, and MD1. Design visualized and exported from KLayout.	49
2.1	Images of the two QA pieces diced from each wafer: the Mini&MD8 (left) and the Testchip&MD8 (right).	55
2.2	Schematic layout of an LS/SS ATLAS Testchip (1 cm × 1.2 cm) containing all structures for QA testing. Design visualized and exported from KLayout.	56
2.3	Schematic layout of a 12-pad row from the ATLAS Testchip. Design visualized and exported using KLayout.	57
2.4	Schematic layout of the Testcarta structure from the ATLAS Testchip. Design visualized and exported using KLayout.	58
2.5	Schematic layout of the polysilicon Bias Resistors from the ATLAS Testchip. Design visualized and exported using KLayout.	59
2.6	Schematic layout of the metal (left) and n-implant (right) Cross-Bridge Resistors from the ATLAS Testchip. Design visualized and exported using KLayout.	60
2.7	Schematic layout of the UP (top) interdigitated structure from an LS ATLAS Testchip. Design visualized and exported using KLayout.	61
2.8	Schematic layout of the Field Oxide capacitor from the ATLAS Testchip. Design visualized and exported using KLayout.	62

2.9	Schematic layout of the Coupling Capacitor from the ATLAS Testchip. Design visualized and exported using KLayout.	63
2.10	Schematic layout of the Punch-Through Protection structure from the ATLAS Testchip. Design visualized and exported using KLayout.	64
2.11	Schematic layout of the Field Oxide Capacitor with p-stop from the ATLAS Testchip. Design visualized and exported using KLayout.	65
2.12	Schematic layout of the Coupling Capacitor for Breakdown Voltage test from the ATLAS Testchip. Design visualized and exported using KLayout.	66
2.13	Schematic layout of the $1183 \times 1183 \mu\text{m}^2$ (left) and $183 \times 183 \mu\text{m}^2$ (right) Monitor Diodes from the ATLAS Testchip. Design visualized and exported using KLayout.	66
2.14	Schematic layout of the Gated Diodes from the ATLAS Testchip. Design visualized and exported using KLayout.	67
2.15	Schematic layout of the ‘5-strips’ structure from the ATLAS Testchip. Design visualized and exported using KLayout.	68
2.16	Schematic layout of the Mini_test_Endcap structure from the ATLAS Testchip. Design visualized and exported using KLayout.	69
2.17	Schematic layout of the MD8 Monitor Diode. Design visualized and exported using KLayout.	70
2.18	Schematic layout of the $1 \times 1 \text{ cm}^2$ Mini sensor. Design visualized and exported using KLayout.	71
2.19	Initial production QA flow of Testchip&MD8 pieces.	73
2.20	Initial production QA flow of Mini&MD8 pieces.	73
3.1	Schematic classification of the facilities used at IMB-CNM for measurements performed on QA pieces.	84
3.2	Schematic classification of the equipment used in the SIAM Laboratory for measurements performed on QA pieces.	85
3.3	Schematic classification of the equipment used in the Radiation Detectors Laboratory for measurements performed on QA pieces.	85
3.4	Configuration of the parametric test station, comprising an automatic probe station, a parametric analyzer, and the software setup.	86
3.5	Probe card used at IMB-CNM (left), probe-terminal connections of the probe card (center), and visual scheme of the probe-terminal switching for a Punch-Through Protection (PTP) test (right).	87
3.6	Metrics ICV software used for parametric testing with the automatic probe station in the SIAM Laboratory [99]. Inset: Image of the joystick controller used for XYZ positioning of the stage.	88
3.7	Example of a raw data file format from a production QA component.	89

3.8	Configuration of the LabRad facilities, including a manual probe station, an LCR meter, several SMUs, a thermal chuck, and the associated software setup.	90
3.9	Coupling box used in the C–V measurement setup (left), and electrical scheme of the internal circuit of the coupling box (right).	91
3.10	Keithley 2470 for I–V measurements on diodes (left) and Keithley 4200-SCS for additional electrical tests (right).	92
3.11	I–V curves obtained from the CBR-M structure of the Testchip for the extraction of parameters R_{ℓ} -M (left) y W_{EFF} -M (right). Production distribution: CERN-44; batch: VPA54856.	95
3.12	I–V curves obtenidas de la estructura CBR-I del Testchip para la extracción de parámetros R_{ℓ} -I (izquierda) y W_{EFF} -I (derecha). Distribución de producción: CERN-44; lote: VPA54856.	96
3.13	C–V (left) and I–V (right) curves measured on the Coupling Capacitor of the Testchip for the extraction of the coupling capacitance and the current at 100 V. Production distribution: CERN-44; batch: VPA54856. . .	98
3.14	Schematic illustration of a typical C–V curve of a standard MOS Field Oxide Capacitor (left) [102]. C–V curve measured on the MOS Field Oxide Capacitor of the Testchip for the extraction of C_{ox} , t_{ox} and V_{FB} . Production distribution: CERN-44; batch: VPA54856 (right).	100
3.15	Schematic illustration of the parameter extraction from a C–V curve of a MOS Field Oxide Capacitor with p-stop (left). C–V curve measured on the MOS Field Oxide Capacitor with p-stop of the Testchip for the extraction of $C_{\text{ox-P}}$, $t_{\text{ox-P}}$, S_{REF} and V_{T} . Production distribution: CERN-44; batch: VPA54856 (right).	102
3.16	C–V curves measured between neighboring strips in (a) UP, (b) MID and (c) LOW interdigitated structures of the Testchip for the extraction of C_{int} . Production distribution: CERN-44; batch: VPA54856.	104
3.17	I–V curves measured between neighboring strips in (a) UP, (b) MID and (c) LOW interdigitated structures of the Testchip for the extraction of R_{int} . Production distribution: CERN-44; batch: VPA54856.	106
3.18	R_{PT} vs. V_{test} measured for the PTP structure of a Testchip, used to extract V_{PT} (eight R_{PT} curves are shown). Production distribution: CERN-44; batch: VPA54856.	109
3.19	I–V curves measured during the RBIAS_IV test in a Testchip, used to extract R_{bias} (six I–V curves are shown). Production distribution: CERN-44; batch: VPA54856.	110
3.20	$1/C^2$ vs. V measured during the MD8_CV test in an MD8, used to extract the full depletion voltage (V_{FD}). Production distribution: CERN-44; batch: VPA54856.	112

3.21	I–V curve measured during the MD8_IV test in an MD8, used to extract the leakage current at 500 V and the breakdown voltage (V_{BD}). Production distribution: CERN-44; batch: VPA54856.	113
3.22	Schematic structure of the Python script hierarchy for QA parameter extraction from standardized data files.	116
3.23	Schematic structure of the Python script hierarchy for QA parameter extraction from raw data files.	116
3.24	Schematic structure of the Python script hierarchy for generating QA standard-format data files from raw data files.	117
3.25	Production QA flow as represented in the Production Database. Alternative stages (highlighted in orange) could be reached from different preceding stages.	118
3.26	Flow diagram illustrating the user-script interaction during data upload to the database.	121
3.27	Schematic structure of the Python script hierarchy for QA parameter upload to the Production Database.	121
3.28	Schematic structure of the Python script hierarchy for QA reporting and analysis of data retrieved from the Production Database.	124
3.29	Structure of the QA_parameters Python dictionary. For each test, the test name is assigned at the top level, followed by the component label, with the corresponding properties at the lowest level.	126
4.1	Distribution (left) and time-evolution (right) plots of the parameter $R - I$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 20327.11 \Omega/\text{cm}$; standard deviation: $\sigma = 283.00 \Omega/\text{cm}$	133
4.2	Distribution (left) and time-evolution (right) plots of the parameter $W_{\text{EFF}} - I$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 18.52 \mu\text{m}$; standard deviation: $\sigma = 0.31 \mu\text{m}$	134
4.3	Images obtained from the reverse-engineering study applied to standard QA samples from the beginning of production: (a) SEM top-view image of a strip with the n-implant linewidth measurement (batch VPX37409, wafer W415); (b) SEM image of the strip cross-section without clear visualization of the n-type implant (VPX37409-W415); and strip-implant measurements for Testchips (c) VPX37409-W415 and (d) VPX37410-W415 obtained using a different developing technique and visualized with an optical microscope in bright-field mode.	135
4.4	Distribution (left) and time-evolution (right) plots of the parameter $R - M$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 8.85 \Omega/\text{cm}$; standard deviation: $\sigma = 0.23 \Omega/\text{cm}$	136

4.5	Distribution (left) and time-evolution (right) plots of the parameter $W_{\text{EFF}} - M$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 20.99 \mu\text{m}$; standard deviation: $\sigma = 1.22 \mu\text{m}$	136
4.6	Distribution (left) and time-evolution (right) plots of the parameter C_{coupl} for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 22.34 \text{ pF/cm}$; standard deviation: $\sigma = 0.62 \text{ pF/cm}$	137
4.7	Distribution (left) and time-evolution (right) plots of the parameter C_{coupl} for samples irradiated with gamma + neutrons. Sample size: $N = 429$; mean: $\mu = 21.61 \text{ pF/cm}$; standard deviation: $\sigma = 0.77 \text{ pF/cm}$	138
4.8	Distribution (left) and time-evolution (right) plots of the parameter $I_{\text{CCPL}_100\text{V}}$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 2.26 \times 10^{-13} \text{ A}$; standard deviation: $\sigma = 1.64 \times 10^{-13} \text{ A}$	138
4.9	Distribution (left) and time-evolution (right) plots of the parameter $I_{\text{CCPL}_100\text{V}}$ for samples irradiated with gamma + neutrons. Measurements from each test site are shown in different colors. Sample size: $N = 409$; mean: $\mu = 2.88 \times 10^{-9} \text{ A}$; standard deviation: $\sigma = 2.60 \times 10^{-9} \text{ A}$	139
4.10	Distribution (left) and time-evolution (right) plots of the parameter C_{ox} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 28.47 \text{ pF}$; standard deviation: $\sigma = 1.43 \text{ pF}$	140
4.11	Distribution (left) and time-evolution (right) plots of the parameter t_{ox} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 0.68 \mu\text{m}$; standard deviation: $\sigma = 0.04 \mu\text{m}$	140
4.12	Distribution (left) and time-evolution (right) plots of the parameter V_{FB} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = -3.10 \text{ V}$; standard deviation: $\sigma = 0.61 \text{ V}$	141
4.13	Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{ox-P}}$ for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = 36.71 \text{ pF}$; standard deviation: $\sigma = 1.39 \text{ pF}$	142
4.14	Distribution (left) and time-evolution (right) plots of the parameter $t_{\text{ox-P}}$ for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = 0.52 \mu\text{m}$; standard deviation: $\sigma = 0.02 \mu\text{m}$	143
4.15	Distribution (left) and time-evolution (right) plots of the parameter V_T for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = -4.71 \text{ V}$; standard deviation: $\sigma = 0.62 \text{ V}$	143
4.16	Distribution (left) and time-evolution (right) plots of the parameter S_{REF} for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = -0.90 \text{ pF/V}$; standard deviation: $\sigma = 0.11 \text{ pF/V}$	144
4.17	Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{int_LOW}}$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 0.89 \text{ pF/cm}$; standard deviation: $\sigma = 0.10 \text{ pF/cm}$	145

4.18	Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{int_LOW}}$ for samples irradiated with gamma + neutrons. Sample size: $N = 383$; mean: $\mu = 0.97$ pF/cm; standard deviation: $\sigma = 0.23$ pF/cm.	145
4.19	Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 1.67 \times 10^{13}$ Ω ; standard deviation: $\sigma = 1.67 \times 10^{13}$ Ω	146
4.20	Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for samples irradiated with gamma + neutrons. Sample size: $N = 443$; mean: $\mu = 1170.58$ M Ω ; standard deviation: $\sigma = 823.14$ M Ω	147
4.21	Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for CYRIC proton-irradiated samples. Sample size: $N = 65$; mean: $\mu = 267.34$ M Ω ; standard deviation: $\sigma = 205.11$ M Ω	147
4.22	Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for neutron-irradiated samples. Sample size: $N = 69$; mean: $\mu = 3671.45$ M Ω ; standard deviation: $\sigma = 1774.89$ M Ω	147
4.23	Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for gamma-irradiated samples. Sample size: $N = 71$; mean: $\mu = 20.76$ M Ω ; standard deviation: $\sigma = 8.95$ M Ω	148
4.24	Distribution (left) and time-evolution (right) plots of the parameter V_{PT} for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 14.99$ V; standard deviation: $\sigma = 0.75$ V.	148
4.25	Distribution (left) and time-evolution (right) plots of the parameter V_{PT} for samples irradiated with gamma + neutrons. Sample size: $N = 440$; mean: $\mu = 23.81$ V; standard deviation: $\sigma = 1.76$ V.	148
4.26	Box plot of the V_{PT} distribution for all irradiation types: pre-irradiated, gamma + neutrons, CYRIC protons, neutrons, and gamma rays. Each blue box represents 50% of the data (from Q1 to Q3), and the horizontal line inside the box marks the median. The upper and lower whiskers extend to $1.5 \times \text{IQR}$	149
4.27	Distribution (left) and time-evolution (right) plots of the parameter R_{bias} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 1.49$ M Ω ; standard deviation: $\sigma = 0.10$ M Ω	150
4.28	Distribution (left) and time-evolution (right) plots of the parameter R_{bias} for samples irradiated with gamma + neutrons. Sample size: $N = 443$; mean: $\mu = 1.74$ M Ω ; standard deviation: $\sigma = 0.14$ M Ω	150
4.29	Time evolution of the parameter R_{bias} for pre-irradiated samples up to a certain production time, with data points colored by Eq. A (red) and Eq. B (blue), and spline interpolations applied to each data set. The green vertical line indicates the point where the trends begin to diverge.	151

4.30	Box plot of the R_{bias} distribution for all irradiation types, normalized to +20 °C. Each blue box represents 50% of the data (from Q1 to Q3), and the horizontal line marks the median.	152
4.31	Distribution (left) and time-evolution (right) plots of the parameter V_{FD} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 210.25$ V; standard deviation: $\sigma = 21.10$ V.	153
4.32	Distribution (left) and time-evolution (right) plots of the parameter V_{FD} for neutron-irradiated samples. Sample size: $N = 264$; mean: $\mu = 767.09$ V; standard deviation: $\sigma = 81.85$ V.	153
4.33	Distribution (left) and time-evolution (right) plots of the parameter $I_{500\text{V}}$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 1.89 \times 10^{-9}$ A/cm ² ; standard deviation: $\sigma = 4.45 \times 10^{-10}$ A/cm ²	155
4.34	Distribution (left) and time-evolution (right) plots of the parameter $I_{500\text{V}}$ for neutron-irradiated samples. Sample size: $N = 286$; mean: $\mu = 7.26 \times 10^{-6}$ A/cm ² ; standard deviation: $\sigma = 2.90 \times 10^{-6}$ A/cm ²	155
4.35	Distribution (left) and time-evolution (right) plots of the parameter $I_{500\text{V}}$ for samples irradiated with gamma + neutrons. Measurements from each test site are shown in different colors. Sample size: $N = 440$; mean: $\mu = 2.84 \times 10^{-5}$ A/cm ² ; standard deviation: $\sigma = 7.67 \times 10^{-6}$ A/cm ²	155
4.36	Distribution (left) and time-evolution (right) plots of the parameter $\text{CCE}_{500\text{V}}$ for neutron-irradiated samples. Measurements from each test site are shown in different colors. Sample size: $N = 342$; mean: $\mu = 8120.91$ e ⁻ ; standard deviation: $\sigma = 697.24$ e ⁻	156
4.37	Distribution (left) and time-evolution (right) plots of the parameter $\text{CCE}_{500\text{V}}$ for Birmingham proton-irradiated samples. Sample size: $N = 231$; mean: $\mu = 12303.33$ e ⁻ ; standard deviation: $\sigma = 939.09$ e ⁻	156
4.38	Distribution (left) and time-evolution (right) plots of the parameter $\text{CCE}_{500\text{V}}$ for CYRIC proton-irradiated samples. Sample size: $N = 54$; mean: $\mu = 12530.13$ e ⁻ ; standard deviation: $\sigma = 670.68$ e ⁻	157
4.39	Six scatter plots with different correlation levels, exemplifying the full correlation range depending on the scattering behavior. Plot (E) illustrates the importance of the chosen range for correlation analysis [109].	160
4.40	Correlation between the pre-irradiated V_T and V_{FB} parameters.	161
4.41	Correlation between the pre-irradiated V_{PT} and S_{REF} parameters. Accepted values are shown in blue, while values from failed tests are shown in red.	162
4.42	Correlation between the $I_{500\text{V}}$ and V_{FD} parameters after neutron irradiation up to 5.1×10^{14} n _{eq} /cm ²	163
4.43	Correlation between the $\text{CCE}_{500\text{V}}$ after Birmingham-proton irradiation and the V_{FD} after neutron irradiation up to 5.1×10^{14} n _{eq} /cm ²	164

4.44	Correlation between the pre-irradiated V_{FD} and the V_{FD} after neutron irradiation up to 5.1×10^{14} n _{eq} /cm ²	164
4.45	V_{PT} extraction from the punch-through resistance (R_{PT}) curve, obtained through a voltage sweep from 0 V to -40 V. Production distribution: CERN-02; batch: VPA37921; wafer: W169.	165
4.46	V_{PT} (left) and R_{int_LOW} (right) extractions from a QA replacement Testchip. Production distribution: CERN-02; batch: VPA37921; wafer: W196.	166
4.47	C–V curves measured at 10 kHz from the MOS capacitor with p-stop for standard production batches (blue) and for samples from batch VPA37921 (low p-stop, red).	167
4.48	Time evolution of the S_{REF} parameter including all measured Testchips and replacement samples from production QA. The four batches exhibiting the lowest S_{REF} values are circled and labeled in red.	168
4.49	Time evolution of the V_{PT} parameter including all measured Testchips and replacement samples from production QA up to last low p-stop case. Data points are color-coded according to the furnace used for p-stop implantation (Eq. A in red and Eq. B in blue), while points with unknown equipment information are shown in green. Labels indicate wafer type and Testchip position within the wafer. An inset provides a magnified view of a narrow region of the plot. The four worst batches are highlighted and labeled in red. One data point corresponding to a measurement error is also shown.	169
4.50	Wafer layouts for sensor types SS (left), R0 (center), and R4 (right). Segments (strip rows) are labelled in the SS-type wafer. The Testchips are indicated in each case according to their position—and thus half-moon position—within the wafer.	170
4.51	R_{PT} vs. voltage curves obtained from PTP structure tests on Testchips from LEFT and RIGHT half-moons of batch VPA46225. For comparison, a standard batch (VPA45756) and a defective batch (VPA42646) are also shown, represented in black and red, respectively.	171
4.52	C–V curves obtained from MOS capacitors with p-stop on Testchips from LEFT and RIGHT half-moons of batch VPA46225. For comparison, a standard batch (VPA45756) and a defective batch (VPA42646) are also shown, represented in black and red, respectively.	172
4.53	Time evolution of the S_{REF} parameter including all measured QA Testchips, replacements, and half-moon Testchips. The four batches exhibiting the lowest S_{REF} values are circled and labeled in red.	172

4.54	Four representations of the V_{PT} parameter measured on four wafers from batch VPA50930 at a QA collaborative institute. In each subfigure, V_{PT} values from different sensor segments are shown in different colors: blue (segment 1), red (segment 2), and green (segment 4). The minimum threshold of 12 V is indicated by a dashed line.	173
4.55	Representations of the V_{PT} parameter measured on wafers from batch VPA53553 (left) and VPA50932 (right) at a QA collaborative institute. In each subfigure, V_{PT} values from different sensor segments are shown in different colors: blue (segment 1), orange (segment 2), and grey (segment 4). The minimum threshold of 12 V is indicated by a dashed line [110].	174
4.56	Current measured at the Coupling Capacitor in 5 V steps up to 100 V for several Testchips from batch VPA42891 before irradiation.	176
4.57	Current measured at the Coupling Capacitor in 5 V steps up to 100 V for several Testchips from batch VPA42891 after neutron irradiation up to $1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$	177
4.58	Comparison between a standard V_{FB} extraction (left) and a low- V_{FB} extraction (right) for Testchips from two production batches.	178
4.59	Time evolution of the V_{FB} parameter, ordered by delivery along the x-axis. A drop-off is observed from deliveries CERN-38 to CERN-45. A rectangle highlights the nine low- V_{FB} values for which Testchip replacements were selected.	179
4.60	Schematic showing the position of Testchips within wafers for SS, LS, and R1 wafer types (left), with QA Testchips circled in the DOWN half-moons. Mean V_{FB} values extracted from the eight tested wafers for each half-moon position (right).	180
5.1	R_{int} as a function of fluence for Main sensors with standard p-stop irradiated with gamma + neutrons, except for two additional intermediate points obtained with neutron-only irradiation (left). Adapted from [113]. The right plot shows R_{int} measured on QA Testchips after proton irradiation, including results from UP, MID, and LOW interdigitated structures.	187
5.2	C-V curves of MOS Capacitors with p-stop measured on four QA Testchips from the rejected batch VPA42646, together with representative C-V curves from QA Testchips of another rejected batch (VPA37921) and a good reference batch (VPA44666).	188
5.3	Dicing scheme of the Mini sensors obtained from R0-type wafers of the rejected batch VPA42646. Mini sensors from the left side of the wafer are circled in green, while those from the opposite side are circled in red.	189

5.4	R_{PT} curves measured on Testchips from the left and right half-moons for (a) type 1, (b) type 2, (c) type 3, and (d) type 4 of the special p-stop batches VPA50957 (red/blue) and VPA50958 (green/purple). Panel (e) presents a table summarizing the V_{PT} values extracted from plots (a)–(d) and the variation (Δ) between the left and right sides of the wafer.	191
5.5	C–V curves of the MOS Capacitors with p-stop measured on Testchips from the left and right half-moons for (a) type 1, (b) type 2, (c) type 3, and (d) type 4 of the special p-stop batches VPA50957 (red/blue) and VPA50958 (green/purple).	192
5.6	V_{PT} values measured on Testchips for the four p-stop process types under pre-irradiation, mid-fluence, full-fluence, and over-irradiation ($\gamma + n$) conditions. Pre- (green) and post-irradiation thresholds are indicated by green and red horizontal lines, respectively. Adapted from [114].	193
5.7	Strip-length- and temperature-normalized R_{int} values measured on UP, MID, and LOW interdigitated structures of Testchips for the four p-stop process types under mid-fluence, full-fluence, and over-irradiation ($\gamma + n$) conditions. Adapted from [114].	193
5.8	CCE as a function of voltage for all p-stop process types 1–4 and all irradiated Mini sensors (full fluence and over irradiation). Adapted from [114].	194
5.9	Schematic of the R0 Main sensor segmentation (left), indicating the left (green) and right (red) positions within the wafer, and the evolution of R_{int} with fluence and dose (right), measured for each segment on both sides of sensors from batch VPA42646 irradiated with $\gamma + n$	195
5.10	Collected charge as a function of voltage on Mini sensors irradiated with $\gamma + n$ up to $4.0 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ (VPA42646-W493), $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ (VPA42646-W531), and $1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ (VPA42646-W492).	196
5.11	Evolution of R_{int} with dose measured on Mini sensors irradiated only with gamma rays, for both the left (green) and right (red) sides of the wafer.	197
5.12	Evolution of R_{int} with dose measured on Mini sensors irradiated with $\gamma + n$, for both the left (green) and right (red) sides of the wafer.	197
5.13	3D schematic (top) and photograph (middle) of the mechanical support made of G10 material used for PS irradiations, and transverse view of the structure with the beam-incident points indicated (bottom) [122].	200
5.14	Mechanical support made of G10 material used for PS irradiations in 2022. Testchips and Mini sensors are placed in each sample cutout. Adapted from [123].	202
5.15	Sample classification for Experiments 1 and 2 from the IRRAD studies performed in 2022.	202

5.16	3D schematic (top) and photograph (middle) of the G10 mechanical support used for the PS irradiation experiment in 2023. Sample arrangement of all QA pieces from batch VPA41725 placed in the support (bottom), indicating the Testchips measured at IMB-CNM. Adapted from [124–126].	204
5.17	Post-annealing I–V curves measured on MD2 structures from the Testchips at $-20\text{ }^{\circ}\text{C}$ for all fluences (left). Leakage current at 700 V before and after annealing as a function of fluence (right).	206
5.18	R_{int} measured after annealing as a function of bias voltage for all fluences (left), and an extended view focusing on the lowest R_{int} range corresponding to higher fluences (right).	206
5.19	R_{int} evolution with fluence before and after annealing, measured on the LOW interdigitated structure of the Testchips at $V_{\text{bias}} = 500\text{ V}$.	207
5.20	Post-annealing R_{int} evolution with fluence, normalized by strip length, obtained from samples in Experiment 1 (left) and Experiment 2 (right) at $V_{\text{bias}} = 500\text{ V}$.	208
5.21	V_{PT} evolution with fluence, before and after annealing (left). Post-annealing V_{PT} evolution with fluence measured from Testchips in Experiment 1 and Experiment 2 (right) at $V_{\text{bias}} = 500\text{ V}$.	208
5.22	R_{bias} evolution with fluence before annealing, measured on Testchips from Experiment 1. Values are normalized to $+20\text{ }^{\circ}\text{C}$.	209
5.23	$\text{CCE}_{500\text{V}}$ as a function of fluence, measured on Mini sensors. Data points from studies performed in 2021 and 2022 (blue squares), and previous investigations are included [127].	209
5.24	Proton fluences measured from the seven Al foils in the setup structures, corresponding to the four nominal irradiation fluences (left). Leakage current measured at 500 V on twelve MD8s as a function of fluence (right). Adapted from [116, 125].	211
5.25	I–V curves measured on MD8s at different angles, in front of and behind G10 block, for both $5.1 \times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ (left) and $1.6 \times 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ (right) irradiation fluences.	211
5.26	Full depletion voltage (V_{FD}) measured at different irradiation angles (1.5° , 6° , 12° , and 90°) under different conditions: (a) $1 \times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ with G10 material, (b) $1 \times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ without G10 material, (c) $1 \times 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ with G10 material, and (d) $1 \times 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ without G10 material.	212
5.27	Post-annealing R_{int} evolution with fluence, normalized by strip length, obtained from Testchips oriented at 90° (top), 6° (middle), and 90° with G10 material (bottom). $V_{\text{bias}} = 500\text{ V}$.	213
5.28	Schematic of the PS proton beam influence on the interdigitated structures (UP, MID, and LOW) of Testchips oriented at 90° (left) and from Testchips at shallow angles (right).	214

5.29	Post-annealing $R_{\text{int_MID}}$ evolution with fluence, normalized by strip length, obtained from Testchips oriented at 90° with and without G10 material. $V_{\text{bias}} = 500$ V.	214
5.30	Post-annealing V_{PT} evolution with fluence, obtained from Testchips oriented at 90° (top), 6° (middle), and 90° with G10 material (bottom). $V_{\text{bias}} = 500$ V.	216
5.31	$\text{CCE}_{500\text{V}}$ measured at four target fluences for several irradiation angles, with and without G10 material (left), and $\text{CCE}_{500\text{V}}$ measured at several irradiation angles without G10 material (right). Measurements were performed after annealing for 80 minutes at 60°C [123].	217
5.32	$\text{CCE}_{500\text{V}}$ evolution as a function of annealing time at 60°C , measured on Mini sensors irradiated to fluences ranging from $3.9 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ to $1.2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Adapted from [123].	217
5.33	$\text{CCE}_{500\text{V}}$ as a function of fluence, measured on Mini sensors. Data points from the 2023 IRRAD experiment (black squares and rhombus) and previous investigations are included [116].	218
5.34	I-V curves measured on MD2 structures from the Testchips at -20°C and $\text{RH} < 5\%$ for all extreme fluences (left): $2.3 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4470), $5 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4430), and $1 \times 10^{18} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4467).	221
5.35	R_{int} evolution with fluence, normalized by strip length, obtained from Testchips irradiated with neutrons (extreme fluences) and $\gamma + n$ (lower fluences). Mean and standard deviation values are shown in yellow. Extension of the R_{int} plot in the extreme fluence range. $V_{\text{bias}} = 500$ V.	222
5.36	R_{bias} evolution with fluence (left), obtained from Testchips irradiated with neutrons (extreme fluences) and $\gamma + n$ (lower fluences). I-V measurements between isolated pads and with the probe tips in the air (right).	222
5.37	Time-evolution plot of the V_{FD} parameter for pre-irradiated Testchips up to middle of production, sorted by batch (top) and ingot (bottom), with each point labelled by the corresponding ingot number.	225
5.38	Time-evolution plot of the V_{FD} parameter for neutron-irradiated Testchips up to middle of production, sorted by QA delivery (top) and by ingot number (bottom).	226
5.39	Number of ingots per production batch.	226
5.40	Frequency distribution of the number of ingots per batch.	227
5.41	Number of production batches per ingot.	227
5.42	Frequency distribution of the number of batches per ingot.	228
5.43	Number of wafers with respect to batches.	228
5.44	Number of wafers with respect to ingots.	229

5.45 Ingot-batch heatmap counting the number of wafers per ingot and per batch.	229
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List of Tables

1.1	Layout parameters for the ITk Strip Barrel, including sensor strip length and pitch [61, 66].	36
1.2	Layout parameters for the ITk Strip Endcap, including sensor strip length and pitch [61, 66].	39
1.3	Features of the Barrel and Endcap sensors, including their ring position, total number of sensors, number of rows, channels per sensor, and minimum/maximum pitch [51].	41
2.1	Testchip structures belonging to Category A or Category B.	57
2.2	Strip length of all Interdigitated structures according to their relative position in the Testchip (LOW, MID, UP) and the Testchip type.	60
2.3	Schematic initial plan for QA pieces (Testchip&MD8 and Mini&MD8) irradiated with protons (p), neutrons (n), or gamma-rays (γ).	75
2.4	Schematic plan for QA pieces (Testchip&MD8 and Mini&MD8) irradiated with protons (p), neutrons (n), or gamma-rays (γ) under the steady-state production regime.	76
3.1	Test types associated with all stages of the QA piece Sensor Testchip&MD8.	119
3.2	Test types associated with all stages of the QA piece Sensor Mini&MD8.	119
3.3	List of all tests associated with the PRE-IRRAD TESTS and POST-IRRAD TESTS stages of the QA piece Sensor Testchip&MD8.	120
3.4	All parameter minimum and maximum thresholds from production QA, associated with each device, test, parameter, and irradiation type.	123
3.5	Legend of thresholds from Table 3.4, showing three types: those from the specifications, those modified during production QA, and the “consistency check” thresholds.	124
4.1	Summary of all QA results and updated thresholds for all relevant irradiation types and parameters, based on all tests performed on Testchips, MD8s, and Mini sensors.	158
4.2	Interpretation of the Pearson correlation coefficient according to its absolute magnitude. Adapted from [109].	159
4.3	$C_{\text{int_LOW}}$, $C_{\text{int_MID}}$, $C_{\text{int_UP}}$, and V_{PT} values measured on the VPA37921-W169 Testchip and all replacement samples from the same batch.	167

4.4	C_{coupl} values before and after neutron irradiation up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, measured on ten Testchips from batch VPA42891.	176
4.5	Lowest V_{FB} values observed during the later stages of production (at the time of this analysis), together with the corresponding values obtained from Testchip replacements for the affected batches.	180
4.6	Batches rejected for QA and QC reasons, and the number of sensors rejected per batch. Adapted from [66].	181
5.1	Four p-stop process conditions used in the fabrication of batches VPA50957 and VPA50958.	184
5.2	Testing distribution plan for Main sensors, half-moons (HM), Mini sensors, and Testchips (TC) of the special p-stop batches (VPA50957 and VPA50958). All devices are classified according to the p-stop processing type and radiation fluence: pre-irradiated, mid fluence ($5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$), full fluence ($1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$), and over-irradiated ($3.4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$).	185
5.3	Irradiation ($\gamma + n$) doses and fluences for each Main and Mini sensor used in Experiments 1 and 2 of the post-irradiation p-stop study.	189
5.4	Gamma irradiation doses for each Mini sensor used in Experiment 3 of the post-irradiation p-stop study, for both the left and right sides of the wafers.	190
5.5	Testchips from batches VPA38186 and VPA37921 used in Experiments 1 and 2, respectively, at four different fluences.	202

The Large Hadron Collider (LHC) at CERN is preparing for its transformation into the upgraded High-Luminosity LHC (HL-LHC), which aims to significantly enhance the accelerator's performance during the 2030–2041 operational period. For the construction of the HL-LHC, new particle tracking detectors have been designed to withstand the major radiation conditions expected from the collisions in the experiments. In particular, the Inner Tracker (ITk) of ATLAS will be a fully-silicon detector composed of pixel sensors and strip sensors.

The fundamentals of semiconductor physics and strip sensor technology are presented in Sections 1.1 and 1.2 of this chapter, followed by a description of the basic properties of strips sensors and the effects of radiation on them (Section 1.3). The ATLAS Inner Tracker and the characteristics of the strip sensors are then presented in Section 1.4.

1.1 Fundamentals of Strip Sensors

1.1.1 Silicon Properties as a Semiconductor

Silicon (Si) is an element from group IV of the periodic table and is widely used in semiconductor device fabrication. Silicon is arranged in a crystalline structure with key electronic properties that make it an ideal substrate for detectors, transistors, and integrated circuits. It crystallizes in a diamond cubic lattice, with each atom forming four covalent bonds with its neighbors. The building block of the unit cell consists of a tetrahedral structure equivalent to a body-centered cubic lattice with missing atoms at four of the corners. Figure 1.1 (a) shows the stable and uniform crystal structure (unit cell) of silicon, highlighting the building block with a dashed line. The tetrahedral bonds of the silicon building blocks are also shown in both 3D (center) and 2D (right) schematic configurations.

The tetra-covalent bond represented in Figure 1.1 (b) and Figure 1.1 (c) extends periodically in the silicon crystal lattice, giving a bond configuration like that shown in Figure 1.2 (left). Energetically, the energy levels of each isolated silicon atom split into infinitely close energies when the atoms are arranged in a lattice. This results in the formation of

valence and conduction bands, such as those represented in the band energy diagram on the right side of Figure 1.2.

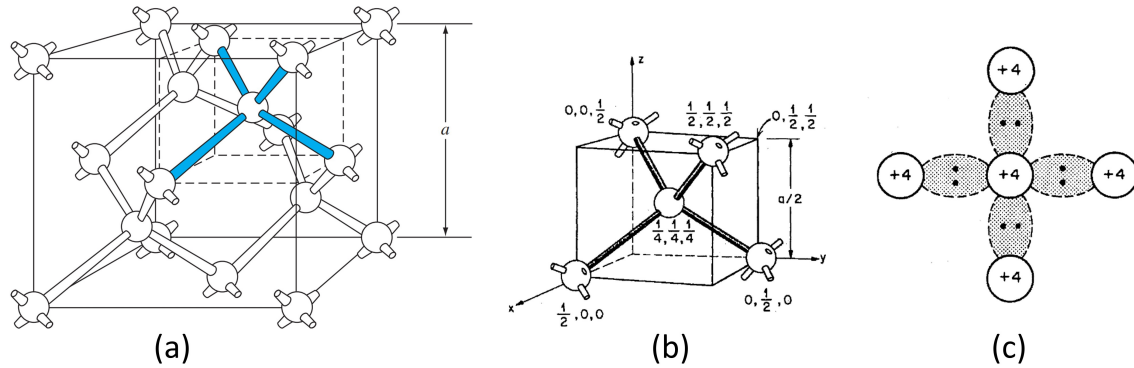


Figure 1.1: (a) Unit cell of the silicon crystalline structure, (b) tetrahedral building block in the diamond cubic lattice, (c) and schematic two-dimensional representation of the tetra-covalent bonds (right) [1, 2].

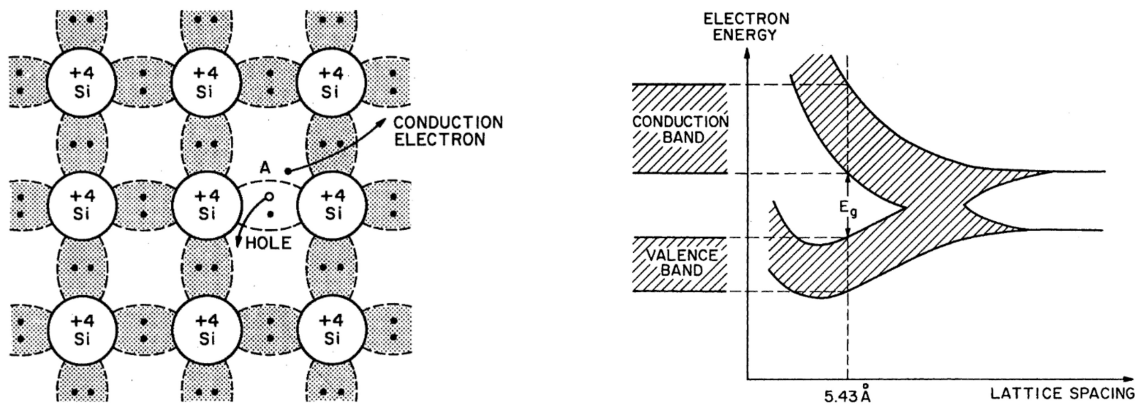


Figure 1.2: Two-dimensional silicon crystal lattice with an electron-hole pair formed after the breaking of a covalent bond at position A (left), and diagram of silicon electron energy with respect to lattice spacing ($5.43 \text{ \AA}$ in crystalline silicon at room temperature) (right) [2].

There exist energy levels between the valence and conduction bands where no possible energy states are permitted, called band gaps. At absolute zero, all valence-band states are occupied by electrons, while the conduction band is empty, and the Fermi level (E_F)—the highest occupied electron energy level in intrinsic semiconductors at 0 K —is located in the middle of the energy gap. At room temperature, a band gap of approximately $E_g = 1.12 \text{ eV}$ separates the two bands. This is the minimum energy required to break electrons free from their bonds, allowing them to move into the conduction band and leaving holes in the valence band. This accessible energy is what gives silicon its semiconductor properties, with charge-carrier mobility manipulated by temperature control, doping (the introduction of impurity atoms), or the application of external electric fields. Both electrons (negative) and holes (positive) act as charge carriers in the conduction and valence bands, respectively.

The characteristics of silicon described so far refer to intrinsic silicon, that is, pure crystalline silicon. In intrinsic silicon, charge mobility can only be tuned by thermally exciting electrons from the valence band to the conduction band. The mobility of the charge carriers is defined as:

$$\mu = \frac{|v|}{E} \quad (1.1)$$

where v is the drift velocity of the carriers and E the module of the electric field. This parameter is always defined as positive for both holes and electrons, despite the positive or negative sign of their velocities. The conductivity is then calculated from the electron and hole mobilities, μ_e and μ_h :

$$\sigma = (ne\mu_e + pe\mu_h) \quad (1.2)$$

where n and p are the electron and hole concentrations, and e is the charge of the electron.

In intrinsic silicon, the carrier concentration (n_i) is the same for electrons and holes. At room temperature, $n = p = n_i \approx 1.0 \times 10^{10} \text{ cm}^{-3}$.

The mobilities are $1350 \text{ cm}^2/\text{V}\cdot\text{s}$ for electrons and $480 \text{ cm}^2/\text{V}\cdot\text{s}$ for holes in intrinsic silicon at room temperature. The intrinsic resistivity, obtained as the inverse of the conductivity, is $\rho = 235 \text{ k}\Omega\text{cm}$ [3–5].

For silicon electronic applications as a semiconductor material, conductivity must be enhanced by adding external impurity atoms (dopants) into the silicon crystal lattice. This process is known as doping, and it is applicable not only to silicon but to any intrinsic semiconductor material.

Dopants are classified into two types:

- **Donor dopants (n-type):** Elements from group V of the periodic table, such as phosphorus or arsenic, with five valence electrons. When introduced into the silicon crystal lattice, the extra electrons can be excited to the conduction band with minimal thermal energy, increasing the free electron concentration.
- **Acceptor dopants (p-type):** Elements from group III of the periodic table, such as boron or gallium, with three valence electrons. Unlike the effect produced by donor atoms, these elements create electron-deficient sites in the silicon crystal lattice, providing holes in the valence band as the majority carriers.

Depending on the positions occupied by the dopants in the crystal lattice, two different kinds of dopants are also distinguished: substitutional impurities, located at lattice sites (vacancies), and interstitial impurities, located between normal lattice sites. Both types of impurities are represented in Figure 1.3.

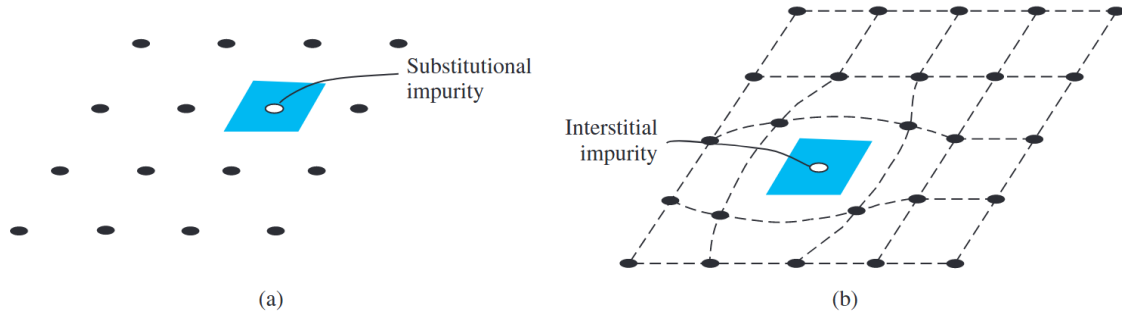


Figure 1.3: Two-dimensional crystal lattices with (a) a substitutional impurity and (b) an interstitial impurity, respectively [1].

A doped (extrinsic) n-type or p-type semiconductor enhances the concentration of electrons or holes, respectively, increasing the conductivity by several orders of magnitude compared to intrinsic semiconductors. Consequently, silicon's electrical properties can be tuned by varying the amount and type of dopants, with conducting electrons dominating in n-type silicon and holes as the primary carriers in p-type silicon.

The scheme in Figure 1.4 shows the energy band gaps for (a) intrinsic and (b, c) extrinsic silicon, the latter being split into p-type and n-type silicon. While electron excitations are thermally promoted in pure silicon, the introduction of dopants dominates in extrinsic silicon at room temperature. For p-type silicon, an extra-hole energy level appears just above the valence band in the band energy diagram. With a small energy supply, an electron from the valence band can jump to that acceptor energy level and ionize acceptor ions, creating more holes in the valence band. Similarly, for n-type silicon, a donor energy level is located just below the conduction band, to which electrons can be promoted with very little energy. The Fermi level, for which the electron occupation probability is 50%, shifts downward—towards the valence band in p-type material—or upward—towards the conduction band in n-type material—affecting the electrical behavior of silicon [2, 6–8].

In extrinsic silicon, the number of carriers comes mostly from ionized atoms introduced into the crystal lattice. N_D and N_A are the concentrations of donor and acceptor ions, respectively, and are much larger than the intrinsic carrier concentration, n_i . Consequently, the conductivity of n-type and p-type silicon can be approximated as:

$$\sigma_{\text{n-type}} \approx eN_D\mu_e \quad (1.3)$$

$$\sigma_{\text{p-type}} \approx eN_A\mu_h \quad (1.4)$$

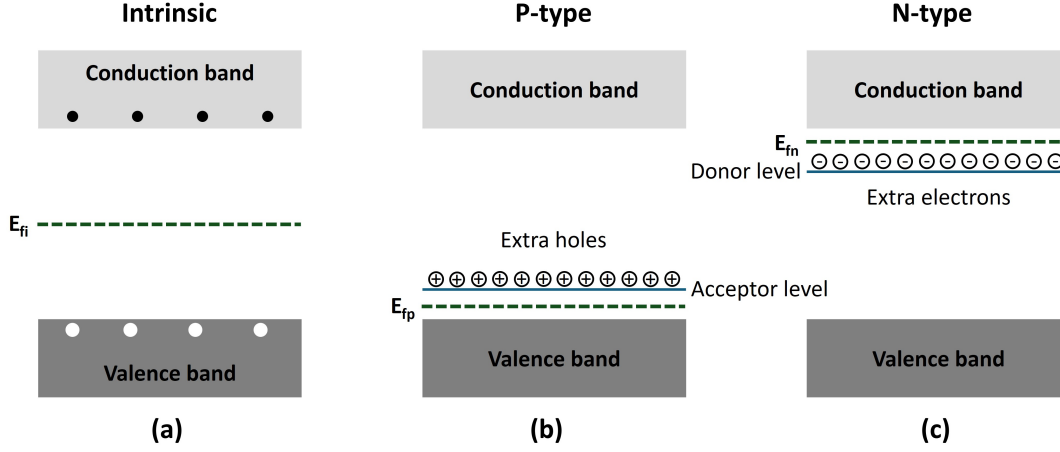


Figure 1.4: Schematic energy band gaps for (a) intrinsic, (b) p-type, and (c) n-type semiconductors.

1.1.2 PN Junction

The functionality of silicon strip sensors relies on the physics of a reverse-biased pn junction, with each strip forming a pn junction with the bulk silicon. The resulting well-defined electric field enables the efficient collection of charges generated by particles crossing the detector. In practice, the strips are segmented electrodes that read out these charges, providing spatial resolution in one dimension.

A pn junction is the fundamental unit of most semiconductor devices, such as diodes, transistors, and other key microelectronic components. It is formed by implanting dopants of opposite types into adjacent regions of a semiconductor. The side with acceptor ions (holes as majority carriers) becomes p-type, while the side with donor ions (electrons as majority carriers) becomes n-type.

At the interface between the two pn-junction regions, holes from the p-side diffuse to the n-side and recombine with electrons. Similarly, electrons from the n-side diffuse to the p-side and recombine with holes. This recombination leaves behind charged dopant ions on each side of the interface, resulting in the formation of the depletion region, where no free carriers are present. An electric field appears in the depletion region at thermal equilibrium, directed from the n-side (positive ions) to the p-side (negative ions), generating a potential barrier without any external force [9, 10]. This potential is the built-in potential, V_{bi} , given by:

$$V_{bi} = \frac{k_B T}{e} \ln \left(\frac{N_A N_D}{n_i^2} \right) \quad (1.5)$$

where k_B is the Boltzmann constant, and T is the temperature.

Figure 1.5 illustrates the n-type and p-type regions forming a pn junction, with accompanying energy band diagrams. The depletion region in Figure 1.5(b) is slightly wider on the p-side than on the n-side, simulating a realistic scenario with a highly n-doped region in a lowly p-doped substrate.

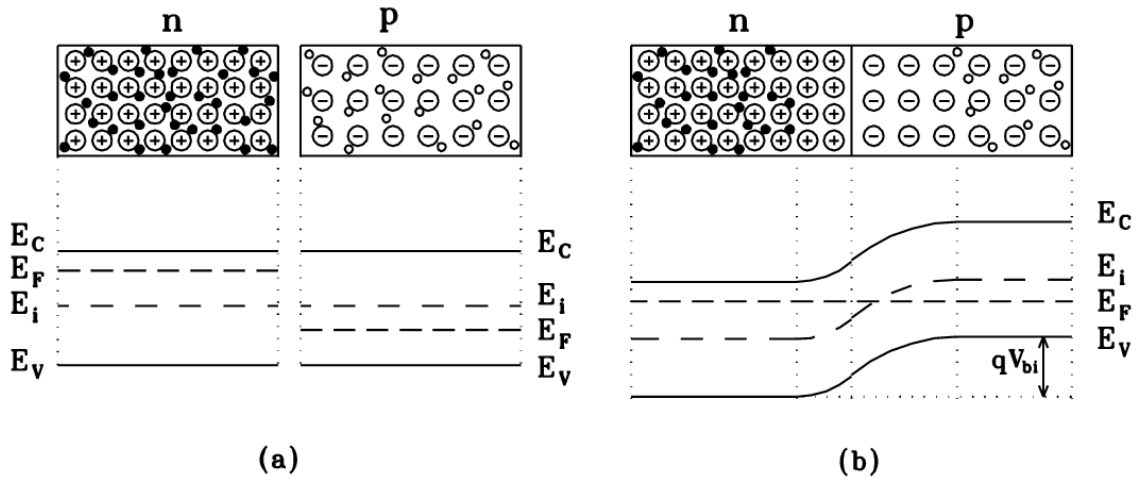


Figure 1.5: Drawings and energy band diagrams of (a) separated n-type and p-type regions, and (b) after forming a pn junction in thermal equilibrium [2].

When an external forward bias is applied to a pn junction, the depletion region narrows as electrons and holes recombine closer to the interface. Conversely, under a reverse bias V_{bias} , the depletion region width W increases according to:

$$W = \sqrt{\frac{2\epsilon_{Si}}{e} \frac{(V_{bi} + V_{bias})}{N_{eff}}} \quad (1.6)$$

where ϵ_{Si} is the silicon permittivity, and $N_{eff} = |N_A - N_D|$ is the effective doping concentration contributing to the electric field.

The depletion region can be widened until the silicon bulk is fully depleted, at which point the width equals the wafer thickness in silicon strip sensors (see Section 1.2). Full charge collection is then achieved with maximum efficiency. The minimum bias voltage required to fully deplete the semiconductor is the full depletion voltage, V_{FD} , calculated as:

$$V_{\text{FD}} = \frac{eN_{\text{eff}}d^2}{2\epsilon_{\text{Si}}} \quad (1.7)$$

where d is the depletion width at full depletion, corresponding to the semiconductor thickness. At full depletion, $V_{\text{bias}} \gg V_{\text{bi}}$ is assumed.

1.1.3 The Strip Sensor

Silicon strip sensors are widely used in high-energy physics (HEP) experiments due to their excellent capability for charged-particle tracking. They offer high spatial resolution, fast signal response, and robust performance under the extreme radiation conditions present in modern colliders such as the Large Hadron Collider (LHC) at CERN. These sensors are essential components of the detectors installed in the advanced tracking systems of experiments such as ATLAS¹ and CMS². The integration of the sensors into these systems provides precise position measurements that enable the reconstruction of particle trajectories, momentum, and decay vertices with micrometer-level accuracy.

The concept of silicon strip sensors relies on the ability to fabricate many parallel, narrow electrodes (“strips”) on a large silicon wafer, with each strip functioning as an independent readout channel. In other words, the wafer is segmented into several strips, thereby reducing occupancy (the fraction of readout channels that register a collision in each event) while maintaining manageable electronic complexity. This makes strip sensors a cost-effective solution for covering large areas in a tracking detector. Unlike the p-on-n strip sensors currently used in the ATLAS Inner Detector, the ATLAS Inner Tracker (ITk) will employ n-on-p strip sensors in the HL-LHC upgrade for higher radiation tolerance, better long-term performance, and to avoid type inversion in the bulk.

1.2 Strip Sensor Technology

1.2.1 Strip Formation and Operating Principles

The strips are narrow, long doped implants placed on the surface of silicon wafers. They are implanted in parallel using lithographic techniques, maintaining a constant strip pitch on the order of micrometers. This segmentation allows each strip to function as a reverse-biased diode with the bulk acting as an individual sensing element [2, 4, 11].

¹ ATLAS: A Toroidal LHC Apparatus

² CMS: Compact Muon Solenoid

The strip width, pitch, and length determine the channel capacitance and the sensor's spatial resolution. Strips are isolated from each other using techniques such as p-stop, p-spray, or oxide isolation, which act as barriers against undesired surface or leakage currents.

Regarding implantation technology, pn junctions can be formed by implanting p-type dopants into an n-type silicon bulk (p-on-n) or n-type dopants into a p-type bulk (n-on-p). Double-sided sensors exist with orthogonal strip orientations on opposite faces, providing two-dimensional position resolution.

P-on-n technology has been widely employed in colliding-beam experiments due to its lower cost and simpler fabrication. This type of sensor relies on hole collection, which have lower mobility compared to electrons. While p-on-n sensors perform well in moderate radiation environments, exposure to high radiation leads to “type inversion” in the silicon bulk. High-energy particles displace silicon atoms from their lattice sites, and a significant fraction of the resulting defects behave electrically like p-type dopants, which increases the effective acceptor concentration and converts the n-type substrate into p-type (see Subsection 1.3.2 for a discussion on bulk damage effects).

In contrast, n-on-p sensors avoid type inversion even under high radiation conditions, since the p-type bulk becomes increasingly p-type due to radiation-induced acceptor creation. In these detectors, the signal is dominated by electrons, which have higher drift velocity and are less susceptible to trapping than holes (see Subsection 1.3.2). Despite the higher technological complexity of n-on-p sensors, for instance the need for strip isolation, their improved performance and enhanced long-term operation under HL-LHC conditions have prompted the replacement of p-on-n technology with the more efficient n-on-p technology in the silicon strip sensors for the upcoming ATLAS and CMS trackers.

When an ionizing particle crosses the silicon in a colliding-beam experiment, it interacts with atoms in the bulk, producing a cloud of electron-hole pairs. Figure 1.6 illustrates two examples of particles crossing the silicon at different angles. In a fully depleted n-on-p sensor, an electric field extends from the top side (n-type implants) to the bottom side (p-type region), causing electrons and holes to drift toward electrodes of opposite polarity.

For angled tracks, as shown in the right-hand image of Figure 1.6, two or more strips may contribute to the collected charge. Evaluating the charge deposition among these strips allows spatial resolution beyond the limit set by the strip pitch. Given the higher mobility of electrons compared to holes, the collection time and signal shape in n-on-p devices are dominated by electron transport [12].

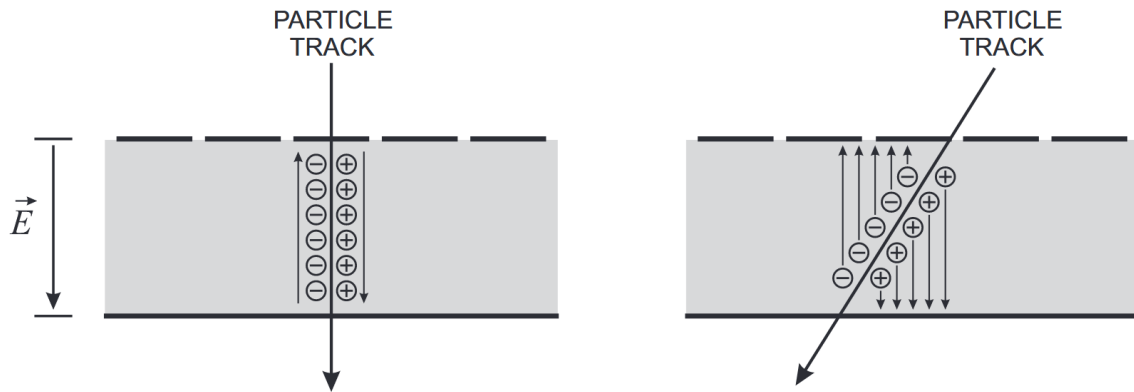


Figure 1.6: Schematic drawing of a transversal section of the silicon bulk showing a particle crossing perpendicular to the surface (left) and a particle crossing at an angle (right) [12].

Strip technology is typically implemented with AC-coupled sensors, in which the doped silicon strips do not directly transmit charge to the front-end electronics. Instead, the collected signal is transferred via a capacitive link (AC coupling) to a second set of metallic strips. These metallic strips are then connected (DC coupling) to a charge-sensitive preamplifier on the readout chip, where customized ASICs (Application-Specific Integrated Circuits) amplify and process the signal before further analysis [4, 13].

1.2.2 Strip Sensor Functionality

The silicon strip sensor shown in Figure 1.7 illustrates a typical design used for High Energy Particle (HEP) tracking experiments. Following the n-on-p technology described previously, the strips are formed by n-type implantations on a lightly p-type doped substrate. The main structural elements of an n-on-p detector are described below.

The **substrate** of a silicon n-on-p strip sensor is made of high-resistivity p-type silicon, typically in the form of a 200–300 μm thick wafer. Under full depletion conditions, the entire bulk is devoid of mobile charges, which maximizes both the charge collection efficiency and the signal amplitude when electron-hole pairs are generated within the substrate. In n-on-p sensors, the depletion region extends from the backplane (a lightly p-doped region) toward the front side, and the bulk is reverse-biased, typically up to 500 V, to achieve full depletion under operational conditions. The bulk thickness, resistivity, and p-doping profile are key parameters that influence depletion and subsequent charge collection.

The **strips** are the most critical structures of the sensor. Segmented n-doped strips are created, typically through phosphorus implantation, on the front side of n-on-p sensors, enabling electron collection. Because electrons have higher mobility than holes, charge is collected more quickly, reducing the probability of trapping and improving the overall

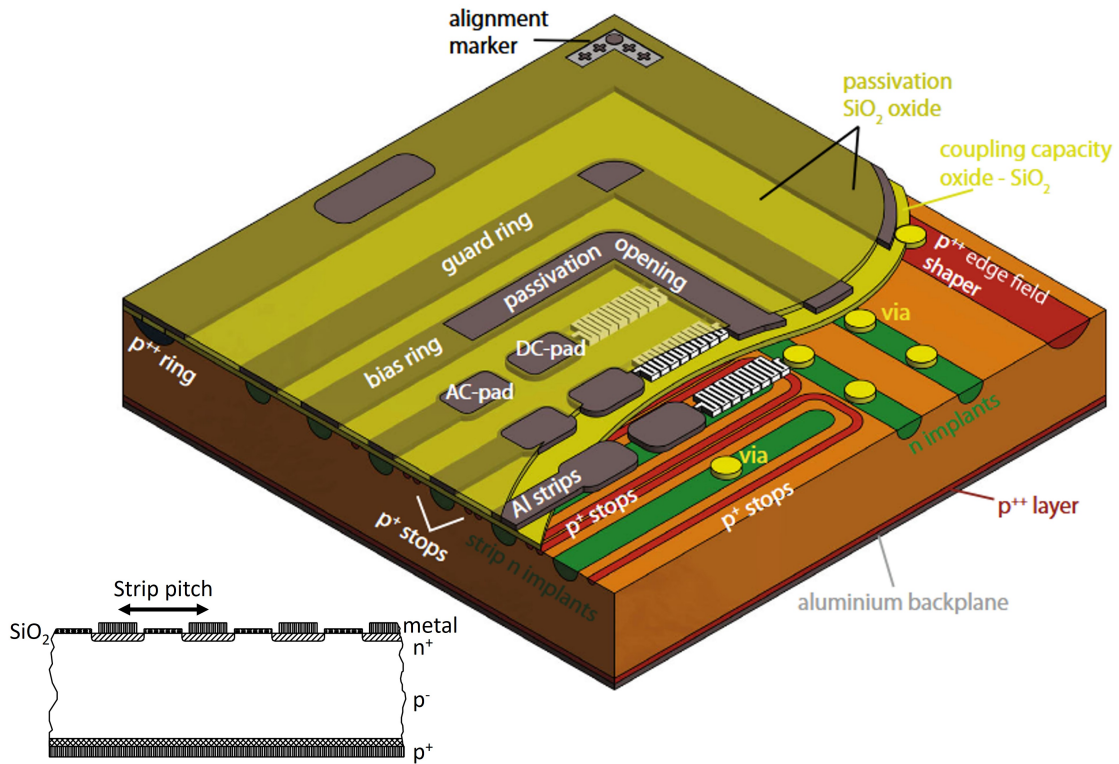


Figure 1.7: Schematic 3D drawing of an n-on-p strip silicon sensor used in CMS HL-LHC experiments [4]. The bottom-left inset shows a simplified cross-sectional view of the sensor. Adapted from [2].

detector performance. As a result, n-on-p sensors are preferred over p-on-n sensors for particle tracking applications, particularly in high-radiation environments.

The strip pitch is typically set between $50\ \mu\text{m}$ and $100\ \mu\text{m}$ in colliding-beam experiments, which determines the intrinsic spatial resolution of the sensor. Variations in the implant width and inter-strip spacing, however, affect the performance of AC coupling and the signal-to-noise ratio [12].

A **metal strip** is deposited on top of each implant, serving as the upper electrode for the readout chip. An **AC coupling capacitor** may be integrated into the sensor, the readout chip, or in between both. In the detector illustrated in Figure 1.7, the coupling capacitor is integrated into the sensor with a dielectric layer between the metal and the n-type implant. The dielectric is typically SiO_2 with a thickness of $100\text{--}200\ \text{nm}$, although Si_4Al_3 can also be used [14, 15]. This implant-oxide-metal stack blocks DC bias voltage while allowing fast electrical pulses (AC) generated by the collected charge carriers to pass to the readout circuit. Sufficient doping of the implant is required to ensure ohmic behavior at the metal contacts; otherwise, rectifying (Schottky-like) behavior could arise, compromising the intended capacitive coupling [16].

A thicker **field oxide**, 500–1000 nm, remains in the inter-strip spacing regions and serves to electrically isolate the strips by preventing surface leakage currents between them. It also reduces the influence of surface states and helps control the electric field distribution, ensuring that the signal charge flows along the intended paths. The inset in Figure 1.7 shows a schematic transversal section of an n-on-p silicon strip sensor, illustrating the relationship between implant, metal, and oxide layers on a p-doped substrate. A **passivation** layer is deposited last over the sensor surface to stabilize the interface properties and shield the device from moisture and other environmental effects. Openings are applied to ensure proper contact with AC, DC, bias, and guard-ring metal pads [17, 18].

AC and DC pads are metal contacts placed over each strip. The AC pads connect to the entire strip metal and ensure AC coupling through the oxide layer beneath. DC pads provide a direct electrical connection to the strip implant via an opening through the oxide.

Positive trapped charges in the oxide and at the silicon-oxide interface are already present in as-grown oxides and increase further with ionizing radiation dose. These charges induce an electron inversion layer in the p-type silicon surface, which generates surface leakage currents contributing to lateral conduction between neighboring n-type strips, as shown in Figure 1.8(a). To prevent this effect, proper isolation of consecutive strips is necessary in n-on-p sensors, and several techniques are employed.

P-stop isolation involves creating highly doped p-type lines surrounding each n-type strip, typically through boron implantation. These implants are centered between neighboring strips and do not contact the strip implants directly (Figure 1.8(b)). The **p-spray** technique provides an alternative, forming a diffuse p-dopant layer just below the SiO₂ (Figure 1.8(c)). The continuous p-spray layer prevents electron accumulation beneath the oxide.

P-stop isolation is technologically more complex because it requires a minimum strip pitch; a narrower strip pitch leads to an increased number of processing defects. Moreover, the high electric field at the p-stop edges can give rise to micro-discharges, leading to a reduction in the signal-to-noise ratio and potentially causing sensor failure when operating at high voltages. In contrast, p-spray isolation is simpler to implement, as it relies on a uniform shallow p-type implant and does not require an additional mask, unlike the p-stop process. After irradiation, p-spray isolation generally exhibits better performance than p-stop; however, at high irradiation levels it can lead to early breakdown and a significant increase in leakage current [19, 20]. A combination of p-stop and p-spray isolation can also be employed to enhance isolation performance, as shown in Figure 1.8(d), by balancing the advantages of each technique.

Another isolation method uses wider metal strips as “field plates” (Figure 1.8(e)), which, when biased, repel electrons from the region around the strip implants. This effect can also be achieved by adding an extra metal layer on top of the field oxide between strips, removing electrons from the accumulation layer [21].

All these isolation techniques help control surface charge and minimize inter-strip leakage current, even after high levels of irradiation.

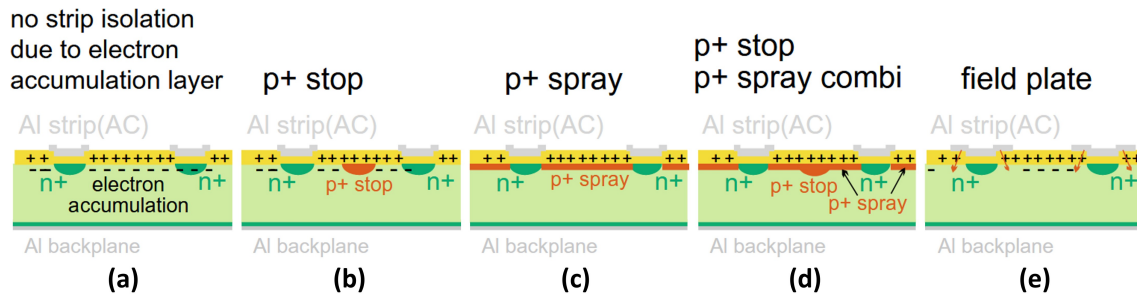


Figure 1.8: Strip isolation mechanisms used in n-on-p detectors: (a) Strips with no isolation, (b) strips isolated with p-stop, (c) strips isolated with p-spray, (d) strips isolated with a combined p-stop and p-spray effect, and (e) field-plate isolation. Adapted from [4].

For full depletion of silicon, a reverse-bias voltage is applied between the strips and the backplane of the sensor. However, in capacitively-coupled sensors this bias voltage is not applied directly through the DC pads; instead, it is applied to a bias ring connected to each strip via a bias resistor, which controls the DC potential.

The **bias resistors** are typically made of polysilicon and located at the end of each strip, with resistance values ranging from a few $M\Omega$ to several $G\Omega$. They stabilize the DC potential (maintaining a uniform and stable DC voltage on all strips during detector operation), ensure proper bulk depletion, and prevent strip potential shifts caused by leakage currents. The large resistance electrically isolates each strip from the bias ring, thereby limiting the coupling of voltage fluctuations from the high-voltage supply into the readout channel. At high (signal) frequencies, the resistor behaves effectively as an open circuit, preventing AC signal charge from leaking to the bias ring.

While polysilicon biasing is the most commonly used method for its radiation tolerance, two alternative methods exist: punch-through biasing, which reduces the spacing between the strip implant and the bias ring implant, and FOXFET biasing, which forms a transistor-like structure at the end of the strip. In both cases, electron flow occurs from the strip implant to the bias ring through the substrate near the silicon-oxide interface. Reducing the spacing between the implant and bias ring may lead to a short circuit if the potential barrier is exceeded. These methods are illustrated in Figure 1.9 for p-on-n sensors, although they are also applicable to n-on-p sensors [22–27].

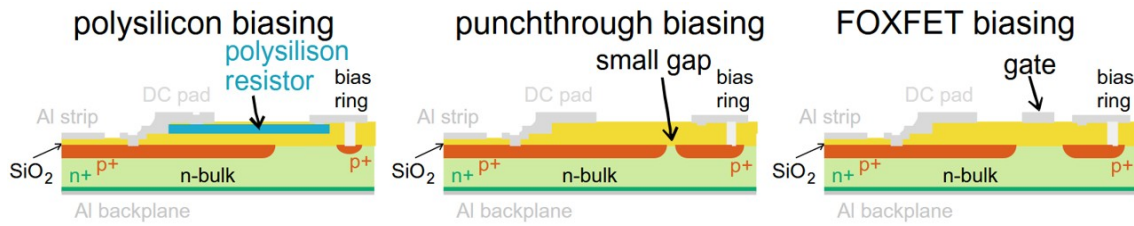


Figure 1.9: Schematics of sensor biasing methods: polysilicon resistor (left), the punch-through effect (center), and FOXFET transistor (right). Adapted from [4].

The **bias ring** is a metal ring surrounding the active strip area. Its main functions are to bring all strips to the same bias voltage via the resistors, stabilizing the DC potential, and collect surface and leakage currents. One or more **guard rings** surround the bias ring to shape the electric field at the sensor edges, preventing premature breakdown and gradually distributing the high voltage from the active area to the edges.

In n-on-p sensors, the **backplane** is uniformly implanted with a highly p-doped layer (typically boron) to form an ohmic contact, and the entire backplane is metalized. In p-on-n sensors, an n-doped layer is implanted instead. The backplane metal and the bias ring in the front serve as terminals to apply the reverse-bias voltage for bulk depletion [28].

The frontside edges are typically implanted with a broad “**edge-field shaper**” of the same type as the backside implantation (see Figure 1.7). No depletion occurs between the edge rings and the backplane, thereby isolating the active region from the sensor sidewalls. This design prevents the depletion region from reaching cracks or defects at the sensor borders, which would otherwise induce leakage currents in the strip area. Modern “slim edge” technologies extend this concept by optimizing the edge termination and field-shaping structures, allowing a significant reduction of the inactive regions at the sensor periphery while maintaining electrical stability and breakdown performance [29, 30].

Finally, the “alignment marks” shown in Figure 1.7 are fiducial marks that serve as precise (micrometric scale) reference points for alignment and positioning during fabrication, assembly, and measurement processes.

1.3 Basic Properties and Radiation Effects of Silicon Strip Sensors

As explained in previous sections, silicon strip sensors are reverse-biased pn-junction devices in which the electrodes are segmented into parallel strips, providing spatial

resolution for charged-particle tracking experiments. Several measurable electrical properties determine the efficiency of depletion, charge transport, noise generation, and the interaction of the device with the front-end electronics [6, 31]. This section presents these properties, along with the effects of radiation on the sensors and their impact on the electrical characteristics.

1.3.1 Basic Electrical Properties

1.3.1.1 Full Depletion Voltage (V_{FD})

Bulk depletion occurs when a reverse bias is applied to the pn junction. Under this electric condition, the electric field removes free charge carriers from the depletion region until the applied bias voltage (V_{bias}) reaches or exceeds the full depletion voltage (V_{FD}), leaving the entire bulk free of mobile charges. In a one-sided abrupt junction, the fully depleted layer extends into the weakly doped bulk, ensuring that the entire silicon thickness is active for charge collection. In these conditions, V_{FD} is directly determined by the bulk thickness d and the effective doping concentration N_{eff} , as expressed in Eq. (1.7) in Section 1.1.

1.3.1.2 Breakdown Voltage (V_{BD})

The breakdown voltage V_{BD} is the maximum reverse bias that the sensor can withstand before the pn junction undergoes electrical breakdown. When breakdown occurs, the leakage current increases abruptly and the junction becomes highly conductive. Two main mechanisms can lead to breakdown: quantum tunneling (Zener breakdown) and avalanche multiplication (avalanche breakdown), the latter occurring at higher V_{BD} .

Quantum tunneling becomes relevant when the potential barrier between the valence and conduction bands is sufficiently narrow for electrons to tunnel through. This can occur when both sides of the junction are relatively highly doped, producing a strong electric field that enables the tunneling process.

Avalanche multiplication, the most important mechanism in silicon sensors, occurs when thermally generated electrons gain kinetic energy from the electric field in the depleted region. If the field is sufficiently high, the carriers acquire enough energy to ionize atoms in the silicon lattice, generating electron-hole (e-h) pairs. These secondary carriers may then undergo further collisions, producing additional e-h pairs. This chain process begins once a critical electric field E_c is reached.

The maximum electric field E_{max} in the sensor is expressed by Eq. (1.8):

$$E_{\max} = \frac{eN_{\text{eff}}W}{\epsilon_{\text{Si}}} = \sqrt{\frac{2eN_{\text{eff}}(V_{\text{bias}} + V_{\text{bi}})}{\epsilon_{\text{Si}}}} \quad (1.8)$$

where e is the electron charge, N_{eff} is the effective doping concentration, W is the depletion width, ϵ_{Si} is the silicon permittivity, and V_{bi} is the built-in voltage. Breakdown occurs when $E_{\max} \geq E_c$. Combining Eq. (1.8) with Eq. (1.6) yields the breakdown voltage:

$$V_{\text{BD}} = \frac{\epsilon_{\text{Si}}E_c^2}{2e}N_{\text{eff}} \quad (1.9)$$

The plot in Figure 1.10 shows a typical current-voltage (I-V) characteristic of a pn junction, illustrating the sudden increase in current once reverse-bias breakdown occurs. In pn-junction-based detectors, this behavior is strongly influenced by the junction geometry, oxide charge accumulation, and the design of guard rings, which help stabilize the electric field at the detector periphery.

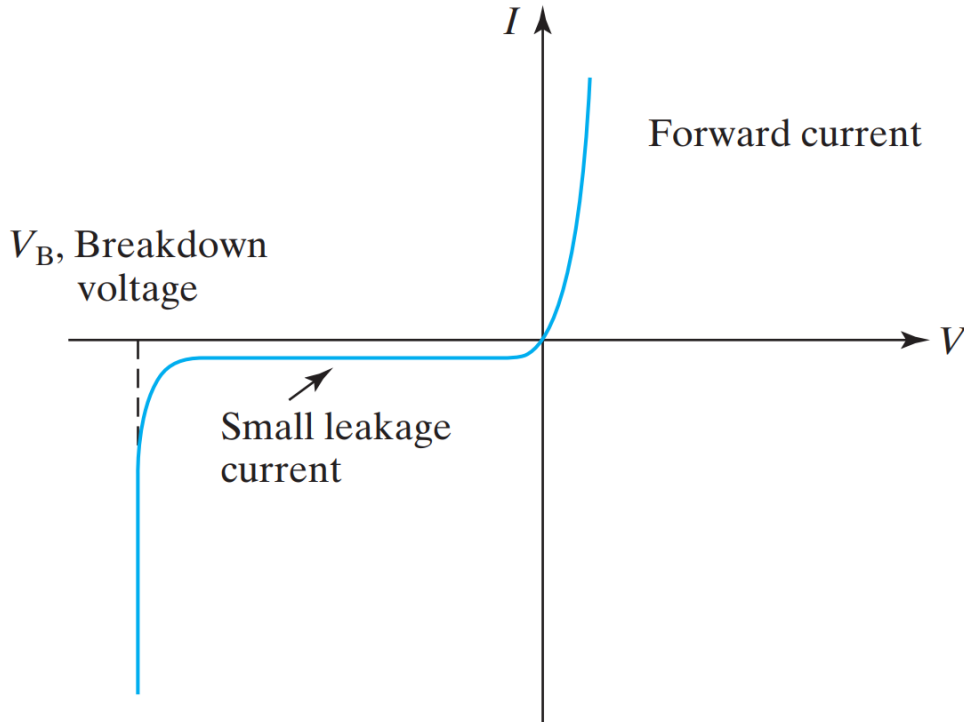


Figure 1.10: I-V characteristics of a pn junction [31].

The plot in Figure 1.11 shows the breakdown voltage as a function of impurity concentration for several semiconductor materials. The breakdown voltage associated with avalanche multiplication decreases with increasing doping concentration, while at even higher concentrations (beyond the dashed line), the tunneling mechanism becomes dominant.

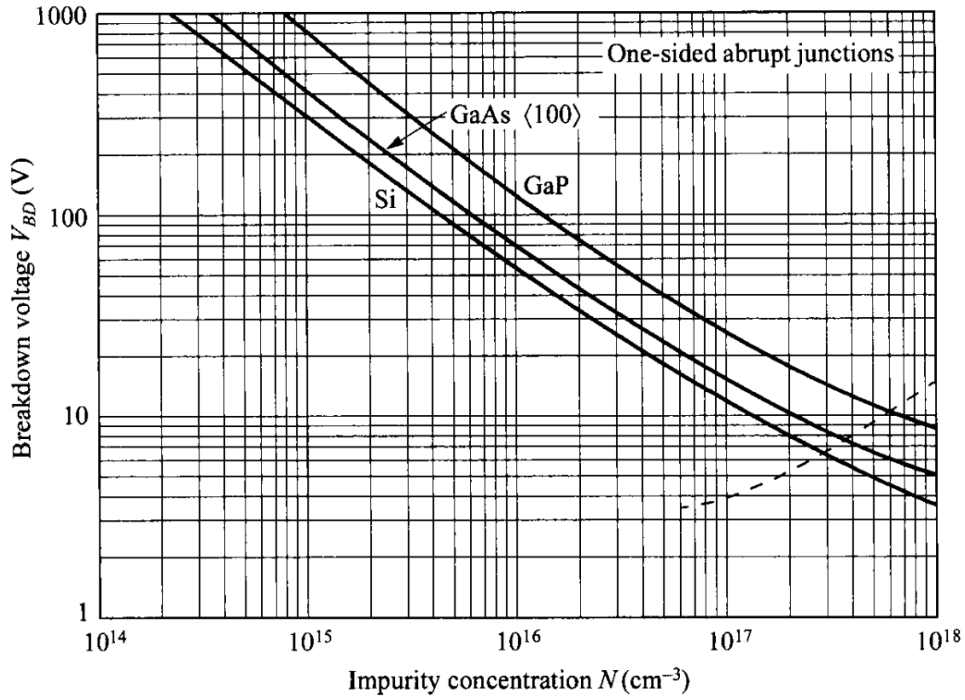


Figure 1.11: Avalanche breakdown voltage plotted over a wide range of impurity concentrations (10^{14} – 10^{18} cm^{-3}) for Si, GaAs $\langle 100 \rangle$, and GaP semiconductor materials. The dashed line indicates the impurity concentration above which the tunneling effect dominates [32].

1.3.1.3 Capacitances

Multiple capacitances appear in a silicon strip sensor—not only in the junction itself, but also from its interaction with other sensor elements such as the substrate, neighboring strips, and the readout electronics. These components form a capacitance network in which parasitic capacitances contribute to noise and reduce signal readout efficiency. The most relevant capacitances are described below:

Bulk Capacitance (C_{bulk}): This capacitance is formed between the depleted bulk and the electrodes. At full depletion, the active region behaves like a parallel-plate capacitor, depending on the silicon permittivity and the depletion depth, which equals the sensor thickness once fully depleted. The bulk capacitance per unit area is given by Eq. (1.10):

$$C_{\text{bulk}} = \frac{\epsilon_{\text{Si}}}{W} \quad (1.10)$$

As the bulk is reverse-biased, this capacitance decreases because the active region widens with increasing depletion depth. It reaches a minimum at the full depletion voltage. C_{bulk} contributes significantly to the strip-to-backplane capacitance (C_{bp}) and is a critical parameter in determining charge-collection time and noise characteristics.

Strip-to-backplane Capacitance (C_{bp}): This capacitance arises from the direct coupling between each strip implant and the metal backplane. It strongly depends on strip implant width, sensor thickness, and depletion depth, similarly to C_{bulk} . It results from the combined effects of the backplane geometry and the bulk capacitance.

Inter-strip Capacitance (C_{int}): This capacitance results from the electrical interaction between neighboring strips. It depends on strip pitch, implant width, strip isolation, and surface passivation. It increases for narrower strip pitches and in the presence of strong surface-charge effects. C_{int} is the dominant contribution to the capacitance load of the amplifier and must be controlled to ensure proper charge sharing between adjacent strips—an effect that is beneficial for improving spatial resolution and strongly influences the electronic noise [4].

The total strip capacitance is the combination of C_{bp} and C_{int} , affecting the amplifier load and constituting an important noise source. In tracking experiments, an upper limit on the total strip capacitance is imposed to guarantee a good signal-to-noise ratio.

Coupling Capacitance (C_{coupl}): This capacitance is intentionally formed between the strip implant and the metal strip connected to the readout electronics. The dielectric between them is a thin oxide (or nitride) layer, producing a large capacitance that improves AC-coupling performance. The coupling capacitor transfers the signal to the readout electronics while blocking any DC component from reaching the preamplifier.

Additional parasitic capacitances may arise from guard rings, bias structures, or sensor edges. Although usually small, they can become important—especially in long-strip designs. The total capacitance must be engineered in design and during fabrication to avoid excessive capacitance (which increases electronic noise) and to maintain good signal quality and spatial resolution.

1.3.1.4 Leakage Current (I_{leak})

The leakage current (I_{leak}) in reverse-biased sensors originates from thermal generation of electron-hole pairs in the bulk, from traps at the silicon-oxide interface, and from edge defects. A low leakage current is required for good sensor performance due to its strong contribution to electronic noise.

The bulk contribution depends on impurity concentration and is proportional to the depleted volume; thus I_{leak} saturates at full depletion. Temperature is also a strong influencing factor and may lead to system overheating (thermal runaway). The temperature dependence is expressed by Eq. (1.11):

$$I_{\text{leak}}(T) \propto T^2 e^{-E_g/(2k_B T)} \quad (1.11)$$

where T is the temperature, E_g the silicon bandgap energy, and k_B the Boltzmann constant. An increase in temperature produces higher leakage currents, and the increased current heats the detector further, potentially reaching a critical temperature at which runaway occurs. This is not a concern at room temperature for non-irradiated detectors, where the critical temperature is relatively high, but leakage current must still be minimized to reduce noise in the readout electronics.

Surface leakage currents, originating at the silicon-oxide interface, are much less temperature dependent. Interface states caused by dangling bonds and oxide charges act as generation-recombination centers, producing charge carriers that contribute to surface currents, particularly between neighboring strips and around isolation structures (p-stop or p-spray). These currents are sensitive to oxide quality and humidity.

Edge-related leakage currents arise from the distortions of the electric field at the sensor periphery, mainly induced by wafer dicing. Guard rings, edge-field shaping implants, and slim-edge designs are implemented in silicon strip sensors to suppress and control leakage current increases and to prevent premature breakdown near the sensor sidewalls, which would otherwise be caused by generation centers in these regions.

1.3.1.5 Inter-Strip Resistance (R_{int}) and Bias Resistance (R_{bias})

The inter-strip resistance R_{int} quantifies the electrical isolation between adjacent strips. It reflects the surface resistivity and the effectiveness of isolation implants (p-stop or p-spray). For non-irradiated detectors, typical R_{int} values are of the order of $\text{G}\Omega$, though surface charges in the inter-strip oxide can modify this parameter.

The bias resistance (R_{bias}) is the resistance of the polysilicon bias resistors that connect each strip to the bias ring. High R_{bias} helps maintain a stable DC potential from the bias ring to the backplane and contributes to noise reduction. The noise generated by the bias resistor is proportional to $\sqrt{k_B T / R_{\text{bias}}}$.

Tracking detectors such as those in ATLAS and CMS typically use R_{bias} values around $1\text{--}2\text{ M}\Omega$, which is sufficient to ensure efficient bulk depletion while keeping noise low. Higher values may be required in experiments with longer signal-integration times.

1.3.1.6 Charge Collection Efficiency (CCE)

Charge Collection Efficiency (CCE) is a parameter that characterizes how efficiently a silicon strip sensor collects charge carriers under an applied electric field. Unlike other electrical properties, CCE requires the presence of charged particles to have meaning. When an ionizing particle traverses the sensor, electron-hole pairs are created and drift toward the electrodes.

The CCE is defined as the ratio of the collected charge Q to the total charge generated in the semiconductor, Q_{dep} :

$$\text{CCE} = \frac{Q(t)}{Q_{\text{dep}}} \quad (1.12)$$

When charge trapping occurs due to defects, the collected charge depends on the trapping time, and the CCE can be expressed as:

$$\text{CCE} = \frac{Q}{Q_{\text{dep}}} e^{-t/\tau_{\text{eff}}} \quad (1.13)$$

where Q is the charge potentially collected without traps, t is the drift time, and τ_{eff} is the effective trapping time [15].

1.3.2 Radiation Effects

Silicon strip sensors used in HEP experiments are exposed to significant radiation environments originating from ionizing and non-ionizing particles. This radiation gradually affects the structural properties of silicon and other detector components. Increasing radiation levels also modify the electrical properties discussed in the previous section, thus deteriorating strip-sensor performance. A comprehensive understanding of radiation effects is essential to predict detector longevity and plan maintenance cycles.

Radiation interacts with the detector mainly through two mechanisms:

- Ionizing radiation, which primarily affects dielectric layers, creates trapped charges in SiO_2 and at the Si-SiO_2 interface. This surface and interface damage alters electrical properties associated with the dielectric layers, such as inter-strip capacitance and resistance, as well as AC-coupling behavior.
- Non-Ionizing Energy Loss (NIEL) produces displacement damage in the silicon bulk by moving atoms from their lattice positions and forming vacancies, interstitials,

or more complex defect clusters. These defects, together with the evolution of effective doping concentration after irradiation, modify key sensor properties such as leakage current, depletion voltage, and charge collection efficiency.

This section discusses radiation effects in silicon strip sensors, classified into bulk damage—the most critical for long-term operation—and surface damage. An additional subsection summarizes annealing, the natural process through which defects migrate, recombine, or undergo further transformations.

1.3.2.1 Bulk Damage

Ionization damage has no significant effect on the silicon bulk since generated electron-hole pairs are quickly swept toward the electrodes. In contrast, bulk damage is caused mainly by Primary Knock-on Atom (PKA) displacements in the lattice. These collisions, typically produced by neutrons, protons, pions, or energetic leptons, generate substitutional defects, interstitials, vacancies (empty lattice sites), or vacancy-interstitial pairs (Frenkel pairs).

The minimum energy required to displace a silicon atom is about 25 eV. However, non-ionizing collisions with higher energy may cause nuclear interactions and secondary cascades that create additional displaced atoms and defect clusters. Energies above 5 keV transferred to a lattice atom are required for cluster formation. Figure 1.12 shows a Monte Carlo simulation of a recoil-atom path after receiving 50 keV from a 1 MeV neutron, resulting in several terminal clusters.

Radiation damage can be quantified using the NIEL formalism [34] in a first-order approach, which considers only the energy transferred in non-ionizing collisions, independent of particle type and energy spectrum. Figure 1.13 shows displacement damage in silicon from neutrons, protons, pions, and electrons as a function of particle energy. The damage, D , is normalized to $95 \text{ MeV} \cdot \text{mb}^3$, corresponding to the damage produced by 1 MeV neutrons, i.e., one 1 MeV neutron equivalent fluence $\Phi_{\text{eq}} [n_{\text{eq}}/\text{cm}^2]$. This normalization allows damage induced by different particles to be compared on a common scale.

Bulk defects, particularly Frenkel pairs, introduce energy levels within the silicon band gap. These defects alter the charge density in the space-charge region by binding to dopants such as boron or phosphorus, acting as generation-recombination centers, or trapping charge carriers (Figure 1.14). Together, these microscopic changes lead to

3 A millibarn (mb) is a non-SI metric unit of area, commonly used to express cross sections, corresponding to 10^{-27} cm^2 .

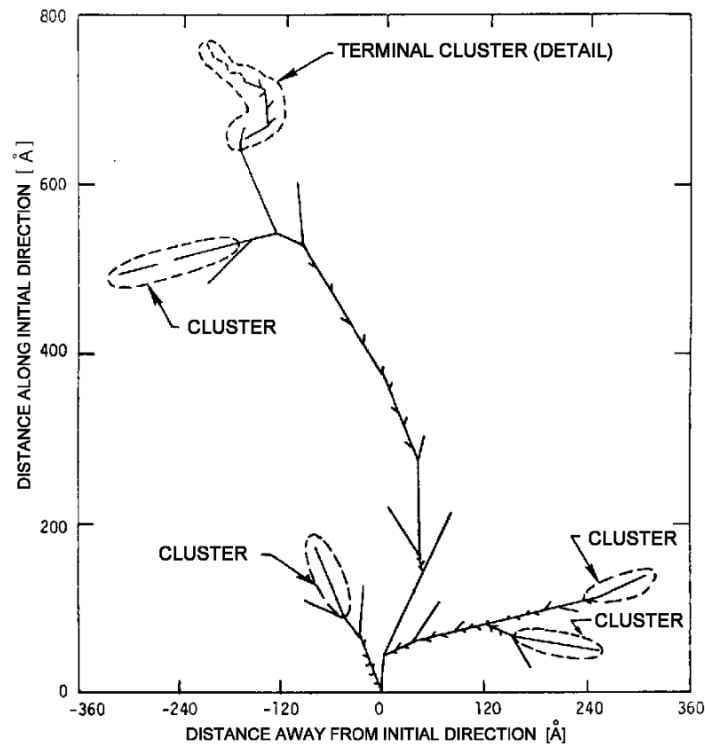


Figure 1.12: Recoil-atom path and resulting defects (displaced atoms and clusters) after receiving 50 keV, approximately the kinetic energy transferred by a 1 MeV neutron [31–33].

macroscopic effects in measurable sensor properties, primarily the depletion voltage, leakage current, and charge collection efficiency [35].

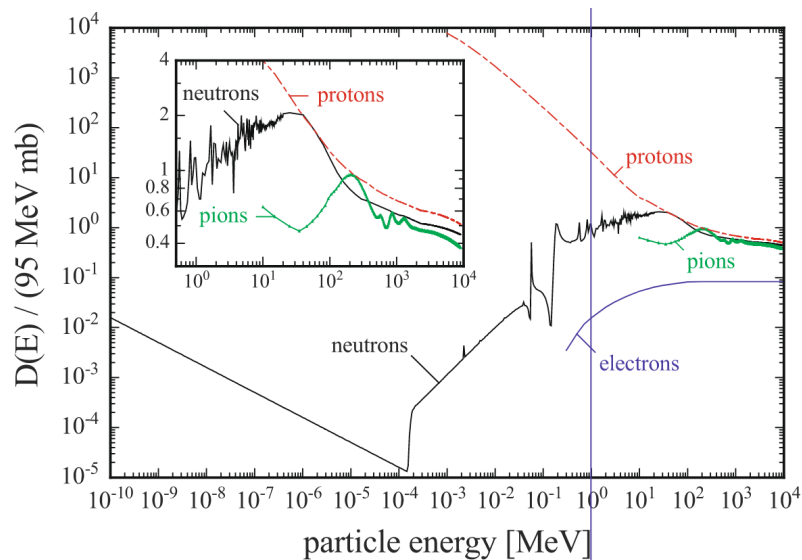


Figure 1.13: Displacement damage $D(E)$ in silicon normalized to 95 MeV·mb as a function of particle energy for neutrons, protons, pions, and electrons. The inset enlarges the higher-energy region [13].

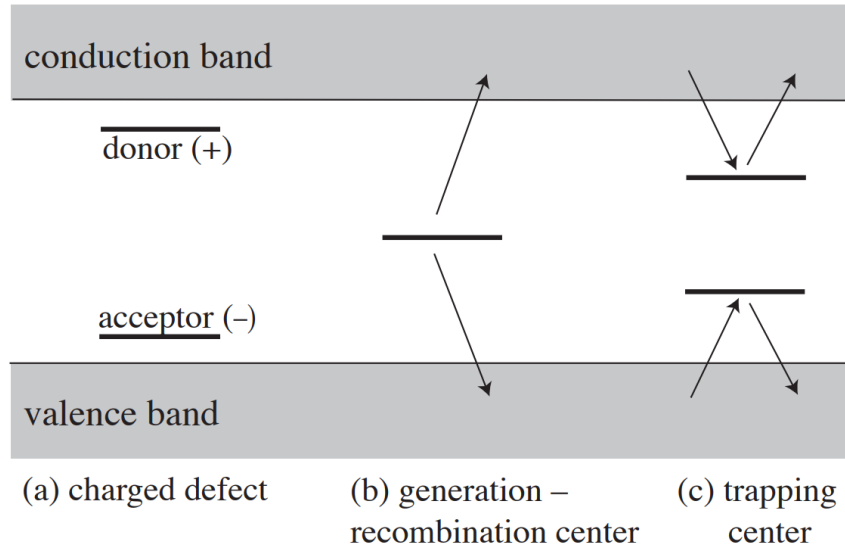


Figure 1.14: Energy-level positions of defects in the silicon band gap acting as (a) charged defects, (b) generation-recombination centers, or (c) trapping centers [36].

Full Depletion Voltage: Donor-like defects (upper half of the band gap) and acceptor-like defects (lower half) modify the effective space charge of the sensor. After irradiation, charged defects may compensate or even reverse the effective doping concentration N_{eff} of the sensor. In n-type silicon, continuous removal of donors and the creation of acceptors reduces the N_{eff} . At sufficiently high fluence, the substrate undergoes type inversion—also called Space-Charge Sign Inversion (SCSI)—from n-type to p-type, changing the electric field distribution and depletion behavior (see Figure 1.15).

After SCSI, acceptor concentration continues to rise with fluence. This is one reason p-type silicon is preferred in harsh radiation environments: it does not undergo type inversion, though N_{eff} still increases with fluence. Higher V_{bias} is required to maintain correct operation, since $V_{\text{FD}} \propto N_{\text{eff}}$. Larger potential differences ensure full depletion and efficient charge collection, although they increase the risk of breakdown.

Leakage current: Mid-gap defects act as generation-recombination centers, increasing the dark current. The increase of leakage current is proportional to the NIEL fluence Φ_{eq} :

$$\frac{\Delta I}{V} = \alpha \Phi_{\text{eq}} \quad (1.14)$$

where V is the depleted volume and α is the “generation current-related damage rate”. This linear relation is widely used to monitor accumulated radiation damage [37].

The main consequences of increased I_{leak} are higher parallel (shot) noise, reduced signal-to-noise ratio, and increased power dissipation. Since rising temperature increases leakage current—and the current increases temperature—thermal runaway can occur

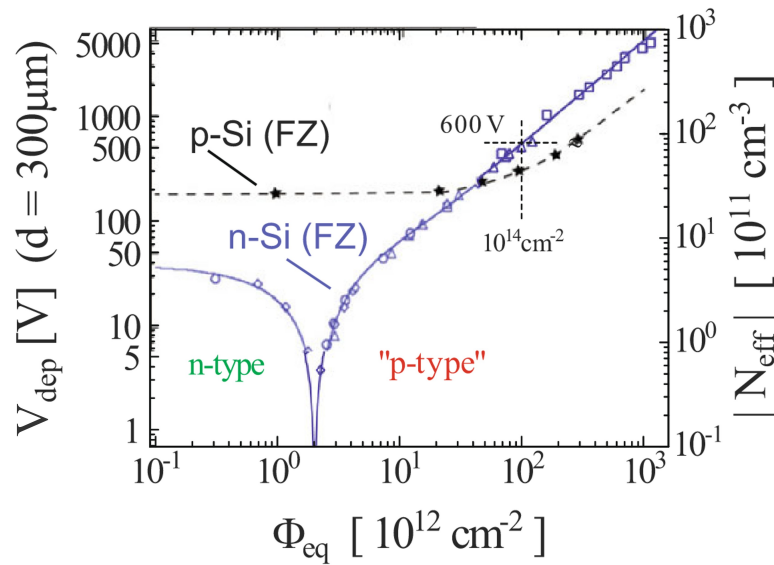


Figure 1.15: Evolution of depletion voltage—and N_{eff} —with fluence, showing type inversion at sufficiently high fluence. Adapted from [13].

even below room temperature. Cooling systems are therefore required to prevent runaway. Figure 1.16 shows the increase of power (and thus leakage current) with temperature for an irradiated sample, reaching thermal runaway below -6°C .

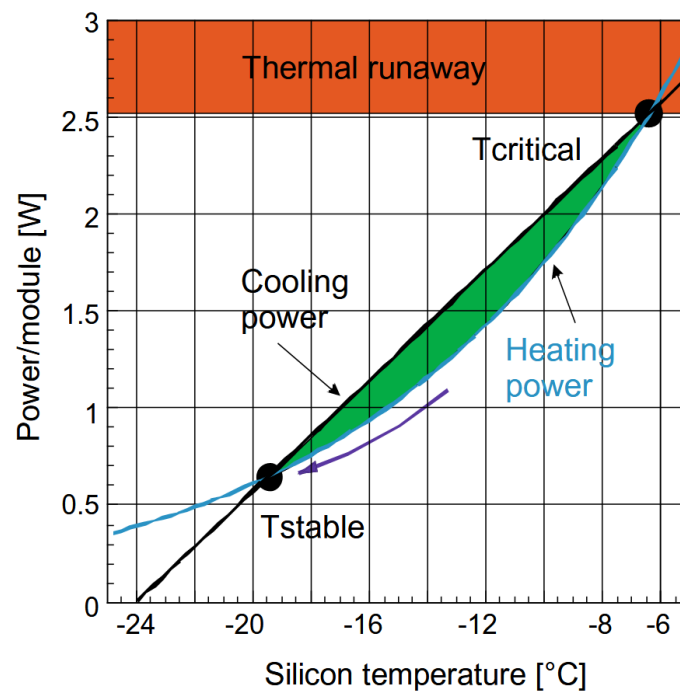


Figure 1.16: Power dissipation vs. silicon temperature, showing thermal runaway above a critical temperature [4].

Charge Collection Efficiency: Several bulk defects act as trapping centers, capturing carriers before they reach the electrodes. The trapping probability, $1/\tau_{\text{eff}}$, is proportional

to carrier drift velocity and defect concentration; both scale linearly with fluence in first approximation:

$$\frac{1}{\tau_{\text{eff}}} = \gamma \Phi_{\text{eq}} \quad (1.15)$$

where γ is the trapping coefficient (proportionality factor between trapping and fluence), which differs for holes and electrons due to their different mobilities.

High radiation levels therefore reduce the CCE, lowering the signal amplitude processed by the readout electronics. Trapping also widens cluster sizes and distorts reconstructed hit positions, degrading spatial resolution.

Radiation effects are particularly severe at high fluence. Overall, the most operation-limiting bulk-damage effects occur at different fluence scales:

- increased I_{leak} at $\Phi_{\text{eq}} \sim 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$,
- high required V_{FD} at $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$,
- significant CCE degradation at $\sim 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$.

These limitations motivate robust sensor designs capable of withstanding extreme radiation levels. Strategies include low-temperature operation and n-on-p technologies to maintain long-term performance.

1.3.2.2 Surface Damage

The oxide layers on the detector surface have an irregular structure, and direct displacement damage in SiO_2 is negligible compared to damage in crystalline silicon.

However, ionizing radiation creates e-h pairs within the SiO_2 and near the Si– SiO_2 interface, producing oxide degradation and conductive charge layers at the silicon surface. These channels increase surface leakage current, worsen strip isolation, and introduce noise. Ionization damage is caused by X-rays, gamma rays, high-energy photons, and charged particles such as electrons, protons, or heavy ions.

Electrons generated in the oxide move toward electrodes, whereas holes, which have much lower mobility in insulators, migrate slowly and become trapped. Because the SiO_2 band gap (8.8 eV) is much larger than that of Si (1.12 eV), trapped holes cannot easily escape. Positive charge accumulation increases nearly linearly with total ionizing dose (TID) until saturation. For high-quality oxides, the saturation charge is typically

$$Q_{\text{ox,sat}} \approx 3 \times 10^{12} \text{ cm}^{-2}.$$

These trapped charges shift the flat-band⁴ voltage and degrade sensor performance.

Surface damage alters several sensor properties:

Inter-strip Resistance and Capacitance: In n-on-p sensors, accumulated positive oxide charge induces electron inversion layers at the surface, reducing inter-strip resistance and increasing inter-strip capacitance. This lowers signal-to-noise ratio and spatial resolution. Positive charges in the field oxide also shift the flat-band voltage.

Depletion behavior: Charge-conductive layers between strip implants after high-dose irradiation hinder full lateral depletion.

Leakage Current: Interface traps create generation-recombination centers that increase surface leakage currents, especially noticeable at low ionization doses. These lateral currents differ from bulk leakage currents and have a greater impact on sensor behavior at low ionization doses.

Breakdown Voltage: Positive oxide charge enhances the electric field at implant edges, promoting micro-discharges and reducing breakdown voltage—a limiting factor in high-radiation environments.

To mitigate surface damage, sensor designs emphasize high-quality oxides, effective strip isolation (p-stop or p-spray), and fabrication techniques that stabilize inter-strip properties up to high doses. Oxide-trapped charge can be partially recovered through annealing.

1.3.2.3 Annealing

Bulk and surface defects can diffuse at temperatures above 150 K, enabling several recombination mechanisms: Frenkel pair recombination, multi-vacancy or multi-interstitial formation, and more complex defect reactions. This thermally activated evolution of the defect population is referred to as annealing and strongly depends on temperature and time. Some mechanisms, such as Frenkel pair recombination, occur rapidly (short-term annealing), while others—particularly the formation or transformation of complex defect structures—develop over much longer timescales (long-term annealing).

In terms of depletion voltage, short-term annealing (hours to days) is beneficial and reduces sensor damage. Long-term annealing (days to months), however, leads to reverse annealing, increasing N_{eff} and V_{FD} , thus degrading sensor performance. Figure 1.17 shows the evolution of these parameters at 60°C annealing, with a minimum change of the

⁴ Flat-band voltage: voltage to be applied to the gate of a MOS structure to achieve no electric field in the semiconductor with the energy bands perfectly flat at the surface [38].

space-charge value at around 80 minutes. Therefore, an annealing step of 80 minutes at 60°C is widely used in research for optimal damage recovery.

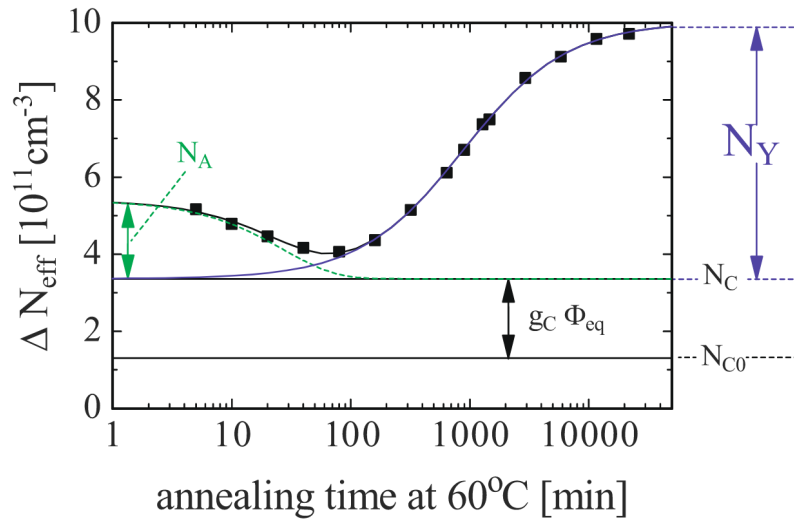


Figure 1.17: Difference in effective doping concentration N_{eff} vs. annealing time at 60°C [13, 36].

In contrast to the behavior of V_{FD} , leakage currents decrease with annealing due to reduced generation-recombination activity over time, making this effect always beneficial to sensor performance.

1.4 Inner Tracker (ITk) Sensors

This section addresses the silicon sensors employed in the ATLAS Inner Tracker (ITk) at CERN. After an introductory description of the LHC and the ITk, the characteristics and specifications of the sensors are described, with special emphasis on silicon strip sensors. Finally, the design of the silicon strip sensors and the structures surrounding them in the silicon wafers are presented.

1.4.1 Inner Tracker

1.4.1.1 The Large Hadron Collider (LHC)

The European Organization for Nuclear Research (CERN) operates the Large Hadron Collider (LHC), the largest and most powerful particle accelerator in the world. The LHC is a 27-kilometer-long ring located in a tunnel 100 meters underground along the France-Switzerland border, near Geneva. In the accelerator, particles are accelerated close to the speed of light using thousands of superconducting electromagnets distributed

along the ring. These magnets, cooled to $-271.3\text{ }^{\circ}\text{C}$ with dedicated cryogenic systems, also guide the particles and “squeeze” the beams to increase the collision probability [39].

Two opposing high-energy proton beams are made to collide at four particle detectors located at different positions along the ring: ATLAS (A Toroidal Large Hadron Collider Apparatus) [40], CMS (Compact Muon Solenoid) [41], ALICE (A Large Ion Collider Experiment) [42], and LHCb (Large Hadron Collider beauty experiment) [43]. Figure 1.18 shows a schematic of the LHC and the positions of its four main detectors.

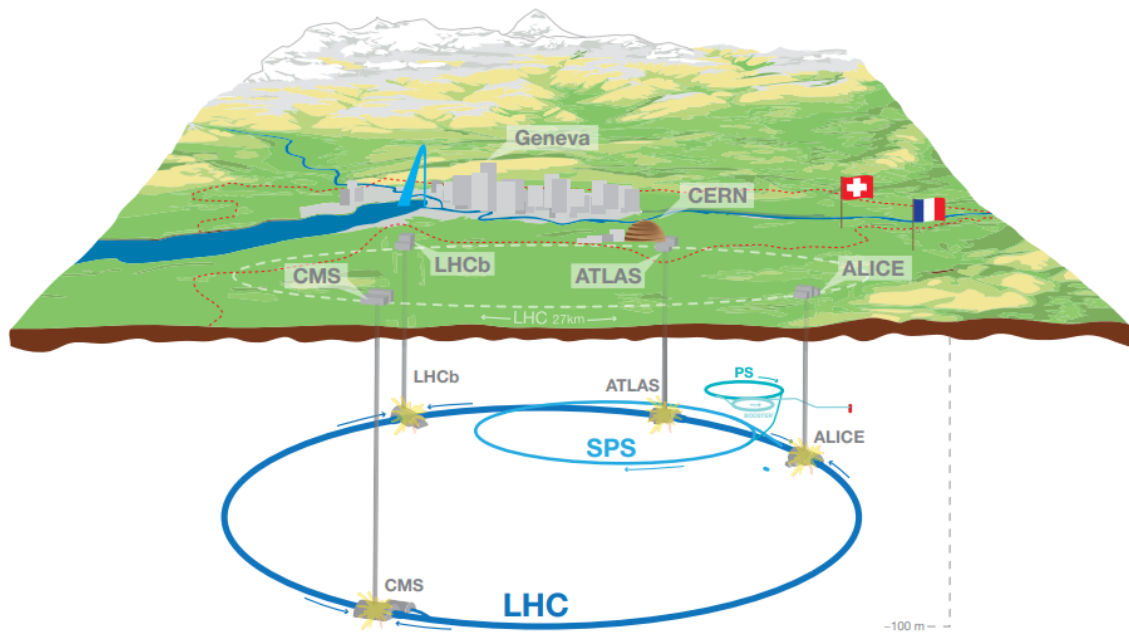


Figure 1.18: Schematic representation of the LHC and its four experimental detectors [44].

All detectors and experiments are part of the CERN accelerator complex. Smaller accelerators in the complex pre-accelerate particles before injection into the LHC. Negative hydrogen ions are initially accelerated in Linear Accelerator 4 (Linac4) [45], and then enter the Proton Synchrotron Booster (PSB) [46], where they lose two electrons and become protons. These 2 GeV protons are injected into the Proton Synchrotron (PS) [47], accelerated to 26 GeV, and then transferred to the Super Proton Synchrotron (SPS) [48], where their energy reaches 450 GeV before injection into the LHC. Collisions at maximum proton energy occur with a total energy of 14 TeV. The CERN accelerator complex is schematized in Figure 1.19 [49].

A total of nine experiments are conducted at the LHC, using the detectors to analyze collision products: ATLAS, CMS, ALICE, LHCb, LHCf, TOTEM, MoEDAL-MAPP, FASER, and SND@LHC. ATLAS and CMS are the largest experiments, exploring the widest physics frontiers. They operate independently, and their results are later cross-checked to validate new discoveries [50, 51].

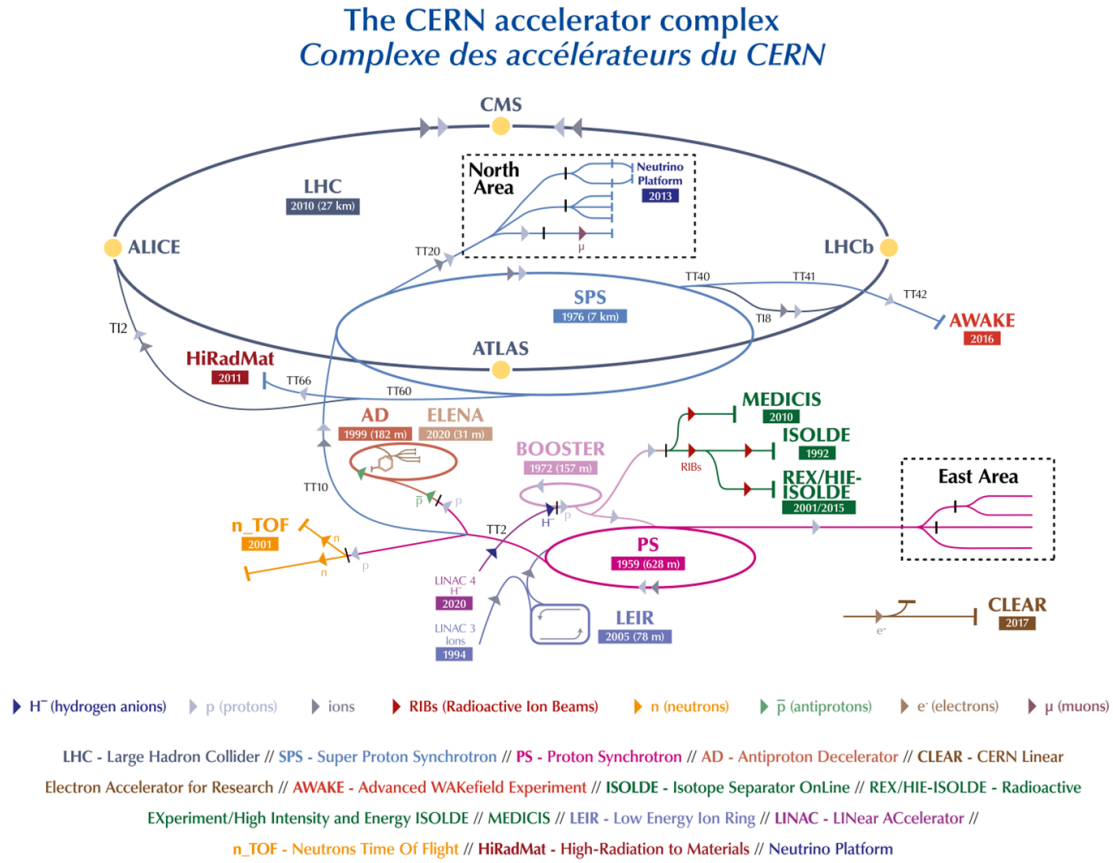


Figure 1.19: Schematic of the CERN accelerator complex [49, 51].

Since its first operation in 2010, the LHC has addressed fundamental questions in physics, including the origin of mass, the nature of dark matter, new forces and particles, and quark-gluon plasma. The most significant achievement was the discovery of the Higgs boson in 2012, providing essential information for understanding matter and advancing high-energy physics (HEP) [52, 53].

A High-Luminosity LHC (HL-LHC) upgrade is now undergoing, aiming to increase luminosity from the current 300 fb^{-1} to 3000 fb^{-1} —one order-of-magnitude improvement. Figure 1.20 shows the timeline for planned runs and long shutdowns. However, Long Shutdown 3 (LS3), intended to replace major detector components for higher radiation tolerance, has been delayed due to the COVID-19 pandemic and extended by four additional months [54–56].

1.4.1.2 Inner Tracker Upgrade

The current Inner Detector of ATLAS, depicted in Figure 1.21, would not have withstood the expected radiation damage under the required high-luminosity conditions. This led

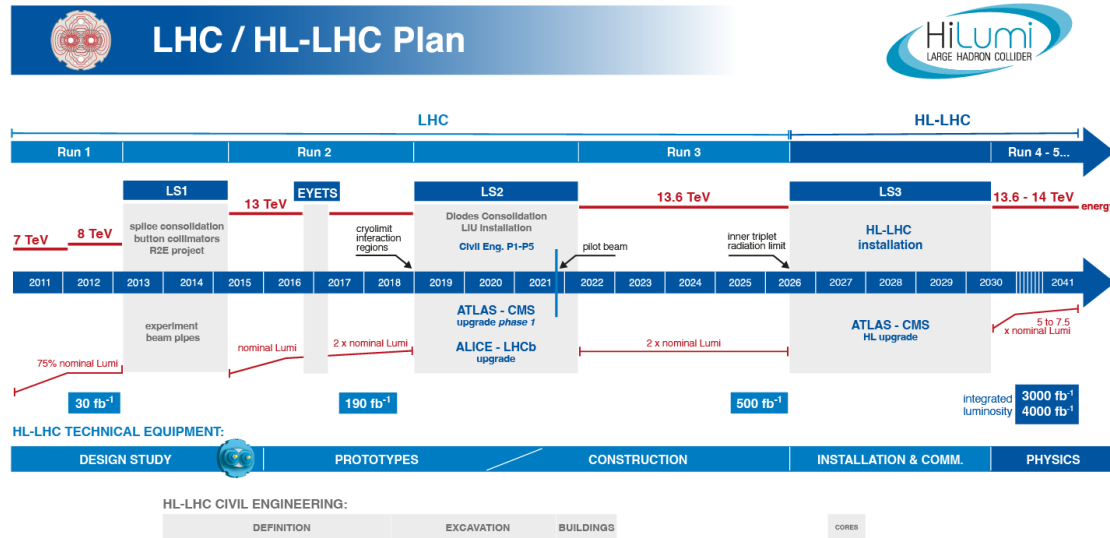


Figure 1.20: Timeline of LHC operations and planned upgrades [57].

the ATLAS Collaboration to decide to replace it with a new all-silicon tracker, called the Inner Tracker (ITk). A schematic of this new all-silicon detector is shown in Figure 1.22.

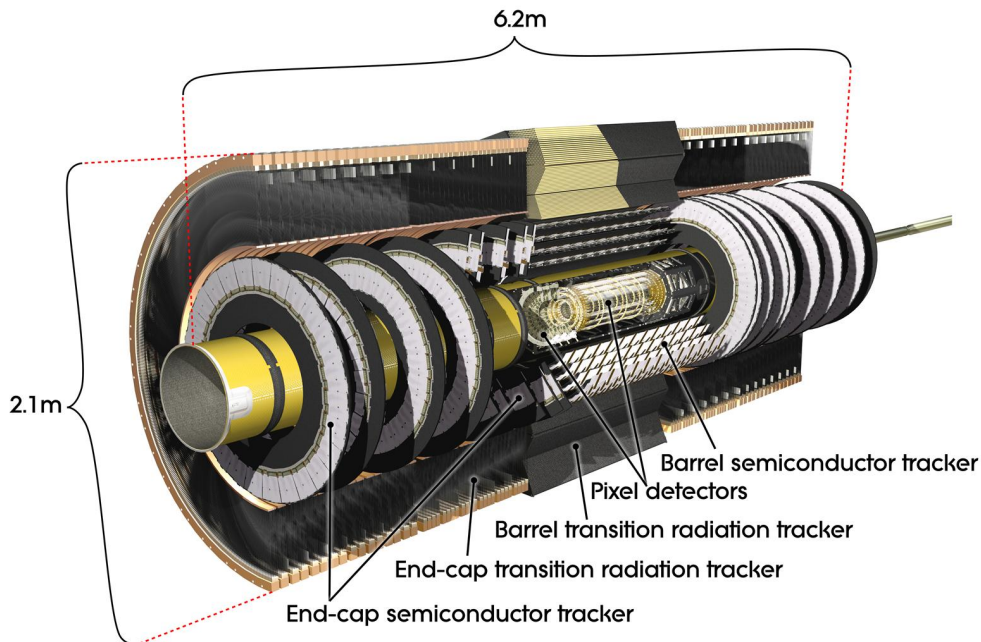


Figure 1.21: Computer-generated image of the ATLAS Inner Detector [58].

The ITk includes a Pixel detector system that reaches twice the current radius and is about four times longer than the existing pixel array. Novel pixel modules contain small pixel cells of $2500 \mu\text{m}^2$ with more readout channels [60]. Additionally, the silicon strip

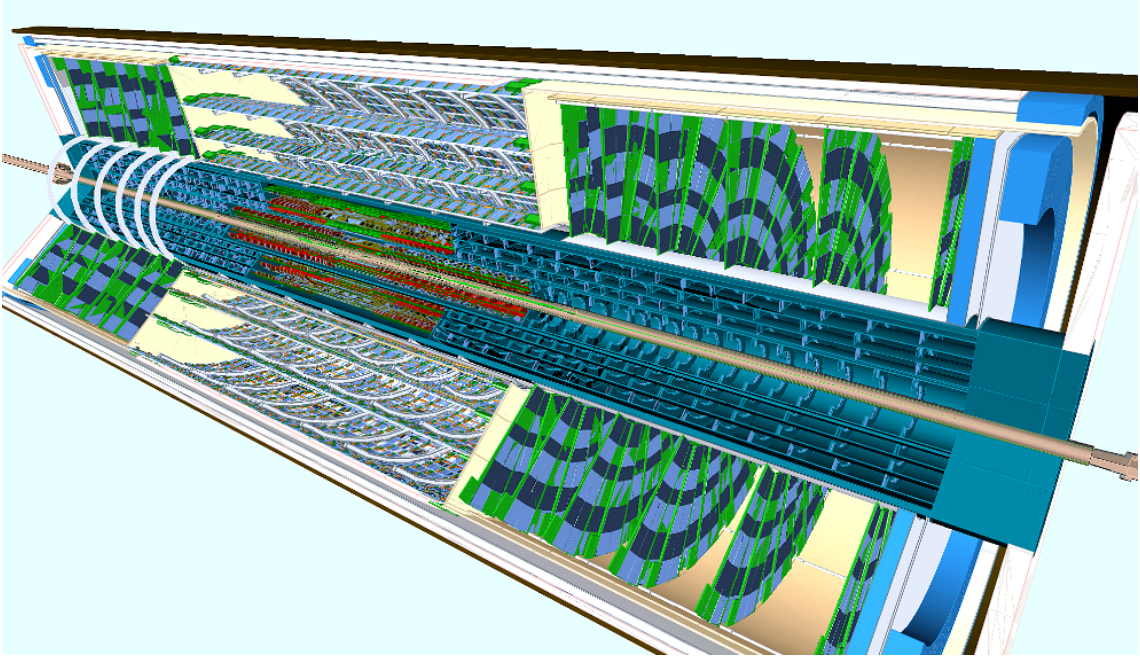


Figure 1.22: Computer-generated image of the new ATLAS Inner Tracker [51, 59].

detector surrounding the Pixel region requires more than three times the silicon surface area of the existing system to cover the entire inner radius of the solenoid. ITk silicon strip sensors are AC-coupled strip sensors using the n-on-p technology described in this chapter [61].

The entire ITk is about 6 m long, with a radius of about 1 m around the beam axis and a total silicon area of 165 m². It is divided into two main parts: the ITk Barrel, with sensors parallel to the beam axis, and the ITk Endcap, subdivided into two regions of sensors perpendicular to the beam axis on each side of the central barrel region [62, 63].

Figure 1.23 shows a schematic of the longitudinal distribution of pixel and strip sensors for half of the detector, along a single direction of the beam axis (z) from the collision point ($z = 0$). Pseudorapidity η , a parameter used to describe the angle of particle trajectories relative to the beam axis, is also represented in this figure and in Figure 1.24, up to $|\eta| = 4.0$, with tracks originating from the primary vertex.

The actual inner detector is limited to particles trajectories with $|\eta| < 2.7$ [40, 65]. In the ITk, higher η values are reached only by Pixel sensors. The relation between η and a particle polar angle (θ) is expressed as:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (1.16)$$

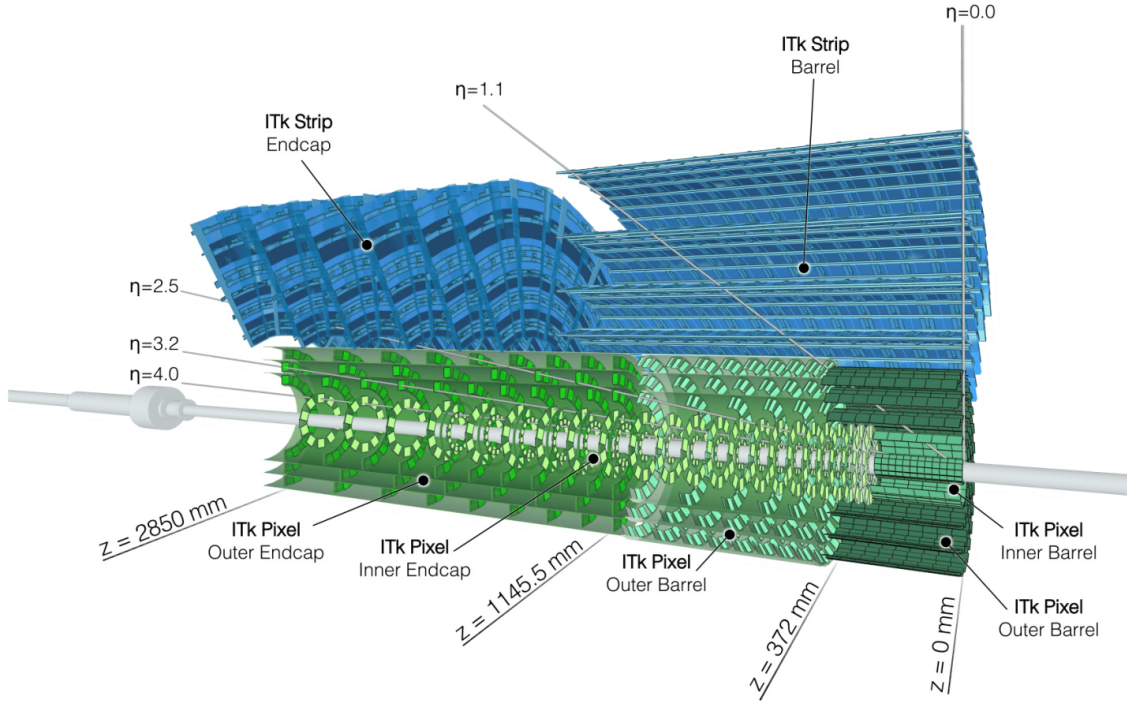


Figure 1.23: 3D rendering of Pixel (green) and Strip (blue) systems in the ATLAS Inner Tracker (ITk), with labeled longitudinal distances starting at $z = 0$ [64].

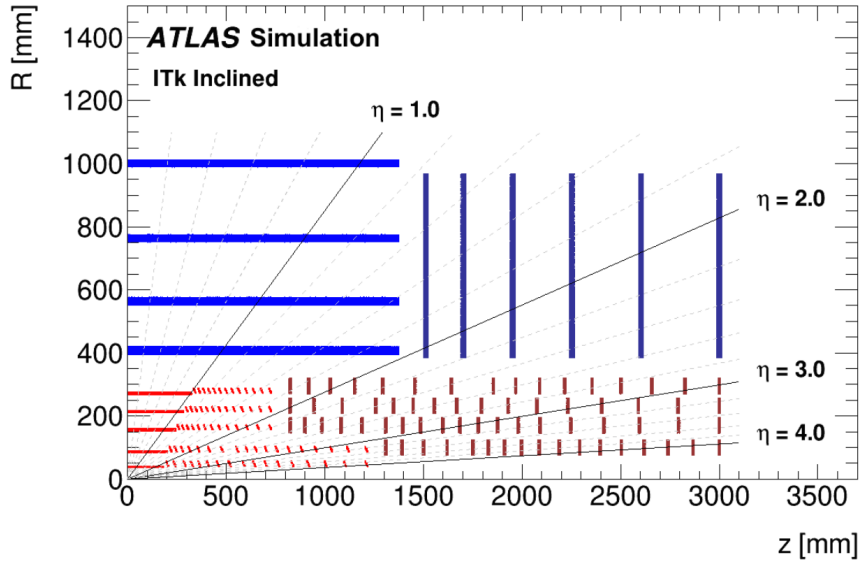


Figure 1.24: Schematic layout of the ITk active detector elements in one quadrant of the detector. Horizontal and vertical lines correspond to Barrel and Endcap layers, respectively. Pixel layers are colored in red, and Strip layers in blue [51].

Radiation in the innermost Pixel region will exceed $2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and 1.7 Grad. ITk strips will be exposed to up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and a 66 Mrad dose (assuming a safety factor of 1.5⁵), roughly ten times higher than for the current SCT. Simulations of neutron equivalent fluence (left) and total ionizing dose (right) expected at the ITk are shown in Figure 1.25, with the highest irradiation values in regions closest to the beamline.

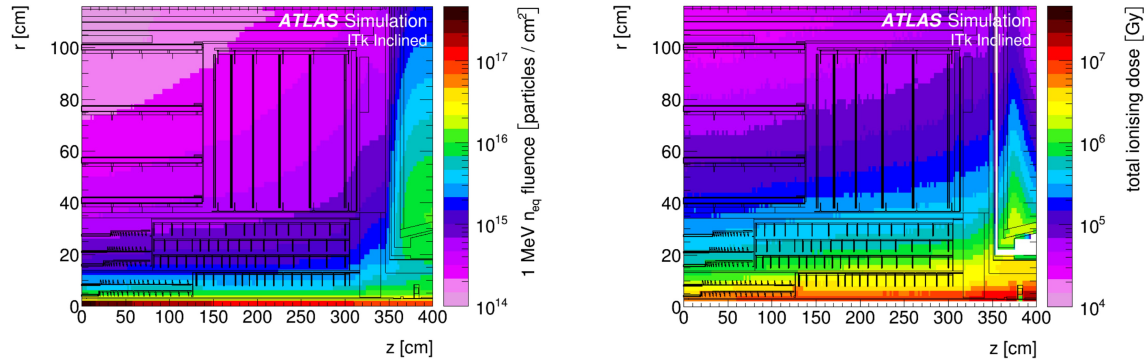


Figure 1.25: 2D schematic layout of the ITk with expected fluence distribution (left) and TID distribution (right) [51].

Overall, the detector design includes optimized technology and geometry to achieve the best possible performance in the HL-LHC environment, within cost and timeline constraints.

Barrel

The Barrel section surrounds the region closest to the collision point along the beam direction. It consists of five Pixel layers surrounded by four Strip layers. The ITk schematic in Figure 1.26 focuses on the Barrel region from a perspective that allows better visualization of the sensor layers in the radial direction. The Pixel Barrel extends up to $z = \pm 1145.5 \text{ mm}$ and $R = 29.1 \text{ cm}$, with Pixel modules installed in the layers nearest to the beamline.

Strip Barrel cylindrical layers are located between $R = 39.9 \text{ cm}$ and $R = 100 \text{ cm}$. Each layer consists of staves arranged along the beamline between $z = -1400 \text{ mm}$ and $z = +1400 \text{ mm}$. Each staff contains several modules equipped with n-on-p silicon strip sensors. Short strip lengths are used for inner sensors, and long strips for the outer layers. The Barrel includes 392 staves, each with 28 modules (14 per staff side). The strip modules are rotated by $\pm 26 \text{ mrad}$ (total stereo angle 52 mrad) to create stereo-strip pairs, enabling precise 3D reconstruction of particle trajectories. The bottom image and inset in Figure 1.27 show the sensor and module installation on the Barrel staves.

- 5 Safety factor of 1.5 determined based on operational experience with the current detector, indicating a radiation performance about 30% higher than the expected from calculations.

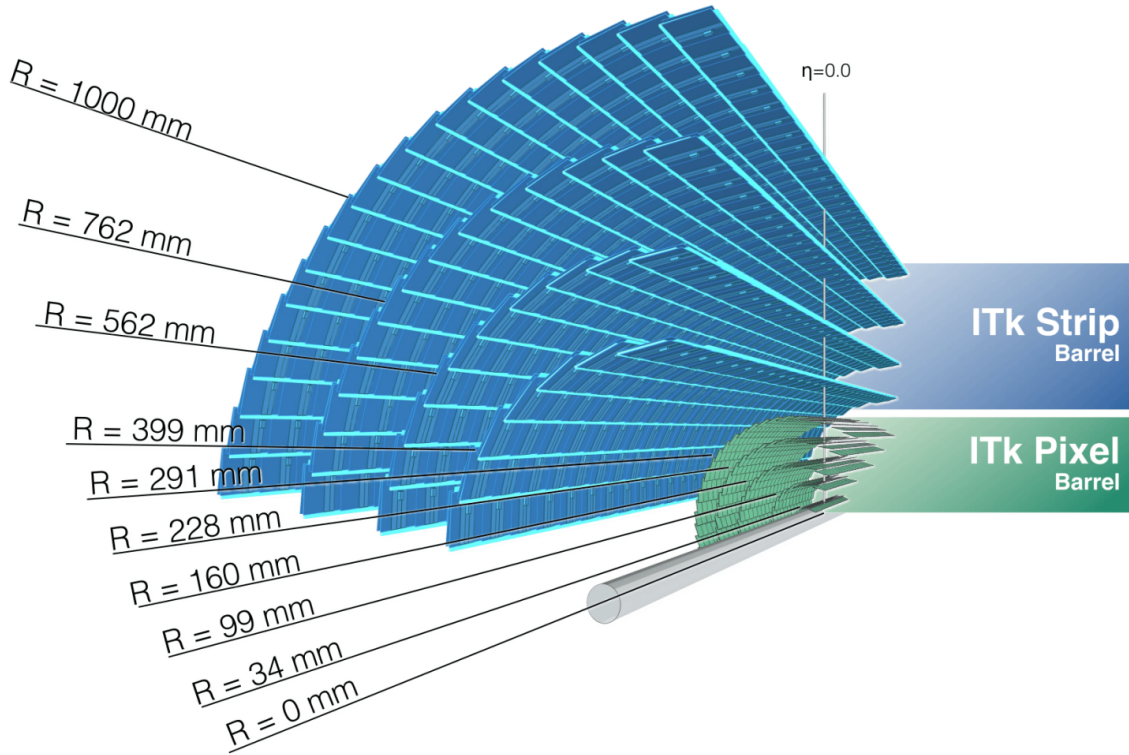


Figure 1.26: 3D rendering of Barrel Pixel and Strip systems in the ATLAS Inner Tracker (ITk), with labeled radius starting at $R = 0$ [64].

Endcap

The Endcap consists of two sections, one on each side of the Barrel region. The Endcap design is based on disks perpendicular to the beam axis. In the Pixel region, silicon pixel modules are mounted on concentric disk layers close to the beamline to track high- η particles, distributed between $|z| = 1145.5$ mm and $|z| = 2850$ mm.

Six disks are installed in each Strip Endcap region, from $|z| = 1512$ mm to $|z| = 3000$ mm, with 32 identical petals, as shown in Figure 1.27 (upper right). Like the Barrel staves, modules are mounted on petal supports that cover the entire area. Nine modules are installed on each side of a petal with a stereo angle of 20 mrad (total stereo angle of 40 mrad). These modules contain trapezoidal silicon strip sensors, with six different designs depending on their position on the petal, arranged across six concentric rings (R0–R5) in each disk.

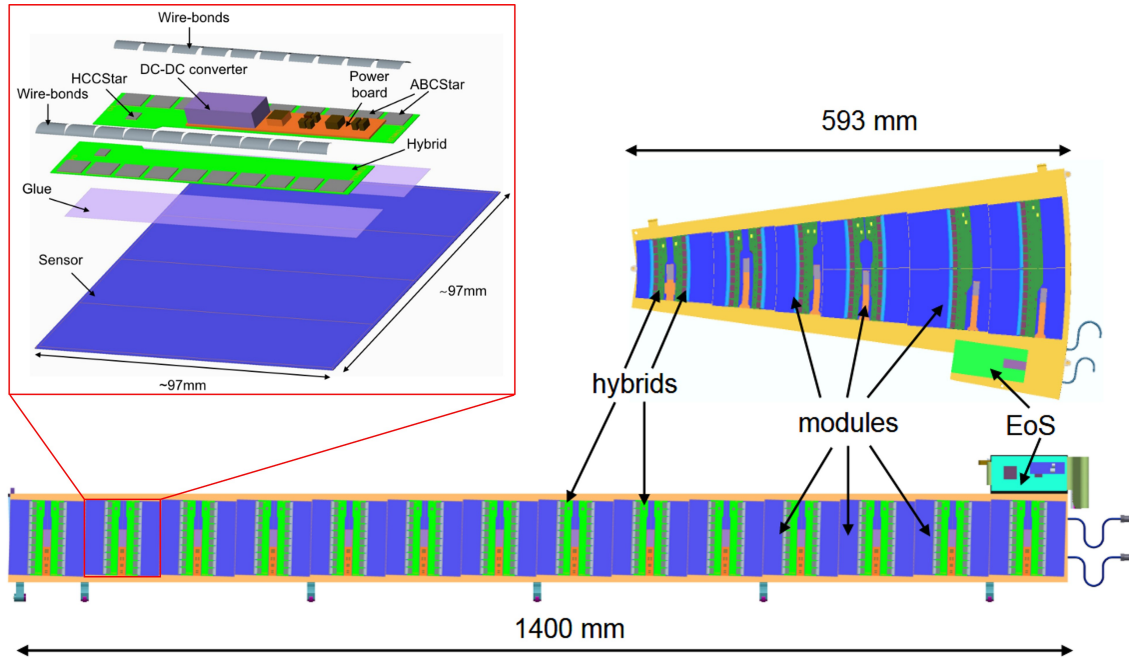


Figure 1.27: Computer-generated images of the Barrel stave (bottom) and the Endcap petal (upper right). In both cases, modules are mounted on rigid carbon-fiber supports. The End-of-Substructure (EoS) card at one end of each petal or stave interfaces with out-of-detector electronics. The inset shows the sensor and other elements (hybrids, ABCStar ASICs, HCCStar chips, Powerboard, and wire-bonds) mounted in a module [51].

1.4.2 ITk Strip Sensor Specifications

1.4.2.1 General Characteristics and Requirements

Silicon strip sensors for the ATLAS ITk are designed using the n-on-p technology described in this chapter and are manufactured on 6-inch floating-zone (FZ) silicon wafers. They are AC-coupled strip sensors with n-type implants in a p-doped silicon bulk, incorporating all required structures to ensure proper performance at the radiation levels expected in the experiments.

The main elements of these sensors include n-type implants (strips), oxide and metal layers over the strips for proper AC-coupling to the readout electronics, polysilicon bias resistors, p-stop implants for inter-strip isolation, and bias and guard rings surrounding the sensor active area. The p-type substrate enhances radiation hardness, making the sensors more resilient under harsh conditions.

Radiation tolerance is essential for optimal strip sensor performance. ITk sensors are expected to be exposed to a maximum fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and a total ionizing dose (TID) of 66 Mrad, including a safety factor of 1.5 to account for potential deviations in fluence and TID calculations. Using the n-on-p strip technology, the signal received at

the readout electronics after irradiation is expected to be approximately double that of the older p-on-n sensors.

All sensors must meet the following mechanical and optical requirements.

- Physical thickness: $320 \pm 15 \mu\text{m}$ (including Total Thickness Variation, TTV)
- Signal-generation (active) thickness: $> 270 \mu\text{m}$
- Uniformity of thickness within sensor (TTV): $20 \mu\text{m}$ (central value $\pm 10 \mu\text{m}$)
- Flatness: Within $200 \mu\text{m}$ when unstressed
- Quality of cut edges: Full-thickness dicing, smooth and clean edges, no chips/cracks $> 40 \mu\text{m}$ inward
- Damage and defects: Device must be free from stains, chemical residues, scratches, systematic bad strips (consecutive or in the same location in multiple sensors), and other defects affecting long-term performance. Sensors and test structures must be protected from ESD, humidity, dust, and chemical contamination.
- Bond pads: Metal quality, adhesion, and strength must allow uniform wirebonding without degrading strips (e.g., standard wirebonding with ultrasonic AlSi(1%) wire of $25 \mu\text{m}$ diameter).
- Pull test: mean $> 10 \text{ g}$ (corrected for angle), RMS $< 10\%$ of mean, and lift-off probability $< 20\%$
- Fiducial marks alignment: Fully visible between cut edges and bias line, and the minimum metal width within and outside marks must be $\geq 10 \mu\text{m}$
- Mask alignment tolerances: $\leq 3 \mu\text{m}$ relative to other masks, with specific contractor-dependent values
- Sensor robustness: Must withstand standard handling procedures without creating additional bad strips or early breakdown

Eight “Main” sensor designs are fabricated, as shown in Figure 1.28. The first two are “short strip” (SS) and “long strip” (LS) Barrel sensors, square-shaped to maximize active wafer area. The remaining six designs correspond to Endcap sensors (R0, R1, R2, R3, R4, and R5, in this order) and are nearly trapezoidal, matching the disk curvature at their respective radial positions within the petal. All sensors are divided into several (2–4) strip segments, depending on the sensor layout.

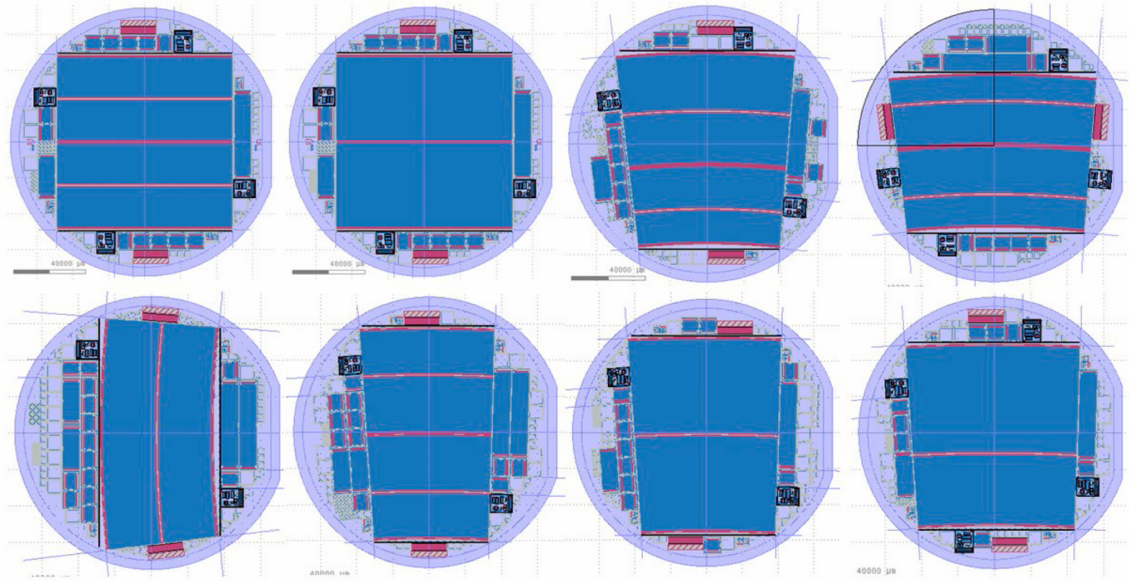


Figure 1.28: Strip sensor designs in 6-inch silicon wafers for the ATLAS ITk [61, 66].

1.4.2.2 Barrel Sensor Features and Specifications

The main parameters describing the Strip Barrel geometry and sensors are given in Table 1.1. The two inner layers use SS sensors with four strip segments of 24.1 mm strip length, while the two outer layers use LS sensors with two strip segments of 48.2 mm strip length. All Barrel sensors have the same strip pitch of 75.5 μm .

Table 1.1: Layout parameters for the ITk Strip Barrel, including sensor strip length and pitch [61, 66].

Layer/Type	Radius [mm]	Channels in ϕ	Strip Length [mm]	Strip Pitch [μm]	Tilt Angle [$^\circ$]
0 (SS)	405	28x1280	24.1	75.5	11.5
1 (SS)	562	40x1280	24.1	75.5	11.0
2 (LS)	762	56x1280	48.2	75.5	10.0
3 (LS)	1000	72x1280	48.2	75.5	10.0

Figure 1.29 shows the schematic layout of an SS sensor, with all element dimensions indicated, including $\pm 20 \mu\text{m}$ dicing tolerance and a minimum metal width of 10 μm . The specifications of the SS sensors are listed below.

Dimensions

- Length: $97621 \pm 20 \mu\text{m}$. Tolerance from dicing.
- Width: $97950 \pm 20 \mu\text{m}$. Tolerance from dicing.

Edges & Dicing

- Edge distances:
 - Longitudinal: $450 \pm 20 \mu\text{m}$
 - Lateral: $550 \pm 20 \mu\text{m}$. Measured from inner bias-ring edge to final dicing cut. This defines the “slim edge” used in “slim dicing”.
- Edge termination: Contractor’s choice.

Strip Geometry

- Strip segments per sensor: 4 rows
- Implanted strips per segment: 1282. Outer strips shape the electric field at the boundary.
- Readout strips per segment: 1280
- Strip pitch: $75.5 \mu\text{m}$

Strip Structures

- Readout implant strip: $16 \mu\text{m}$ wide, high-doped n-implant
- Readout metal strip: $22 \mu\text{m}$ wide aluminium, capacitively coupled to implant. Overhang: $3 \mu\text{m}$ per side.
- Polysilicon bias resistors: Either overlapping or running beside the implant

Isolation & Protection

- Isolation structure: $6\text{--}8 \mu\text{m}$ wide p-implant between strips, surrounding the readout implants. Approximated implantation dose: $\sim 4 \times 10^{12} \text{ ions/cm}^2$.
- Punch-through protection (PTP): $\leq 20 \mu\text{m}$ gap between bias rail and strip-implant end. Gap covered by conductive layer insulated from bulk and implant.

High-Voltage & Contact Features

- HV contact: Backplane metallized over p-type implant
- n-bias contacts: On bias ring, aligned with readout pad rows
- DC-probe pads: On each strip’s bias-resistor contact and strip-end

Wirebonding & Pad Layout

- Readout bond pads: $200 \times 56 \mu\text{m}^2$, two rows per segment

- Chip boundary markers: Indicate 1st and 128th pads per ASIC

Passivation

- Strip side: Fully passivated with uniform thickness
- Backplane: Unpassivated

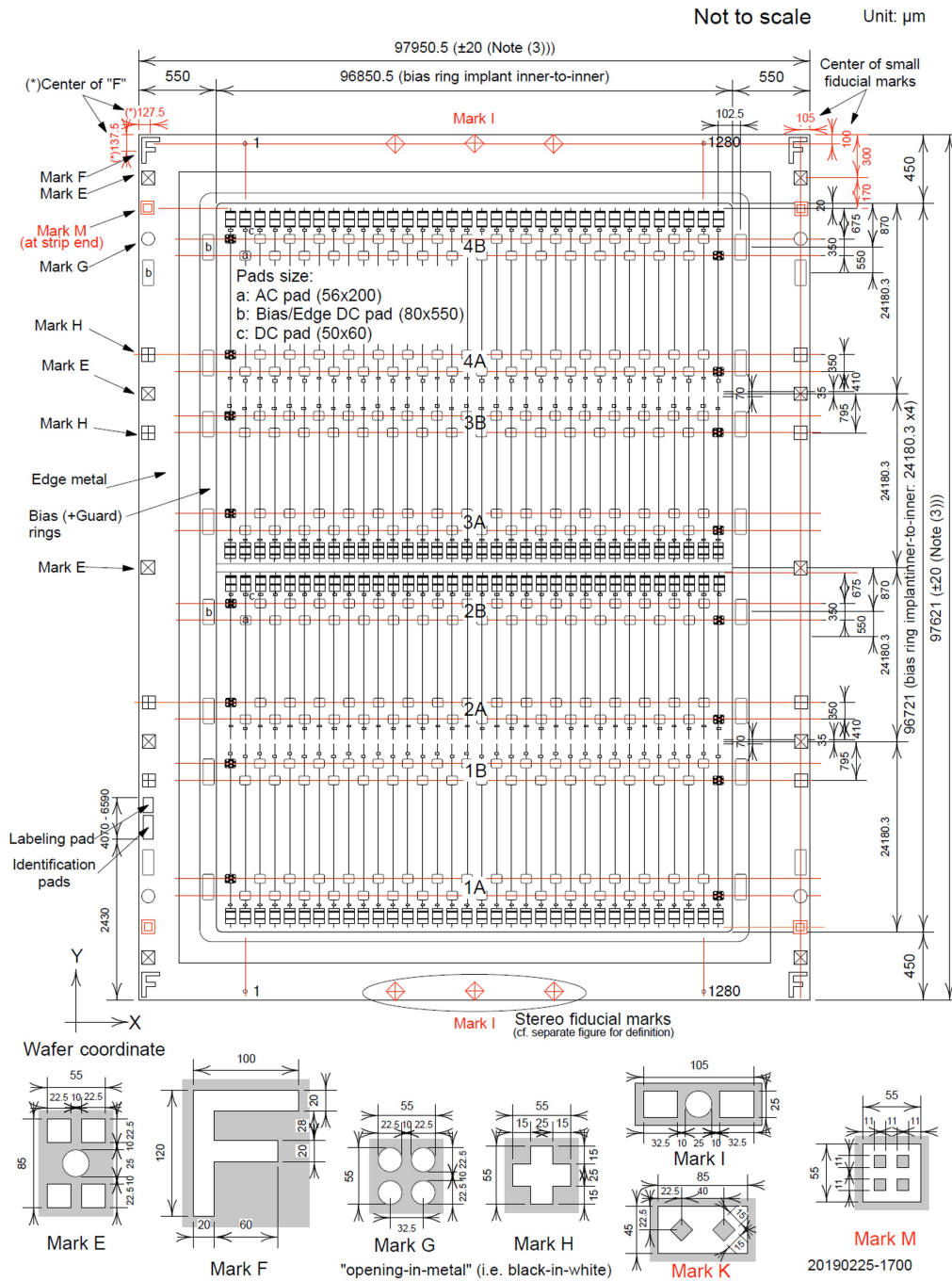


Figure 1.29: Schematic layout of the square SS sensor, showing the dimensions of all design features. Fiducial marks are indicated at the bottom of the image [67].

The LS sensors present the same features and specifications, differing only in the number of strip segments (2 rows) and the characteristics that result from this.

1.4.2.3 Endcap Sensor Features and Specifications

Endcap sensors have radially arranged strips oriented toward the beam axis. Each Endcap sensor is divided into several segments (see Figure 1.28), with strip lengths ranging from 19 mm in the inner row to 60.2 mm in the outer row, while keeping the strip occupancy below 1%. The strip pitch varies from 69.9 μm to 80.7 μm , depending on the disk ring and row. These and other parameters are detailed in Table 1.2.

Table 1.2: Layout parameters for the ITk Strip Endcap, including sensor strip length and pitch [61, 66].

Ring	Row	Inner Radius [mm]	Strip Length [mm]	Strip Pitch [μm]
Ring 0	Row 0	384.5	19.0	75.5
	Row 1	403.5	24.0	79.2
	Row 2	427.5	29.0	74.9
	Row 3	456.4	32.0	80.2
Ring 1	Row 0	489.8	18.1	69.9
	Row 1	507.9	27.1	72.9
	Row 2	535.0	24.1	75.6
	Row 3	559.1	15.1	78.6
Ring 2	Row 0	575.6	30.8	75.7
	Row 1	606.4	30.8	79.8
Ring 3	Row 0	638.6	32.2	71.1
	Row 1	670.8	26.2	74.3
	Row 2	697.1	26.2	77.5
	Row 3	723.3	32.2	80.7
Ring 4	Row 0	756.9	54.6	75.0
	Row 1	811.5	54.6	80.3
Ring 5	Row 0	867.5	40.2	76.2
	Row 1	907.6	60.2	80.5

Many Endcap sensor specifications are equivalent to those of Barrel (SS/LS) designs, as their basic structure, implant widths, and biasing follow the SS sensor specifications. The main differences with respect to the SS sensors are outlined below.

Shape and Strip Geometry

- Sensor edges differ from SS barrel sensors. Trapezoidal shape versus square shape.

- Variable strip pitch and length (see Table 1.2)

Strip Segments

- Number of strips per segment: Differs from the SS sensor. Total number of channels per sensor in Table 1.3, resulting from contribution of all rows.

Pads

- AC/DC pads in strips: Arranged in fan geometry, following the circular boundary of the sensor
- HV pads: in the bias ring, aligned along the circle of the AC pads; in bias and edge rings, parallel to the bias ring

Fiducial Marks

- Arrangement differs from SS sensor to accommodate circular geometry

Endcap sensors are designed with a stereo angle (Figure 1.30), laid out in fan geometry with center at focal point F, rotated 20 mrad relative to origin O (perpendicular beam axis).

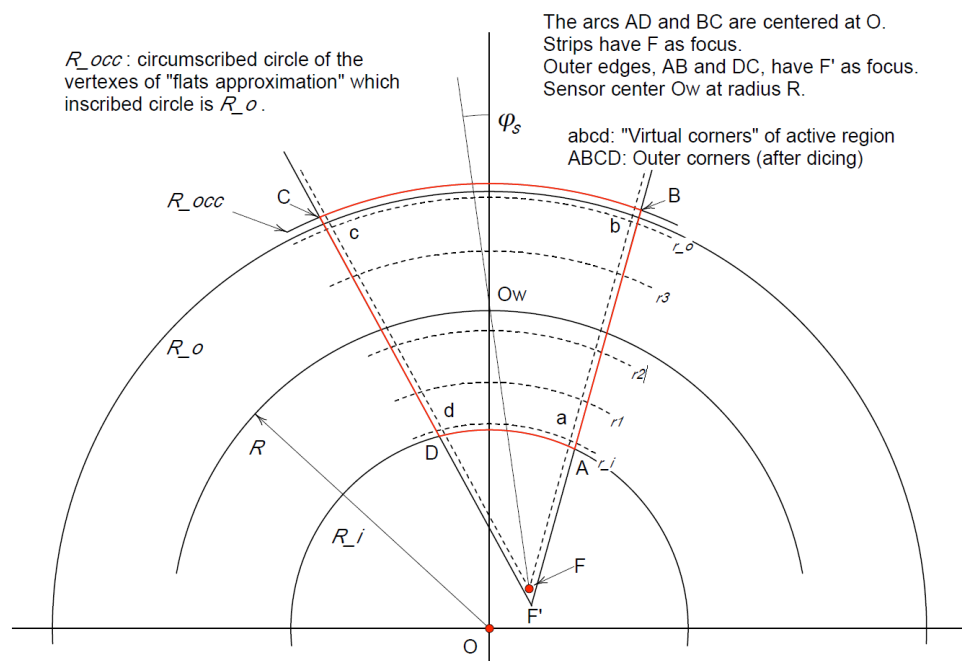


Figure 1.30: Parameters defining the stereo angle of Endcap sensors [67].

Table 1.3 summarizes general features of Barrel and Endcap sensors, including number of sensors, shape, rows, channels per sensor, and minimum/maximum strip pitch.

Table 1.3: Features of the Barrel and Endcap sensors, including their ring position, total number of sensors, number of rows, channels per sensor, and minimum/maximum pitch [51].

Sensor type	Number of sensors	Shape	Number of rows	Channels per sensor	Min/max pitch (μm)
Short-strips	3808	Square	4	5128	75.5
Long-strips	7168	Square	2	2564	75.5
EC Ring 0	768		4	4360	73.5/84
EC Ring 1	768		4	5640	69/81
EC Ring 2	768		2	3076	73.5/84
EC Ring 3	1536		4	3592	70.6/83.5
EC Ring 4	1536		2	2052	73.4/83.9
EC Ring 5	1536		2	2308	74.8/83.6

1.4.2.4 Electrical Pre-Irradiation Specifications of Strip Sensors

The large number of sensors ($> 20\,000$) to be manufactured throughout the full ITk strip sensor production must comply with the following pre-irradiation requirements.

- Process reproducibility: To be controlled and monitored by the contractor (flat-band voltage (V_{FB}), oxide thickness (t_{ox}), polysilicon resistivity, aluminum sheet resistance, etching uniformity, dielectric strength, etc.)
- Wafer bulk: p-type, FZ
- Wafer crystal orientation: $\langle 100 \rangle$
- Wafer oxygen concentration: $1.5 \times 10^{16} - 6.5 \times 10^{17} \text{ atoms/cm}^3$
- Wafer resistivity: $\geq 3.5 \text{ k}\Omega\cdot\text{cm}$
- Initial depletion voltage (V_{FD}): $< 350 \text{ V}$

- Maximum operating voltage: 500 V
- Total initial leakage current: $< 0.1 \mu\text{A}/\text{cm}^2$ at 500 V, RH $< 20\%$. Normalized to 20°C with guard ring floating.
- Leakage current stability: Variation $\leq 15\%$ over first 24 h at 500 V in dry air (RH $< 20\%$), after correction for temperature fluctuations
- Resistance of n-implant strip: $< 50 \text{ k}\Omega/\text{cm}$
- Resistance of aluminum readout strips: $< 30 \Omega/\text{cm}$
- Resistance of (polysilicon) bias resistor (R_{bias}): $1.5 \pm 0.5 \text{ M}\Omega$
- Inter-strip resistance (R_{int}): $> 10 \times R_{\text{bias}}$ at 300 V at room temperature (RT)
- Inter-strip capacitance (C_{int}): $< 1 \text{ pF}/\text{cm}$ at 300 V at RT. Measured at 100 kHz at the Main sensor and at 1 MHz at miniature sensors.

C_{int} must be scaled for the Endcap sensors (fan geometry) using:

$$C_2 = f \frac{\ln(d_2/a)}{\ln(d_1/a)} C_1, \quad d_2 = 75.5 \mu\text{m}, f = 1.12, a = 20 \mu\text{m}$$

where C_1 is the measured C_{int} .

- AC coupling capacitance (C_{coupl}): $\geq 20 \text{ pF}/\text{cm}$, measured at 1 kHz
- Onset voltage of microdischarge (V_{MD}): $> 500 \text{ V}$
- Percentage of bad strips: $< 1\%$ per segment and $< 1\%$ per sensor. Less than 8 consecutive bad strips.

Definition of bad strips: Failing bias resistance, coupling capacitance, or any of the following faults:

- Defective coupling dielectric: Short between metal and substrate at 100 V
- Defective metal strip: Metal breaks or shorts to neighbors
- Defective implant strip: Implant breaks or shorts to neighbors
- Defective bias resistor: Resistor breaks or insufficient isolation
- Microdischarge strips: Onset of microdischarge detected

1.4.2.5 Electrical Post-Irradiation Specifications of Strip Sensors

All sensors must comply not only with pre-irradiation specifications but also with additional post-irradiation requirements for a fluence of up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and an ionizing dose of 66 Mrad. The specified measurement results assume an annealing period of 7 days at $+25^\circ\text{C}$ (or 80 min at $+60^\circ\text{C}$) and are obtained at -20°C .

- Maximum operating voltage: Within pre-irradiation acceptance limits
- Total leakage current: $< 0.1 \text{ mA}/\text{cm}^2$ at -20°C , for bias voltages up to 500 V
- Leakage current stability: Within pre-irradiation acceptance limits, after correction for temperature fluctuations
- Resistance of (polysilicon) bias resistor (R_{bias}): Within pre-irradiation limits
- Inter-strip resistance (R_{int}): Within pre-irradiation limits at 400 V, -20°C
- Inter-strip capacitance (C_{int}): Within pre-irradiation limits at 400 V, -20°C
- Onset voltage of microdischarge (V_{MD}): $> 500 \text{ V}$ or $> V_{\text{FD}} + 50 \text{ V}$. Additionally, electrical noise measurement with readout electronics (peaking time of 25 ns).
- Collected charge: > 7500 electrons per MIP at 500 V
- Defective strips: Number of strips failing pre-irradiation criteria must remain within pre-irradiation acceptance limits after irradiation

1.4.3 Wafer Layout

The schematic wafer designs for the Barrel and Endcap sensors were already presented in Figure 1.28 of this chapter. Each wafer contains a Main sensor centered on the wafer, surrounded by four “half-moon” wafer sections. These half-moon structures include miniature sensors, test chips, diodes, and other devices. Enlarged images of the LS and R0 wafer layouts are shown in Figure 1.31, where the extrapolated dicing lines on each side of the Main sensor are also visible.

For each production batch (all batch sensors being of the same type), it is specified that two additional cuts are made on one half-moon of every wafer. These cuts divide the diced half-moons into three regions:

- The **Testchip&MD8** piece, containing the ATLAS Testchip, an MD8 diode, and smaller diodes.

- The **Mini&MD8** piece, containing a miniature (Mini) sensor and an MD8 diode.
- A third half-moon region containing the remaining devices.

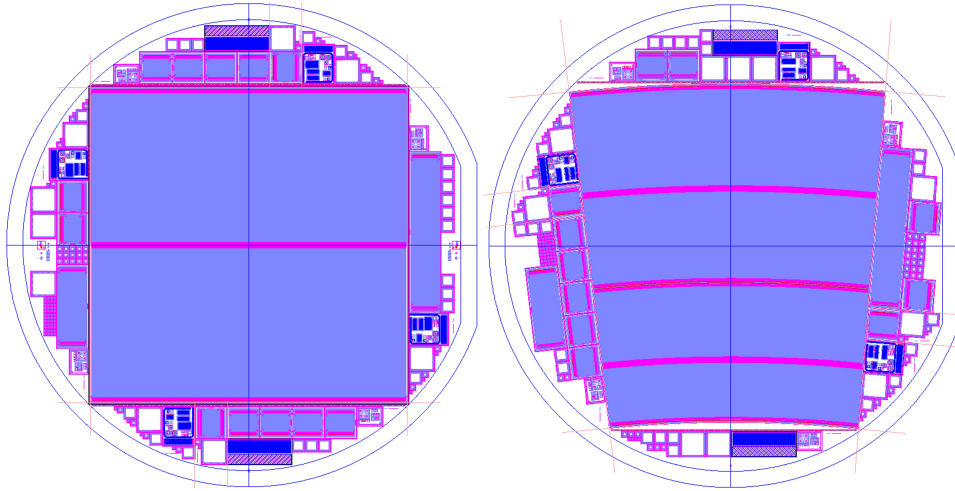


Figure 1.31: Wafer layout design of the LS (left) and R0 (right) sensors. Design visualized and exported from KLayout.

1.4.3.1 Main Sensors

The properties, characteristics, and design of the Main sensors were described in detail in the previous section. There are common features for all Main sensors, while others depend on the sensor type and geometry. Figure 1.32 shows a fragment of the LS Main sensor layout, including the sensor edges, guard ring, bias ring, bias resistors, and the strip array with AC and DC pads in one quadrant of the sensor.

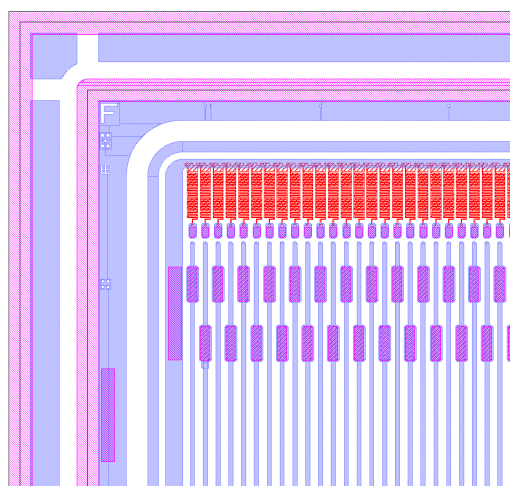


Figure 1.32: Layout of the upper-left quadrant of the LS Main sensor with its principal technological structures (implants of strips and p-stops not shown). Design visualized and exported from KLayout.

1.4.3.2 Half-Moon Structures

The most relevant devices in the wafer half-moons are the Testchip&MD8 and Mini&MD8 pieces, used for Quality Assurance (QA) purposes (see Chapter 2). Typical dimensions of QA pieces from LS/SS (Barrel) and R1 (Endcap) wafers are shown in Figure 1.33.

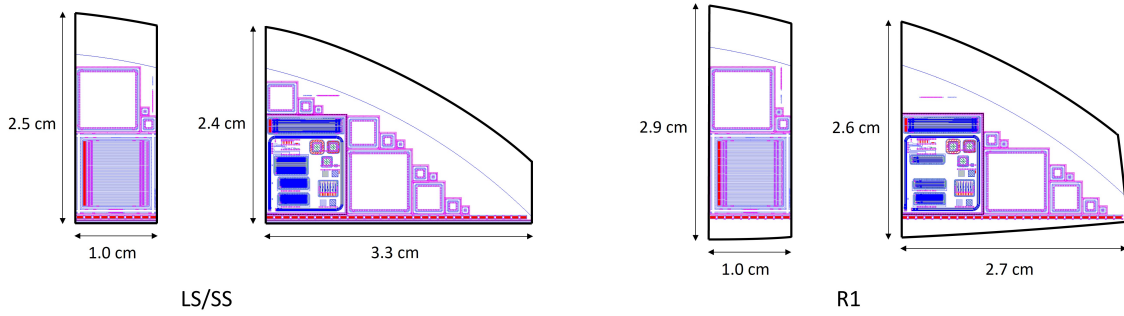


Figure 1.33: Dimensioned Testchip&MD8 and Mini&MD8 layout pieces corresponding to LS/SS (left) and R1 (right) wafers.

Each of the QA devices that compose the Testchip&MD8 or Mini&MD8 pieces is shown in Figure 1.34: the ATLAS Testchip, the Monitor Diode MD8 and the Mini sensor.

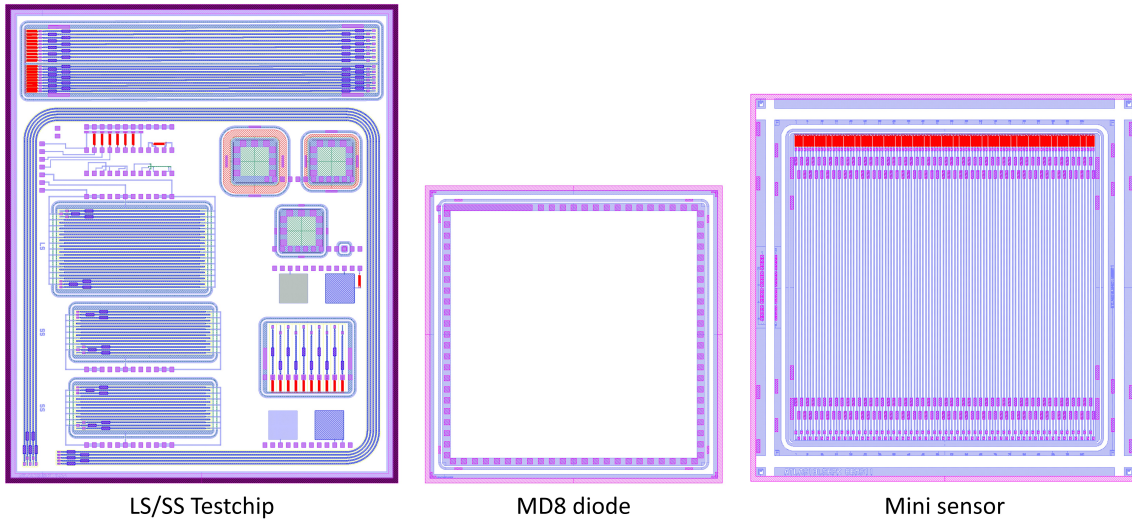


Figure 1.34: QA devices: ATLAS Testchip LS/SS (left), MD8 diode (center), and Mini sensor (right). Design visualized and exported from KLayout.

Diced QA pieces are circled in yellow in Figure 1.35. Their positions in the wafer (UP, LOW, LEFT, or RIGHT half-moons) depend on the sensor (wafer) type. Although only one Testchip, one Mini, and two MD8 diodes are diced from each wafer, more identical devices are arranged across the remaining half-moons. One QA piece of each type is diced from every wafer of all batches. Testchip&MD8 and Mini&MD8 pieces are selected from a few wafers for QA distribution and measurement plans.

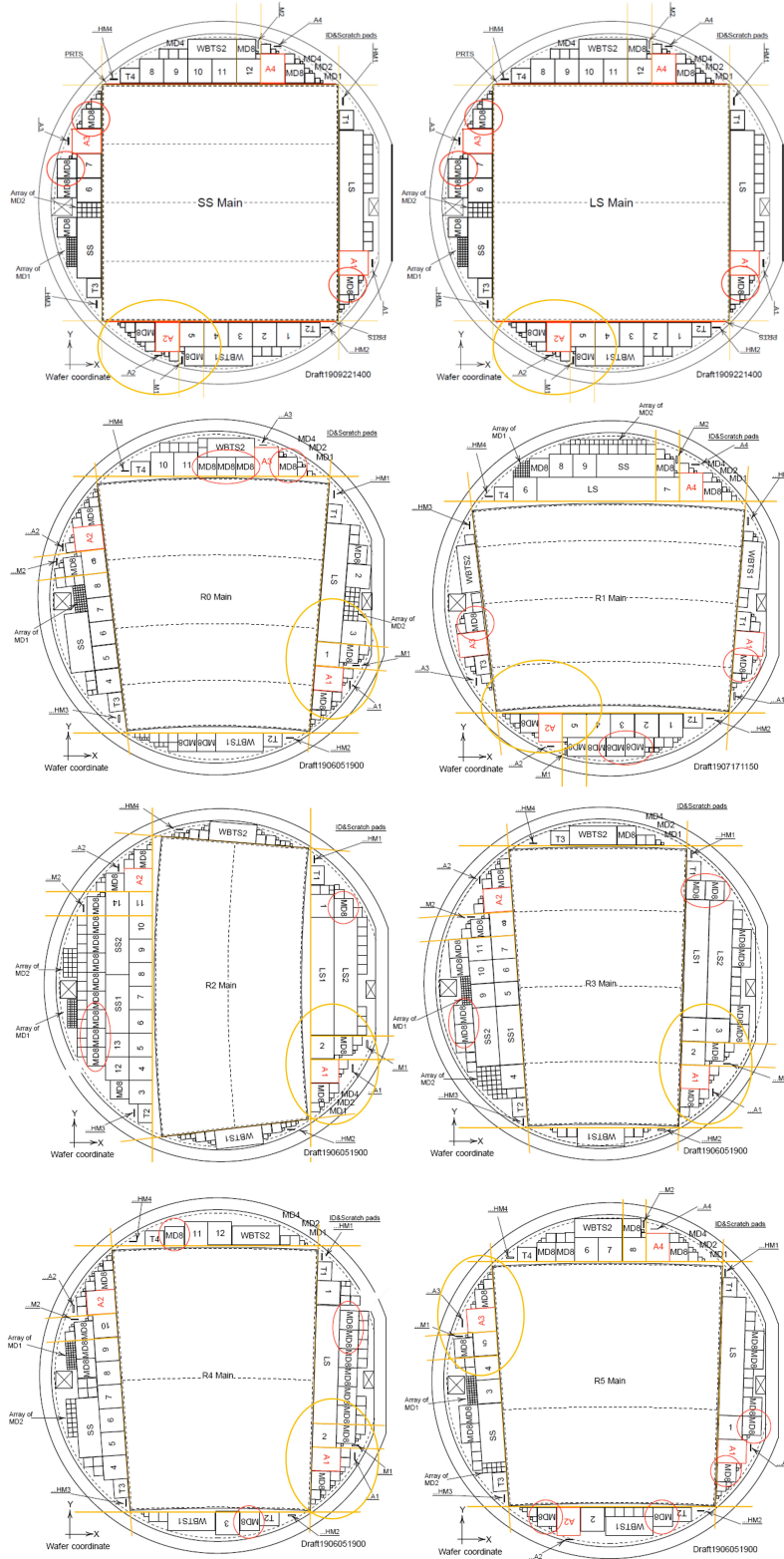


Figure 1.35: Schematics of the eight sensor wafer designs (SS, LS, R0, R1, R2, R3, R4, and R5) used in the ATLAS ITk. Positions of diced QA pieces circled in yellow (one Testchip&MD8 and one Mini&MD8 per wafer).

The Testchip is a $1\text{ cm} \times 1.2\text{ cm}$ device containing several test structures specifically designed for QA purposes: bias resistors, cross-bridge resistors, interdigitated structures, coupling capacitors, MOS capacitors, punch-through protection (PTP) structures, monitoring diodes, gated diodes, strip-like structures, and an Endcap strip-like structure. All these elements are described in detail in Chapter 2. Although they are practically identical for all wafer types, the interdigitated structures are adapted to the sensor type in each case. These structures, used for inter-strip resistance tests, contain strip patterns with total lengths matching the Main sensor strip lengths in the corresponding rows. As described earlier in this chapter, strip length is a variable parameter for each sensor type.

For LS and SS (Barrel) Testchips, the design is required to be the same, with interdigitated structures containing the “long-strip” and “short-strip” lengths of the Barrel sensors in both LS and SS wafers. This Testchip layout is shown in Figure 1.34. For the Endcap (R0–R5) Testchips, whose layouts are depicted in Figure 1.36, the designs differ only in the interdigitated structures.

The miniature sensors have a design similar to that of the Main sensors but with dimensions adapted to a reduced sensitive area. They all contain 104 strips with a $75.5\text{ }\mu\text{m}$ pitch, but three miniature-sensor types are defined according to their external dimensions:

- Mini: $1 \times 1\text{ cm}^2$, strip length $8\,000\text{ }\mu\text{m}$
- Mini_SS: $1 \times 2.6\text{ cm}^2$, strip length $2,418\text{ }\mu\text{m}$
- Mini_LS: $1 \times 5\text{ cm}^2$, strip length $4,836\text{ }\mu\text{m}$

Miniature-sensor layouts are shown in Figure 1.37. Their structure follows the pattern illustrated in Figure 1.32 for the Main sensor design. The Mini on the right-hand side of Figure 1.37 belongs to the Mini&MD8 piece tested in the QA program.

Four different types of diodes are included in the wafer design: MD8 ($8 \times 8\text{ mm}^2$), MD4 ($4 \times 4\text{ mm}^2$), MD2 ($2 \times 2\text{ mm}^2$) and MD1 ($1 \times 1\text{ mm}^2$). All are shown in Figure 1.38. These diodes include a central square n-implant region, surrounded by a guard ring and an edge structure similar to those of the Main sensors. The bias ring consists of a metal “ring” layer over the n-type implant, containing several probing pads (passivation openings).

Additionally, a wire-bonding test structure (WBTS) with a specialized design is included in the wafer half-moons. It consists of a strip-like structure with characteristics similar to those of the Main sensor, but with all strips connected to a common metal pad for wire-bonding tuning purposes during module assembly.

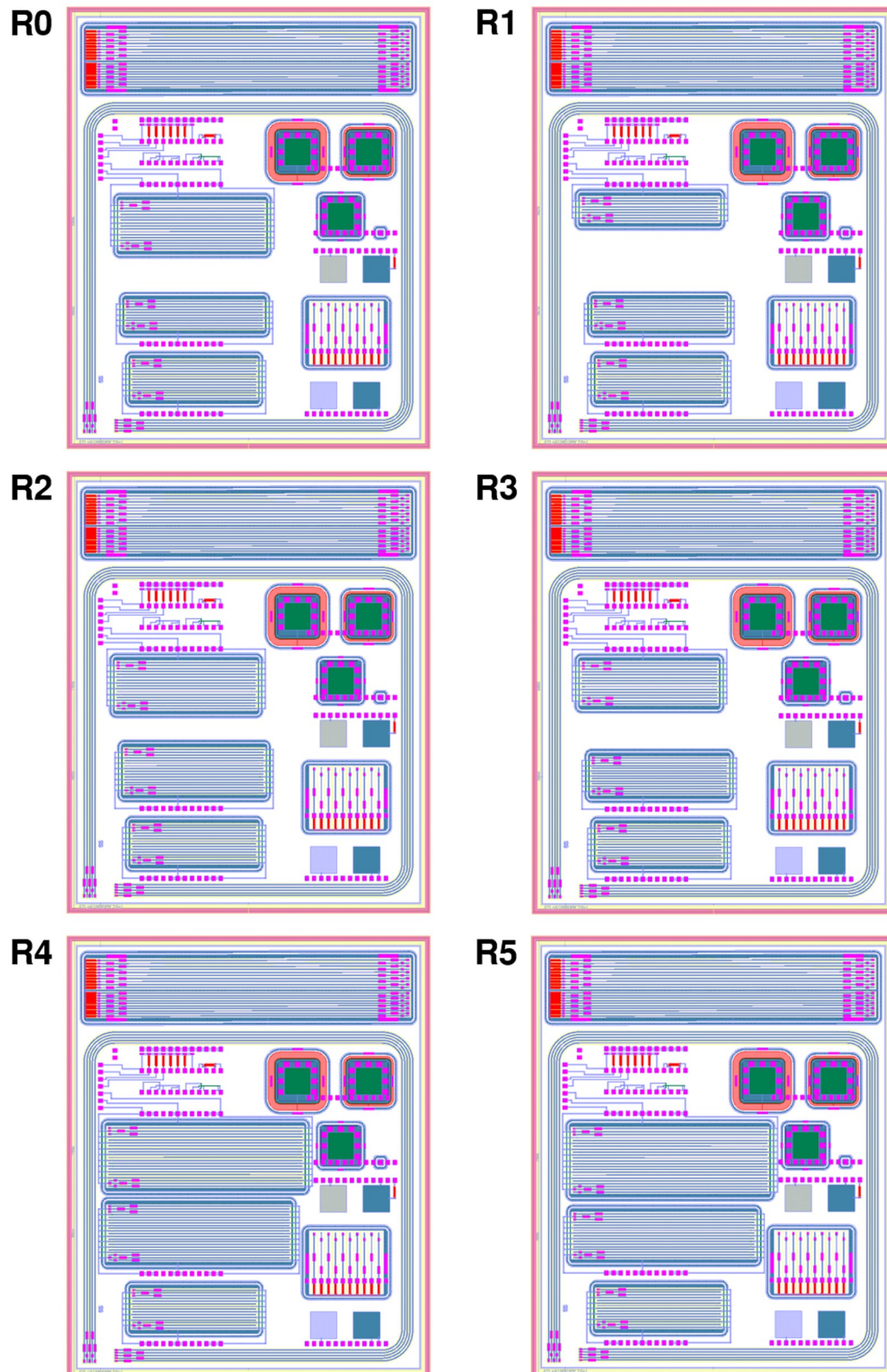


Figure 1.36: Testchip layouts from R0, R1, R2, R3, R4, and R5 Endcap wafers. Different interdigitated structures appear in each Testchip [11].

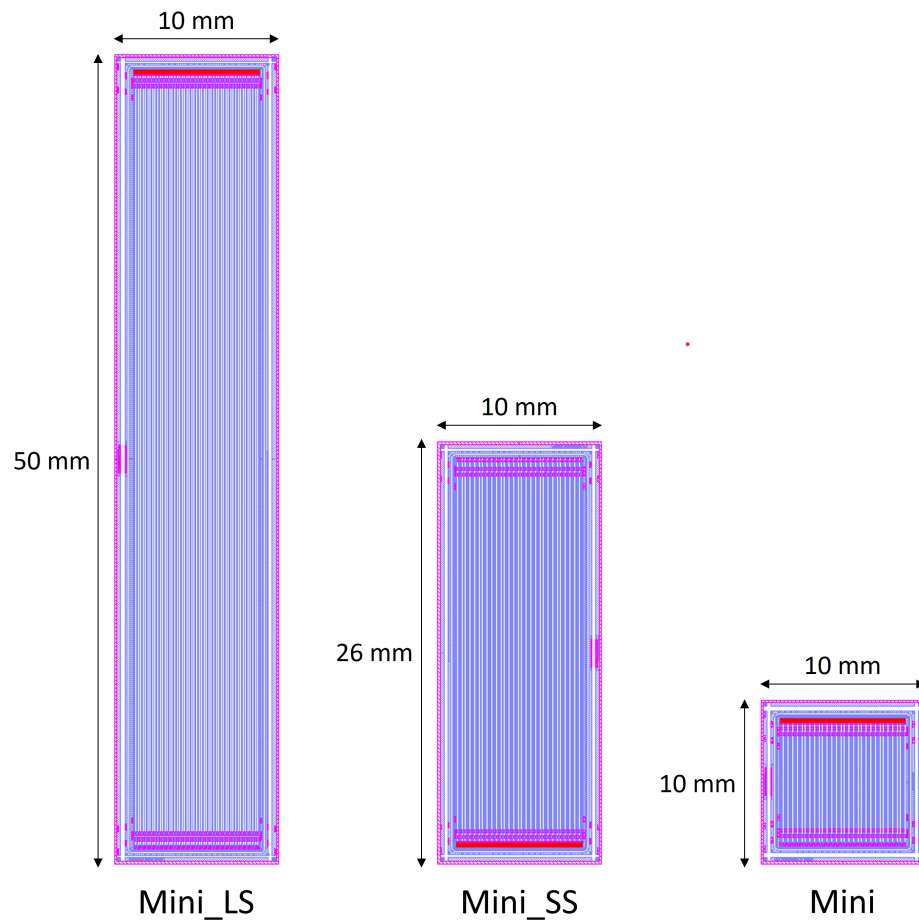


Figure 1.37: Miniature sensor layouts and their dimensions: Mini_LS, Mini_SS and Mini. Design visualized and exported from KLayout.

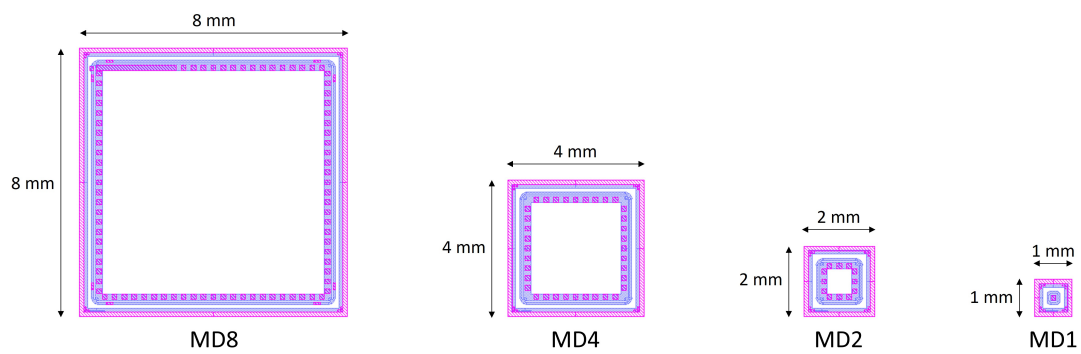


Figure 1.38: Monitor Diode layouts and their dimensions: MD8, MD4, MD2, and MD1. Design visualized and exported from KLayout.

1.5 State of the Art and Open Questions at the Start of This Work

The design and operation of silicon strip sensors for particle tracking experiments were well established at the beginning of this thesis, including the physical principles of pn-junction devices, the effects of radiation on bulk and surface properties, and the basic quality requirements for large-area detectors. Nevertheless, several gaps remained when transitioning from previous detector generations to the upgraded ATLAS Inner Tracker (ITk) for use in the HL-LHC, particularly in moving from 4-inch wafer sensor technology to 6-inch FZ wafers for the ITk strip sensors.

The main challenge addressed in this thesis was managing the transition from the prototyping phase to large-scale production for the ATLAS ITk upgrade, along with all the implications arising from the ITk strip sensor production itself:

- At the start of this work, there was no comprehensive Quality Assurance (QA) framework encompassing pre-irradiation testing, targeted irradiations (neutrons, protons, gamma rays, and gamma + neutrons), post-irradiation measurements, parameter extraction methods, and database-driven reporting, suitable for continuous monitoring during a long production.
- The Strips Collaboration required unified, automated tools to standardize raw data files and extract results from standardized files across all the testing institutes distributed worldwide, including test methods and setups, parameter extraction, plotting, pass/fail evaluation, database interaction, and global reporting. This should ensure QA traceability and reproducibility throughout the full sensor production.
- Parameter assessment and batch approval relied on ITk strip sensor specifications; however, procedures for defining, maintaining, and revising “soft” thresholds (see Section 2.1) had not yet been established to monitor process variability without compromising yield, while ensuring sensor reliability.
- Some parameters critical for monitoring the fabrication process—particularly those related to oxide quality or p-stop quality, such as V_{FB} , S_{REF} and V_{PT} (see Chapter 3)—had not been yet used as early-warning indicators in large-scale, systematic production QA. Consequently, deviations in the fabrication process could not be identified straightforwardly from these parameters.

- The impact and quantification of radiation-induced damage on some of the technological-oriented parameters of the ITk strip sensors were still under investigation and some questions remained open at the start of production.

This thesis addresses these points by establishing a production QA methodology that integrates automated measurement tests, data analysis, and database management to enable early-stage decisions based on large volumes of measurement data obtained at worldwide spread testing sites. It also provides an improved understanding of strip sensor performance through the systematic analysis of large amounts of sensor properties after exposure to different types and levels of irradiation.

Applied to the ATLAS ITk, Quality Assurance (QA) consists of a systematic set of activities designed to ensure that quality requirements are met throughout the entire detector fabrication process. In particular, the QA process for strip sensor production is described in detail in this chapter. QA works in close coordination with Quality Control (QC), which is responsible for verifying that the final product (strip sensors) meets the required quality standards. The two are complementary aspects of quality management of any production process.

Testchips, monitoring diodes, and miniature sensors were selected as essential devices for QA testing. Specifically, several structures were integrated into the Testchips to monitor key parameters and to ensure the correct fabrication of the sensors.

The production flow was meticulously designed, and neutron, proton, and gamma-ray irradiations were scheduled to be performed at dedicated irradiation facilities. Following this, the samples were distributed among several institutions within the QA Collaboration for testing and analysis.

2.1 Quality Assurance vs. Quality Control

2.1.1 Quality Assurance

According to ISO 9000, Quality Assurance (QA) is defined as “part of quality management focused on providing confidence that quality requirements will be fulfilled” [68]. It is a proactive process, oriented toward the fabrication workflow, and intended to prevent defects before they occur. QA was integrated into the ATLAS ITk detector, playing an important role in evaluating the fabrication process. In particular, the work presented in this thesis has been developed within the framework of the QA strategy for strip sensor production for the ATLAS ITk.

The ATLAS ITk QA community has been responsible for monitoring technological stability and tracking variations throughout the entire manufacturing process. This has involved establishing standards and specifications, as well as systematic procedures to ensure a high-quality production process. Such measures made it possible to predict and

prevent deviations in key parameters, with all parameters obtained from these devices required to fall within the maximum and minimum thresholds defined by the ATLAS Collaboration [69–71].

A distinction was made between “hard” thresholds—specified in the Technical Specification for the Supply of Silicon Sensors for the ATLAS Inner Tracker Upgrade Project⁶ [67] and corresponding to well-studied and well-established parameters—and “soft” thresholds, defined by the QA Collaboration based on production statistics in order to control process variability. The soft thresholds were initially determined from the mean value and standard deviation of prototype or pre-production results for each parameter without hard thresholds. Specifically, an acceptable range was considered to be within $\pm 3\sigma$ around the mean value. In several cases, the soft thresholds were further refined throughout production QA as more statistics became available at later stages.

The QA process also ensured that the radiation hardness was met up to the required levels, as validated during the prototyping phase [72].

2.1.2 Quality Control

Similar to the QA definition, Quality Control (QC) can be described as “part of quality management focused on fulfilling quality requirements.” Thus, QC operates as a reactive process focused on the final product, with the purpose of detecting any defects.

Within the quality management of the strip sensors, QC [73–75] has been closely tied to QA. It has been responsible for inspecting and measuring the sensors, identifying defects, and performing acceptance tests on the finished Main sensors to be installed in the experiment. For this purpose, the following tests were performed on every sensor: visual inspections and visual captures recorded for each individual sensor, metrology tests to ensure the sensor planarity with a maximum bow of 200 μm , and I–V/C–V scans for the electrical bulk characterization. Additional QC tests were also performed on subsets of each batch: tests to guarantee a sensor thickness within $320 \mu\text{m} \pm 15 \mu\text{m}$ (one per batch), long-term stability tests (LTS) to monitor leakage-current stability over tens of hours (10–20% of the batch sensors), and full strip tests in which each strip is characterized by measuring the strip current, the bias resistance, and the coupling capacitance (2–5% of the batch sensors) [66].

⁶ The *Technical Specification for the Supply of Silicon Sensors for the ATLAS Inner Tracker Upgrade Project* defines all required properties and characteristics of silicon pixel and strip sensors for the ATLAS ITk upgrade, as well as the acceptance limits for their physical and electrical parameters. These specifications are based on the *Technical Design Report for the ATLAS Inner Tracker Strip Detector* [51].

The QC team has been inspecting all finished items from each fabrication batch to verify that they meet quality standards. In contrast, QA evaluates only a few wafers per batch—irradiated with different particles or left non-irradiated—assuming that the characteristics of a single wafer are representative of the entire batch.

In general, QA ensures that the production process can achieve quality results, whilst QC verifies whether the actual products meet the defined standards. They have complemented each other in quality management during the production process. QA has reduced the likelihood of errors, whereas QC has ensured that any remaining issues were caught before the sensors were finally used in the experiment.

2.2 Designed Test Structures

Only a few representative wafers were selected from each batch for QA purposes. However, two QA pieces were diced from all batch wafers: the Testchip&MD8 and the Mini&MD8. Pieces not selected for QA evaluation were packaged and stored properly.

The main devices in the Testchip&MD8 piece are the Testchip, containing several test structures, and the MD8 monitoring diode. In turn, the Mini&MD8 piece is mainly composed of a miniature sensor (Mini sensor), emulating the Main sensor of the wafer but with smaller dimensions, and an MD8 diode as well [76].

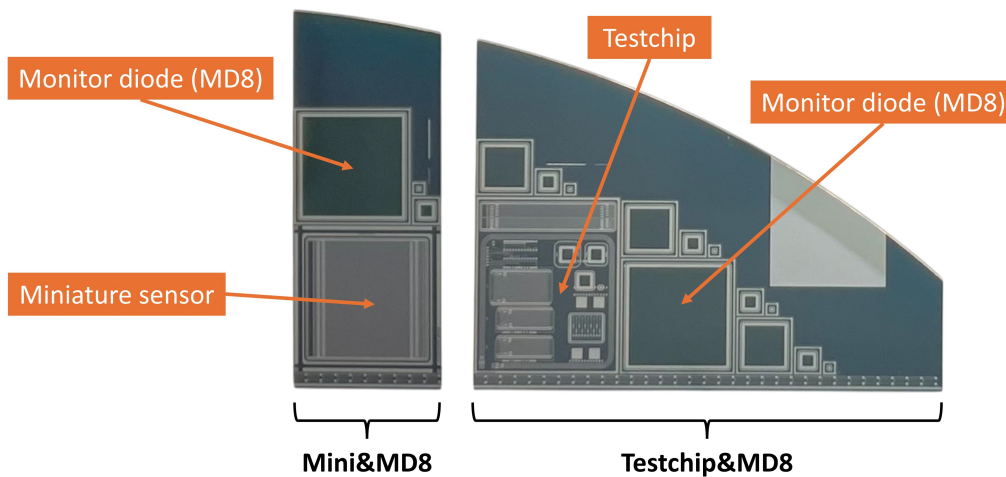


Figure 2.1: Images of the two QA pieces diced from each wafer: the Mini&MD8 (left) and the Testchip&MD8 (right).

Apart from the QA pieces diced from each wafer, several other Testchips, MD8s, and Mini sensors were implemented in the wafer layout, although they were neither diced nor added to the systematic measurement plan of the strip sensor QA. All these components are placed in wafer half-moons allocated for this purpose.

2.2.1 Testchip&MD8

The ATLAS Testchip is of high importance within the QA strategy [69, 77]. It is a piece with a roughly $1\text{ cm} \times 1.2\text{ cm}$ cut-edge containing several structures specifically designed to demonstrate the correct fabrication of the sensor. Each of these structures contains microelectronic devices (e.g. resistors, capacitors, etc.) with properties or configurations comparable to those in the Main sensor. This is what allows QA monitoring of strip sensors without intervening directly on the sensors to be used in the experiment, but instead on equivalent structures fabricated in a different location of the respective wafers. Figure 2.2 illustrates the schematic layout of the Testchip with a legend of all layers employed in the design and in the microelectronic fabrication.

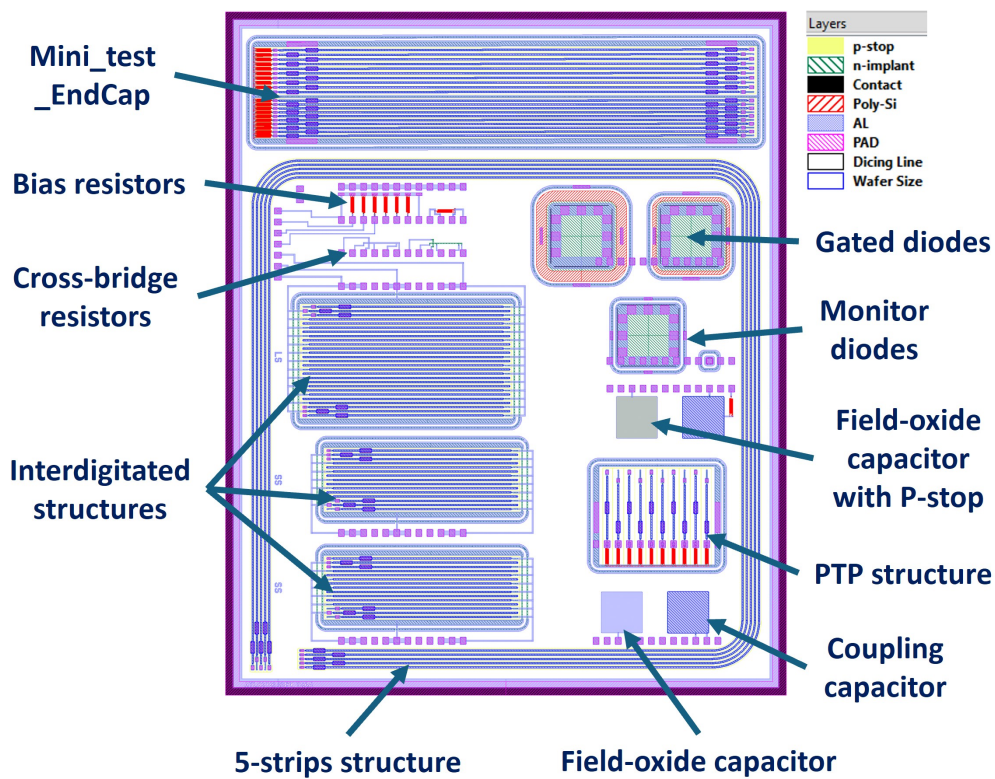


Figure 2.2: Schematic layout of an LS/SS ATLAS Testchip ($1\text{ cm} \times 1.2\text{ cm}$) containing all structures for QA testing. Design visualized and exported from KLayout.

The Testchip structures can be classified into two different categories based on their relevance to standardized QA tasks. Table 2.1 lists the structures in each category [71].

Structures in Category A were chosen as the main ones to be systematically evaluated for accurate and appropriate QA monitoring. They are essential, as they allow the extraction of key parameters to validate sensor fabrication and provide a comprehensive understanding of the technology and its behavior before and after irradiation with neutrons, protons, or gamma rays. These structures were tested throughout the entire production

Table 2.1: Testchip structures belonging to Category A or Category B.

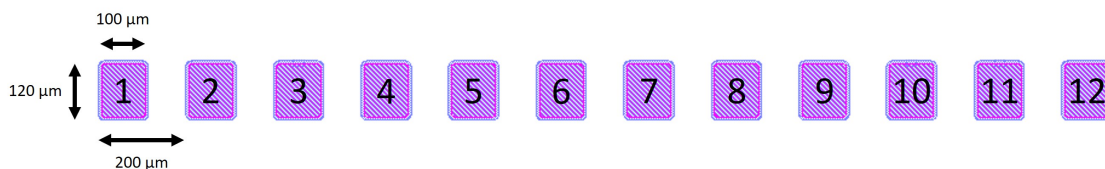
CATEGORY A	CATEGORY B
Bias Resistors	MOS Field Oxide Capacitor with P-stop
Cross-Bridge Resistors	Coupling Capacitor for V_{BD} test
Interdigitated Structures	Monitor Diodes
Coupling Capacitor	Gated Diodes
MOS Field Oxide Capacitor	5-strips Structure
PTP Structure	Mini_test_EndCap

process, and the results were used for batch acceptance following the previously defined acceptance criteria.

On the other hand, Category B structures are considered alternative and complementary. In fact, they were not included in the production measurement plan, but a few were tested occasionally for more detailed studies or to cross-check unexpected or non-compliant results obtained from Category A structures. Acceptance criteria were not defined for Category B structures.

A special mention must be made of the MOS Field Oxide capacitor with p-stop, a Category B structure that was later added to the systematic testing program after approximately seven months of production. A defect observed in the p-stop implantation of a few samples was crucial in deciding to monitor this structure.

All Category A structures and several Category B structures are linked to 1×12 sets of (nearly) squared-shaped probe-card pads. The pads are $100 \mu\text{m} \times 120 \mu\text{m}$ and arranged in a line with a pitch of $200 \mu\text{m}$. They are numbered from 1 to 12, from left to right, to facilitate test descriptions and references to pad connections following the same convention. Figure 2.3 shows a schematic layout of a pad row in a Testchip.

**Figure 2.3:** Schematic layout of a 12-pad row from the ATLAS Testchip. Design visualized and exported using KLayout.

Probe-card pad rows were especially designed for automatic testing using a probe card in an automatic probe station. The probe cards were also designed and specifically fabricated for the ATLAS Testchip. This is the test method systematically used in production QA for non-irradiated samples. In addition, Testchips can be tested when wire-bonded to a test

board. For this reason, several test structures are also connected to bonding pads. The pad design—whether for probe-card or wire-bonding tests—allows for automatic testing by connecting a switch matrix to the test instruments.

Regardless of the Category A–B classification, most of the test structures are arranged in two columns within the Testchip. This layout optimizes space in the Testchip and simplifies the automatic measurements performed with the probe card, which moves vertically across the Testchip, going through these two columns and making contact with the pad row associated with each structure or group of structures. Each pad row is located on a 50 μm grid within the Testchip, and all the structures connected to that pad row are considered to belong to the same “module”. The Testchip structures are described in this section following the test order.

2.2.1.1 Testcarta

The Testcarta structure is not included in Table 2.1, as it is not intended for parameter extraction. It consists of a probe-card pad row with the pads connected by a metal layer from one end to the other (see Figure 2.4). As the name suggests, its main purpose is to test the proper needle contacts between the probe card and the pads. This structure is located in the upper left part of the Testchip, where the initial testing position (0, 0) is set for all automatic measurements.

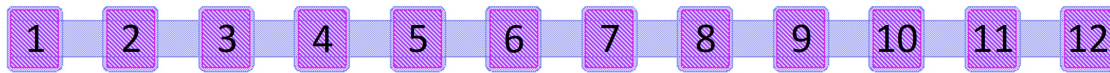


Figure 2.4: Schematic layout of the Testcarta structure from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.2 Bias Resistors

An ensemble of six polysilicon bias resistors is located just below the Testcarta structure [27]. Only the first eight pads from this 12-pad row are occupied, with the first (pad #1) and last (pad #8) connected to a metal strip in contact with all the bias resistors, placing them at the same potential as the test instrument. Pads 2–7 are connected to the six polysilicon resistors (one resistor per pad), as illustrated in Figure 2.5. Pads 1–4 (including the first three resistors) are also linked to wire-bonding pads on the left side of the layout. The Bias Resistors are equivalent to those used in the Main sensors to bias the strips, providing current protection against potential strip breakdown. The polysilicon is grown over a thick oxide in a zigzag (meander) shape, connecting the strip n-type implant to a

metal terminal. Each resistor is $5\ \mu\text{m}$ wide (polysilicon width) and about $1874\ \mu\text{m}$ long, measured along the nominal central path of the meander.

Additionally, this module includes a Kelvin resistor (or 4-wire resistor) on pads 9–12. It consists of a polysilicon bias resistor similar to those on pads 2–7 but with a different configuration. The terminals of the resistor are connected to two different pads each, allowing a current to be forced through two terminals while measuring resistance using the other two terminals. This eliminates cable resistance and provides a high-precision measurement. Despite this, the Kelvin resistor is not included in the systematic QA measuring plan, and only the standard Bias Resistors are tested for every Testchip.

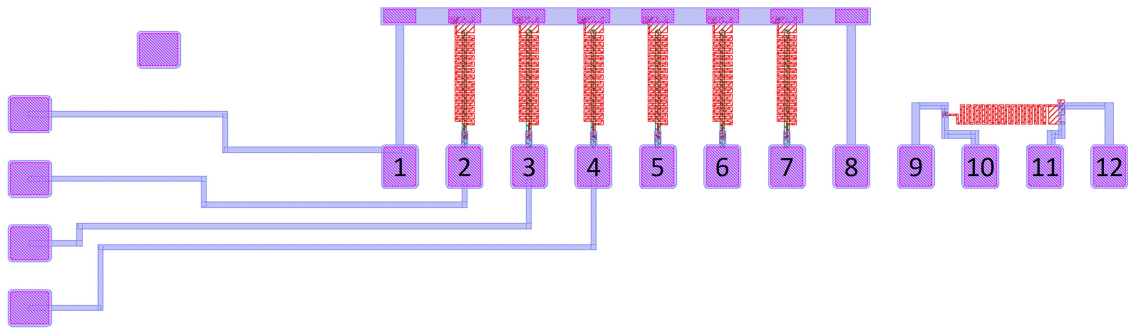


Figure 2.5: Schematic layout of the polysilicon Bias Resistors from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.3 Cross-Bridge Resistors (CBR)

A cross-bridge resistor (CBR) consists of a Greek-cross structure coupled to a bridge resistor [78, 79]. Two CBRs are implemented in this module: one for the strip metal layer, encompassing pads 1–6, and another for the strip n-implant, encompassing pads 7–12. In both cases, the widths of the metal and implant layers—identical for the Greek cross and the bridge—match those of the strip metal and strip implant in the Main sensor, respectively. Both the Greek-cross measurement and the bridge measurement require a four-terminal (Kelvin) configuration; however, the structures are arranged so that they can be tested using only six contact pads in total.

For the metal CBR, each arm of the Greek cross has a total length of $103.5\ \mu\text{m}$, measured from the center of the cross, and the bridge (bar) length is $L = 400\ \mu\text{m}$. The strip metal linewidth in the Main sensor layout is $W = 25\ \mu\text{m}$, and this same linewidth is replicated in the metal CBR layout. In any case, the nominal metal width is set to $22\ \mu\text{m}$, after accounting for metal-etching during fabrication.

The arm length for the implant CBR is $68\ \mu\text{m}$, while the bridge (bar) length is $L = 400\ \mu\text{m}$, as in the metal CBR. In this case, the layout implant linewidth is $W = 14\ \mu\text{m}$, which also

corresponds to the strip implant linewidth in the Main sensor. However, $W = 16 \mu\text{m}$ is considered the nominal implant linewidth to account for dopant lateral diffusion during the implantation of the strip n-type implants in the wafer.

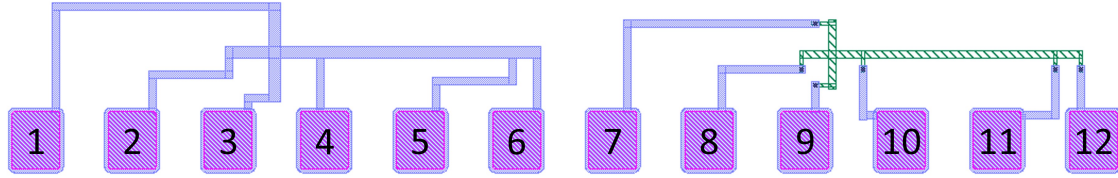


Figure 2.6: Schematic layout of the metal (left) and n-implant (right) Cross-Bridge Resistors from the ATLAS Testchip. Design visualized and exported using KLayout.

It is crucial to know the bar length ($400 \mu\text{m}$) in both CBR structures to obtain the metal and implant linewidths with high precision.

2.2.1.4 Interdigitated Structures

Three interdigitated structures are laid out on the left side of the Testchip, one above the other, labelled UP (at the top of the Testchip, just below the CBRs), MID (below UP), and LOW (at the bottom). Each structure is formed of interdigitated strips with a total equivalent length equal to the strip length in the corresponding Main sensor. The strip pitch in the Main sensor is also preserved. Additionally, a bias ring is included to bias the silicon bulk for parameter extraction of the corresponding test.

Table 2.2: Strip length of all Interdigitated structures according to their relative position in the Testchip (LOW, MID, UP) and the Testchip type.

TESTCHIP TYPE (SENSOR TYPE)	POSITION	STRIP LENGTH [cm]
ALL	LOW	2.401
SS & LS	MID	2.401
	UP	4.836
R0	MID	1.895
	UP	3.192
R1	MID	1.805
	UP	1.508
R2	MID	3.080
	UP	3.080
R3	MID	2.618
	UP	2.618
R4	MID	5.030
	UP	5.390
R5	MID	4.016
	UP	5.929

Unlike the other Testchip structures, the Interdigitated structures can vary depending on the wafer type. The strip lengths in the Testchip structures correspond to the strip lengths of the sensor hosted in the same Barrel (SS, LS) or Endcap (R0–R5) wafers. LOW structures are identical for all Testchips, with a strip length of 2.401 cm. This value corresponds to the SS sensor strip length; keeping it equal in all LOW structures serves as a good comparator without the need for normalization factors.

For SS and LS sensors, a unique strip length is defined for each type—2.401 cm and 4.836 cm, respectively—, so these two lengths are used for MID and UP structures in both SS and LS Testchips. Endcap sensors were designed with up to four strip rows of different strip lengths, depending on the sensor type (see Section 1.4). In all cases, the highest strip row corresponds to the UP interdigitated structure, while the lowest corresponds to the MID structure. All values used to design these structures are presented in Table 2.2. Parameters obtained from these structures can be normalized to strip length when comparisons between structures of different lengths are required.

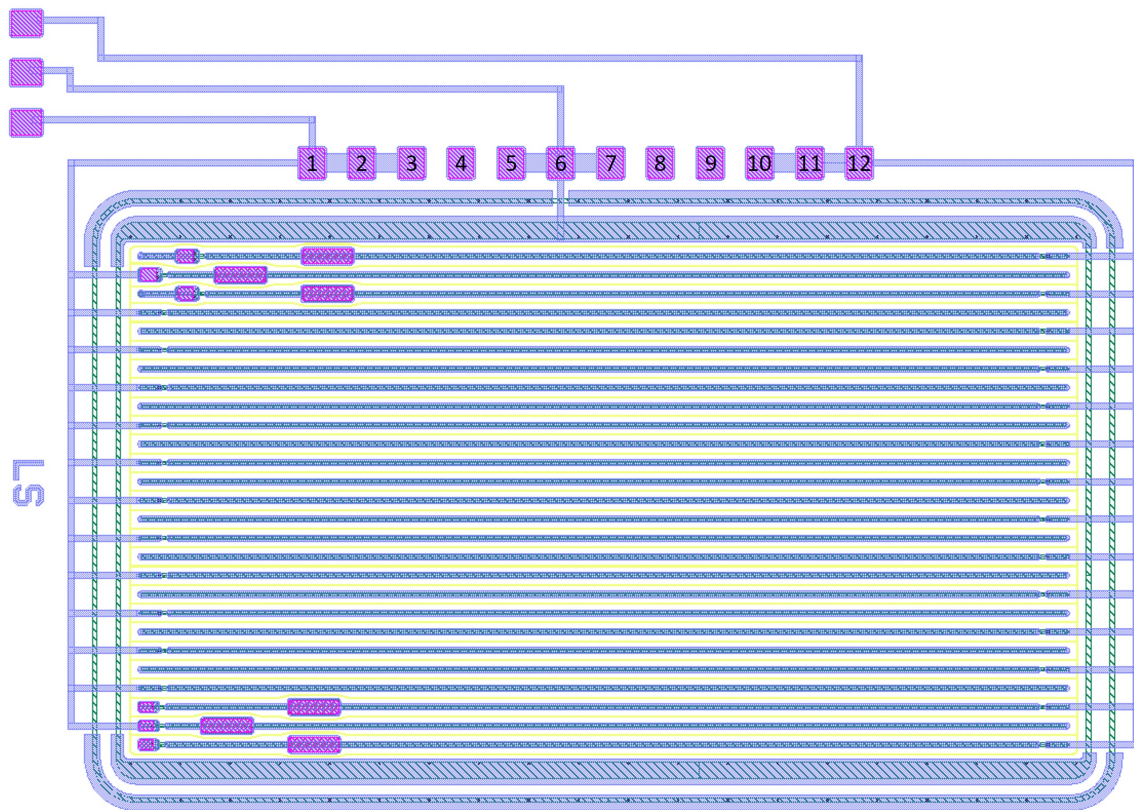


Figure 2.7: Schematic layout of the UP (top) interdigitated structure from an LS ATLAS Testchip. Design visualized and exported using KLayout.

Figure 2.7 shows an UP interdigitated structure from an LS Testchip, illustrating the connection of the probe-card pads to the device. Pad #1 is connected to a “central” strip, pad #2 is connected to “neighbor” strips, and pad #6 is connected to the bias ring. Each of these contact pads is also connected to wire-bonding pads at the left edge of the Testchip,

as described previously for the CBR structures. The LOW structure can additionally be wire-bonded to the probe-card contact pads due to the proximity of the lowest pad row to the Testchip bottom edge.

2.2.1.5 MOS Field Oxide Capacitor

This structure consists of a square-shaped MOS capacitor with the same dielectric as the inter-strip oxide (field oxide) in the Main sensor. A metal layer deposited on top of the field oxide (SiO_2) layer creates a MOS configuration. When a potential difference is applied between the silicon and the metal (gate), the capacitance can be measured, with the primary objective of determining the oxide thickness.

The Field Oxide Capacitor, laid out in Figure 2.8, has an area of $556\,000\,\mu\text{m}^2$, practically the same as the area of the central strip of the ‘5-strips’ structure in the Testchip—the ‘5-strips’ structure corresponds to Category B and is briefly described later in this chapter. Probe-card pads 1–6 are reserved for this structure, although only pad #3 is contacted with the capacitor metal. This structure can also be tested by wire-bonding the same pad (pad #3) to a test board due to its proximity to the bottom edge of the Testchip.

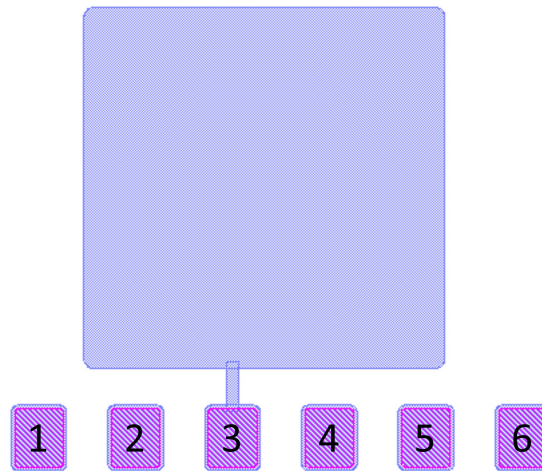


Figure 2.8: Schematic layout of the Field Oxide capacitor from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.6 Coupling Capacitor

The Coupling Capacitor is located just to the right side of the Field Oxide Capacitor in the Testchip. It consists of a square capacitor with a total area of $544\,000\,\mu\text{m}^2$, equivalent to the area of the central strip of the ‘5-strips’ structure in the Testchip. Therefore, the same coupling capacitance as in the ‘5-strips’ structure can be obtained from this capacitor,

but with a lower perimeter-to-area ratio. For this reason, the capacitance is normalized per unit length (pF/cm) to make it comparable to the coupling capacitance measured in the Main sensor strips.

The dielectric in this capacitor is the SiO₂ coupling oxide, considerably thinner than the field oxide used in the Field Oxide Capacitor. The capacitor also includes a metal layer and an n-implant layer. In fact, the implant layer preserves the same area as the strip implant mentioned before. The Coupling Capacitor layout is shown in Figure 2.9.

Probe-card pads 7–12 are assigned to the Coupling Capacitor, although only pad #11 is directly connected to the metal. Pad #10 also establishes connection with the capacitor via an n-implant channel. As in the Field Oxide Capacitor, the contact pads can also be wire-bonded due to their proximity to the bottom edge of the Testchip.

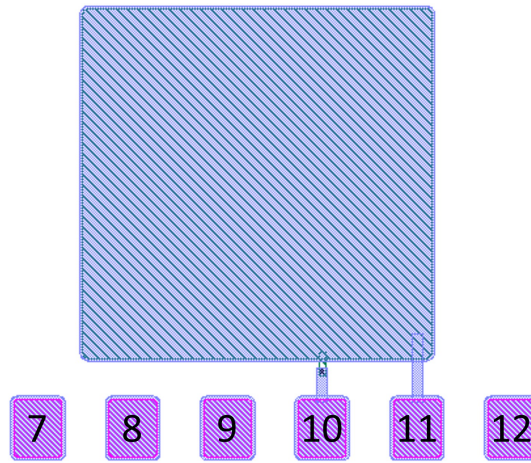


Figure 2.9: Schematic layout of the Coupling Capacitor from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.7 Punch-through Protection (PTP) Structure

The Punch-through Protection (PTP) [80, 81] structure is located just above the Coupling Capacitor and the Field Oxide Capacitor. Punch-through protection was implemented on the Main sensor strips to prevent the coupling capacitors from being damaged by large voltage differences that could short-circuit the strip implants and the backplane. The distance between the strip implants and the bias ring implant is reduced at one end of the strips (20 μm), and a p-stop implantation line isolates both parts. The punch-through effect occurs when the voltage exceeds the threshold that normally prevents current flow between these two implants.

The PTP structure consists of ten strip ends (the side containing the polysilicon resistors) arranged according to the design rules of the Main sensor strips (maintaining the strip

metal and implant linewidths, the strip pitch, etc.). A bias ring is included, along with a guard ring surrounding it. Contact pads #1 and #12 are connected to the bias ring, while pads 2–11 are connected to each of the ten strips of this structure. All 12 pads are arranged in the same pad row and can be contacted by a probe card. These pads can also be wire-bonded due to their proximity to the bottom edge of the Testchip. Figure 2.10 shows a schematic layout of the PTP structure.

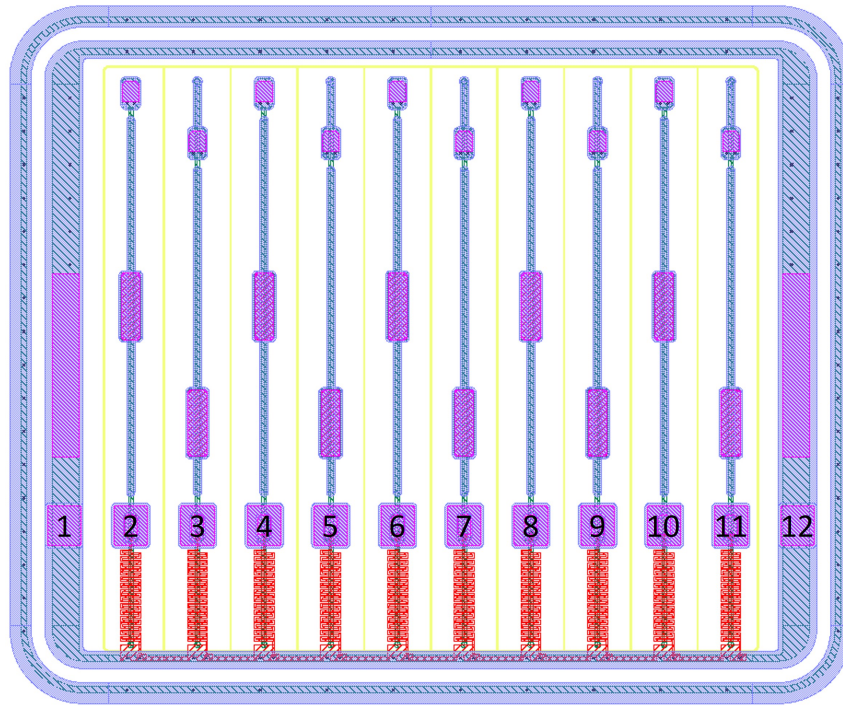


Figure 2.10: Schematic layout of the Punch-Through Protection structure from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.8 MOS Field Oxide Capacitor with P-Stop

The Field Oxide Capacitor with p-stop [82], shown in Figure 2.11, is a MOS capacitor similar to the one described above in this section. Additionally, a p-stop layer is implanted underneath the entire capacitor area. This capacitor has the same area as the Field Oxide Capacitor described previously ($556\,000\,\mu\text{m}^2$). Probe-card pads 1–6 are associated with this structure, but only pad #3 makes contact with the capacitor metal.

Beyond measuring the thickness of the oxide above the p-stops, which is thinner than the field oxide, tests performed on this structure provide additional information on the quality of the p-stop implantation in the capacitor, as well as in the Testchip, and, by extension, across the entire wafer.

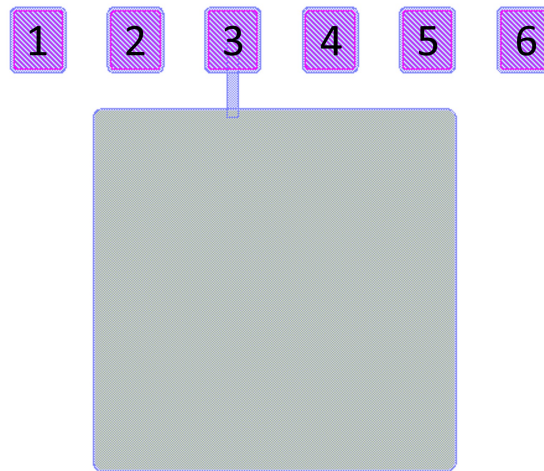


Figure 2.11: Schematic layout of the Field Oxide Capacitor with p-stop from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.9 Additional Structures (Category B)

The structures corresponding to Category B are described in this section, although they were not part of the systematic QA testing plan. They were considered backup structures for potential additional studies to be performed at any stage of production. In particular, the test of the MOS capacitor with p-stop was implemented at later stage: a low p-stop implantation detected on a few production Testchips motivated the testing of this structure as a double-check for improved p-stop monitoring. The other Category B structures were not required for further tests during production.

Coupling Capacitor for Breakdown Voltage test

This structure consists of the same square coupling capacitors as described previously, but with a bias resistor added in series with the metal layer covering the capacitor area. That is, the capacitor includes a metal layer, an oxide, and a n-implant layer as well. As with the Coupling Capacitor described earlier, the total implant area ($544\,000\,\mu\text{m}^2$) corresponds to the central strip of the ‘5-strips’ structure. Probe-card pads 7–12 are assigned to this structure. Pad #10 establishes a direct connection between the probe card and the capacitor, while pad #12 contacts the capacitor through the resistor in series. The layout design is presented in Figure 2.12.

The purpose of this structure is to determine the Breakdown Voltage (V_{BD}) of the coupling capacitor in a destructive test. The resistor in series with the metal limits high current pulses during breakdown, protecting the testing equipment.

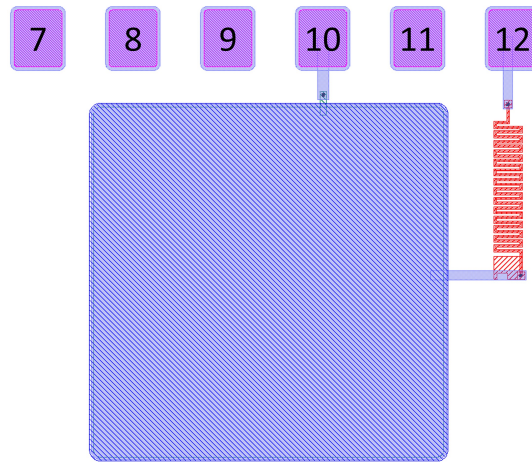


Figure 2.12: Schematic layout of the Coupling Capacitor for Breakdown Voltage test from the ATLAS Testchip. Design visualized and exported using KLayout.

Monitor Diodes

As discussed in Chapter 1, several square diodes were included in the sensor wafer layout. The $8 \times 8 \text{ mm}^2$ (MD8) diodes are described below in this section.

Diodes described in this section are the Monitor Diodes MD2 and MD1, which follow the MD8 design but have smaller dimensions to fit within the Testchip. Specifically, they are two square diodes with metal contact layers of $1183 \times 1183 \mu\text{m}^2$ (MD2) and $183 \times 183 \mu\text{m}^2$ (MD1), respectively. Like the MD8s and the Main sensor, these monitoring diodes contain edge structures of $2 \times 2 \text{ mm}^2$ (MD2) and $1 \times 1 \text{ mm}^2$ (MD1) when placed in wafer half-moons. Nevertheless, this dicing structure is not included in the Testchip design.

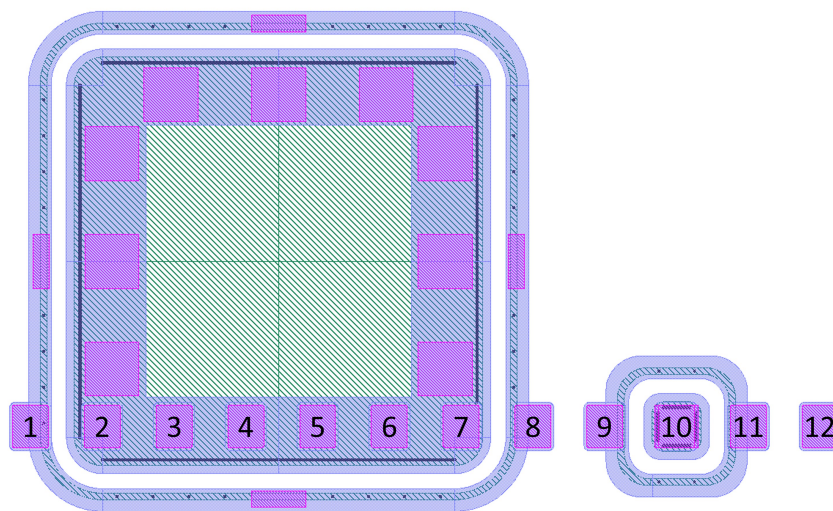


Figure 2.13: Schematic layout of the $1183 \times 1183 \mu\text{m}^2$ (left) and $183 \times 183 \mu\text{m}^2$ (right) Monitor Diodes from the ATLAS Testchip. Design visualized and exported using KLayout.

Figure 2.13 shows the layout of the Monitor Diodes, including a probe-card pad row overlapping the structures and contacting both the implant layer and the guard ring of each diode. Pads 1–8 correspond to the larger diode, while pads 9–12 correspond to the smaller one.

Gated Diodes

Two gated diodes are included in the Testchip for characterization of the Si surface and the Si–SiO₂ interface, via parametrization of the surface generation current. This allows for a better understanding of leakage currents and the quality of the silicon surface or the silicon–oxide interface.

These square diodes each contain a metal layer with the same dimensions as the larger Monitor Diode ($1183 \times 1183 \mu\text{m}^2$). They also include a polysilicon gate of different lengths: the diode on the left in Figure 2.14 has a polysilicon gate $60 \mu\text{m}$ long, while the diode on the right has a polysilicon gate $180 \mu\text{m}$ long. A set of probe-card pads covers both Gated Diodes, enabling automatic testing.

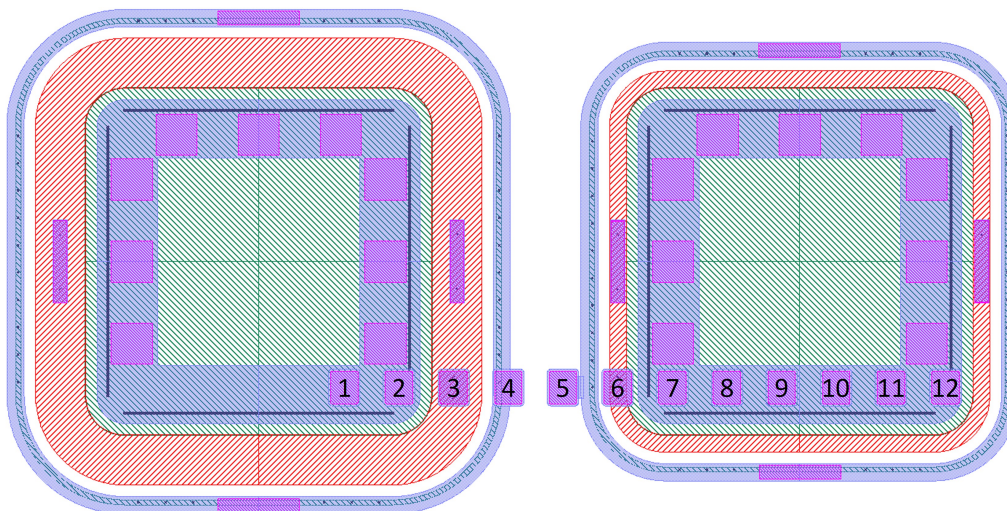


Figure 2.14: Schematic layout of the Gated Diodes from the ATLAS Testchip. Design visualized and exported using KLayout.

‘5-strips’ Structure

This structure consists of five parallel strips curved to enclose the other Testchip structures. Only the Mini_test_Endcap structure, described in the next section, is placed outside of the ‘5-strips’ structure. The main characteristics of the sensor strips are projected here, including the barrel strip pitch ($75.5 \mu\text{m}$), the p-stop implants between strips, and

the AC/DC pads. The total strip length (central strip length of $34\,000\ \mu\text{m}$) maximizes the available space in the Testchip design.

The ‘5-strips’ structure, shown in Figure 2.15, does not have probe-card pads but can be wire-bonded to AC and DC pads due to the proximity to the Testchip edge. Several parameters can be extracted from this structure, including strip implant resistance, strip metal resistance, coupling capacitance, and inter-strip resistance and capacitance.

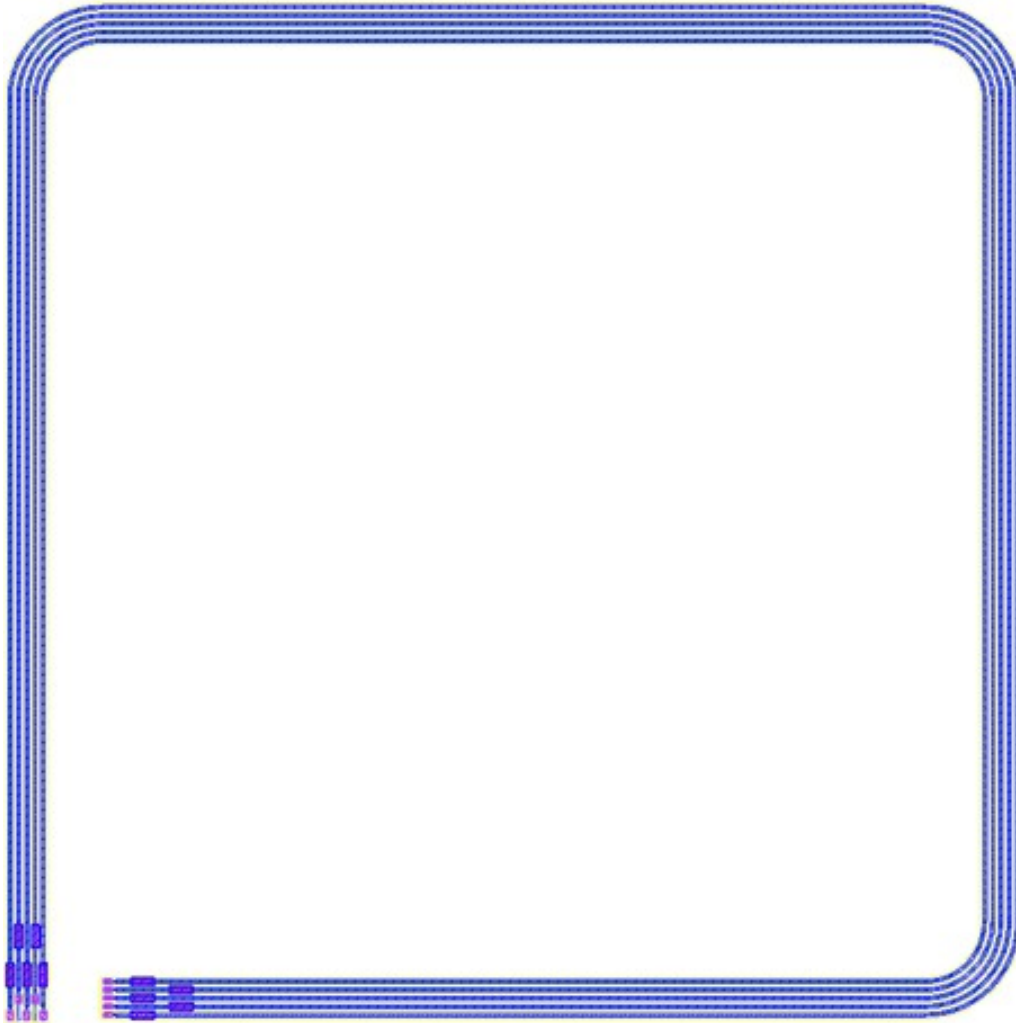


Figure 2.15: Schematic layout of the ‘5-strips’ structure from the ATLAS Testchip. Design visualized and exported using KLayout.

Mini_test_Endcap Structure

The Mini_test_Endcap structure is a miniature sensor that emulates two different active areas of the Endcap R3 sensor—with non-parallel strips—shown in Figure 2.16. The first active area, in the lower part of the layout, has a strip pitch starting from $70\ \mu\text{m}$ with an

angular pitch of $109.505261\ \mu\text{rad}$. The second area, in the upper part of the structure, has a strip pitch ending with $83.9\ \mu\text{m}$ with an angular pitch of $171.688015\ \mu\text{rad}$.

The structure also contains a bias ring and a guard ring, similar to the Main sensor, with two active areas separated by a bias ring line. Like the ‘5-strips’ structure, no probe-contact pads are added, but AC, DC, and bias pads can be wire bonded due to proximity to the Testchip edge. Inter-strip properties can be obtained from this device.

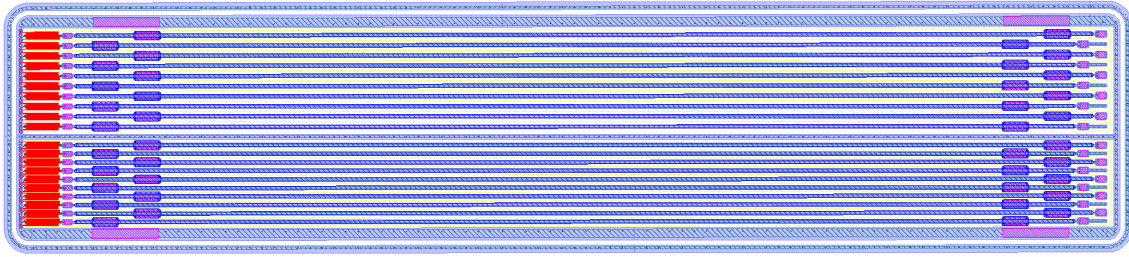


Figure 2.16: Schematic layout of the Mini_test_Endcap structure from the ATLAS Testchip. Design visualized and exported using KLayout.

2.2.1.10 Monitor Diode MD8

The primary Monitor Diode (MD8) of the Testchip&MD8 piece is not part of the Testchip itself but is adjacent to it. Several other MD8s are included in the wafer design apart from those in the Testchip&MD8 pieces, as discussed in Chapter 1; all of them share the same design.

The MD8, laid out in Figure 2.17, consists of an $8 \times 8\ \text{mm}^2$ square diode, with a central n^+ implant area, surrounded by a guard ring and an edge structure, similar to the Main sensor. Wire-bonding pads are included to contact the n^+ implant and edge implant. The diodes also have an opening in the top metal, centered on the structure, allowing laser light to penetrate into the bulk silicon and make the diode responsive to optical signals. The guard ring adjacent to the bias ring is fully passivated except for a few contact pads. These pads are used to connect the guard ring to ground (GND) during I–V/C–V tests, isolating effects caused by the edge region of the MD8 and enabling separate study of silicon bulk effects.

The implant layer is not shown in the layout in Figure 2.17, as this information is proprietary to the manufacturer, HPK. The layouts of layers such as the n-type implant and the p-stop implant are only known for the Testchip.

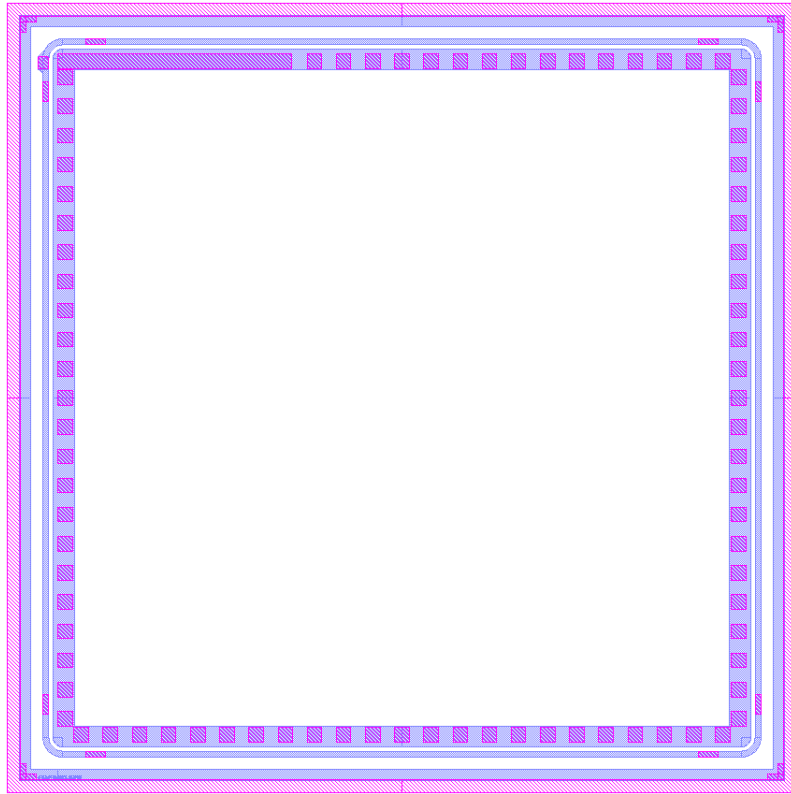


Figure 2.17: Schematic layout of the MD8 Monitor Diode. Design visualized and exported using KLayout.

2.2.2 Mini&MD8

Diced Mini&MD8 pieces consist of a Mini sensor and an MD8 Monitor Diode. Each device is a self-contained testable structure and, unlike the ATLAS Testchip, they do not include any substructures.

2.2.2.1 Mini Sensor

The Mini sensor is a scaled-down reproduction of the barrel Main sensor. Each Mini sensor has 104 readout strips, maintaining the strip pitch of $75.5\ \mu\text{m}$ and the design characteristics of the Main sensor, except for those changes required by the reduced sensitive area. The bias ring, guard ring, and edge structure of the Main sensor are also implemented in these devices.

As explained in Section 1.4, three different miniature sensor types (Mini, Mini_SS and Mini_LS) were designed and placed on each sensor wafer, but only Mini-type sensors ($1 \times 1\ \text{cm}^2$, strip length $8\ 000\ \mu\text{m}$) were part of the systematic production QA plan, as these are the devices belonging to the finally diced Mini&MD8 pieces. They were primarily

used to test the charge collection efficiency (CCE) after irradiations at target fluences and doses.

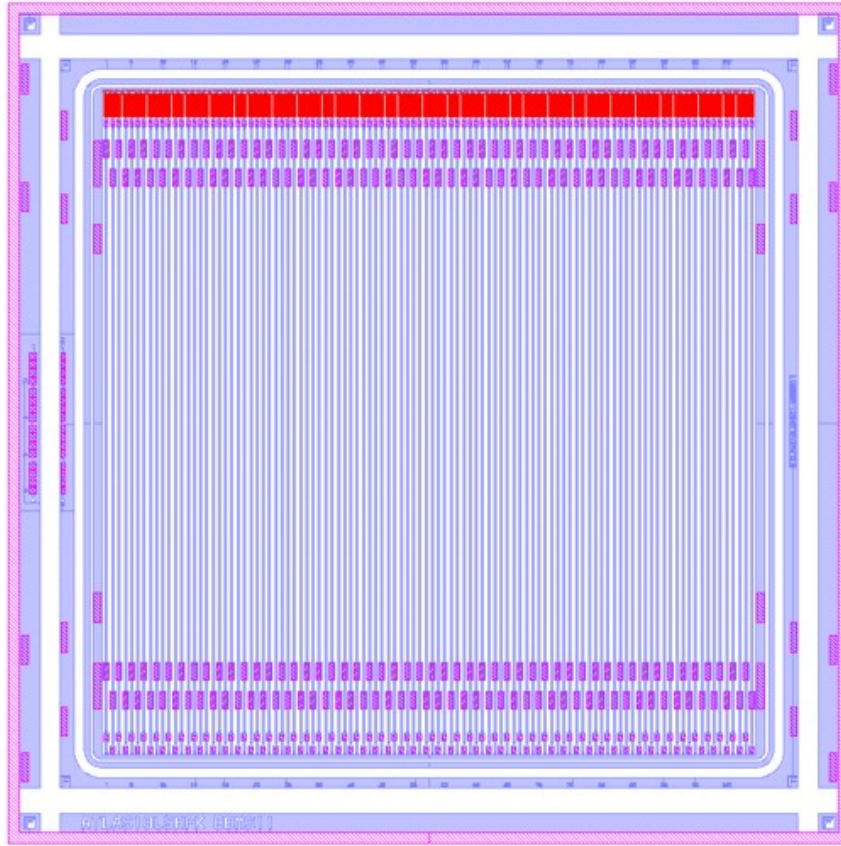


Figure 2.18: Schematic layout of the $1 \times 1 \text{ cm}^2$ Mini sensor. Design visualized and exported using KLayout.

2.2.2.2 Monitor Diode MD8

The MD8 diode in the Mini&MD8 piece is identical to the MD8 described in Section 2.2.1. In this case, however, the MD8 is placed on top of the Mini sensor.

2.3 Production Flow

The ITk strip sensor production began in early 2020. A total of 22 000 wafers were initially expected to be fabricated over four years; however, the process extended to nearly five years, with completion now projected for April 2026. Therefore, sensor production—and consequently production QA—is still ongoing at the time of writing, although the fabrication of the strip sensors is already complete (except replacements for sensor rejections), and only the QA/QC evaluation remains to be finalized.

Several years before production began, a prototyping phase was carried out to analyze and verify the technology of the ATLAS17LS prototype sensors and the corresponding QA components for implementation in the ATLAS ITk. Pre-production started later, in January 2020, representing an additional 5% of the ATLAS18 sensors required for full production. This was followed by years of full production, which experienced some delays due to the COVID-19 pandemic and a slight increase in the total number of sensors planned. Entire batches and individual sensors rejected due to production failures had to be replaced. Moreover, sensor fabrication was scheduled to stop permanently four months before the final tests and evaluations. Considering all these factors, the final target for fabricated sensors reached 25,051—the first 1,041 sensors for pre-production plus a new total of 24,010 for production—allowing a margin to account for rejections or possible damage in later phases of the experiment.

Regarding batch rejection due to QA, a procedure was followed whenever fabrication defects were observed. First, the QA Collaboration informed Hamamatsu Photonics K.K. (HPK) of anomalies detected in Testchips, Mini sensors, or MD8s—i.e., results outside the specified limits for each parameter. Simultaneously, the QA Collaboration tested additional devices from the suspect batch to double-check the results while HPK reviewed its own data and provided feedback. Whole production batches were rejected when non-acceptable defects were confirmed.

HPK, the Japanese foundry, was responsible for all strip sensor fabrication. Production was organized in monthly deliveries of batches, each containing around 40 wafers. Due to the large number of institutes (test sites and irradiation centers) involved, production flows for both QC and QA were planned in advance.

In QC, the flow started at HPK, then sensors were sent to reception sites (CERN and KEK), from where they were distributed to all sensor QC sites responsible for QC testing. After evaluation, sensors were sent to Module sites for the next step in ITk assembly.

This thesis focuses on production QA. For the Testchip&MD8 [71], approximately 12 batches were sent monthly from HPK to two distribution points: CERN and KEK. From there, they were distributed to the subsequent institutions in the production chain. On average, 12 non-irradiated Testchip&MD8 pieces were sent directly to IMB-CNM⁷ (Barcelona) for pre-irradiation tests. Some of the remaining pieces were irradiated to evaluate radiation hardness: 12 pieces every six months were sent to the Cyclotron and Radioisotope Center (CYRIC, Japan) for proton irradiation, 6 pieces per month to the University of Birmingham for proton irradiation, 6 pieces per month to the Jozef Stefan Institute⁸ (JSI, Ljubljana) for neutron irradiation, and 6 pieces per month to UJP PRAHA

⁷ Institut de Microelectrònica de Barcelona, Centro Nacional de Microelectrónica

⁸ Jozef Stefan Institute

a.s. (Prague) for gamma irradiation. After irradiation, each site distributed the samples to the corresponding test sites: CYRIC protons (KEK/Tsukuba), Birmingham protons (Birmingham), neutrons (Toronto), and gamma rays (Prague). Test sites collected data from all received pieces and conducted thorough analyses to determine batch acceptance. Figure 2.19 shows the production QA flow for Testchip&MD8 pieces.

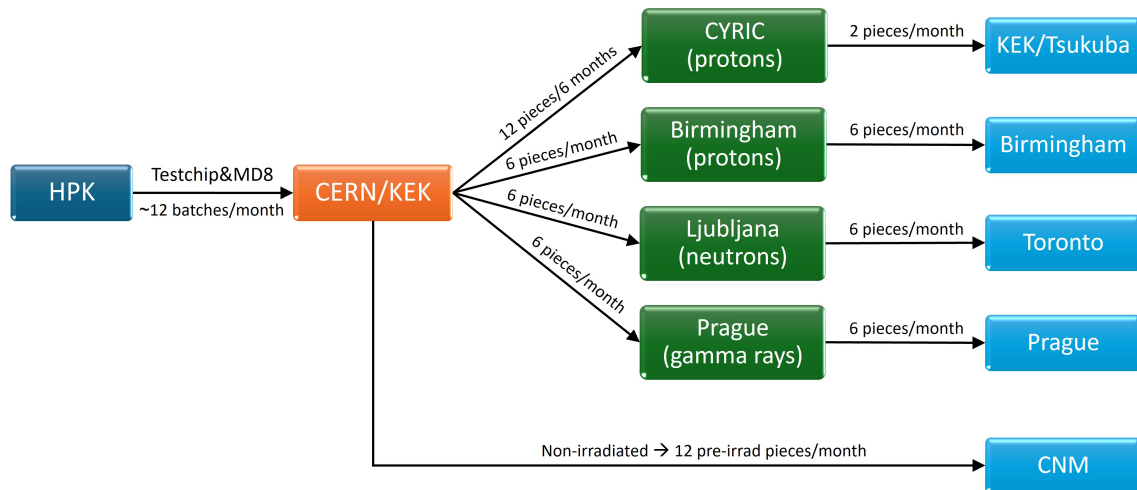


Figure 2.19: Initial production QA flow of Testchip&MD8 pieces.

The Mini&MD8 production flow was similar. 12 batches were initially sent from HPK to CERN and KEK. No pre-irradiation tests were planned; some selected Mini&MD8 pieces were sent to CYRIC (12 pieces/6 months), Birmingham (6 pieces/month), and Ljubljana (12 pieces/month) for irradiation. Each center then distributed the irradiated Mini&MD8s to the test sites according to particle type: CYRIC protons (KEK/Tsukuba), Birmingham protons (Birmingham and Toronto), and neutrons (Toronto, Ljubljana, and Valencia). Figure 2.20 shows the Mini&MD8 production flow.

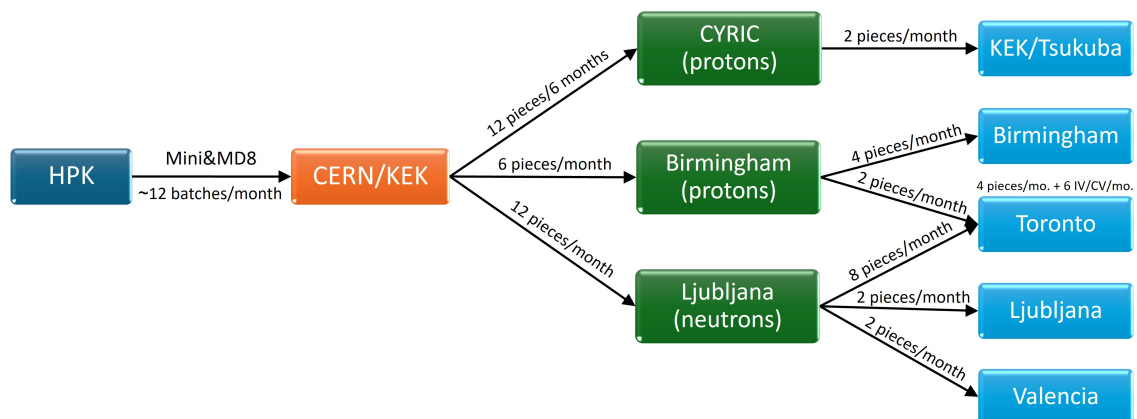


Figure 2.20: Initial production QA flow of Mini&MD8 pieces.

These flows represent the initial delivery plans, but some changes occurred during production due to unexpected factors or task descoping. For instance, KEK stopped being

a QA distribution center during production, and CERN absorbed all related responsibilities. For Testchip&MD8s, proton irradiations at Birmingham were replaced by combined neutron and gamma irradiations, which were then tested in Birmingham, Toronto, and Prague; gamma-only irradiations were discontinued. The Mini&MD8 flow was also affected when Toronto stopped receiving Mini&MD8 pieces irradiated with protons from Birmingham. Additionally, a new proton irradiation center (CSNS⁹) and a new testing institute (IHEP¹⁰), both in China, joined the QA Collaboration near the end of production to compensate for reduced CYRIC availability in 2025.

Overall, the QA/QC Collaboration received monthly deliveries of sensors and QA pieces for irradiation and testing. A four-month window was provided by contract with HPK, starting from each delivery date, to accept or reject batches. Consequently, proper evaluation of measured parameters was performed throughout the production process to ensure compliance with specifications. Approval decisions were communicated to the foundry every month.

With 100% of sensors fabricated and only a few evaluations pending, approximately 2,600 samples have been distributed to QA sites over these years. More than 600 batches have been approved, and six batches were rejected based on QA, QC, or both. Including individual sensor rejections in QC, roughly 3% of the fabricated sensors were ultimately rejected, explaining why production reached approximately 103% of the initially expected total.

2.4 Irradiations

The irradiation of semiconductor devices induces different effects in the bulk and at the surface, depending on the type of radiation. Neutrons, protons, and heavy ions primarily cause displacement damage in the lattice due to their mass, creating vacancies and defect clusters that degrade bulk properties. In contrast, gamma rays, electrons, and other charged particles produce ionization damage through ionizing interactions, generating trapped charges and interface states in oxides and at surfaces, which alter threshold voltages and leakage currents.

Based on the total radiation levels calculated through Monte-Carlo simulations [83, 84] for the ITk strip sensors, a neutron equivalent fluence¹¹ of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and a total ionizing dose (TID) of 66 Mrad (660 kGy) were set as target irradiations to ensure the required radiation hardness. These target values include a safety factor of 1.5 [67].

⁹ China Spallation Neutron Source

¹⁰ Institute of High Energy Physics

¹¹ “Neutron equivalent” refers to the damage caused by 1 MeV neutrons.

A QA irradiation plan was designed for all QA pieces included in the production flow, except for those intended to be measured non-irradiated at IMB-CNM. Irradiating one Testchip, one Mini sensor, and one MD8 from each batch with protons, neutrons, and gamma rays would have provided a comprehensive mapping of irradiation effects. However, this would have required testing many QA pieces throughout production. To reduce the workload, the original plan considered irradiating at least one Mini&MD8 with protons or neutrons to study displacement damage, and one Testchip&MD8 with protons or gamma rays to study ionization damage for each batch.

To organize this, batches were split into odd and even groups. One Testchip&MD8 and one Mini&MD8 were selected from each batch for pre-irradiation testing. Additionally, Mini&MD8 pieces from odd batches were irradiated with neutrons, and Testchip&MD8 pieces from odd batches were irradiated with protons. Complementary to these, Mini&MD8 pieces from even batches were irradiated with protons, while Testchip&MD8 pieces from even batches were irradiated with gamma rays and neutrons.

This configuration ensured that at least one Testchip in each batch reached the target TID (to study ionization damage) and one Mini sensor in each batch reached the target fluence (to study displacement damage). The irradiation plan is summarized in Table 2.3.

Table 2.3: Schematic initial plan for QA pieces (Testchip&MD8 and Mini&MD8) irradiated with protons (p), neutrons (n), or gamma-rays (γ).

Initial irradiation plan		QA pieces	
		Mini&MD8	Testchip&MD8
Batch	Odd	Ljubljana, n $\rightarrow 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	Birmingham, p $\rightarrow 5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
		Ljubljana, n $\rightarrow 5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$	CYRIC, p $\rightarrow 66 \text{ Mrad}$
	Even	Birmingham/CYRIC, p $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	Ljubljana, n $\rightarrow 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
			Prague, $\gamma \rightarrow 66 \text{ Mrad}$
	All	Birmingham, pre-irrad	CNM, pre-irrad

Alterations at the irradiation facilities, as well as QA descoping decisions based on early results, slightly optimized the initial plan. From February 2023, the production process entered a steady state with the irradiation plan shown in Table 2.4. Later, in the final year of production, CSNS joined the QA irradiation program to provide 80 MeV proton irradiation. One in every six Mini&MD8 pieces was scheduled to be irradiated at this facility.

Table 2.4: Schematic plan for QA pieces (Testchip&MD8 and Mini&MD8) irradiated with protons (p), neutrons (n), or gamma-rays (γ) under the steady-state production regime.

Steady-state irradiation plan		QA pieces	
		Mini&MD8	Testchip&MD8
Batch	Odd	Ljubljana, $n \rightarrow 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	Prague + Ljubljana, $\gamma+n$ 66 Mrad + $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
	Even	Birmingham, $p \rightarrow 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	Prague + Ljubljana, $\gamma+n$ 66 Mrad + $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
		Ljubljana, $n \rightarrow 5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (MD8)	
	All	CYRIC (1/6), $p \rightarrow 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	CYRIC (1/6), $p \rightarrow 66 \text{ Mrad}$ CNM, pre-irrad

2.4.1 Protons

Systematic proton irradiations were performed on QA pieces at the MC40 Cyclotron (27 MeV) at Birmingham. These were complemented by higher-energy proton irradiations at CYRIC (70 MeV) in Japan, carried out once every six months to cross-check the results. To mitigate the effect of reduced CYRIC availability from 2025, CSNS (80 MeV) was added to the QA irradiation program.

The MC40 Cyclotron is located at the University of Birmingham (UK). This university has operated particle accelerators since the 1930s, and the MC40 is the most recent, imported from Minneapolis in 2002. It serves both commercial and research purposes, with a flexible range of ions (protons, deuterons, helium-3, and helium-4) and energies (2.7–38 MeV) [85]. CYRIC, on the other hand, has been based at Tohoku University in Sendai (Japan) since 1977. It hosts two cyclotrons: HM12, used for generating positron-emitting radionuclides, and 930, which accelerates ions to a variety of energies [86, 87]. The CSNS facility, located at the Dongguan Campus of IHEP (China), contains a powerful linear accelerator for particle physics research as well as applications in material science, life sciences, and new energy [88]. CSNS was constructed in two phases: CSNS-I, providing the 80 MeV linac energy used for QA irradiations, and CSNS-II, an upgrade still under completion.

The Mini sensors were irradiated with TIDs equivalent to the target fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at both Birmingham and CYRIC. At the MC40 (27 MeV protons), this corresponds to a TID of 200 Mrad, while at CYRIC (70 MeV protons) it is approximately 120 Mrad. In both cases, the dose received by the Minis was higher than the expected value under real-experiment conditions. Consequently, their good performance under these conditions was sufficient to confirm the TID tolerance of the Minis, which were primarily intended for displacement damage studies. At CSNS (80 MeV), Mini&MD8

pieces were irradiated to measure the charge collection efficiency (CCE) of the Minis and to perform I–V and C–V tests on the MD8s. However, no results are available at the time of writing.

For proton-irradiated Testchips, the focus was ionization damage. The target TID of 66 Mrad was used, corresponding to an equivalent fluence of $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (mid fluence) at MC40. This relatively low fluence still allowed to extract the full depletion voltage (V_{FD}) from the C–V curve of a measured MD8 diode. However, it was seen that irradiation at full fluence caused excessive bulk damage, making the C–V curve of an MD8 meaningless.

2.4.2 Neutrons

Neutron irradiations were performed on QA pieces at the JSI Triga Mark II Reactor in Ljubljana (Slovenia) throughout the production process. Operating since 1966 and reconstructed in 1991, the reactor has been used for training, research, and isotope production, including irradiation of silicon components for ATLAS experiment studies at CERN [89].

Mini&MD8s were irradiated up to full fluence ($1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$) and mid fluence ($5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$). Full-fluence Minis enabled the study of bulk damage, while MD8s irradiated at both fluences served to monitor the degradation of the leakage current and the V_{FD} (meaningless C–V at full fluence).

Testchips were irradiated with neutrons up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, allowing observation of pure displacement damage, without the ionization effects present in proton irradiation. Gamma + neutron irradiation of the Testchips was later performed to study the combined effects of ionization and displacement damage.

2.4.3 Gamma Rays

Gamma irradiations were performed at UJP PRAHA a.s. in Prague, Czech Republic. The company has been involved in ionizing radiation for many years, providing irradiation services upon request, producing transport and storage containers, and offering other radiation-related services. Gamma irradiation of the QA pieces was performed using a ^{60}Co radionuclide source [90] that emits high-energy gamma rays at 1.17 MeV and 1.33 MeV.

Only Testchip&MD8 pieces were irradiated to a TID of 66 Mrad. Unlike pure neutron irradiations, these exposures produce almost solely ionization damage, allowing the isolation of ionization effects from particle-mass-induced bulk damage [91, 92].

2.4.4 Gamma + Neutrons

Gamma + neutron irradiation consisted of first exposing samples to 66 Mrad gamma rays at UJP (Prague) and then irradiating them with 1.6×10^{15} n_{eq}/cm² neutrons at the Triga reactor (Ljubljana). This combination allowed the effects of both ionization and displacement damage at target dose and fluence, respectively, to be studied on selected QA pieces. It represented a target scenario of the ITk detector's expected state after years of operation.

2.5 Original Contributions of This Thesis to the Quality Assurance of ITk Strip Sensors

This thesis provides a set of original contributions that extend beyond the prototyping phase and sustain the quality assurance of the strip sensor production, including additional studies primarily aimed at understanding sensor performance under radiation:

- Development of a complete QA program within the framework of the ITk Strip Sensor Collaboration, following the distribution flows for sample (Testchip&MD8 and Mini&MD8) irradiation and testing described in this chapter.
- Development of new and original Python scripts to extract parameters from raw and standardized files, upload the data to the ITk Production Database (PDB), and generate reports.
- Definition, implementation, and optimization of non-specified thresholds (“soft” thresholds and “consistency check” thresholds) to complement “hard” specifications (the ones stated expressly in the contract by the collaboration), improve monitoring of production results, and enable rapid identification of potential parameter deviations.
- Introduction and systematic use of the CFLD-P_{CV} test from the MOS Capacitor with p-stop, along with the integration of the S_{REF} and V_{PT} parameters and their extraction methods and analysis (see Section 3.2) as robust indicators of p-stop implantation quality, enabling early detection of deviations in the p-stop doping concentration.

- Consolidated analysis of pre- and post-irradiation (protons, neutrons, gamma rays, and gamma + neutrons) trends, parameter correlations, and the implications of deviations in key parameters under HL-LHC conditions.
- Detection, analysis, decision-making, and mitigation of production deviations (e.g., low p-stop), establishing bidirectional feedback with the manufacturer (HPK) and, in the worst-case scenarios, leading to batch rejection to ensure overall detector performance.
- Additional investigations prompted by anomalous behaviors observed during production QA monitoring, particularly regarding low p-stop implantation quality, the evolution of sensor performance under high-energy proton irradiation, the impact of high-level irradiation on device properties, and the understanding of batches and silicon ingots used throughout production.

Together, these elements constitute the first fully integrated QA program for ITk strip sensors within the framework of a large collaboration, combining laboratory-level detailed analysis with an industrial-scale production process.

Since this thesis was carried out within a multi-institutional collaboration, and to make the scope of the work explicit, the author's direct contributions and the collaborative inputs are summarized below:

Author's direct contributions

- Definition of test methods for all the test structures used in QA, like measurement strategies, test ranges, setup implementation, etc. Standardization of these methods and definition of common data files for the compatibility and exchangeability of the analysis methods across the collaboration.
- Pre-irradiation testing at IMB-CNM using automatic and manual probe stations for Testchips and MD8s, respectively, including configuration, calibration, and measurements, and execution of the QA plan throughout the entire production process.
- Development of Python scripts to convert raw data files from pre-irradiation measurements at IMB-CNM into standardized files, following the data format used by all collaborating institutes.
- Design and implementation of algorithms for parameter extraction from standardized data files for all Testchip, MD8 and Mini sensor tests (CBR_IV, CCPL_C, CCPL_IV, CFLD_CV, CFLD-P_CV, INT_C, INT_IV, PTP_IV, RBIAS_IV, MD8_CV,

MD8_IV, and MINI_CCE), including plotting and results file generation, with algorithms used by all collaboration members.

- Integration with the Production Database (PDB): development of new data upload scripts accessible to all collaborators, along with reporting scripts for global QA analysis, enabling automated large-scale monitoring during ITk strip sensor production.
- Development of original reporting tools on behalf of the QA Collaboration, including generation of distribution and time-evolution analysis, investigation of pre- and post-irradiation results, identification and exploration of parameter correlations, and definition and tuning of soft thresholds and consistency checks. Establishment of continuous monitoring of all sensor parameters based on statistical trends.
- Detection and analysis of incidents (e.g., low p-stop), implementation of the CFLD-P_CV test for validation, and mitigation proposals leading to acceptance or rejection decisions.
- Further investigations on QA-related studies, including:
 - a) low p-stop implantation quality in some production batches and the effects of radiation on low p-stop doping samples;
 - b) effects of high-energy proton damage on Testchips and Mini sensors;
 - c) analysis of extremely irradiated Testchips; and
 - d) control and correlation between silicon ingots, wafers, and production batches.
- While studies (c) and (d) were entirely conducted by the thesis author, the other two were large-scale studies involving multiple collaborating institutes. Personal contributions to the low p-stop studies included all pre-irradiation tests on Testchips and half-moons performed at IMB-CNM; part of the post-irradiation measurements on the special p-stop batches and within the post-irradiation effects study (presented in Chapter 5), and direct participation in the global analysis, with primary responsibility for the latter study.
- For the proton damage studies, the author performed testing of irradiated Testchips at different irradiation angles, with and without G10 material, carried out local analysis, and contributed to the overall study analysis.

Collaborative contributions

- The Testchip design and the first version of the QA flow were defined at the start of this work, providing the technological baseline from which the analyses and subsequent investigations presented in this thesis were developed.
- Sensor and QA devices fabrication: HPK.
- Irradiations: several facilities (Birmingham, CYRIC, CSNS, JSI, UJP) coordinated via CERN/KEK.
- Post-irradiation QA testing at collaborating QA test sites (Toronto, Birmingham, Prague, Ljubljana, Valencia, etc.). Tasks performed within the systematic production QA plan developed at CNM.
- Participation of other QA test sites in the low p-stop studies presented in Chapter 5, including post-irradiation measurements performed across several institutes, and contributions to both local and global analyses, particularly in the study of the special p-stop batches.
- Participation of other QA test sites in the high-energy proton damage studies as a function of fluence (Chapter 5), including testing of several irradiated Testchips and Mini sensors. Contribution to parameter analysis, with particular focus on Charge Collection Efficiency (CCE) and annealing studies.

Several tests were conducted at IMB-CNM to collect data from all the structures described in Section 2.2. From the outset, the objective was to measure and analyze all test structures in the Testchips and the MD8 Monitor Diodes as part of the Quality Assurance (QA) monitoring process.

For these purposes, two main measurement setups were used at IMB-CNM, both based on semiconductor probe stations specifically designed for testing electronic devices on silicon wafers. The raw data from the measurements were used to calculate various parameters through different extraction methods. Prior to this, the parameters, extraction features, and parameter thresholds were defined for each test.

A complete set of Python scripts was developed for parameter extraction, data upload to a collaborative database, and data analysis. The ultimate objective of this process was to generate reports on parameter evolution and status throughout the entire production.

3.1 Measurement Setups and Equipment

The QA pieces Testchip&MD8 and Mini&MD8, described in Chapter 2, were irradiated with different particles at specific fluence levels. Following irradiation, several institutes performed measurements on both irradiated and non-irradiated test structures. Within the framework of the ITk Strip Sensor QA Collaboration, a wide variety of equipment was used to measure all test structures. Depending on the type of tests and the irradiation characteristics of the samples, different equipment was employed.

The pre-irradiation measurement program for the ATLAS Testchips included the use of an automatic probe station operating with a probe card and a switch matrix. After irradiation, each Testchip&MD8 piece was wire-bonded to a custom-made test board—namely, a printed circuit board (PCB) designed with numerous lines to enable wire-bonding with the large number of test structures located on the QA pieces. The output channels resulting from the bonding were connected to a multi-way cable, serving a function similar to that of the switch matrix in the automatic probe facility [71].

In addition, manual probe tables and supplementary instruments were used for measurements performed on monitoring diodes (e.g., Capacitance-Voltage (C-V) and Current-Voltage (I-V) sweeps on pre-irradiated MD8s). These tools were also used to measure certain Testchip structures at institutes without automatic probe stations or to perform tests under special conditions. Measurements at different temperatures and humidity levels were sometimes required, and extraordinary tests could also be more easily configured using this setup.

On the other hand, Mini&MD8 pieces utilized a different technology based on a portable readout system for microstrip silicon sensors called ALiBaVa. The system takes its name from the collaboration that developed it, also called ALiBaVa, which involved IMB-CNM, IFIC (Instituto de Física Corpuscular), and the University of Liverpool. This collaboration was integrated into the RD50 Collaboration at CERN. The purpose of the system is to measure the charge collected in the silicon strips to extract the charge collection efficiency (CCE) of the Mini sensors. To this end, the ALiBaVa system comprises data acquisition hardware along with dedicated data processing software. The hardware consists of two main components: a small board with Beetle ASIC chips for sensor readout (daughterboard) along with a β -radiation source (^{90}Sr), and a second board for analogue data processing and trigger signal handling (motherboard) [93–95].

IMB-CNM primarily focused on testing pre-irradiated Testchip&MD8 pieces, although additional experiments were occasionally conducted on irradiated pieces as well. The scheme in Figure 3.1 illustrates the facilities used at this institute to extract the electrical properties of the chips, showing two main measurement setups located in separate laboratories within the IMB-CNM institute.

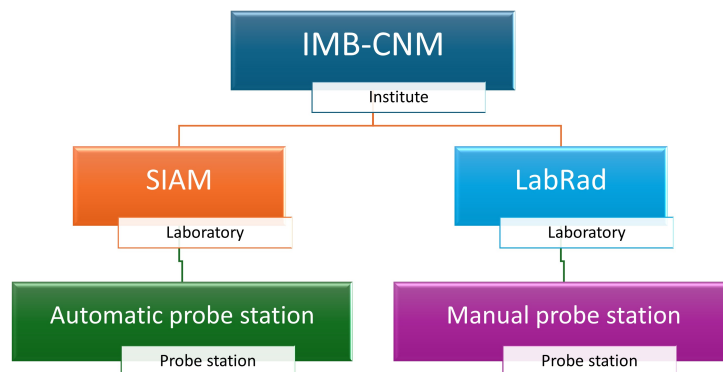


Figure 3.1: Schematic classification of the facilities used at IMB-CNM for measurements performed on QA pieces.

On the one hand, the Electrical Characterization Laboratory is equipped with automatic Systems for Measurement Acquisition (SIAM), which enable the electrical characterization of semiconductor devices. The setup includes an automatic probe station and specialized

measurement instruments. Automatic tests of the ATLAS Testchips were conducted using this equipment, as illustrated in Figure 3.2.

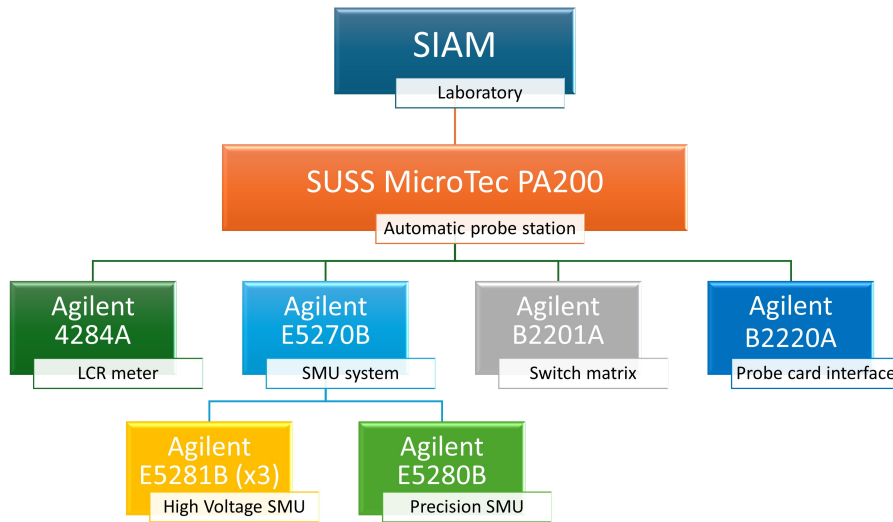


Figure 3.2: Schematic classification of the equipment used in the SIAM Laboratory for measurements performed on QA pieces.

On the other hand, a manual probe station is located in the Radiation Detectors Laboratory of the institute (LabRad). Non-automated measurements were performed there, primarily on pre-irradiated MD8 devices, but also on other Testchip structures for specific purposes, both before and after irradiation. This probe station provides both temperature and humidity control and is equipped with several instruments, as illustrated in Figure 3.3. Additionally, a nitrogen dry cabinet is installed there to store IMB-CNM components throughout the entire production process.

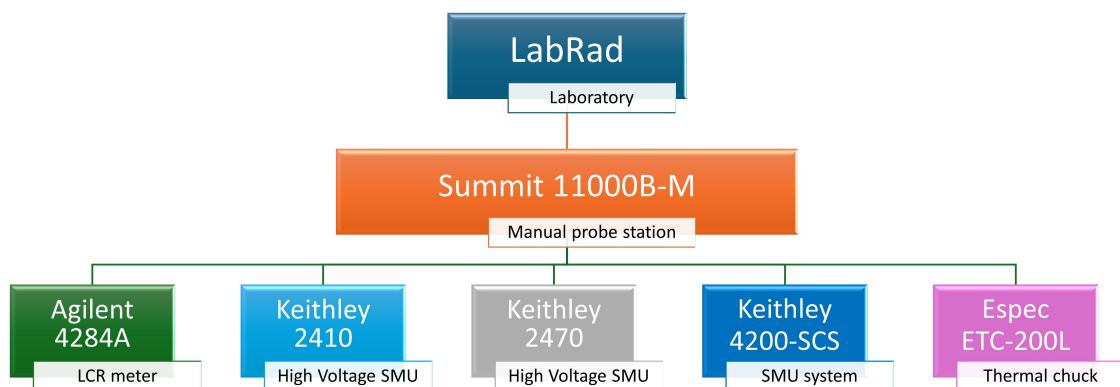


Figure 3.3: Schematic classification of the equipment used in the Radiation Detectors Laboratory for measurements performed on QA pieces.

The configuration of these facilities and the specifications of the instruments are explained in detail in Section 3.1.1 and 3.1.2.

3.1.1 Automatic Tests

The non-irradiated Testchip&MD8 pieces from the production QA were tested at the Electrical Characterization Laboratory (hereafter referred to as the SIAM Laboratory) using a parametric test station, consisting of a SUSS MicroTec PA200 automatic probe station and an Agilent 41000 parametric analyzer. The Agilent 41000 includes the LCR meter Agilent 4284A, three SMUs (Source/Measurement Units) Agilent E5280B, one SMU Agilent E5281B, and a switch matrix. The facility is completed by the software configuration, which controls the entire station [96].

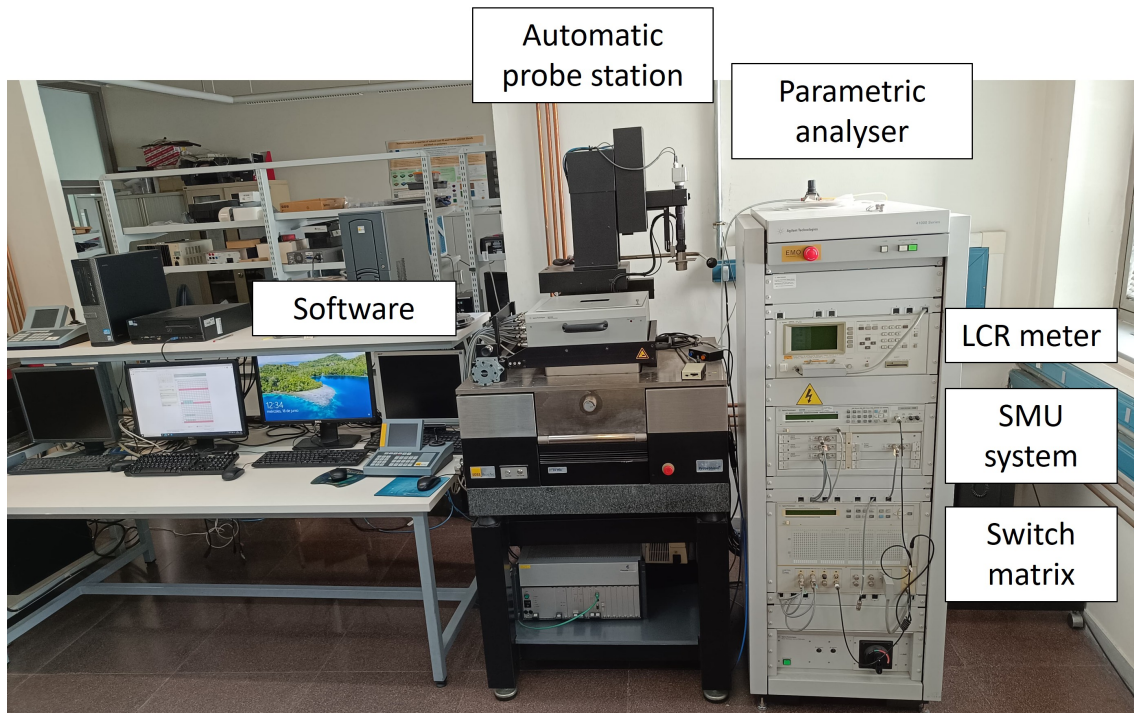


Figure 3.4: Configuration of the parametric test station, comprising an automatic probe station, a parametric analyzer, and the software setup.

The automatic probe station contains a chuck—a metallic flat platform designed to hold silicon wafers or dies (chips diced from a wafer). A reliable hold of the devices is ensured by a vacuum system connected to the chuck. Additionally, a 12-tip probe card (Figure 3.5) was designed to contact the Testchip test structures, which are located on the Testchip beneath (or above) rows of 12 metal pads connected to the devices. The probe card connects to a switch matrix (Agilent B2201A) that automatically links the probes with the SMUs and the LCR meter of the parametric analyzer.

Regarding chuck positioning, the stage allows movement of the chuck along the X, Y, and Z axes, as well as rotation at an adjustable θ angle [97]. This system does not use manipulators but instead operates via a physical joystick controller. An internal microscope transmits the image to a screen, enabling positioning, alignment, and visual

monitoring of the devices. The inset image in Figure 3.6 shows the joystick tool used to calibrate the initial positioning of the sample (device) and to establish contact between the probes and the pad rows.

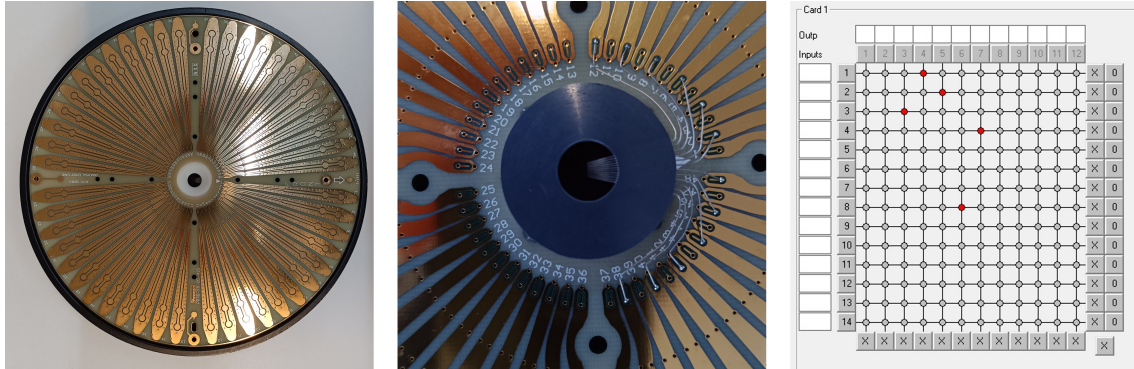


Figure 3.5: Probe card used at IMB-CNM (left), probe-terminal connections of the probe card (center), and visual scheme of the probe-terminal switching for a Punch-Through Protection (PTP) test (right).

The SUSS ProbeShield of the equipment ensures noise floor isolation and electromagnetic shielding from the environment. This enables the detection of high-quality, low-level signals with increased sensitivity. Overall, the SUSS MicroTec PA200 provides versatility, stability, and flexibility for failure analysis and low-signal measurements [98].

Returning to the instruments comprising the parametric analyzer, the Agilent 4284A measures parameters such as capacitance (C), inductance (L), resistance (R), and impedance (Z). The instrument generates an AC signal (ranging from 20 Hz to 1 MHz) with a voltage applied to the device under test (DUT). It then measures the response voltage and current in the device, using phase and amplitude relationships to calculate the LCR parameters. An internal correction factor, known as the OPEN correction, is applied to improve measurement precision. This correction is performed when no device is connected to the test terminals, which are “open” at that moment. For the measurements, 4-terminal connections are used to avoid errors caused by cable and connectors resistance.

The SMUs installed in the modular mainframe Agilent E5270B can both source voltage or current signals and measure the resulting current or voltage, respectively. They are primarily used to apply a voltage sweep between two values and measure the resulting current at each voltage point, or vice versa (apply a current sweep and measure the voltage). The voltage range extends up to ± 200 V, while currents can be measured from femtoamperes (fA) to amperes (A). These capabilities, combined with the high resolution of the equipment, allow for precise measurement of very sensitive devices.

Both the SMUs and the LCR meter from the parametric analyzer are controlled by the Metrics ICV software (Figure 3.6) [99]. The switch matrix connections are defined within this software to link the instruments with the probes used in each test, depending on

the electrical properties being applied and measured. The Metrics ICV interface allows measurements of either a single device on the chuck or multiple dies arranged in a grid on a wafer. For QA measurements at IMB-CNM, each Testchip was tested by measuring every individual test structure one after another, systematically covering the entire chip. The tests were conducted in darkness at room temperature (21–27 °C) under “uncontrolled” relative humidity (35–60%), unlike the tests performed at LabRad, where temperature and humidity control is critical for accurate leakage-current measurements. Before the program execution, input properties were recorded at the beginning of the output file. To execute the program, a test script containing measurement methods was called. Partial Testchip measurements can be selected by enabling individual tests within the script. The test script, in turn, calls additional scripts organized into modules and algorithms detailing the electrical properties applied and measured in each test.

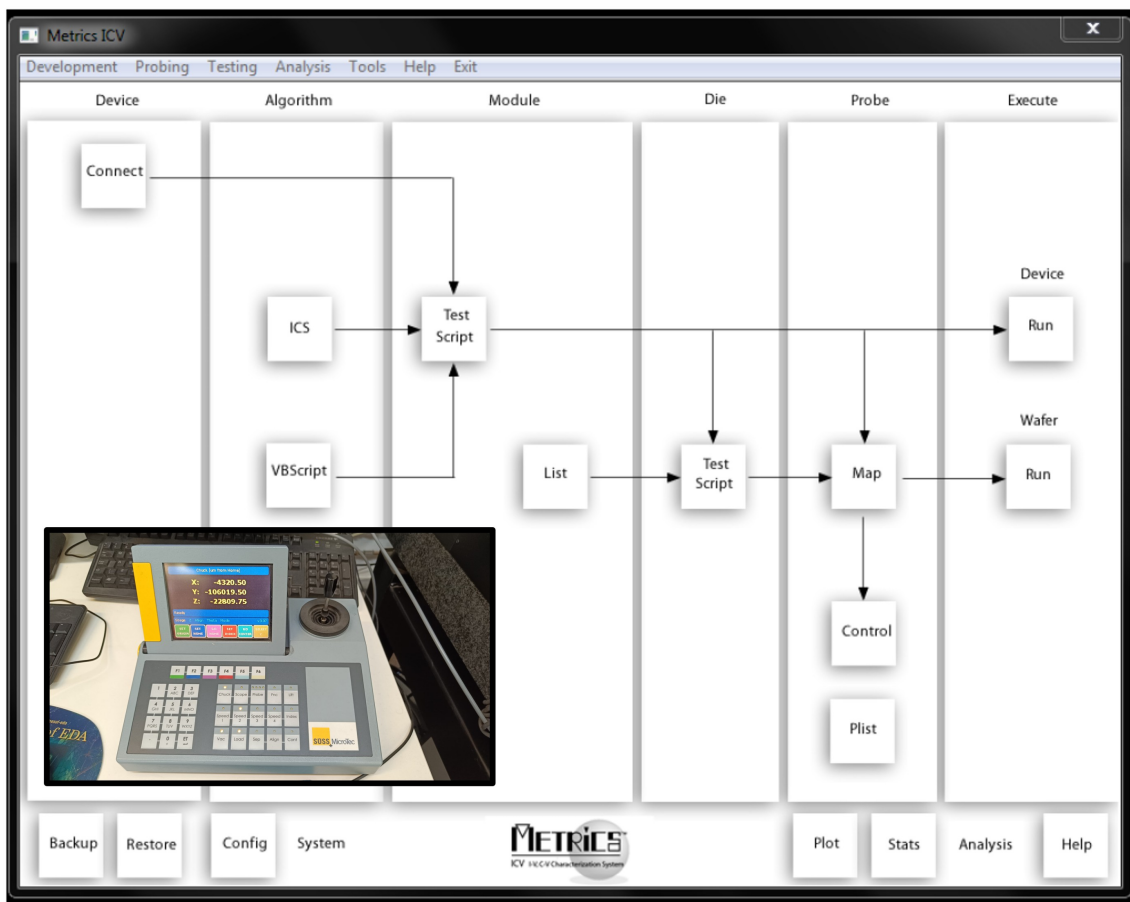


Figure 3.6: Metrics ICV software used for parametric testing with the automatic probe station in the SIAM Laboratory [99]. Inset: Image of the joystick controller used for XYZ positioning of the stage.

The raw data files generated from the measurements follow a specific format, with tests ordered sequentially within each file. Figure 3.7 shows an example of the beginning of such a file. Global Testchip properties and features are listed at the start, followed by

the wafer and die position (0,0 for QA measurements). Each test is then recorded one by one, in the order specified by the test script. For every test, several initial parameters are extracted, followed by detailed measurement data (e.g., current, voltage, capacitance). During production, these file structures were subsequently processed using Python scripts to ensure the proper generation of standardized data files, as agreed upon by the ITk Strip Sensor QA test community.

In addition, the Metrics ICV software includes various tools and graphical user interfaces (GUIs) that assist with test parameterization and monitoring. During each test, a reference test plot is displayed on the screen. Once the test is complete, the actual plot of the performed test appears before the next test begins. A separate window also opens to provide real-time information about the ongoing measurements, including the test structure, duration, algorithms used, and more.

```
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  Process[s]      20US85L0712527
  Lot[s]         VPA55339
  Wafer[s]        W12527
  Mask[s]         ATLAS18LS
  Operator[s]     ebach 27.0 46
  Date[s]         06/11/2025
  Time[s]         16:55:28
  WaferInfo[s]    U=UM|S=101600|X=7500|Y=7500|F=0|X0=6|Y0=13|IX=0|IY=0|SA=0|WC=ONDIE|CX=0|CY=0|
<END GLOBAL>
<BEG> Wafer (Wafer1)
  <BEG> Die (0,0)
    <BEG> DIETEST (scripts\diescripts\QA_test_chip\qa_test.die)
      <BEG> Module (Contact test (0,0))
        <BEG> MODTEST (scripts\modscripts\QA_test_chip\testcarta.scr)
          <BEG> Module (QA_test_chip\pad1-2)
            <BEG> Algorithm (QA_test_chip\testcarta - TESTCARTA)
              <BEG PARMS>
                externglob1[c]      0
                externglob2[c]      0
                externglob3[c]      0
                externglob4[c]      0
                Stress Time[c]      -1
                VA-START[c]         -0.005
                VA-STOP[c]          0.005
                VA-COMPL[c]         0.1
                VK-VALUE[c]         0
                VK-COMPL[c]         0.1
                RES005              5.51953
              <END PARMS>
              <BEG DATA>
                VA      IA      VK      IK      R
                -0.005  -0.001417  0      0      0.0014205  3.52858
                -0.004  -0.001202  0      0      0.0011885  3.32779
                -0.003  -0.000966  0      0      0.00094225  3.10559
                -0.002  -0.00070415  0      0      0.0007112  2.8403
                -0.001  -0.0004845  0      0      0.0004661  2.06398
                0       -0.00022785  0      0      0.00022445  -0
                0.001   5.18e-006  0      0      -4.9715e-006  193.05
                0.002   5.1335e-005  0      0      -6.0245e-005  38.9598
                0.003   9.0985e-005  0      0      -0.00010907  32.9725
                0.004   0.0007247  0      0      -0.000723  5.51953
                0.005   0.0009422  0      0      -0.00096705  5.30673
              <END DATA>
            <END> Algorithm (QA_test_chip\testcarta - TESTCARTA)
          <END> Module (QA_test_chip\pad1-2)
        <END> Module (QA_test_chip\pad3-4)
```

Figure 3.7: Example of a raw data file format from a production QA component.

3.1.2 Manual Tests

Manual tests were conducted in the Radiation Detectors Laboratory. For QA, only C–V and I–V measurements on the MD8 diodes were performed. However, several additional

experiments requiring more customization and flexibility—such as those explained in Chapter 5—were also carried out there, as well as the characterization of the first QA Testchip prototypes. The most notable component in this setup is the Summit 11000B-M manual probe station, manufactured by Cascade Microtech. The additional equipment shown in Figure 3.3, together with the associated software (based on in-house TCL scripts), is also part of the measurement setup, as illustrated in Figure 3.8.

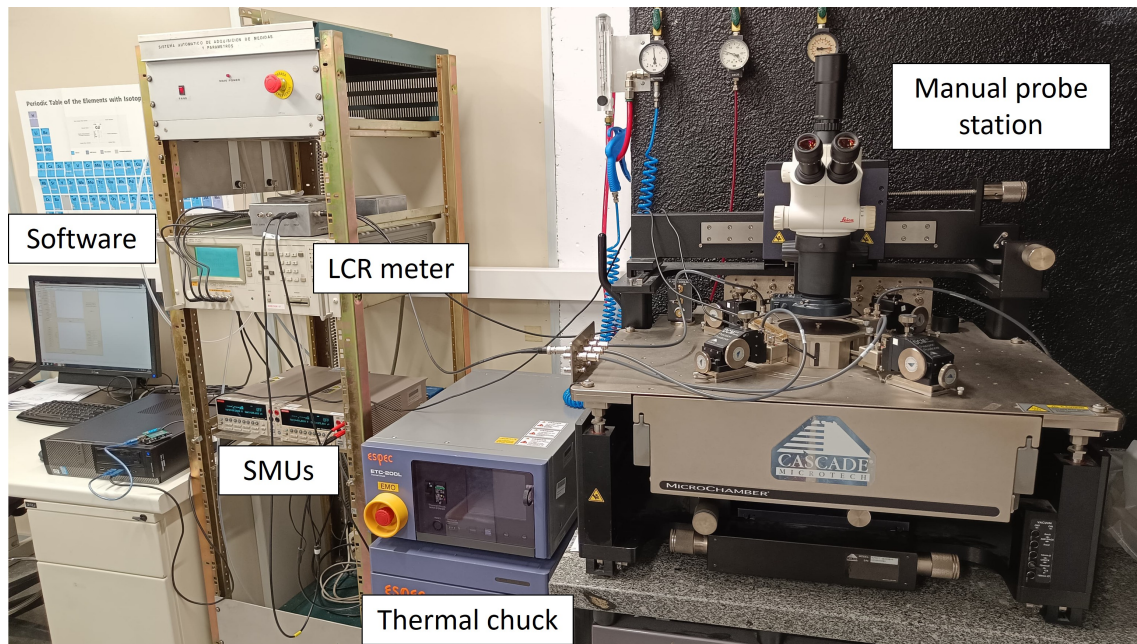


Figure 3.8: Configuration of the LabRad facilities, including a manual probe station, an LCR meter, several SMUs, a thermal chuck, and the associated software setup.

The Summit 11000B-M station consists of a probe station mounted on a test bench. In contrast to the automatic probe station described in the previous section, it has only four manual probes, each controlled by a manipulator. These four probes can be used individually or in combination. Probe positioning on the chip pads is done manually. The user observes the chips—and thus the probe-to-pad contact performance—directly through the two eyepieces of a stereoscopic microscope. For non-irradiated QA samples, electrical tests were conducted at a controlled room temperature of $(20 \pm 1)^\circ\text{C}$ (achieved through air conditioning), with a nitrogen flow used to maintain dry conditions ($\text{RH} < 5\%$).

The LCR meter used for the MD8 C–V measurements is the same model employed in the SIAM Laboratory. The Agilent 4284A provides a test voltage signal in the range of 5 mV to 2 V rms and an internal DC bias voltage of 0 V, 1.5 V or 2 V selectable [100]; however, this is insufficient to obtain the complete C–V curve of the diode. Therefore, external voltages can be supplied to both the central diode and the guard ring (if needed) using two SMUs (Keithley 2410). A custom coupling box, fabricated at CERN, is used to connect the LCR meter to the SMUs without damaging the internal circuits and components of the

LCR meter. An image and schematic drawing of the coupling box are shown in Figure 3.9. With this configuration, high-voltage C–V curves can be measured. The connection to the coupling box is made using coaxial cables, whereas the connection to the probe station requires triaxial cables. In this case, coaxial-to-triaxial adapters are employed.

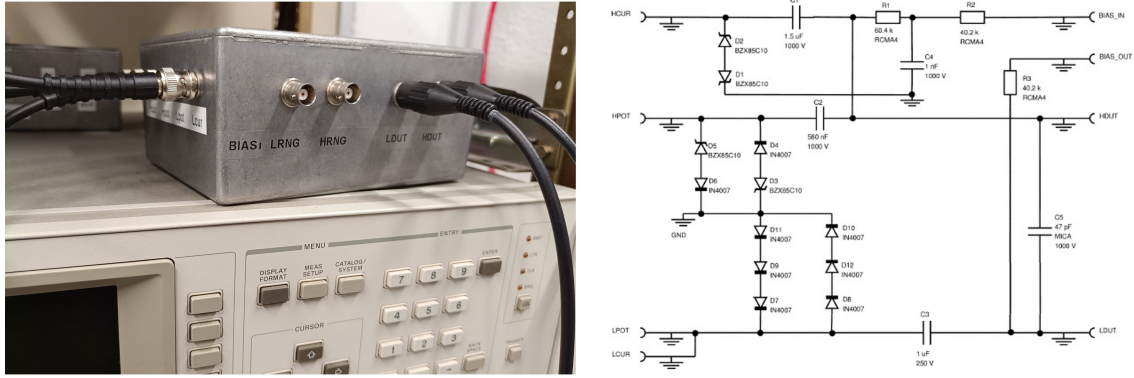


Figure 3.9: Coupling box used in the C–V measurement setup (left), and electrical scheme of the internal circuit of the coupling box (right).

Regarding the SMUs, two Keithley 2410 units can be used. With two SMUs, it is possible to measure the diode capacitance while the guard ring is also biased, although this second connection was omitted in the QA tests of the MD8, as specified in the QA test procedures [71]. Thus, only one Keithley 2410 was used to provide the DC bias to the central diode and was connected to a computer via a GPIB-USB-HS connector. The software installed on the computer detected and controlled the instruments in the setup. A custom-made program was used: TCL/Tk, a combination of the Tool Command Language (TCL) and the graphical library Tk.

On the other hand, I–V curves were obtained from the MD8 diodes using a single probe contacting the central diode and connected to another instrument: the Keithley 2470. This SMU, equipped with triaxial terminals and a touchscreen, is useful for testing low currents faster and with higher precision than the Keithley 2410. An image of this instrument is shown in Figure 3.10 (left).

Figure 3.10 (right) also illustrates the Keithley 4200-SCS, a Semiconductor Characterization System (SCS) that integrates several modules (instruments) within a single mainframe. Although it was not directly used for production QA tests, it was employed to manually measure other sensors and a few Testchip structures—for instance, some of the additional tests presented in Chapter 5. Among others, the Keithley 4200-SCS comprises SMUs and CVUs (Capacitance-Voltage Units) with a wide range of testing capabilities to obtain electrical properties from transistors, diodes, 2D materials, MEMS devices, and more. In particular, 4-probe measurements can be performed using all the tips of the manual probe station along with several SMUs simultaneously.



Figure 3.10: Keithley 2470 for I–V measurements on diodes (left) and Keithley 4200-SCS for additional electrical tests (right).

As mentioned before, tests on non-irradiated QA diodes were conducted at controlled room temperature of $(20 \pm 1)^\circ\text{C}$. However, tests on irradiated samples needed to be performed at -20°C in accordance with the test specifications [71]. To achieve this, DUTs were cooled to this temperature using the ESPEC ETC-200L thermal chuck system. This apparatus can control the temperature of the chuck—and thus the temperature of the DUT—within a range from -70°C to 205°C .

A dry environment is achieved by connecting the probe station measurement chamber to a nitrogen flow circuit, which reduces the relative humidity to well below 5%.

3.2 Tests Made at IMB-CNM

The test structures described in Section 2.2 were measured for all production batches according to the production flow explained in Section 2.3. In this section, only the tests performed at IMB-CNM—on non-irradiated Testchip&MD8 pieces—are presented. Measurement methods are described for each test, and parameter-extraction methods are detailed. Custom-made Python scripts used for extracting and plotting parameters, as well as for applying parameter acceptance criteria, are also described here. Most of the criteria are extracted from the Technical Specification for the Supply of Silicon Sensors for the ATLAS Inner Tracker Upgrade Project [67].

Before the production QA tests started, an initial characterization phase was conducted on the first prototypes using the manual probe station of the Radiation Detectors Laboratory at IMB-CNM. During this initial period, several prototype Testchip were characterized and evaluated in detail, and the first reference values were extracted from the obtained results. This phase was also useful for establishing the measurement conditions for the tests to be performed in production in the automatic setup (e.g., signal amplitude

and frequency in the C–V measurements of the MOS Field Oxide Capacitor, voltage used to bias the Interdigitated structures, sweep steps and limits in various sweeps, etc.). In addition, beyond the Testchip prototyping phase and production QA, several additional experiments were performed using the manual probe station, particularly for tests requiring very specific conditions, thanks to the setup’s ability to accommodate customized experiments. Some of these additional experiments will be presented in Chapter 5.

Tests on the automatic probe station (SIAM Laboratory) were performed at room temperature (22–27 °C) and relative humidity (20–50%). The parameters extracted from these measurements are not strongly dependent on temperature or humidity, which supports the validity of the results obtained under such “uncontrolled” conditions. However, temperature control is indispensable during I–V acquisition for accurate leakage current extraction. For this reason, the production QA tests of the MD8 devices were performed using the manual probe station in the Radiation Detectors Laboratory.

In the following subsections, the tests performed on each test structure are presented.

3.2.1 Testcarta

The structures inside the Testchip, defined in Section 2.2, were tested sequentially using the automatic probe station, following a programmed order. However, the first programmed test was not intended to extract any parameters for QA analysis. In fact, the Testcarta structure consists of a row of isolated metal pads and was included solely to check the contact between the probe tips and the pads. This process was required only once, at the beginning of a measurement sequence. Once the contact was established, it remained valid for all subsequent measurements.

Measurement Methods and Result Interpretation

Contact verification is performed by measuring the resistance of each pair of pads (1–2, 3–4, 5–6, 7–8, 9–10, 11–12). A voltage sweep from –5 mV to +5 mV is applied to each pair, in steps of 1 mV, and the resulting current is measured. The calculated resistance serves as an indicator of the contact quality. Generally, values between 3 Ω and 100 Ω are considered acceptable. Higher values—especially in the k Ω range or more—are indicative of poor contact or even a missing contact, consistent with an open circuit caused by uncontacted probe tips. The resistance threshold is not particularly strict; the order of magnitude is sufficient to confirm valid contact. In any case, a warning message appears

on the screen every time a Testcarta resistance is higher than $100\ \Omega$. The compliance current in this measurement is $I_{\text{compl}} = 0.1\ \text{A}$.

3.2.2 CBR_IV

The Cross-Bridge Resistor (CBR) tests were performed on both metal and implant CBRs. The objective was to measure the sheet resistance and the effective line width of the strip metal and the strip implant as explained in [101]. Measurement methods for metal and implant structures were defined in the same manner. The measurement parameters for each of the two structures were chosen to maximize accuracy accounting with the limits of the setup, based on the manual tests initially performed on the prototype Testchips.

Measurement Methods

Each metal and implant CBR on the Testchip is associated with six metal pads (A, B, C, D, E, F). The first four pads (A, B, C, D) of each structure are used to measure the material resistance in the Greek cross. For the Greek-cross metal, a current sweep is applied between pads A and B (I_{AB}), from 0 to 30 mA, with steps of 0.3 mA. The voltage is measured between pads D and C (V_{DC}). The same procedure is applied to the Greek cross with the implant layer, this time with a current sweep from 0 to 200 μA in steps of 2 μA . These low currents were chosen to remain within the acceptable ranges of the test instruments while avoiding self-heating of the layers and subsequent measurement errors.

Pads C, D, E and F are used to measure the material resistance in the “bridge” part of the CBRs. A current sweep is forced between pads C and F (I_{CF}), from 0 to 20 mA in steps of 0.2 mA. The voltage is then measured between pads D and E (V_{DE}), with a sweep from 0 to 100 μA in steps of 1 μA .

At the beginning of production, no initial hold time was configured for these measurements. However, after a few months it was observed that the first data point was measured with reduced precision. To improve accuracy, a hold time of 2 seconds was introduced and maintained until the end of production. Additionally, a compliance limit of 10 V was set for all voltage sweeps performed in the CBR_IV tests.

Extraction Method

Thanks to the symmetry of the CBR Greek cross, sheet resistance extraction is simplified while maintaining high accuracy [101].

$$R_{\text{MEAS1}} = \frac{V_{\text{DC}}}{I_{\text{AB}}} \quad R_{\text{MEAS2}} = \frac{V_{\text{DE}}}{I_{\text{CF}}} \quad (3.1)$$

$$R_S = \frac{\pi}{\ln 2} \cdot R_{\text{MEAS1}} \quad (3.2)$$

The corresponding effective line width (W_{EFF}) for both the metal and the implant is extracted using the calculated sheet resistance (R_S) and the length (L) of the CBR bar, which is $400 \mu\text{m}$ for both structures.

$$W_{\text{EFF}} = R_S \cdot L \cdot \frac{1}{R_{\text{MEAS2}}} \quad (3.3)$$

The resistances of the n-implant (R -I) and the metal (R -M), normalized per unit length, are obtained from Eq. (3.4):

$$R = \frac{R_S}{W_{\text{EFF}}} \quad (3.4)$$

The resistance and the effective line width were extracted and plotted throughout production using custom-made Python scripts. Figures 3.11 and 3.12 illustrate the extraction of these parameters for the metal and implant structures, respectively. In each figure, the plot on the left shows the I-V curve used to extract R_{MEAS1} from the Greek cross, while the plot on the right shows the I-V curve used to extract R_{MEAS2} from the bar. The desired parameters are then calculated from these resistance values.

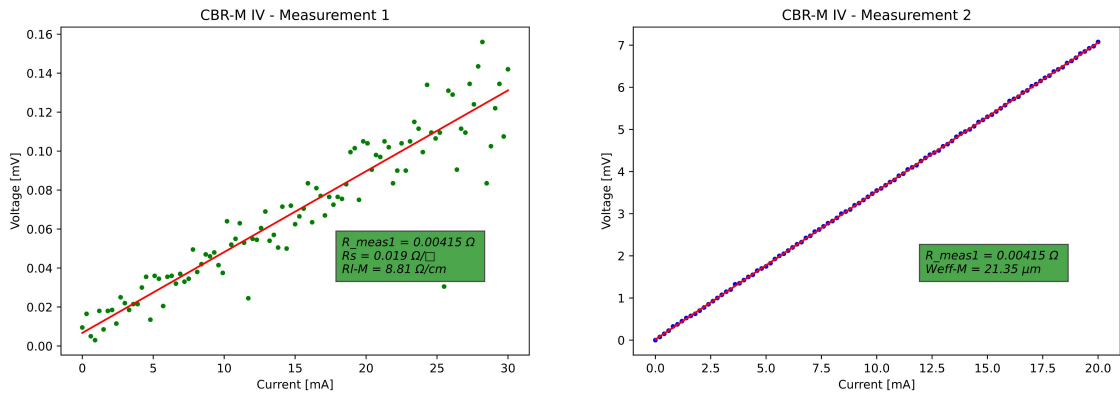


Figure 3.11: I-V curves obtained from the CBR-M structure of the Testchip for the extraction of parameters R_{ℓ} -M (left) y W_{EFF} -M (right). Production distribution: CERN-44; batch: VPA54856.

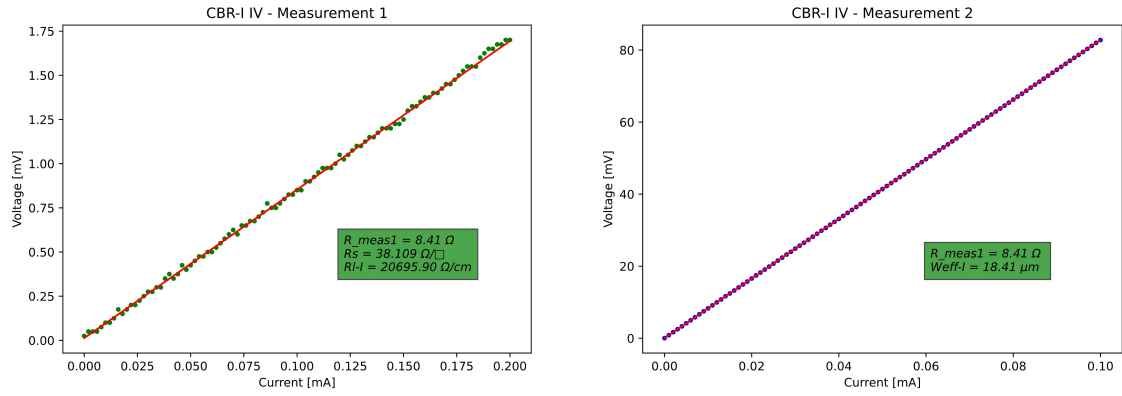


Figure 3.12: I-V curves obtenidas de la estructura CBR-I del Testchip para la extracción de parámetros $R\ell$ -I (izquierda) y W_{EFF} -I (derecha). Distribución de producción: CERN-44; lote: VPA54856.

Criteria – Thresholds

The acceptance criteria for the sheet resistance were defined according to the specifications of the ATLAS Inner Tracker Strip Sensors.

- Resistance of n-implant strip: $< 50 \text{ k}\Omega/cm$
- Resistance of aluminum read-out strips: $< 30 \Omega/cm$

In addition, minimum thresholds were introduced during production to detect potential outliers.

- Resistance of n-implant strip: $> 18 \text{ k}\Omega/cm$
- Resistance of aluminum read-out strips: $> 6 \Omega/cm$

No specifications were initially defined for the effective line width. Instead, “soft” thresholds (defined in Section 2.1) were later established by the ITk Strip Sensor QA Collaboration, based on the expected nominal values and pre-production results. These soft thresholds are non-restrictive and are intended to monitor and control process variability.

- $W_{EFF} [\text{METAL}] > W_{EFF} [\text{IMPLANT}] + 1 \mu m$ (ensuring at least a $0.5 \mu m$ metal overhang over the implant)
- $18 \mu m < W_{EFF} [\text{METAL}] < 26 \mu m$
- $13 \mu m < W_{EFF} [\text{IMPLANT}] < 19 \mu m$

The minimum soft threshold for the effective line width of the implant was later increased to $15 \mu m$ based on production parameter analysis, as it was not defined as a strict specification.

3.2.3 CCPL_C and CCPL_IV

The Coupling Capacitor was tested to extract the coupling capacitance using a low perimeter-to-area ratio, and to determine the dielectric current limit (dielectric breakdown voltage) of the coupling oxide up to 100 V.

Measurement Methods

For the CCPL_C test, an Agilent 4284A LCR meter is used to apply a voltage sweep from -5 V to +5 V in 1 V steps. Pad #10 and pad #11 are connected to the square-shaped coupling capacitor: pad #11 connects the metal to the AC output of the LCR meter, while pad #10 connects the capacitor implant to the voltage output of the instrument. The capacitance is measured at 1 kHz with CR in parallel and a signal amplitude of 0.5 V.

For the CCPL_IV test, additional SMUs are employed to measure the current at 100 V, with a compliance limit set to 100 nA. The implant (pad #10) is grounded, and a voltage sweep from 0 to 10 V is applied to the metal (pad #11) in 0.5 V steps. If the measured current neither reaches compliance nor exceeds 10 nA, a second voltage sweep from 0 to 100 V is applied between the metal and the implant in 5 V steps.

Extraction Method

In the CCPL_C test, the capacitance at 0 V (C_{meas}) was chosen as the reference for the coupling capacitance calculation. The coupling capacitance (C_{coupl}) of the strips in the main detector, expressed in pF/cm, is given by:

$$C_{\text{coupl}} = \frac{C_{\text{meas}}}{l_{5\text{-strip}}} = \frac{C_{\text{meas}}}{3.4 \text{ cm}} \quad (3.5)$$

where $l_{5\text{-strip}}$ is the length (34 000 μm) of the central strip of the ‘5-strips’ structure in the Testchip.

In the CCPL_IV test, two voltage sweeps are performed, as explained in the previous section. The sweeps were generally executed without anomalies and recorded in the output data files during production QA. If the current reaches compliance or exceeds 10 nA during the 0–10 V sweep, the measurement continues, and the subsequent 0–100 V sweep is skipped. Nevertheless, a file corresponding to the 100 V sweep is generated, containing a single current value at 100 V set to 9.99E+99 A.

If the 0–10 V sweep is recorded without issues, the 0–100 V sweep is analyzed. Should the current reach compliance or exceed 10 nA, the measurement continues (even if the

current has reached compliance) to ensure a value is recorded at 100 V. In cases where negative currents are registered at 10 V or 100 V due to high noise-signal ratio, the absolute values are recorded in the database.

An example of the extraction of both the capacitance and the dielectric current limit up to 100 V is shown in Figure 3.13.

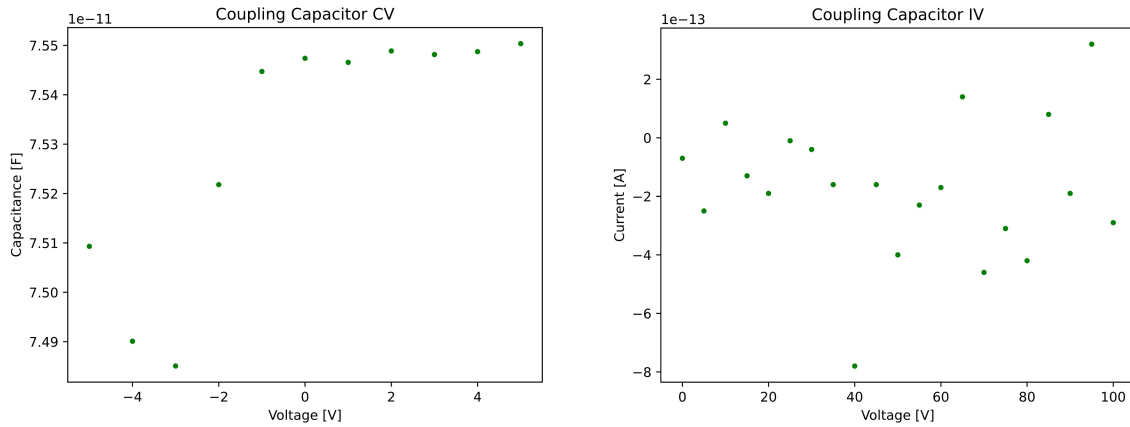


Figure 3.13: C–V (left) and I–V (right) curves measured on the Coupling Capacitor of the Testchip for the extraction of the coupling capacitance and the current at 100 V. Production distribution: CERN-44; batch: VPA54856.

Criteria – Thresholds

The minimum threshold for the coupling capacitance was set by the specifications at 20 pF/cm. Initially, no maximum threshold was defined, but one was later introduced during production as a non-restrictive limit to better monitor the parameter trend. The current maximum threshold for this parameter is 25 pF/cm.

For the dielectric current limit up to 100 V, the maximum threshold was also specified as 10 nA. No minimum threshold was considered at the beginning of production; however, a minimum of 0 A was later established to prevent negative (and thus unexpected) values.

3.2.4 CFLD_CV

The MOS Field Oxide Capacitor exhibits dielectric properties equivalent to those of the inter-strip oxide (“field oxide”) in the Main sensors. It was tested to extract the field oxide capacitance (C_{ox}), the field oxide thickness (t_{ox}) and the flat-band voltage (V_{FB}) from the high frequency C–V curve.

Measurement Methods

The Agilent 4284A LCR meter is used together with a voltage source and an external bias adaptor. The MOS metal gate (pad #3) is connected to the HIGH output, and the backplane to the LOW output of the LCR meter. After an initial hold time of 10 s, the device is biased from +2 to -20 V in steps of 100 mV, with a step waiting time of 100 ms. The capacitance is then measured at 10 kHz, with CR in series, using a signal amplitude of 100 mV.

Extraction Method

The behavior of a MOS capacitor after biasing is shown in the schematic of Figure 3.14 (left). The visual inspection of the measured C–V curve is helpful for understanding the parameter extraction process. Three regions are distinguished in such a curve according to the behavior of the MOS capacitor: accumulation, depletion, and inversion, which exhibits higher capacitances measured at low frequency. As an example, the plot in Figure 3.14 (right) shows the C–V curve from an actual measurement performed on a production Testchip at IMB-CNM.

The parameters extracted from this test can be understood from the physical principles of a capacitor. Gauss's law for the electric field in a dielectric states that for a closed Gaussian surface S :

$$\Phi_E = \frac{Q}{\epsilon} = \iint_S \mathbf{E} \cdot d\mathbf{A} = EA \quad (3.6)$$

where Φ_E is the net flux through a closed surface, Q is the charge enclosed, and ϵ is the dielectric permittivity. The final step assumes that the MOS capacitor behaves like a parallel-plate capacitor, in which the electric field is perpendicular to the charged surface of area A .

Using the definition of capacitance for an ideal capacitor, together with this MOS capacitor geometry, the capacitance can be expressed in terms of charge Q and voltage V as follows:

$$C = \frac{Q}{V} = \frac{\epsilon EA}{Ed} = \frac{\epsilon A}{d} \quad (3.7)$$

where d is the thickness of the dielectric, assuming a uniform electric field such that $V = E \cdot d$.

In strong accumulation, the measured capacitance corresponds to the oxide capacitance (C_{ox}) of the device. The equivalent oxide thickness of the field oxide (t_{ox}) is then calculated from C_{ox} as:

$$t_{ox} = \frac{\epsilon_{ox} \cdot A}{C_{ox}} \quad (3.8)$$

where ϵ_{ox} is the permittivity of silicon oxide, and A is the capacitor area ($556\,000\,\mu\text{m}^2$).

On the other hand, the flat-band voltage (V_{FB}) is obtained from the semiconductor flat-band capacitance (C_{FB}) which is calculated using Eq. (3.10). This capacitance is derived from C_{ox} and the semiconductor capacitance at one Debye length (λ_d), which is obtained using Eq. (3.9):

$$\lambda_d = \sqrt{\frac{\epsilon_{Si} \cdot k_B \cdot T}{q^2 \cdot N_A}} \quad (3.9)$$

where ϵ_{Si} is the permittivity of silicon, k_B is the Boltzmann constant, T is the temperature, q is the elementary charge, and N_A is the substrate dopant density. For the QA measurements, the nominal pre-irradiation value was used: $N_A = 4 \times 10^{12}\,\text{cm}^{-3}$.

$$\frac{1}{C_{FB}} = \frac{1}{C_{ox}} + \frac{\lambda_d}{A \cdot \epsilon_{Si}} \quad (3.10)$$

The V_{FB} is calculated using an algorithm that identifies the voltage corresponding to C_{FB} in the depletion region of the C-V plot. Specifically, an interpolation is performed between the two capacitance values surrounding C_{FB} in that part of the curve.

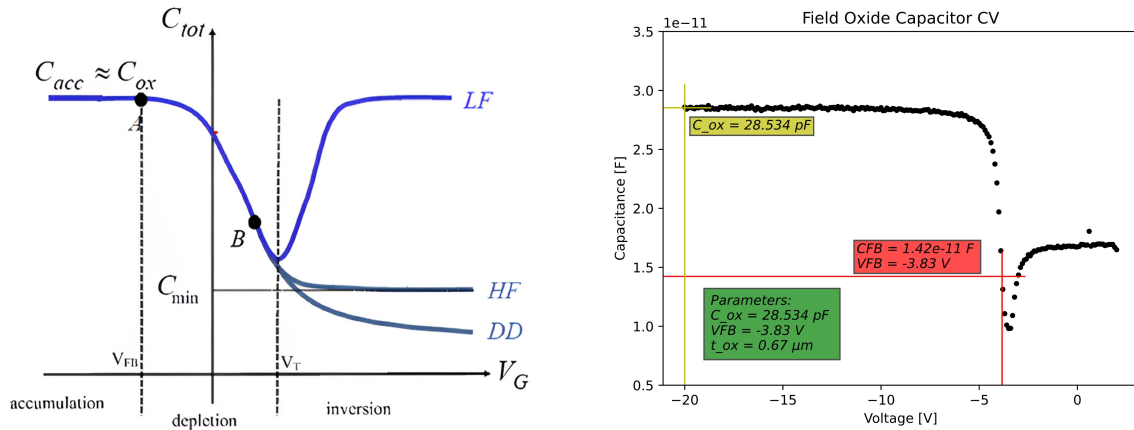


Figure 3.14: Schematic illustration of a typical C-V curve of a standard MOS Field Oxide Capacitor (left) [102]. C-V curve measured on the MOS Field Oxide Capacitor of the Testchip for the extraction of C_{ox} , t_{ox} and V_{FB} . Production distribution: CERN-44; batch: VPA54856 (right).

Criteria – Thresholds

No specifications were defined for these calculated parameters prior to production. Instead, minimum and maximum soft thresholds were established based on observations and analyses of pre-production results, and these thresholds were maintained throughout the entire production process.

- $24 \text{ pF} < C_{\text{ox}} < 34 \text{ pF}$
- $0.55 \text{ } \mu\text{m} < t_{\text{ox}} < 0.80 \text{ } \mu\text{m}$
- $-5 \text{ V} < V_{\text{FB}} < 0 \text{ V}$

3.2.5 CFLD-P_CV

This test was performed on a MOS Field Oxide Capacitor, similar to the one described in the previous section, but with a p-stop implant layer beneath the entire capacitor area. The aim is to control the oxide above the p-stop implant and the characteristics of the doping profile. As with the standard MOS capacitor (without p-stop), the p-stop oxide capacitance ($C_{\text{ox-P}}$) and the p-stop equivalent field oxide thickness ($t_{\text{ox-P}}$) were extracted from the high-frequency C–V curve. Unlike the standard MOS capacitor test, the flat-band voltage and flat-band capacitance were not extracted from the C–V curve. Instead, two additional parameters were defined: the slope of the C–V curve from accumulation to depletion (S_{REF}), and the voltage at the intersection between the extrapolated slope and the horizontal line at $C_{\text{ox-P}}$ (V_{T}). These parameters do not have direct physical meaning (although both are related to the properties of the p layer [82]); they were solely used to monitor the p-stop profile throughout production.

Measurement Methods

The measurement methods for this test are equivalent to those used in the CFLD_CV test. The Agilent 4284A LCR meter is employed together with a voltage source and an external bias adaptor. The MOS metal gate (pad #9) is connected to the HIGH output, and the backplane to the LOW output of the LCR meter. After an initial hold time of 10 s, the device is biased from +10 to -20 V in steps of 100 mV, with a step waiting time of 100 ms. In this case, the capacitance is also measured at 10 kHz, with CR in series, using a signal amplitude of 100 mV.

Extraction Method

Figure 3.15 (left) provides a schematic illustration of the parameter extraction for this test, while Figure 3.15 (right) shows the corresponding plot from an actual extraction performed on a production Testchip. The measured C–V curve is comparable to that observed in the CFLD_CV test, despite differences in the inversion region (right side) of the curve. In this case, capacitance in strong accumulation corresponds to the p-stop oxide capacitance ($C_{\text{ox-P}}$). The p-stop equivalent field oxide thickness ($t_{\text{ox-P}}$) is calculated from the $C_{\text{ox-P}}$ as:

$$t_{\text{ox-P}} = \frac{\epsilon_{\text{ox}} \cdot A}{C_{\text{ox-P}}} \quad (3.11)$$

where ϵ_{ox} is the permittivity of the silicon oxide, and A is the capacitor area (556 000 μm^2).

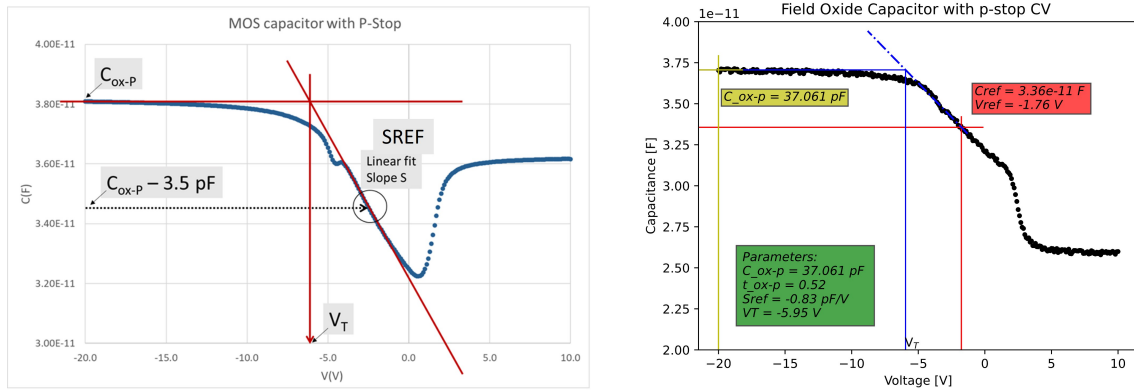


Figure 3.15: Schematic illustration of the parameter extraction from a C–V curve of a MOS Field Oxide Capacitor with p-stop (left). C–V curve measured on the MOS Field Oxide Capacitor with p-stop of the Testchip for the extraction of $C_{\text{ox-P}}$, $t_{\text{ox-P}}$, S_{REF} and V_T . Production distribution: CERN-44; batch: VPA54856 (right).

For the calculation of the S_{REF} parameter, a reference capacitance value is first defined as:

$$C_{\text{REF}} = C_{\text{ox-P}} - 3.5 \text{ pF} \quad (3.12)$$

The S_{REF} parameter is obtained as the slope of a linear fit performed on the accumulation-to-depletion portion of the C–V curve around C_{REF} . During production, the linear regression was computed using a Python statistical algorithm over a range of $\pm 0.8 \text{ V}$ around C_{REF} .

The threshold voltage (V_T) is extracted as the voltage at the intersection of the fitted line with slope S_{REF} and the horizontal line at $C_{\text{ox-P}}$:

$$V_T = \frac{C_{\text{ox-P}} - b}{S_{\text{REF}}} \quad (3.13)$$

where b is the Y-intercept, also determined using the Python linear-fitting algorithm.

Criteria – Thresholds

All thresholds corresponding to these parameters were defined during production QA, when the CFLD-P_CV test was incorporated into the QA measurement program. The criteria for threshold selection were based on the mean value of the initial measured results, with a range equal to three times the standard deviation (σ). The decision was further supported with the variability observed in CFLD_CV test parameters that are equivalent to those in the CFLD-P_CV test.

- $32 \text{ pF} < C_{\text{ox-P}} < 40 \text{ pF}$
- $0.48 \text{ } \mu\text{m} < t_{\text{ox-P}} < 0.60 \text{ } \mu\text{m}$
- $-1.50 \text{ pF/V} < S_{\text{REF}} < -0.20 \text{ pF/V}$
- $-7 \text{ V} < V_T < -3 \text{ V}$

3.2.6 INT_C

There are three different interdigitated structures (UP, MID, and LOW) on the Testchip, all of which were measured as part of the QA monitoring process. In particular, the INT_C test was designed to measure the inter-strip capacitance (C_{int}) of all three structures.

Measurement Methods

The inter-strip capacitance is measured using the Agilent 4284A LCR meter with the assistance of SMUs. Pad #7 (bias ring) is connected to ground (GND), and the backplane is biased at -150 V to fully deplete the bulk. Simultaneously, pad #1 (“central” strip) is connected to the HIGH output of the LCR meter, and pad #10 (neighboring strips) to the LOW output. The capacitance between consecutive strips is measured with CR in parallel at a frequency of 100 kHz and a signal amplitude of 0.5 V . A voltage sweep from -5 to $+5 \text{ V}$ in 1 V steps is applied, and the capacitance is recorded at each point. The capacitance at 0 V is selected as the reference measured value (C_{meas}).

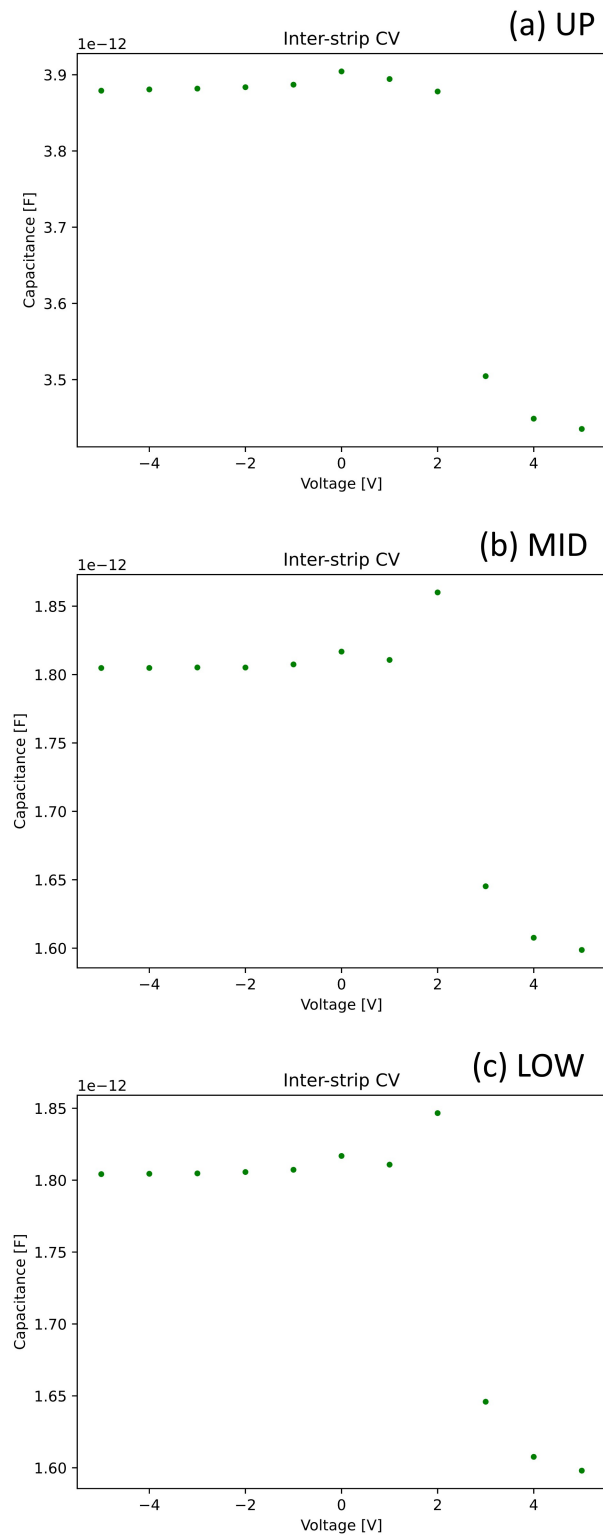


Figure 3.16: C-V curves measured between neighboring strips in (a) UP, (b) MID and (c) LOW interdigitated structures of the Testchip for the extraction of C_{int} . Production distribution: CERN-44; batch: VPA54856.

Extraction Method

The inter-strip capacitance is defined per unit length and is calculated from the measured capacitance as follows:

$$C_{\text{int}} = \frac{C_{\text{meas}}}{l_{\text{strip}}} \quad (3.14)$$

where l_{strip} is the length of a strip corresponding to the equivalent strip row (UP, MID, or LOW) in the Main sensor. The interdigitated structures in Testchips from Endcap designs correspond only to the upper and lower strip rows of the Endcap Main sensors.

The plots in Figure 3.16 show the capacitance values measured over the full voltage sweep for a standard production Testchip, although only the capacitance at 0 V is used for the C_{int} calculation. The capacitance values in plot (a) are approximately twice those in plots (b) and (c). This difference arises from variations in strip length between the structures, as the values are shown prior normalization by strip length.

Criteria – Thresholds

The minimum threshold for C_{int} was initially set at 1 pF/cm but was later revised to a less restrictive value of 1.3 pF/cm, due to the limited measurement precision and the fact that the C_{int} soft threshold is not a strict specification. Additionally, a minimum “consistency check” threshold of 0 pF/cm was specified to identify possible negative capacitances arising from measurement errors.

3.2.7 INT_IV

The Interdigitated structures (UP, MID, and LOW) on the Testchip were also tested to determine the inter-strip resistance (R_{int}) with the first neighboring strips. This was achieved using a straightforward resistance measurement.

Measurement Methods

For this measurement, several SMUs are required for different purposes. First, pad #7 (bias ring) is connected to ground (GND), and the backplane is biased at –150 V to fully deplete the bulk. Another SMU is used to apply a voltage sweep to the central strip (pad #1), while a constant voltage of 0 V is applied to pad #10 (neighboring strips). The voltage sweep is applied from –5 to +5 V in 0.1 V steps, following an initial hold time of 10 s,

and the current is recorded. A compliance current of $0.1\ \mu\text{A}$ is set for the measured strip, and a compliance current of $1\ \mu\text{A}$ is set for the other sourced elements in the structure.

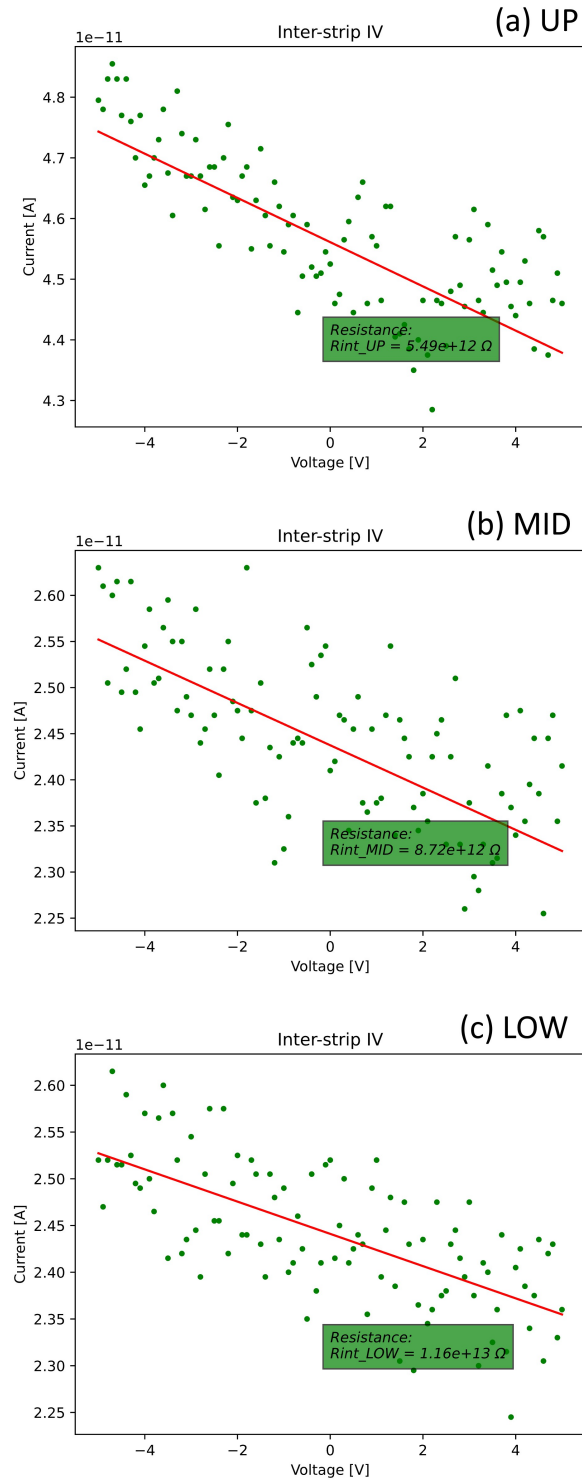


Figure 3.17: I–V curves measured between neighboring strips in (a) UP, (b) MID and (c) LOW interdigitated structures of the Testchip for the extraction of R_{int} . Production distribution: CERN-44; batch: VPA54856.

Extraction Method

The inter-strip resistance (R_{int}) is calculated as twice the inverse of the slope of the I–V curve. This factor of 2 accounts for the fact that each “central” strip has two neighboring strips; therefore, the current from a central strip flows toward both neighbors and must be divided by 2. The resulting R_{int} represents the resistance between two adjacent strips. If the current is too low to reliably extract the resistance from the slope, R_{int} is calculated directly from the current measured at 5 V.

Figure 3.17 shows the I–V curves measured for the Interdigitated structures—(a) UP, (b) MID, and (c) LOW—of a standard production Testchip. In each plot, the red line represents the linear regression used to calculate R_{int} during production.

Criteria – Thresholds

The minimum soft threshold for R_{int} was $10 \times R_{\text{bias}}$ ($R_{\text{int}} > 15 \text{ M}\Omega$)—i.e. ten times the nominal resistance of the polysilicon bias resistors in both the Main sensor and the Testchip. A maximum threshold of $5 \times 10^{13} \Omega$ was added later to act as a consistency check.

3.2.8 PTP_IV

This test was designed to extract the punch-through voltage (V_{PT}) from the Punch-Through Protection (PTP) structure in the Testchip. The objective of the test is to validate the functionality of the punch-through protection and, in addition, to monitor the consistency of the p-stop doping implant profile.

Measurement Methods

The PTP_IV test can be performed either with or without the first neighboring strips of the “central” strip under test.

For measurements involving the first neighboring strips, several SMUs are required to supply appropriate voltages to each element of the test structure. Specifically, pad #1 (bias ring) is connected to the HIGH output, and the backplane to the LOW output of an SMU to bias the bulk of the structure. A reverse bias of -400 V is applied to the backplane while the bias ring is grounded at 0 V . Another SMU is connected to the implant of a strip (e.g., pad #5) with neighbors—not those at the edges—while two additional SMUs

are connected to the first neighboring strip implants (pads #4 y #6). A voltage sweep is then applied synchronously to the three strips from 0 V to -40 V in 0.2 V steps, following an initial hold time of 3 s. The current is measured in the central strip, and an I–V curve is obtained. The compliance current for the central strip measurement is set to 1 mA, while less restrictive compliance limits are applied to the other SMUs.

The measurement procedure that avoids using the first neighboring strips is performed similarly, but with only a single SMU connected to the strip from which the I–V curve is obtained.

At IMB-CNM, all measurements were performed without neighboring strips throughout the entire production process for simplicity—initial pre-production tests showed that the difference in V_{PT} measured with or without neighbors was not significant.

Extraction Method

The PTP effective resistance (R_{eff} or R_{PT}) is calculated at each voltage point of the I–V curve as:

$$R_{\text{eff}} = \frac{V_{\text{test}}}{I_{\text{test}}} \quad (3.15)$$

where V_{test} corresponds to each voltage value in the I–V curve, and I_{test} to the corresponding current value.

A new R_{eff} –V curve is plotted to extract V_{PT} , defined as the voltage at which R_{eff} equals half of R_{bias} :

$$V_{PT} = V \left(R_{\text{eff}} = \frac{R_{\text{bias}}}{2} \right) \quad (3.16)$$

For this calculation, the nominal R_{bias} (1.5 M Ω) was used for all V_{PT} extractions during production. The algorithm developed to extract V_{PT} interpolates the value $R_{\text{bias}}/2$ on the R_{eff} –V curve.

Figure 3.18 shows the R_{eff} –V curve from the PTP structure of a standard production Testchip. Eight overlapping curves are plotted, corresponding to voltage sweeps performed on eight different strips of the PTP structure. This repetitive measurement across the strips also allows monitoring of the variability of the p-stop doping concentration across the wafer. The extraction of V_{PT} is illustrated in the plot.

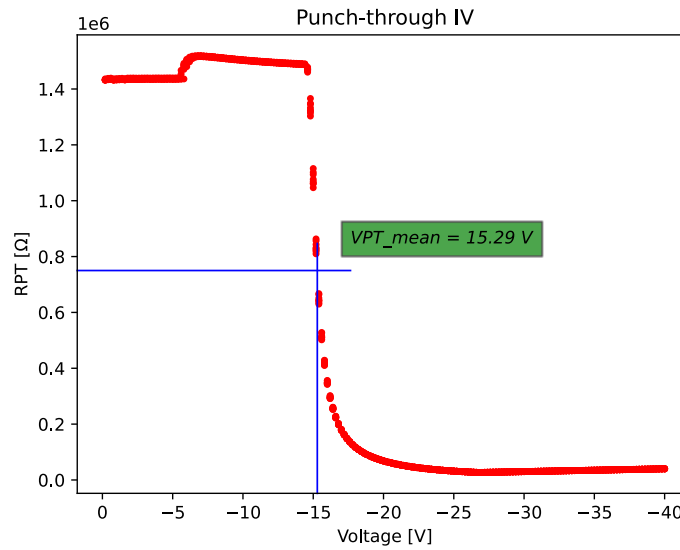


Figure 3.18: R_{PT} vs. V_{test} measured for the PTP structure of a Testchip, used to extract V_{PT} (eight R_{PT} curves are shown). Production distribution: CERN-44; batch: VPA54856.

Criteria – Thresholds

The acceptable V_{PT} values in production are those within the range of 12–18 V. These are soft thresholds that were defined during production as this value was not fixed in the specifications document. Initially, the maximum threshold for this parameter was set at 17 V, but it was later made less restrictive and increased to 18 V after reviewing the statistical data from the first months of production.

3.2.9 RBIAS_IV

The RBIAS_IV test was included in the production QA program to measure and verify the good quality of the polysilicon bias resistors of the strip sensors.

Measurement Methods

For this measurement, two SMUs are used to source and measure the electrical properties. Pad #1 is connected to ground (GND), while a voltage sweep is applied individually from pads #2 to #7. The I–V sweep is performed from –5 V to +5 V in 0.1 V steps, and the current is measured at each pad. A compliance current of 10 mA is applied.

Extraction Method

The bias resistance (R_{bias}) is extracted from the slope of the I-V curve calculated for each of the six resistors. The mean of the inverse slopes is taken as the R_{bias} parameter. Figure 3.19 shows the extraction of R_{bias} as the mean value obtained from the six overlapping I-V curves.

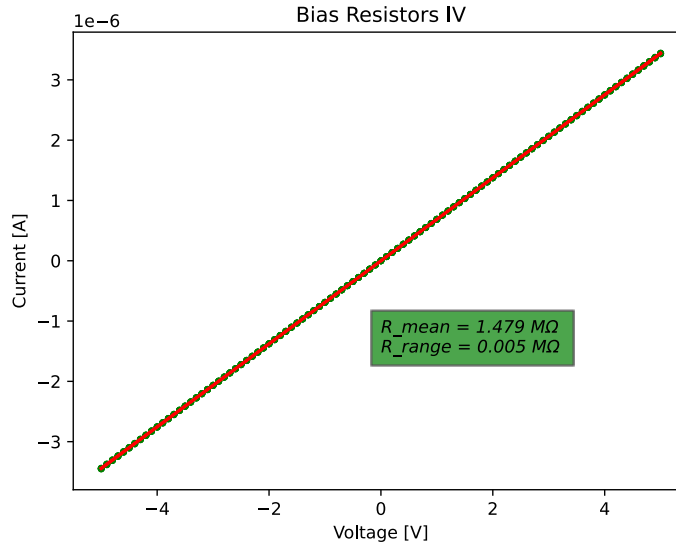


Figure 3.19: I-V curves measured during the RBIAS_IV test in a Testchip, used to extract R_{bias} (six I-V curves are shown). Production distribution: CERN-44; batch: VPA54856.

Criteria – Thresholds

The acceptance criteria for R_{bias} were defined by the ATLAS ITk Strip Sensor specifications, with a nominal value of $1.5 \text{ M}\Omega$ and an allowed deviation of $\pm 0.5 \text{ M}\Omega$. Accordingly, the minimum threshold was set to $1 \text{ M}\Omega$ and the maximum threshold to $2 \text{ M}\Omega$ for R_{bias} measurements during production.

3.2.10 MD8_CV

MD8 Monitor Diodes are used to measure the depletion voltage before and after irradiation. For this purpose, on non-irradiated samples, the full depletion voltage (V_{FD}) is extracted using the MD8_CV test at IMB-CNM.

Measurement Methods

Non-irradiated MD8 diodes are tested on the manual probe station in the Radiation Detectors Laboratory at IMB-CNM to ensure controlled temperature and humidity conditions. For the MD8_CV test, an Agilent 4284A LCR meter is used to measure the capacitance of the diodes, along with a SMU (Keithley 2410) to supply the required voltage. First, an OPEN-circuit correction is performed to calibrate the capacitance measurement. Next, the HIGH output of the SMU is connected to the MD8 bias contact, while the LOW output is connected to the backplane at 0 V. A reverse bias voltage is then applied from 0 V to 700 V in 10 V steps, following an initial hold time of 10 s. The step waiting time is also set to 10 s, and 10 measurements are taken at each point with an interval of 0.2 s.

The test is conducted with CR in series, using a signal amplitude of 100 mV at a frequency of 1 kHz. A compliance current of 0.1 mA is set to prevent undesired high currents over the test voltage range. All parameters are configured manually via the software (TCL/Tk) controlling the instruments. Additionally, the temperature is maintained at $T = 21 \pm 2^\circ\text{C}$, and the relative humidity is kept below 20% (in practice, the RH during all measurements was below 5%).

Extraction Method

For the extraction of the V_{FD} , the data must be plotted like $1/C^2$ vs. V , as shown in Figure 3.20. The full depletion voltage V_{FD} corresponds to the voltage at the intersection between the initial linear region of the curve and the plateau in the second region. At the beginning of production, both regions of the curve were approximated by straight lines using linear regression. Later, a new fitting method was implemented, employing an algorithm specifically designed for this extraction. This method fits the entire curve using an equation that combines three components: a linear fit starting at 50 V, an asymptotic fit starting at 200 V, and a third fit for large V_{FD} near the upper end of the data range. Several input parameters and variables are optimized to achieve the best possible global fit [103].

Criteria – Thresholds

The maximum threshold for V_{FD} is defined by the ATLAS ITk Strip Sensor specifications: $V_{\text{FD}} < 350$ V. Additionally, a minimum soft threshold ($V_{\text{FD}} > 150$ V) was implemented during production after reviewing the distribution profile of this parameter in non-irradiated diodes.

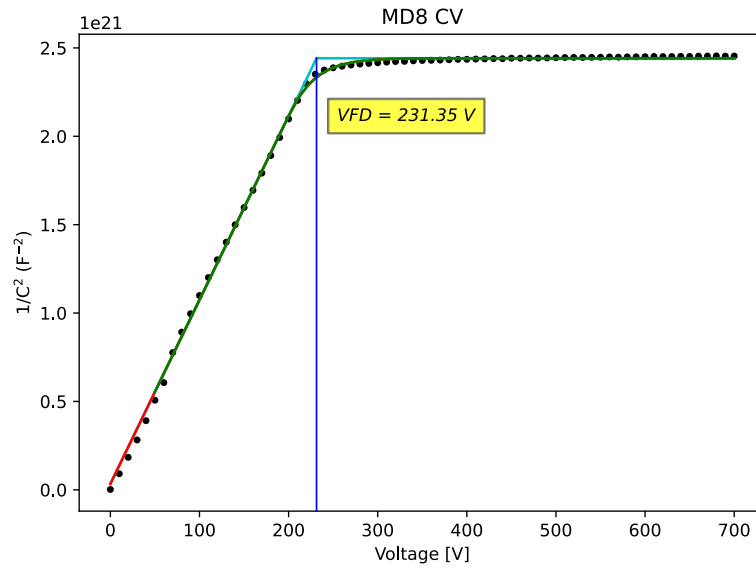


Figure 3.20: $1/C^2$ vs. V measured during the MD8_CV test in an MD8, used to extract the full depletion voltage (V_{FD}). Production distribution: CERN-44; batch: VPA54856.

3.2.11 MD8_IV

As with V_{FD} , the diodes also provide a means to monitor the leakage current of the sensors. For this reason, the leakage current in the MD8 diodes is monitored during production, along with the breakdown voltage (V_{BD}) extracted from the I–V curve.

Measurement Methods

In this case, only a SMU (Keithley 2470) is used to source and measure the diode. The bias ring is connected to the HIGH output, and the backplane to the LOW output. All input parameters are set via the touchscreen of the Keithley 2470. First, an integration time of 10 NPLC (Number of Power Line Cycles), equivalent to 200 ms, and 100 readings per trigger are selected in the settings menu. A reverse voltage sweep is then applied from 0 V to 700 V in 10 V steps, with a step waiting time of 10 s. A compliance current is set to 100 nA/cm².

Extraction Method

The leakage current is extracted at 500 V directly from the I–V curve. Figure 3.21 shows an example of the extraction point, indicated with blue lines. The parameter of interest is the leakage current at 500 V per unit area (I_{500}). Therefore, the current extracted from the curve is divided by the MD8 active area (0.5095 cm²).

The other parameter extracted from this test is V_{BD} , i.e. the voltage at which the I-V curve exhibits breakdown. If no breakdown is detected before 700 V (the maximum applied voltage), this parameter is set to $V_{BD} = 9.99E + 99$, as illustrated in the example below.

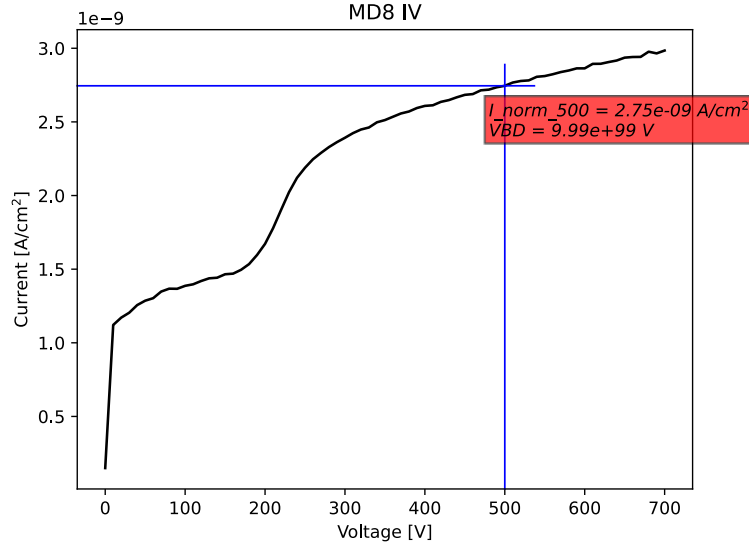


Figure 3.21: I-V curve measured during the MD8_IV test in an MD8, used to extract the leakage current at 500 V and the breakdown voltage (V_{BD}). Production distribution: CERN-44; batch: VPA54856.

Criteria – Thresholds

The following thresholds were defined by the ATLAS ITk Strip Sensor specifications:

- $I_{500} < 100$ nA (maximum threshold)
- $V_{BD} > 500$ V (minimum threshold)

For the minimum leakage current (I_{500}) threshold at 500 V, the condition $I_{500} > 1 \times 10^{-11}$ A was established midway through production. On the other hand, a maximum threshold for the breakdown voltage was set after reviewing the corresponding statistical data: $V_{BD} < 1000$ V.

3.3 Database and Scripts

A collaborative online database was developed by the ATLAS Inner Tracker (ITk) team. This system, known as the ATLAS ITk Production Database (ITk PDB), was designed to keep track of all components intended for use in the Inner Tracker of the ATLAS experiment at CERN. The Tracker consists of approximately 500 000 components, organized

across multiple hierarchical levels. Information related to all these components is being stored in the ITk PDB throughout the construction process. This practice will continue until the full assembly of the Tracker and throughout the operational phase of the High-Luminosity Large Hadron Collider (HL-LHC), which is expected to last around 10 years. Overall, the data must remain accessible in the database for a period of approximately 20 years [104, 105].

In particular, Quality Assurance (QA) pieces are also recorded in the database (DB) [106]. In the terminology of the Production Database (PDB), each QA piece is classified as a component. Initially, dummy components were created to test the database functionality. Currently, actual components are assigned to the corresponding pieces from all production batches and wafers. Any member involved in the ATLAS experiment can be registered in the database, with their permission level determined by their role within the affiliated institute.

Database access is available through an online platform or via Python scripts. The graphical user interface (GUI) enables users to efficiently navigate the various items within the database. These items are organized into three menus, each corresponding to different functionalities. The first menu provides access to Components, Batches, Results, and Shipments associated with the user or their institution. The second menu allows users to browse any Component, Batch, Result, or Shipment recorded in the database. The third menu enables users to search for information related to Component Types, Batch Types, Test Types, and the Institutes participating in the ATLAS Collaboration. Additionally, the PDB includes a dedicated section containing a user manual with comprehensive instructions for using the platform.

Alternatively, Python scripts offer a more advanced method for accessing the database through programmatic interaction. For this purpose, the Python wrapper `itkdb` enables streamlined communication with the PDB via its Application Programming Interface (API).

A set of Python scripts was developed primarily for extracting QA parameters and uploading data to the database. The `itkdb` tool was used to interface the functions and algorithms implemented in these scripts with the database. Two main types of interaction with the database API are supported: (1) retrieving data from the PDB using GET requests, and (2) submitting data to it using POST requests.

3.3.1 Extraction Algorithms

The QA pieces Testchip&MD8 and Mini&MD8, described in Chapter 2, were irradiated with different particles at specific fluence levels. Pre-irradiation measurements were

conducted at IMB-CNM, whereas post-irradiation measurements were performed by other institutes.

During the entire production QA, each test site has been responsible for converting raw measurement data into data files in a standardized format. This file includes the chip specifications, test conditions, and the collected data. Several descriptive elements are common across all data files, while other properties vary depending on the test structure and measurement type. The filename appears in the header of the file, whereas other information—such as wafer type, batch number, wafer number, component type, label, serial number, date and time of the test, test site, and operator—is included in the body of the file. These data are associated with the characteristics of the measured components and with the measurement conditions. In contrast, properties such as test type, setup instruments, and operational conditions are specific to each individual test. The measured data are printed at the end of the file in a well-defined format.

A complete set of Python scripts was developed to extract parameters and other relevant information either from standardized data files or directly from raw data files. This system is organized into a structured script hierarchy, headed by three main scripts: `generacion_datafiles.py`, `generacion_graficos.py`, and `QA_param_extraction.py`. These primary scripts are executed by the user and internally call additional modules (i.e., lower-level scripts) that provide supplementary functions and utilities.

The most prominent script in the framework is `QA_param_extraction.py`, which enables the extraction of QA parameters from data stored in standardized file formats. Parameter extraction was performed for each test, with results visualized through plots and exported as text and Excel files (Figure 3.22). These processes were implemented using two modules specifically developed for this purpose.

One of these modules, `QA_param_extraction.py`, is organized into three sections: (1) a definition of constants required for the calculations, (2) a collection of algorithms for QA parameter extraction, and (3) functions for generating CSV and XLSX files containing the results of all tests. The extraction algorithms were individually designed for each test, taking into account the specific characteristics of the corresponding parameters. Similarly, the file generation routines include dedicated functions for each parameter.

In parallel, all plotting functions are encapsulated within a Python class defined in the script `f_plot.py`. A dedicated plotting function was implemented for each test, tailored to the specific features of the associated measurements.

Additionally, a set of supporting modules was developed to manage configuration settings (e.g., input and output directories), handle QA labels, and implement an algorithm that

converts data files into Python dictionaries. This complete set of scripts was made available to the ATLAS ITk Strip Sensors community via the GitLab platform, ensuring accessibility, version control, and collaborative development.

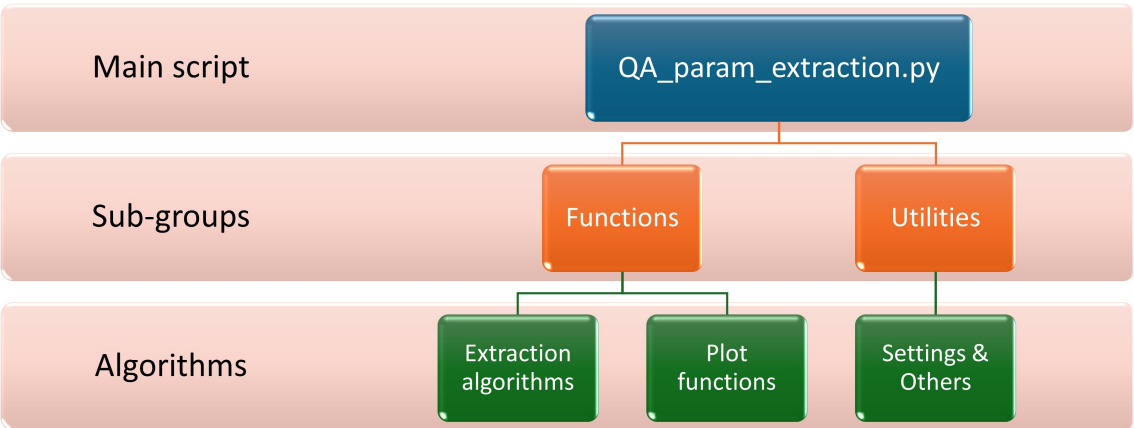


Figure 3.22: Schematic structure of the Python script hierarchy for QA parameter extraction from standardized data files.

The other two main scripts were specifically developed for exclusive use at IMB-CNM. The purpose of the script `generacion_graficos.py` is similar to that of `QA_param_extraction.py`, with the key difference being that it processes data directly from raw data files rather than from standard-format data files. To support this, an additional module was implemented to handle raw data selection and preprocessing prior to parameter extraction (Figure 3.23). These functions were developed in accordance with the structure and characteristics of the raw data files generated by the automatic probe station used at IMB-CNM.

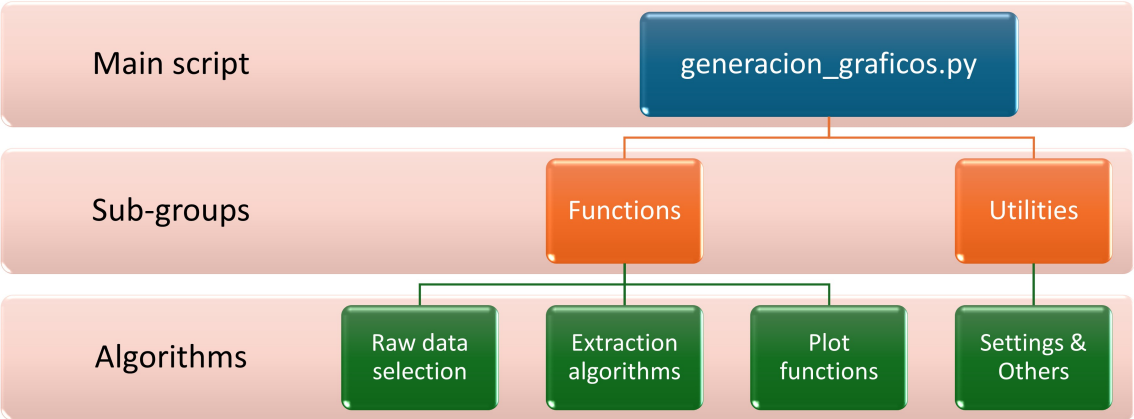


Figure 3.23: Schematic structure of the Python script hierarchy for QA parameter extraction from raw data files.

The final main script within the parameter extraction suite is `generacion_datafiles.py`. As with `generacion_graficos.py`, it includes the raw data selection module,

which is used to convert raw data into conventional, standard-format data files (Figure 3.24). Indeed, this is the primary objective of the script. Additionally, two separate scripts were developed for the same purpose, specifically for data measured using the manual probe station. As this equipment differs from the automatic probe station, the raw data is produced in a different format. Consequently, distinct algorithms were implemented to convert these files into the standard-format structure.

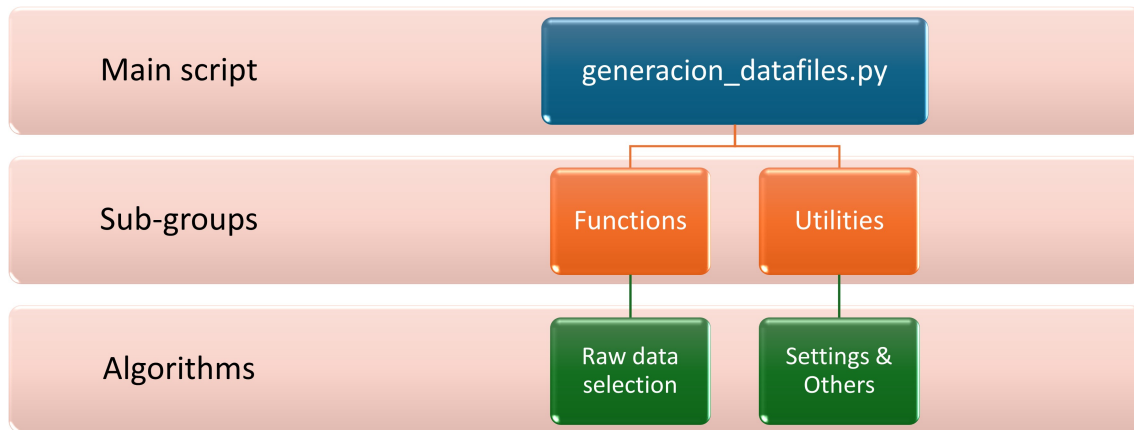


Figure 3.24: Schematic structure of the Python script hierarchy for generating QA standard-format data files from raw data files.

Overall, commonly used function modules are invoked and integrated by the main scripts to extract various QA parameters throughout the production process, while also generating the corresponding data files and plots for each test.

3.3.2 Upload Scripts

The parameters extracted from the data files—using the scripts described in Section 3.3.1—had to be uploaded to the PDB and made available to all members of the ATLAS ITk Strip Sensor Collaboration. To this end, a new set of scripts was developed and made accessible to all collaborators.

3.3.2.1 Database Structure

To explain the structure of the scripts, it is first necessary to understand how the database operates. In the context of QA operations within the database, four components were defined there for data upload. Two of them, named Sensor QAchip test and Sensor QAmini test, are dummy components created to test the PDB prior to the commencement of pre-production and production data uploads. These dummy components do not correspond to any specific physical QA pieces (Testchip&MD8 and Mini&MD8) diced from the wafers.

In contrast, the other two QA components in the database—Sensor Testchip&MD8 and Sensor Mini&MD8—are associated with actual chips fabricated by HPK. These components were used throughout both the pre-production and production phases.

The Sensor Testchip&MD8 component is assigned seven stages in the database: RECEPTION, FURTHER DICED, IRRADIATION, PRE-IRRAD TESTS, POST-IRRAD TESTS, PASS, and EXPERIMENTS. Each of these stages includes multiple tests, which correspond either to physical measurements conducted in the laboratory or to specific steps in the production QA workflow.

In comparison, the Sensor Mini&MD8 component is assigned six stages, identical to those of the Sensor Testchip&MD8 but without the FURTHER DICED stage.

For both QA components, each stage is flagged according to its type, which is primarily categorized as INITIAL, ALTERNATIVE, or FINAL. The production QA workflow must be preserved within the PDB, and components are required to progress through the stages in a defined sequence. While the paths between stages may vary depending on specific production QA requirements, the flowchart shown in Figure 3.25 illustrates the most logical progression.

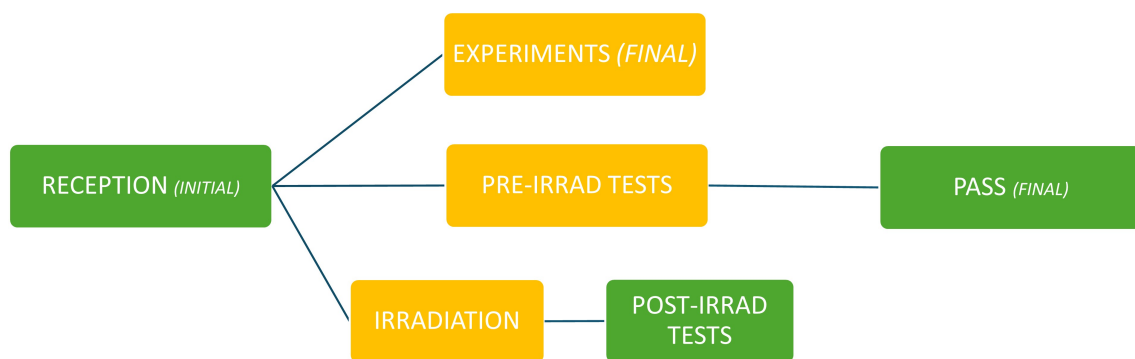


Figure 3.25: Production QA flow as represented in the Production Database. Alternative stages (highlighted in orange) could be reached from different preceding stages.

The tests enabled at each stage are presented in Tables 3.1 and 3.2 for both QA pieces. Pre-irradiation and post-irradiation tests conducted in the laboratory are listed in Table 3.3. The properties and parameters extracted from the measurements are defined in the PDB for each test. These parameters correspond to those explained in Section 3.2.

Table 3.1: Test types associated with all stages of the QA piece Sensor Testchip&MD8.

STAGE (<i>Testchip&MD8</i>)	TESTS
RECEPTION	Reception Date
FURTHER DICED	No associated test type with this stage
IRRADIATION	Irradiation test
PRE-IRRAD TESTS	16 tests from <i>Testchip&MD8</i>
POST-IRRAD TESTS	13 tests from <i>Testchip&MD8</i>
PASS	Pass Comments
EXPERIMENTS	17 tests (Irradiation test and 16 tests from <i>Testchip&MD8</i>)

Table 3.2: Test types associated with all stages of the QA piece Sensor Mini&MD8.

STAGE (<i>Mini&MD8</i>)	TESTS
RECEPTION	Reception Date
IRRADIATION	Irradiation test
PRE-IRRAD TESTS	MD8_IV, MD8_CV, MINI_CCE, MINI_IV
POST-IRRAD TESTS	MD8_IV, MD8_CV, MINI_CCE, MINI_IV
PASS	Pass Comments
EXPERIMENTS	Irradiation, MD8_IV, MD8_CV, MINI_CCE, MINI_IV

3.3.2.2 Upload Scripts and Modules

Returning to the QA upload scripts, they were developed to upload test results for every component involved in the pre-production and production processes. The operational routine is described as follows: first, a local folder containing all test data files to be uploaded—one standardized data file per test—is created. The path to this data folder is specified in the `QA_settings.txt` file, which the main script references upon execution. The script `QA_Upload.py` is then run, calling other modules to access the various functions and constants required for the upload process.

The user-script interaction for data upload is illustrated in Figure 3.26. Once `QA_Upload.py` is executed, data are extracted from the test files, and parameters are obtained for each test. The user then reviews and closes the plots, deciding whether each measurement is acceptable. If a measurement is deemed unsatisfactory, the corresponding test will not be uploaded, and the user must choose whether to abort the process or continue uploading the remaining tests. Conversely, if the measurement is acceptable, an automatic threshold evaluation is performed, and the next test is evaluated automatically until all test data files have been processed.

Table 3.3: List of all tests associated with the PRE-IRRAD TESTS and POST-IRRAD TESTS stages of the QA piece Sensor Testchip&MD8.

PRE-IRRAD TESTS (Testchip&MD8)	POST-IRRAD TESTS (Testchip&MD8)
CBR-I_IV	-
CBR-M_IV	-
CCPL_C	CCPL_C
CCPL_IV100	CCPL_IV100
CFLD_CV	CFLD_CV
CFLD-P_CV	-
INT_LOW_C	INT_LOW_C
INT_MID_C	INT_MID_C
INT_UP_C	INT_UP_C
INT_LOW_IV	INT_LOW_IV
INT_MID_IV	INT_MID_IV
INT_UP_IV	INT_UP_IV
PTP_IV	PTP_IV
RBIAS_IV	RBIAS_IV
MD8_IV	MD8_IV
MD8_CV	MD8_CV

The set of scripts for QA upload follows its own Python structure (Figure 3.27), similar to that employed for parameter extraction. In this case, the main script, `QA_Upload.py`, was designed to be straightforward, with all operations for the upload process imported from other well-organized modules containing various functions. The two most notable modules directly accessed by `QA_Upload.py` are `dbAccess.py` and `QADataParser.py`. The former belongs to the package `itk_pdb`, which predates the Python wrapper `itkdb`. Both packages were developed with the same objective: accessing the PDB. In fact, `itkdb` is the preferred tool within the ITk Strip Sensor Collaboration for this purpose, as it has undergone further development over the years. Nonetheless, certain functionalities—such as file attachments during upload—were absent from the newer Python wrapper when the QA Upload script suite was initially developed. Meanwhile, `QADataParser.py` is the most robust script in this collection. It serves as the module from which all sub-modules are invoked and contains the most critical upload function.

The QA upload scripts was designed to extract parameters for each test—similarly to the local parameter extraction script—in order to generate plots of the results and upload them to the database. Consequently, the extraction algorithms and plotting functions are the same as those used in the local extraction process, although they are organized in a

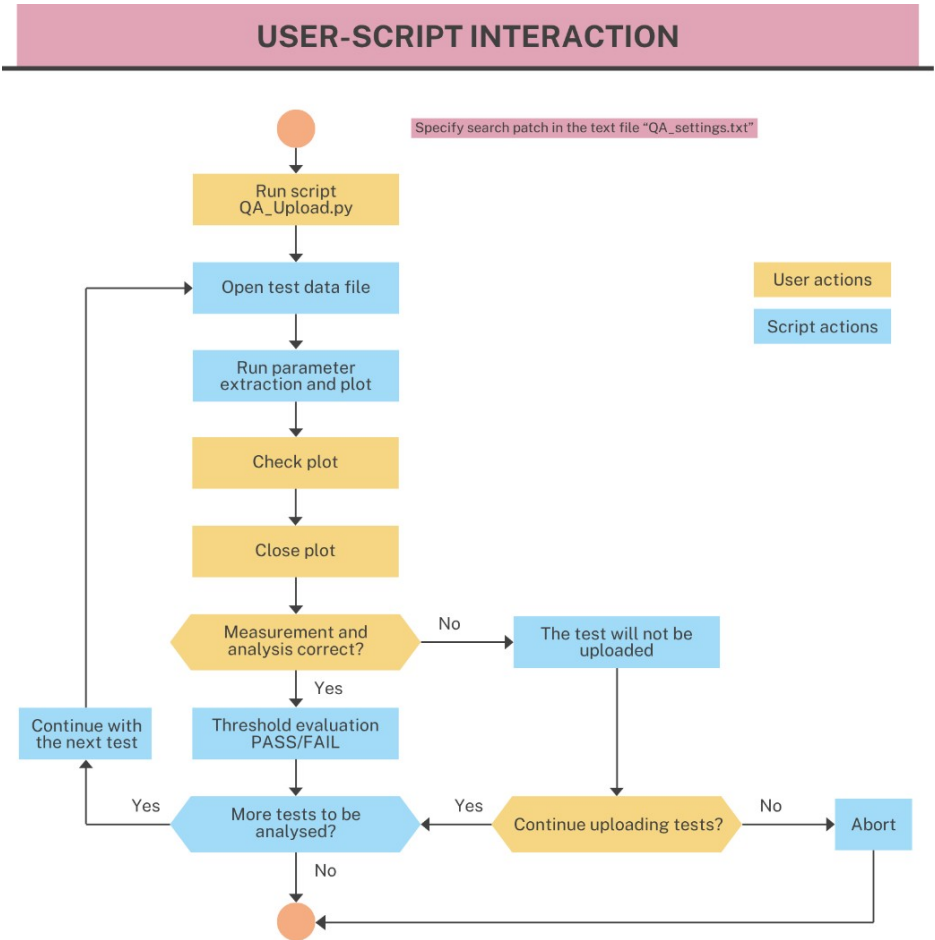


Figure 3.26: Flow diagram illustrating the user-script interaction during data upload to the database.

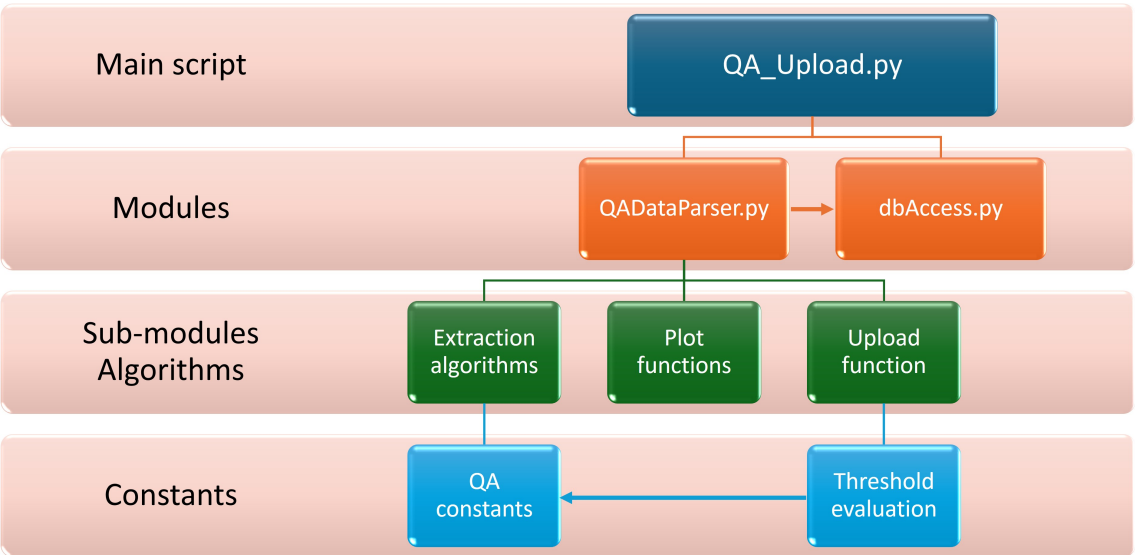


Figure 3.27: Schematic structure of the Python script hierarchy for QA parameter upload to the Production Database.

completely different structure. In this case, each extraction function was implemented in a separate script, functioning as an individual module imported by `QADataParser.py`. Each extraction module calls the sub-module `QA_constants.py` whenever a physical or technical QA constant is needed in the extraction algorithms. Regarding the plotting functions, the imported module is exactly the same as that used for local extraction.

The final and most significant function is the Upload function, defined within the `QADataParser.py` script. The algorithm for this function was developed to access the PDB and upload the parameters and properties of the Testchips, MD8s, and Minis. The upload is done test by test. Prior to this, all results are obtained through the relevant extraction algorithms, using variable types (integer, float, string...) and units consistent with those defined in the database. Additionally, a file attachment function is integrated into the Upload algorithm to ensure that data files for each test are correctly linked in the database. Finally, an additional module is imported to evaluate threshold values for each parameter immediately before upload. This enables tests to be flagged as PASSED or FAILED, depending on whether the parameters fall within the defined threshold limits or not. These thresholds vary between pre-irradiated and post-irradiated tests, and they also differ depending on the type of irradiation—protons, neutrons, gamma rays, or gamma + neutrons.

3.3.2.3 QA Thresholds

All pre-irradiation and post-irradiation thresholds are defined in the `QA_constants.py` script, together with the other physical and technical constants used in the parameter-extraction algorithms. These thresholds were not all established from the beginning; rather, they were progressively added and updated throughout production QA.

All thresholds included in `QA_constants.py` are listed in Table 3.4. Specifically, the minimum and maximum thresholds are provided for each parameter and irradiation type (pre-irradiation, neutrons, protons, and gamma rays), with distinctions made between different irradiation fluences when applicable. The table also includes both the initial thresholds and the final modifications introduced during QA monitoring.

For the thresholds defined at the start of production, hard thresholds—from the ATLAS ITk Strip Sensor specifications—are highlighted in yellow, in contrast to soft thresholds. The same color-coding convention has been applied to the latest optimized thresholds, except for those that were modified following statistical analysis and review. Table cells containing soft thresholds that were further adjusted to better match production parameter trends are colored differently, as indicated in Table 3.5, which serves as the legend for Table 3.4.

Table 3.4: All parameter minimum and maximum thresholds from production QA, associated with each device, test, parameter, and irradiation type.

DEVICE	TEST	PARAMETER	IRRADIATION TYPE	Thresholds		New Thresholds	
				Min	Max	Min	Max
CBR	CBR_I_IV	R-I (Ω/cm)	Pre-irrad		50000.00	18000.00	50000.00
		WEFF-I (μm)	Pre-irrad	13.00	19.00	15.00	19.00
	CBR_M_IV	R-M (Ω/cm)	Pre-irrad		30.00	6	30.00
		WEFF-M (μm)	Pre-irrad	18.00	26.00	18.00	26.00
Coupling Capacitor	CCPL_C	CCOUP_L (pF/cm)	Pre-irrad	20.00		20.00	25
			n Ljubljana 1.6e15	20.00		20.00	25
			p Bham/CYRIC/CSNS	20.00		20.00	25
			γ Prague	20.00		20.00	25
			$\gamma+n$	20.00		20.00	25
	CCPL_IV	ICCPL_100V (A)	Pre-irrad		1.00E-08	0	1.00E-08
			n Ljubljana 1.6e15		1.00E-08	0	1.00E-08
			p Bham/CYRIC/CSNS		1.00E-08	0	1.00E-08
			γ Prague		1.00E-08	0	1.00E-08
			$\gamma+n$		1.00E-08	0	1.00E-08
MOS Capacitor	CFLD_CV	C_OX (pF)	Pre-irrad	24	34	24	34
		T_OX (μm)		0.55	0.80	0.55	0.80
		VFB (V)		-5	0	-5	0
		C_OX (pF)	γ Prague	24	34	24	34
		T_OX (μm)		0.55	0.80	0.55	0.80
		VFB (V)		-50	0	-50	0
MOS Capacitor with P-stop	CFLD-P_CV	C_OX-P (pF)	Pre-irrad	32.00	40.00	32.00	40.00
		T_OX-P (μm)		0.48	0.60	0.48	0.60
		SREF (pF/V)		-1.50	-0.20	-1.50	-0.20
		VT (V)		-7.00	-3.00	-7.00	-3.00
Interdigitated Structures	INT_LOW_C INT_MID_C INT_UP_C	CINT_LOW (pF/cm) CINT_MID (pF/cm) CINT_UP (pF/cm)	Pre-irrad		1.00	0	1.30
			n Ljubljana 1.6e15		2.00	0	2.00
			p Bham/CYRIC/CSNS		2.00	0	2.00
			γ Prague		2.00	0	2.00
			$\gamma+n$		2.00	0	2.00
	INT_LOW_IV INT_MID_IV INT_UP_IV	RINT_LOW (Ω) RINT_MID (Ω) RINT_UP (Ω)	Pre-irrad	1.50E+07		1.50E+07	5.00E+13
			n Ljubljana 1.6e15	1.50E+07		1.50E+07	1.00E+10
			p Bham/CYRIC/CSNS	1.50E+07		1.50E+07	1.00E+10
			γ Prague	1.50E+06		1.00E+06	1.00E+08
			$\gamma+n$	1.50E+07		1.50E+07	1.00E+10
PTP Structure	PTP_IV	AVERAGE_VPT (V)	Pre-irrad	12	17	12	18
			n Ljubljana 1.6e15	5	50	25	50
			p Bham/CYRIC/CSNS	5	50	25	50
			γ Prague	5	50	5	20
			$\gamma+n$	5	50	18	30
Bias Resistors	RBIAS_IV	AVERAGE_RBIS (M Ω)	Pre-irrad	1.00	2.00	1.00	2.00
			n Ljubljana 1.6e15	1.00	2.00	1.00	2.00
			p Bham/CYRIC/CSNS	1.00	2.00	1.00	2.00
			γ Prague	1.00	2.00	1.00	2.20
			$\gamma+n$	1.00	2.00	1.00	2.20
MD8	MD8_IV	NORM_CURRENT_500V (A/cm ²)	Pre-irrad		1.00E-07	1.00E-11	1.00E-07
			n Ljubljana 5.1e14		1.00E-04	1.00E-11	2.00E-05
			n Ljubljana 1.6e15		1.00E-04	1.00E-11	1.00E-04
			p Bham/CYRIC/CSNS		1.00E-04	1.00E-11	2.00E-05
			γ Prague		1.00E-06	1.00E-11	1.00E-06
			$\gamma+n$		1.00E-04	1.00E-11	1.00E-04
		VBD (V)	Pre-irrad	500		500	1000
			n Ljubljana 5.1e14	500		500	1000
			n Ljubljana 1.6e15	500		500	1000
			p Bham/CYRIC/CSNS	500		500	1000
			γ Prague	500		500	1000
			$\gamma+n$	500		500	1000
	MD8_CV	VFD (V)	Pre-irrad		350	150	350
			n Ljubljana 5.1e14		850	400	850
			p Bham/CYRIC/CSNS		450	150	450
			γ Prague		350	150	350
Mini	MINI_CCE	CCE_500V (e)	n Ljubljana 1.6e15	6350		6350	16000
			p Bham/CYRIC/CSNS	6350		9000	16000

Additionally, “consistency check” thresholds were introduced for certain parameters lacking defined minimum or maximum limits, in order to facilitate the detection of outliers. These thresholds help identify unexpected negative values due to measurement errors (for parameters that should always be positive) or to trigger alerts for unusually high values, particularly in cases where the primary concern is the minimum threshold.

Table 3.5: Legend of thresholds from Table 3.4, showing three types: those from the specifications, those modified during production QA, and the “consistency check” thresholds.

"Hard thresholds" from the Specifications
Thresholds changed due to QA production statistics
<i>"Consistency check" thresholds</i>

3.3.3 Reporting Scripts

An important set of scripts was dedicated to downloading data from the PDB and performing the corresponding data analysis (Figure 3.28). This reporting task was carried out on behalf of the entire QA Collaboration. A robust script was developed midway through production and was progressively improved until the end of the production phase. The package `itkdb` was extensively used in `QA_reporting.py` to repeatedly access the database—for instance, to retrieve a list of components, to obtain detailed information about these components and their associated tests, and to extract irradiation-related data for the tests. The primary objective of these scripts is to generate distribution and time-evolution plots for each parameter, and to identify correlations between different parameters, regardless of whether they were irradiated with various particles or not.

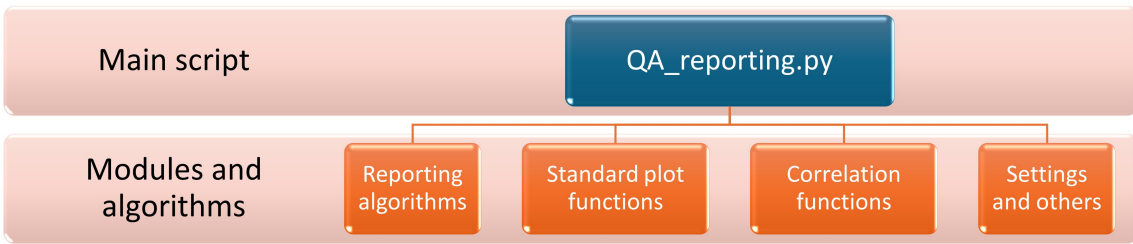


Figure 3.28: Schematic structure of the Python script hierarchy for QA reporting and analysis of data retrieved from the Production Database.

The `QA_reporting.py` script is structured into several sections. Initially, it imports various Python libraries and modules necessary for the required operations. Subsequently, input variables and filters are defined within the script to select the relevant dataset. The more restrictive the input criteria, the more specific the resulting output. These input variables include the parameter(s) to be plotted, the type of analysis, the type of plot, the component type, the current stage in the PDB, irradiation details, and the date

range. Additional optional variables—such as the project name, the current test location within the database, or the batch number—may also be specified to refine the selection further. Furthermore, external text files listing unwanted components (identified by Serial Numbers) can be referenced to mask (i.e., exclude) them from the final analysis.

The second part of the script evaluates which components comply with the specified irradiation characteristics. If non-irradiated chips are being analyzed, the program rapidly bypasses this algorithm. Otherwise, the script accesses the PDB and searches for the IRRADIATION test associated with each component. It then checks the irradiation particle types, fluences, and irradiation sites according to the irradiation parameters defined at the beginning of the script. Only those components in the database that match the specified irradiation conditions are selected. In the case of irradiations with both gamma rays and neutrons, two separate IRRADIATION tests are uploaded for each component. Therefore, the algorithm is designed to identify and retrieve information from both tests in order to fully characterize this dual irradiation.

Once the initial filters are applied and the irradiation characteristics have been retrieved, the remaining components are queried again in the PDB to obtain comprehensive information from all associated tests (including parameters, properties, etc.). This information is organized into a Python dictionary named `QA_parameters`. From this point onward, this dictionary serves as a key and versatile tool, from which all relevant data are accessed and utilized for various purposes.

The structure of `QA_parameters` is straightforward and hierarchical, progressing in a single direction from general to specific (Figure 3.29). The top-level key corresponds to the test name. Multiple test names may appear if the search involves more than one parameter. The second level contains the labels of the analyzed components. Each label uniquely identifies a component and is composed of the batch number and the serial number (e.g. VPA49796-20USBSL0709694). The final level holds all properties of interest associated with each test and label.

Once the `QA_parameters` dictionary is completed, a major block of algorithms is executed within the script. Additional modules are imported, including the plotting module, the test-correlation module, and others dedicated to settings and functional operations. The plotting module consists of a comprehensive set of functions, imported from the main script, to visualize the extracted results. A complex script was specifically developed to generate various types of plots, tailored to accommodate the particular features of the analyses conducted for each test and parameter.

Within the plotting module, several Python libraries—such as `matplotlib`, `seaborn`, and `statistics`—are employed for data processing and graphical representation. In particular, `matplotlib` and `seaborn` are used to create a broad range of graphs. The primary objective

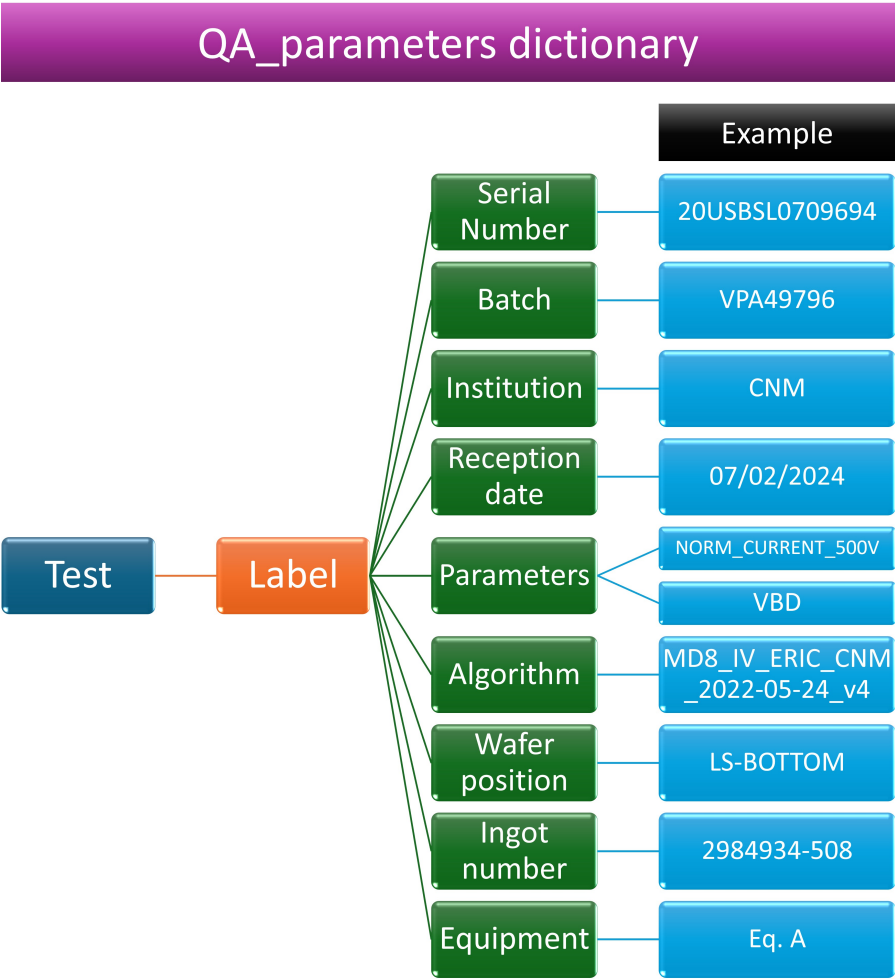


Figure 3.29: Structure of the QA_parameters Python dictionary. For each test, the test name is assigned at the top level, followed by the component label, with the corresponding properties at the lowest level.

of QA reporting is to provide visual insights into the distribution and time evolution of each parameter, for both pre-irradiated and post-irradiated components. Accordingly, two dedicated plotting algorithms were implemented to enable the automatic generation of these types of visualizations. The resulting plots include a legend indicating the number of components analyzed, as well as the mean value and standard deviation of the parameter under consideration.

Regarding the time-evolution plots, these depict a given parameter on the y-axis against production time on the x-axis, including maximum and minimum thresholds represented by horizontal lines. The x-axis is labelled with reception dates by default, though this can be switched to production delivery dates or other relevant options as required. In contrast, distribution plots are presented as histograms, with parameter values along the x-axis and frequency counts on the y-axis. Thresholds are illustrated as vertical lines within these histograms.

Furthermore, both the distribution and time-evolution plotting algorithms incorporate a conditional routine to differentiate representations made before and after detailed analysis. Prior to analysis, the bar width for distribution plots is set automatically, and batch labels are displayed above each data point in the time-evolution plots. Following analysis, these labels are omitted, and the bar width for distribution plots is fixed according to the specific parameter and irradiation type. In this latter case, the plots also include a Gaussian curve fitting the distribution. The bar width, plot legend, and axis titles are defined within a subset of functions located in the same script, with each function tailored specifically for the corresponding test.

Three additional subsets of functions are defined within the plotting script to obtain parameter thresholds, automatically generate plot titles, and modify the x-axis variables in the case of time-evolution plots. The data points on the x-axis can be ordered according to component reception date, production delivery date, ingot number, or the furnaces employed during fabrication.

Moreover, several minor customizations can be applied to the basic plots, such as displaying data points in different colors. This allows for distinctions to be made based on test sites or fabrication equipment, for example. In some analyses, a spline function was also used to illustrate the overall trend of the data points.

Another significant module imported into `QA_reporting.py` is the one used to search for correlations between parameters. This module enables any parameter to be directly plotted against any other parameter extracted under the same irradiation conditions. If the irradiation types differ, two separate runs of the main script are required, as only one irradiation type can be specified at the beginning of each run. During the first run, the values of the first parameter are extracted to an Excel sheet. In the second run, the data for the second parameter are appended to the same Excel sheet, and the plot is generated in Python using the data from the Excel file.

Additionally, analogous functions were incorporated into this module to plot correlations between production batches and the ingots from which they were derived. However, in this case, the purpose was solely for internal verification.

3.3.4 Additional Scripts

During the course of this thesis, many other scripts were developed for various purposes, although they were less significant than the main script sets described in the previous sections. Nevertheless, some of these scripts were very useful for QA purposes despite involving a smaller amount of programmed code. They were primarily designed to

register components in the PDB, manage the shipment of components to other institutes, and update the component stages.

The script `registerQA.py` was originally designed to register QA components in the database and was initially created by members of the QA Collaboration. Subsequently, an enhanced version of this script was developed as part of the QA scripts suite. This updated script registers components in the PDB using customized input files containing the required Serial Numbers. A specific format for output files was also established. The algorithm searches for the input Serial Numbers in the database; if a Serial Number already exists, the action is skipped, and a warning message is displayed on the screen. The process then continues. If the component is not previously registered in the PDB, the script accesses the database API and registers the component accordingly. The output file contains two sorted lists: one with registered components and another with those skipped.

Once a component is registered in the PDB, the subsequent steps involve uploading the reception date of the component, advancing the component stage from RECEPTION to the next stage, and shipping the component to the test site responsible for its measurement. The scripts enabling these processes were developed at IMB-CNM, although they are used by other members who handle these tasks. To optimize and automate these procedures for multiple components simultaneously, several scripts were created.

First, `QA_reception_date.py` was developed to upload a batch of components sharing the same reception date. This script reads input files where the reception date is specified on the first line, followed by the Serial Numbers (one per line). Next, `QA_setStage.py` is executed to update the current stage of the components in the database (from RECEPTION to their next natural stage, typically PRE-IRRAD TESTS or POST-IRRAD TESTS). The components are then shipped to the institutes responsible for conducting the measurements and uploading the corresponding data.

Unlike the other scripts, the shipment process is facilitated by `ship.py`, a script accessible to the entire QA community. This script was also adapted to accommodate specific input data formats.

Another type of script was developed to search for tests already uploaded to the database and replace them if necessary. The mechanism is straightforward: if a test is uploaded accidentally and needs to be replaced, the script's algorithm locates the test in the database, deletes it, and uploads the correct replacement. As with many other operations described previously, this process can also be performed directly via the PDB interface, without taking more time than using the script. However, the advantage of the script lies in its automation and its capability to handle large numbers of components or tests simultaneously.

All in all, every script described in this subsection interfaces with the PDB through API commands developed specifically for this purpose. There is a wide range of commands available to GET and POST information regarding components, batches, tests, institutes, shipments, and more. This information can be downloaded, uploaded, appended, deleted, attached, and so forth. In other words, the PDB offers a vast array of possibilities and combinations.

4 Results of the Quality Assurance during Production of the ATLAS ITk Strip Sensors

Pre-irradiated and irradiated QA pieces were measured throughout the full production period at several test sites [77], all of which uploaded the corresponding data and parameters to the ITk Production Database (PDB). The data remain stored in the PDB, and the reporting scripts presented in Chapter 3 were used for data download, analysis, and visualization. While the post-irradiation measurements were performed at collaborating institutes, the full parameter extraction and the complete analytical interpretation of the results were carried out within the framework of this thesis.

Distribution and time-evolution plots for all QA parameters and irradiation types (pre-irradiated, protons, neutrons, gamma rays, and gamma + neutrons) are presented in Section 4.1, with particular emphasis on the most relevant results. Correlations between different parameters are discussed in Section 4.2, and production QA incidences are reported in Section 4.3.

4.1 Parameter Distribution and Time Evolution

All parameter distribution and time-evolution plots were produced at different stages throughout the entire production QA, approximately every six months. For each analysis, raw graphs were initially plotted—without predefined limits and showing each individual data point—to identify bad measurements, and discard outliers that could distort the statistics (mean and standard deviation) of the nominal parameter behavior over production. This iterative procedure enabled continuous monitoring of the parameters.

On the one hand, distribution plots were used to verify that the measured values were centered around the expected values, exhibited no abnormally large spread or secondary peaks, and remained within the minimum and maximum thresholds defined by the specifications (or within soft thresholds, when applicable). The Gaussian fit of each distribution—highlighted with a red dashed line—is also included. Complementarily, time-evolution plots provide a visual representation of each parameter as a function of the production time, with the “Reception Date” at CERN shown on the x-axis. These plots are a good indicator of parameter stability during manufacturing; conversely, deviations

from the initial trend allow for the rapid (or even, preventive) identification of potential defects.

Since distribution and time-evolution plots are complementary and convey similar information from different perspectives, vertical red lines indicating the acceptance thresholds are included in both plot types, together with statistical information such as the number of entries (sample size, N), the mean (μ), and the standard deviation (σ). Each plot is labelled with the parameter name, plot type (distribution or time evolution), test type, irradiation type, and analysis state (all or masked¹² values).

Verifying that a parameter meets the specifications provides confidence in the fabricated devices and, by extension, in the optimal performance of the sensors. The identification of bad measurements, tails, asymmetries, or other unexpected features served as an early warning of potential defects at certain points in the production process. Such findings led to further measurements, additional analysis, and, when necessary, iteration with the manufacturer and further corrective actions.

The results in this section are presented parameter by parameter, including pre-irradiation results and all irradiation types to which the samples were subjected. In general, pre-irradiated devices and those irradiated with gamma rays and neutrons ($\gamma + n$) have the largest available data sets and the most reliable statistics. Furthermore, $\gamma + n$ irradiation is representative of both ionization and displacement damage in the sensor material. For both pre-irradiated and $\gamma + n$ samples, tests were performed across all production batches, although $\gamma + n$ irradiation began once the production process was already underway.

Results from Testchips irradiated with protons at Birmingham (MC40 Cyclotron, 27 MeV) have not been included in this analysis. Inter-strip resistance (R_{int}) values significantly lower than expected were measured at Birmingham during the early months of production, and these results were later confirmed by other groups using alternative setups. This pointed to possible deviations in the irradiation facility's performance; consequently, the MC40 irradiation campaign on Testchips was replaced with combined $\gamma + n$ irradiation.

All plotted values, representative of their respective batches, correspond to tests and QA pieces marked as "PASS" in the ITk Production Database (PDB). In other words, for all QA pieces included here, every test was validated, leading to their acceptance and transition to the PASS stage in the PDB (see Section 3.3), and ultimately contributing to batch approval.

¹² After proper analysis, outliers and incorrectly extracted values are "masked" (omitted) from both the plots and the statistical calculations so as not to affect the mean and standard deviation of the production validated values.

Although reporting tasks were carried out continuously throughout the production process, all plots presented in this section correspond to the most recent analysis. This data set includes approximately 600 pre-irradiation values per parameter and up to 450 post-irradiation values, depending on the irradiation type and the duration of the measurement period. At the time of writing, production has not yet fully concluded but it is very close to completion, with three remaining batches still to be tested and approved by January 2026.

4.1.1 Implant Resistance per Unit Length ($R-I$) and Implant Effective Linewidth ($W_{\text{EFF}}-I$)

The implant resistance per unit length ($R-I$) and the implant effective linewidth ($W_{\text{EFF}}-I$), extracted from the n-implant cross-bridge resistor (CBR), were monitored throughout production to ensure their reproducibility. These parameters, which were measured only for pre-irradiated samples, are shown in Figure 4.1 and Figure 4.2, respectively.

The $R-I$ distribution ($\mu = 20.3 \text{ k}\Omega/\text{cm}$) appears reasonable and lies well below the maximum threshold defined by the specifications ($50 \text{ k}\Omega/\text{cm}$). The $R-I$ trend remained nearly stable over time. Both the distribution and time-evolution plots in Figure 4.1 include the minimum “consistency check” threshold ($18 \text{ k}\Omega/\text{cm}$), which was introduced midway through production for additional control after reviewing accumulated statistics and earlier results.

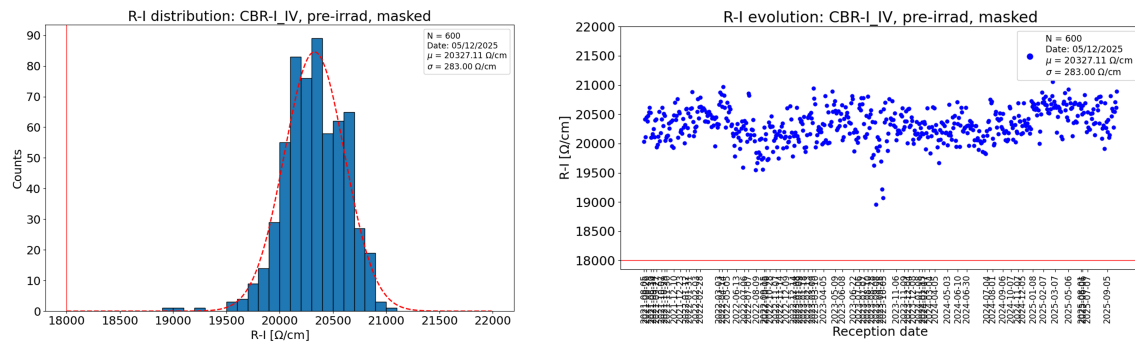


Figure 4.1: Distribution (left) and time-evolution (right) plots of the parameter $R-I$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 20327.11 \Omega/\text{cm}$; standard deviation: $\sigma = 283.00 \Omega/\text{cm}$.

$W_{\text{EFF}}-I$ also exhibits a stable behavior over the production QA period, as illustrated in Figure 4.2 (right), but is shifted approximately $2.5 \mu\text{m}$ with respect to the nominal value of $16 \mu\text{m}$. The distribution is well shaped, with the Gaussian centered at $18.52 \mu\text{m}$ (Figure 4.2 (left)), close to the maximum (soft) threshold of $19 \mu\text{m}$. As a result, some values exceed this upper threshold; however, they were accepted for their proximity to the limit and

the fact that a slightly wider implant was not considered critical for maintaining optimal sensor performance.

The observed shift in $W_{\text{EFF}} - I$ led the QA Collaboration to adjust the minimum threshold midway through production. This threshold was raised from $13 \mu\text{m}$ to $15 \mu\text{m}$, closer to the bulk of the distribution, in order to enable rapid identification of potential outliers. The decision to keep the upper threshold unchanged was intended to maintain tight monitoring of this effect.

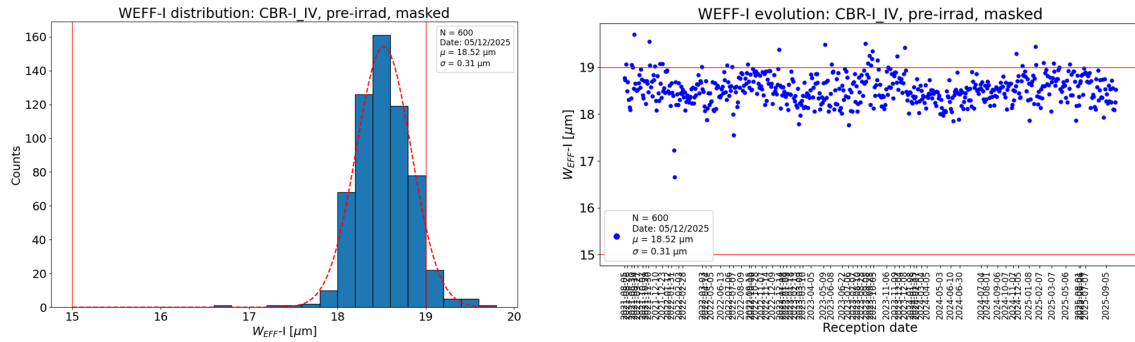


Figure 4.2: Distribution (left) and time-evolution (right) plots of the parameter $W_{\text{EFF}} - I$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 18.52 \mu\text{m}$; standard deviation: $\sigma = 0.31 \mu\text{m}$.

To gain a better understanding of the increased $W_{\text{EFF}} - I$ values, a reverse-engineering study was carried out at IMB-CNM to measure $W_{\text{EFF}} - I$ with higher precision and to investigate whether the observed shift originated from a systematic measurement bias or from a real increase in implant linewidth. The images shown in Figure 4.3 were obtained during this study.

Image (a) was recorded using scanning electron microscopy (SEM) after treating the sample with a hydrofluoric acid (HF) solution. The width of the oxide opening used to define the implantation is $15.33 \mu\text{m}$, but this image does not offer information about the implant profile and the implant lateral diffusion. Image (b), also obtained by SEM, did not yield conclusive results either, as the n-type implant did not develop with sufficient contrast compared to the metal and oxide layers. Finally, a different developing technique was applied, selectively attacking the aluminum and allowing the n-implant profile to be visualized. Two images corresponding to different standard samples are shown in Figure 4.3 (c) and (d). These were recorded using an optical microscope in bright-field mode. The measured $W_{\text{EFF}} - I$ values of $18.7 \mu\text{m}$ and $19.4 \mu\text{m}$ at the widest part of the implant profile, which exhibits a trapezoidal shape, suggest the presence of a genuinely wider n-type implant in the strips, possibly due to lateral dopant diffusion underneath the metal and oxide layers.

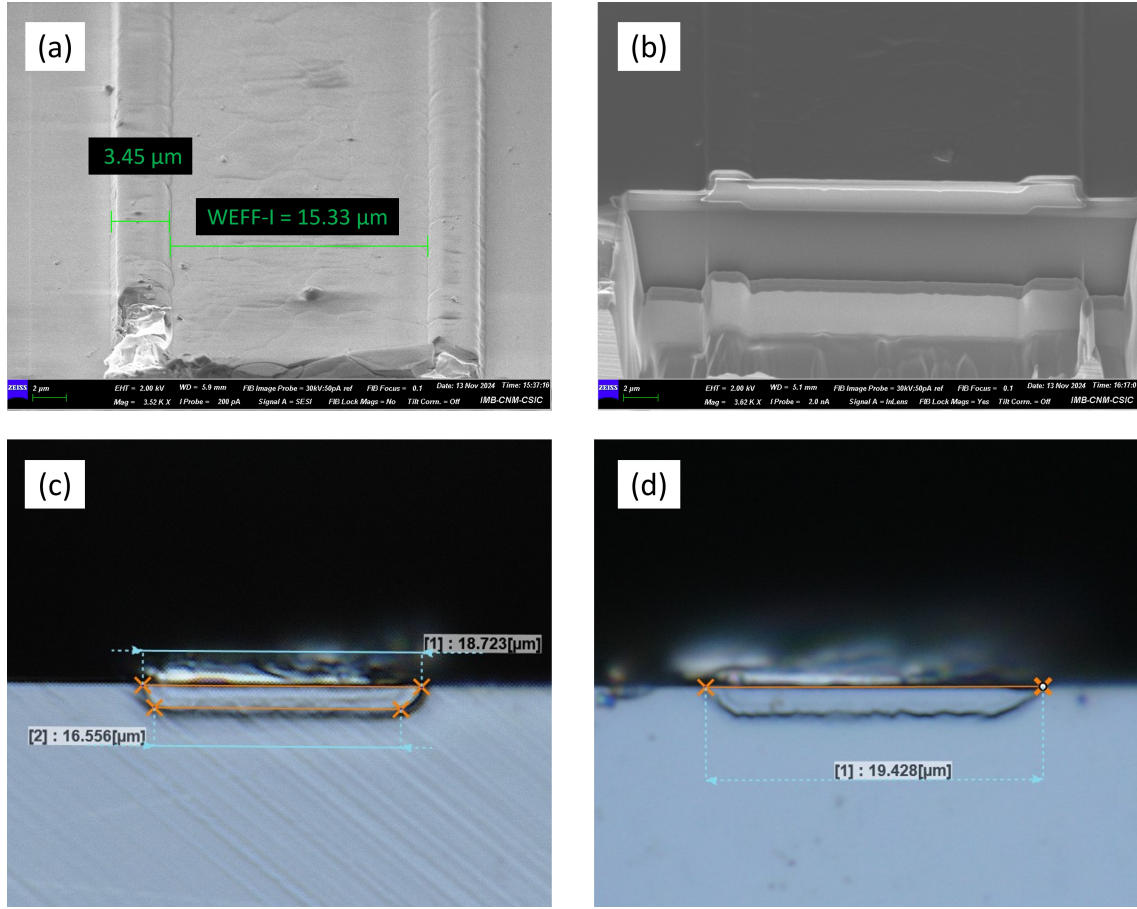


Figure 4.3: Images obtained from the reverse-engineering study applied to standard QA samples from the beginning of production: (a) SEM top-view image of a strip with the n-implant linewidth measurement (batch VPX37409, wafer W415); (b) SEM image of the strip cross-section without clear visualization of the n-type implant (VPX37409-W415); and strip-implant measurements for Testchips (c) VPX37409-W415 and (d) VPX37410-W415 obtained using a different developing technique and visualized with an optical microscope in bright-field mode.

4.1.2 Metal Resistance per Unit Length ($R-M$) and Metal Effective Linewidth ($W_{\text{EFF}-M}$)

The metal resistance per unit length ($R - M$), extracted from the metal cross-bridge resistor (CBR), is shown through distribution and time-evolution plots in Figure 4.4 (left and right, respectively). The parameter exhibits a well-shaped distribution ($\mu = 8.85 \Omega/\text{cm}$) and a stable behavior over time within the defined thresholds. As for the $R - I$ parameter, a new minimum threshold of $6 \Omega/\text{cm}$ was introduced during production to better constrain the measured values within the specified limits.

The metal effective linewidth ($W_{\text{EFF}} - M$), shown in Figure 4.5, exhibits a distribution ($\mu = 20.99 \mu\text{m}$) with relatively large dispersion, with a mean value shifted by approximately $1 \mu\text{m}$ with respect to the nominal value of $22 \mu\text{m}$. Despite this shift, all measured values

remained within the acceptance thresholds and displayed a stable behavior throughout the production period. No additional analysis was required beyond routine monitoring of this parameter.

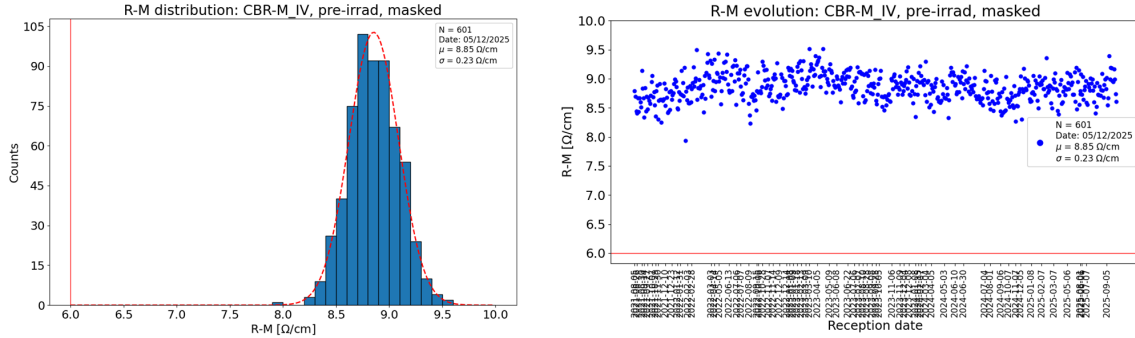


Figure 4.4: Distribution (left) and time-evolution (right) plots of the parameter $R - M$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 8.85 \Omega/\text{cm}$; standard deviation: $\sigma = 0.23 \Omega/\text{cm}$.

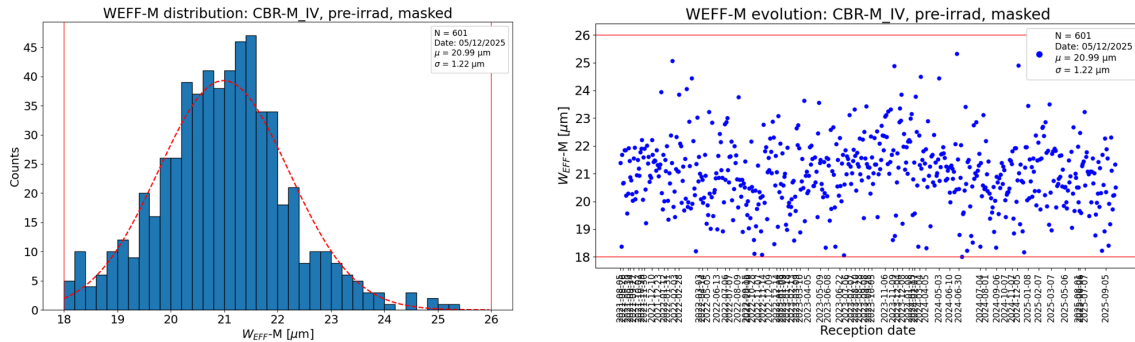


Figure 4.5: Distribution (left) and time-evolution (right) plots of the parameter $W_{\text{EFF}} - M$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 20.99 \mu\text{m}$; standard deviation: $\sigma = 1.22 \mu\text{m}$.

Based on the measured implant and metal linewidths, a sufficient overlap of the metal over the implant appears to be ensured, although it is smaller than expected. The photographs in Figure 4.3 (a) and (b) indicate an overlap of 3.45 μm . Considering the lateral diffusion of the implant underneath the metal layer, a metal-implant overlap of approximately 2 μm should be maintained.

Accurate measurement and monitoring of these dimensions are critical in strip sensors, as variations in implant width and metal overlap could directly affect the inter-strip spacing, and thus the inter-strip capacitance (C_{int}), the inter-strip resistance (R_{int}), surface electric fields, and charge-sharing behavior. These factors, in turn, influence signal noise and breakdown voltage. Insufficient overlap may create high-field regions at strip edges, increasing leakage currents and potentially leading to early breakdown.

4.1.3 Coupling Capacitance (C_{coupl})

The coupling capacitance (C_{coupl}) measured on the Testchip is representative of the coupling capacitance between the strip implant and the readout metal in the Main sensor and is an important parameter for sensor readout.

This parameter remained stable for both pre-irradiated and irradiated Testchips, with mean values of 22.34 pF/cm for pre-irradiated samples and 21.6 pF/cm after $\gamma + n$ irradiation. In all cases, the value distributions are above the minimum threshold of 20 pF/cm. A maximum threshold of 25 pF/cm was introduced later in production to further constrain the acceptable range.

A small decrease in the mean C_{coupl} value is observed after irradiation. This trend appears consistently across all irradiation types ($\gamma + n$, protons, neutrons, and gamma rays), although in most cases the pre-irradiation values remain within the measurement uncertainty of the irradiated results.

After gamma-ray irradiation, C_{coupl} values are slightly lower than those measured after the other irradiation types. This behavior may be related to ionization damage in the oxide, which can introduce traps and reduce the effective dielectric capacitance.

Distribution and time-evolution plots for pre-irradiated samples and $\gamma + n$ -irradiated samples are shown in Figures 4.6 and 4.7, respectively. A low-value shoulder is visible in all distributions, independent of the test equipment used. This suggests that the effect may be related to normal fabrication fluctuations. Nevertheless, the technological process remained overall stable and reproducible, and C_{coupl} demonstrates robustness under radiation conditions.

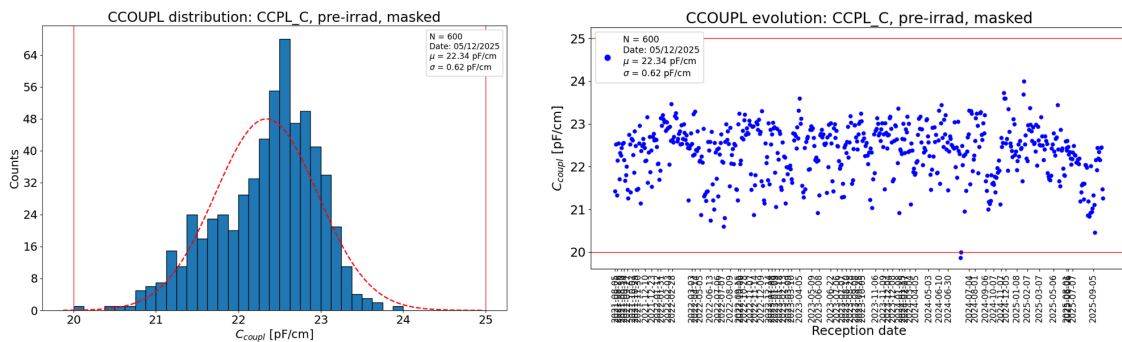


Figure 4.6: Distribution (left) and time-evolution (right) plots of the parameter C_{coupl} for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 22.34$ pF/cm; standard deviation: $\sigma = 0.62$ pF/cm.

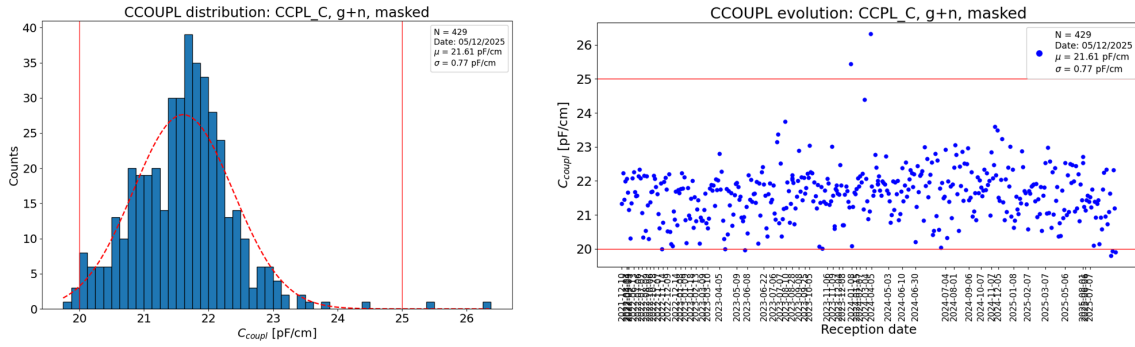


Figure 4.7: Distribution (left) and time-evolution (right) plots of the parameter C_{coupl} for samples irradiated with gamma + neutrons. Sample size: $N = 429$; mean: $\mu = 21.61$ pF/cm; standard deviation: $\sigma = 0.77$ pF/cm.

4.1.4 Coupling Oxide Current at 100 V ($I_{\text{CCPL_100V}}$)

The coupling oxide current at 100 V ($I_{\text{CCPL_100V}}$) is the current measured through the coupling capacitor at an applied voltage of 100 V. Its primary purpose is to verify that no dielectric breakdown occurs in the capacitor up to a potential difference of 100 V.

Figure 4.8 shows the distribution (left) and time evolution (right) of $I_{\text{CCPL_100V}}$ for pre-irradiated samples. All measured values were well below the specification limit of 10 nA and remained stable throughout production, with a mean value of 2.26×10^{-13} A.

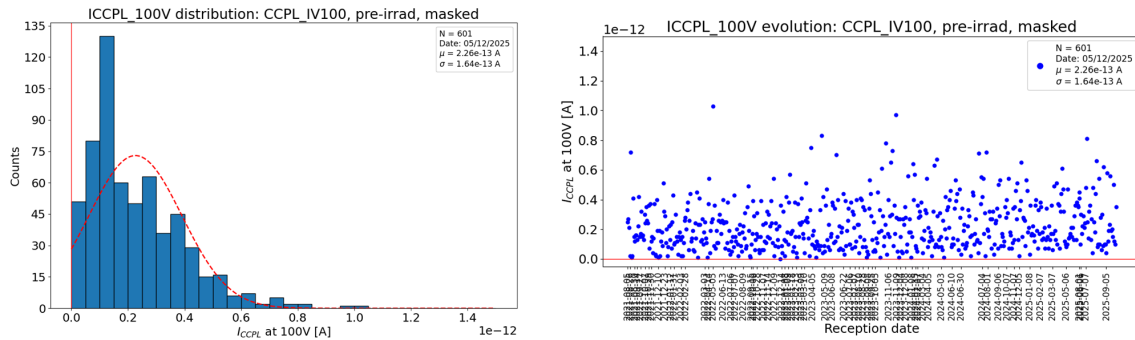


Figure 4.8: Distribution (left) and time-evolution (right) plots of the parameter $I_{\text{CCPL_100V}}$ for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 2.26 \times 10^{-13}$ A; standard deviation: $\sigma = 1.64 \times 10^{-13}$ A.

Figure 4.9 presents the corresponding measurements for samples irradiated with $\gamma + n$. In this case, the measured currents ($\mu = 2.88 \times 10^{-9}$ A) are approximately four orders of magnitude higher than those observed in pre-irradiated samples. Three distinct distributions are visible in the $\gamma + n$ plots, corresponding to measurements performed at different test sites and shown in different colors. For each individual test site, the parameter remained stable over time. The differences observed between sites are mainly attributed to small variations in the measurement temperature and to differences in

the measurement setups. Since the measured currents are on the order of picoamperes (pA), they can be significantly influenced by minor leakage currents in the cables or connectors, as well as by the accuracy of the measuring instrumentation. In addition, although the target temperature for I_{CCPL_100V} measurements is $-20\text{ }^{\circ}\text{C}$, this value is not achieved with the same precision across all setups. Nevertheless, the overall behavior of the parameter is understood, and the observed differences are not considered critical.

In general, all irradiated Testchip Coupling Capacitors exhibit higher current values due to defects introduced in the coupling oxide. In particular, gamma-ray and $\gamma + n$ irradiation result in larger I_{CCPL_100V} values, consistent with increased surface damage associated with ionizing radiation which creates traps in the oxide interface and bulk that facilitates the conduction by charge “trap-hopping” through the oxide [107].

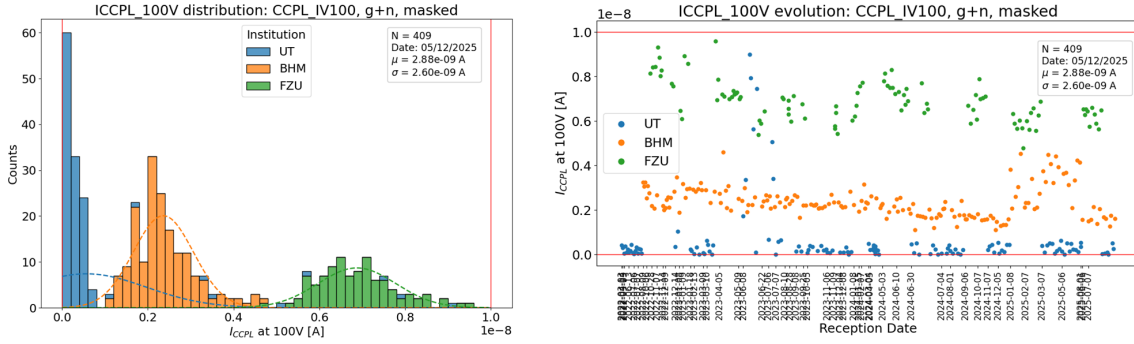


Figure 4.9: Distribution (left) and time-evolution (right) plots of the parameter I_{CCPL_100V} for samples irradiated with gamma + neutrons. Measurements from each test site are shown in different colors. Sample size: $N = 409$; mean: $\mu = 2.88 \times 10^{-9}\text{ A}$; standard deviation: $\sigma = 2.60 \times 10^{-9}\text{ A}$.

4.1.5 Oxide Capacitance (C_{ox}) and Oxide Thickness (t_{ox})

The oxide capacitance (C_{ox}) of the Field Oxide MOS Capacitor was extracted from the C–V curve, as shown in Figure 3.14 in Section 3.2. For each measured capacitance, the MOS oxide thickness (t_{ox}), which corresponds to the inter-strip oxide thickness, was calculated using Eq. (3.8). These two parameters are inversely proportional, which makes their respective distribution and time-evolution plots symmetric. Only pre-irradiated measurements yielded meaningful results, due to the large bulk damage induced by neutron or proton irradiation.

The oxide capacitance (C_{ox}) values ($\mu = 28.47\text{ pF}$) measured across all production QA are shown in Figure 4.10. This parameter remained stable throughout production, although slightly higher values were observed during the first months, contributing to a small tail on the right side of the distribution. Additionally, the points are not uniformly distributed

across the range; minor jumps at the upper and lower ends separate the central distribution from the more distant values. This effect is associated with a calibration characteristic of the LCR meter, likely related to its software, and is asymmetric relative to the mean capacitance.

As expected, the t_{ox} plots in Figure 4.11 are symmetric to those of C_{ox} but with inverted features. A shoulder is visible on the left side of the distribution ($\mu = 0.68 \mu\text{m}$), reflecting lower t_{ox} values during the first production months, as also seen in the time-evolution plot.

The soft thresholds defined for both parameters remained unchanged throughout production, as the parameters consistently stayed within the acceptable range.

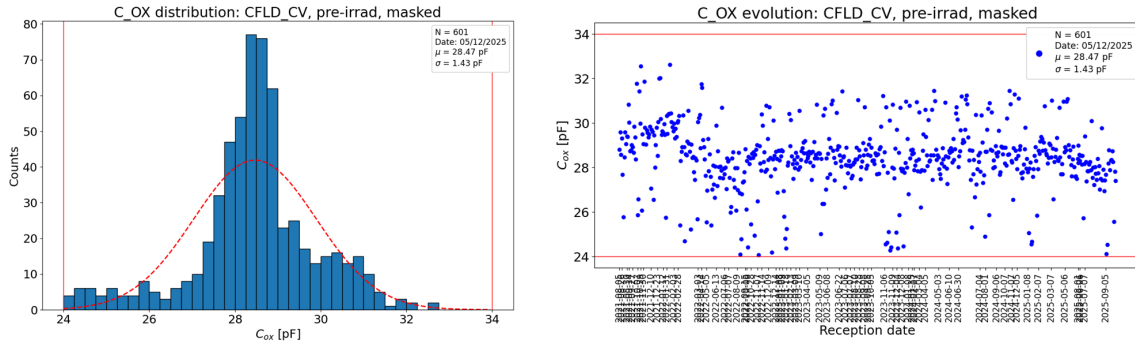


Figure 4.10: Distribution (left) and time-evolution (right) plots of the parameter C_{ox} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 28.47$ pF; standard deviation: $\sigma = 1.43$ pF.

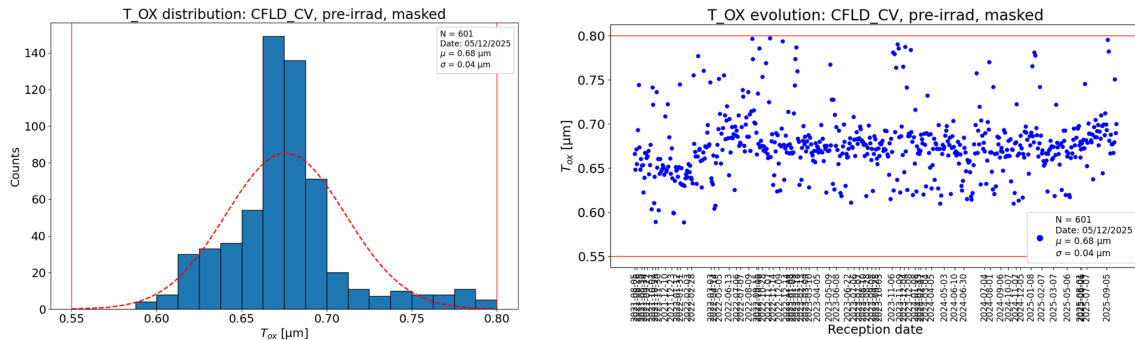


Figure 4.11: Distribution (left) and time-evolution (right) plots of the parameter t_{ox} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 0.68 \mu\text{m}$; standard deviation: $\sigma = 0.04 \mu\text{m}$.

4.1.6 Flat-Band Voltage (V_{FB})

The flat-band voltage (V_{FB}) is also extracted from the Field Oxide MOS Capacitor by interpolating the flat-band capacitance in the C-V curve (see Eq. (3.10)). It provides an

indicator of charges in the SiO₂ or at the Si–SiO₂ interface. Figure 4.12 (left) shows the time evolution of V_{FB} for pre-irradiated samples.

Overall, V_{FB} remained steady during production, with a mean value of -3.10 ± 0.61 V. However, a decrease was observed after approximately one year of production, and a second, larger drop occurred near the end of the production period. This is visible in the distribution plot (Figure 4.12, left) as a tail at lower values. A similar effect was observed in V_T measured from MOS Capacitors with p-stop implantation (next section), which may indicate trapped charges in the oxide, suggesting possible lower-quality oxide. These observations were reported to the manufacturer (HPK), understood, and corrected¹³. The final V_{FB} measurements returned to the expected range.

A few V_{FB} values fell below the minimum threshold during the second drop. These were monitored closely, but no batches were rejected. The out-of-threshold values were few, close to the (soft-)limit, and the issue was already understood and addressed.

Although slight reductions in V_{FB} do not represent a critical issue for the sensors, trapped charges in the oxide can produce effects similar to those caused by radiation. Irradiated samples exhibit shifts to higher (more negative) V_{FB} , particularly under highly ionizing irradiation. For example, gamma-irradiated (66 Mrad) Testchips measured during QA showed $V_{FB} = -36.51 \pm 4.84$ V, significantly lower than non-irradiated samples. For samples irradiated with protons or neutrons at the target fluences, V_{FB} could not be reliably measured due to severe substrate damage.

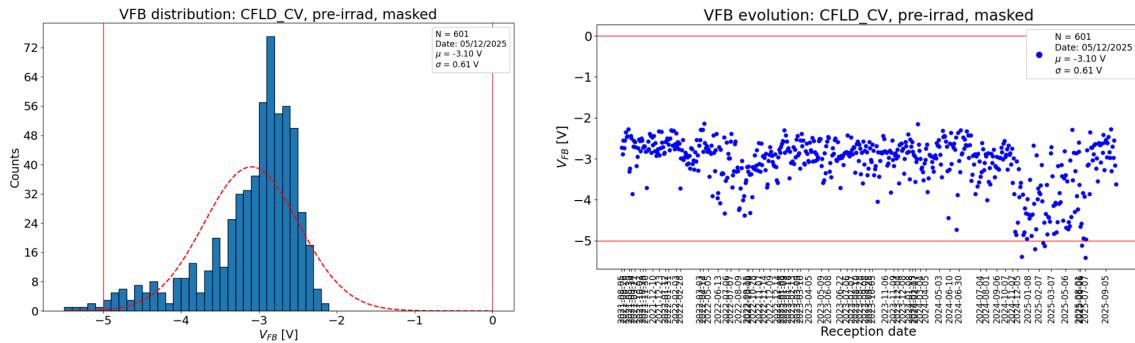


Figure 4.12: Distribution (left) and time-evolution (right) plots of the parameter V_{FB} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = -3.10$ V; standard deviation: $\sigma = 0.61$ V.

¹³ HPK found that the V_{FB} drop was related to the use of a different annealing furnace during a certain period of production.

4.1.7 P-Stop Oxide Capacitance ($C_{\text{ox-P}}$) and P-Stop Oxide Thickness ($t_{\text{ox-P}}$)

The p-stop oxide capacitance ($C_{\text{ox-P}}$) and thickness ($t_{\text{ox-P}}$) extracted from the MOS Capacitor with p-stop are analogous to the parameters described in Section 4.1.5, but with the additional effect of the p-stop layer implanted in the silicon beneath the oxide. $C_{\text{ox-P}}$ has a mean value of 36.71 ± 1.39 pF, higher than in the MOS without p-stop, which corresponds to a lower oxide thickness: $t_{\text{ox-P}} = 0.52 \pm 0.02$ μm . This lower oxide thickness above the p-stop compared to the inter-strip region (field oxide) is related to the fabrication steps used in the foundry to produce the microstrip sensors.

Data from this test began to be collected after the start of the production process, resulting in slightly lower statistics ($N = 530$). The later implementation of the CFLD-P_CV test provided an additional check to identify low p-stop implantations in a few batches; this issue is discussed further in Section 4.2.

$C_{\text{ox-P}}$ (Figure 4.13) remained stable throughout production, although the distribution exhibits a small elbow on the left side of the histogram, corresponding to the lower range of the parameter values. This feature is likely related to the LCR meter calibration, as noted in Section 4.1.5. $t_{\text{ox-P}}$ plots (Figure 4.14) are symmetric to the $C_{\text{ox-P}}$ plots, as $t_{\text{ox-P}}$ is calculated directly from $C_{\text{ox-P}}$ using Eq. (3.11). While the distributions show relatively high dispersion, all values remain within acceptance limits, except for one slightly below the minimum threshold, which was accepted due to its proximity to the (soft-)limit.

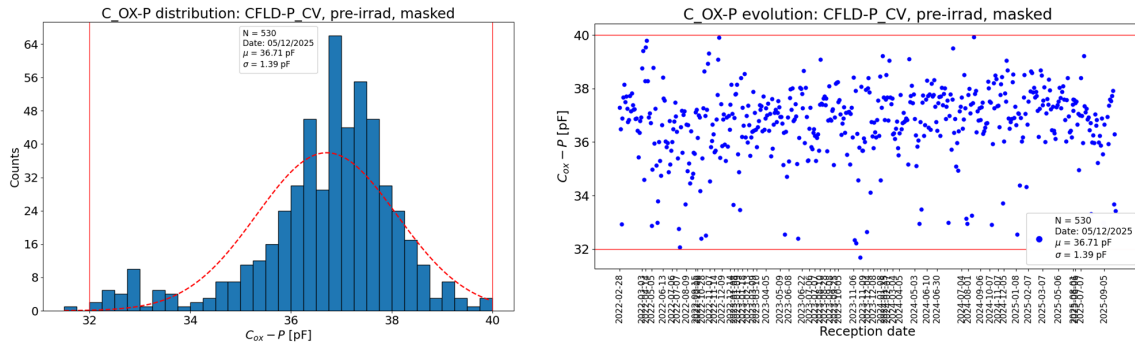


Figure 4.13: Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{ox-P}}$ for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = 36.71$ pF; standard deviation: $\sigma = 1.39$ pF.

4.1.8 Threshold Voltage (V_T)

The threshold voltage (V_T) extracted from the MOS Capacitor with p-stop, with a mean value of $\mu = -4.71$ V, is calculated using a method different from that used for V_{FB} (see Figure 3.15). Its interpretation is similar to V_{FB} , as it provides information about

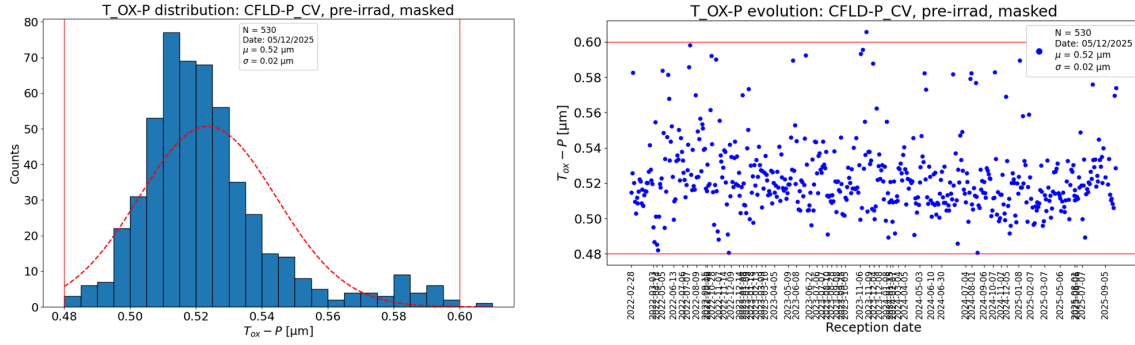


Figure 4.14: Distribution (left) and time-evolution (right) plots of the parameter t_{ox-P} for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = 0.52 \mu m$; standard deviation: $\sigma = 0.02 \mu m$.

charges trapped in the oxide and helps monitor the parameter's stability over time. V_T measurements were not collected at the start of production QA, but once implemented, they were used to confirm the trends observed in V_{FB} . A drop-off visible in the time-evolution plot (Figure 4.15) coincides with the decline observed in V_{FB} during the same period (Figure 4.12).

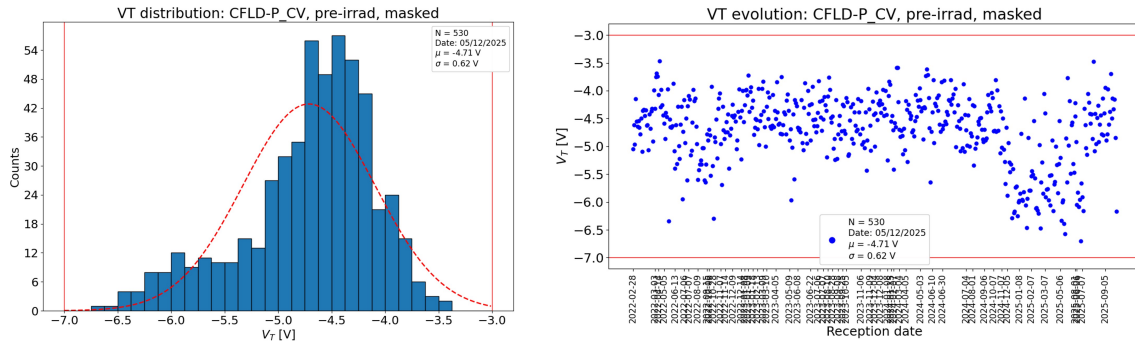


Figure 4.15: Distribution (left) and time-evolution (right) plots of the parameter V_T for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = -4.71 V$; standard deviation: $\sigma = 0.62 V$.

4.1.9 Slope of the MOS Capacitor C-V Curve from Accumulation to Depletion (S_{REF})

In the MOS Capacitor with p-stop, the p-stop implant affects the depletion rate of silicon beneath the oxide, and the slope of the C-V curve from accumulation to depletion serves as an indicator of the p-stop doping level as a function of depth. S_{REF} corresponds to the initial slope at the beginning of depletion. A faster depletion rate—and thus a more negative S_{REF} value—indicates a lower p-stop doping concentration.

S_{REF} was the parameter that motivated the QA Collaboration to include the MOS Capacitor with p-stop (Category B, see Section 2.2) in the regular QA measurement plan. After

observing isolated anomalous punch-through voltage (V_{PT}) values indicating low p-stop implantation, S_{REF} and V_{PT} were monitored carefully, with further studies performed when necessary.

A few batches with p-stop issues were flagged as “failed” in the database, and the corresponding sensors were rejected by the collaboration (as will be explained later). Nevertheless, only components from approved batches, marked as “PASS” in the PDB, are included in the plots shown in Figure 4.16.

The S_{REF} parameter exhibits a well-shaped distribution, with a mean of $\mu = -0.90$ pF/V and most values within the acceptance limits. Therefore, the overall quality of the p-stop implantation—and consequently the effectiveness of the p-stop isolation—is considered satisfactory. Only one value slightly exceeds the minimum soft threshold of -1.50 pF/V, but it was accepted due to its proximity to the threshold and the successful performance of replacement devices from the same batch in additional tests.

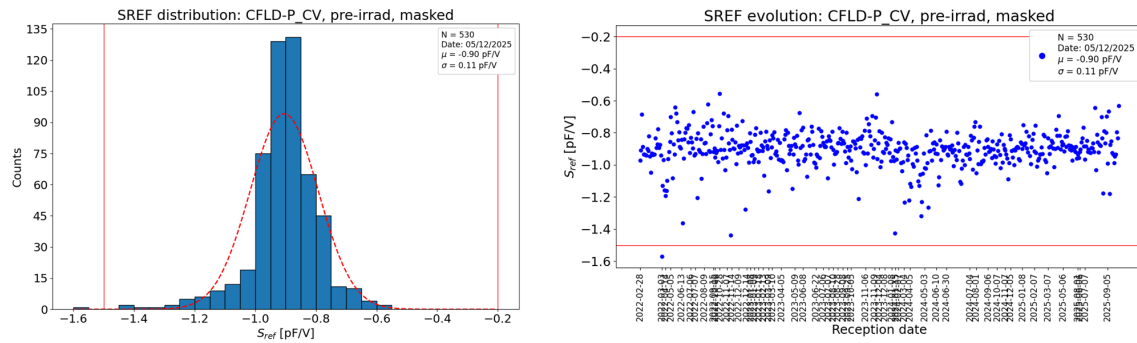


Figure 4.16: Distribution (left) and time-evolution (right) plots of the parameter S_{REF} for pre-irradiated samples. Sample size: $N = 530$; mean: $\mu = -0.90$ pF/V; standard deviation: $\sigma = 0.11$ pF/V.

4.1.10 Inter-Strip Capacitance (C_{int})

The inter-strip capacitance (C_{int}) was extracted from the three Interdigitated structures on the Testchip. Distribution and time-evolution plots were obtained for all structures and irradiation types. After analysis, the pre-irradiated and $\gamma + n$ -irradiated samples were selected as the most representative of the device performance. Furthermore, the lower (SS) interdigitated structure (C_{int_LOW}), which is identical in all Testchips, can be taken as representative of all three structures (LOW, MID, and UP).

Figures 4.17 and 4.18 show the distribution and time evolution of C_{int_LOW} for pre-irradiated and $\gamma + n$ -irradiated samples, respectively. In pre-irradiated samples, C_{int_LOW} remained stable until about halfway through production. After that, dispersion increased slightly, with some values shifted to lower capacitances (forming a small secondary peak).

This shift is likely due to instrument calibration effects similar to those observed for the coupling capacitance. Despite this, all values ($\mu = 0.89$ pF/cm) remain well below the maximum threshold of 1.30 pF/cm. Although the specification threshold is 1 pF/cm, a decision was taken to accept values up to 1.30 pF/cm in view of the limited measurement precision. The limitation is partially related to the fact that the test structure is not specifically designed to measure C_{int} , but rather the inter-strip resistance (R_{int}).

For $\gamma + n$ -irradiated samples, due to the more complex test setup, the capacitance correction applied by the switch array in the measurement system is comparable to the inter-strip capacitance itself, which broadens the distribution (Figure 4.18). Nevertheless, the capacitance ($\mu = 0.97$ pF/cm) remained largely unchanged after irradiation and was stable throughout production. Such stability ensures that electronic noise contributions from capacitive loading and charge sharing between strips stay within design limits, maintaining adequate spatial resolution throughout the operational life of the detector.

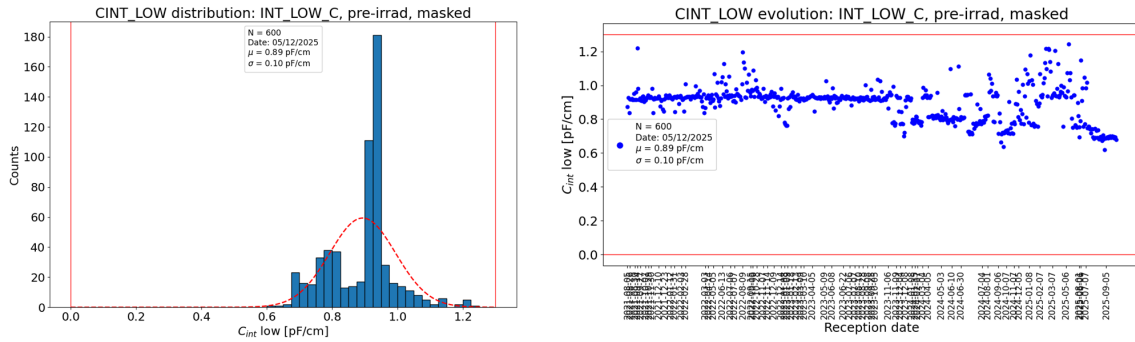


Figure 4.17: Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{int_LOW}}$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 0.89$ pF/cm; standard deviation: $\sigma = 0.10$ pF/cm.

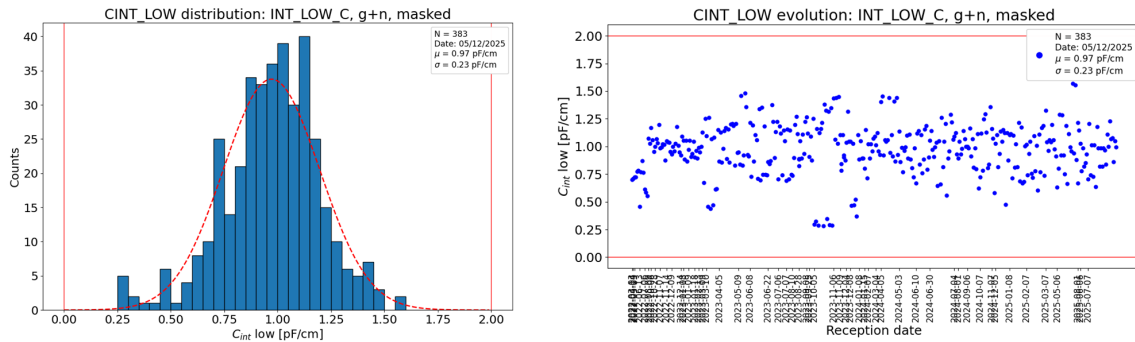


Figure 4.18: Distribution (left) and time-evolution (right) plots of the parameter $C_{\text{int_LOW}}$ for samples irradiated with gamma + neutrons. Sample size: $N = 383$; mean: $\mu = 0.97$ pF/cm; standard deviation: $\sigma = 0.23$ pF/cm.

4.1.11 Inter-Strip Resistance (R_{int})

The inter-strip resistance (R_{int}) was measured for all irradiation types, including non-irradiated Testchips. As with C_{int} , only $R_{\text{int_LOW}}$ is considered in this analysis, as it is representative of the LOW, MID, and UP structures.

Figure 4.19 shows $R_{\text{int_LOW}}$ for pre-irradiated samples. All values are above the minimum threshold of $15 \text{ M}\Omega$, with a mean of $1.67 \times 10^{13} \Omega$. The distribution is broad, but even large variations are not critical, as they remain far above the minimum requirement. A few values exceed the maximum threshold, which is used only as a consistency check.

Ionizing radiation induces positive charges in the oxide, leading to electron accumulation and formation of a conductive channel at the Si-SiO₂ interface that electrically connects adjacent strips and reduces inter-strip resistance. After 66 Mrad gamma-ray irradiation (Figure 4.23), $R_{\text{int_LOW}}$ drops to just above the minimum threshold, with a mean of $20.76 \text{ M}\Omega$. Other irradiation types yield higher but still reduced values: $\gamma + n$, $1170.58 \text{ M}\Omega$ (Figure 4.20); CYRIC protons, $267.34 \text{ M}\Omega$ (Figure 4.21); and neutrons, $3671.45 \text{ M}\Omega$ (Figure 4.22). These results show that ionizing radiation, particularly γ rays and protons, dominates the reduction of inter-strip resistance, while pure neutron irradiation causes less reduction in inter-strip isolation due to minimal oxide charge buildup compared to ionizing radiation; the remaining effect arises from secondary ionization by recoil nuclei and bulk damage in the silicon lattice that alters the depletion region around the p-stop.

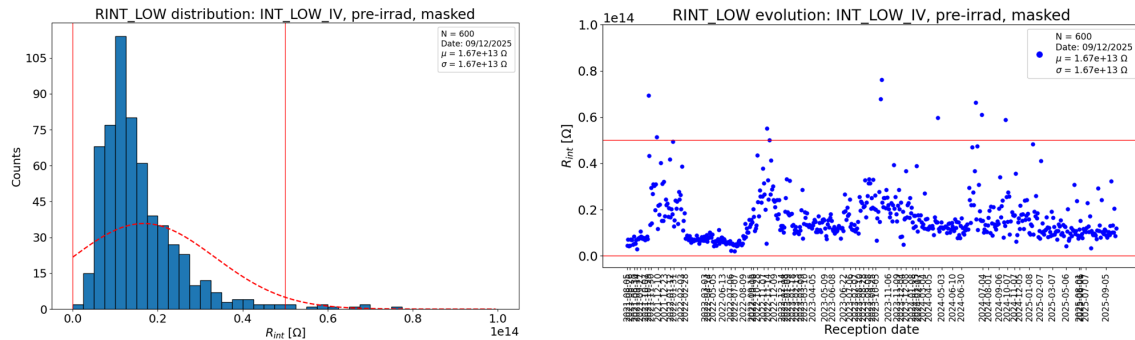


Figure 4.19: Distribution (left) and time-evolution (right) plots of the parameter $R_{\text{int_LOW}}$ for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 1.67 \times 10^{13} \Omega$; standard deviation: $\sigma = 1.67 \times 10^{13} \Omega$.

Overall, R_{int} values remained within acceptance limits and were monitored throughout production QA.

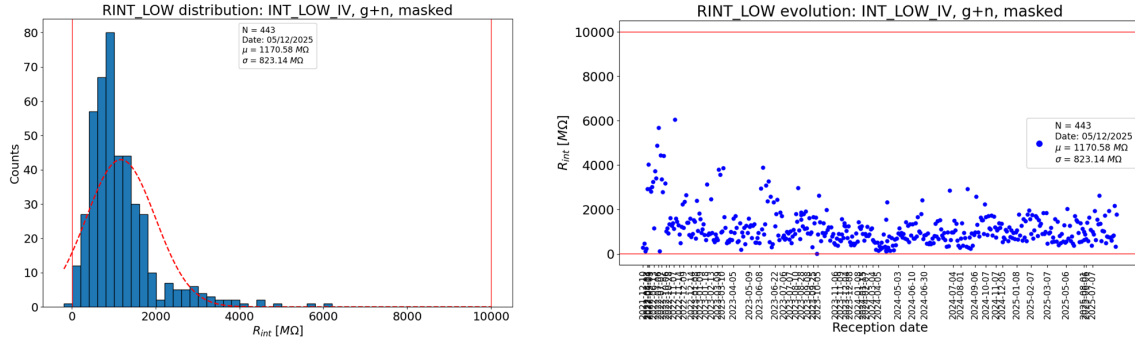


Figure 4.20: Distribution (left) and time-evolution (right) plots of the parameter R_{int_LOW} for samples irradiated with gamma + neutrons. Sample size: $N = 443$; mean: $\mu = 1170.58$ MΩ; standard deviation: $\sigma = 823.14$ MΩ.

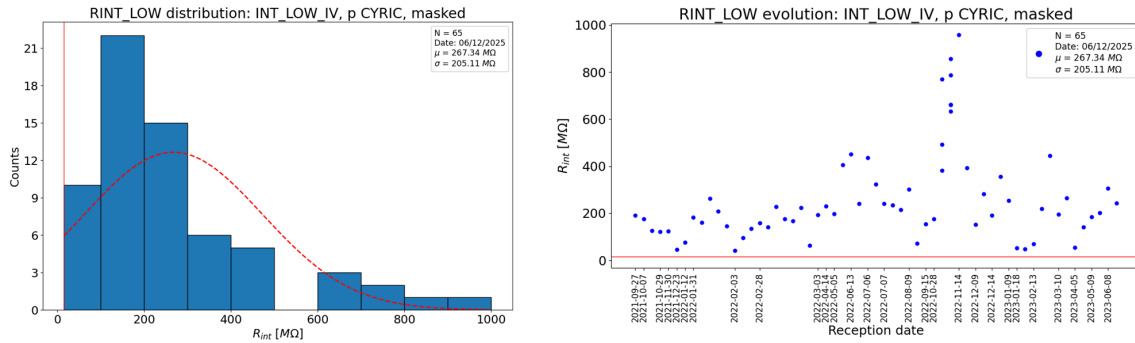


Figure 4.21: Distribution (left) and time-evolution (right) plots of the parameter R_{int_LOW} for CYRIC proton-irradiated samples. Sample size: $N = 65$; mean: $\mu = 267.34$ MΩ; standard deviation: $\sigma = 205.11$ MΩ.

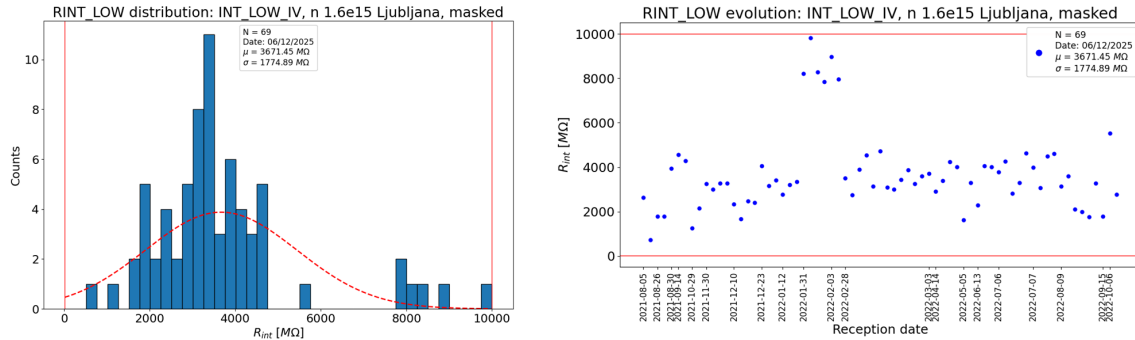


Figure 4.22: Distribution (left) and time-evolution (right) plots of the parameter R_{int_LOW} for neutron-irradiated samples. Sample size: $N = 69$; mean: $\mu = 3671.45$ MΩ; standard deviation: $\sigma = 1774.89$ MΩ.

4.1.12 Punch-Through Voltage (V_{PT})

The punch-through voltage (V_{PT}) is the voltage required to activate the Punch-Through Protection structure (PTP), which grounds the strips if the potential difference between the strips and the bias ring becomes too high due to a beam-loss event. Figures 4.24

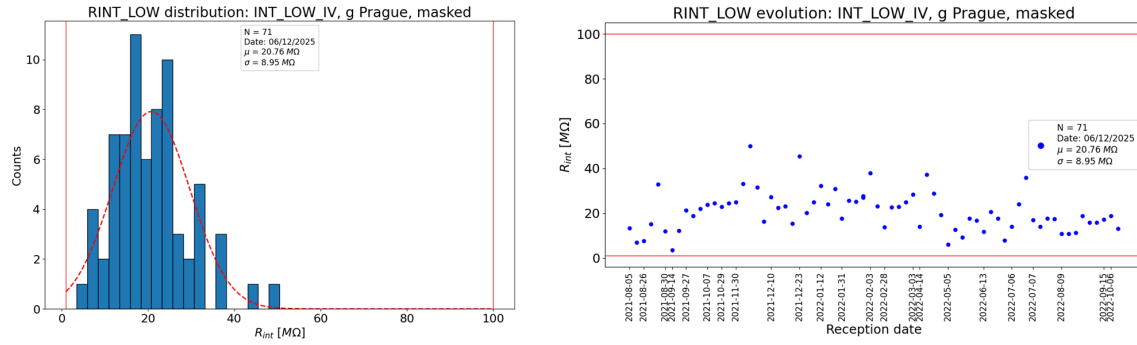


Figure 4.23: Distribution (left) and time-evolution (right) plots of the parameter R_{int_LOW} for gamma-irradiated samples. Sample size: $N = 71$; mean: $\mu = 20.76$ MΩ; standard deviation: $\sigma = 8.95$ MΩ.

and 4.25 show the distribution and time-evolution of V_{PT} for pre-irradiated and $\gamma + n$ -irradiated Testchips, respectively. In both cases, the parameter exhibits stable behavior over time, although the distribution shows slightly increased dispersion.

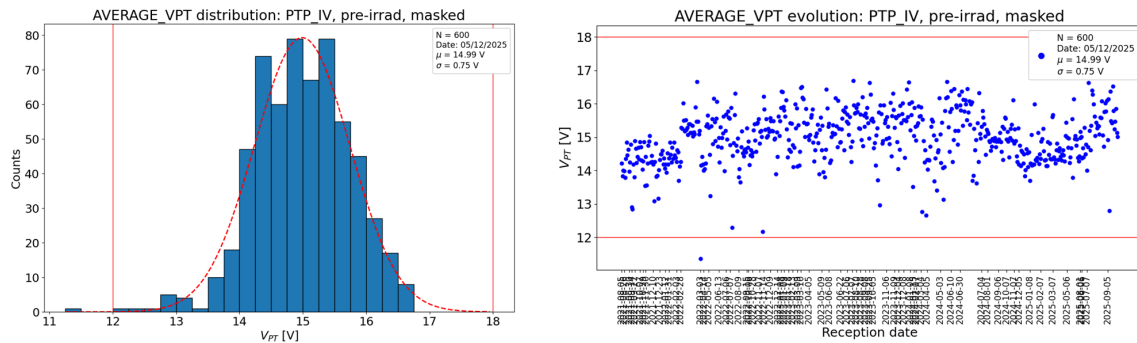


Figure 4.24: Distribution (left) and time-evolution (right) plots of the parameter V_{PT} for pre-irradiated samples. Sample size: $N = 600$; mean: $\mu = 14.99$ V; standard deviation: $\sigma = 0.75$ V.

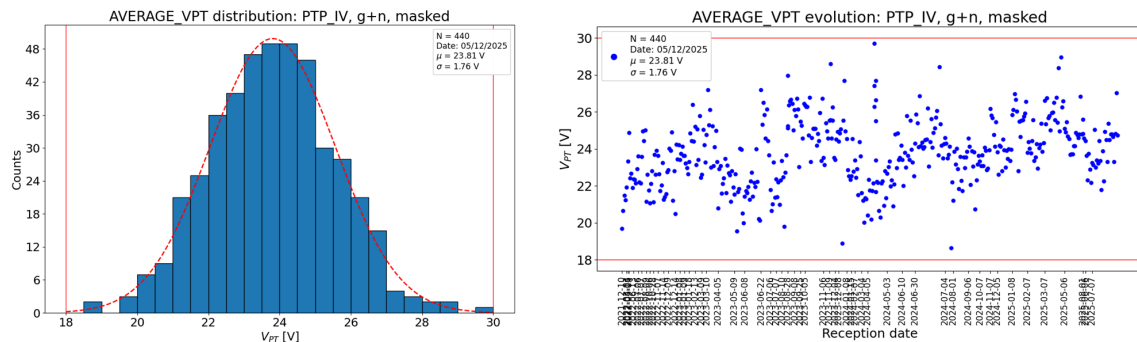


Figure 4.25: Distribution (left) and time-evolution (right) plots of the parameter V_{PT} for samples irradiated with gamma + neutrons. Sample size: $N = 440$; mean: $\mu = 23.81$ V; standard deviation: $\sigma = 1.76$ V.

The box plot in Figure 4.26 presents V_{PT} distributions for all irradiation types studied. After gamma-ray irradiation, V_{PT} ($\mu = 10.42$ V) decreases compared to pre-irradiated samples

($\mu = 14.99$ V), as ionization-induced surface conductive layers facilitate interconnection between strips. Conversely, displacement damage from neutrons or protons increases bulk resistivity and the punch-through voltage. The highest V_{PT} values occur after neutron irradiation ($\mu = 41.03$ V), while protons ($\mu = 36.07$ V) and $\gamma + n$ ($\mu = 23.81$ V) produce intermediate values due to combined ionization and displacement effects. Overall, the increase in punch-through potential observed after proton or $\gamma + n$ irradiation indicates that displacement damage in the bulk dominates over ionization-induced surface currents in determining the performance of this structure.

Although gamma-ray-only irradiation results in slightly lower V_{PT} values—and thus a reduced punch-through barrier—this is not considered critical, as pure gamma-ray exposure is not a realistic scenario in the ATLAS ITk experiment. Therefore, the punch-through protection functionality is expected to be preserved throughout the detector’s operational lifetime.

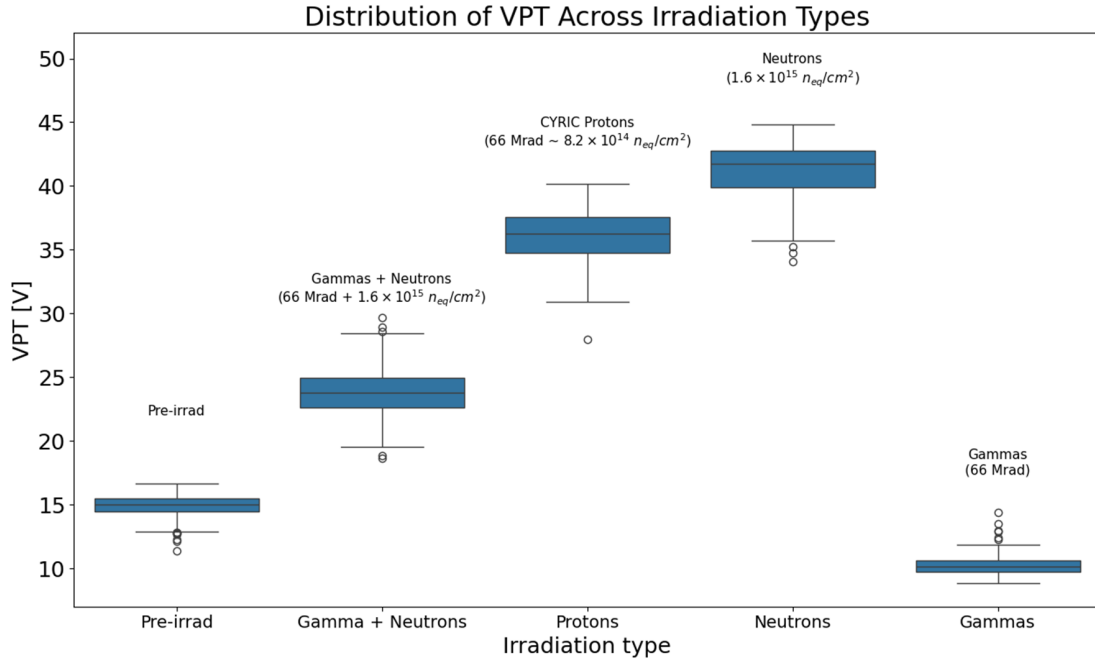


Figure 4.26: Box plot of the V_{PT} distribution for all irradiation types: pre-irradiated, gamma + neutrons, CYRIC protons, neutrons, and gamma rays. Each blue box represents 50% of the data (from Q1 to Q3), and the horizontal line inside the box marks the median. The upper and lower whiskers extend to $1.5 \times \text{IQR}$.

4.1.13 Bias Resistance (R_{bias})

The bias resistance (R_{bias}) monitors the resistance of polysilicon biasing resistors. This parameter remained stable and within acceptance limits for Testchips irradiated with

CYRIC protons, neutrons, and gamma rays, for which data were collected during the early part of production.

However, in pre-irradiated and $\gamma + n$ -irradiated samples, a slight increase in dispersion was observed after a few months, followed by a decrease in R_{bias} in later production stages (Figures 4.27 and 4.28). HPK was informed, and the trend was corrected. R_{bias} remained well within specifications (1–2 M Ω) throughout production.

The temporary decrease in R_{bias} and increased dispersion was associated with the use of different fabrication furnaces. Figure 4.29 differentiates resistors manufactured with Equipment A (red) and Equipment B (blue), applies spline interpolation to separate the two trends, and shows that the effect was primarily linked to Equipment A, but later recovered during production.

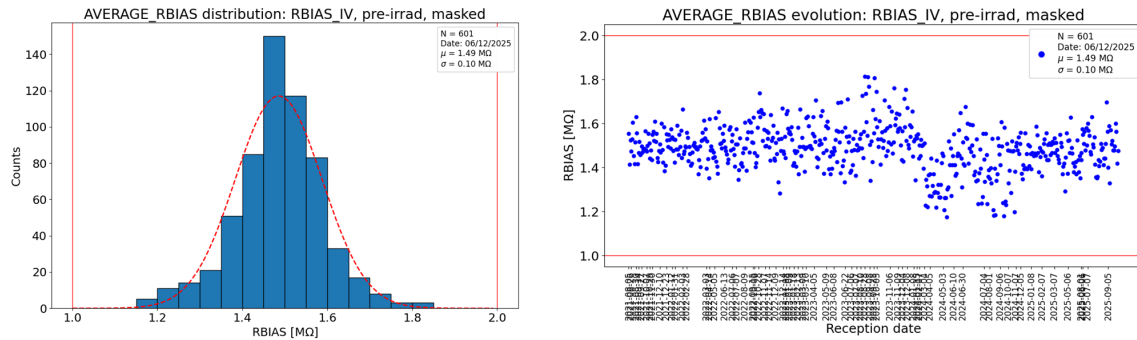


Figure 4.27: Distribution (left) and time-evolution (right) plots of the parameter R_{bias} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 1.49$ M Ω ; standard deviation: $\sigma = 0.10$ M Ω .

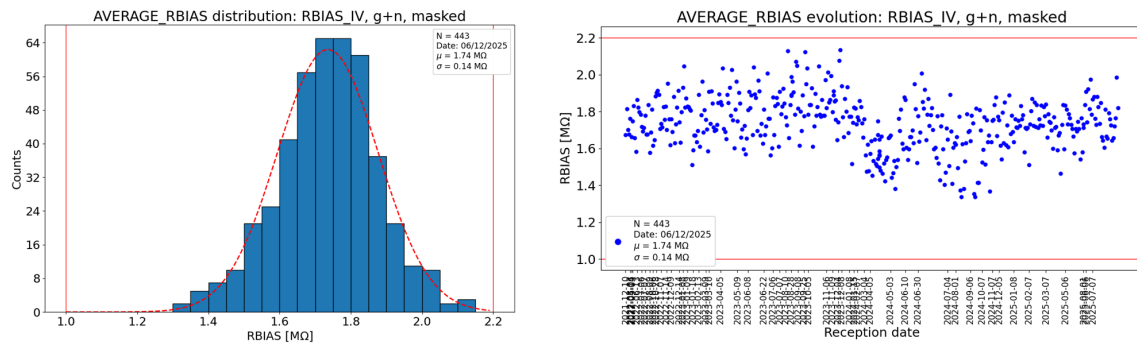


Figure 4.28: Distribution (left) and time-evolution (right) plots of the parameter R_{bias} for samples irradiated with gamma + neutrons. Sample size: $N = 443$; mean: $\mu = 1.74$ M Ω ; standard deviation: $\sigma = 0.14$ M Ω .

After irradiation, R_{bias} increases slightly due to radiation-induced changes in the polysilicon. Figure 4.30 shows R_{bias} distributions for all irradiation types. The largest increase occurs for gamma-ray ($\mu = 1.73$ M Ω) and $\gamma + n$ ($\mu = 1.74$ M Ω) irradiation, while protons ($\mu = 1.62$ M Ω) and neutrons ($\mu = 1.60$ M Ω) exhibit intermediate increases.

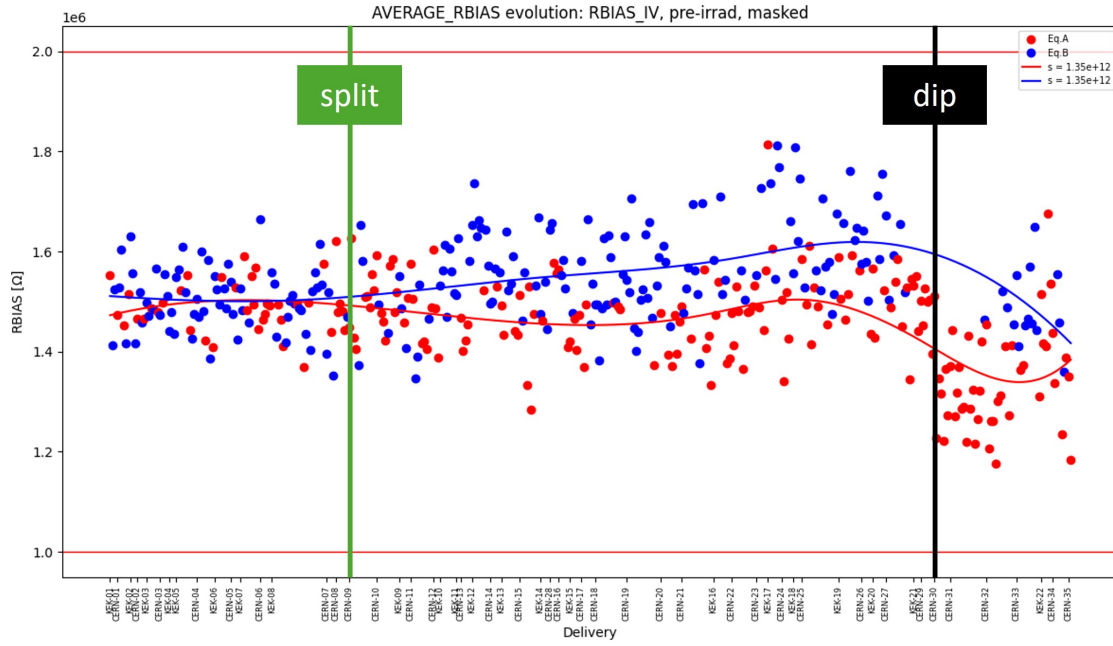


Figure 4.29: Time evolution of the parameter R_{bias} for pre-irradiated samples up to a certain production time, with data points colored by Eq. A (red) and Eq. B (blue), and spline interpolations applied to each data set. The green vertical line indicates the point where the trends begin to diverge.

Neutron and proton irradiation transfers enough energy to silicon lattice atoms to displace them from their original positions, producing acceptor removal and creating vacancies and interstitials in the polysilicon mono-crystalline grains. This damage alters the crystalline structure of the polysilicon grains, affecting the intrinsic resistivity of the polysilicon, but at a lower level than the mono-crystalline silicon, due to the different conduction mechanisms in the polysilicon. Gamma-ray irradiation, on the other hand, primarily affects the material through ionization, modifying the oxide interfaces and creating positive charge trapping in the oxides. This could affect the resistance of the polysilicon resistors through the depletion of the polysilicon areas close to the oxide interface. All these phenomena are subject of further investigation within the research group.

R_{bias} is highly dependent on test temperature. Pre-irradiated samples were tested at a controlled room temperature, while irradiated samples were measured at approximately $-20\text{ }^{\circ}\text{C}$. All values presented include temperature correction factors, ensuring consistent comparison across irradiation types.

The temperature normalization of R_{bias} was derived from an R_{bias} temperature-dependence study [27], in which R_{bias} was measured at multiple temperatures for differently irradiated

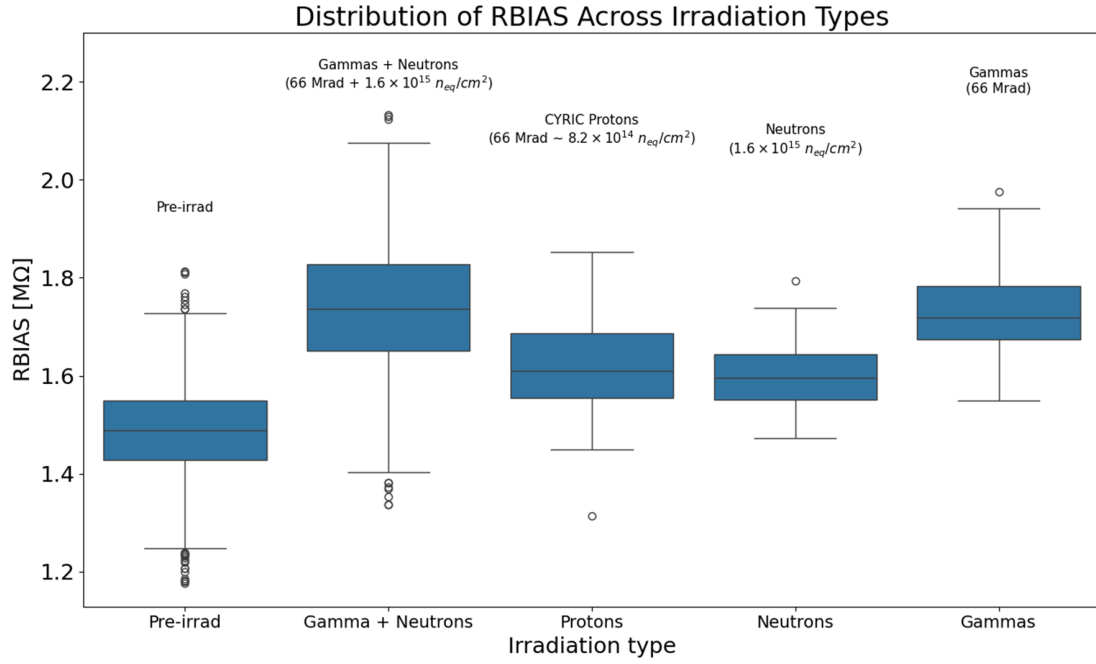


Figure 4.30: Box plot of the R_{bias} distribution for all irradiation types, normalized to +20 °C. Each blue box represents 50% of the data (from Q1 to Q3), and the horizontal line marks the median.

Testchips, covering several fluence levels. This enabled the extraction of the average polysilicon activation energy,

$$E_a = (55.8 \pm 0.1) \times 10^{-3} \text{ eV}.$$

From the measured data, an exponential dependence of R_{bias} on temperature was observed, from which the correction expressed in Eq. (4.1) was derived:

$$R_{\text{bias}} = R_m(T_m) \cdot \exp\left(\frac{E_a}{2k_B} \left(\frac{1}{T} - \frac{1}{T_m}\right)\right) \quad (4.1)$$

where R_m is the measured bias resistance, k_B is the Boltzmann constant, T_m is the test temperature, and T is the temperature to which the measured bias resistance is normalized (+20 °C for all QA measurements).

4.1.14 Full Depletion Voltage (V_{FD})

The full depletion voltage (V_{FD}) is extracted from the C–V curve of MD8 diodes. Reliable results are obtained only for pre-irradiated (Figure 4.31) and neutron-irradiated (Figure 4.32)

samples. Neutron irradiation was performed up to an intermediate fluence of $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$.

The measurement setup is limited to a maximum bias voltage of 1000 V. For higher neutron fluences, the expected V_{FD} would likely exceed the accessible measurement range, preventing a reliable determination.

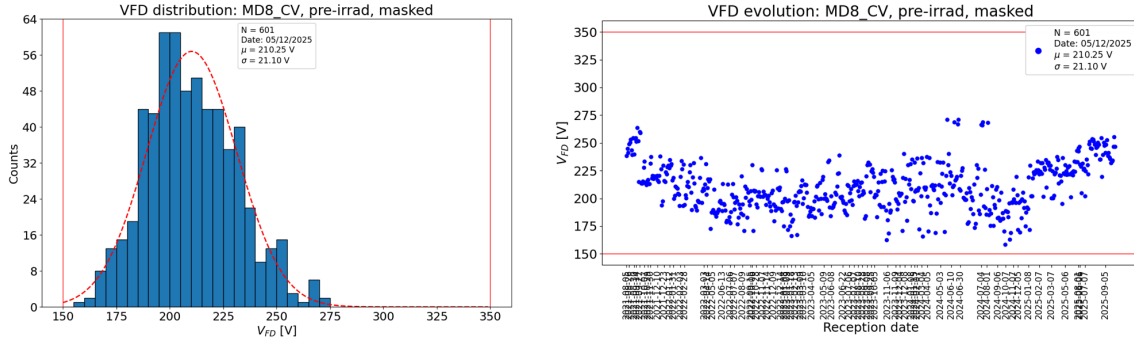


Figure 4.31: Distribution (left) and time-evolution (right) plots of the parameter V_{FD} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 210.25 \text{ V}$; standard deviation: $\sigma = 21.10 \text{ V}$.

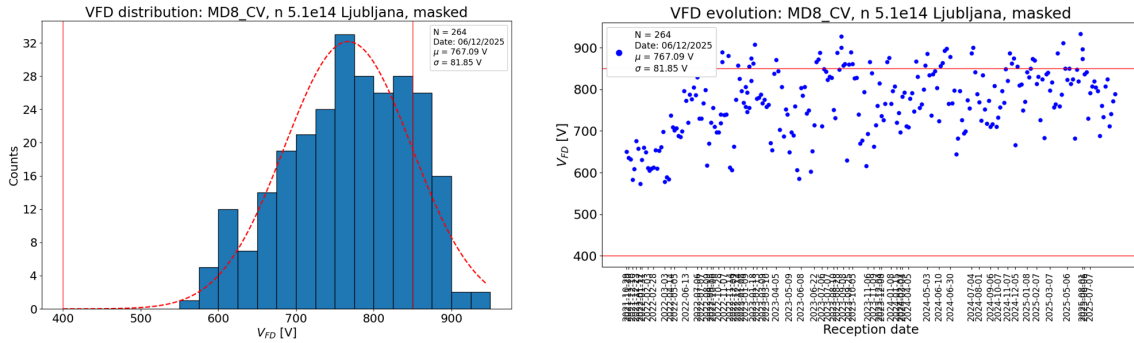


Figure 4.32: Distribution (left) and time-evolution (right) plots of the parameter V_{FD} for neutron-irradiated samples. Sample size: $N = 264$; mean: $\mu = 767.09 \text{ V}$; standard deviation: $\sigma = 81.85 \text{ V}$.

During the first year of production, pre-irradiated and neutron-irradiated samples showed opposite trends: V_{FD} decreased for pre-irradiated samples and increased for irradiated ones, along with an increase in dispersion. For pre-irradiated samples, all measured values ($\mu = 210.25 \text{ V}$) remained within the specification limit ($< 350 \text{ V}$). A minimum threshold of 150 V was implemented as a consistency check after the initial downward trend, but all values still fell within the acceptance range.

Some neutron-irradiated MD8s exhibited V_{FD} values ($\mu = 767.09 \text{ V}$) slightly above the maximum threshold of 850 V . Measurements were taken at -20°C , and potential systematic errors were considered. After investigation, temperature was ruled out as the cause of the high extracted values, which were ultimately attributed to a real device effect rather than to measurement errors. However, the collected charge at 500 V remained above the required threshold, and these batches were therefore accepted.

Further investigations are being carried out by the collaboration to understand whether this effect is related to the presence of impurity atoms in the silicon bulk in some wafers, which could lead to variations in the types or concentrations of defects induced by irradiation, or to other causes.

4.1.15 Leakage Current at 500 V (I_{500V}) and Breakdown Voltage (V_{BD})

The leakage current at 500 V (I_{500V}) for MD8 diodes is normalized per unit area. Pre-irradiated samples (Figure 4.33) exhibit fluctuations due to seasonal temperature variations affecting room-temperature measurements. These fluctuations result in a broad distribution ($\mu = 1.89 \times 10^{-9}$ A/cm²) with a small tail at higher values. This effect is not critical, as the measured currents are two orders of magnitude below the maximum threshold (100 nA/cm²) defined by the specifications.

Neutron irradiation significantly increases I_{500V} (Figure 4.34); however, the measured values ($\mu = 7.26 \times 10^{-6}$ A/cm²) remain within acceptance limits. The distribution shows two distinct peaks, the first of which corresponds to measurements taken at -24 °C early in production, when the initial setup operated at lower temperatures.

Figure 4.35 presents I_{500V} for $\gamma + n$ -irradiated samples, for which the leakage current ($\mu = 2.84 \times 10^{-5}$ A/cm²) slightly increases compared to neutron-irradiated MD8s. In the distribution and time-evolution plots, the values have been separated by colors according to the test site. Orange and green points follow a constant trend throughout production with a very narrow distribution. Conversely, blue points show more fluctuations and correspond to values recorded at the same institute as the neutron-irradiated MD8s illustrated in Figure 4.34. The trend from this institute is very similar to that from pure-neutron irradiation, but with a proportional increase of current due to the combined displacement and ionization damage absorbed by the samples. In any case, the parameter remains stable for each institute, and temperature-attributed fluctuations are understood.

Leakage current measurements confirm that no MD8 exhibits breakdown below 500 V for pre- or post-irradiated conditions (protons, neutrons, $\gamma + n$). Breakdown below 500 V could compromise sensor functionality at the experiment; however, this was observed only after pure gamma-ray irradiation, which does not represent realistic conditions for the ATLAS ITk.

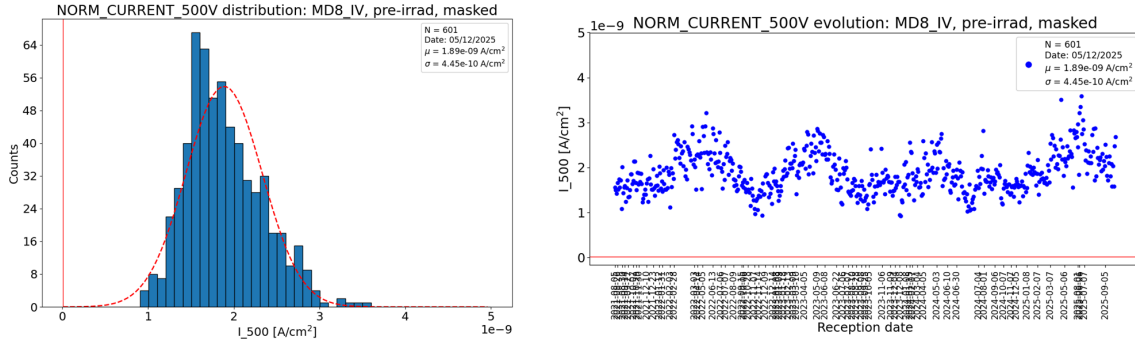


Figure 4.33: Distribution (left) and time-evolution (right) plots of the parameter I_{500V} for pre-irradiated samples. Sample size: $N = 601$; mean: $\mu = 1.89 \times 10^{-9}$ A/cm²; standard deviation: $\sigma = 4.45 \times 10^{-10}$ A/cm².

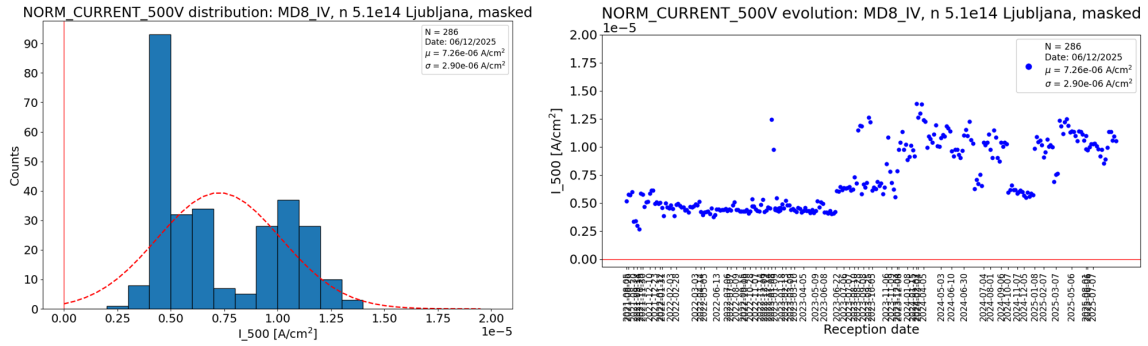


Figure 4.34: Distribution (left) and time-evolution (right) plots of the parameter I_{500V} for neutron-irradiated samples. Sample size: $N = 286$; mean: $\mu = 7.26 \times 10^{-6}$ A/cm²; standard deviation: $\sigma = 2.90 \times 10^{-6}$ A/cm².

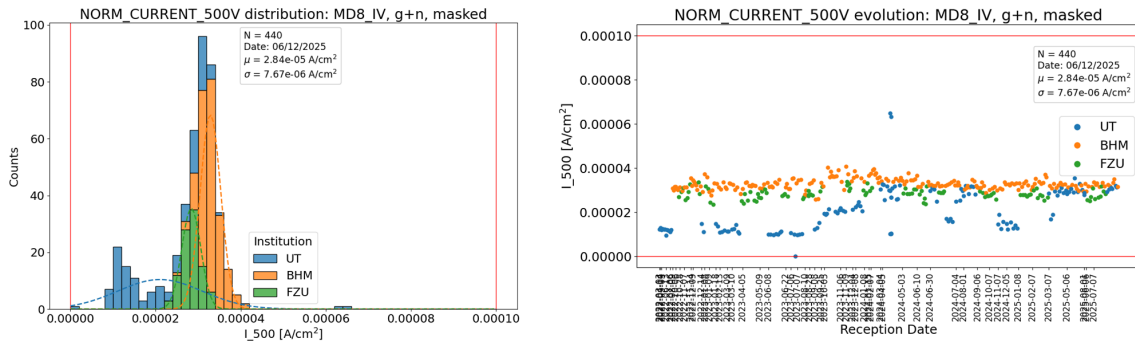


Figure 4.35: Distribution (left) and time-evolution (right) plots of the parameter I_{500V} for samples irradiated with gamma + neutrons. Measurements from each test site are shown in different colors. Sample size: $N = 440$; mean: $\mu = 2.84 \times 10^{-5}$ A/cm²; standard deviation: $\sigma = 7.67 \times 10^{-6}$ A/cm².

4.1.16 Charge Collection Efficiency at 500 V (CCE_{500V})

The charge collection efficiency (CCE) is the only parameter in this chapter not tested at IMB-CNM but is part of the QA program. CCE was measured in Mini sensors at 500 V

(CCE_{500V}) after irradiation with neutrons (Figure 4.36), Birmingham protons (Figure 4.37), and CYRIC protons (Figure 4.38).

Neutron-irradiated Mini sensors show a CCE_{500V} mean value of $\mu = 8120.91 \text{ e}^-$. Distribution and time-evolution plots are color-coded by test site. The results indicate a consistent trend, with all values above the specification (6350 e^-).

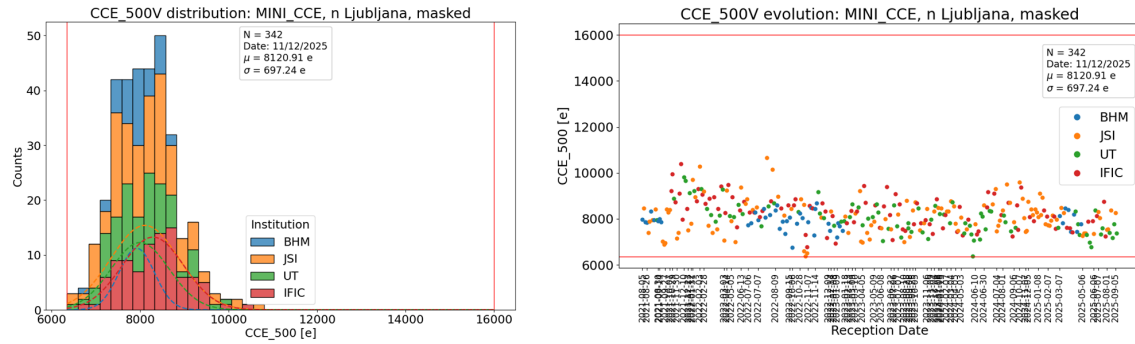


Figure 4.36: Distribution (left) and time-evolution (right) plots of the parameter CCE_{500V} for neutron-irradiated samples. Measurements from each test site are shown in different colors. Sample size: $N = 342$; mean: $\mu = 8120.91 \text{ e}^-$; standard deviation: $\sigma = 697.24 \text{ e}^-$.

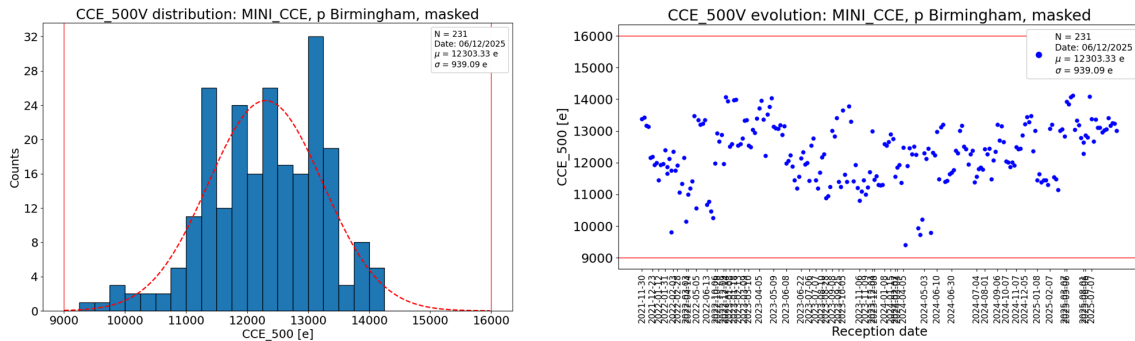


Figure 4.37: Distribution (left) and time-evolution (right) plots of the parameter CCE_{500V} for Birmingham proton-irradiated samples. Sample size: $N = 231$; mean: $\mu = 12303.33 \text{ e}^-$; standard deviation: $\sigma = 939.09 \text{ e}^-$.

Higher CCE_{500V} values were measured after proton irradiation at both Birmingham ($\mu = 12303.33 \text{ e}^-$) and CYRIC ($\mu = 12530.13 \text{ e}^-$), with mean values above 12000 e^- . It is already known that, for fluences below $1.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ (those used in the QA program), proton-irradiated samples exhibit better CCE than neutron-irradiated samples [108]. At higher fluences, the opposite trend occurs. Proton irradiation, however, appears to induce more charge trapping than neutron irradiation. The higher collected charge in proton-irradiated samples at the target (lower) fluences can be attributed to a stronger electric field under the collecting electrodes, as V_{FD} increases more slowly after proton irradiation than after neutron irradiation. At higher fluences, this advantage disappears, and charge trapping becomes the dominant effect.

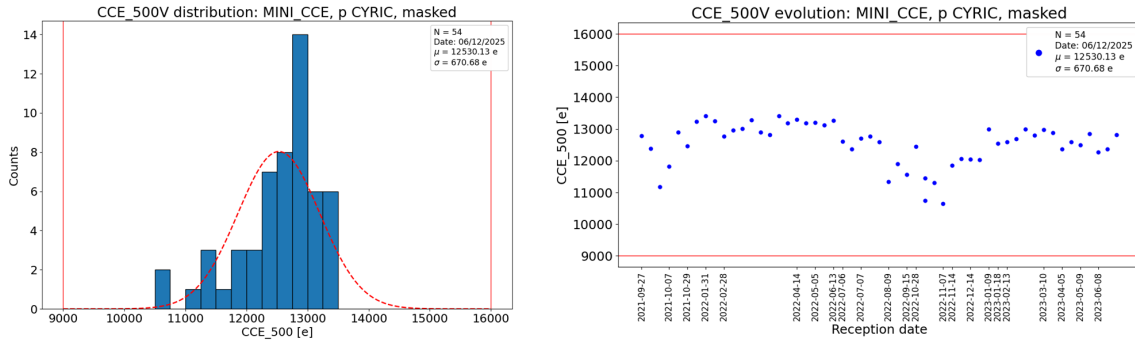


Figure 4.38: Distribution (left) and time-evolution (right) plots of the parameter CCE_{500V} for CYRIC proton-irradiated samples. Sample size: $N = 54$; mean: $\mu = 12530.13 \text{ e}^-$; standard deviation: $\sigma = 670.68 \text{ e}^-$.

The QA Collaboration introduced a stricter lower threshold of 9000 e^- to ensure better control of measurements on proton-irradiated samples. In all cases, this parameter remained stable throughout production.

4.1.17 Summary of QA Trends and Physical/Technological Insights

All relevant production QA results are detailed in Table 4.1. For each device (Testchip, MD8, and Mini sensor), all tests, parameters, irradiation types, and thresholds are summarized. Yellow cells indicate specifications, orange cells represent updated thresholds, and italicized numbers correspond to “consistency check” thresholds, as previously described in Table 3.5. Mean values and standard deviations are presented for each parameter. All mean values fall within thresholds, except for breakdown observed after pure gamma-ray irradiation, which does not reflect realistic ATLAS ITk conditions.

The results discussed in Section 4.1 provide a clear and consistent physical interpretation based on QA parameters analyzed across representative Testchips and MD8s. Overall, the electrical properties of the devices reflect the expected behavior on the bulk features—mainly determined by doping levels and substrate quality—and surface effects, which are influenced by oxide quality, interface traps, and p-stop implantation.

Parameters such as V_{FD} , I_{500V} , and CCE remain stable throughout production, indicating that the high-resistivity substrates are well controlled. Surface-sensitive parameters (e.g., R_{int} , C_{int} , V_{FB} , C_{coupl} , I_{CCPL_100V} , V_{PT} , and S_{REF}) also exhibit a stable behavior, with only minor variations associated with oxide charges, as reflected in the flat-band voltage. Other parameters, such as R_{bias} and the implant and metal W_{EFF} , remain well controlled throughout the full sensor production as well. These observations match what is expected for silicon strip sensors.

Table 4.1: Summary of all QA results and updated thresholds for all relevant irradiation types and parameters, based on all tests performed on Testchips, MD8s, and Mini sensors.

DEVICE	TEST	PARAMETER	IRRADIATION TYPE	New Thresholds		Mean μ	Std. Dev. σ
				Min	Max		
CBR	CBR_I_IV	R-I (Ω/cm)	Pre-irrad	18000.00	50000.00	20327.11	283.00
		WEFF-I (μm)	Pre-irrad	15.00	19.00	18.52	0.31
	CBR_M_IV	R-M (Ω/cm)	Pre-irrad	6	30.00	8.85	0.23
		WEFF-M (μm)	Pre-irrad	18.00	26.00	20.99	1.22
Coupling Capacitor	CCPL_C	CCOUP_L (pF/cm)	Pre-irrad	20.00	25	22.34	0.62
			n Ljubljana 1.6e15	20.00	25	21.88	0.67
			p CYRIC	20.00	25	22.03	0.62
			γ Prague	20.00	25	21.44	0.64
			$\gamma+n$	20.00	25	21.61	0.77
	CCPL_IV	ICCPL_100V (A)	Pre-irrad	0	1.00E-08	2.26E-13	1.64E-13
			n Ljubljana 1.6e15	0	1.00E-08	2.50E-10	3.38E-10
			p CYRIC	0	1.00E-08	3.39E-10	6.95E-10
			γ Prague	0	1.00E-08	6.34E-09	1.92E-09
			$\gamma+n$	0	1.00E-08	2.88E-09	2.60E-09
MOS Capacitor	CFLD_CV	C_OX (pF)	Pre-irrad	24	34	28.47	1.43
		T_OX (μm)		0.55	0.80	0.68	0.04
		VFB (V)		-5	0	-3.10	0.61
		C_OX (pF)	γ Prague	24	34	24.00	1.50
		T_OX (μm)		0.55	0.80	0.79	0.04
		VFB (V)		-50	0	-36.51	4.84
MOS Capacitor with P-stop	CFLD-P_CV	C_OX-P (pF)	Pre-irrad	32.00	40.00	36.71	1.39
		T_OX-P (μm)		0.48	0.60	0.52	0.02
		SREF (pF/V)		-1.50	-0.20	-0.90	0.11
		VT (V)		-7.00	-3.00	-4.71	0.62
Interdigitated Structures	INT_LOW_C	CINT_LOW (pF/cm)	Pre-irrad	0	1.30	0.89	0.1
			n Ljubljana 1.6e15	0	2.00	0.85	0.29
			p CYRIC	0	2.00	-	-
			γ Prague	0	2.00	0.83	0.17
			$\gamma+n$	0	2.00	0.97	0.23
	INT_LOW_IV	RINT_LOW (Ω)	Pre-irrad	1.50E+07	5.00E+13	2.24E+13	1.40E+14
			n Ljubljana 1.6e15	1.50E+07	1.00E+10	3.67E+09	1.67E+09
			p CYRIC	1.50E+07	1.00E+10	2.67E+08	2.05E+08
			γ Prague	1.00E+06	1.00E+08	2.08E+07	8.95E+06
			$\gamma+n$	1.50E+07	1.00E+10	1.17E+09	8.23E+08
PTP Structure	PTP_IV	AVERAGE_VPT (V)	Pre-irrad	12	18	14.99	0.75
			n Ljubljana 1.6e15	25	50	41.03	2.57
			p CYRIC	25	50	36.07	2.17
			γ Prague	5	20	10.42	1.02
			$\gamma+n$	18	30	23.81	1.76
Bias Resistors	RBIAS_IV	AVERAGE_RBIAS (M Ω)	Pre-irrad	1.00	2.00	1.49	0.10
			n Ljubljana 1.6e15	1.00	2.00	1.60	0.07
			p CYRIC	1.00	2.00	1.62	0.09
			γ Prague	1.00	2.20	1.73	0.09
			$\gamma+n$	1.00	2.20	1.74	0.14
MD8	MD8_IV	NORM_CURRENT_500V (A/cm ²)	Pre-irrad	1.00E-11	1.00E-07	1.89E-09	4.45E-10
			n Ljubljana 5.1e14	1.00E-11	2.00E-05	7.26E-06	2.90E-06
			n Ljubljana 1.6e15	1.00E-11	1.00E-04	1.20E-05	4.68E-06
			p CYRIC	1.00E-11	2.00E-05	1.39E-05	8.88E-07
			γ Prague	1.00E-11	1.00E-06	1.21E-08	1.00E-08
			$\gamma+n$	1.00E-11	1.00E-04	2.84E-05	7.67E-06
		VBD (V)	Pre-irrad	500	1000	660.00	14.14
			n Ljubljana 5.1e14	500	1000	1000.00	0.00
			n Ljubljana 1.6e15	500	1000	1000.00	0.00
			p CYRIC	500	1000	1000.00	0.00
			γ Prague	500	1000	491.79	65.53
			$\gamma+n$	500	1000	1000.00	0.00
	MD8_CV	VFD (V)	Pre-irrad	150	350	210.25	21.10
			n Ljubljana 5.1e14	400	850	767.09	81.85
			p CYRIC	150	450	290.70	74.44
			γ Prague	150	350	170.77	26.12
Mini	MINI_CCE	CCE_500V (e)	n Ljubljana 1.6e15	6350	16000	8124.10	697.89
			p Bham	9000	16000	12303.33	939.09
			p CYRIC	9000	16000	12530.13	670.68

In general, production data exhibit narrow distributions and high reproducibility for the main monitored parameters, confirming that both the fabrication process and the QA methods are robust. Overall, the sensors demonstrate optimal performance, with proper depletion behavior, stable leakage currents, and adequate inter-strip isolation suitable for the radiation environment of the ITk. These results provide a solid physical and technological basis for interpreting the irradiation studies in Chapter 5.

4.2 Parameter Correlations

To complement and gain a deeper understanding of the production QA results presented in the previous section, correlation plots are shown to identify potential similarities or dependencies between parameters, arising from their physical characteristics or from bulk and surface effects induced by radiation. The parameter-to-parameter correlations examined throughout production QA are presented in this section.

For a clearer interpretation of the scatter plots, the Pearson correlation coefficient has been extracted in each case as a useful indicator of linearity, and thus of correlation strength. This coefficient ranges from -1 to $+1$, with $+1$ indicating a perfect positive linear relationship (both parameters increase together), -1 a perfect negative linear relationship (one parameter increases while the other decreases), and 0 indicating the absence of linear correlation.

Figure 4.39 shows scatter plots of parameters exhibiting different degrees of correlation, with the data points distributed differently in each case. In addition, plot (E) in Figure 4.39 compares the Pearson coefficient as a function of the selected data range (0.6 vs. 0.34), highlighting the importance of range selection for correct interpretation according to the criteria listed in Table 4.2. Visual and numerical analyses are considered in this section to evaluate the correlations between strip sensor parameters.

Table 4.2: Interpretation of the Pearson correlation coefficient according to its absolute magnitude. Adapted from [109].

Absolute value of the Pearson Correlation Coefficient	Interpretation
0.00 – 0.09	Negligible correlation
0.10 – 0.39	Weak correlation
0.40 – 0.69	Moderate correlation
0.70 – 0.89	Strong correlation
0.90 – 1.00	Very strong correlation

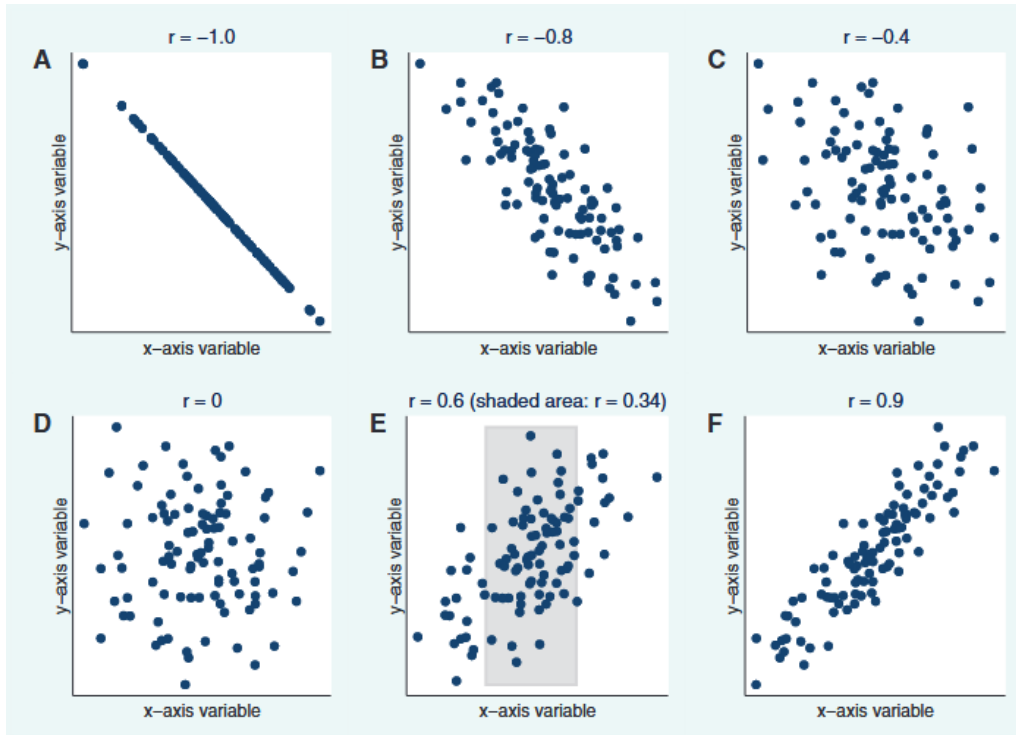


Figure 4.39: Six scatter plots with different correlation levels, exemplifying the full correlation range depending on the scattering behavior. Plot (E) illustrates the importance of the chosen range for correlation analysis [109].

4.2.1 V_T vs. V_{FB} (Pre-Irradiated)

The V_T parameter corresponds to the CFLD-P_CV test (MOS Capacitor with p-stop), which was implemented after production had already begun. As discussed in Section 4.1, the extraction of this parameter differs slightly from that of V_{FB} from the standard MOS Capacitor; however, both parameters provide information related to the voltage at which the silicon in the MOS structure transitions from accumulation to depletion. Therefore, a certain degree of correlation between these two parameters is expected.

Figure 4.40 shows the correlation between pre-irradiated V_T and V_{FB} , with data points distributed linearly and yielding a Pearson correlation coefficient of 0.87. This confirms the strong correlation expected between these two parameters and supports their use as a cross-check for detecting potential charge variations in the sensor field-oxide layer.

4.2.2 V_{PT} vs. S_{REF} (Pre-Irradiated)

The S_{REF} parameter also belongs to the CFLD-P_CV test (MOS with p-stop) implemented during production. A low V_{PT} value measured in one batch indicated a potential issue

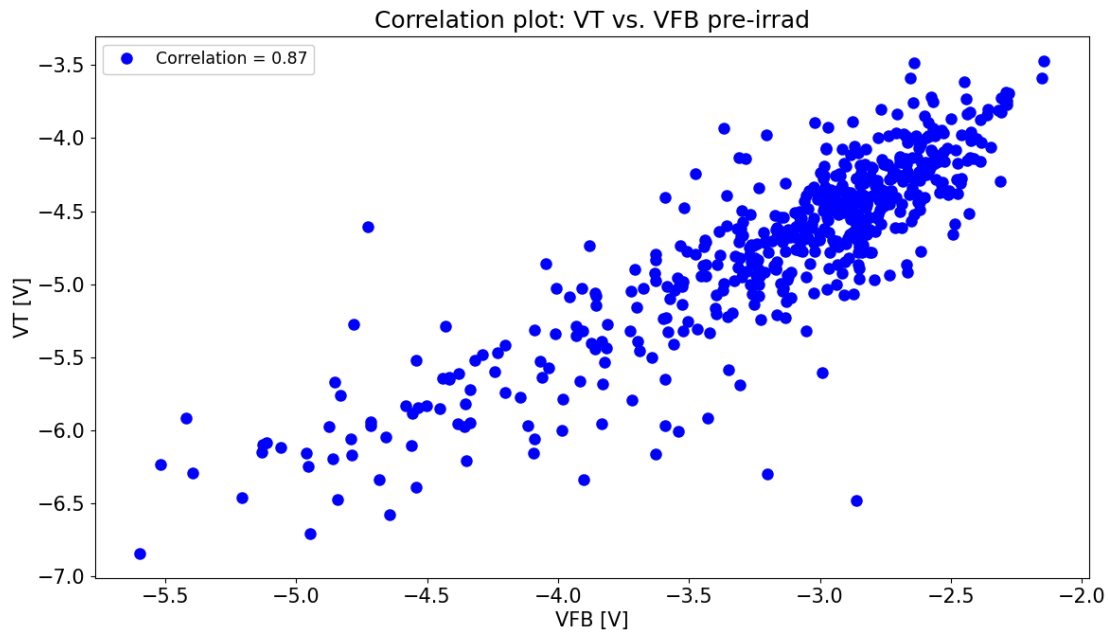


Figure 4.40: Correlation between the pre-irradiated V_T and V_{FB} parameters.

with the p-stop implantation. As a result, the MOS capacitor with p-stop (structure from Category B) was tested and subsequently added to the standard QA testing plan.

While V_{PT} indicates the voltage required for punch-through (shorting the strip implant to the bias ring, isolated by a p-stop trace), S_{REF} represents the depletion rate of the silicon immediately beneath the oxide. In both cases, a weak p-stop implantation leads to a reduction in the effects represented by these parameters. Consequently, lower V_{PT} values correspond to lower S_{REF} values.

Figure 4.41 illustrates the correlation between V_{PT} and S_{REF} measured on pre-irradiated Testchips. Results from tests labeled as “PASSED” (blue) in the database are clustered within a narrow V_{PT} range (approximately 13–17 V), making it more difficult to observe a possible correlation. Therefore, unlike the plots in Section 4.1, this analysis also includes values from failed tests of non-accepted components (red) across several rejected batches, in order to improve the statistical robustness and assess the correlation over a more appropriate data range.

A clear linear relationship is then observed, with a Pearson correlation coefficient of 0.91, indicating strong correlation. This confirms the usefulness of the S_{REF} parameter as an independent cross-check for low p-stop implantation. Both parameters serve as reliable early indicators of potential variations in p-stop implantation quality.

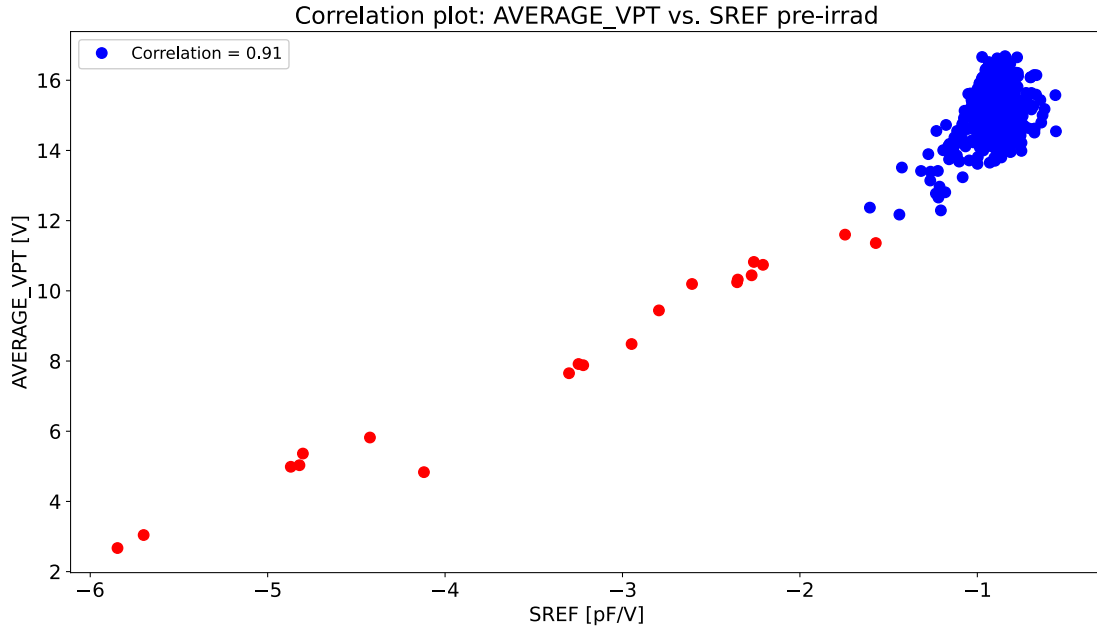


Figure 4.41: Correlation between the pre-irradiated V_{PT} and S_{REF} parameters. Accepted values are shown in blue, while values from failed tests are shown in red.

4.2.3 I_{500V} vs. V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

The large dispersion and increasing trend of V_{FD} values observed after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ (see Figure 4.32) prompted the QA Collaboration to further investigate this effect, particularly after several samples were found to exceed the maximum threshold of 850 V.

The relationship between V_{FD} and I_{500V} was examined for parameters extracted from MD8s irradiated with neutrons up to a fluence of $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$. The resulting correlation plot, shown in Figure 4.42, exhibits a non-linear relationship with a Pearson correlation coefficient of 0.36, indicating weak correlation according to the criteria in Table 4.2. Consequently, the higher V_{FD} values observed after pure-neutron mid-fluence irradiation do not imply more severe bulk damage that would translate into higher leakage currents across the sensor.

4.2.4 CCE_{500V} Irradiated with Bham Protons vs. V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$

Possible changes in the charge collection could also arise from the high V_{FD} described in the previous section. To confirm or exclude this effect, V_{FD} after neutron mid-fluence ($5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$) irradiation was compared with CCE_{500V} measured after Birmingham-

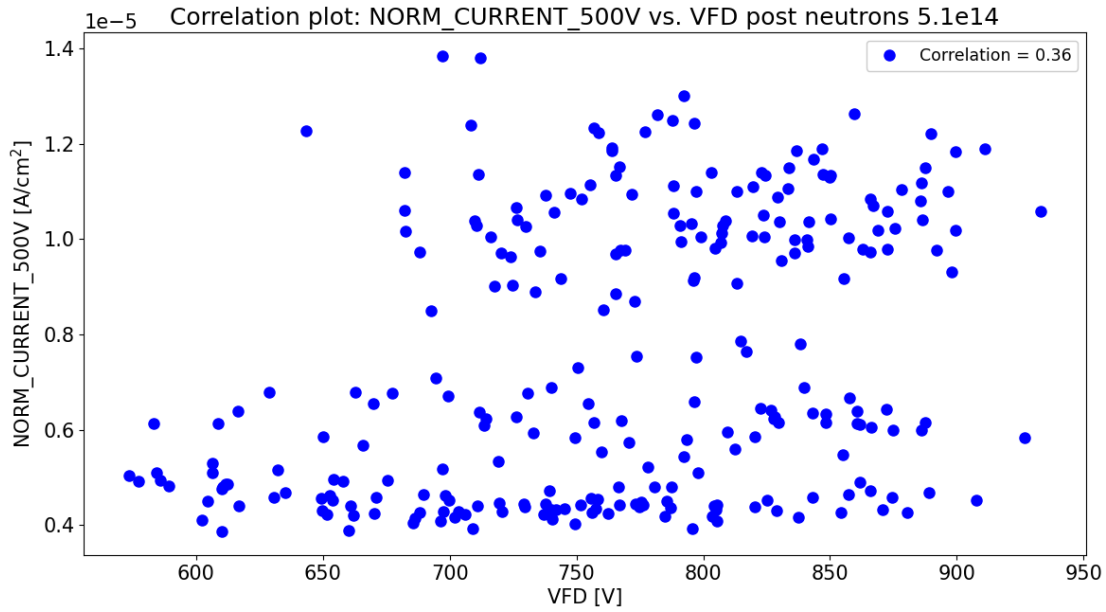


Figure 4.42: Correlation between the I_{500V} and V_{FD} parameters after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$.

proton irradiation (66 Mrad). The relationship between these two parameters, shown in Figure 4.43, exhibits negligible correlation, indicating that higher V_{FD} values are not directly associated with higher CCE_{500V} values. The charge collection efficiency depends on the balance between carrier drift time and trapping, whereas depletion is primarily governed by the effective space charge.

The relationship between V_{FD} measured after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ and CCE_{500V} after CYRIC-proton irradiation was also analyzed and showed weak correlation. However, the limited number of available data points prevented the extraction of statistically significant conclusions, mainly due to mismatched batches between the MD8s and Mini sensors selected in the QA process.

4.2.5 V_{FD} Irradiated with Neutrons up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ vs. Pre-Irradiated V_{FD}

A potential correlation between V_{FD} measured after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ and pre-irradiated V_{FD} was investigated. As noted in Section 4.1.14, opposite trends were observed for these two parameters at the beginning of production. The QA Collaboration initially suspected a possible correlation; however, this hypothesis was discarded after observing the extremely weak correlation shown in Figure 4.44. The increase in V_{FD} after neutron remains under investigation, as discussed in Chapter 4.3.4.

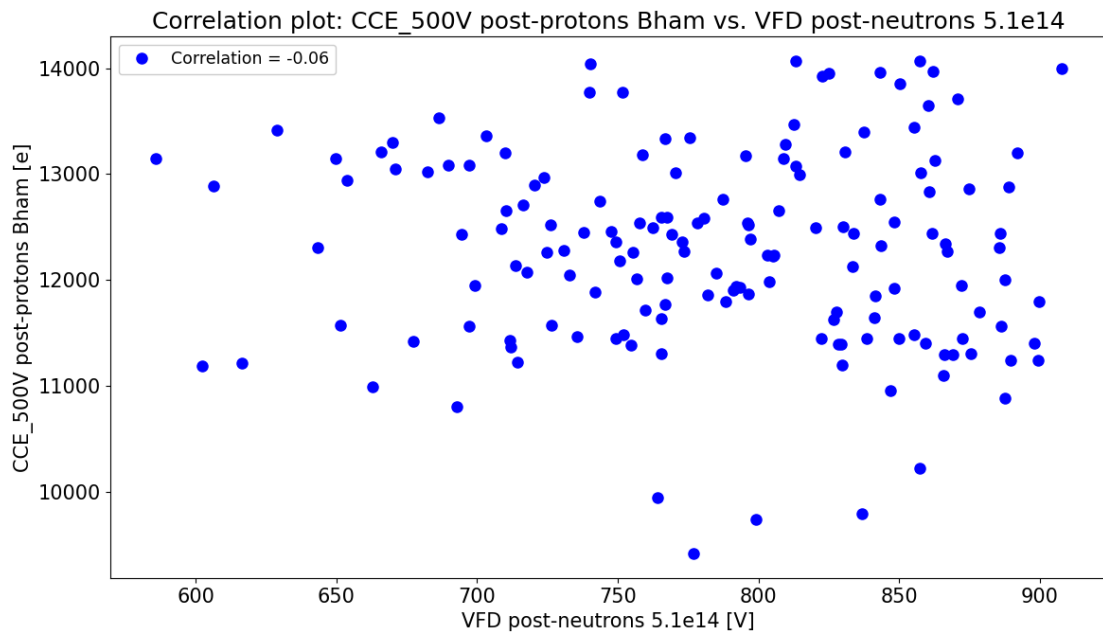


Figure 4.43: Correlation between the CCE_{500V} after Birmingham-proton irradiation and the V_{FD} after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$.

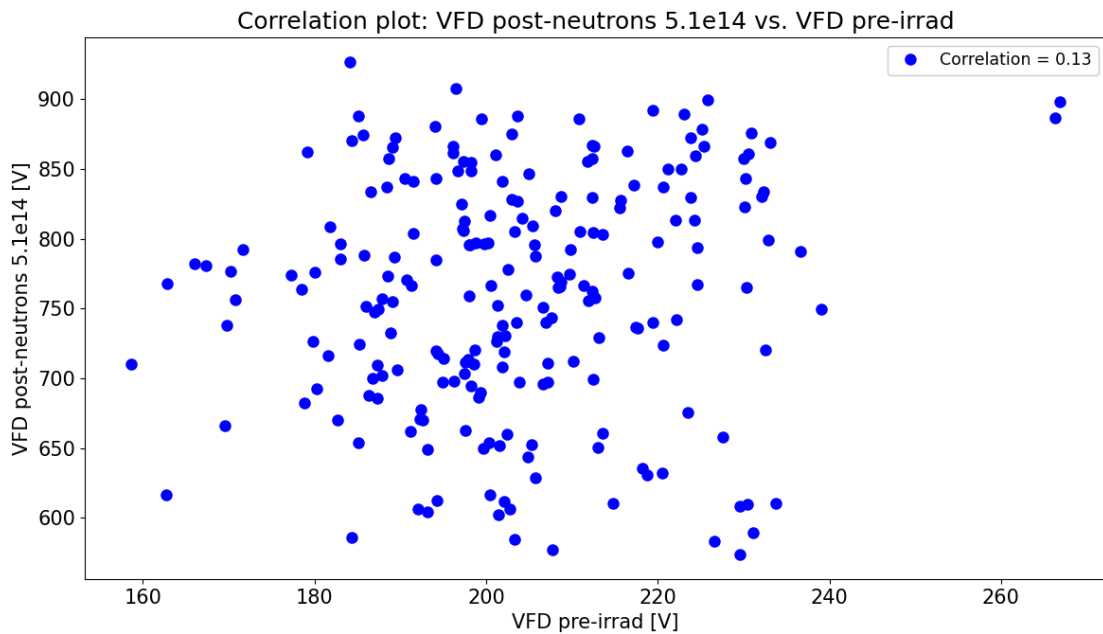


Figure 4.44: Correlation between the pre-irradiated V_{FD} and the V_{FD} after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$.

4.3 Incidences During Production

One of the main QA objectives from the beginning of production was to prevent defects in the fabrication process of the sensors. Throughout sensor production, several incidents

occurred, including irradiation-site issues, unexpected measurement problems, and parameter failures caused by changes or anomalies in the fabrication process. This section presents three major QA incidences related to anomalous parameter values observed during production and detected or investigated at IMB-CNM.

4.3.1 Low P-Stop Implantation

At the very beginning of production, specifically during the second delivery of samples, a case of low punch-through voltage (V_{PT}) was detected at IMB-CNM in a pre-irradiated Testchip from batch VPA37921 (wafer W169). The absolute value of V_{PT} , measured in the punch-through structure of the Testchip, was well below the minimum threshold defined for this parameter (12 V), in contrast to the values obtained from previously tested batches. This low V_{PT} extraction is shown in Figure 4.45.

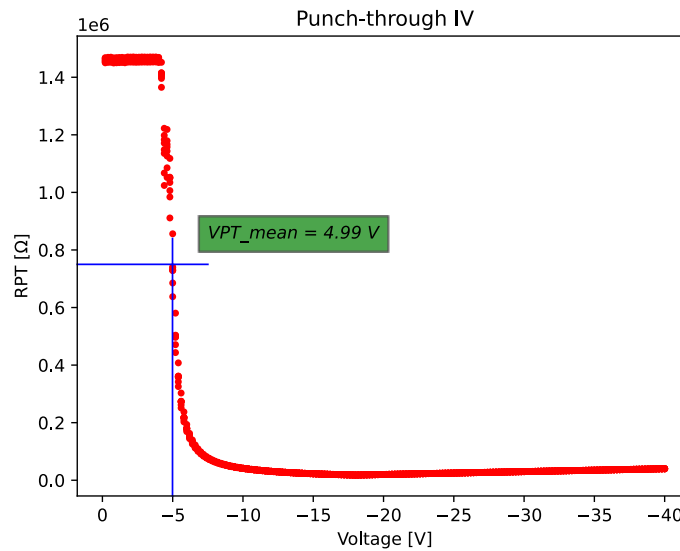


Figure 4.45: V_{PT} extraction from the punch-through resistance (R_{PT}) curve, obtained through a voltage sweep from 0 V to -40 V. Production distribution: CERN-02; batch: VPA37921; wafer: W169.

In addition, tests performed on the interdigitated structures (INT_C and INT_IV) also yielded poor results. All inter-strip capacitance values exceeded the maximum threshold of 1.00 pF/cm (later extended to 1.30 pF/cm). The I-V curve reached breakdown within the limits of the extraction range (-5 V to +5 V). Consequently, the inter-strip resistance (R_{int}), calculated as the inverse slope over the full range, was not meaningful and significantly deviated from the expected value.

With V_{PT} , R_{int} , and C_{int} all failing, poor isolation between strips was suspected, which could compromise the sensor's optimal performance. From that point onward, several

checks were performed, and the issue was quickly attributed to inadequate p-stop implantation. Later in production, this problem reappeared in several subsequent batches, prompting further studies to investigate the origin and characteristics of the poor p-stop isolation observed in those batches.

4.3.1.1 Initial Checks with Batch VPA37921

Following the first failed PTP_IV test at IMB-CNM, three replacement Testchips (wafers W175, W196, and W212) from the same batch were requested to investigate the anomalous results. All replacements exhibited similarly low V_{PT} values, high C_{int} values, and incorrect R_{int} extraction. As an example, Figure 4.46 shows the V_{PT} extraction (left) and the incorrect R_{int} extraction (right) for a QA replacement Testchip from wafer W196, where the inter-strip current reaches the compliance limit.

Subsequently, two additional Testchips and Mini sensors (wafers W186 and W187) were received and measured for further verification. The results were consistent with those previously obtained. All V_{PT} and C_{int} values measured on Testchips from batch VPA37921 are summarized in Table 4.3, with V_{PT} values in the range of 2–6 V and C_{int} values between 1 and 2 pF/cm.

This issue was immediately communicated to the foundry (HPK) to investigate the cause of the undesired parameter values, implement corrective actions to resolve any fabrication errors, and prevent the recurrence of similar issues.

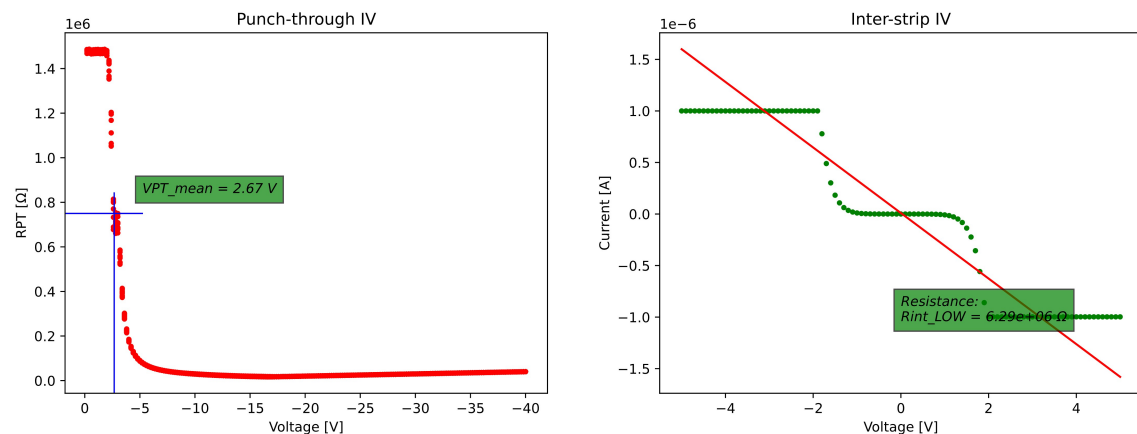


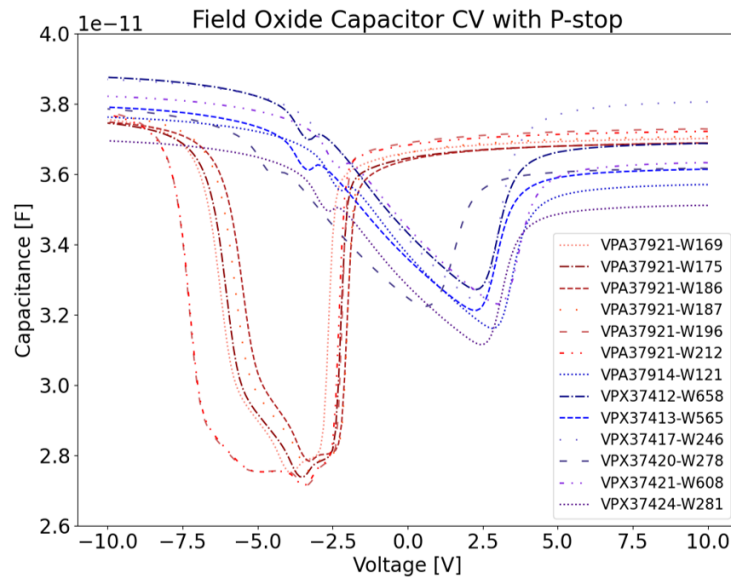
Figure 4.46: V_{PT} (left) and R_{int_LOW} (right) extractions from a QA replacement Testchip. Production distribution: CERN-02; batch: VPA37921; wafer: W196.

Table 4.3: $C_{\text{int_LOW}}$, $C_{\text{int_MID}}$, $C_{\text{int_UP}}$, and V_{PT} values measured on the VPA37921-W169 Testchip and all replacement samples from the same batch.

Wafer number	INT_LOW_C (pF/cm)	INT_MID_C (pF/cm)	INT_UP_C (pF/cm)	AVERAGE_VPT (V)
W00169	1.30	1.32	1.50	4.987
W00175	1.14	1.20	1.35	5.032
W00186	1.07	1.08	1.34	5.821
W00187	1.05	1.10	1.31	5.364
W00196	1.80	1.80	1.93	2.672
W00212	1.59	1.57	1.77	3.043

4.3.1.2 Implementation of the CFLD-P_CV Test

In parallel with the PTP_IV tests performed on Testchip replacements from batch VPA37921, the MOS capacitor with p-stop (Category B) was also tested. A distinctly different behavior of the C–V curve was observed, confirming that the p-stop implantation profile was responsible for the low V_{PT} values. Several representative C–V curves are shown in Figure 4.47 for Testchips from batch VPA37921 (red) and from standard production batches (blue). Clear differences are observed in both curve shape and depletion rate, the latter being lower in standard batches.

**Figure 4.47:** C–V curves measured at 10 kHz from the MOS capacitor with p-stop for standard production batches (blue) and for samples from batch VPA37921 (low p-stop, red).

As a result, the CFLD-P_CV test was implemented in the IMB-CNM automatic probe station software, and the extracted parameters were incorporated into the systematic QA evaluation plan as an independent cross-check for detecting future low p-stop implantations (see the parameter extraction in Figure 3.15 of Chapter 3). In particular,

the S_{REF} parameter was selected for monitoring, as it reflects the increased depletion rate in samples with insufficient p-stop implantation.

4.3.1.3 V_{PT} and S_{REF} Measurements for All Batches with Low P-Stop Implantation

Several additional Testchips exhibited low p-stop implantation at different points during production, with V_{PT} and S_{REF} values falling below the expected range and outside the defined thresholds. For each case, at least three replacement samples from the same batch were requested and tested to rule out measurement errors and to confirm reproducibility within the batch.

The time evolution of the S_{REF} parameter is shown in Figure 4.48, where four batches—VPA37921 (R0), VPA42646 (R0), VPA46225 (R4), and VPA50930 (SS)—clearly stand out as having low p-stop doping concentration.

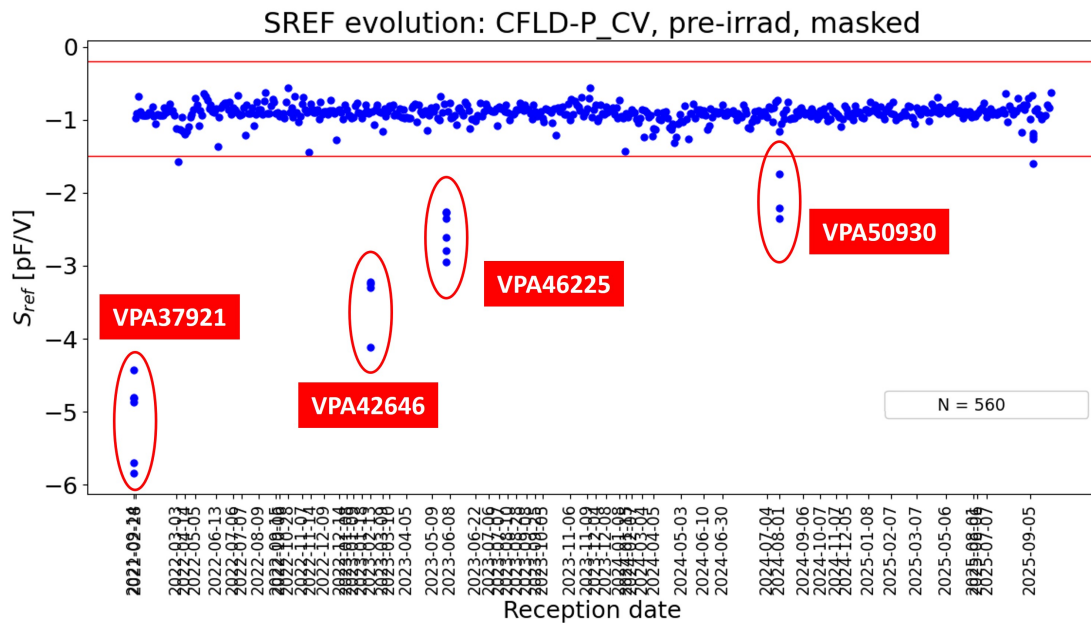


Figure 4.48: Time evolution of the S_{REF} parameter including all measured Testchips and replacement samples from production QA. The four batches exhibiting the lowest S_{REF} values are circled and labeled in red.

After several months of communication with the foundry (HPK), the origin of the low p-stop implantation issue was identified and mitigated. The problem was traced to an anomaly in the equipment used for the p-stop implantation process. Two furnaces (Equipment A and Equipment B) were used interchangeably for the post-implantation annealing; however, on some occasions, one of them applied a non-uniform temperature across the processed samples. Although the issue was understood and subsequently

corrected, the decision was made to reject the four batches affected by low p-stop implantation (see Section 4.3.4).

Figure 4.49 shows the time evolution of all V_{PT} values measured on Testchips and replacements up to the last rejected batch in production QA. Each data point is labeled with the wafer type (SS, LS, R0, R1, R2, R3, R4, or R5) and the Testchip position within the wafer (UP, DOWN, LEFT, or RIGHT). The four rejected batches are highlighted in red. The plot clearly shows that all Testchips from the rejected batches, as well as others with relatively low V_{PT} values, were fabricated using the same furnace (Eq. A), and are therefore plotted in red. The worst cases also corresponded to Testchips located in the right half-moon regions of the wafer.

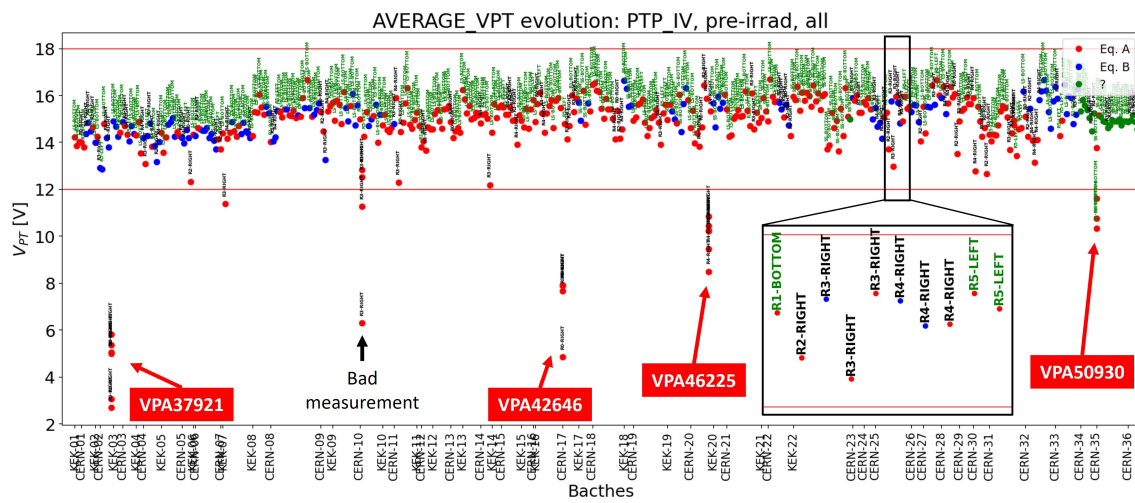


Figure 4.49: Time evolution of the V_{PT} parameter including all measured Testchips and replacement samples from production QA up to last low p-stop case. Data points are color-coded according to the furnace used for p-stop implantation (Eq. A in red and Eq. B in blue), while points with unknown equipment information are shown in green. Labels indicate wafer type and Testchip position within the wafer. An inset provides a magnified view of a narrow region of the plot. The four worst batches are highlighted and labeled in red. One data point corresponding to a measurement error is also shown.

Figures 4.48 and 4.49 exhibit strong similarities, reflecting the strong correlation between the S_{REF} and V_{PT} parameters.

4.3.1.4 P-Stop Variability Across the Wafers and Batches

Inspections of QA Testchips from batch VPA37921 revealed variations in the p-stop implantation level among wafers within the same batch. The wafers with higher wafer number within the batch deployed worse p-stop isolation than the first wafers of the batch, as deduced from the punch-through voltage (V_{PT}) values in Table 4.3.

The non-uniformity of the p-stop isolation across the batch was also indicative of the poor performance of the furnace employed for the post-implantation annealing, given that consecutive wafers within the batch were processed together in the same furnace. According to the explanation provided by HPK, non-uniform heat diffusion in Equipment A was probably the main cause of the low p-stop doping concentration and thus of the variability within the batch.

On the other hand, p-stop variability across the wafer was also observed in those bad cases ending up with batch rejection. In the framework of QA tasks, the V_{PT} parameter was measured in Testchips located at different half-moons within the wafer—tested in wafers from rejected batches. The half-moons from wafers from rejected batches (VPA37921, VPA42646, VPA46225, and VPA50930) were sent to the IMB-CNM, where measurements and subsequent analysis of the p-stop uniformity across the wafer were performed.

QC groups tested V_{PT} as well in Main strip sensors for a complete mapping of the p-stop quality over the sensor (and the wafer). Main sensors from rejected batches were chosen for this purpose.

Wafer layouts in Figure 4.50 are representative of all wafer types used in these studies: R0 for batches VPA37921 and VPA42646, R4 for batch VPA46225, and SS for batch VPA50930.

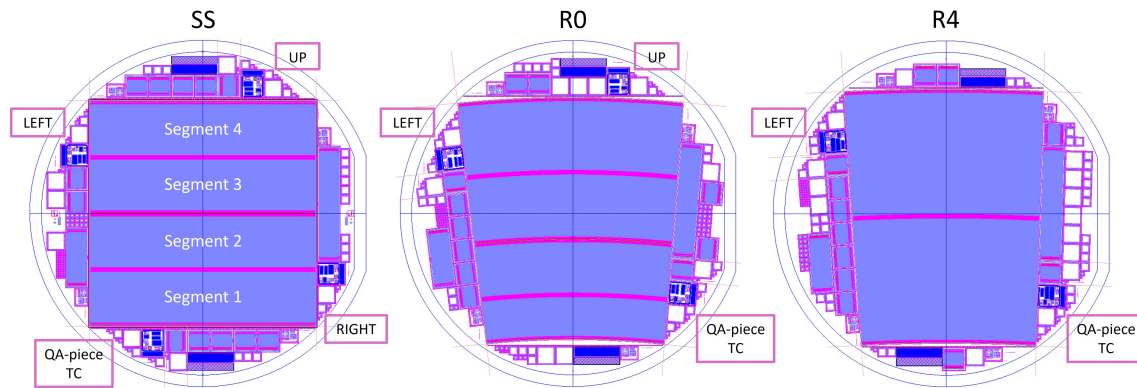


Figure 4.50: Wafer layouts for sensor types SS (left), R0 (center), and R4 (right). Segments (strip rows) are labelled in the SS-type wafer. The Testchips are indicated in each case according to their position—and thus half-moon position—within the wafer.

For example, the p-stop variability across the wafer, checked using half-moon Testchips in batch VPA46225, is represented in Figures 4.51 and 4.52. Whereas Figure 4.51 shows the punch-through resistance (R_{PT}) curves for the V_{PT} extraction, Figure 4.52 shows the C–V curves for the S_{REF} extraction. Both correspond to the equivalent structures tested in the production Testchips. Either LEFT and RIGHT half-moons from several wafers belonging to batch VPA46225 were used in this study, with one Testchip in each half-moon (LEFT and RIGHT) as schematized in the R4 layout in Figure 4.50. Additionally, one black curve

from a standard good batch (VPA45756) and a red curve from a known defective Testchip from batch VPA42646 are included as good and bad references in both Figures.

The V_{PT} parameter is around 15–16 V (well within the acceptance range) for the good reference batch and for the LEFT half-moons (labelled HM in Figures 4.51 and 4.52) of batch VPA46225. Conversely, the V_{PT} is shifted to less negative values (indicating lower p-stop concentration) for the defective batch and for the RIGHT half-moons (labelled TC in Figures 4.51 and 4.52) from batch VPA46225.

V_{PT} and S_{REF} extracted values are consistent, clearly showing distinct curves for good and bad cases in both parameter representations. Regarding the C–V curves measured on the MOS Capacitors with p-stop for the S_{REF} extraction, the transition from accumulation to depletion is faster in Testchips with defective p-stop, with slight variations in the curve profile. The capacitance also behaves differently in the inversion region compared to capacitors with a properly implemented p-stop, even though it is measured at the same frequency.

These large differences observed between measurements performed on different structures of the same wafer, located at different positions within the wafer, demonstrate the lack of uniformity in the p-stop implantation across the wafer.

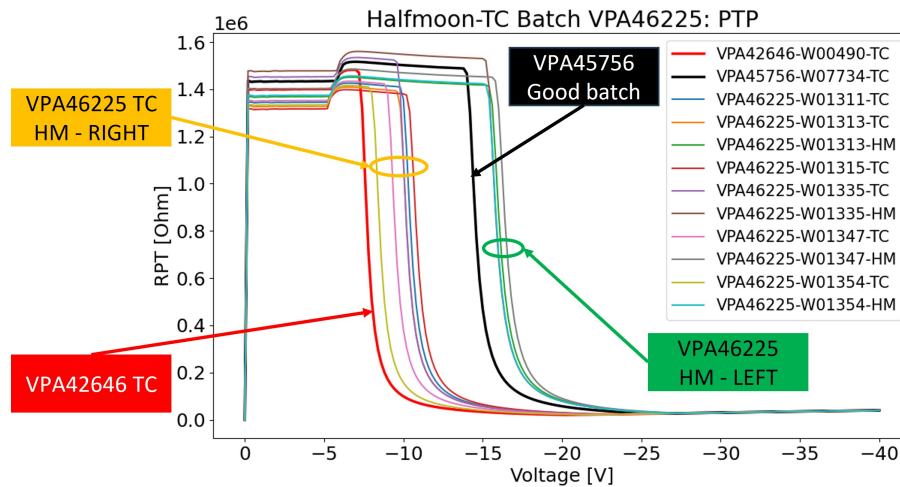


Figure 4.51: R_{PT} vs. voltage curves obtained from PTP structure tests on Testchips from LEFT and RIGHT half-moons of batch VPA46225. For comparison, a standard batch (VPA45756) and a defective batch (VPA42646) are also shown, represented in black and red, respectively.

This study was also performed on other defective batches, confirming the results. The S_{REF} representation in Figure 4.53 groups all measurements in production Testchips along with replacements and Testchips from different half-moons from each wafer and batch. The plot shows that, for batches VPA42646 and VPA46225, the S_{REF} measured on the left side of the wafer falls within the standard production distribution, in contrast to the measurements on the right side, which lie well below the minimum threshold of

–1.5 pF/V. In batch VPA50930, S_{REF} exhibits low values in the LEFT half-moon and higher values in the DOWN half-moon.

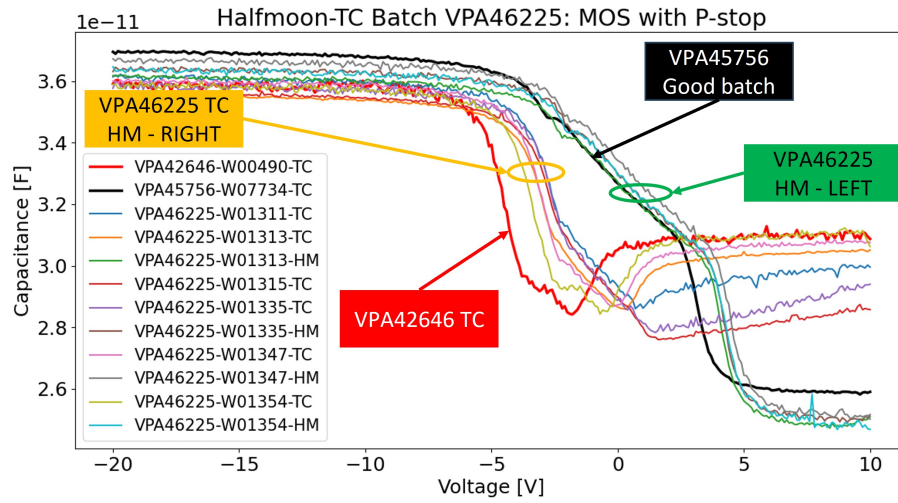


Figure 4.52: C–V curves obtained from MOS capacitors with p-stop on Testchips from LEFT and RIGHT half-moons of batch VPA46225. For comparison, a standard batch (VPA45756) and a defective batch (VPA42646) are also shown, represented in black and red, respectively.

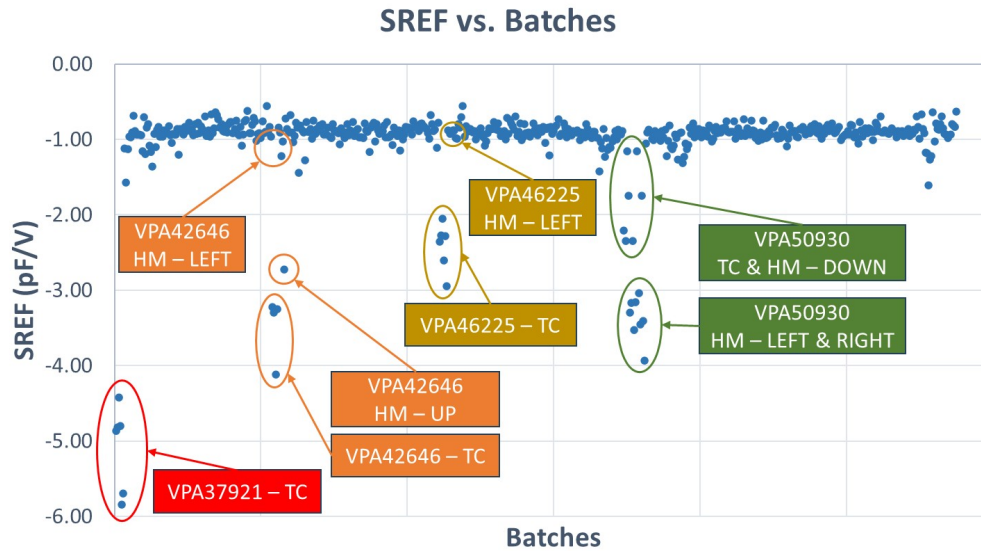


Figure 4.53: Time evolution of the S_{REF} parameter including all measured QA Testchips, replacements, and half-moon Testchips. The four batches exhibiting the lowest S_{REF} values are circled and labeled in red.

Consequently, a decrease in the p-stop implantation level from the left to the right side of the wafer is interpreted from the previous plot, although a parabolic-like trend is observed in batch VPA50930. For a better mapping of the p-stop variability across the wafer, the V_{PT} parameter was measured on different strips and on different segments within wafers of defective Main sensors.

Plots in Figure 4.54 illustrate the V_{PT} measured in four Main sensors from batch VPA50930 at another QA collaborative institute, at strip numbers 10, 325, 640, 955, and 1270 of segments 1, 2, and 4 (see the SS-type segmentation in Figure 4.50). Segment 3 was skipped since DC pads are adjacent to segment 2 DC pads.

These results confirm the high variability of the p-stop across the wafer. Although the largest differences are observed in the horizontal direction, p-stop non-uniformity is also detected vertically within the wafer. In fact, no linear variation is observed in any direction. The V_{PT} exhibits a parabolic shape, and the worst values are measured in the segment ends (left and right) within the Main sensor. QA results obtained from the Testchip near segment 1 and strips 300–400 are consistent with the Main sensor results.

Overall, the best p-stop performance is achieved in the central part of the Main sensor, especially in the lowest strip rows—highlighted in blue color in the plots in Figure 4.54.

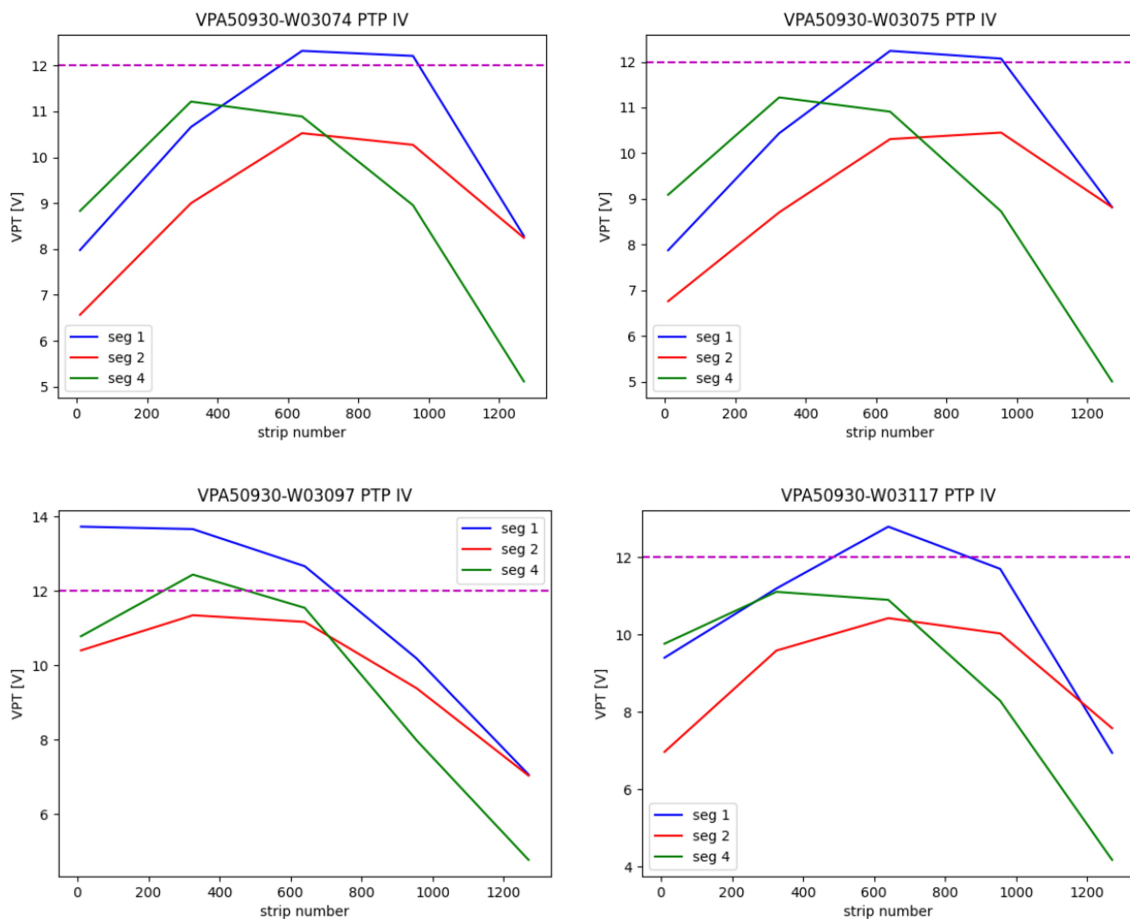


Figure 4.54: Four representations of the V_{PT} parameter measured on four wafers from batch VPA50930 at a QA collaborative institute. In each subfigure, V_{PT} values from different sensor segments are shown in different colors: blue (segment 1), red (segment 2), and green (segment 4). The minimum threshold of 12 V is indicated by a dashed line.

An additional study was conducted by processing two Main sensors with a different furnace each one. The V_{PT} parameter was extracted from both sensors, measured at different strip rows and numbers to check the p-stop variability across the wafer. These measurements were also performed in another collaborative institute.

Wafer VPA53553-W03492, which was processed using furnace B, exhibited a uniform V_{PT} distribution across the wafer (see the left plot in Figure 4.55). In contrast, wafer VPA50932-W03132, processed with furnace A, showed a non-uniform V_{PT} profile with a pronounced parabolic shape, where V_{PT} values decreased toward the wafer edge, particularly in segment 2, reaching levels approximately four standard deviations below the average. This behavior is depicted in the right plot in Figure 4.55.

Despite this spatial variation, the V_{PT} values measured on the corresponding QA Testchips remain close to the overall mean, at around 15 V.

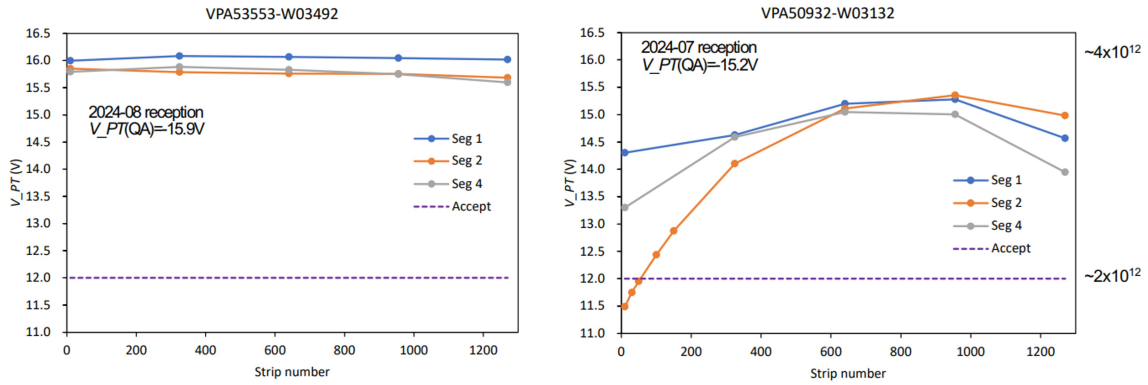


Figure 4.55: Representations of the V_{PT} parameter measured on wafers from batch VPA53553 (left) and VPA50932 (right) at a QA collaborative institute. In each subfigure, V_{PT} values from different sensor segments are shown in different colors: blue (segment 1), orange (segment 2), and grey (segment 4). The minimum threshold of 12 V is indicated by a dashed line [110].

The investigation of the origin of the low p-stop concentration was completed with TCAD simulations on MOS capacitors with p-stop, together with standard capacitors. Standard C–V responses matched the nominal p-type implantation specified for the process, corresponding to a surface dopant density of $4 \times 10^{12} \text{ q/cm}^2$. In contrast, defective C–V profiles indicated a reduced p-type dopant density, mainly in the surface. The C–V curves of the rejected batches were consistent with a p-stop density more than one order of magnitude below the nominal value and almost null at the surface regions, suggesting n-type surface contamination due to the anomalous thermal process previously identified [82].

The p-stop density was also correlated with V_{PT} , with the nominal dopant density at the surface of $4 \times 10^{12} \text{ q/cm}^2$ corresponding to $V_{PT} = 16 \text{ V}$. Accordingly, the minimum threshold of $V_{PT} = 12 \text{ V}$ was scaled to half the nominal p-stop density, $2 \times 10^{12} \text{ q/cm}^2$, while $V_{PT} = 6 \text{ V}$ corresponded to a density of $8 \times 10^{11} \text{ q/cm}^2$. Radiation damage effects

were also simulated by varying the space-charge density, leading to the conclusion that a minimum p-stop surface density of $2 \times 10^{12} \text{ q/cm}^2$ is sufficient to maintain strip isolation in the presence of Si-SiO₂ interface charge densities of up to 10^{12} q/cm^2 [110].

From a technological perspective, the QA results presented in this chapter highlight that p-stop implantation is critical for the sensor's strip isolation performance. Correlations between S_{REF} and V_{PT} , together with C_{int} and R_{int} measurements, demonstrate that these parameters are reliable early indicators of implantation quality and are sensitive to variations in implantation dose or temperature uniformity within the furnaces.

This sensitivity enabled the QA team to detect and quickly address p-stop fabrication issues, thereby ensuring optimal p-stop isolation in the Main sensors intended for the ITk, and demonstrating the value of QA structures for monitoring process stability.

4.3.2 Tests of Capacitances

All post-irradiation CCPL_C and CCPL_IV tests performed on the Coupling Capacitors of the Testchips from batch VPA42891 in a QA test site failed, likely due to an electrostatic discharge (ESD) incidence. After $\gamma + n$ irradiation, a high coupling capacitance (C_{coupl}) was observed, and the current reached the compliance limit (10^{-7} A) at 25 V, well below the 100 V that the capacitor is specified to withstand.

As these parameters are critical for proper sensor performance after irradiation, both C_{coupl} and $I_{\text{CCPL}_100\text{V}}$ were re-evaluated at IMB-CNM. The coupling capacitances of ten pre-irradiated Testchips from batch VPA42891 were measured to verify their values. Subsequently, these Testchips were irradiated with neutrons up to a fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in Ljubljana and then returned to IMB-CNM for remeasurement. The currents through the coupling capacitors were also measured.

Coupling capacitances (C_{coupl}) before and after neutron irradiation were measured at 1 kHz using a parallel CR configuration and a signal amplitude of 0.5 V. After irradiation, the values were slightly lower than the pre-irradiated ones; however, this behavior was expected, and all values remained within specifications. The C_{coupl} values are listed in Table 4.4.

The currents measured on pre-irradiated and post-irradiated Testchips are shown in Figures 4.56 and 4.57, respectively. In both cases, the current measured at the coupling capacitor did not reach breakdown before 100 V.

Overall, all coupling capacitances were successfully verified, indicating optimal performance of the Coupling Capacitor in the Testchip and, consequently, of the AC-coupling devices

Table 4.4: C_{coupl} values before and after neutron irradiation up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, measured on ten Testchips from batch VPA42891.

Batch VPA42891	Pre-irrad	Post-irrad
Wafer	C_{coupl} (pF/cm)	C_{coupl} (pF/cm)
W5199	22.68	22.41
W5224	22.79	22.34
W5194	22.62	22.50
W5186	22.76	22.51
W5204	22.62	22.35
W5212	22.82	22.55
W5216	22.79	22.51
W5232	22.82	22.55
W5228	22.62	22.34
W5221	22.91	22.64

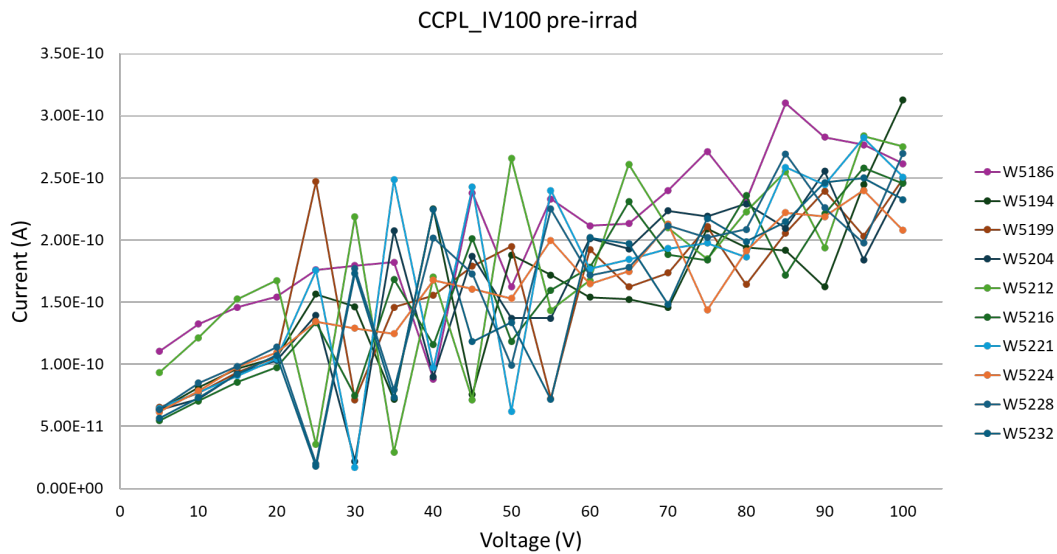


Figure 4.56: Current measured at the Coupling Capacitor in 5 V steps up to 100 V for several Testchips from batch VPA42891 before irradiation.

in the Main sensors for batch VPA42891. Nevertheless it is worth mentioning that several C_{coupl} failures have been observed throughout production in post-irradiation measurements, likely related to electrostatic discharge (ESD) incidents during irradiation, handling, shipment, or testing.

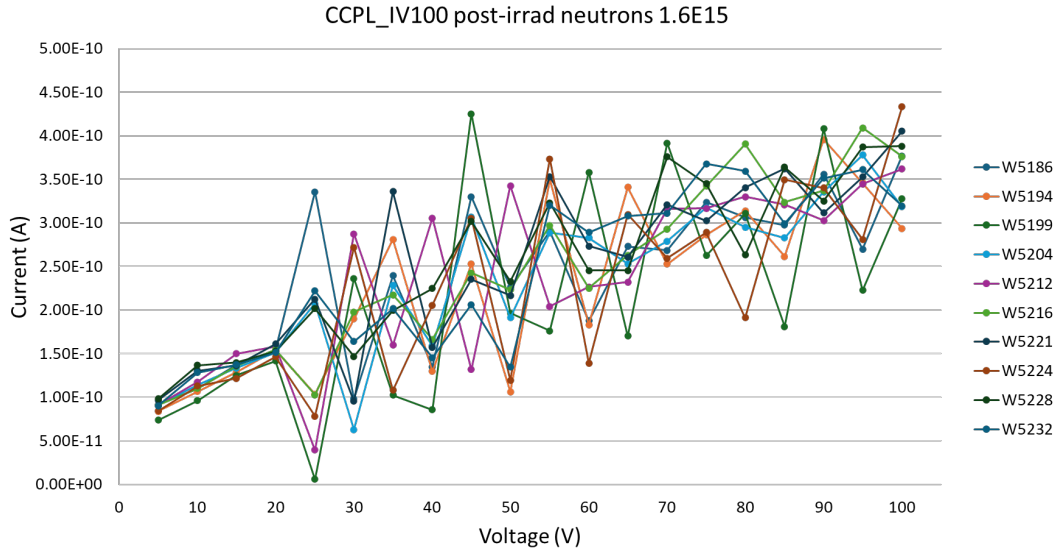


Figure 4.57: Current measured at the Coupling Capacitor in 5 V steps up to 100 V for several Testchips from batch VPA42891 after neutron irradiation up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

4.3.3 Low Flat-Band Voltage

Very low (highly negative) flat-band voltage (V_{FB}) values were observed in the MOS Field Oxide Capacitor from the Testchip of batches delivered during a short period of production. Some V_{FB} values even exceeded the minimum QA threshold ($< -5 \text{ V}$). The first out-of-threshold value ($V_{\text{FB}} = -5.39 \text{ V}$) corresponded to batch VPA54497 (CERN-39). Based on this value, the oxide trapped charge density (N_{ox}) was calculated for batch VPA54497, yielding $1.44 \times 10^{11} \text{ cm}^{-2}$. This value is relatively high compared to the production-wide mean of $6.91 \times 10^{10} \text{ cm}^{-2}$. Consequently, the low flat-band voltage was associated with increased oxide-trapped charge, likely due to reduced oxide quality as a result of a manufacturing issue. The N_{ox} calculation was performed using Eq. (4.2) [32, 111]:

$$N_{\text{ox}} = \frac{C_{\text{ox}}}{e} (\Phi_{\text{ms}} - V_{\text{FB}}) \quad (4.2)$$

where C_{ox} is the oxide capacitance per unit area, e is the elementary charge, $\Phi_{\text{ms}} = \Phi_m - \Phi_s$ is the work function difference between the metal and the semiconductor, and V_{FB} is the flat-band voltage. The semiconductor work function Φ_s is obtained using Eq. (4.3):

$$\Phi_s = \chi + \frac{E_g}{2} + \phi_F \quad (4.3)$$

where χ is the silicon electron affinity, E_g is the silicon band-gap energy, and ϕ_F is the Fermi potential relative to the intrinsic energy level, which depends on the doping concentration. For a p-type substrate, ϕ_F is given by Eq. (4.4):

$$\phi_F = \frac{k_B T}{e} \ln\left(\frac{N_A}{n_i}\right) \quad (4.4)$$

where k_B is the Boltzmann constant, T is the temperature, N_A is the acceptor concentration, and n_i is the intrinsic carrier concentration.

Figure 4.58 shows the V_{FB} extraction from a MOS Capacitor from a standard production batch and from a “bad-case” batch exhibiting low V_{FB} .

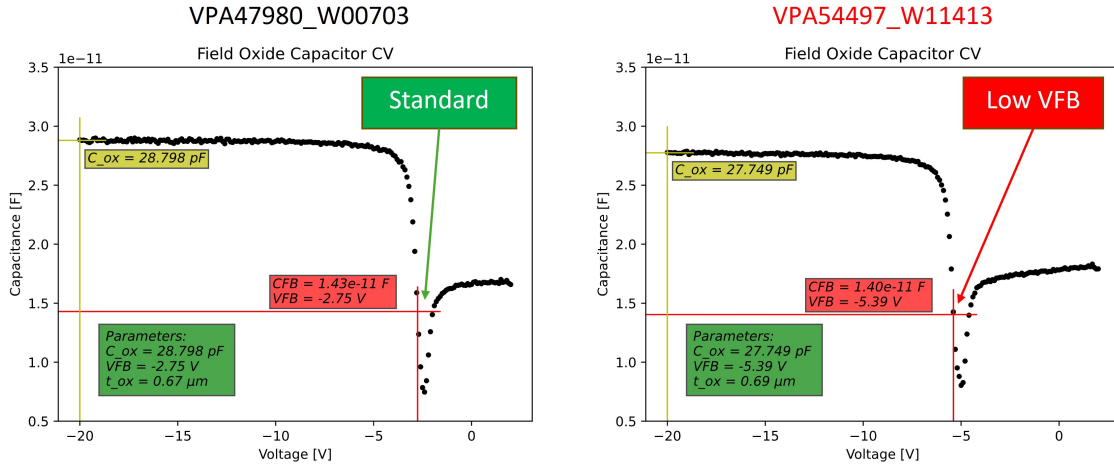


Figure 4.58: Comparison between a standard V_{FB} extraction (left) and a low- V_{FB} extraction (right) for Testchips from two production batches.

No anomalous effects were observed in MD8 I–V and C–V characteristics, CCE (post-irradiation), R_{int} (post-irradiation), C_{int} , or V_{PT} (pre- or post-irradiation). Nevertheless, this drop-off effect was communicated to HPK, who reported a minor variation in the fabrication process and ensured that the V_{FB} parameter would recover shortly in subsequent sensor deliveries.

4.3.3.1 Results from Testchip Replacements

As part of the standard QA procedure, three Testchip replacements from the same batch (VPA54497) were requested for the first sample with a V_{FB} value outside the acceptance limits. All replacement Testchips exhibited consistent results, with V_{FB} values below the minimum threshold. This occurred at the beginning of the V_{FB} drop-off period, and eight additional Testchips (those with the lowest V_{FB} values) were selected for further verification.

The V_{FB} values corresponding to these worst cases (one out-of-threshold value plus eight additional low values) are enclosed within the rectangle in Figure 4.59. The drop-off region is also circled in the same plot.

All V_{FB} values measured on the selected Testchips and their corresponding replacements are listed in Table 4.5. Failed tests from batch VPA54497 are highlighted in red. Although some variation is observed among different Testchips from the same batch, the results are consistent with the initial measurements, confirming a genuine decrease in flat-band voltage.

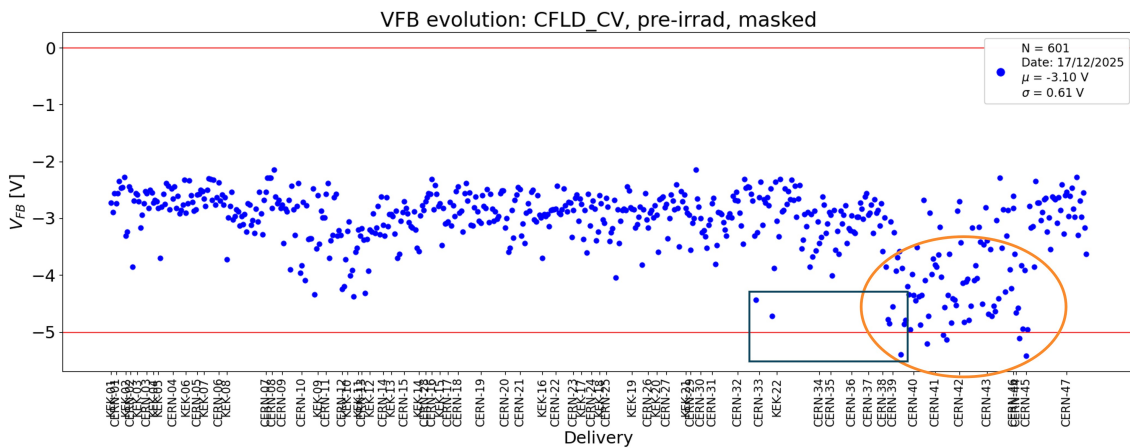


Figure 4.59: Time evolution of the V_{FB} parameter, ordered by delivery along the x-axis. A drop-off is observed from deliveries CERN-38 to CERN-45. A rectangle highlights the nine low- V_{FB} values for which Testchip replacements were selected.

The drop-off observed in the time-evolution plot is also reflected in the corresponding distribution plot as a low-value tail, as shown in Figure 4.12.

4.3.3.2 Results from Testchips from Half-Moons

Additional CFLD_CV tests were performed on Testchips from different half-moons of the wafer to investigate the flat-band voltage behavior. For this study, eight wafers with the lowest V_{FB} values up to CERN-39 were requested. All corresponded to Testchips already measured at IMB-CNM and listed in Tabl 4.5 (grey rows).

The half-moons analyzed belonged to wafer types SS, LS, and R1. For each wafer, the V_{FB} was measured on four Testchips corresponding to the UP, DOWN, LEFT, and RIGHT half-moon positions, as shown schematically in Figure 4.60. No clear V_{FB} trend or systematic distribution across the wafer was observed. However, slightly lower values tended to appear in Testchips from the DOWN half-moons, which had been diced and measured several months earlier in all cases.

Table 4.5: Lowest V_{FB} values observed during the later stages of production (at the time of this analysis), together with the corresponding values obtained from Testchip replacements for the affected batches.

	Measurement (batch + wafer)	Serial Number	V_{FB} (V)
CERN-32	VPA51792_W10639_7_A2_CFLD_CV_001.dat	20USBSL0710639	-4.44
	VPA51792_W10637_7_A2_CFLD_CV_001.dat	20USBSL0710637	-4.41
	VPA51792_W10660_7_A2_CFLD_CV_001.dat	20USBSL0710660	-4.68
	VPA51792_W10683_7_A2_CFLD_CV_001.dat	20USBSL0710683	-4.67
CERN-33	VPA51832_W01117_7_A2_CFLD_CV_001.dat	20USES10701117	-4.73
	VPA51832_W01116_7_A2_CFLD_CV_001.dat	20USES10701116	-4.56
	VPA51832_W01136_7_A2_CFLD_CV_001.dat	20USES10701136	-4.97
	VPA51832_W01160_7_A2_CFLD_CV_001.dat	20USES10701160	-5.08
CERN-38	VPA51835_W01267_7_A2_CFLD_CV_001.dat	20USES10701267	-4.56
	VPA51835_W01251_7_A2_CFLD_CV_001.dat	20USES10701251	-3.26
	VPA51835_W01272_7_A2_CFLD_CV_001.dat	20USES10701272	-4.45
	VPA51835_W01292_7_A2_CFLD_CV_001.dat	20USES10701292	-4.48
	VPA54278_W03768_7_A2_CFLD_CV_001.dat	20USBSS0703768	-4.78
	VPA54278_W03767_7_A2_CFLD_CV_001.dat	20USBSS0703767	-4.01
	VPA54278_W03789_7_A2_CFLD_CV_001.dat	20USBSS0703789	-5.54
	VPA54278_W03810_7_A2_CFLD_CV_001.dat	20USBSS0703810	-5.01
	VPA54279_W03902_7_A2_CFLD_CV_001.dat	20USBSS0703902	-4.85
	VPA54279_W03901_7_A2_CFLD_CV_001.dat	20USBSS0703901	-4.37
	VPA54279_W03921_7_A2_CFLD_CV_001.dat	20USBSS0703921	-5.65
	VPA54279_W03940_7_A2_CFLD_CV_001.dat	20USBSS0703940	-5.09
CERN-39	VPA54497_W11413_7_A2_CFLD_CV_001.dat	20USBSL0711413	-5.39
	VPA54497_W11411_7_A2_CFLD_CV_001.dat	20USBSL0711411	-5.13
	VPA54497_W11438_7_A2_CFLD_CV_001.dat	20USBSL0711438	-5.52
	VPA54497_W11456_7_A2_CFLD_CV_001.dat	20USBSL0711456	-5.60
	VPA54499_W11368_7_A2_CFLD_CV_001.dat	20USBSL0711368	-4.86
	VPA54499_W11367_7_A2_CFLD_CV_001.dat	20USBSL0711367	-3.61
	VPA54499_W11389_7_A2_CFLD_CV_001.dat	20USBSL0711389	-4.63
	VPA54499_W11408_7_A2_CFLD_CV_001.dat	20USBSL0711408	-4.46
	VPA54500_W11322_7_A2_CFLD_CV_001.dat	20USBSL0711322	-4.79
	VPA54500_W11321_7_A2_CFLD_CV_001.dat	20USBSL0711321	-4.25
	VPA54500_W11338_7_A2_CFLD_CV_001.dat	20USBSL0711338	-3.88
	VPA54500_W11364_7_A2_CFLD_CV_001.dat	20USBSL0711364	-4.78
	VPA54503_W04040_7_A2_CFLD_CV_001.dat	20USBSS0704040	-4.95
	VPA54503_W04039_7_A2_CFLD_CV_001.dat	20USBSS0704039	-3.48
	VPA54503_W04058_7_A2_CFLD_CV_001.dat	20USBSS0704058	-4.62
	VPA54503_W04081_7_A2_CFLD_CV_001.dat	20USBSS0704081	-4.39

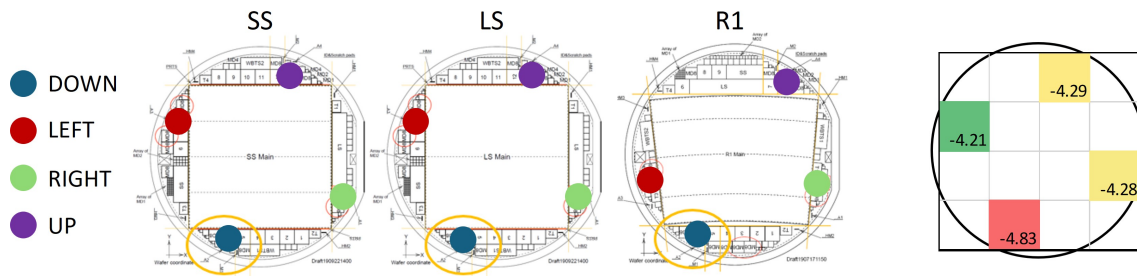


Figure 4.60: Schematic showing the position of Testchips within wafers for SS, LS, and R1 wafer types (left), with QA Testchips circled in the DOWN half-moons. Mean V_{FB} values extracted from the eight tested wafers for each half-moon position (right).

All Testchips are planned to be remeasured in the future to monitor any potential evolution. Nevertheless, the final portion of the time-evolution plot in Figure 4.59 already shows the V_{FB} recovery to the normal distribution observed at the start of production. Further tests of the post-irradiation effects of the low V_{FB} are planned to be done on Mini sensors,

although no effects have been observed so far in CCE tests of these devices. This incidence is considered a manufacturing fluctuation, detected during QA and subsequently corrected by HPK, but without negative consequences for the Main-sensor performance in the experiment.

4.3.4 QA Batch Rejections

The three most significant production QA incidents involving IMB-CNM have been described above. In addition, several minor interventions were required throughout production, including measurement adjustments, refinements of parameter extraction, and the testing of Testchip and MD8 replacements following isolated anomalous measurements.

The incident with the greatest impact on production was the low p-stop implantation discussed above. Four production batches were rejected due to clearly defective p-stop implantation, in accordance with HPK contract conditions. In total, six production batches were ultimately rejected: four for QA reasons and two for QC reasons. All rejected batches and their corresponding rejection causes are summarized in Table 4.6. Therefore, the QA-QC methodology effectively protected detector performance.

Table 4.6: Batches rejected for QA and QC reasons, and the number of sensors rejected per batch. Adapted from [66].

Rejected batches	Sensors	Grounds for rejection
VPA37921	43 R0	QA: Low and non-uniform p-stop implantation
VPA38906	26 R2	QC: Many failed stability and I-V tests
VPA38205	29 R2	QC: Many failed stability tests
VPA42646	44 R0	QA: Low and non-uniform p-stop implantation
VPA46225	34 R4	QA: Low and non-uniform p-stop implantation
VPA50930	28 SS	QA: Low and non-uniform p-stop implantation

During this thesis research, several complementary studies were conducted at IMB-CNM in parallel with the QA of the strip sensor production. All these activities took place within the framework of the QA ITk Strip Sensor Collaboration. Some of them were carried out exclusively at IMB-CNM, while others were performed in collaboration with other QA test sites.

Most of these studies were motivated by anomalous behaviors observed during production monitoring and are expected to continue beyond the end of the QA period. In this chapter, studies on wafers with low p-stop implantation (Section 5.1), the evolution of 24 GeV proton-induced damage with fluence on Testchips and Mini sensors (Section 5.2), irradiations at extreme fluences on Testchips (Section 5.3), and ingot-batch relationships (Section 5.4) are presented.

5.1 Low P-Stop Implantation

5.1.1 Origin of the Problem

A batch with a p-stop implantation level well below the acceptance limits was detected at the beginning of production QA, leading to the rejection of the batch (VPA37921). A basic analysis of this issue is described in Section 4.3, including the initial checks performed on this first rejected batch, the incorporation of the CFLD-P_CV test into the systematic measurement plan, and the study of the p-stop variability across the wafer for several rejected batches.

In addition to the standard measurements and verifications carried out under the QA requirements, further experiments were performed to gain deeper insight into the characteristics of the p-stop. This ultimately became one of the most extensive experimental efforts within the framework of the ITk Strip Sensor Collaboration, encompassing several checks and sub-studies aimed at investigating the origin and properties of the poor p-stop isolation observed in QA-production-rejected batches.

5.1.2 Experiments Made

Two additional experiments were conducted to achieve a better understanding of the p-stop dependence on process variations and the impact of a low p-stop on sensor performance: a study of the p-stop characteristics across different technological options on batches specially fabricated for this purpose, and an analysis of post-irradiation effects on the p-stop implantation for both standard and low p-stop devices.

Special p-stop batches

HPK produced two special batches, VPA50957 and VPA50958, incorporating four different p-stop process variations for evaluation by the ITk Collaboration. The primary objective of these batches was to assess the effect of the process variations on p-stop performance and to provide feedback to HPK for potential process optimization. Each batch (LS type) contained six to eight wafers per process variation. The total number of test samples was 56 Main sensors and the corresponding QA pieces. The process variations are defined in Table 5.1.

Table 5.1: Four p-stop process conditions used in the fabrication of batches VPA50957 and VPA50958.

Type	P-stop process variation	VPA50957	VPA50958	Total
1	Conventional process condition (reference)	6	7	13
2	Lower temperature than type 1	8	7	15
3	Little lower temperature than type 2	7	7	14
4	Another method condition	7	7	14
Total		28	28	56

The aims of this process split were to establish a reference using the current production process (type 1), to investigate whether lower temperatures could result in shallower impurity diffusion and lower dopant density (types 2 and 3), and to test a proprietary thermal method designed to reduce defects or impurities in the inter-strip oxide layer (type 4).

First, several tests were conducted before irradiation to verify proper inter-strip isolation and uniformity across the wafer. On the one hand, the punch-through voltage (V_{PT}) and the C-V characteristic of the MOS Capacitor with p-stop were measured at the automatic probe station (SIAM Laboratory) of the IMB-CNM, at room temperature, using Testchips representative of all p-stop processes and batches. Specifically, two Testchips from two

wafers were measured for each batch and process type, for a total of 32 Testchips. For each wafer, the two Testchips were taken from opposite sides (left and right) of the wafer.

Table 5.2: Testing distribution plan for Main sensors, half-moons (HM), Mini sensors, and Testchips (TC) of the special p-stop batches (VPA50957 and VPA50958). All devices are classified according to the p-stop processing type and radiation fluence: pre-irradiated, mid fluence (5.1×10^{14} n_{eq}/cm²), full fluence (1.6×10^{15} n_{eq}/cm²), and over-irradiated (3.4×10^{15} n_{eq}/cm²).

Batch	Wafer	Type	Main Sensor		HM	Mini		TC		
			Pre-irrad	5.10E+14	Pre-irrad	3.50E+15	1.60E+15	3.40E+15	1.60E+15	5.10E+14
VPA50957	W10358	Type 1								
	W10359		Carleton		CNM	Ljubljana		Prague		
	W10360									
	W10361		Cambridge		CNM		Ljubljana			Prague
	W10362	Type 4	Cambridge						Prague	
	W10364									
	W10366									
	W10367		Carleton		CNM	Toronto		Toronto		
	W10368	Type 2	Prague	Prague					Toronto	
	W10369		Cambridge		CNM		Toronto			Toronto
	W10370									
	W10371									
	W10372	Type 3								
	W10379									
	W10380		Carleton		CNM	Valencia		CNM		
	W10381		Prague	Prague					CNM	
	W10382	Type 1	Cambridge		CNM		Valencia			CNM
	W10383		Cambridge							
	W10384									
	W10385									
	W10386	Type 4								
	W10389		Carleton		CNM	Ljubljana		Prague		
	W10390		Prague	Prague					Prague	
	W10391		Cambridge		CNM		Ljubljana			Prague
	W10392	Type 2								
	W10394									
	W10395									
	W10396									
VPA50958	W10312	Type 1	Carleton		CNM	Valencia		Toronto		
	W10313								Toronto	
	W10314		Cambridge		CNM		Valencia			Toronto
	W10315									
	W10316	Type 4								
	W10317									
	W10323		Carleton		CNM	Toronto		Toronto		
	W10324		Prague	Prague					Toronto	
	W10325	Type 2	Cambridge		CNM		Toronto			Toronto
	W10326		Cambridge							
	W10329									
	W10330									
	W10331	Type 3								
	W10334									
	W10335		Carleton		CNM	Valencia		CNM		
	W10337		Prague	Prague					CNM	
	W10338	Type 1	Cambridge		CNM		Valencia			CNM
	W10339									
	W10341									
	W10342									
	W10345	Type 4								
	W10346		Carleton		CNM	Ljubljana		Prague		
	W10347		Prague	Prague					Prague	
	W10349		Cambridge		CNM		Ljubljana			Prague
	W10350	Type 2	Cambridge							
	W10351									
	W10352									

In parallel, Main sensor tests were also carried out before irradiation for the same purpose by collaborating institutes. These included Full Strip tests on at least two Main sensors per type (one per batch); I–V and C–V measurements to ensure sensor quality; I–V and long-term stability (LTS) tests [112] to verify breakdown voltage (V_{BD}) stability before and after LTS; and inter-strip resistance (R_{int}) and V_{PT} measurements at selected locations across strips for the bottom and top segments for all types 1–4 (LS-type sensors only contain two segments).

Subsequently, 24 Testchips were irradiated with gamma + neutron ($\gamma + n$) radiation. Some were irradiated up to “mid fluence” ($21 \text{ Mrad} + 5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$), others up to “full fluence” ($66 \text{ Mrad} + 1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$), and others accidentally over-irradiated up to $66 \text{ Mrad} + 3.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ (over-irradiated). Sixteen Mini sensors were also irradiated, eight up to full fluence and eight up to $3.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The over-irradiated QA pieces were nevertheless used in the study by accounting for the actual received radiation ($3.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$). Six Main sensors from types 2–4 were also irradiated with $\gamma + n$ up to a total ionizing dose (TID) and fluence of 25 Mrad and $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$, respectively.

All devices initially used in this study are listed in Table 5.2, along with their corresponding test sites and radiation fluences ($\text{n}_{eq}/\text{cm}^2$). All pre-irradiation measurements on half-moons were performed at IMB-CNM, as well as a subset of the post-irradiation $\gamma + n$ measurements on six Testchips: two irradiated up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$, two up to $1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, and two up to $3.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. These pre-irradiation and post-irradiation measurements are highlighted in green and purple, respectively, in Table 5.2. The post-irradiation tests were conducted using the manual probe station in the Radiation Detectors Laboratory (LabRad) at IMB-CNM, at -20°C under dry conditions ($\text{RH} < 5\%$).

After irradiation, the tests performed on the irradiated QA pieces and Main sensors were intended to evaluate the performance of the devices fabricated using the new p-stop thermal processes. For this purpose, R_{int} and V_{PT} were measured on Testchips, V_{PT} was also measured in Main sensors at different locations, and the charge collection efficiency (CCE) was extracted from the Mini sensors. Following the initial analysis, Main sensors from types 2–4 were also irradiated up to full fluence. The results of all these experiments are detailed in Section 5.1.2.

Post-irradiation effects on the p-stop

Apart from a reduction in V_{PT} , no clear effects were observed in other pre-irradiation QA/QC tests, as the decrease in the p-stop doping was not sufficient to produce a measurable degradation in strip isolation. The impact of this issue after irradiation therefore remained uncertain, and sensors with moderately reduced p-stop doping may have gone

undetected due to QA batch sampling. This study, conducted at IMB-CNM as part of this thesis, aims to evaluate the consequences of low p-stop doping on sensor performance under realistic operating conditions after irradiation.

To this end, three interrelated experiments were planned using Main sensors and Mini sensors from the rejected batch VPA42646:

1. **Full irradiation of a Main sensor:** A Main sensor with the lowest p-stop doping concentration (W514) was irradiated with combined gamma and neutron exposure up to the target fluence ($66 \text{ Mrad} + 1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$). This was intended to provide a rapid assessment of the final sensor performance—and thus the level of degradation—under worst-case conditions.
2. **Intermediate-fluence studies with Main sensors:** Main sensors were irradiated with combined $\gamma + n$ radiation to intermediate fluences in order to study the evolution of R_{int} . A minimum in R_{int} had been observed at mid fluence ($21 \text{ Mrad} + 5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$) in previous studies [113], as illustrated in plots in Figure 5.1, representing a potential worst-case scenario. This experiment aimed to explore additional fluences around this point to better characterize the minimum.
3. **Gamma-only irradiation of Mini sensors:** Several Mini sensors were irradiated with gamma rays only to investigate the degradation of R_{int} . The goals were to identify the total ionizing dose at which failure occurs ($R_{\text{int}} < 15 \text{ M}\Omega$) for both nominal and low p-stop cases, to investigate potential saturation of the degradation, and, in a later step, to add neutron irradiation to determine when and how R_{int} recovers to acceptable values.

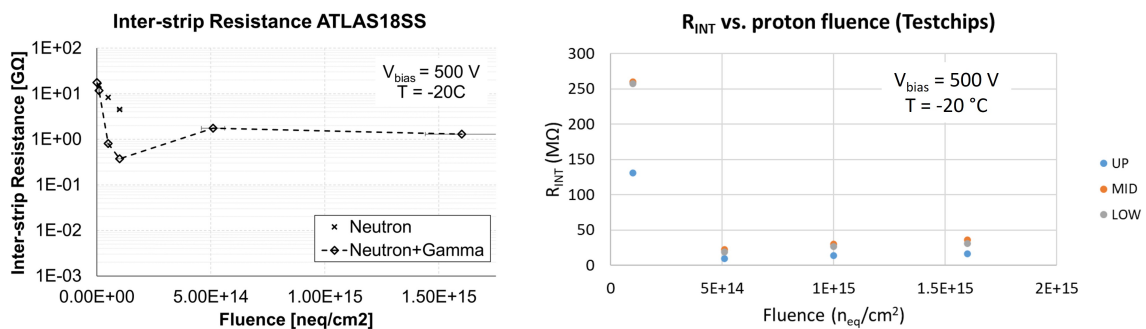


Figure 5.1: R_{int} as a function of fluence for Main sensors with standard p-stop irradiated with gamma + neutrons, except for two additional intermediate points obtained with neutron-only irradiation (left). Adapted from [113]. The right plot shows R_{int} measured on QA Testchips after proton irradiation, including results from UP, MID, and LOW interdigitated structures.

Batch VPA42646 (R0) had been rejected due to poor p-stop performance. Figure 5.2 shows the C–V curves obtained from MOS Capacitors with p-stop from this batch, which

indicate a low p-stop doping concentration. For comparison, representative curves from a good batch (VPA44666) and another defective batch (VPA37921) are also included.

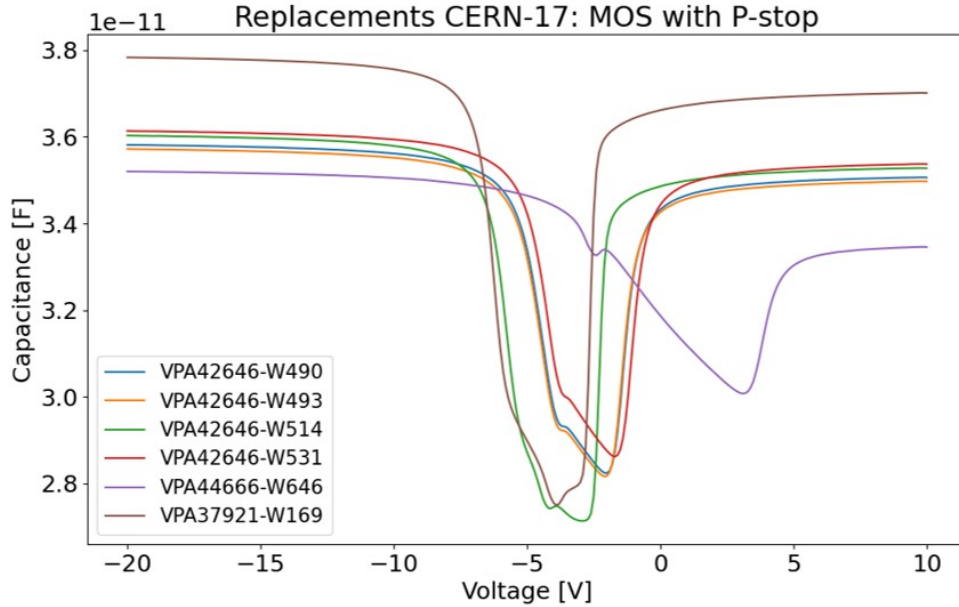


Figure 5.2: C-V curves of MOS Capacitors with p-stop measured on four QA Testchips from the rejected batch VPA42646, together with representative C-V curves from QA Testchips of another rejected batch (VPA37921) and a good reference batch (VPA44666).

For Experiments 1 and 2, five Main sensors from batch VPA42646 were irradiated with γ + n at different doses and fluences to analyze the irradiation effects on R_{int} . In addition, three Mini sensors were irradiated for CCE measurements.

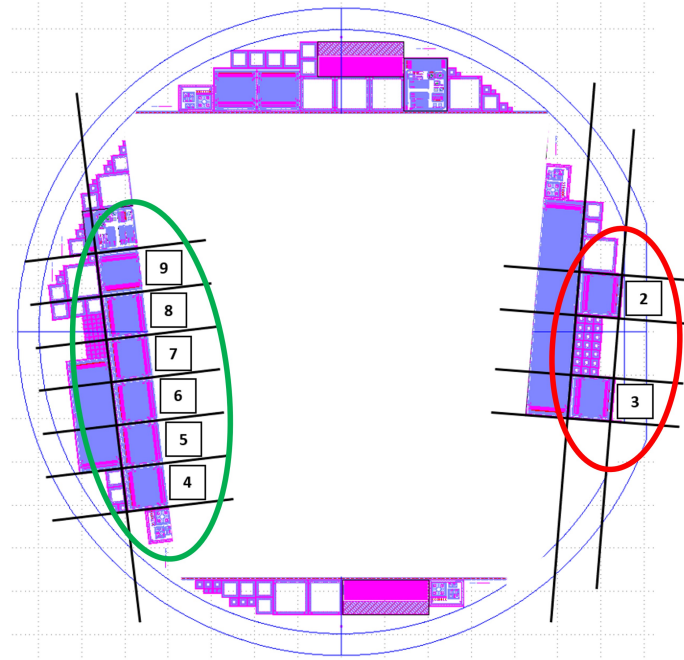
Table 5.3 summarizes the TID and fluence employed to irradiate each device (Main and Mini sensors), covering values from 2 Mrad and $5.0 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ to 66 Mrad and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

For Experiment 3, twelve Mini sensors were diced from the half-moons of affected wafers: six from the left (good) side and six from the right (bad) side of the wafer. Previous studies had shown that the low p-stop effect predominantly affected the right side of the wafer; this dicing scheme therefore provided Mini sensors with both nominal and reduced p-stop implantation dose. This setup allowed a direct comparison between sensors with good and poor p-stop performance.

The dicing scheme of the Mini sensors from R0-type wafers is shown in Figure 5.3. Three different wafers (W490, W493, and W514) from batch VPA42646 were required to obtain all Mini sensors from the right side of the wafer layout (only two Mini sensors per wafer). In contrast, all Mini sensors from the left side were diced from wafer W490.

Table 5.3: Irradiation ($\gamma + n$) doses and fluences for each Main and Mini sensor used in Experiments 1 and 2 of the post-irradiation p-stop study.

Type	Wafer	TID (Mrad)	Fluence (n_{eq}/cm^2)
MAIN	W531	2.0	5.0×10^{13}
MAIN	W532	4.1	1.0×10^{14}
MAIN	W493	16.5	4.0×10^{14}
MAIN	W490	21	5.1×10^{14}
MAIN	W514	66	1.6×10^{15}
Mini	W493	16.5	4.0×10^{14}
Mini	W531	21	5.1×10^{14}
Mini	W492	66	1.6×10^{15}

**Figure 5.3:** Dicing scheme of the Mini sensors obtained from R0-type wafers of the rejected batch VPA42646. Mini sensors from the left side of the wafer are circled in green, while those from the opposite side are circled in red.

These Mini sensors were irradiated with gamma rays up to 1, 3, 5, 10, 21, and 66 Mrad, following the distribution listed in Table 5.4. Given the well-known progressive degradation of inter-strip isolation with increasing gamma dose, the recovery of R_{int} observed in Figure 5.1—after the minimum around $5.1 \times 10^{14} n_{eq}/cm^2$ —was expected to be driven by neutron irradiation. For this reason, the gamma irradiations summarized in Table 5.4 were subsequently complemented with neutron irradiations at fluences corresponding

to each dose, allowing the individual and combined effects of $\gamma + n$ irradiation on the sensors to be studied.

Table 5.4: Gamma irradiation doses for each Mini sensor used in Experiment 3 of the post-irradiation p-stop study, for both the left and right sides of the wafers.

Wafer	Type	Position within the wafer	Gamma TID (Mrad)
W490	Mini 4	left	1
W490	Mini 5	left	3
W490	Mini 6	left	5
W490	Mini 7	left	10
W490	Mini 8	left	21
W490	Mini 9	left	66
W490	Mini 3	right	1
W490	Mini 2	right	3
W493	Mini 3	right	5
W493	Mini 2	right	10
W514	Mini 3	right	21
W514	Mini 2	right	66

5.1.3 Results

The results of the two experiments described in the previous subsection—the special p-stop batches study and the post-irradiation p-stop performance study—are presented here, along with the corresponding conclusions and proposed next steps.

Special p-stop batches

For all processed p-stop types, all pre-irradiation tests on both Main sensors and half-moon Testchips met the ATLAS ITk Strip Sensor specifications (or at least fell within the parameter-monitoring soft thresholds): $V_{BD} > 500$ V, $I_{500V} < 0.1 \mu\text{A}/\text{cm}^2$, and V_{PT} between 12 and 18 V, as well as a successful Full Strip Test.

Figure 5.4 shows the punch-through resistance (R_{PT}) curves used to extract the V_{PT} values from half-moon measurements performed at IMB-CNM for all p-stop process conditions (types 1–4). These results are consistent with those obtained for the Main sensors, with type 4 exhibiting both the smallest V_{PT} variation across the wafer and the highest V_{PT} value

(approximately 2 V higher than the other V_{PT} values in absolute terms). The differences observed in type-4 samples are attributed to the modified processes.

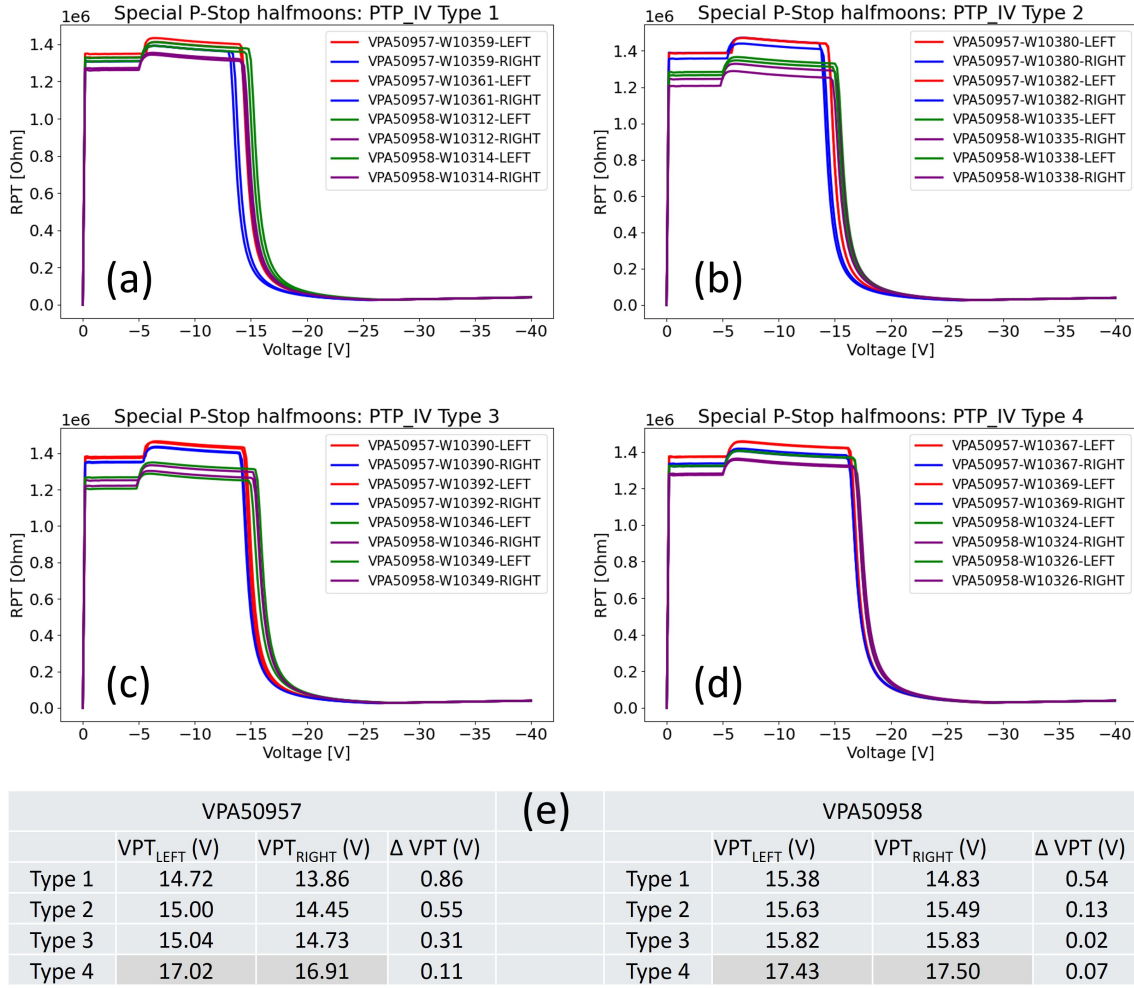


Figure 5.4: R_{PT} curves measured on Testchips from the left and right half-moons for (a) type 1, (b) type 2, (c) type 3, and (d) type 4 of the special p-stop batches VPA50957 (red/blue) and VPA50958 (green/purple). Panel (e) presents a table summarizing the V_{PT} values extracted from plots (a)–(d) and the variation (Δ) between the left and right sides of the wafer.

The plots in Figure 5.5 show the C–V curves of MOS Capacitors with p-stop, used to extract S_{REF} values to complement the V_{PT} results. These measurements were performed on Testchips from left and right half-moons. The extracted S_{REF} values are consistent with the corresponding V_{PT} values measured on the same Testchips, i.e., a lower V_{PT} corresponds to a higher S_{REF} . Overall, V_{PT} and S_{REF} are within acceptance limits, thereby validating these p-stop fabrication processes and confirming proper p-stop isolation based on the pre-irradiation results.

After irradiation, all V_{PT} values measured on Testchips remained within the specifications, with the exception of one over-irradiated sample, as shown in Figure 5.6. In general, V_{PT} tends to increase with fluence and TID, remaining relatively constant for type-3 and

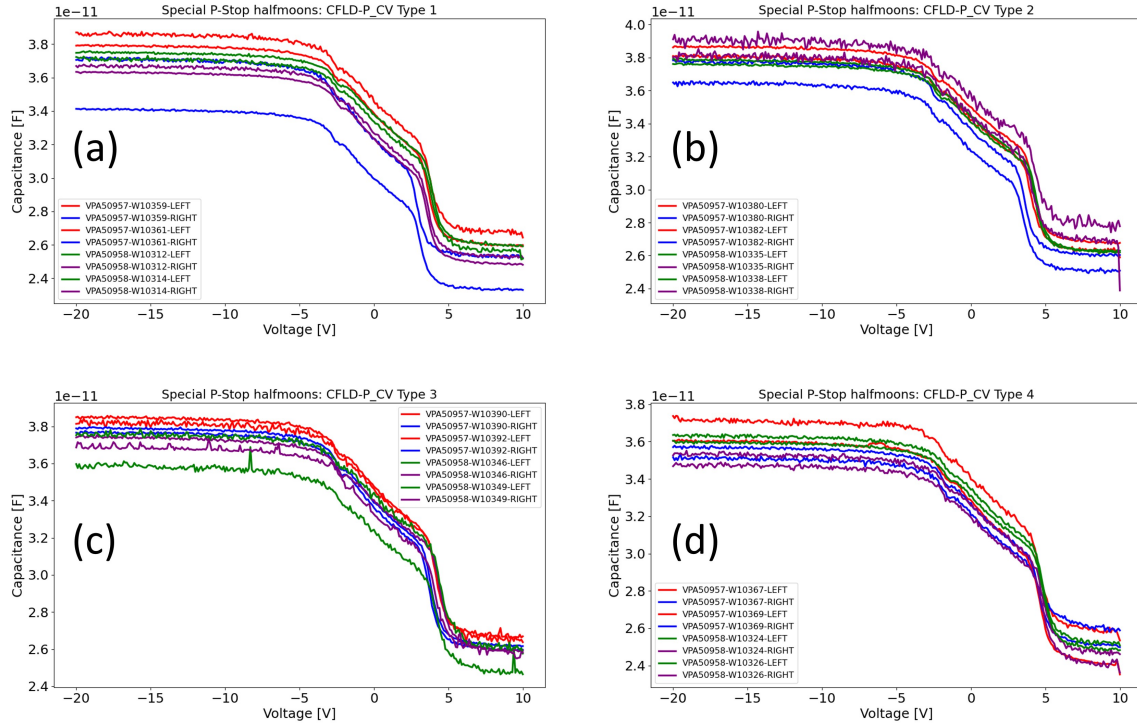


Figure 5.5: C–V curves of the MOS Capacitors with p-stop measured on Testchips from the left and right half-moons for (a) type 1, (b) type 2, (c) type 3, and (d) type 4 of the special p-stop batches VPA50957 (red/blue) and VPA50958 (green/purple).

type-4 Testchips. In contrast, a significant increase in V_{PT} , reaching nearly 35 V, was observed in Main sensors—measured at six different positions within the wafer—after mid-fluence irradiation.

It was verified that V_{PT} in Testchips shows no temperature dependence, whereas this parameter varies significantly in Main sensors, possibly due to the increasing and significant leakage current with temperature. For this reason, additional Main sensors were irradiated up to full fluence to compare their behavior with that of sensors irradiated only up to mid fluence. The newly irradiated Main sensors exhibited V_{PT} values slightly above the maximum threshold but, unexpectedly, lower than those measured after mid-fluence irradiation. This effect is still under investigation. For all irradiation conditions (pre-irradiation, mid fluence, and full fluence), V_{PT} increases from type 2 to type 4. All these measurements are shown in Figure 5.6, within the acceptance limits indicated by horizontal red lines, except for a single data point slightly above the maximum threshold. In any case, the p-stop functionality is maintained under the irradiation conditions studied for all samples.

Although measurements were performed at -20 , -25 , and -30 °C at different laboratories, R_{int} values were normalized to -20 °C due their strong temperature dependence. As shown in Figure 5.7, where R_{int} is normalized by strip length, this parameter decreases

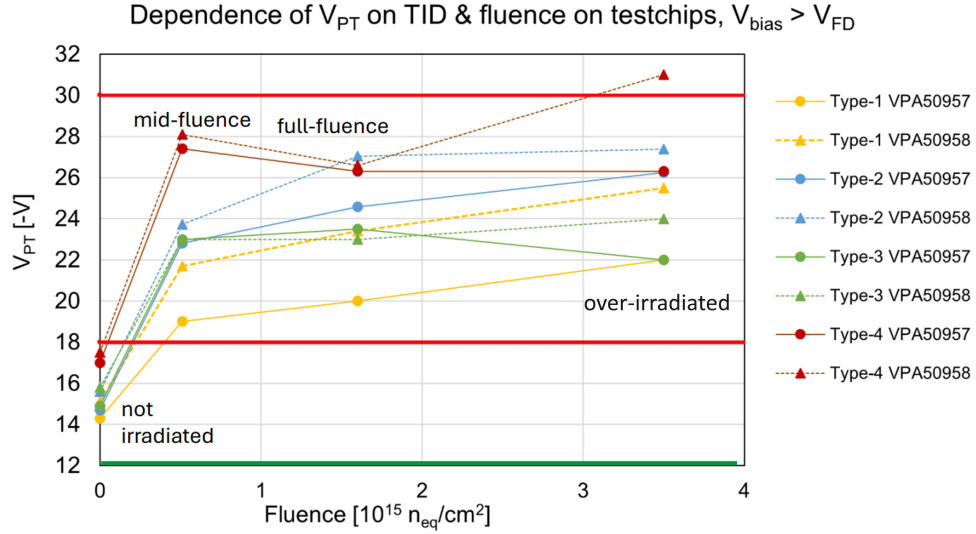


Figure 5.6: V_{PT} values measured on Testchips for the four p-stop process types under pre-irradiation, mid-fluence, full-fluence, and over-irradiation ($\gamma + n$) conditions. Pre- (green) and post-irradiation thresholds are indicated by green and red horizontal lines, respectively. Adapted from [114].

with increasing fluence and dose for all p-stop process types. Nevertheless, all R_{int} values meet the specifications ($R_{int} > 15 \text{ M}\Omega$).

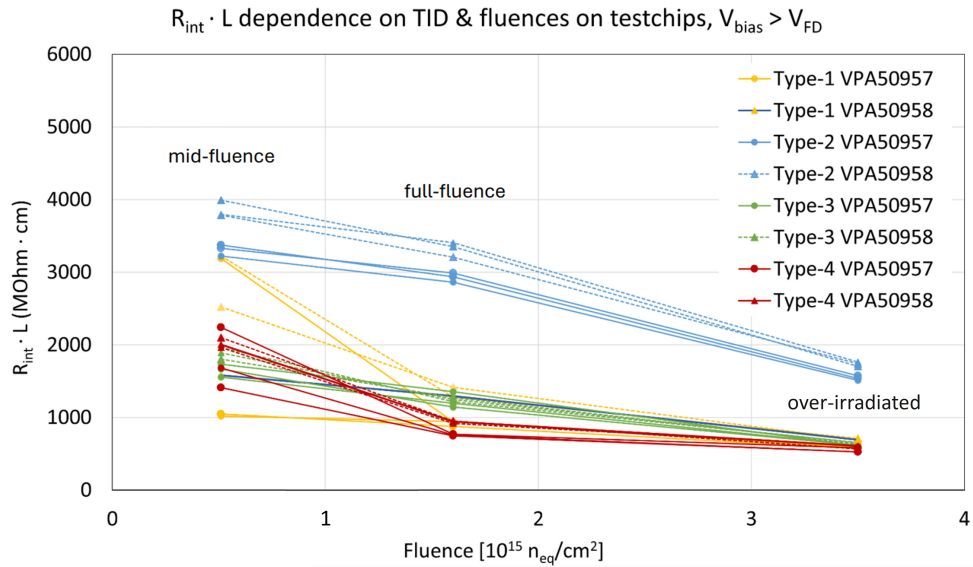


Figure 5.7: Strip-length- and temperature-normalized R_{int} values measured on UP, MID, and LOW interdigitated structures of Testchips for the four p-stop process types under mid-fluence, full-fluence, and over-irradiation ($\gamma + n$) conditions. Adapted from [114].

Type 4 exhibits the lowest R_{int} , suggesting a less effective p-stop implantation, which contrasts with the conclusions drawn from the V_{PT} analysis, where the same type shows the highest V_{PT} . Indeed, the general R_{int} trend from type 2 to type 4 is unexpectedly opposite to that observed for V_{PT} across all p-stop process types measured on Main sensors,

possibly due to the larger contribution of displacement damage to the V_{PT} parameter, as discussed in Section 4.1.

Anyway, further studies are required to achieve a better understanding of this behavior. Nevertheless, the differences observed in R_{int} and V_{PT} among the different p-stop process types are small and not significant under the expected operating conditions. All parameters meet the specifications at the target (realistic) fluences and doses.

Regarding the charge collection efficiency, all CCE tests performed on Mini sensors irradiated up to full fluence meet the specifications ($CCE_{500V} > 6350 \text{ e}^-$ at -500 V). Measurements of CCE_{500V} on over-irradiated Mini sensors fall slightly below the minimum threshold; however, this is not critical, as these devices were irradiated beyond the expected operating fluence under real experimental conditions. The collected charge as a function of bias voltage is shown in Figure 5.8 for p-stop process types 1–4 under full-fluence and over-irradiation conditions.

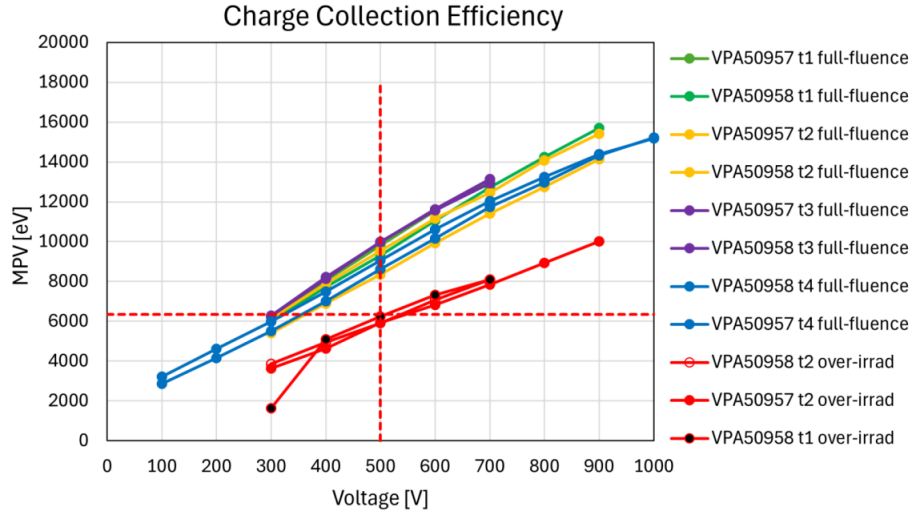


Figure 5.8: CCE as a function of voltage for all p-stop process types 1–4 and all irradiated Mini sensors (full fluence and over irradiation). Adapted from [114].

In any case, as explained in Chapter 4.3.4, the foundry identified the origin of the low p-stop implantation and implemented corrective measures. The proposed process variations and the additional studies presented here contributed to a more robust fabrication process and to a comprehensive understanding of p-stop behavior under harsh radiation conditions.

Post-irradiation effects on the p-stop

Experiments 1 and 2 performed on Main sensors were combined for the extraction and representation of R_{int} over a wide range of fluences and doses. With the additional $\gamma + n$

irradiation data, a new minimum in R_{int} was identified close to the previously observed minimum at $21 \text{ Mrad} + 5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. At low irradiation levels, TID effects dominate, leading to a decrease in R_{int} up to approximately $4.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. As irradiation progresses, displacement damage becomes the dominant mechanism, resulting in an increase in R_{int} , as shown in Figure 5.9 (right).

The schematic on the left side of Figure 5.9 illustrates the Main sensor segmentation, while the right-hand plot shows the R_{int} values for all segments (S0, S1, S2, and S3) on both the left (good, green) and right (bad, red) sides of the wafer. For all irradiation fluences, significantly lower R_{int} values are observed on the right (red) side of the sensor, consistent with a reduced p-stop implantation level. TCAD simulations [82, 110] indicate a p-stop density variation within the wafer from approximately $0.5 \times 10^{12} \text{ cm}^{-2}$ to $1.0 \times 10^{12} \text{ cm}^{-2}$, corresponding to about one-eighth to one-quarter of the nominal value. Nevertheless, the measured R_{int} values remain well within specifications. Two data points corresponding to measurements in segment S3 in the Main sensor do not follow the general trend observed for the other values; this isolated behavior may be related to local p-stop implantation defects.

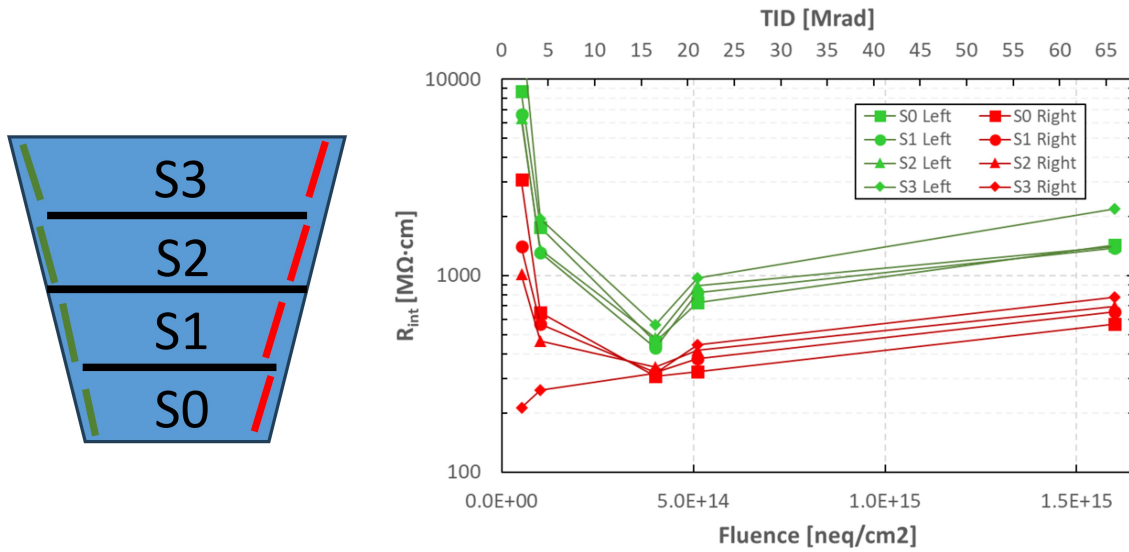


Figure 5.9: Schematic of the R0 Main sensor segmentation (left), indicating the left (green) and right (red) positions within the wafer, and the evolution of R_{int} with fluence and dose (right), measured for each segment on both sides of sensors from batch VPA42646 irradiated with $\gamma + n$.

The three additional Mini sensors from batch VPA42646 (Table 5.3), irradiated together with the Main sensors, were also tested for CCE, and the results are shown in Figure 5.10. All $\text{CCE}_{500\text{V}}$ measurements on these Mini sensors irradiated with $\gamma + n$ up to $4.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ meet the specifications, indicating good performance despite the low p-stop implantation in batch VPA42646. Therefore, the general post-irradiation performance of the sensors is not affected by the low p-stop implantation.

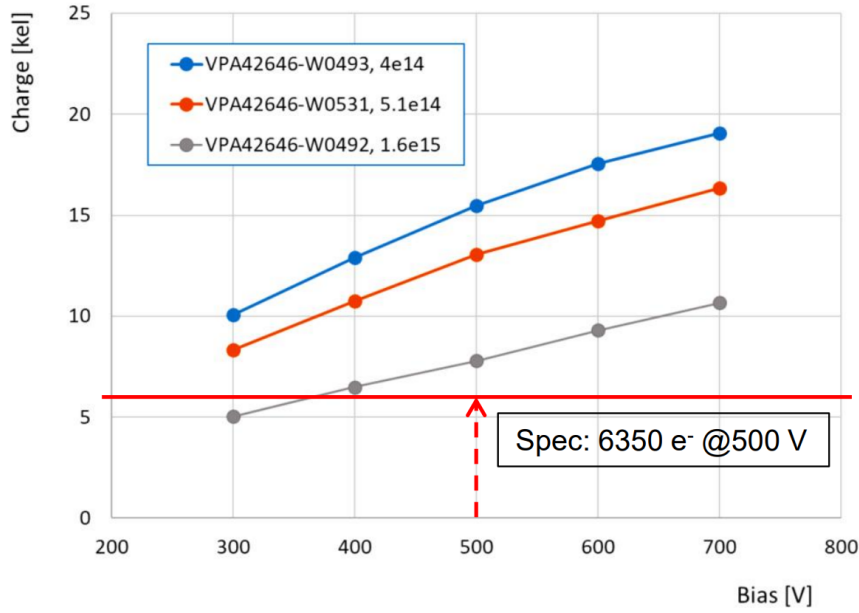


Figure 5.10: Collected charge as a function of voltage on Mini sensors irradiated with $\gamma + n$ up to $4.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (VPA42646-W493), $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (VPA42646-W531), and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (VPA42646-W492).

Regarding Experiment 3, the gamma dose at which R_{int} falls below specifications is significantly lower for Mini sensors with low p-stop implantation doses, which were selected from the right side of the wafers (see Table 5.4). For the “good” Mini sensors (green), this occurs at approximately 14 Mrad, whereas for low p-stop Minis (red) it occurs around 4 Mrad, as indicated in Figure 5.11. These measurements were obtained using gamma irradiation only, implying that the observed degradation is more severe than what would be expected under realistic experimental conditions. Additionally, the TID-induced damage exhibits saturation at doses higher than 20 Mrad (200 kGy).

In contrast, the combined effect of the $\gamma + n$ irradiation on Mini sensors alters the R_{int} trend observed under gamma-only irradiation, yielding R_{int} values several orders of magnitude higher at large fluences. For Mini sensors with low p-stop implantation irradiated with $\gamma + n$, R_{int} remains significantly lower than in standard sensors, although still well above the specified limits.

The observed minimum in R_{int} may therefore be influenced by the p-stop implantation level. Further investigations will focus on determining both the position and magnitude of this minimum. In particular, a mapping of the R_{int} as a function of TID and NIEL (Non-Ionizing Energy Loss) is already planned, with emphasis on $\gamma + n$ fluences and doses close to the R_{int} minimum.

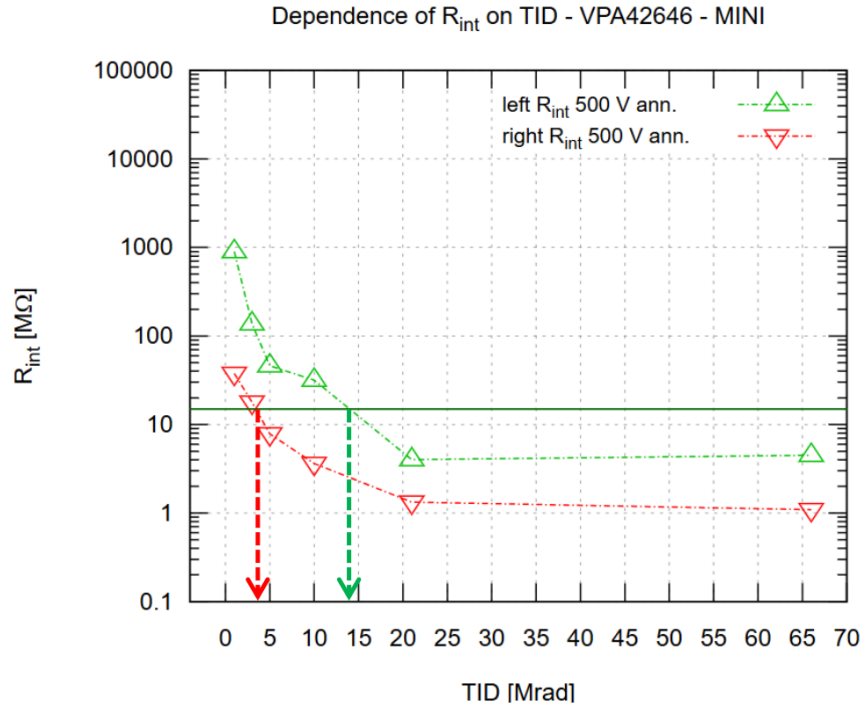


Figure 5.11: Evolution of R_{int} with dose measured on Mini sensors irradiated only with gamma rays, for both the left (green) and right (red) sides of the wafer.

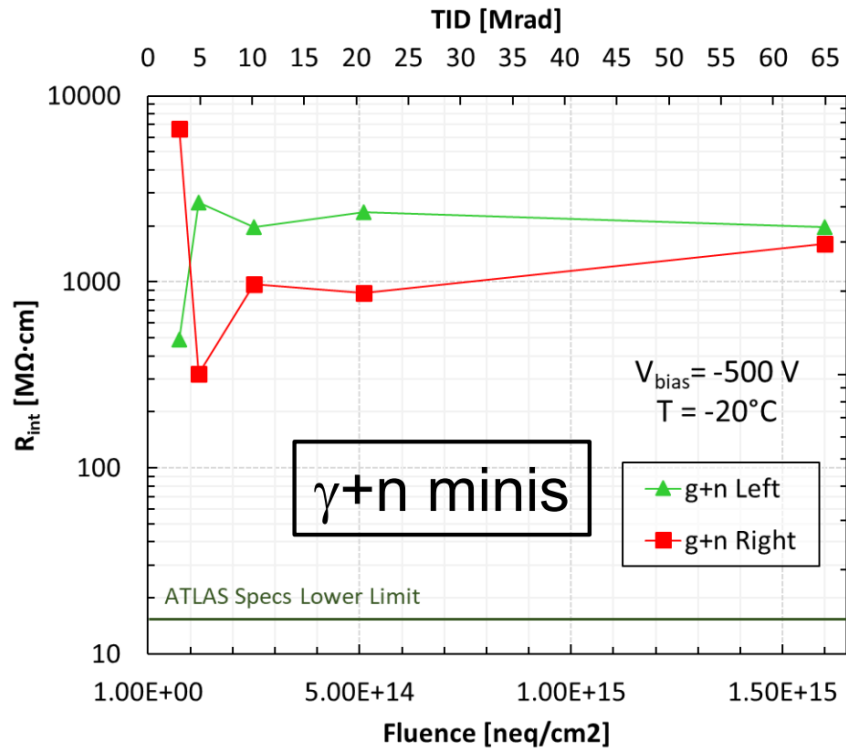


Figure 5.12: Evolution of R_{int} with dose measured on Mini sensors irradiated with $\gamma + n$, for both the left (green) and right (red) sides of the wafer.

Overall, these results show that a reduced p-stop implantation weakens surface isolation and increases the sensor's sensitivity to radiation-induced charge buildup, highlighting the importance of precise p-stop control for long-term detector stability and performance.

5.2 Study of 24 GeV Proton Damage as a Function of Fluence on Testchips and Mini Sensors

5.2.1 Origin of the Problem

The ITk strip sensors will have to withstand a fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in the real experiment (this value includes a safety factor of 1.5). To verify the radiation hardness of the sensors, several studies were conducted during sensor development, in which sensors were subjected to various irradiation conditions, including reactor neutrons (Ljubljana), 25 MeV protons (CYRIC), and 70 MeV protons (MC40), which were also used in production QA procedures. Highly energetic protons (24 GeV) were also employed in these studies and were obtained from the IRRAD facility [115] at the CERN Proton Synchrotron (PS).

Due to its lower availability, the IRRAD facility was not one of the QA irradiation sites for the systematic production process; however, it was included in several irradiation campaigns to study the effects of high-energy hadrons (24 GeV) on production samples.

Radiation damage induced in silicon sensors can vary depending on the type of irradiating particle, even for the same non-ionizing energy loss (NIEL). In future experiments in the upgraded ATLAS ITk, both neutrons and charged hadrons will induce bulk damage, with neutrons even dominating in some of the less-exposed regions of the ITk. Irradiation studies with 24 GeV protons are therefore relevant, as the damage produced closely mimics that caused by the hadrons expected in ATLAS at energies of hundreds of MeV [116].

Earlier studies of ITk strip sensor prototypes (ATLAS17LS) irradiated with 24 GeV protons [117–119] demonstrated good radiation tolerance, although a larger degradation was observed compared to sensors irradiated with CYRIC and Birmingham protons. However, subsequent tests on ATLAS18 production sensors irradiated up to a fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ revealed charge collection below the QA threshold (6350 e^- at 500 V) and higher leakage current compared to sensors irradiated with CYRIC and Birmingham MC40 protons.

No clear evidence of an issue with the IRRAD irradiation setup was identified. The observed degradation could instead be related to intrinsic characteristics of the 24 GeV

PS proton beam, consistent with features previously observed in ATLAS17LS irradiations at the PS [118]. These unexpected results motivated the dedicated irradiation studies and simulations presented in the following sections, aimed at understanding the origin of the reduced charge collection.

5.2.2 Experiments Made

Two experiments were carried out in 2021 and 2022 to study the irradiation effects on ATLAS18 samples exposed to 24 GeV protons from the IRRAD test facility. The IMB-CNM contribution to these experiments, which are presented together in this chapter, focused on the study of several QA parameters of Testchips irradiated in 2022 to four different proton fluences.

One year later, in 2023, and following a detailed analysis of the previous studies, a new irradiation campaign was conducted at IRRAD to perform a systematic study of the effect of the incident angle and the mechanical support material used for 24 GeV proton irradiation, again at the same four fluence levels.

The IRRAD PS proton beam used in these experiments was narrow and exhibited an approximately Gaussian intensity distribution, with full widths at half maximum of $\text{FWHM}_x = 7.8 \text{ mm}$ and $\text{FWHM}_y = 9.7 \text{ mm}$ [120, 121]. During irradiation, the samples were held at a fixed position within the beam rather than being scanned.

These irradiation conditions were dictated by limitations of the IRRAD facility, which constrained the size and spatial distribution of the samples and prevented uniform irradiation across their full area. As a result, different regions of a given sample—and, in some cases, different test structures on the same device—were exposed to significantly different fluences. This non-uniform irradiation is shown in the following sections to play a key role in the interpretation of the experimental results and in the observed variations in sensor performance.

Basic study of damage from the PS proton beam at four fluences (2021, 2022)

The first experiment investigating PS proton-induced damage on ATLAS18 samples began in 2021 with the irradiation of Testchip&MD8 and Mini&MD8 pieces to a fluence of $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. For the irradiation, the samples were placed one behind the other in a custom-made support specifically designed for this purpose, consisting of a structure made of G10 glass-epoxy material. The QA pieces were tilted by 2.25° relative to the proton beam to improve the uniformity of the irradiation across these small devices. Figure 5.13 shows a 3D schematic (top) and a photograph (middle) of the G10 mechanical

support, as well as a transverse view of the structure with the beam-incident points indicated (bottom), corresponding to the Testchip&MD8 and Mini&MD8 irradiation columns.

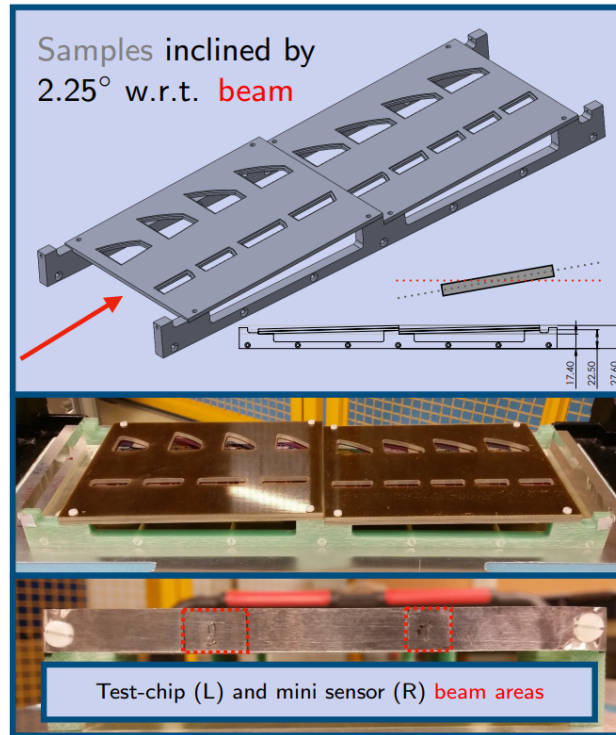


Figure 5.13: 3D schematic (top) and photograph (middle) of the mechanical support made of G10 material used for PS irradiations, and transverse view of the structure with the beam-incident points indicated (bottom) [122].

This was the first IRRAD experiment performed with ATLAS18 samples revealing very low charge collection efficiency after annealing, typically outside QA specifications ($CCE_{500V} > 6350 e^-$), and leakage current substantially higher than that observed in samples irradiated with protons to the same equivalent fluence at CYRIC and MC40 [122]. While IMB-CNM did not play a significant role in this study, it was instrumental in the design, planning, measurements, and analysis of the subsequent IRRAD studies.

A series of follow-up proton irradiations at IRRAD was arranged to support three dedicated studies, with irradiation runs completed in 2022:

- **Experiment 1: Study of “special” damage from the PS proton beam**
 - The objective was to repeat the 2021 experiment to verify the previous results, extending it to several fluences in order to study a broader radiation range and better understand the IRRAD observations.

- Eight Mini sensors and eight Testchips from the standard batch VPA38186 were used, irradiated at four different fluences: $1.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $1.0 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.
- **Experiment 2: Study of damage in low inter-strip isolation sensors**
 - The objective was to improve the understanding of bulk and surface damage in samples exhibiting low p-stop implantation from the rejected batch VPA37921, despite showing “normal” CCE after MC40 proton irradiation.
 - Eight Mini sensors and eight Testchips were used, irradiated at the same four fluences as in Experiment 1.
- **Experiment 3: Study of long-term annealing behavior**
 - The objective was to gain a better understanding of the long-term annealing effects on the CCE of Mini sensors.
 - Eight Mini sensors were irradiated at the same four fluences.

The author’s work in this thesis contributed to Experiments 1 and 2, which were conducted in parallel. The results from Experiment 1 served as a reference for comparison with those obtained from Experiment 2. The annealing study planned for Experiment 3 was ultimately not performed, as unintentional annealing occurred during the shipment of the samples from CERN.

The setup employed in Experiments 1 and 2 is illustrated in Figure 5.14. A G10-material support was designed to hold the samples for proper irradiation. This setup is very similar to that used in the previous IRRAD experiment in 2021, and the same PS beam characteristics were maintained. In this case, the samples were irradiated at a shallow angle of 1.45° with respect to the beam. A total of 32 sample cutouts were included in the support, allowing the irradiations of Experiments 1 and 2 to be performed one after the other.

The schematic shown in Figure 5.15 provides an alternative illustration of the setup, indicating the irradiation fluences assigned to each column in the support, the Testchips and Mini sensors corresponding to each fluence, and the classification of samples according to Experiment 1 or Experiment 2. In addition, the schematic shows the test sites assigned to each sample for subsequent measurements.

The Testchips distributed to IMB-CNM are summarized in 5.5. For each experiment (1 and 2), one Testchip per fluence was measured at IMB-CNM to extract the Testchip parameters as a function of fluence. Measurements were performed at -20°C under dry conditions before annealing, followed by annealing for 80 minutes at 60°C , and

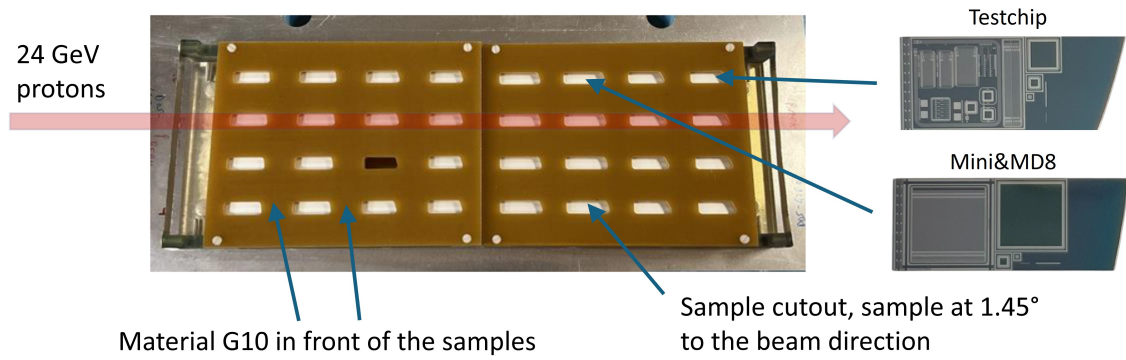


Figure 5.14: Mechanical support made of G10 material used for PS irradiations in 2022. Testchips and Mini sensors are placed in each sample cutout. Adapted from [123].

EXPERIMENT 1				EXPERIMENT 2 + ANNEALING STUDIES				
	LS M1	LS M1	LS A2	LS A2	R0 M1	R0 M1	R0 A1	R0 A1
1.0e14	20USBSL0101304	20USBSL0101305	20USBSL0701304	20USBSL0701305	20USES00100197 20USES00100255	20USES00100212 20USES00100261	20USES00700197	20USES00700212
5.1e14	20USBSL0101302	20USBSL0101303	20USBSL0701302	20USBSL0701303	20USES00100195 20USES00100247	20USES00100196 20USES00100252	20USES00700195	20USES00700196
→ Beam	20USBSL0101299 20USBSL0101320	20USBSL0101300	20USBSL0701299 Broken. Empty	20USBSL0701300	20USES00100188 20USES00100230	20USES00100194 20USES00100242	20USES00700188	20USES00700194
1.0e15	20USBSL0101297 20USBSL0101311	20USBSL0101298	20USBSL0701297	20USBSL0701298	20USES00100179 20USES00100219	20USES00100180 20USES00100224	20USES00700179	20USES00700180
	POLISHED							
Destination:	Ljubljana	Toronto	Birmingham	CNM	Birmingham	Toronto	Birmingham	CNM

Figure 5.15: Sample classification for Experiments 1 and 2 from the IRRAD studies performed in 2022.

then repeated at $-20\text{ }^{\circ}\text{C}$. These tests were carried out using the manual probe station in the Radiation Detectors Laboratory at IMB-CNM, equipped with a thermal chuck for accurate temperature control.

Table 5.5: Testchips from batches VPA38186 and VPA37921 used in Experiments 1 and 2, respectively, at four different fluences.

Proton fluence (n_{eq}/cm^2)	Experiment 1 (batch VPA38186)	Experiment 2 (batch VPA37921)
1.0E14	20USBSL0701305	20USES00700212
5.1E14	20USBSL0701303	20USES00700196
1.0E15	20USBSL0701300	20USES00700194
1.6E15	20USBSL0701298	20USES00700180

Overall, a comprehensive study of sensor damage was performed for both standard and low p-stop batches, followed by investigations of setup material and tilt angle effects.

Study of the effects of angle and material for a PS beam at four fluences (2023)

Results from the previous experiments conducted in 2021 and 2022 suggested a potential increase in effective fluence due to secondary particles produced either by the G10 glass-epoxy material or by the silicon itself when irradiated at shallow angles. This effect could explain the observed decrease in CCE at high IRRAD-proton fluences. Consequently, a new experiment was designed in 2023 to better understand the origin of the reduced charge collection, using Testchip&MD8 and Mini&MD8 pieces from production QA.

The IRRAD proton beam employed in this experiment was the same as in previous studies, exhibiting a Gaussian intensity distribution with full widths at half maximum of $\text{FWHM}_x = 7.8 \text{ mm}$ and $\text{FWHM}_y = 9.7 \text{ mm}$.

Figure 5.16 illustrates both a schematic (top) and a photograph (middle) of the new setup used in this experiment. A G10 mechanical support was fabricated to hold four columns of devices, corresponding to one irradiation fluence per column. All samples—including Testchips, MD8s, and Mini sensors from batch VPA41725—were cut to $1 \times 1 \text{ cm}^2$ and arranged in holders (rows) perpendicular to the beam axis. The holders were oriented at different angles (90° , 12° , 6° , and 1.5°), with and without G10 blocks in front of the devices. The holders were made of a thin layer of PolyEther Ether Ketone (PEEK). The sample arrangement and classification are shown in the bottom schematic of Figure 5.16.

Seven layers of aluminum (Al) foils were placed at different points along the beam axis to obtain dosimetry data. The proton fluence was determined from the radioactive decay of Na-24 induced in the Al foils.

For each angle, four irradiation fluences were studied: $1.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $1.0 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

Each column, corresponding to a given proton fluence, was separated by 2.4 cm from the neighboring columns. The samples were kept at a fixed position during irradiation, with the beam centered on one column at a time, and each column was irradiated sequentially up to the target fluence. However, as will be shown in the Results section, the target fluences were not fully reached because the experiment was interrupted due to a technical incident at the IRRAD facility.

Monte-Carlo (Geant4) simulations showed that the influence of irradiation from one column on neighboring columns via secondary radiation was below 1% for the eight holders closest to the beam origin, and below 4% for the furthest holders [116].

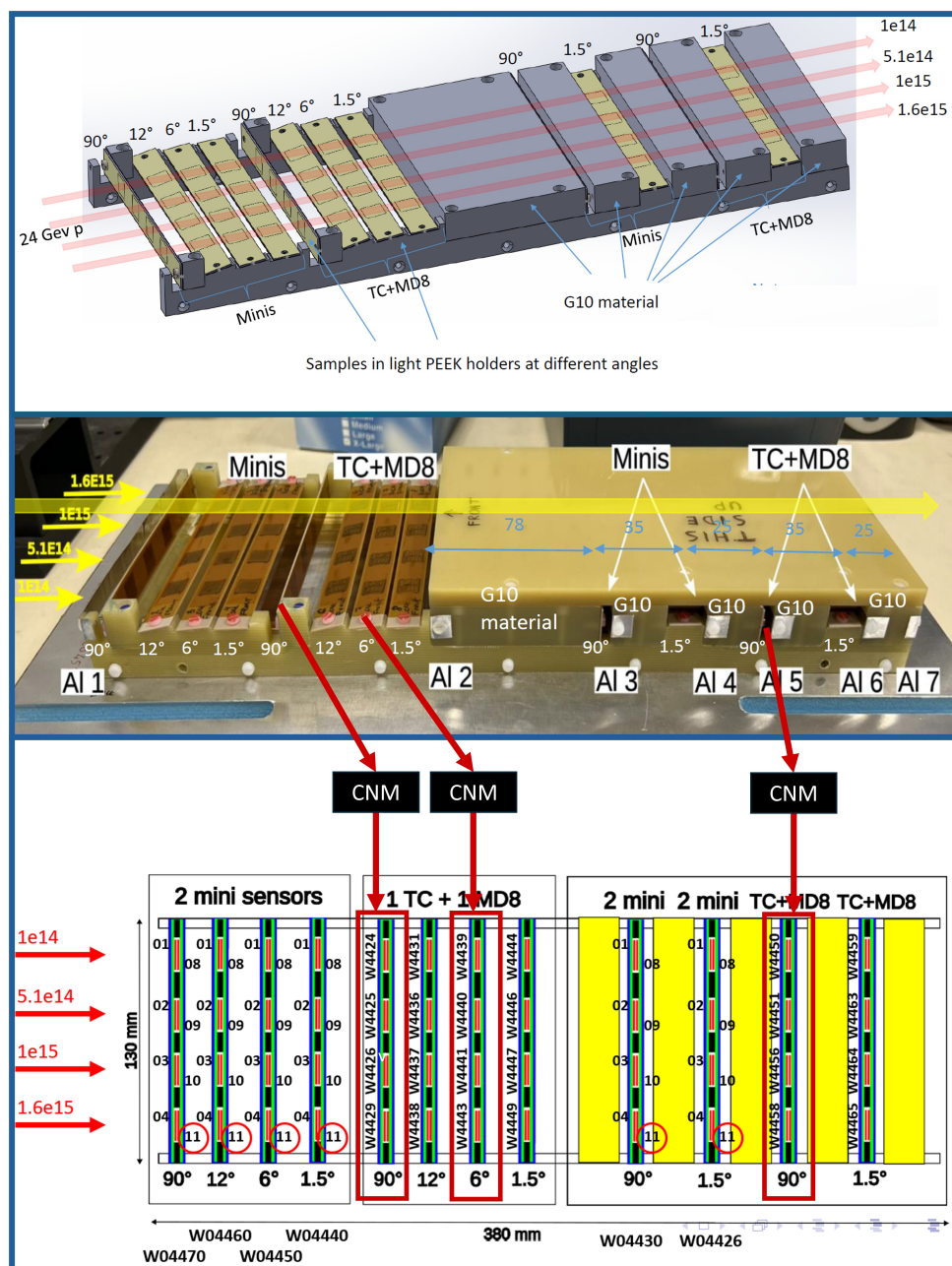


Figure 5.16: 3D schematic (top) and photograph (middle) of the G10 mechanical support used for the PS irradiation experiment in 2023. Sample arrangement of all QA pieces from batch VPA41725 placed in the support (bottom), indicating the Testchips measured at IMB-CNM. Adapted from [124–126].

The diced MD8s and Testchips used in this experiment were distributed among various test sites to perform different studies. The measurement plan is the following:

MD8:

- Ljubljana: Measure C–V and I–V curves for two fluences (5.1×10^{14} n_{eq}/cm² and 1.6×10^{15} n_{eq}/cm²) at all angles, with and without G10 material.

- Study the effect of angle.
- Toronto: Measure C–V and I–V curves for two fluences (1×10^{14} n_{eq}/cm² and 1×10^{15} n_{eq}/cm²) at all angles, with and without G10 material.
- Study the effect of angle.

Testchip:

- IMB-CNM: Measure R_{int} and V_{PT} for all fluences at three angles (90°, 6°, and 90° with G10 material).
 - Study the damage with fluence and material.
- Toronto: Measure R_{int} and V_{PT} for all fluences at three angles (12°, 1.5°, and 1.5° with G10 material).
 - Study the damage with fluence and material.

In total, 12 Testchips were measured at IMB-CNM after proton irradiation of Testchips oriented at 90°, 6°, and 90° with G10 material in front of the devices.

Additional measurements were performed at other collaborating institutes using the Mini sensors irradiated in this experiment, focusing on CCE and annealing studies. A brief analysis of these results is also provided at the end of the Results section.

5.2.3 Results

Basic study of damage from the PS proton beam at four fluences

In this subsection, results from Experiment 1 and Experiment 2 corresponding to the study performed in 2022 are presented together to analyze the differences observed between standard Testchips and those with poor p-stop doping concentration. The inter-strip resistance (R_{int}), the punch-through voltage (V_{PT}), and the bias resistance (R_{bias}) were the most significant parameters measured from the eight Testchips assigned to IMB-CNM in this study, both before and after annealing for 80 min at 60 °C.

I–V measurements were also performed on the MD2 diodes of the four standard Testchips (batch VPA38186), before and after annealing, providing an initial characterization of proton-irradiation effects at various fluences. The left plot in Figure 5.17 shows the I–V curves measured on the MD2 structures after annealing, while the right plot illustrates this leakage current at 700 V for both pre- and post-annealing conditions. The leakage current exhibits an increasing linear trend with irradiation fluence due to the formation

of mid-gap defects in the bulk, in agreement with Eq. (1.14) in Chapter 1. This current slightly decreases after annealing, which produces beneficial effects on the sensors.

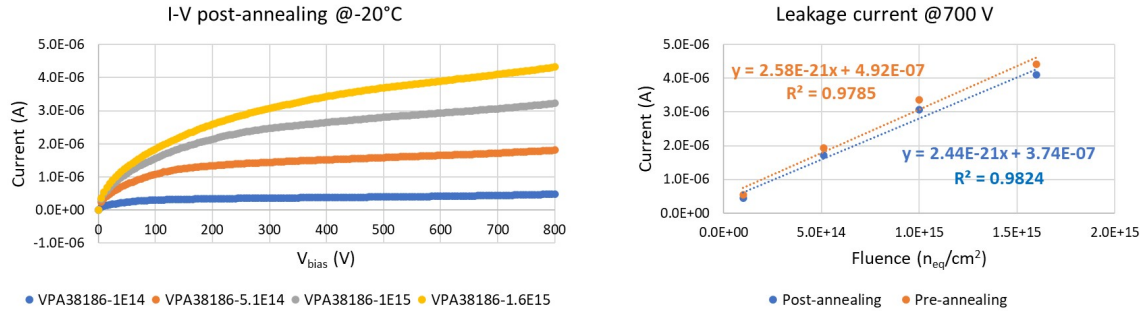


Figure 5.17: Post-annealing I–V curves measured on MD2 structures from the Testchips at -20°C for all fluences (left). Leakage current at 700 V before and after annealing as a function of fluence (right).

After irradiation, R_{int} increases with bias voltage (V_{bias}) due to the progressive depletion of the silicon bulk. The R_{int} trend as a function of voltage is shown in Figure 5.18, exhibiting a rapid increase with V_{bias} at lower fluences. This increase becomes limited at higher fluences, nearly saturating at large V_{bias} values. In the right plot of Figure 5.18, only the three highest fluence values are shown, as R_{int} lies outside the plot range for the fluence $1.0 \times 10^{14} n_{eq}/cm^2$.

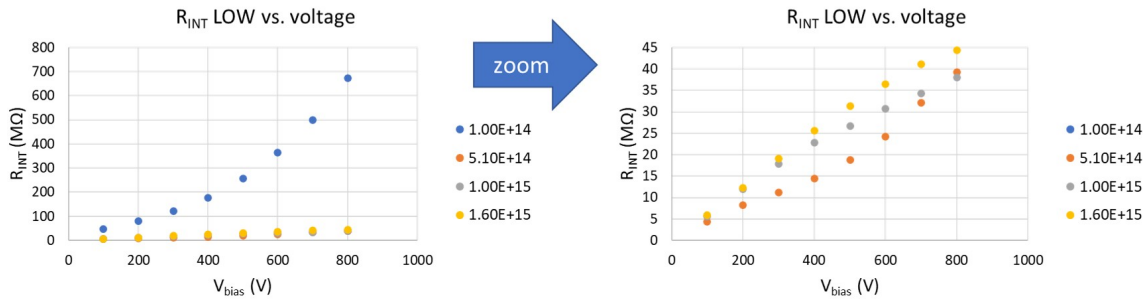


Figure 5.18: R_{int} measured after annealing as a function of bias voltage for all fluences (left), and an extended view focusing on the lowest R_{int} range corresponding to higher fluences (right).

The R_{int} measured at 500 V in the LOW interdigitated structure, before and after annealing, is shown in Figure 5.19 for the four target fluences. In both pre- and post-annealing cases, R_{int} decreases at the low fluences up to $5.1 \times 10^{14} n_{eq}/cm^2$ and increases for higher fluence values. This behavior has already been discussed in Figure 5.1 of this chapter and is supported by results obtained from Main sensors after neutron + gamma irradiation [113]. The initial decrease in R_{int} is attributed to ionization damage, which tends to saturate with accumulated dose. Once R_{int} reaches a minimum, displacement damage becomes dominant, leading to a subsequent increase in R_{int} with proton fluence.

From the comparison in Figure 5.19, annealing is observed to increase R_{int} at low fluence ($1.0 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$), while at higher fluences it reduces R_{int} , likely as a consequence of exceeding the beneficial annealing interval.

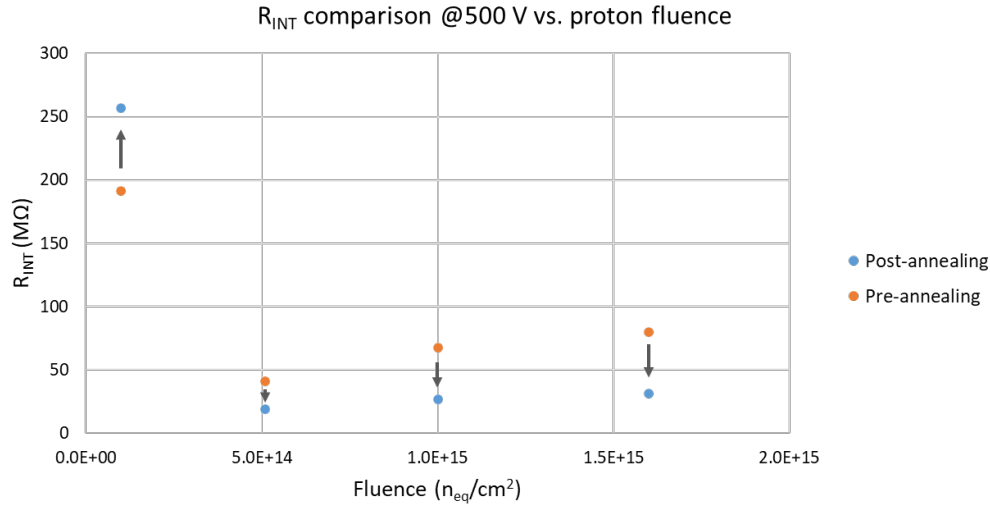


Figure 5.19: R_{int} evolution with fluence before and after annealing, measured on the LOW interdigitated structure of the Testchips at $V_{\text{bias}} = 500 \text{ V}$.

R_{int} is also shown in Figure 5.20, normalized by strip length, to allow a direct comparison among the UP, MID, and LOW interdigitated structures. The left plot in Figure 5.20 presents data from Experiment 1, while the right plot corresponds to Experiment 2, performed on low p-stop samples. The decreasing-increasing trend described above is preserved for both Testchip types; however, R_{int} values are significantly lower for Testchips from Experiment 2, which have a lower p-stop implantation dose, consistent with their poorer strip isolation.

Compared to Experiment 1, a large variability in R_{int} is observed in Experiment 2 among the different interdigitated-structure measurements at each proton fluence. This behavior is likely caused by significant non-uniformity of the p-stop doping, both within a single wafer (UP, MID, LOW) and between wafers.

The comparison of V_{PT} values before and after annealing is shown in Figure 5.21 (left). In absolute terms, V_{PT} values are higher for batch VPA38186 (standard batch) than for batch VPA37921 (low p-stop implantation) at all irradiation fluences, confirming the low p-stop effects observed in previous experiments (see Section 4.3 and Section 5.1).

Similarly to the R_{int} behavior, the absolute value of V_{PT} decreases at lower fluences and begins to increase at higher fluences, where ionization damage saturates and displacement damage becomes dominant. This correlation between R_{int} and V_{PT} was expected, as higher resistance between strip implants requires a higher voltage to break the potential barrier between them.

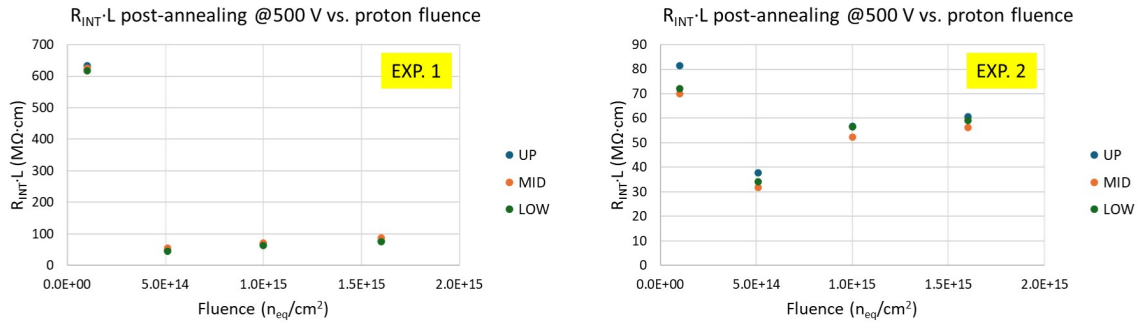


Figure 5.20: Post-annealing R_{int} evolution with fluence, normalized by strip length, obtained from samples in Experiment 1 (left) and Experiment 2 (right) at $V_{bias} = 500$ V.

The right plot in Figure 5.21 compares V_{PT} values measured after annealing in Experiment 1 and Experiment 2. The absolute value of V_{PT} is lower for Testchips from batch VPA37921 due to the reduced p-stop implantation level in this batch.

Overall, both R_{int} and V_{PT} results are consistent with those discussed in the post-irradiation effects described in Section 5.1 and with previous Main sensor studies performed at IMB-CNM after $\gamma + n$ irradiation [113].

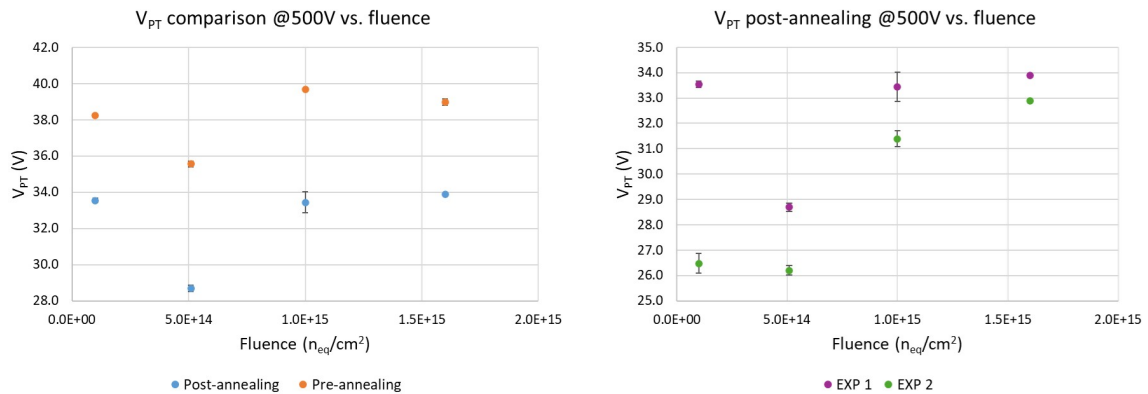


Figure 5.21: V_{PT} evolution with fluence, before and after annealing (left). Post-annealing V_{PT} evolution with fluence measured from Testchips in Experiment 1 and Experiment 2 (right) at $V_{bias} = 500$ V.

The bias resistance (R_{bias}) was measured only in Experiment 1 before annealing and normalized to $+20^\circ C$ using Eq. (4.1), after being measured at $-20^\circ C$ at IMB-CNM. The obtained values, shown in Figure 5.22, fall within the expected dispersion range, around $1.70 M\Omega$, for all fluences (see R_{bias} results from production QA in Chapter 4.3.4). These measurements are highly precise, resulting in error bars too small to be visible in the plot. The slightly lower resistance observed at $1.0 \times 10^{14} n_{eq}/cm^2$ may be attributed to the reduced irradiation effects at this fluence level.

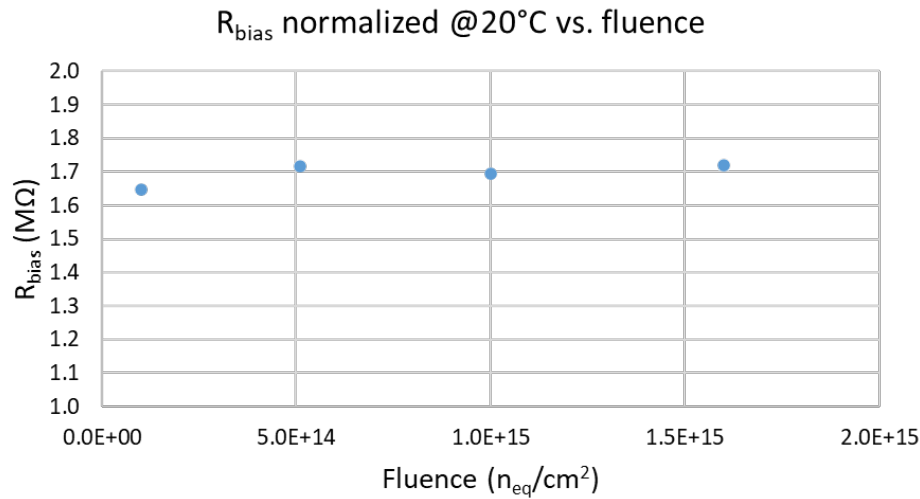


Figure 5.22: R_{bias} evolution with fluence before annealing, measured on Testchips from Experiment 1. Values are normalized to +20 °C.

Similar measurements performed in Birmingham were found to be consistent with the IMB-CNM results. In contrast, the charge collection efficiency (CCE) was measured on Mini sensors at the Ljubljana and Toronto test sites, yielding low CCE values similar to those observed in earlier experiments, such as the 2021 study. $\text{CCE}_{500\text{V}}$ values from the 2021 and 2022 experiments are shown in Figure 5.23, together with data points from previous studies. The charge collection measured in this study remains below the minimum threshold of 6350 e^- , confirming the 2021 observations.

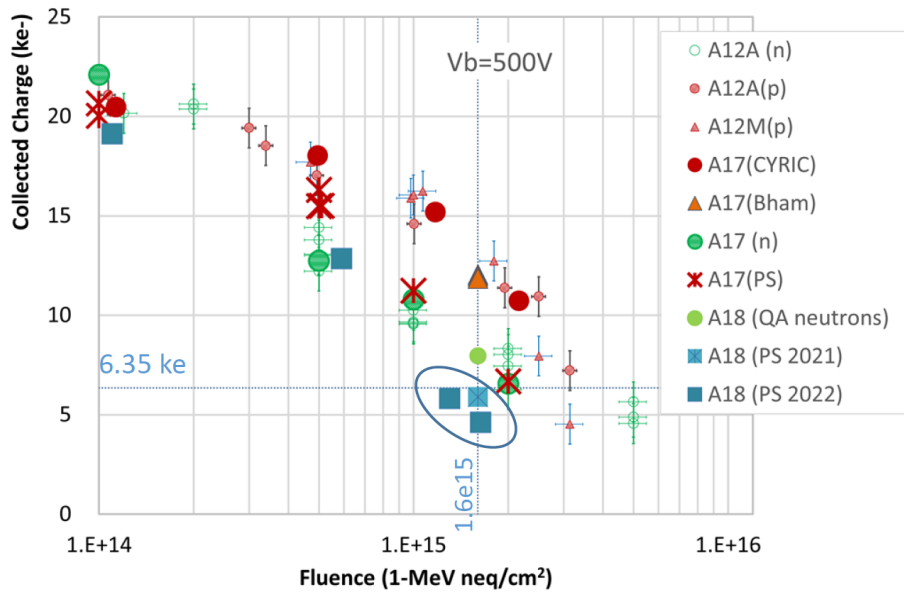


Figure 5.23: $\text{CCE}_{500\text{V}}$ as a function of fluence, measured on Mini sensors. Data points from studies performed in 2021 and 2022 (blue squares), and previous investigations are included [127].

The study was complemented by Geant4 simulations, performed by collaborating institutes, which indicated that the effective fluence could be larger than expected due to secondary particles generated by 24 GeV protons interacting with the support material and the silicon of the test structures when irradiated at shallow angles. According to the simulations, the shallow angle and secondary particles scattered from the G10 material could increase the fluence by approximately 30% and 40%, respectively [116, 127].

The CCE degradation observed in this analysis, attributed to the increased effective fluence confirmed by Geant4 simulations, motivated the QA Collaboration to further investigate the effects of irradiation angle and G10 material. This was done through a fourth PS irradiation experiment conducted in 2023, and the corresponding results are presented in the following subsection.

Study of the effects of angle and material for the PS beam at four fluences

For the 2023 irradiations with 24 GeV protons at CERN PS, a technical incident at the IRRAD facility interrupted the irradiation before the target fluences were reached. The dosimetry, obtained from the Al foils placed in the support structure, showed delivered fluences lower than the target values, as shown in Figure 5.24 (left). However, a significant increase in fluence was observed along the beam direction, especially in the Al foils located behind blocks of G10 material. Geant4 simulations confirmed this increase in fluence due to scattered secondary particles produced by the G10 material [116]. This increased fluence could explain the reduced CCE observed in the earlier experiments.

Leakage currents measured on MD8s are consistent with the measured fluences, confirming that fluences determined from Al foils are an adequate indicator of silicon bulk damage. The current values at 500 V are illustrated in the right plot of Figure 5.24 for target fluences of $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

The current values in Figure 5.24 (right) were extracted from the I–V curves shown in Figure 5.25 for both fluences: $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (left plot) and $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (right plot). These plots demonstrate the large increase of current—and thus the increase of effective fluence—caused by the presence of G10 material, due to the secondary-particle effects. The narrow proton beam geometry also influences the leakage current, which is lower for 90° irradiations in absence of G10 blocks. Overall, fluence dominates over angle or material effects.

The full depletion voltage (V_{FD}), represented in Figure 5.26 for different fluences ($1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ and $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$), irradiation angles (1.5°, 6°, 12°, and 90°), and with or without G10 material, was extracted from C–V curves measured on MD8s. While V_{FD} shows no

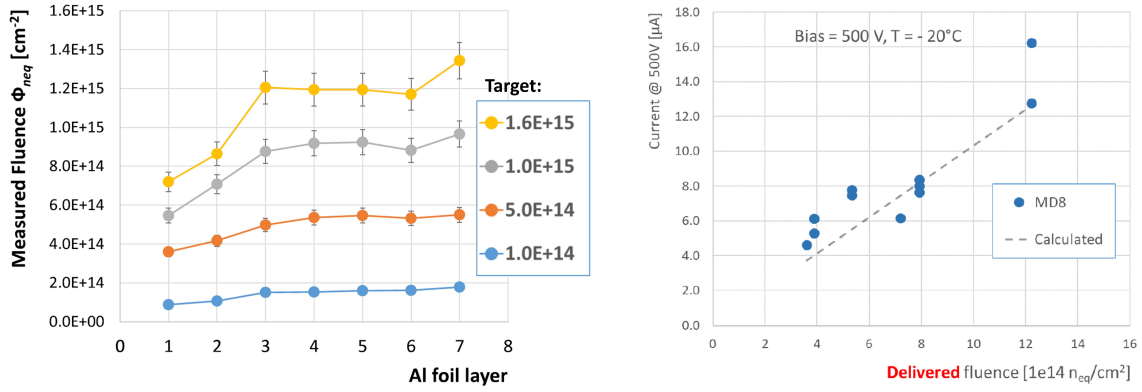


Figure 5.24: Proton fluences measured from the seven Al foils in the setup structures, corresponding to the four nominal irradiation fluences (left). Leakage current measured at 500 V on twelve MD8s as a function of fluence (right). Adapted from [116, 125].

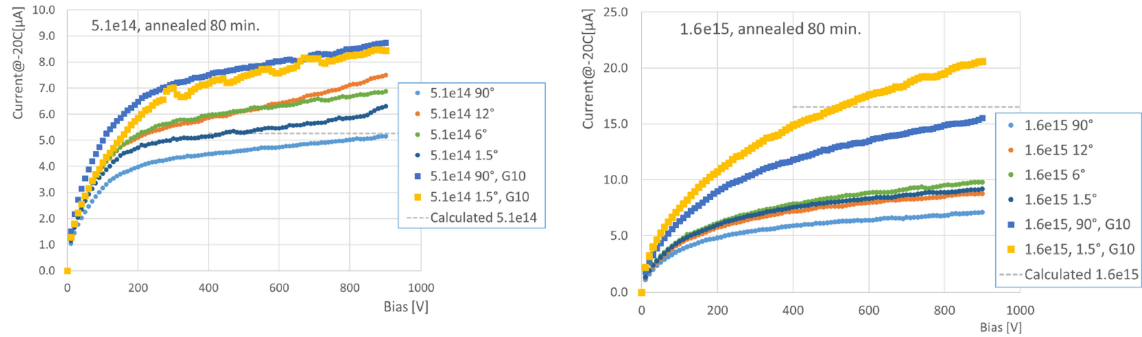


Figure 5.25: I-V curves measured on MD8s at different angles, in front of and behind G10 block, for both 5.1×10^{14} n_{eq}/cm² (left) and 1.6×10^{15} n_{eq}/cm² (right) irradiation fluences.

dependence on irradiation angle, it increases with fluence and the presence of material, due to the larger effective doping concentration induced by radiation.

At IMB-CNM, the R_{int} and V_{PT} parameters were extracted from twelve irradiated Testchips to study the effects of fluence and material on sensor performance. Figure 5.27 illustrates R_{int} measured from Testchips oriented at 90° (top), 6° (middle), and 90° with G10 material (bottom). For each Testchip, R_{int} values were obtained from the UP, MID, and LOW interdigitated structures.

For 90° irradiation, R_{int} decreases at low fluences but increases at higher fluences. This decreasing-increasing trend was already observed in the 2022 study performed on batch VPA38186, with a minimum around 5.1×10^{14} n_{eq}/cm². Additionally, a high dispersion is observed among R_{int} values measured at different interdigitated structures within the same Testchip. This dispersion is reduced for Testchips irradiated at 6°, suggesting a potential effect of the non-uniformity of the beam intensity due to its gaussian profile.

In contrast, R_{int} values obtained for 90° irradiation with G10 material are much lower than the others, due to the increased fluence from secondary particles. In this case, a

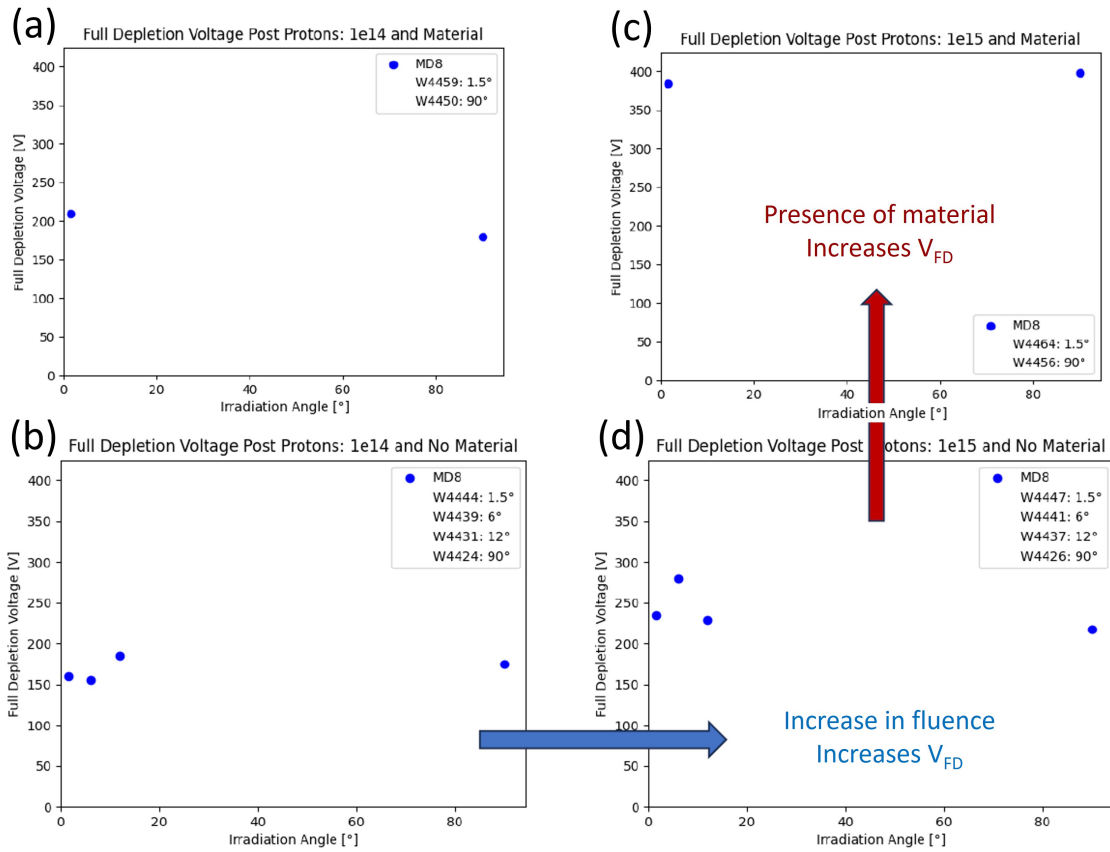


Figure 5.26: Full depletion voltage (V_{FD}) measured at different irradiation angles (1.5°, 6°, 12°, and 90°) under different conditions: (a) 1×10^{14} n_{eq}/cm^2 with G10 material, (b) 1×10^{14} n_{eq}/cm^2 without G10 material, (c) 1×10^{15} n_{eq}/cm^2 with G10 material, and (d) 1×10^{15} n_{eq}/cm^2 without G10 material.

decrease and subsequent increase in R_{int} is observed, similar to the 2022 study, but R_{int} decreases again above $\sim 1 \times 10^{15}$ n_{eq}/cm^2 , reaching higher fluences not covered in other measurements.

Overall, R_{int} results from IMB-CNM are consistent with those measured at Toronto at different angles [126], showing small angle dependence, but a clear evolution with fluence and a strong influence of G10 material, which increases the effective fluence due to the secondary particles.

To illustrate the effect of an irradiation beam with finite size and a Gaussian profile, the Testchip irradiation conditions are schematized in Figure 5.28 for both 90° and shallow irradiation angles. The interdigitated test structures used to measure R_{int} , circled in red, receive different irradiation intensities when oriented at 90° relative to the beam. In contrast, at shallow angles, all interdigitated structures are exposed to similar irradiation intensities, despite the non-uniformity of the beam from across the Testchip from left to right (the Testchips in Figure 5.28 are rotated 90° clockwise for easier comparison with

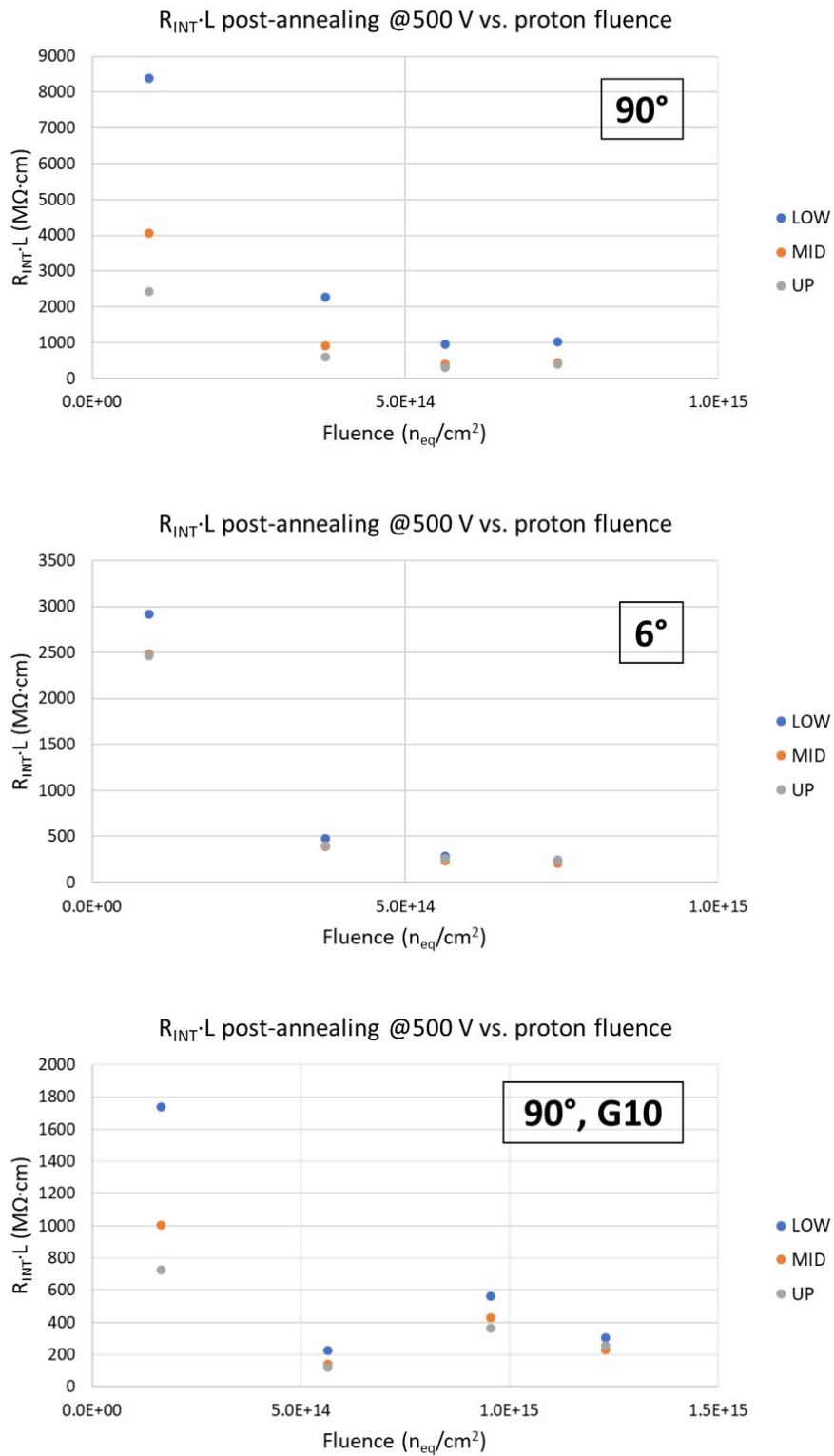


Figure 5.27: Post-annealing R_{int} evolution with fluence, normalized by strip length, obtained from Testchips oriented at 90° (top), 6° (middle), and 90° with G10 material (bottom). $V_{bias} = 500$ V.

previous setup images). This explains the reduced dispersion in R_{int} from the UP to LOW interdigitated structures at a 6° angle of incidence, compared to the greater R_{int} variability observed after 90° irradiation.

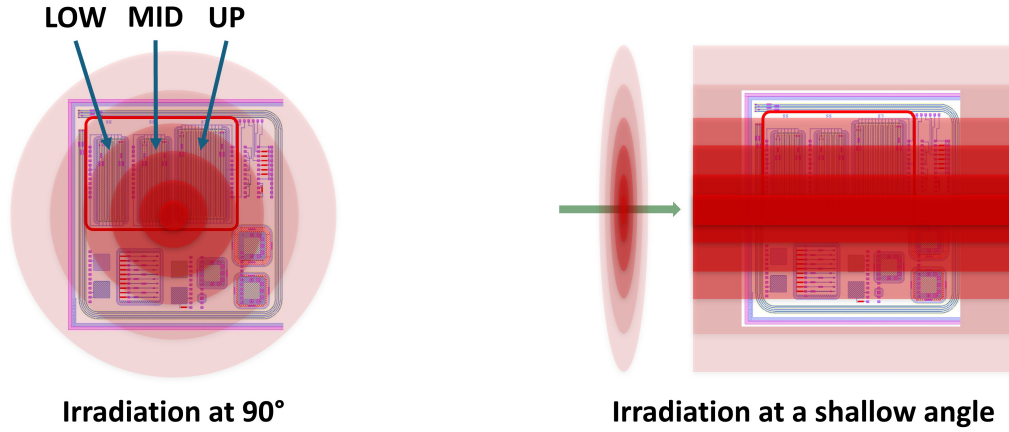


Figure 5.28: Schematic of the PS proton beam influence on the interdigitated structures (UP, MID, and LOW) of Testchips oriented at 90° (left) and from Testchips at shallow angles (right).

Figure 5.29 shows the R_{int} measured in the MID interdigitated structure at 90° both with and without G10 blocks in front of the samples. The data indicate that the presence of G10 material produces a measurable effect at low fluences.

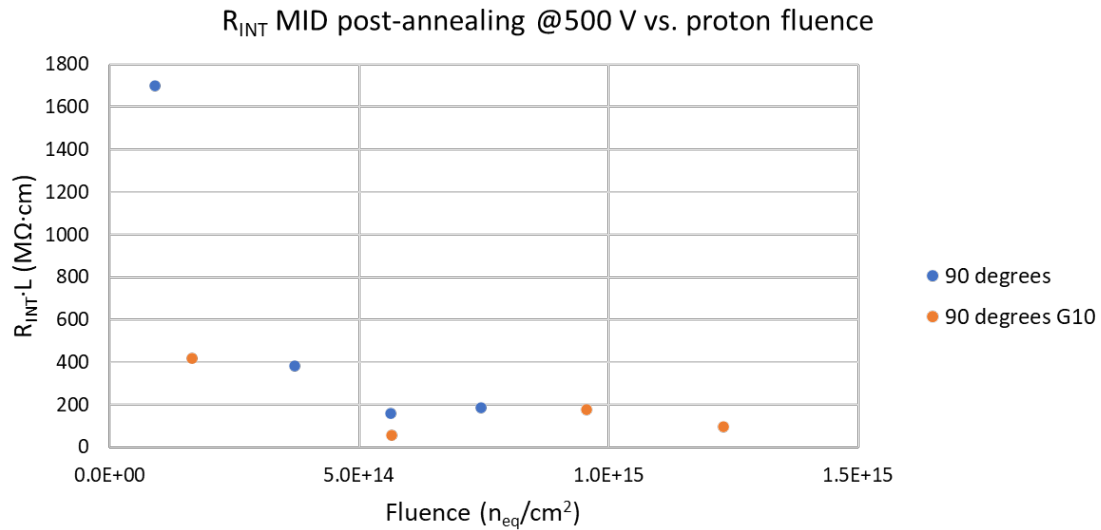


Figure 5.29: Post-annealing $R_{\text{int_MID}}$ evolution with fluence, normalized by strip length, obtained from Testchips oriented at 90° with and without G10 material. $V_{\text{bias}} = 500$ V.

On the other hand, V_{PT} measurements are illustrated in Figure 5.30 for the same angles and fluences as R_{int} , with the punch-through structure biased at 500 V. For 90° irradiation, V_{PT} (in absolute value) decreases with increasing fluence. A different dependence of V_{PT} on fluence is observed for 6° irradiation and 90° irradiation behind G10, where V_{PT} initially

increases after reaching a minimum and then decreases again at higher fluences. This variation between angles and presence of G10 material may be attributed to differences in the total ionizing dose (TID) arising from secondary particles. However, no V_{PT} values are available for 90° Testchips at higher fluences, so a potential increasing trend cannot be confirmed.

The V_{PT} results at IMB-CNM are also consistent with those obtained at Toronto [126], although measurement uncertainties and V_{PT} variability among different Testchips complicate precise analysis.

Additionally, measurements of R_{bias} at the Toronto test site showed no dependence on either the irradiation angle or the presence of G10 material, over fluences ranging from $1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ to $1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. At these fluences, 24 GeV proton irradiations do not produce sufficient damage in the polysilicon resistors to cause a detectable change in the bias resistance. Consequently, variations in the effective fluence due to material or angle are imperceptible.

Overall, the results obtained from the Testchip measurements in this study confirm that the irradiation angle and the presence of material influence the test structures, as reflected in the behavior of the parameters. The presence of G10 material produces a pronounced effect on the leakage current, V_{FD} , and R_{int} , due to the increased production of secondary particles. In contrast, only weak angular effects are observed in most cases. The dependence of R_{int} on the irradiation angle manifests primarily as an increased dispersion among the values measured in different interdigitated structures, without altering the overall R_{int} trends.

Regarding studies without direct IMB-CNM contributions, irradiated Mini sensors were used for CCE measurements [123]. A significant influence of the G10 material on the collected charge at 500 V (CCE_{500V}) is observed, caused by an increase in the effective fluence experienced by the Mini sensors. Consequently, samples containing G10 material exhibit lower collected charge compared to samples irradiated to the same target fluence without G10 material, as shown in Figure 5.31 (left). An angular dependence of the CCE is also observed in Mini sensors without G10 material, as illustrated in Figure 5.31 (right). Nevertheless, all CCE_{500V} values remain well above the QA acceptance limit of 6350 e^- , both for samples with and without G10 material.

In parallel, annealing studies on Mini sensors were also carried out. For fluences below $1.2 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, a significant beneficial annealing effect is observed for annealing times up to ~200 minutes at 60 °C, as shown in Figure 5.32, corresponding to the expected (“usual”) behavior. In contrast, at a fluence of approximately $1.2 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, no beneficial annealing is observed; instead, an “unusual” drop in collected charge occurs after short annealing times [123].

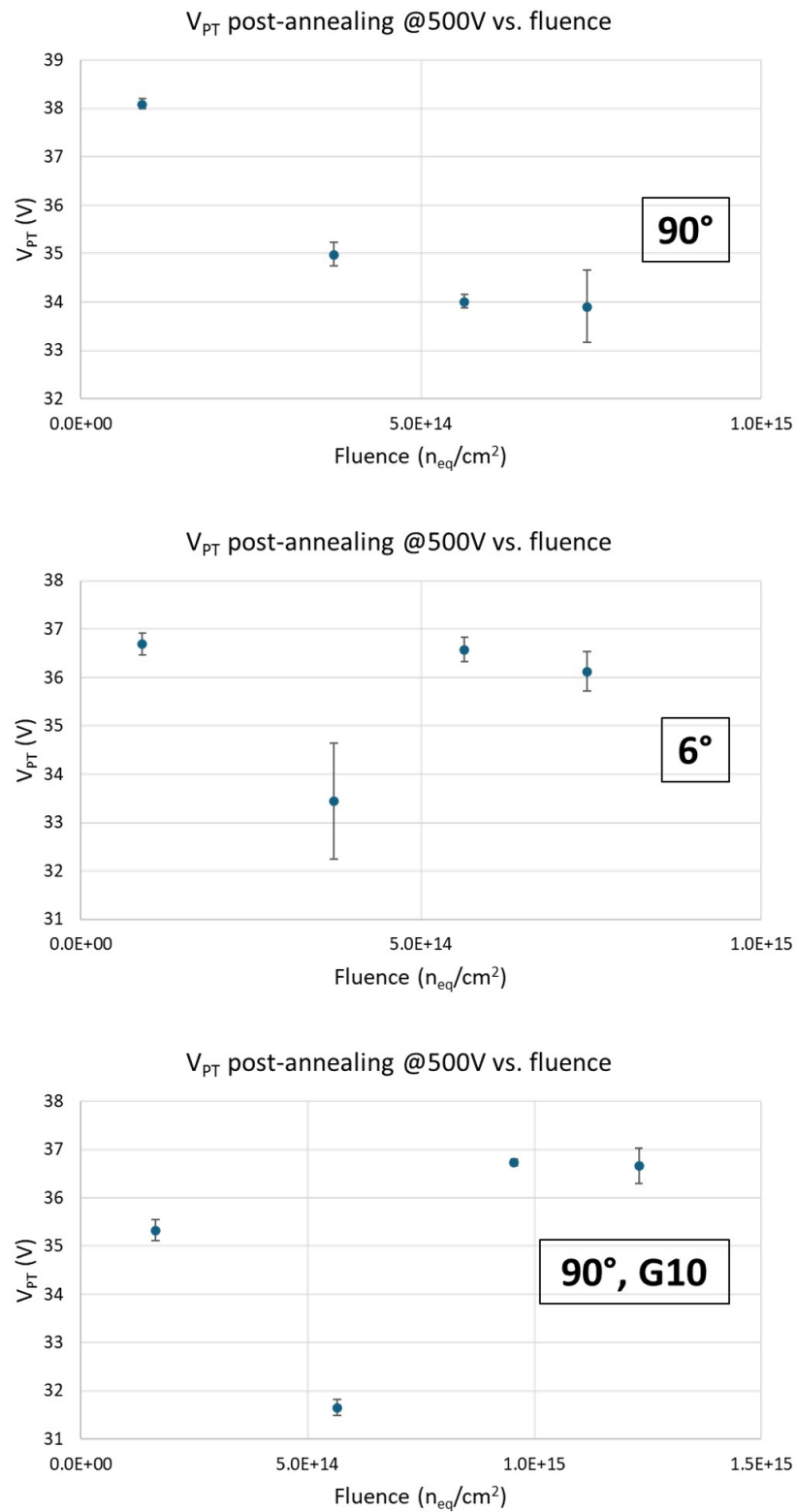


Figure 5.30: Post-annealing V_{PT} evolution with fluence, obtained from Testchips oriented at 90° (top), 6° (middle), and 90° with G10 material (bottom). $V_{bias} = 500$ V.

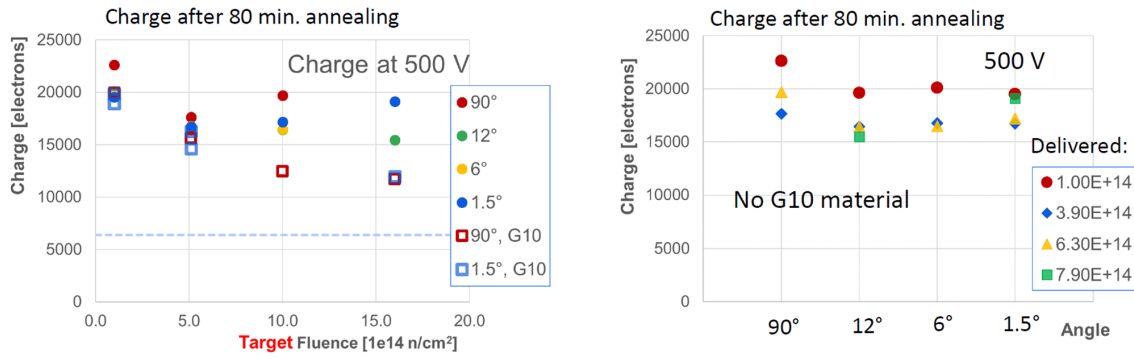


Figure 5.31: CCE_{500V} measured at four target fluences for several irradiation angles, with and without G10 material (left), and CCE_{500V} measured at several irradiation angles without G10 material (right). Measurements were performed after annealing for 80 minutes at 60 °C [123].

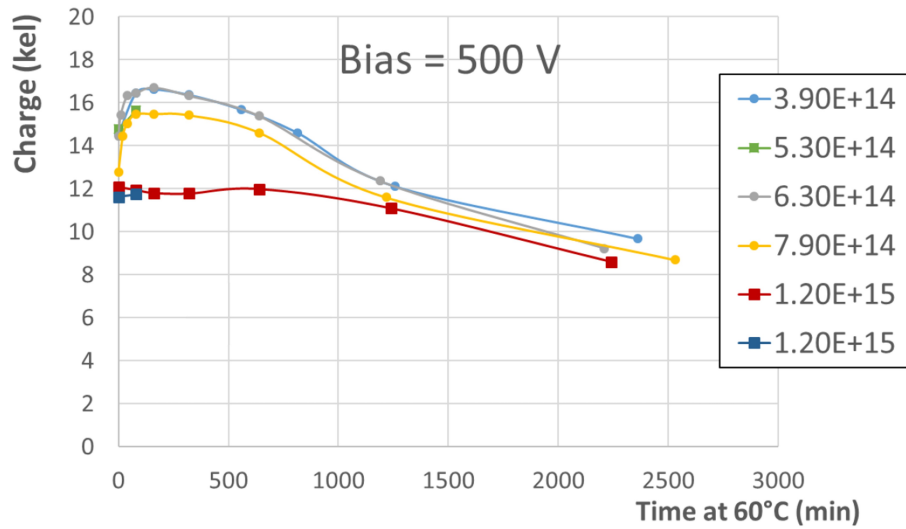


Figure 5.32: CCE_{500V} evolution as a function of annealing time at 60 °C, measured on Mini sensors irradiated to fluences ranging from $3.9 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ to $1.2 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. Adapted from [123].

The CCE “usual” and “unusual” behaviors observed in Figure 5.32 were further investigated using the Edge Transient-Current Technique (E-TCT) with a ^{90}Sr source. These measurements show an increase in the effective depletion depth after “usual” annealing. In contrast, a “double peak” velocity profile appears after “unusual annealing” for 80 minutes at 60 °C, likely due to the formation of two depletion regions induced by irradiation with 24 GeV protons [123].

For neutrons and low-energy protons, the front peak is dominant, with a significantly smaller back peak. More than 50% of the bulk damage in the ATLAS ITk strip detector is expected to originate from neutrons, with the remainder caused by charged hadrons, whose maximum fluence in the most exposed detector regions is approximately $7 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$. To better reproduce the irradiation conditions expected in the experiment, Mini sensors irradiated with $7 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ PS protons were subsequently irradiated with

8.8×10^{14} n_{eq}/cm^2 reactor neutrons in Ljubljana. This resulted in a total equivalent fluence of 1.6×10^{15} n_{eq}/cm^2 , corresponding to the target fluence expected for ATLAS ITk strips after an integrated luminosity of 4000 fb^{-1} , including a safety factor of 1.5.

The collected charge in these Mini sensors remains above the QA acceptance level and increases with annealing for 80 minutes at 60°C . Consistently, standard (“usual”) annealing behavior is observed, indicating that the “unusual” annealing and the “double peak” effect are associated with the high-energy proton fluence, rather than the total equivalent fluence [116].

Overall, the low CCE issue has been understood. It is primarily attributed to an increase in the effective fluence caused by scattering of secondary particles generated by G10 material placed in front of the samples during the experiment. The PS proton irradiations performed in 2021 and 2022 did not reflect the realistic irradiation conditions expected for ITk experiments, in which the CCE is required to meet specifications. All CCE_{500V} results from the 2023 IRRAD experiment have been added to the existing data presented in Figure 5.23, as shown in Figure 5.33 (black squares and rhombus).

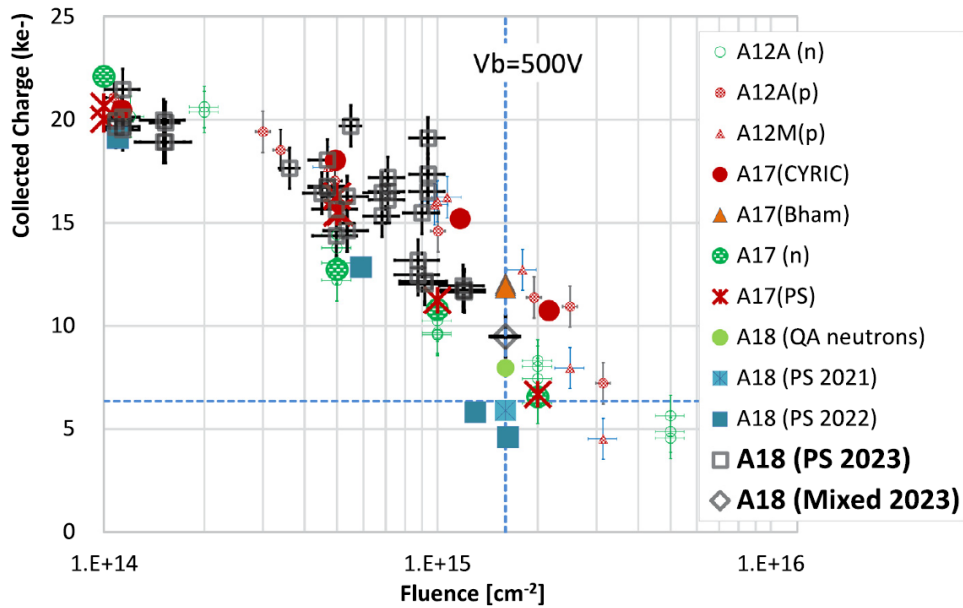


Figure 5.33: CCE_{500V} as a function of fluence, measured on Mini sensors. Data points from the 2023 IRRAD experiment (black squares and rhombus) and previous investigations are included [116].

The proton-damage study in this section offers important insights into how high-energy protons interact with strip sensor structures and provides practical guidance for future detector design and irradiation qualification. The results confirm that displacement damage is the main mechanism arising from 24 GeV proton irradiation, causing increases in leakage current and full depletion voltage (V_{FD}). Degradation of inter-strip resistance (R_{int}) is also observed, originating from early ionization-induced surface damage, with

partial recovery at higher fluences that may arise from the increasing relative contribution of displacement damage mechanisms. Secondary-particle production further amplifies these effects due to the presence of the setup material (G10). This shows that damage depends on the effective fluence incident on the sensors, rather than only by the nominal beam fluence, highlighting the need to consider scattering environments when extrapolating irradiation tests to real detector operation. At the same time, a certain angular dependence is observed due to the influence of the beam's Gaussian profile on 90° irradiations when comparing test structures across different wafer regions (e.g., the Interdigitated structures); however, the angular effect is minimal when comparing results from the same structures.

From a technological perspective, these findings emphasize the importance of modelling secondary-particle behavior when planning irradiation campaigns. The observation that R_{int} shows only increased spread, without a systematic change with angle, indicates that inter-strip isolation structures are robust against primary irradiation. However, their sensitivity to secondary scattered particles from additional material reveals a potential vulnerability to elevated ionization and surface charge. The reduction in collected charge in presence of G10 further confirms that attention should be paid to the surrounding setup material when performing experimental irradiations of these sensors.

Overall, this study provides crucial quantitative evidence that future sensor qualification must account for carefully controlled irradiation geometries and low-material environments to ensure laboratory tests accurately reflect the actual sensor performance in experimental conditions.

5.3 Study of Extreme Fluence Irradiations

5.3.1 Origin of the Problem

As explained in previous sections of this chapter, several experiments were conducted within the framework of the ITk Strip Sensor Collaboration, comprising the irradiation of samples up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ or below. This fluence corresponds to the expected level in the ITk experiment, including a safety factor of 1.5. However, the performance of ITk strip sensors at higher fluences remained unknown.

A new experiment was therefore designed to study the bulk damage induced by neutrons in strip sensors at fluences one or two orders of magnitude higher than $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

5.3.2 Experiment Made

Three Testchips from different wafers in batch VPA41725 were irradiated with reactor neutrons in Ljubljana up to the following fluences:

- VPA41725-W4470: $2.3 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$
- VPA41725-W4430: $5 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$
- VPA41725-W4467: $1 \times 10^{18} \text{ n}_{\text{eq}}/\text{cm}^2$

These samples were irradiated for 40 hours at full reactor power, during which their temperature ranged between 45 °C and 100 °C. After irradiation, they were kept at room temperature for approximately three weeks waiting for the radioactivity to decrease, as they were too radioactive to be placed in the freezer. Consequently, the additional annealing step of 80 minutes at 60 °C was no longer performed.

For this study, R_{int} , V_{PT} , and R_{bias} parameters were measured on the Testchips to observe their behavior after extreme fluence irradiations, together with an initial I–V characterization. All measurements were performed at the Radiation Detectors Laboratory using the manual probe station connected to a thermal chuck, at –20 °C and relative humidity (RH) below 5%. I–V curves were measured using a Keithley 2470, while the other parameters were obtained with a Keithley 4200-SCS together with a Keithley 2410 for bulk biasing (see Section 3.1).

Since this study was carried out at IMB-CNM, previous IMB-CNM measurements performed under the same conditions on mid-fluence, full-fluence, and over-irradiated Testchips were used for comparison with the newly irradiated samples. The earlier available results correspond to the special p-stop batches presented in Section 5.1, which were irradiated with gamma and neutrons ($\gamma + n$) up to $5.1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, and $3.4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. As explained in Section 5.1, these special p-stop batches were divided into four types according to the p-stop implantation process used. In particular, Testchips from type 2—fabricated using a p-stop process at a lower temperature than that of a standard production Testchip, but exhibiting similar results—were selected as the reference for this study.

5.3.3 Results

Initial I–V curves from MD2 diodes of all Testchips (W4470, W4430, and W4467) irradiated to extreme fluences, shown in Figure 5.34, exhibited no significant differences among them. At such high irradiation fluences, the silicon bulk becomes so heavily damaged

that the radiation-induced effects appear to saturate. Earlier studies performed on other types of silicon detectors irradiated at extreme neutron fluences did not show saturation, resulting in measurable I–V differences [128]. However, these references correspond to sensors irradiated up to a maximum fluence of $1 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$, which is still below the minimum fluence reached in the present experiment.

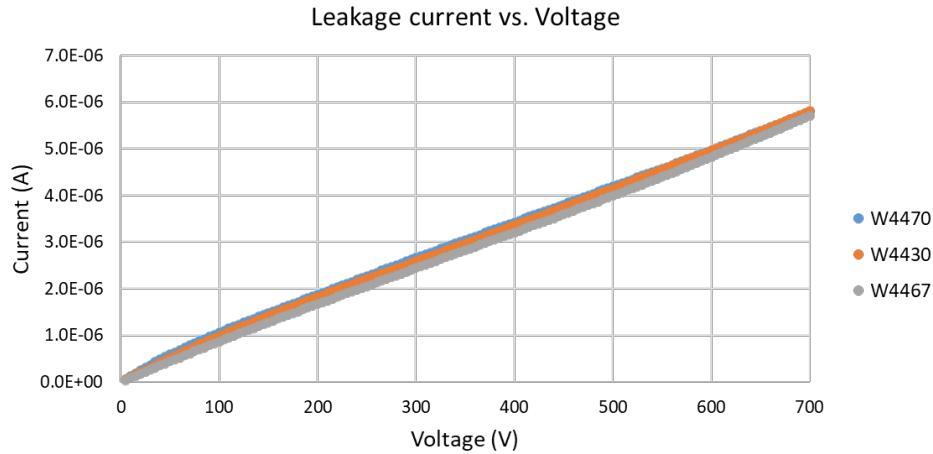


Figure 5.34: I–V curves measured on MD2 structures from the Testchips at -20°C and $\text{RH} < 5\%$ for all extreme fluences (left): $2.3 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4470), $5 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4430), and $1 \times 10^{18} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4467).

R_{int} was measured on all interdigitated structures in the Testchips irradiated to extreme fluences. The resulting values are approximately two orders of magnitude smaller than those obtained at lower fluences. Therefore, R_{int} exhibits a decreasing trend with fluence, although it is difficult to make a quantitative comparison between Testchips irradiated only with neutrons and those irradiated with $\gamma + n$. In any case, as shown in Section 5.1, gamma irradiation induces a decrease in R_{int} ; thus, even lower values could be obtained after $\gamma + n$ irradiation at extreme fluences, resulting in a more pronounced R_{int} change with fluence.

The left plot in Figure 5.35 shows the evolution of R_{int} with fluence, including samples irradiated with $\gamma + n$ and with neutrons only. The production QA mean value and standard deviation are represented in yellow, corresponding to $\gamma + n$ irradiation up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Despite the large production standard deviation, all results appear reasonable and fall within the expected range. The plot on the right shows an extension of the R_{int} evolution in the extreme-fluence irradiation range. UP, MID, and LOW R_{int} values are shown for all fluences in both plots.

The R_{bias} behavior is shown in Figure 5.36 (left) for full-fluence, over-irradiated, and extreme-fluence Testchips. R_{bias} is significantly higher in the extremely irradiated Testchips. The highest resistance, observed at the maximum fluence tested, is approximately

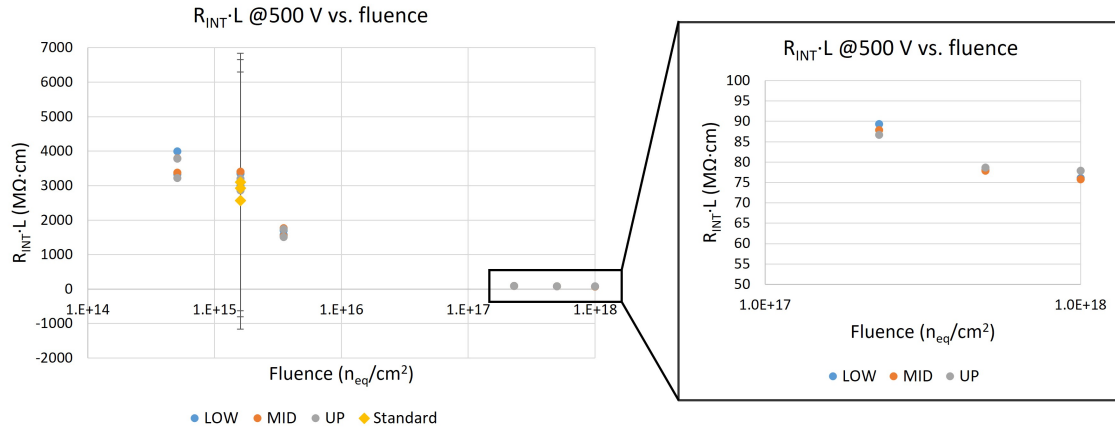


Figure 5.35: R_{int} evolution with fluence, normalized by strip length, obtained from Testchips irradiated with neutrons (extreme fluences) and $\gamma+n$ (lower fluences). Mean and standard deviation values are shown in yellow. Extension of the R_{int} plot in the extreme fluence range. $V_{\text{bias}} = 500$ V.

$3.7 \times 10^{12} \Omega$, indicating substantial degradation of the polysilicon bias resistors at extreme fluences.

To ensure the validity of these results, additional I–V measurements were performed with probe tips in the air and between isolated pads on the Testchips. These measurements, acquired with sufficient precision, are shown in Figure 5.36 (right). They yielded resistances of approximately $7\text{--}9 \times 10^{12} \Omega$ extracted from very low currents corresponding to roughly half of the values obtained from the currents measured in the bias resistors. Therefore, parasitic currents are sufficiently low so as not to interfere with an accurate measurement of R_{bias} , validating the results presented in Figure 5.36 (left).

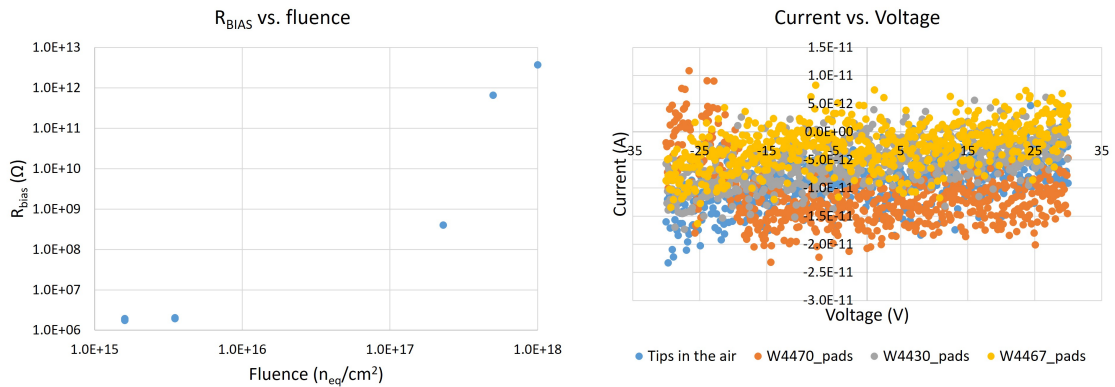


Figure 5.36: R_{bias} evolution with fluence (left), obtained from Testchips irradiated with neutrons (extreme fluences) and $\gamma + n$ (lower fluences). I–V measurements between isolated pads and with the probe tips in the air (right).

The extraction of V_{PT} was not possible. Although R_{PT} curves were measured, they did not exhibit their typical behavior, with the measured current even showing an opposite sign due to the severe bulk damage.

In conclusion, Testchips irradiated with neutrons at extreme fluences sustained significant damage, preventing the extraction of V_{PT} . Although samples irradiated only with neutrons were compared with those irradiated with $\gamma + n$, the general trend indicates an increase in R_{bias} and a decrease in R_{int} with fluence. At extreme fluences, the polysilicon bias resistors become non-functional.

Since earlier studies on extremely irradiated silicon sensors showed a decrease in the reverse current after annealing [128], and given that the actual annealing state of the present samples is unclear, future measurements after additional annealing steps are proposed to study potential evolution of the extreme radiation effects. Further neutron irradiations and measurements are also planned on extremely irradiated Mini sensors and on Testchips at intermediate fluences— $1.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, $1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$, and $5 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ —in order to better characterize the R_{int} and R_{bias} dependence on fluence and to determine the fluence levels at which the strip technology becomes non-functional. The results will serve as guidance for designing radiation-tolerant sensors and for establishing safe operational limits in future collider experiments.

5.4 Investigation of the Relationship Between Ingots and Batches

5.4.1 Origin of the Problem

All ITk strip sensors were manufactured using 6-inch wafers obtained from high resistivity p-type Float Zone silicon ingots [129–131]. During production QA, the potential impact of the ingots used for sensor fabrication on certain results and observed trends was evaluated. It was hypothesized that the choice of ingots could be linked to various unexpected behaviors during this period, including the incidences described in Section 4.3, as well as the cases where the full depletion voltage (V_{FD}) was above the maximum threshold of 850 V in some MD8s after neutron irradiation up to $5.1 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ (see Section 4.1).

To investigate a possible ingot-related influence, ingot data were collected for all production batches in order to evaluate the number of ingots per batch, the number of batches per ingot, and any potential effects of ingot origin on QA results.

5.4.2 Experiment Made

Each silicon ingot is labelled by the foundry with a 7+3-digit identifier (e.g., 2985172-502). This information is available to the QA Collaboration; however, detailed information on the ingot-to-batch processing was not directly provided by HPK. Consequently, Python scripts were developed to retrieve data for all sensor wafers from the Production Database (PDB) in order to study the relationship between ingots, wafers, and batches. Information on all production batches and the ingot numbers associated with each batch was extracted from there.

In addition to data extraction, the Python scripts were used to generate plots illustrating the ingot-batch relationships and to search for specific patterns in the time evolution of QA parameters that could indicate a possible ingot influence on the measured results.

5.4.3 Results

As shown in Section 4.1.14, the V_{FD} parameter exhibited opposite trends for pre-irradiated and neutron-irradiated samples, particularly during the early stages of production QA. Several measurements fell outside the specified thresholds and showed large dispersion after neutron irradiation, based on tests performed at the University of Toronto. To rule out measurement setup issues as the source of this observation, additional measurements were carried out using alternative setups (e.g., at IMB-CNM), which yielded consistent results.

Differences in silicon bulk properties originating from wafers produced from different ingots were considered as a possible factor affecting bulk depletion. For this reason, time-evolution plots of V_{FD} were generated as a function of ingot number at the corresponding production time, in order to identify any ingot-related patterns.

Figure 5.37 shows the time evolution of the V_{FD} for pre-irradiated Testchips, sorted by batch number (top) and ingot number (bottom) along the x-axis. In the ingot-sorted plot, ingot numbers are used to label each data point. Compared to the batch-sorted representation, the ingot-sorted plot reveals a “block-like” clustering of data points, suggesting a potential influence of the ingot on the V_{FD} of wafers extracted from it and, consequently, on the sensors fabricated from those wafers.

Similar time-evolution plots for V_{FD} measured on neutron-irradiated samples are shown in Figure 5.38. The top plot is sorted by QA delivery, while the bottom plot is sorted by ingot number. In this case, no clear conclusions can be drawn regarding a potential ingot influence. A relatively large dispersion is observed even among wafers originating from

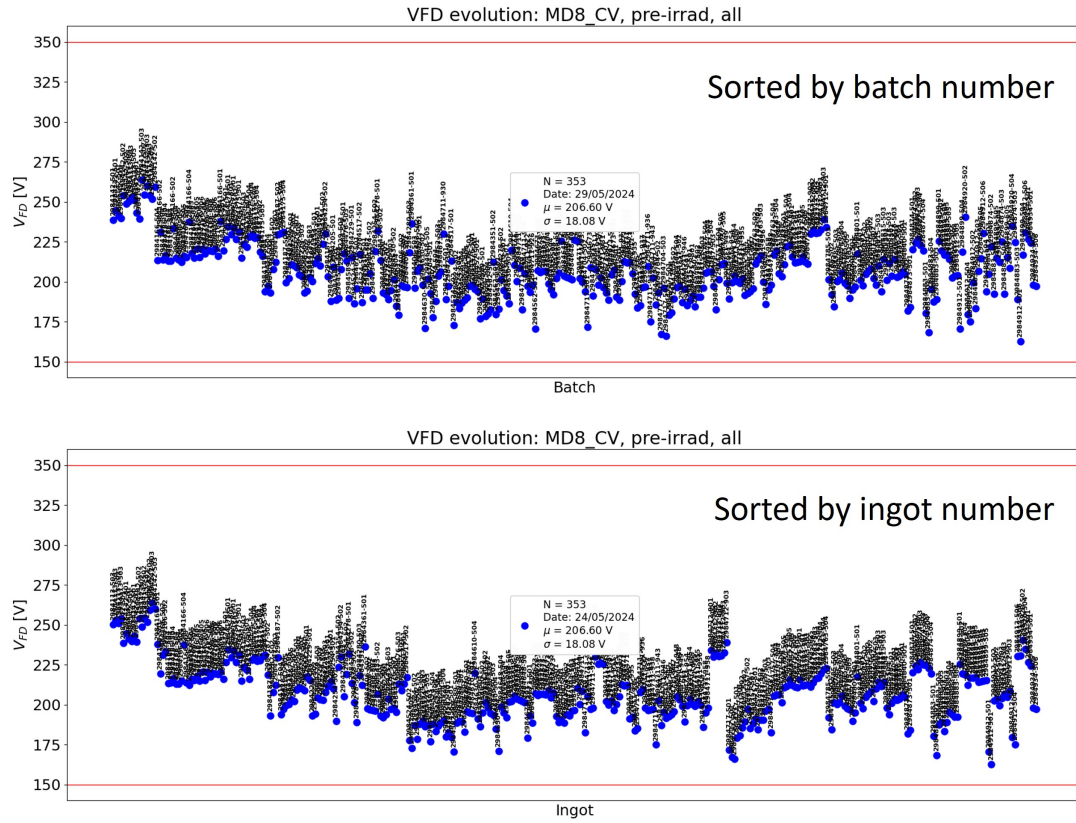


Figure 5.37: Time-evolution plot of the V_{FD} parameter for pre-irradiated Testchips up to middle of production, sorted by batch (top) and ingot (bottom), with each point labelled by the corresponding ingot number.

the same ingot, suggesting that the ingot-related behavior observed in pre-irradiated samples may be altered by neutron irradiation effects. This also rules out the possible influence of the specific ingot on the increasing effect on the post-neutron-irradiation V_{FD} .

Following the analysis of these plots, the relationship between ingots and batches was studied in further detail, focusing on the number of ingots per batch and the number of batches per ingot. It was hypothesized that the presence of multiple ingots within a single batch could contribute to variations in QA results for certain parameters, as previously considered for V_{PT} variability within batches prior to the analysis presented in Section 4.3.

It was expected that each batch would contain wafers originating from a single ingot, or at most from two ingots. This assumption was confirmed by the results shown in Figures 5.39 and 5.40. Figure 5.39 shows the number of ingots used to supply wafers for each production batch, while Figure 5.40 presents the corresponding frequency distribution. In most cases, batches consist of wafers from a single ingot; batches containing wafers from

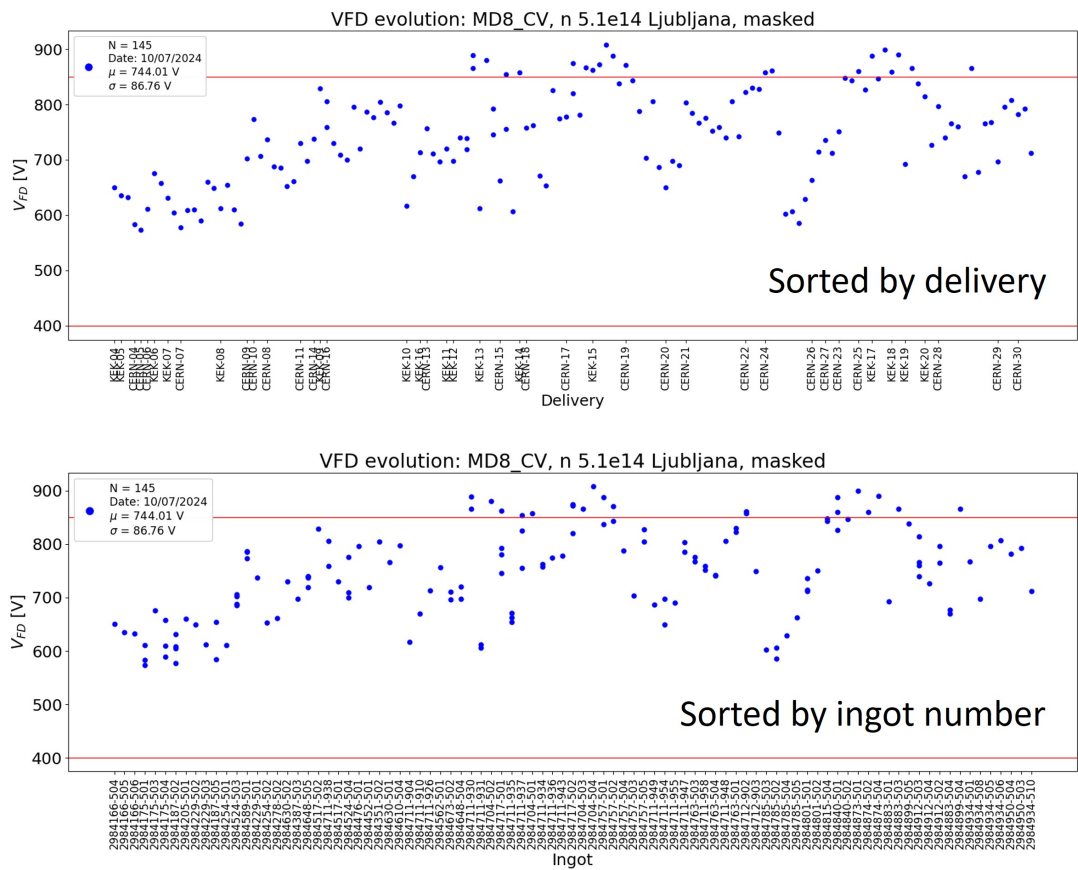


Figure 5.38: Time-evolution plot of the V_{FD} parameter for neutron-irradiated Testchips up to middle of production, sorted by QA delivery (top) and by ingot number (bottom).

two ingots occur less frequently, while only a small fraction of batches involve wafers from three to six ingots.

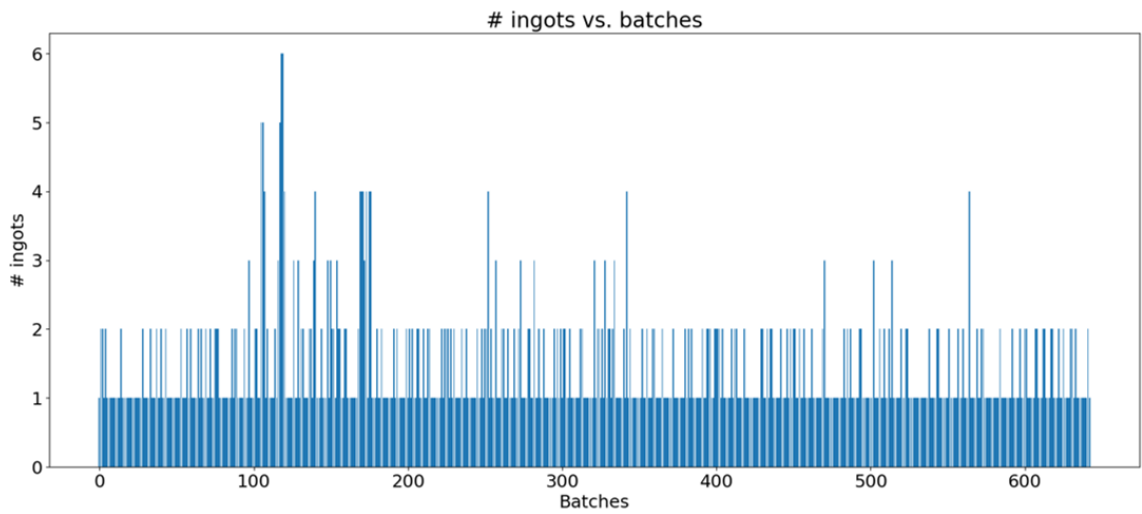


Figure 5.39: Number of ingots per production batch.

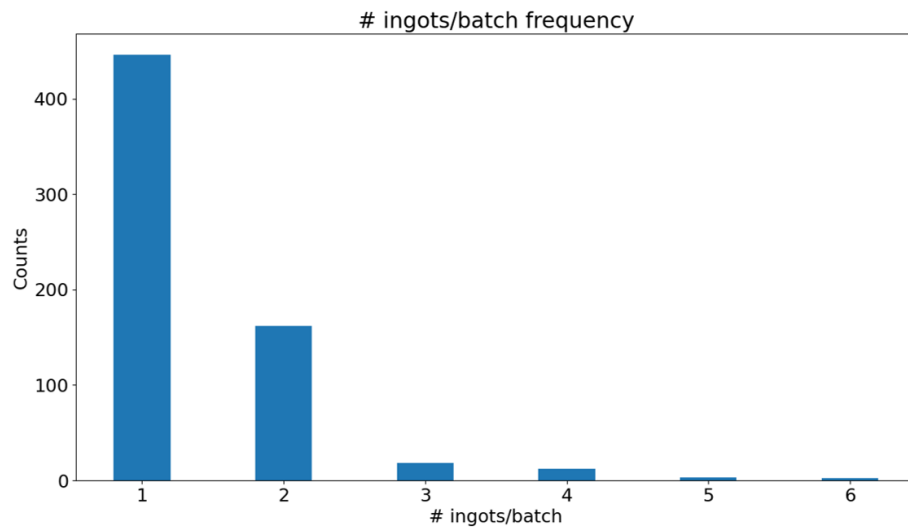


Figure 5.40: Frequency distribution of the number of ingots per batch.

The complementary representation is shown in Figures 5.41 and 5.42, which display the number of batches supplied by each ingot and the corresponding frequency distribution. Based on the plots, the most common case is that one ingot supplies wafers to a single batch. A significant fraction of ingots provides wafers to two to five batches, with a decreasing frequency for ingots supplying up to eleven batches.

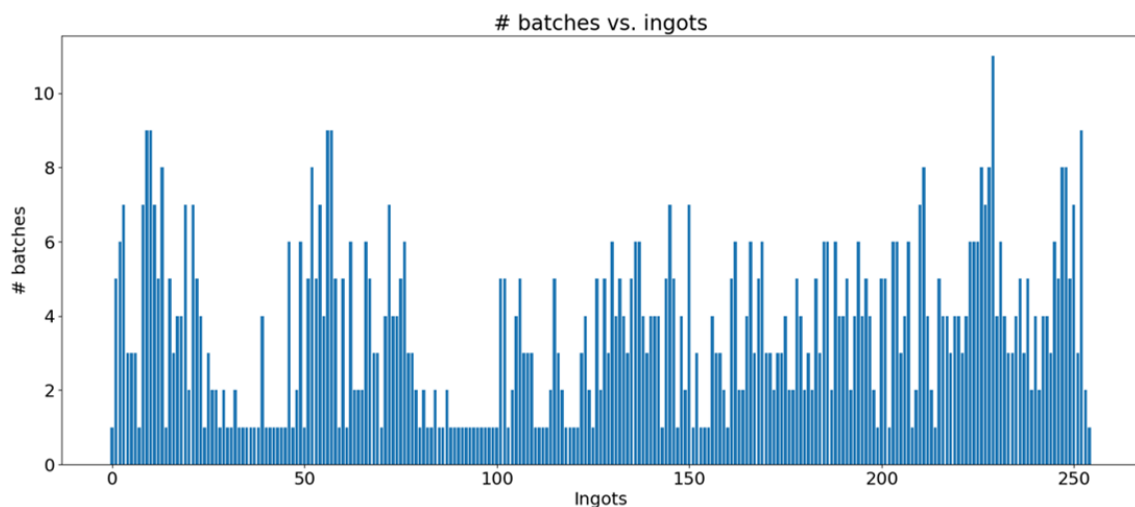


Figure 5.41: Number of production batches per ingot.

Additional plots were generated to further characterize the relationship between batches, ingots, and wafer counts. Figure 5.43 shows the number of wafers per batch, while Figure 5.44 presents the number of wafers per ingot.

The number of wafers per batch remains close to 40 throughout production, reaching a stable production regime after approximately the first 150 fabricated batches. In contrast, the number of wafers per ingot exhibits large variability, ranging from only a few wafers

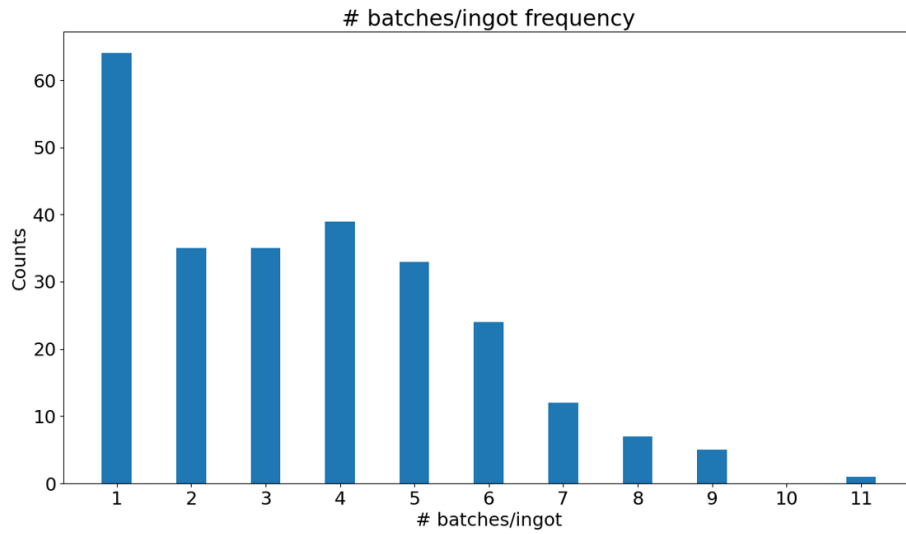


Figure 5.42: Frequency distribution of the number of batches per ingot.

to nearly 300 wafers per ingot, indicating significant fluctuations¹⁴ in ingot usage during production.

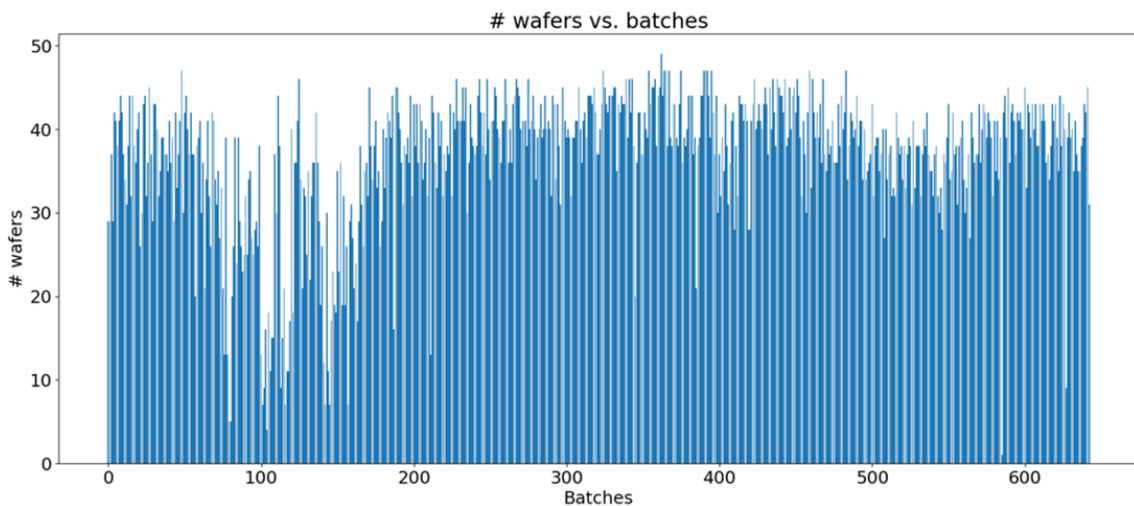


Figure 5.43: Number of wafers with respect to batches.

Figure 5.45 shows a two-dimensional heatmap correlating ingots and batches, with the color scale representing the number of wafers associated with each ingot-batch combination. Brighter colors correspond to larger numbers of wafers, while darker colors indicate fewer wafers shared between a given batch and ingot.

From the results presented in this section, it can be stated that only a limited number of batches were supplied by multiple ingots. Despite these few cases and the reduced

¹⁴ During the production of the ITk strip sensors for ATLAS at HPK, the strip sensors for the CMS upgrade were also being manufactured in parallel. It is very likely that wafers were being taken for batches from both productions at the same time.

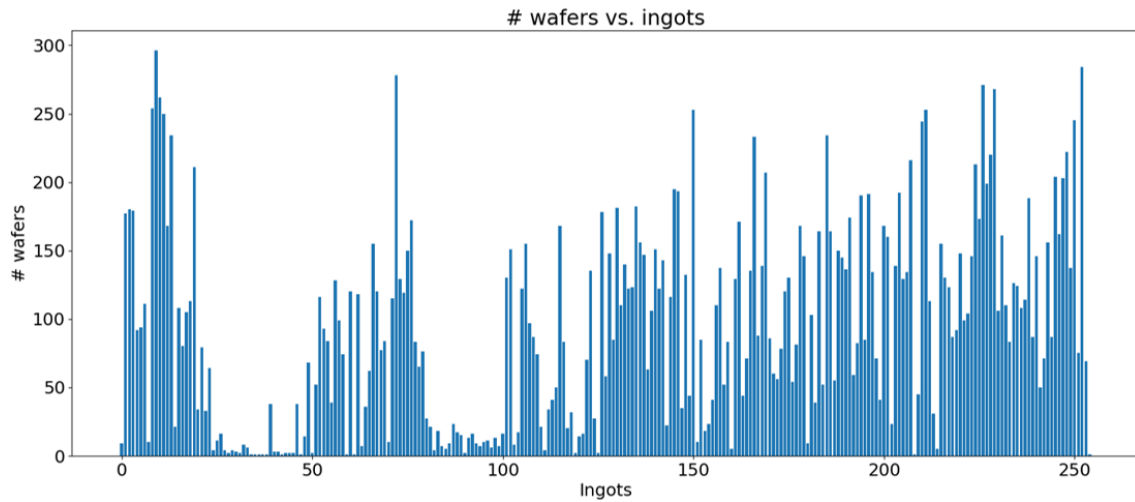


Figure 5.44: Number of wafers with respect to ingots.

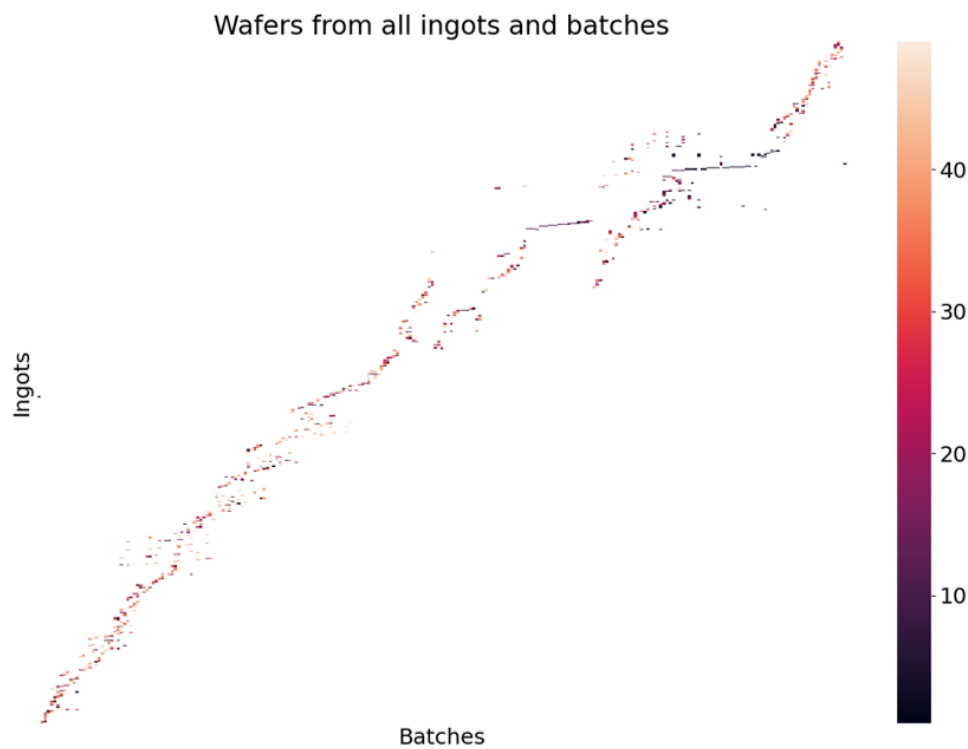


Figure 5.45: Ingot-batch heatmap counting the number of wafers per ingot and per batch.

number of wafers per ingot during a significant part of the production, the observed trends in batch composition and wafer selection from ingots align with expectations. Overall, no significant or systematic influence of ingot origin on the QA parameters has been identified.

Understanding ingot and batch variability can inform future fabrication strategies, enabling more predictive process control and improving the long-term uniformity of large-scale sensor production.

Conclusions

This thesis has presented a comprehensive study in the framework of the Quality Assurance (QA) of the ATLAS Inner Tracker (ITk) silicon strip sensors, designed to withstand the harsh environmental conditions expected in the High-Luminosity Large Hadron Collider (HL-LHC) at CERN. Design understanding, test procedures, control software, measurements, and analysis were carried out to ensure compliance with the quality requirements defined for the silicon strip sensors, complemented by additional investigations providing deeper insight into the physics of strip sensor technology.

Starting from the physical principles of semiconductors and the design of n-on-p strip sensors, this work showed how fundamental parameters (e.g., depletion voltage, leakage current, inter-strip properties, coupling and oxide capacitances, and charge collection) determine sensor performance before and after irradiation. The studies were developed within the ITk strip sensor QA program and included dedicated instrumentation, automated measurement and analysis tools, evaluation of production data under various radiation conditions, identification and mitigation of unexpected parameter behaviors, and additional studies of QA-related phenomena beyond nominal operation. As a result, a validated QA methodology was established, ensuring that the delivered strip sensors meet the stringent quality requirements of the ITk upgrade, and providing effective feedback between the ATLAS ITk Collaboration and the manufacturer, Hamamatsu Photonics K.K. (HPK).

The work, carried out at the Institut de Microelectrònica de Barcelona (IMB-CNM), was fully integrated into the QA program and conducted in parallel with Quality Control (QC), which is responsible for testing the final strip sensors to be installed in the experiment. Several test devices (Testchips, MD8 diodes, and Mini sensors) were specially designed to characterize and monitor key sensor properties throughout production. Within the QA program, these devices were measured being representative of each production batch, many of them irradiated to target fluences and doses of up to $1.6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and 66 Mrad, respectively, which correspond to the expected radiation levels at the HL-LHC, including a safety factor of 1.5. This approach enabled the identification of potential fabrication defects in a non-destructive manner, avoiding irradiation and damage on the Main sensors.

Standardized pre-irradiation measurements were performed on Testchips and MD8 diodes from all production QA batches, using both automatic and manual probe stations, establishing the basis at IMB-CNM for automated measurement methods for future production tests on sensors fabricated with similar technologies. Several Python scripts were developed to automatically analyze measurement data, generate the required data files, and create relevant characteristic plots. Additional Python scripts were programmed to upload results and produce reports by connecting to the ITk Production Database (PDB) through the specifically developed itkdb interface. Together, these elements constituted a powerful production quality assurance methodology developed at IMB-CNM. These elements ensured the application of quality criteria, enabled identification of defective devices—such as due to the low p-stop quality in a few batches—and allowed rapid feedback to HPK and the production QA Collaboration. The reporting scripts also made it possible to monitor production trends over time and to compare results across different sites, production batches, substrate ingots, and irradiation conditions. The reporting scripts are easily configurable to access any PDB information and can be used for a wide range of purposes.

More than 600 pre-irradiation measurements per parameter, performed at IMB-CNM, and up to 450 post-irradiation data points were plotted in distribution and time-evolution plots for a comprehensive analysis of the QA results obtained throughout the ATLAS ITk strip sensor production. The evaluation was performed across all relevant irradiation types (gamma rays, neutrons, protons, and combined $\gamma + n$ irradiations) giving a complete assessment of sensor performance under conditions representative of HL-LHC operation. The systematic use of distribution and time-evolution plots enabled continuous monitoring of key parameters, ensuring stability and early detection of anomalies. All major technological parameters remained within acceptance limits and exhibited predictable trends, even in samples irradiated at the highest fluences tested, allowing for rapid intervention in case of outliers or unexpected trend behaviors.

Implant and metal properties (R_I , $W_{\text{EFF-I}}$, R_M , $W_{\text{EFF-M}}$) remained consistent throughout production, confirming uniform dopant diffusion and proper metal deposition, etching and overlap. Oxide-related parameters (C_{coupl} , $I_{\text{CCPL-100V}}$, C_{ox} , t_{ox} , V_{FB}) indicated excellent dielectric quality, with the exception of a few isolated batches exhibiting a low flat-band voltage; this issue was subsequently corrected, restoring minimal trapped charge in the oxide. Surface-related parameters—inter-strip capacitance (C_{int}) and inter-strip resistance (R_{int})—showed the expected sensitivity to ionizing radiation: C_{int} increased and R_{int} decreased after ionizing radiation due to the formation of additional electron accumulation layers, whereas neutron-induced displacement damage more effectively preserved surface isolation. Parameters associated with the p-stop implantation ($C_{\text{ox-P}}$, $t_{\text{ox-P}}$, V_T , S_{REF} , V_{PT}) proved to be the best early-warning indicators, enabling the rapid

detection of batches with an insufficient p-stop dose. This defect was later confirmed by TCAD simulations to degrade p-stop doping profile by more than an order of magnitude.

Bulk-related parameters behaved in line with the known physics of displacement damage: neutron and proton irradiations increased the full depletion voltage (V_{FD}) by raising the effective doping concentration, increased the leakage current (I_{500V}) proportionally to NIEL, and reduced the charge collection efficiency (CCE_{500V}) due to carrier trapping. Correlation studies confirmed strong relationships between V_T-V_{FB} and $V_{PT}-S_{REF}$, illustrating consistent MOS Capacitor behavior and coherent control of p-stop doping. Conversely, bulk-dominated correlations such as I_{500V} vs. V_{FD} or CCE_{500V} vs. V_{FD} were weak, as expected from the decoupling of generation current, effective doping concentration, and trapping effects. Only γ -irradiated batches showed systematic degradation of surface properties (e.g., V_{PT} reduction and R_{int} decrease), consistent with ionization damage in the surface oxides. Across the full production, nearly all batches (more than 600) were validated, with only a few rejected in accordance with the QA procedures and the CERN-HPK contract conditions. This outcome demonstrates that the QA framework efficiently identified deviations, enabled rapid mitigation, and ensured that the final ITk strip sensors meet the stringent radiation-hardness and performance requirements for HL-LHC operation.

Several production incidents were detected and identified during these years. The most notable problem was low p-stop doping concentration in a few batches, which was revealed by simultaneous failures in V_{PT} and R_{int} in a Testchip from an early delivery. To monitor this effect, the MOS Capacitor with p-stop (CFLD-P_CV) was added to the systematic test plan, with S_{REF} serving as a cross-check for isolation defects. Detailed investigations, including replacements and studies of the p-stop variability across the sensor wafer, identified the use of non-uniform temperature in a processing furnace as the cause of the poor p-stop performance. Corrective measures were implemented at the foundry to prevent this issue in future production batches. Other minor concerns, such as temporary V_{FB} variations and occasional post-irradiation coupling-capacitor failures, were attributed to oxide charge effects and likely ESD or handling damage; in all cases, these issues were managed without affecting the overall performance of the strip sensors. In total, four production batches were rejected for QA reasons and two additional batches for QC reasons, demonstrating that the methodology ensured detector performance.

Four additional studies extended the understanding of sensor physics and production processes beyond the systematic QA program. Special production batches with four different p-stop process types were tested. All types met the specifications both before and after irradiation, at least up to the target fluences expected for HL-LHC operation. Differences in V_{PT} and S_{REF} were small and well within the acceptance limits but provided useful information for process optimization. Post-irradiation studies of low p-stop

implantation showed a fast decrease in R_{int} under gamma irradiation and a recovery after neutron irradiation (when displacement damage was added). The higher influence of gamma irradiation at low fluences, together with the recovery observed at higher fluence levels, resulted in a minimum in R_{int} at a certain fluence value (still above minimum thresholds), which appeared to be shifted to lower fluences due to low p-stop effects and is still under investigation. These results confirm that inter-strip isolation is governed by compensation effects coming from the bulk and surface damage. The p-stop dose plays an important role in controlling this balance.

Irradiations at the CERN PS showed a reduced charge collection efficiency (CCE) at high proton fluence compared to lower-energy protons. Measurements at several collaborating institutes and Geant4 simulations demonstrated that this effect is mainly caused by secondary particles produced by shallow irradiation angles and by the G10 support material of the experimental setup, increasing the effective fluence. Several experiments studied angle and material effects and confirmed the dominant role of the material. The low CCE due to the increased effective fluence was recovered when using more realistic low-material irradiation setups. Annealing and E-TCT measurements further clarified the unusual CCE behavior observed under specific PS-proton conditions. Overall, these findings show that the low CCE is mainly caused by experimental setup effects from increased local damage, not by a fundamental problem with the sensor design or performance.

Measurements on Testchips irradiated with neutrons up to extreme fluences (up to $1 \times 10^{18} \text{ n}_{\text{eq}}/\text{cm}^2$) were carried out to explore damage levels far beyond those expected at the HL-LHC. They exhibited severe bulk damage, loss of punch-through functionality, a large decrease in R_{int} , and an increase in R_{bias} into the $T\Omega$ range, resulting in the bias resistors losing functionality as well. Physically, these results show that the material has reached a very heavily damaged state. In this state, there are so many defects that both bulk transport and surface isolation mechanisms stop working properly. Although these results are not relevant for operation, they warrant further investigation, as they may provide reference points for future collider environments.

An analysis of the ingot-batch relationship was performed to investigate any potential ingot dependence. While the pre-irradiation V_{FD} showed some clustering by ingot label, no clear ingot-related influence on QA parameters was observed across production. Batch composition and wafer usage were consistent with production expectations. This indicates that crystal growth fluctuations within the same growth method have only a minor impact on the final detector performance, confirming the robustness of the material selection and processing.

The production QA results indicate that the QA program successfully ensured that quality requirements were met throughout the entire fabrication process, with sensors fulfilling specifications and showing radiation hardness, and providing feedback to the manufacturer, including batch rejection when detecting unexpected effects not compatible with optimal sensor performance. Additional studies complemented the QA program by addressing less-common scenarios, variations in the fabrication process, and extreme conditions. They provided key understanding of strip sensor technology and its performance under different irradiation conditions, confirmed the robustness of the ITk strip sensors under HL-LHC requirements, and established a solid basis for future studies on sensor performance in extreme radiation environments.

Throughout this work, several important lessons have emerged that improve our understanding and development of ITk strip detectors. First, analyzing thousands of measurements systematically showed which parameters are most sensitive to fabrication variations and therefore critical for process control. In particular, parameters associated with p-stop (S_{REF} , V_{PT} , V_T) proved to be reliable early indicators of implantation quality, helping to detect both isolated defects and wafer- or batch-level non-uniformities. Strong correlations between surface-related parameters confirmed how surface doping, inter-strip isolation, and post-irradiation stability interact, giving a clearer picture of how small process differences affect the sensors' final electrical behavior.

Overall, these findings show that the QA program developed in this thesis is more than just a quality-control tool; it also provides a framework that deepens our understanding of silicon strip detector technology and supports the development of more robust sensors for future collider experiments.

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List of Publications

- È. Bach et al. “Analysis of the quality assurance results from the initial part of production of the ATLAS18 ITK strip sensors.” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1064** (2024), p. 169435. DOI: 10.1016/j.nima.2024.169435
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- I. Mandić et al. “Radiation effects of CERN-PS 24 GeV/c protons in silicon strip sensors, evaluated with ATLAS18 ITk strip sensor test structures.” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1082** (2026), p. 170917. DOI: 10.1016/j.nima.2025.170917

List of Conferences

- 12th International Conference on Position Sensitive Detectors (PSD12), University of Birmingham, Birmingham (UK), 12–17 September 2021. Poster contribution.
- 13th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD13), Simon Fraser University, Vancouver (Canada), 3–8 December 2023. Oral contribution.
- ATLAS Upgrade Week (AUW), Oral contribution, CERN, Geneva (Switzerland), 26–30 April 2021.
- Inner Tracker (ITk) Week, Oral contribution, CERN, Geneva (Switzerland), 6–10 September 2021.
- ATLAS Upgrade Week (AUW), Oral contribution, CERN, Geneva (Switzerland), 14–18 November 2021.
- 6th Scientific Meeting of PhD Students (JPhD2021), Poster contribution, Universitat Autònoma de Barcelona (UAB), Barcelona (Spain), 25–26 November 2021.
- Inner Tracker (ITk) Week, Oral contribution, University of Bonn, Bonn (Germany), 12–16 September 2022.
- Performance Assessment Review (PAR+), Oral contribution on behalf of the ITk-Strips Collaboration, CERN, Geneva (Switzerland), 26 September 2022.
- Inner Tracker (ITk) Week, Oral contribution, CERN, Geneva (Switzerland), 6–10 March 2023.
- Young Researchers Day 2023 (YRD2023), Oral contribution, IMB-CNM, Barcelona (Spain), 20 April 2023.
- 7th Scientific Meeting of PhD Students 2023 (JPhD2023), Poster contribution, Universitat Autònoma de Barcelona (UAB), Barcelona (Spain), 7–9 June 2023.
- Young Researchers Day 2024 (YRD2024), Oral contribution, IMB-CNM, Barcelona (Spain), 25 April 2024.

- Inner Tracker (ITk) Week, Oral contribution, CERN, Geneva (Switzerland), 9–13 September 2024.
- 8th Scientific Meeting of PhD Students 2024 (JPhD2024), Oral contribution, Universitat Autònoma de Barcelona (UAB), Barcelona (Spain), 27–29 November 2024.
- Inner Tracker (ITk) Week, Oral contribution, CERN, Geneva (Switzerland), 12–16 May 2025.