Electrical characterization of surface properties of the ATLAS17LS sensors after neutron, proton and gamma irradiation

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12th Hiroshima symposium, Hiroshima, 14 to 18 December, 2019

Introduction

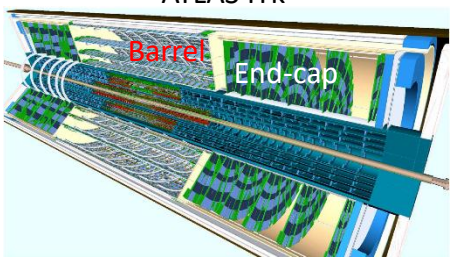
- **ATLAS Inner Tracker (ITk) strip sensors**
  - Single-sided n^+ - in - p (FZ) <100>
  - 6-inch wafer processing
  - thickness 300-320 µm
  - AC-coupled readout, strips biased via poly-silicon bias resistors
  - common p-stop isolation (4e12 ions/cm^2)
  - ITk includes: 2 barrel types: Short Strips (SS) and Long Strips (LS)
    6 End-Cap types: R0-R5

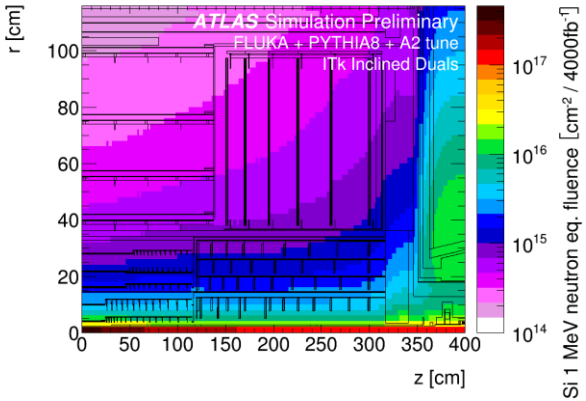
- **maximal nominal radiation fluences (doses) based on 4000 fb^{-1}**
  - strip barrel: 6.4 x 10^{14} n_{eq}/cm^2 (0.29 MGy)
  - strip end-cap: 10.6 x 10^{14} n_{eq}/cm^2 (0.44 MGy)
- Testing with safety factor 1.5

- **high radiation fluence impact on sensor properties:**
  - bulk damage: - increase of leakage current
    - depletion characteristics and CCE change
  - surface damage: - charge raise at the Si-SiO_2 interface
    - influences break-down voltage, inter-electrode isolation and other electrical surface parameters

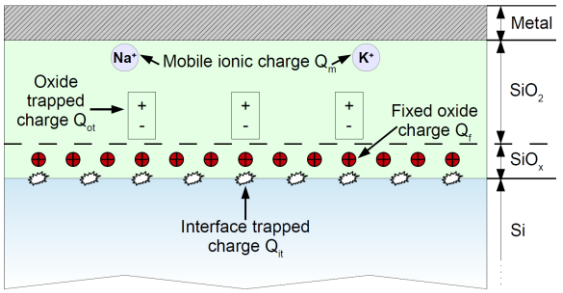
- verification of sensor properties before and after irradiation by protons, neutrons and gammas at many ATLAS institutions

ATLAS ITk





Radiation environment ATLAS Phase II upgrade (4000fb^{-1})

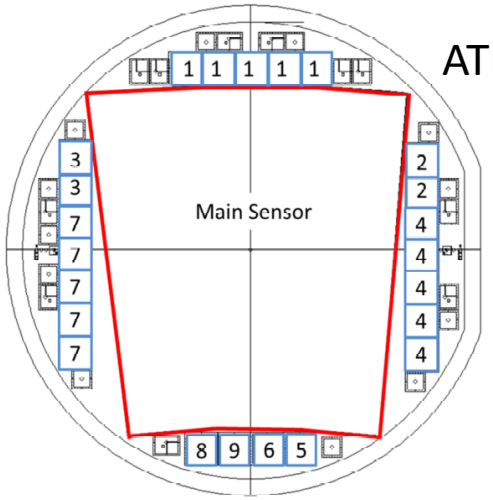


Christoph Klein Thesis https://doi.org/10.17863/CAM.45814

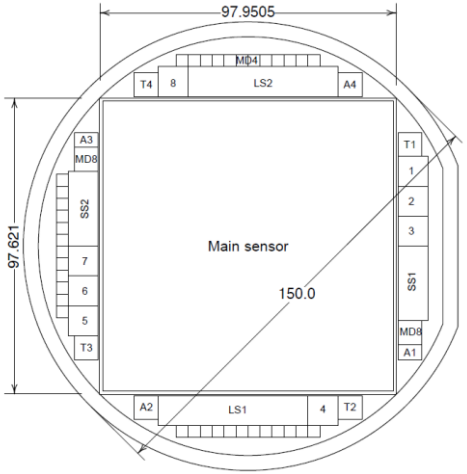
ATLAS ITk strip sensor prototypes

Last 2 main sensor prototype submissions:

- **ATLAS12EC (R0 EndCap) HPK**
  - First main ATLAS ITk sensor for EC region
  - Minis with variant pitch, coupling and PTP structure configurations
  - characterization of non-irradiated main sensors and irradiated mini sensors in [R. F. H. Hunter et al. *NIM A 924, p. 142 (*2019)]
- **ATLAS17LS (barrel LS) HPK and IFX**
  - qualifying vendors as a part of ATLAS strip sensors **Market Survey Step3**
  - new features from 12 design: strip pitch 74.5 -> 75.5um; passivation
  - mini sensors: 1×1cm, SS(1×2.6cm), LS(1×5cm), diodes, TEST structures



ATLAS12EC



ATLAS17LS

this talk summarizes results from surface evaluation of HPK latest prototype submission of ATLAS17LS main and mini sensors after irradiation by protons, neutrons and gammas and compares results with ATLAS12EC main sensors

Step-3 Qualification requirements from Market Survey MS-4086/EP for ATLAS Strip Tracker Upgrade

- **The final qualification step required the production of full-size and fully featured prototype sensors according to the specifications stated in MS-4086/EP document.**

- **Sensor shall fulfill the following electrical specifications before and after irradiation:**

3.6.1 Electrical Specifications by ATLAS

Electrical measurements to be performed by the contractor(s) on each sensor (except where otherwise stated). Only sensors fulfilling the electrical requirements will be accepted.

3.6.1.1 Specifications for quality assurance

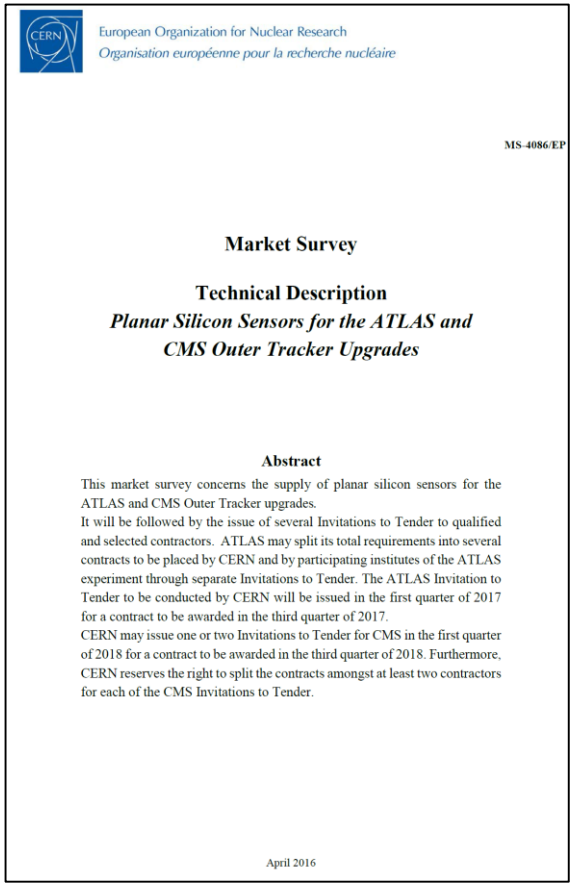
Electrical measurements to be performed by the contractor on each sensor (except where otherwise stated).

- Full depletion voltage: < 330 V (preference for < 150 V)
- Maximum operating voltage: 600 V
- Poly-silicon bias resistors: 1-2 MOhm
- Inter-strip resistance: > 10 x R_{bias} at 300 V at 23 C
- Inter-strip capacitance: < 1 pF/cm at 300 V, measured at 100 kHz
- Coupling capacitance: > 20pF/cm at 1 kHz
- Resistance of readout Al strips: < 15 Ohm/cm
- Resistance of n-implant strip: < 20 kOhm/cm
- Onset of micro-discharge at > 600 V (preferred)
- Total initial leakage current, including guard ring: < 0.1 $\mu A/cm^2$ at 600 V at room temperature
- Number of strip defects < 1% per strip/segment and < 1% per sensor (due to dielectric punch-through, metal and implant strip defects (opens and shorts), micro-discharging strip or bias resistor failures)

3.6.1.2 Measurements after irradiation

Sensors shall fulfil the following requirements after being subjected to irradiation with ionizing and non-ionizing radiation to a fluence of up to $2\times10^{15} n_{eq}/cm^2$ (60 Mrad). Irradiations and the subsequent measurements will be performed by ATLAS.
Measurements are performed at T = -20°C.

- Onset of micro-discharge at > 600 V or V_{fd} + 50 V after irradiation (if lower)
- Inter-strip resistance: > 10 x R_{bias} at 400 V and for T = -20°C
- Collected charge > 7500 electrons per MIP at 500V



European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

MS-4086/EP

Market Survey

Technical Description
Planar Silicon Sensors for the ATLAS and CMS Outer Tracker Upgrades

Abstract

This market survey concerns the supply of planar silicon sensors for the ATLAS and CMS Outer Tracker upgrades.
It will be followed by the issue of several Invitations to Tender to qualified and selected contractors. ATLAS may split its total requirements into several contracts to be placed by CERN and by participating institutes of the ATLAS experiment through separate Invitations to Tender. The ATLAS Invitation to Tender to be conducted by CERN will be issued in the first quarter of 2017 for a contract to be awarded in the third quarter of 2017.
CERN may issue one or two Invitations to Tender for CMS in the first quarter of 2018 for a contract to be awarded in the third quarter of 2018. Furthermore, CERN reserves the right to split the contracts amongst at least two contractors for each of the CMS Invitations to Tender.

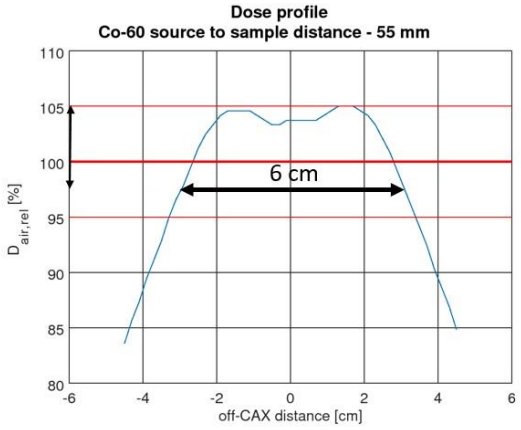
April 2016

Irradiations

		ATLAS17LS		ATLAS12EC
		HPK	IFX	HPK (only mains shown)
Total number of samples irradiated		**567 (2 mains)**	**102 (2 mains)**	**3**
Protons	(24 GeV) at CERN PS	89 (1)	0	1
	(70 MeV) at CYRIC, Tohoku Uni	139	58 (1)	2
	(28 MeV) at Birmingham	88	0	
	(23 MeV) at KIT	55	0	
Neutrons	Ljubljana TRIGA reactor	121 (1)	21 (1)	
Gammas	(^{60}Co) at UJP Praha	75	23	

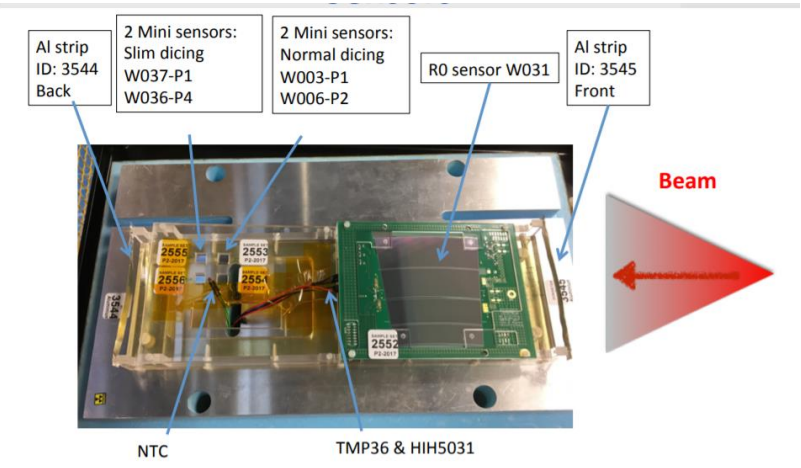
^{60}Co in UJP Praha

- Diameter of sensor irradiation area: 6 cm
- Homogeneity in irradiation area: ±5%



^{60}Co Terabalt, ÚJP Praha

CERN PS



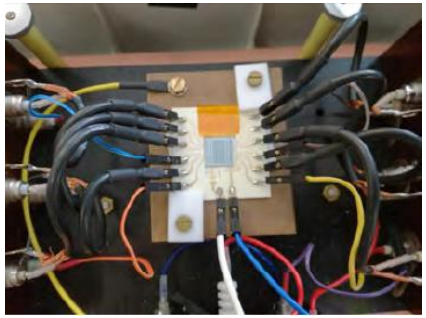
Institutions participating in evaluation of ATLAS17LS sensors

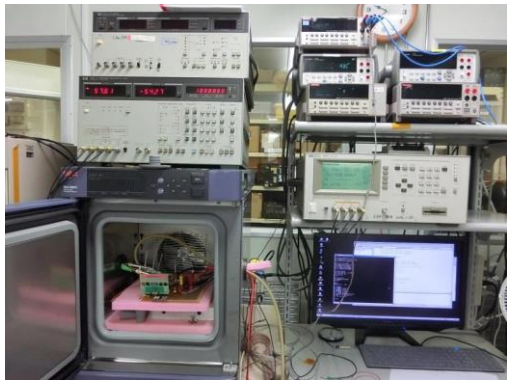
Institution	Test
IFIC (CERN, Valencia)	**IV/CV**, CCE, Test beam
Toronto	**IV/CV Surface studies**, CCE, Test beam
KEK/Tsukuba U.	**IV/CV, Surface studies**, CCE
DESY (Zeuthen), Humboldt U (Berlin)	**Surface studies**, TCT , Test beam
DESY (Hamburg)	**IV/CV, Surface studies**, Test beam
Simon Fraser University (Vancouver)	**IV/CV, Surface studies,** CCE
Santa Cruz	**IV/CV, Surface studies,** CCE
Cambridge	**IV/CV, Surface studies,** Test beam
Institute of Physics (Prague)	**IV/CV, Surface studies,** Test beam
CNM (Barcelona)	**IV/CV, Surface studies**
Carleton (Ottawa)	**IV/CV, Surface studies,** Test beam
Liverpool	CCE
Freiburg	CCE, TCT, Test beam
IJS (Ljubljana)	CCE, Edge TCT
Birmingham	CCE, Test beam
UCT (Cape Town), RAL, University of Dortmund, Charles University (Prague)	Test beam

Electrical tests of sensors

- IV (current, breakdown voltage)
- Inter-strip Resistance (R_{int})
- Inter-strip Capacitance (C_{int})
- Bias Resistance (R_{bias})
- Coupling Capacitance (C_{coup})
- Implant and Metal Resistance
- PTP (beam loss protection) Effectiveness

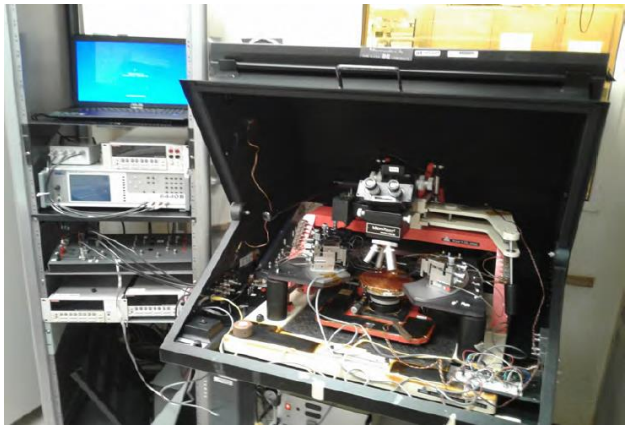
Sample on PCB (wirebonded)

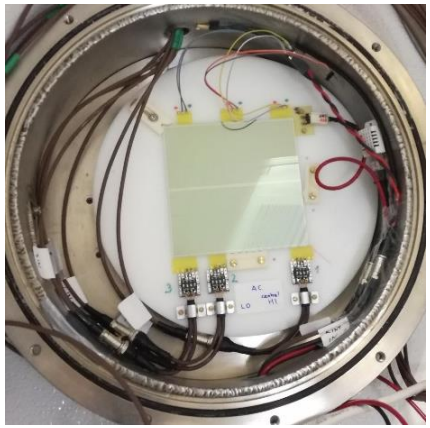


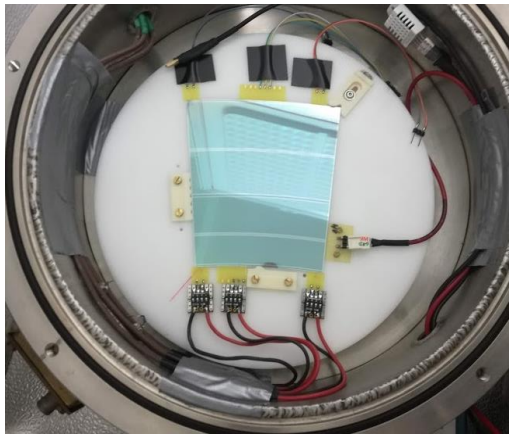


Measurement conditions:

- **Non-irradiated sensors:** measured mainly in probe stations at RT
- **Irradiated sensors:** wire bonded to PCB board or a jig
  tested in freezer (at -20°C or lower)
  in dry N_2 atmosphere



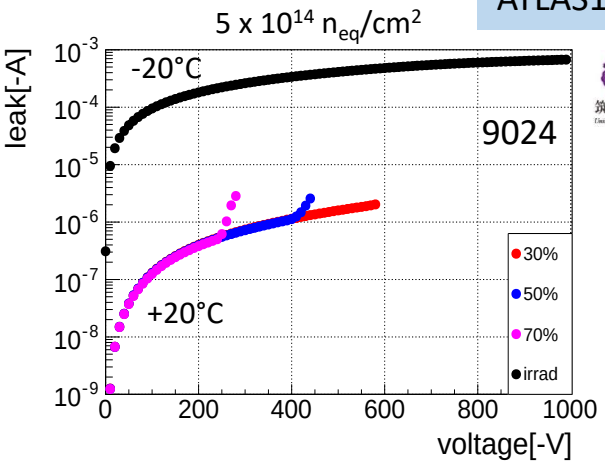


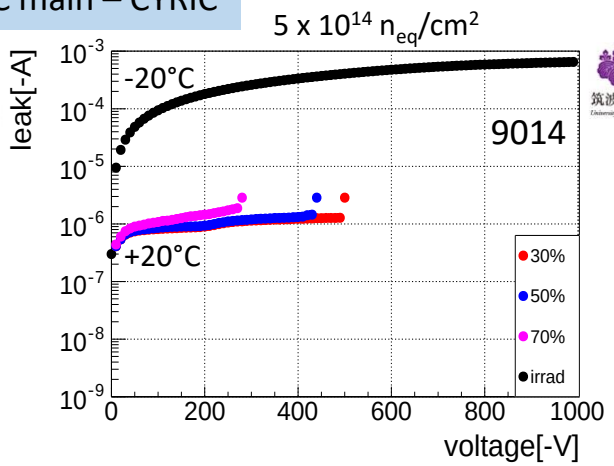


IV and onset of microdischarge: **main** ATLAS12EC and ATLAS17LS

ATLAS Specs for these submissions: Onset Voltage of Microdischarge (V_{MD}) > 600V

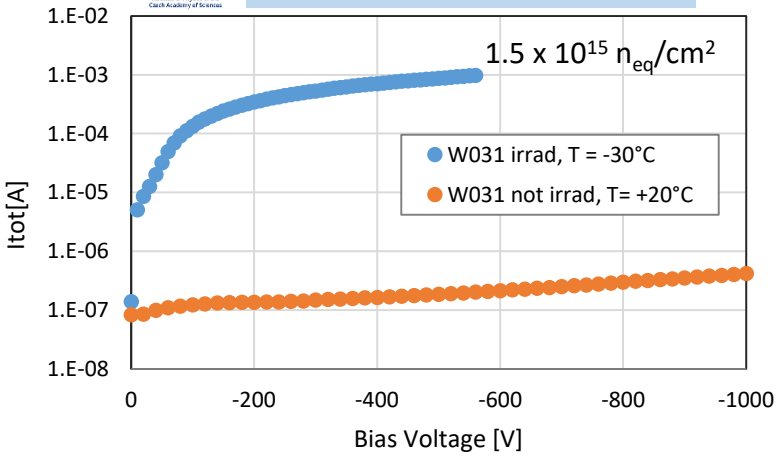
ATLAS12EC main – CYRIC



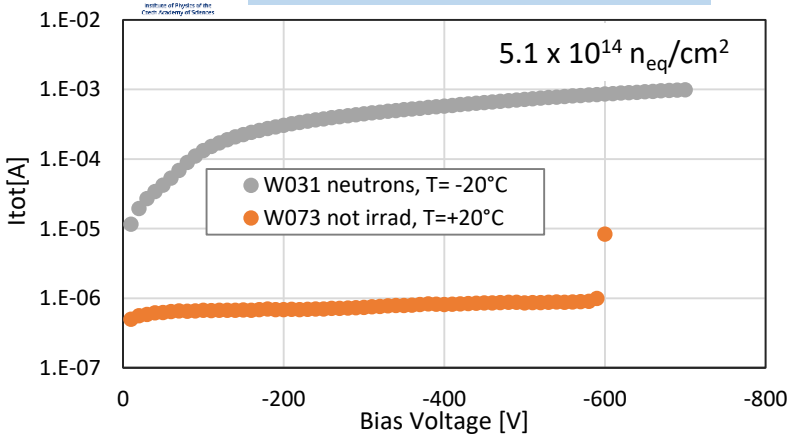


all sensors tested after annealing

ATLAS12EC main - CERN PS



ATLAS17LS main - neutrons

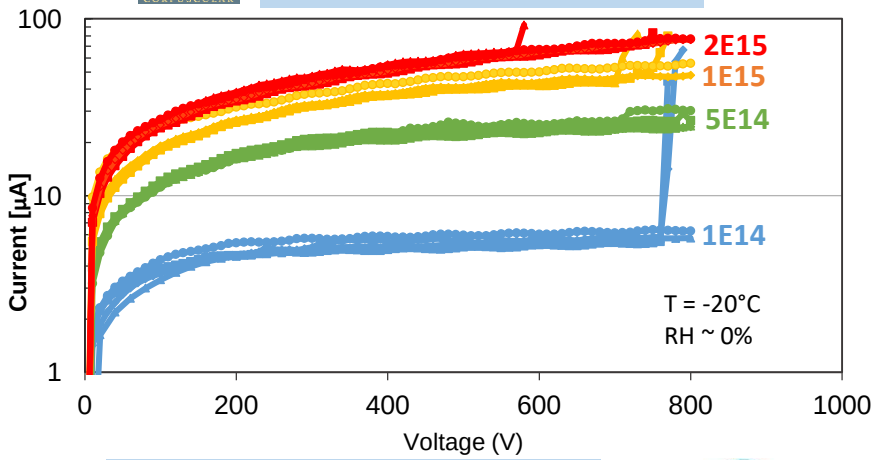


- No onset of microdischarge observed in main sensors after proton or neutron irradiations

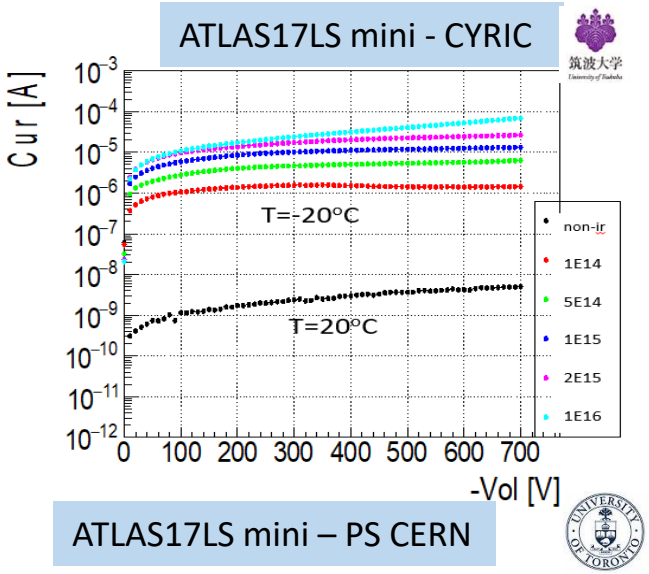
IV and Onset of Microdischarge: proton and gamma irradiated **mini** ATLAS17LS

ATLAS Specs for these submission: Onset Voltage of Microdischarge (V_{MD}) > 600V

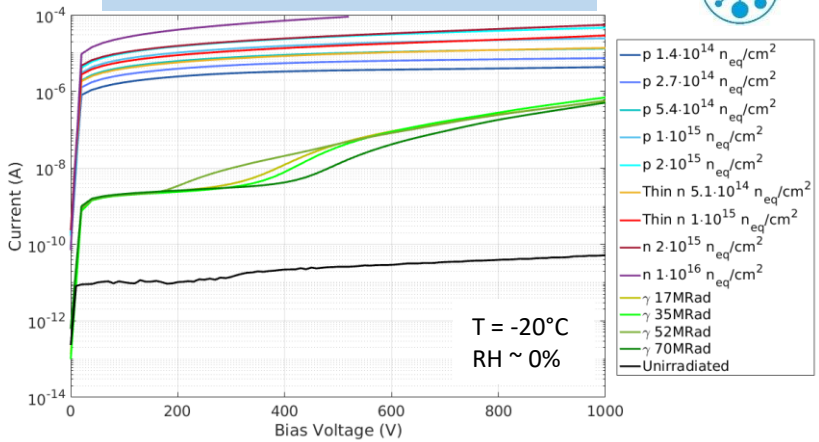
ATLAS17LS mini - PS CERN



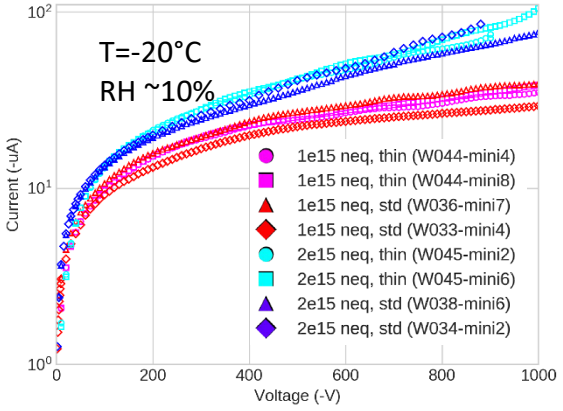
ATLAS17LS mini - CYRIC



ATLAS17LS mini – n, p(KIT), γ



ATLAS17LS mini – PS CERN



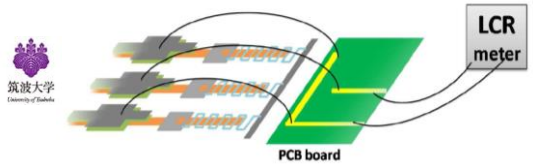
	Active	Physical
	Thickness	
std	290	320
thin	240	320

- Results of all institutions in agreement
- After irradiations: 1 mini sensor out of 80 has onset voltage of microdischarge bellow 600V

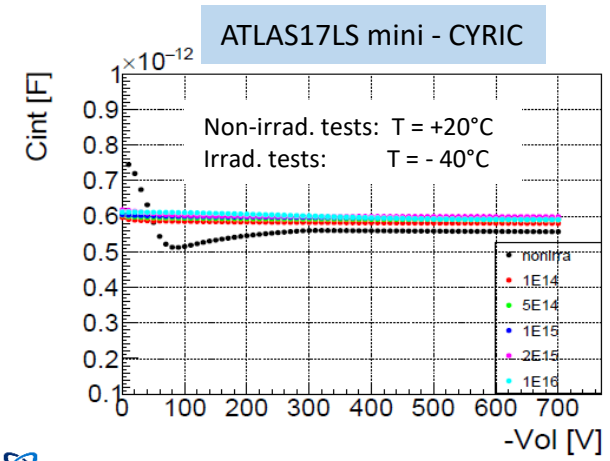
Inter-strip capacitance: ATLAS12EC and ATLAS17LS

- C_{int} contributes to the input capacitance of FE electronics and determines the noise level of the detector
- C_{int} measured by LCR meter between the central strip and its first neighbors (others floating)
- next 2nd and 3rd neighbors add ~10%

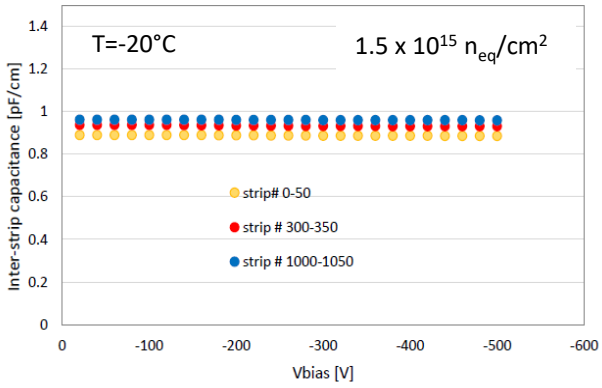
ATLAS Specs: < 1 pF/cm at 300V for non-irrad.
at 400V after irrad.



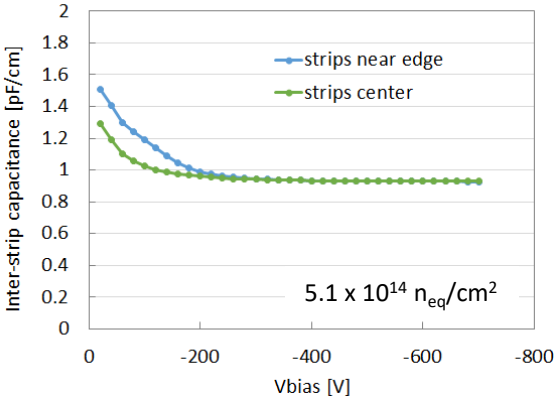
ATLAS17LS mini - CYRIC



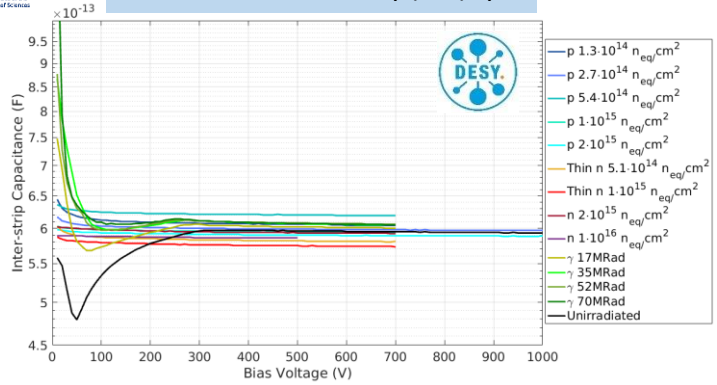
ATLAS12EC main - CERN PS



ATLAS17LS main - neutron



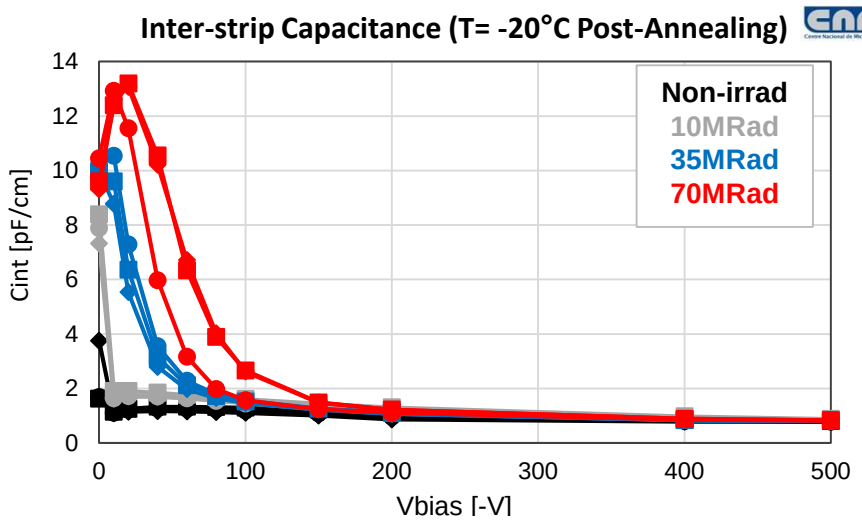
ATLAS17LS mini – n, p(KIT), γ

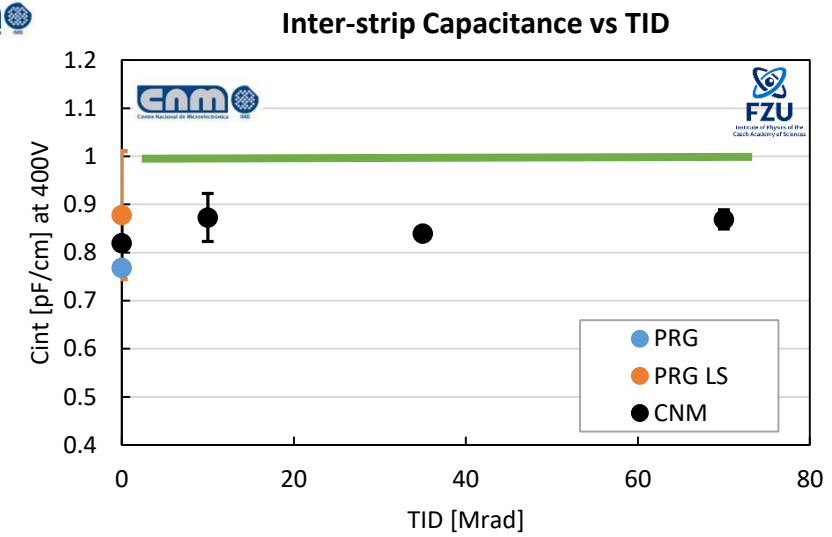


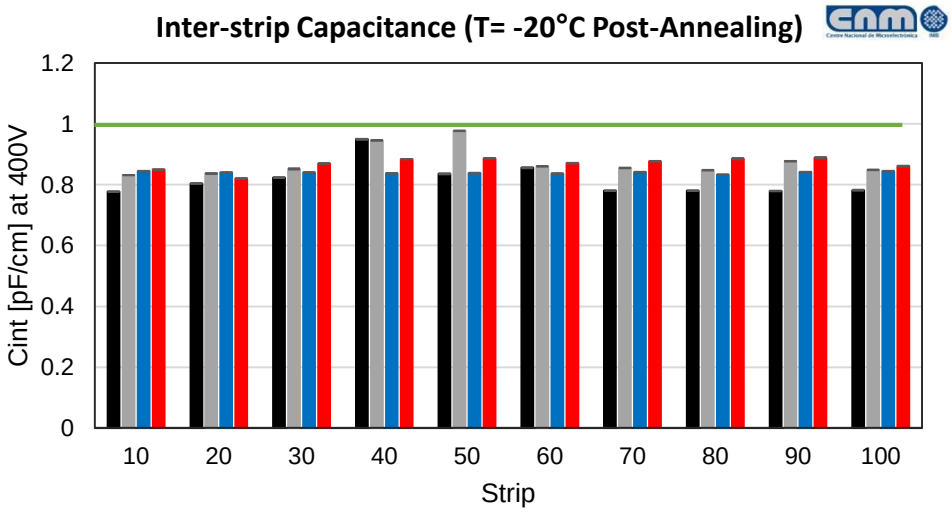
- No change of C_{int} after proton, neutron or gamma irradiations
- All tested main and mini sensors of both ATLAS12EC and ATLAS17LS types are within specs before and after irradiation

Inter-strip capacitance: gamma irradiated mini ATLAS17LS

ATLAS Specs: < 1 pF/cm at 400V







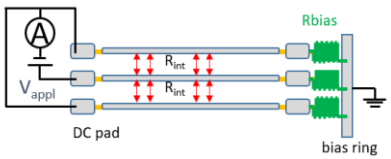
- All mini sensors within specifications both before and after gamma irradiations
- No change of C_{int} after gamma irradiation

Inter-strip resistance: main ATLAS12EC and ATLAS17LS

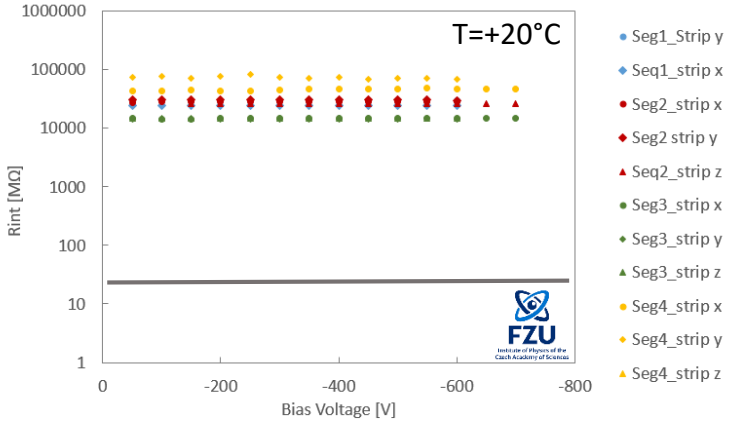
Measurements of Inter-strip resistance (R_{int}) - verification of neighboring strips isolation

ATLAS Specs: non-irradiated: R_{int}>15MOhm at 300V at +23°C
irradiated: R_{int}>15MOhm at 400V at -20°C

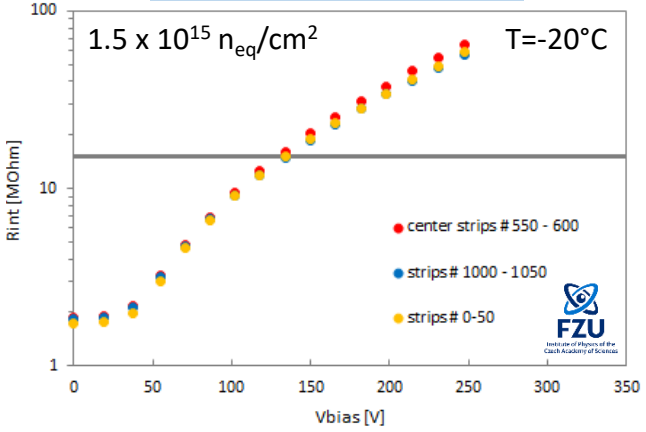
R_{int}= 2/(dI/dV_{appl})

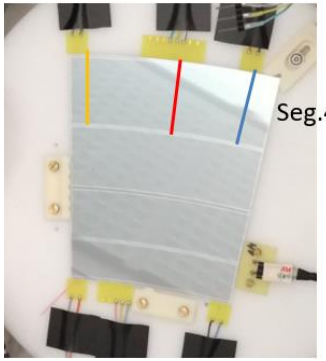


ATLAS12EC – non-irrad

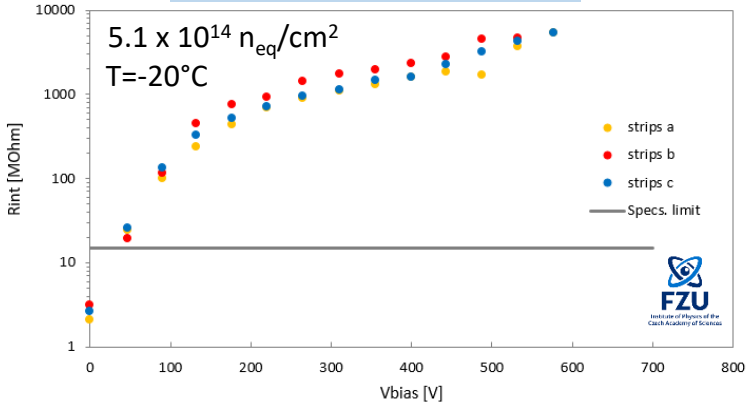


ATLAS12EC - CERN PS





ATLAS17LS - neutrons

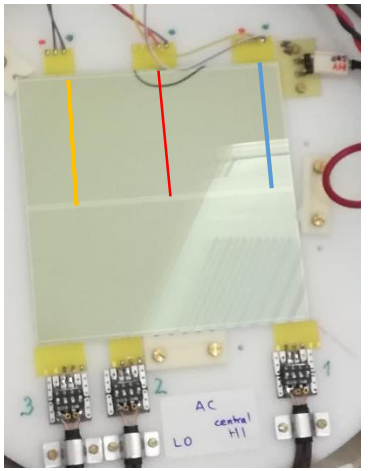


<u>Non- irradiated main sensors</u>:

- R_{int}/strip = 15-80 GΩ
- R_{int} is independent of Vbias

<u>Irradiated sensors:</u>

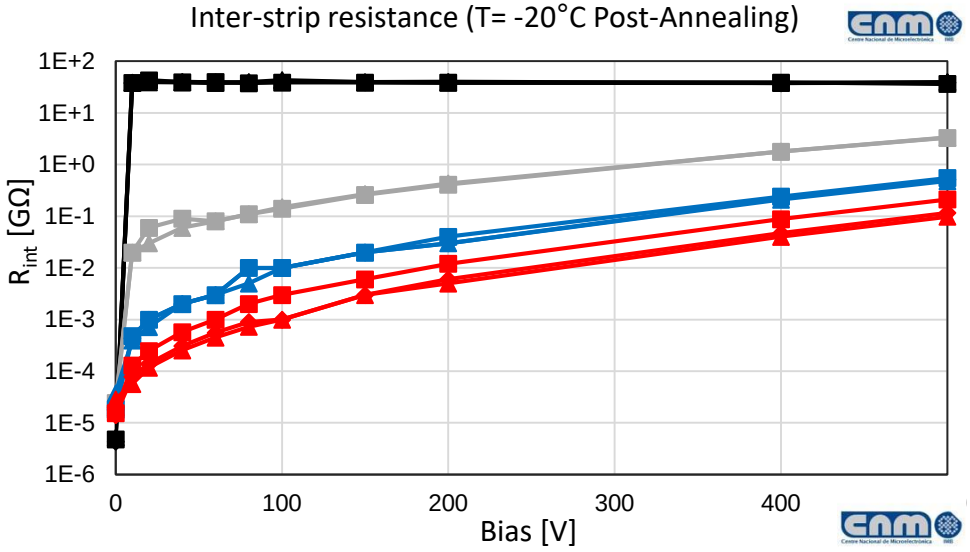
- R_{int} increases with bias voltage - Bias field reduces conductivity between strips
- R_{int} ~ 1 GOhm at 400V for neutrons
- R_{int} > 70 MOhm at 400V for protons

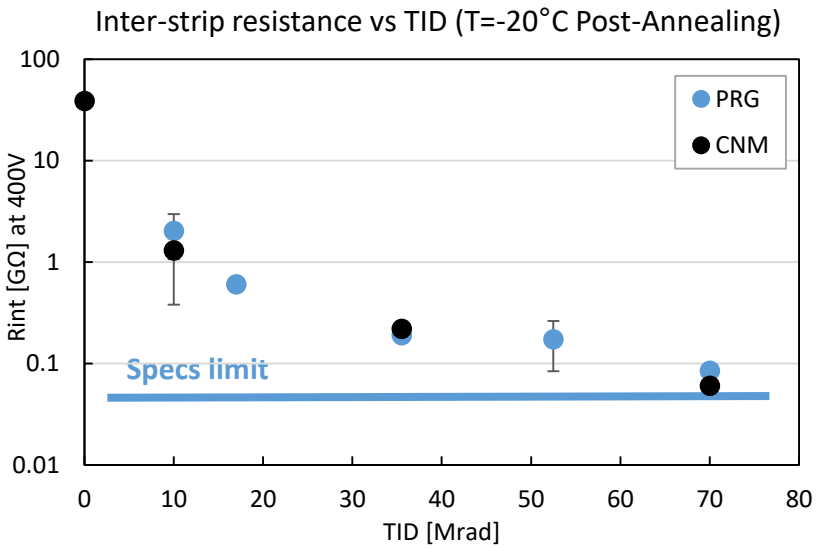


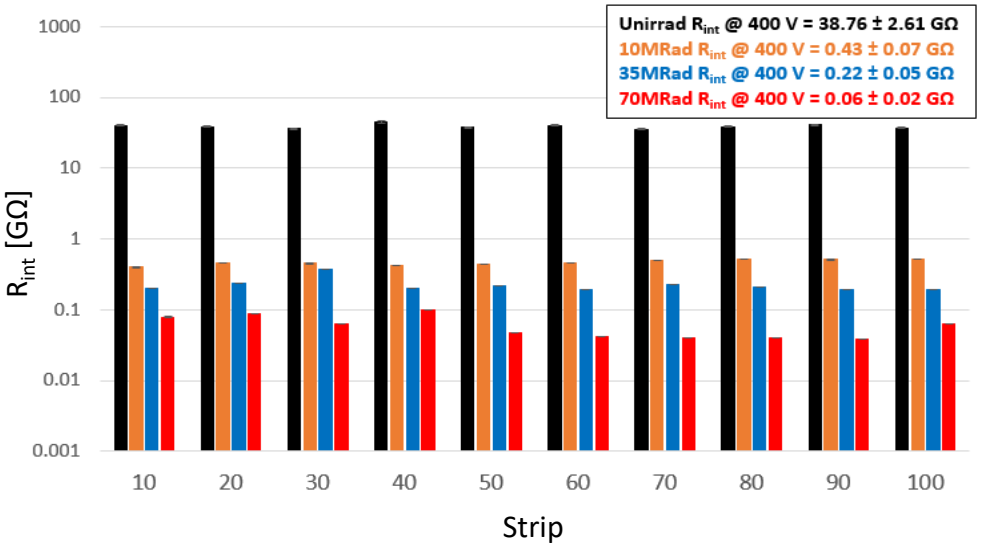
Main sensors irradiated by neutrons and protons fulfill specifications

Inter-strip resistance: γ irradiated mini ATLAS17LS

ATLAS Specs: $R_{int} > 10 \cdot R_{bias}$ @ 400 V

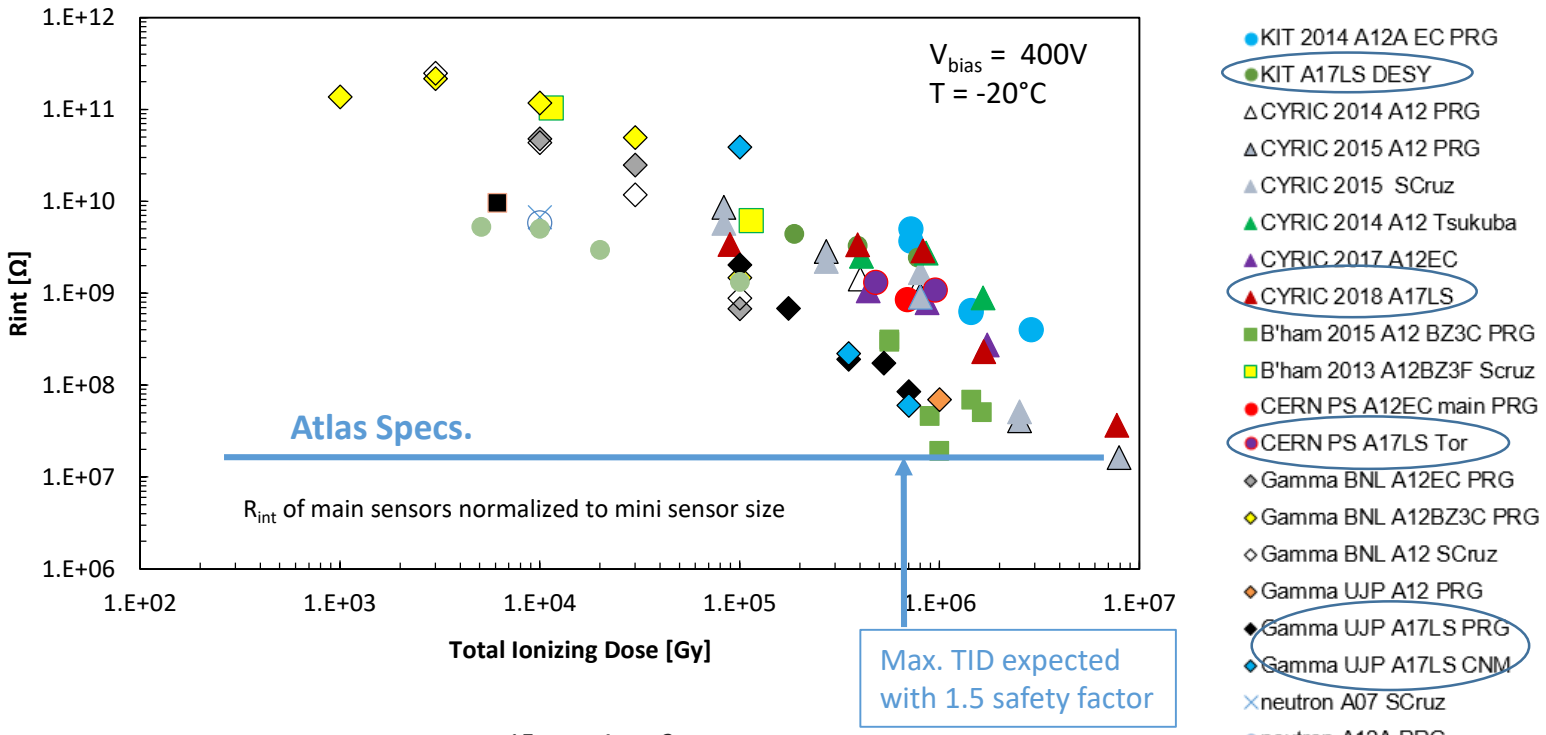






R_{int} decreases with increasing gamma dose but all sensors fulfill specs even at highest TID.

Inter-strip resistance vs. total ionizing dose (protons, neutrons and gammas)



- TID in irradiated sensors at $1x10^{15}$ n_{eq}/cm^2 has been assessed to be:

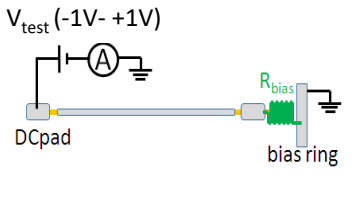
$1x10^{15}$ n_{eq}/cm^2			TID [Gy]
neutrons	reactor	minis	1e4
		main	1.2e4
protons	B'ham		1.14e6
	KIT		1.44e6
	CYRIC		0.77e6
	CERN PS		0.48e6

All irradiated sensors fulfill specs up to max. predicted TID

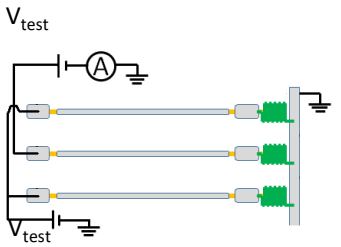
Bias resistance: proton and gamma irradiated ATLAS17LS

ATLAS Specs: 1.5 ± 0.5 MΩ*

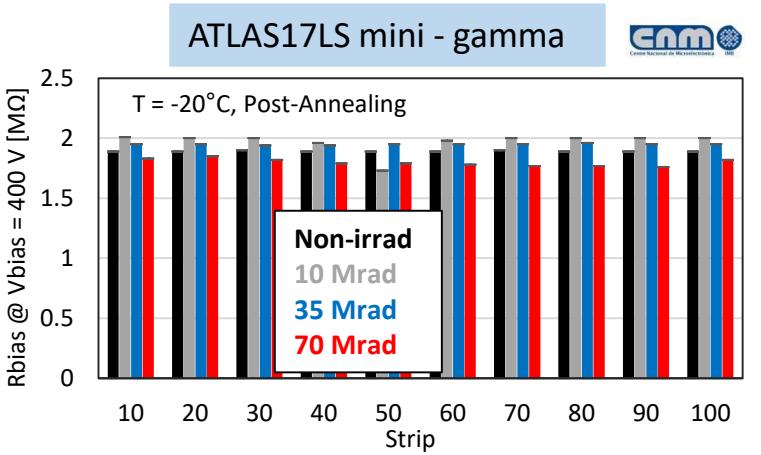
*no temperature specified

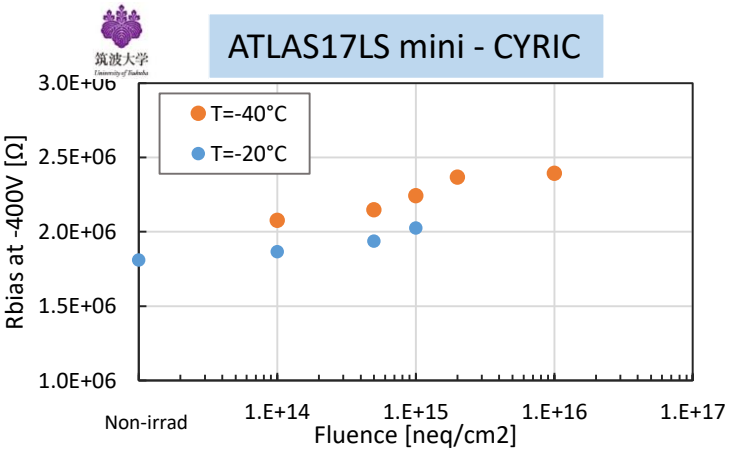


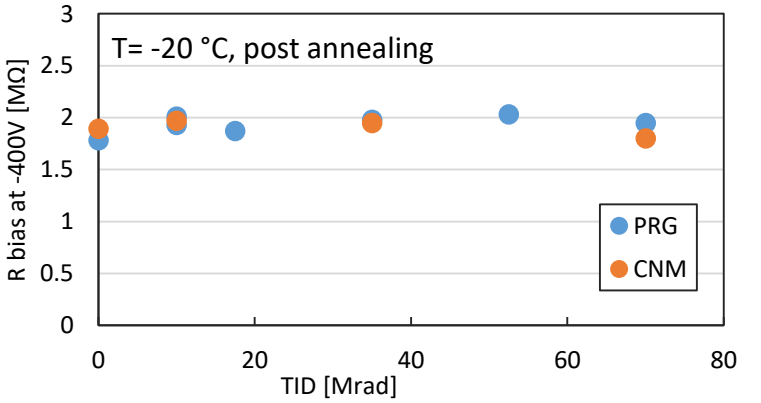
Method for non-irradiated sensors



Method for irradiated sensors







- Bias resistance (R_{bias}) is slightly temperature dependent
- Non-irradiated sensors: R_{bias} ≈ 1.5 MΩ at 20°C; R_{bias} ≈ 1.8-1.9 MΩ at −20°C
- R_{bias} is slightly increasing with proton fluence
- R_{bias} doesn't change after gamma irradiation
- R_{bias} is at limit of ATLAS specs if measured at cold

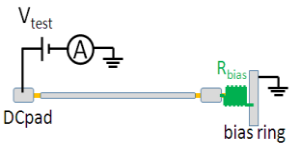
Punch –Through Protection: ATLAS17LS gamma

- PTP structures: to protect the AC coupling capacitors against large signal current, induced for example by beam splash
- Different designs during prototyping, PTP structure with full gate coverage chosen in main ATLAS12EC, ATLAS17LS
- The effectiveness of PTP structure measured with DC method

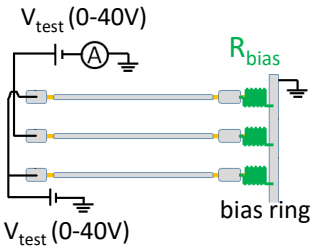
No ATLAS Specs defined

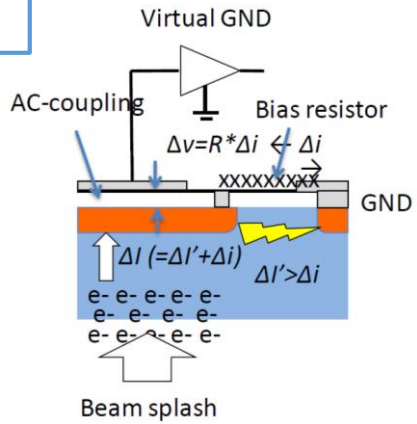
DC Method:

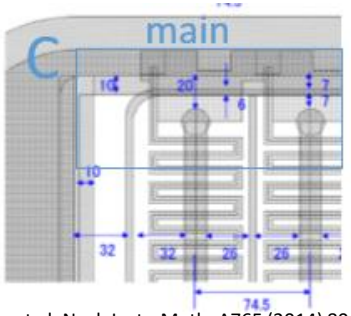
for non-irradiated sensors



for irradiated sensors

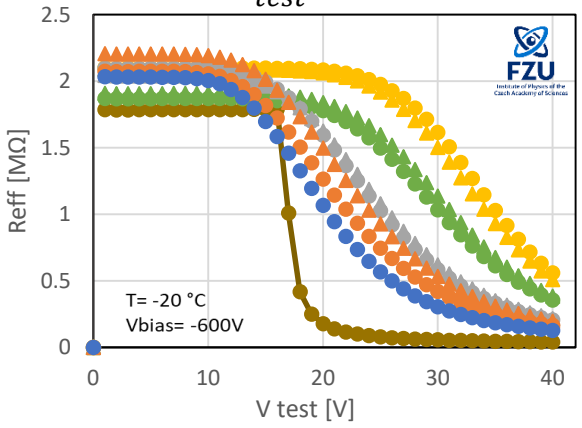


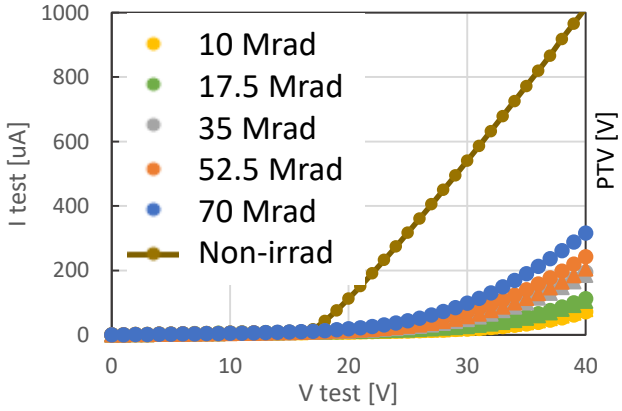




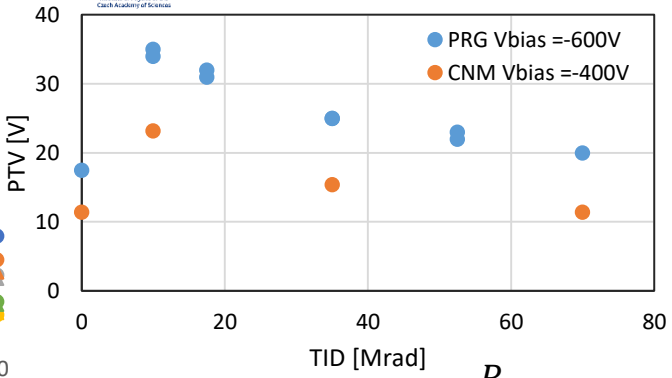
[Y. Unno et al. Nucl. Instr. Meth. A765 (2014) 80-90]

$$R_{eff} = \frac{V_{test}}{I_{test}}$$





Punch Through Voltage (PTV)



$$PTV = V(Reff = \frac{R_{bias}}{2})$$

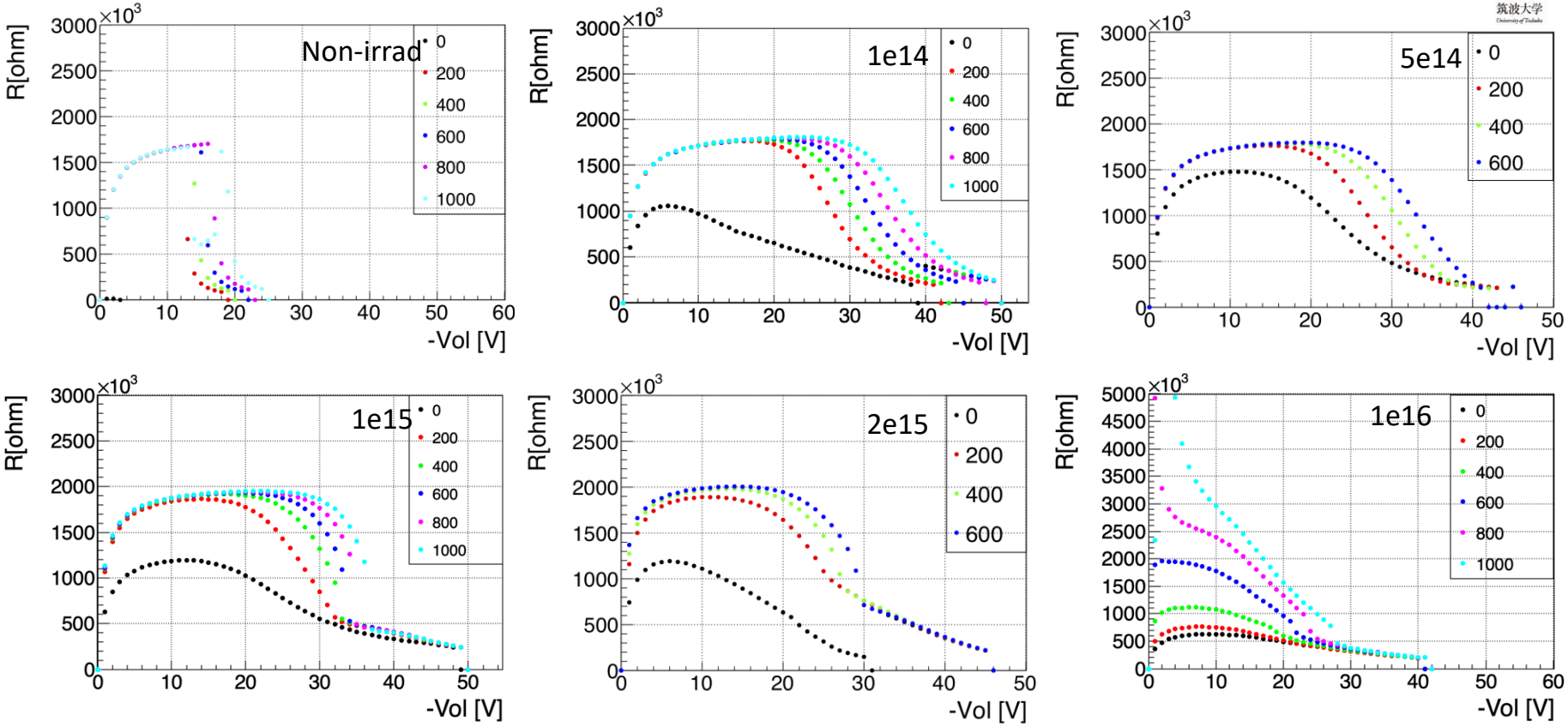
- Initial increase of PTV from 0 to 10 Mrad, followed by a decrease with increasing TID
- Good performance of PTP structure

Punch Through Protection: ATLAS17LS protons

ATLAS17LS mini - CYRIC

curves are at different V_{bias}

T=-20°C



PT voltage increases with increasing bias voltage and stays quite stable with increasing proton fluence

Summary of surface parameters

Parameter	Specifications for non-irradiated and irradiated production sensors	Test
Onset voltage of microdischarges	> 500 V	**100% sensors after irradiation**
Resistance of Al read-out strips	< 30 kΩ/cm	**A12EC: 13-20 Ω/cm** **A17LS: 8.8±0.5 Ω/cm**
Resistance of n-implant strip	< 50 kΩ/cm	**A12EC: 20.5-21kΩ/cm** **A17LS: 8.85 kΩ/cm** **gamma irrad. <20 kΩ/cm**
R_{bias} (Poly-silicon) of bias resistor	1.5 ± 0.5 MΩ	**Non-irrad: 1.5 MΩ at 20°C** **1.9 MΩ at –20°C** **Irrad: 2-2.4 MΩ if measured at -20;-40°C**
Interstrip resistance	10 x R_{bias} at 300V at RT (non-irrad) 400V at -20°C (irradiated)	**Non-irrad: 15-80 GΩ** **Irrad: 1 GΩ for n (5.1e14 n_{eq}/cm^2) ,** **200 MΩ for p (1.5e15 n_{eq}/cm^2)** **60 MΩ for γ (70Mrad)**
AC coupling capacitance	≥ 20 pF/cm, measured at 1 kHz	**25pF/cm, no change with irradiation**
Interstrip capacitance	< 1 pF/cm at 300V at RT (non-irrad), 400V at -20°C (irradiated) measured at 100 kHz for main (at 1MHz for mini)	**100% of tested sensors before and after irradiation C_{int}<1pF/cm**

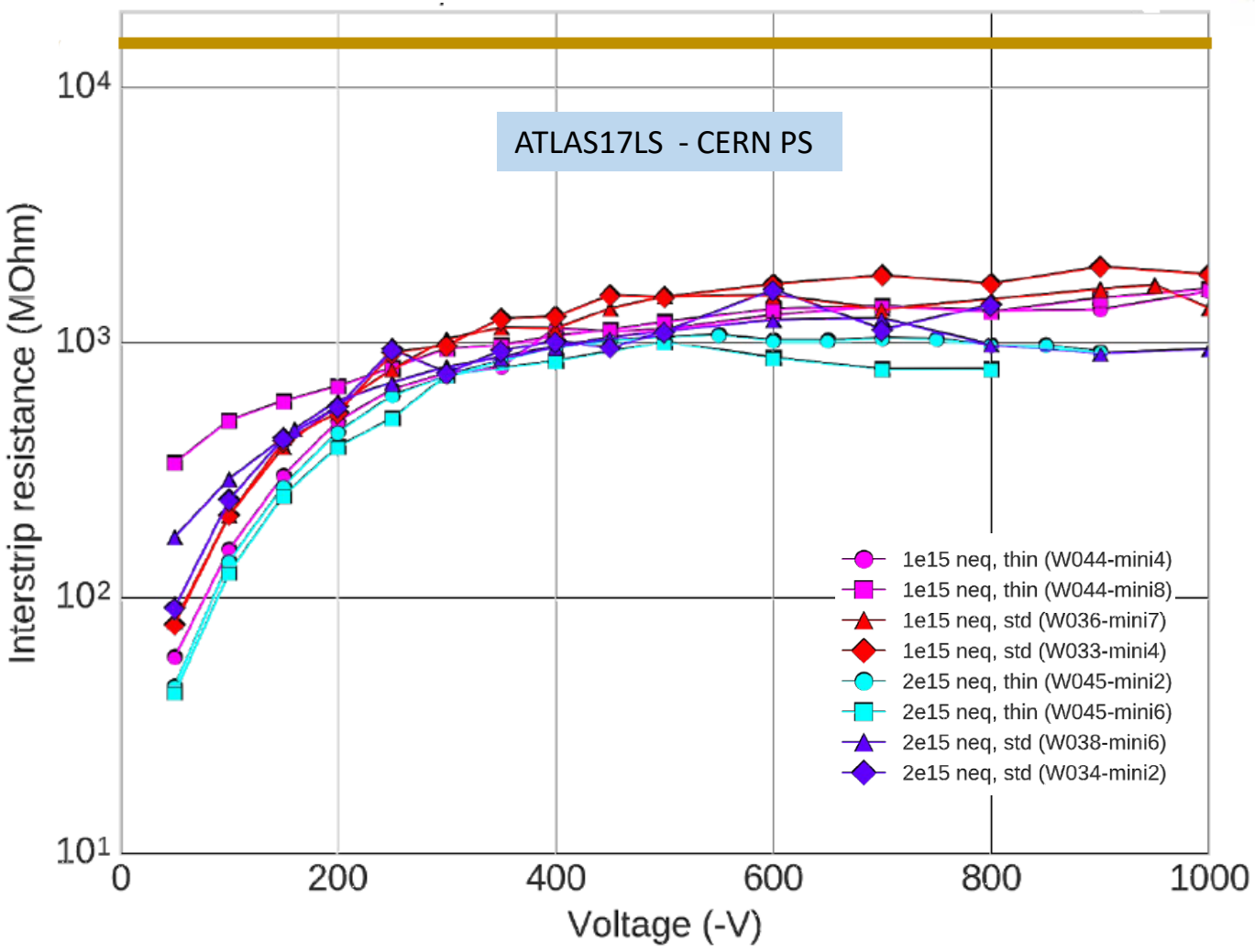
Parameters within the specifications

Conclusions

- **HPK ATLAS12EC and ATLAS17LS sensors were measured by ATLAS ITk institutes before and after irradiation**
- **ATLAS17LS as a part of Market Survey Step 3 qualification process**
- **ATLAS17LS-HPK sensors, non-irradiated and irradiated with gamma, protons and neutrons fulfill all the ATLAS Specs imposed for the Market Survey Step 3**
- **Specifications for production sensors were updated: maximal operational voltage got reduced to 500V due to max HV decision**
- **ATLAS12EC and ATLAS17LS sensors satisfy the ATLAS ITk performance requirements**

Backup slides

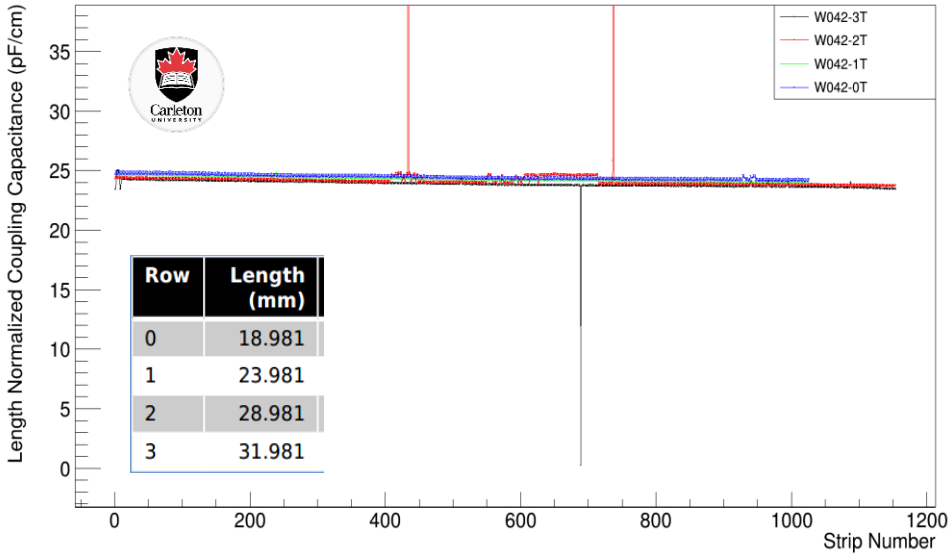
Inter-strip resistance ATLAS17LS mini



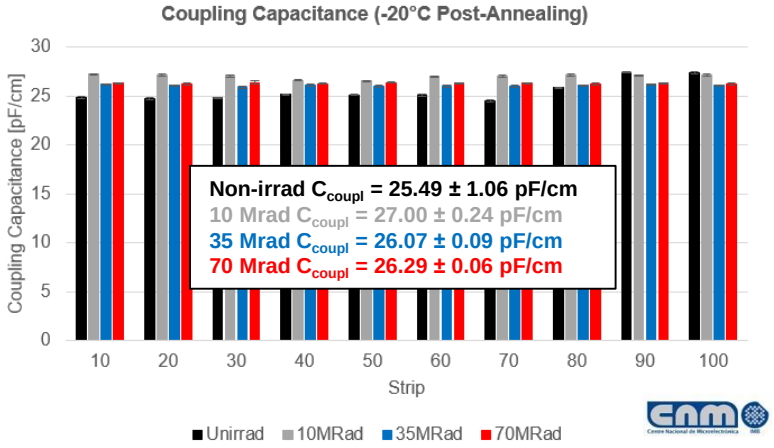
Coupling Capacitance: main ATLAS12EC, mini ATLAS17LS

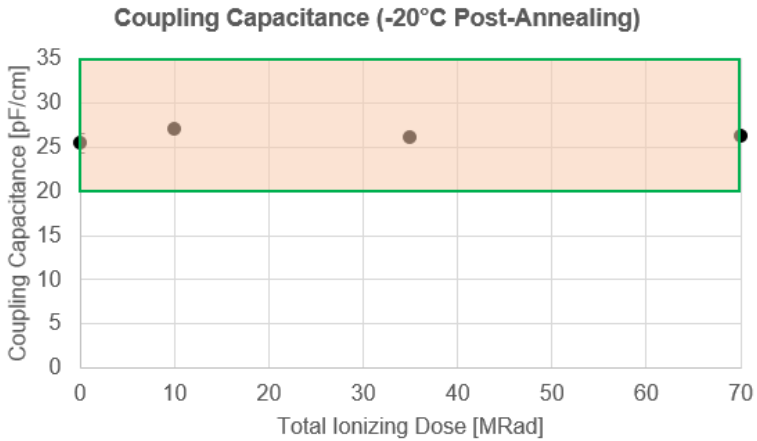
ATLAS Specs:> 20pF/cm

Main ATLAS12EC – non-irrad



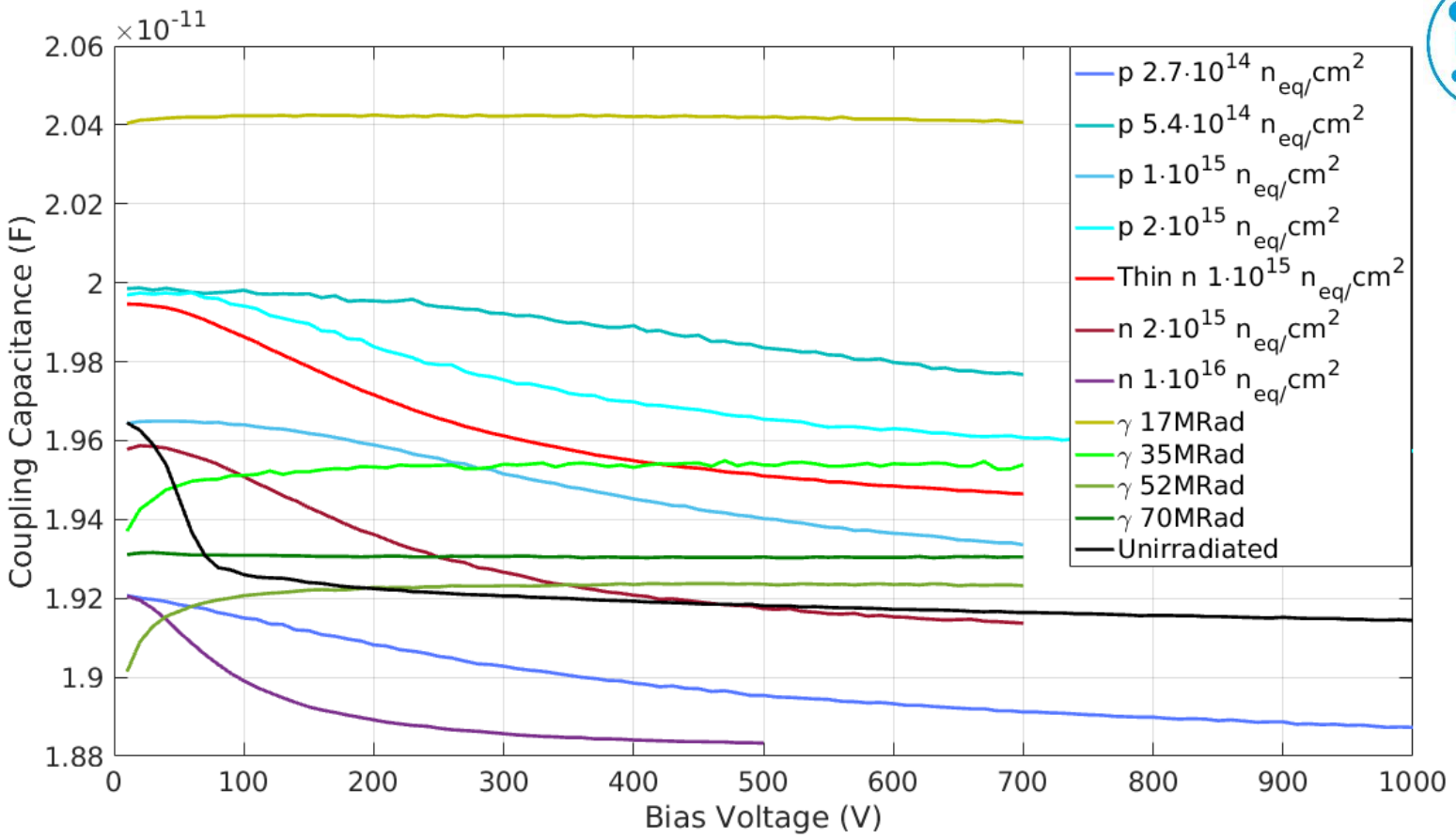
ATLAS17LS - gamma





- C_{coupl} must be large to maximize signal and its integrity
- C_{coup} doesn't change with gamma or proton irradiations
- C_{coup} meets the specs

Coupling Capacitance: mini ATLAS17LS

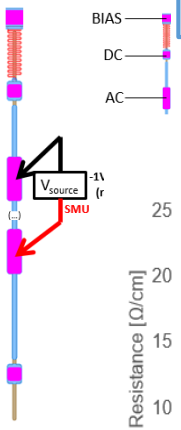


- C_{coup} doesn't change with gamma, neutron or proton irradiations
- C_{coup} meets the specs

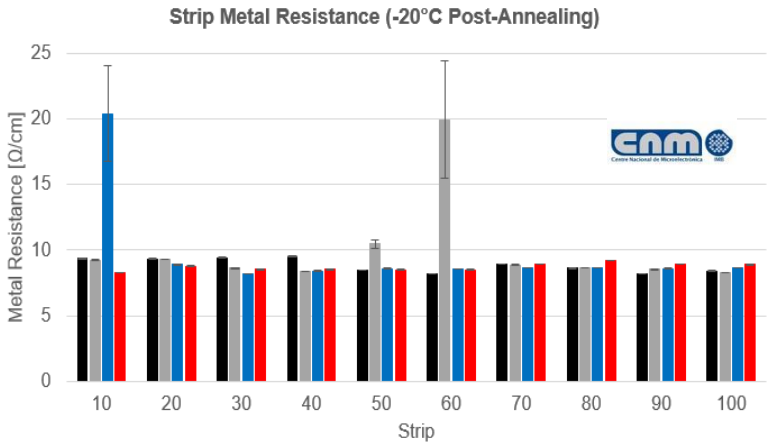
Metal and Implant resistance: ATLAS17LS

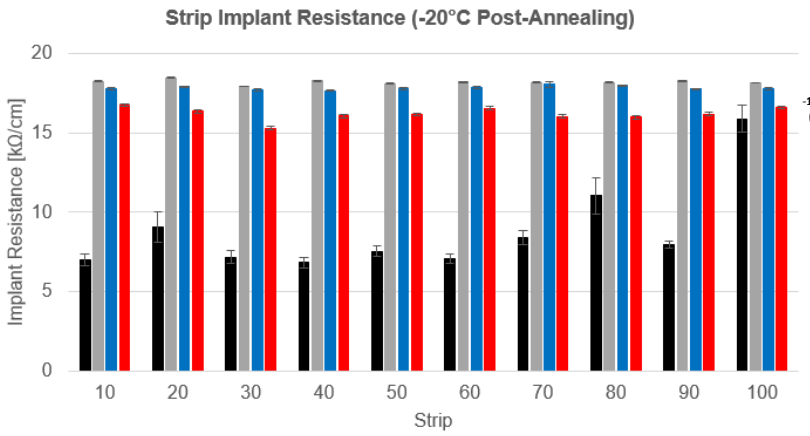
Metal resistance: ATLAS Specs:< 30 Ω/cm

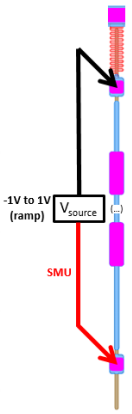
Implant resistance: ATLAS Specs:< 50 kΩ/cm

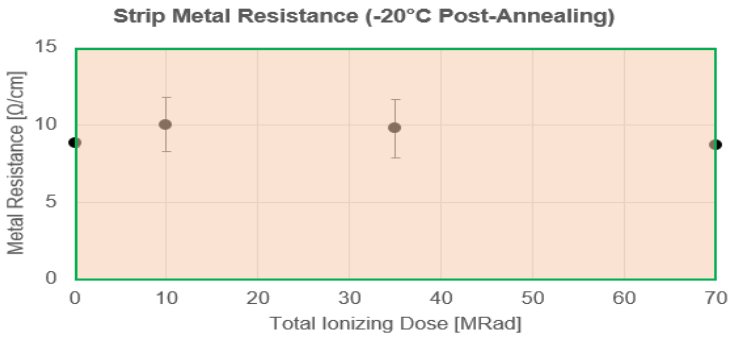


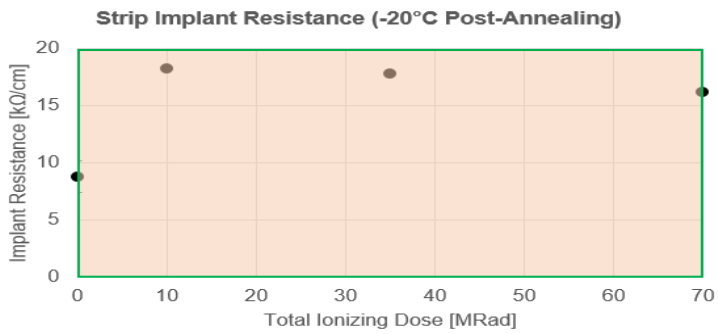
ATLAS17LS mini - gamma











- Non-irrad. ATLAS12EC: R_{metal} =13 - 20 Ω/cm
- ATLAS17LS: R_{metal} = 8.8 ± 0.5 Ω/cm
- R_{metal} does not change with TID

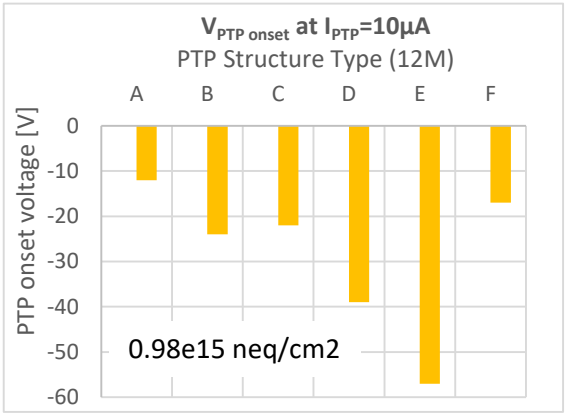
- Non-irrad. ATLAS12EC: R_{imp} = 20.5 - 21kΩ/cm
- Non-irrad. ATLAS17LS: R_{imp} = 8.8 ± 2.8 kΩ/cm
- R_{imp} increases after gamma irradiation, <20 kΩ/cm

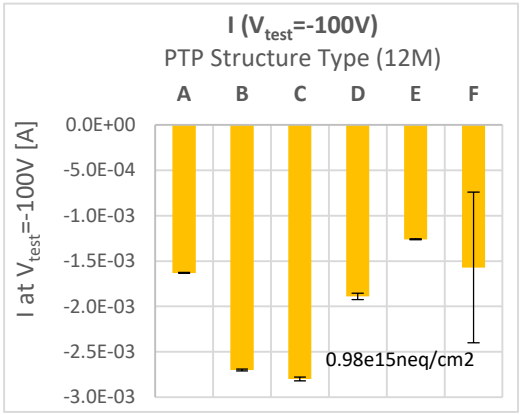
- ATLAS17LS fulfill the Specs before and after gamma irradiation

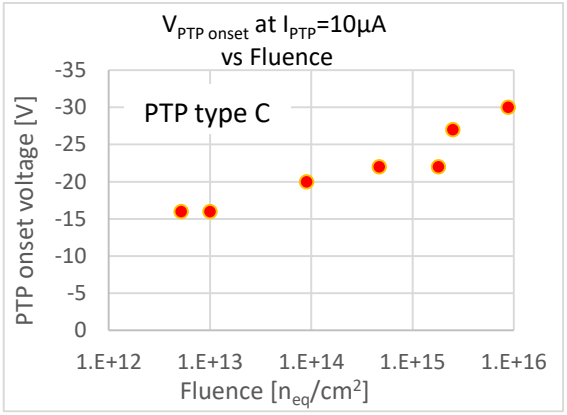
PTP - Structure dependence

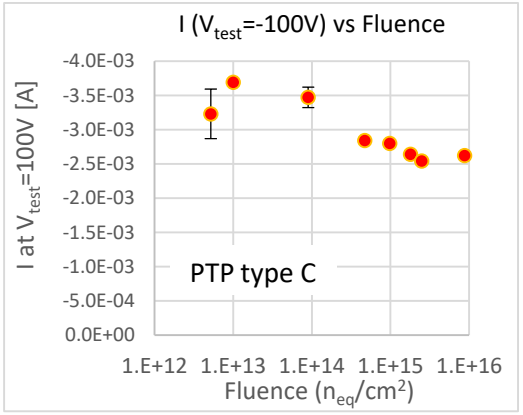
Very good performance of “C” type (full gate) structure also after proton irradiation:

- steep increase in current
- small PTP onset voltage (~20V)
- largest current at V_{PTP}=-100V.





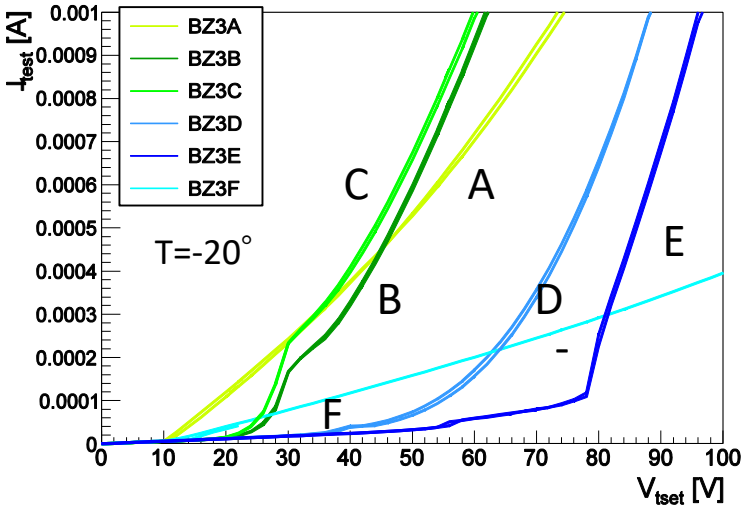




modest increase of $V_{PTP\ onset}$ up to 2x10^{15}
$V_{PTP\ onset}$ < 25V

large I (V_{TEST}=-100V) even at 1x10^{16}
2.5mA=2.5mC/s= 6e11 mips/s/strip

PTP: ATLAS12M, HV:-1000V & Fluence: 0.98e15



The novel full gate PTP structure “C” doubles the allowable current without increasing the onset voltage.