Gamma irradiation of ATLAS18 ITk strip sensors affected by static charge

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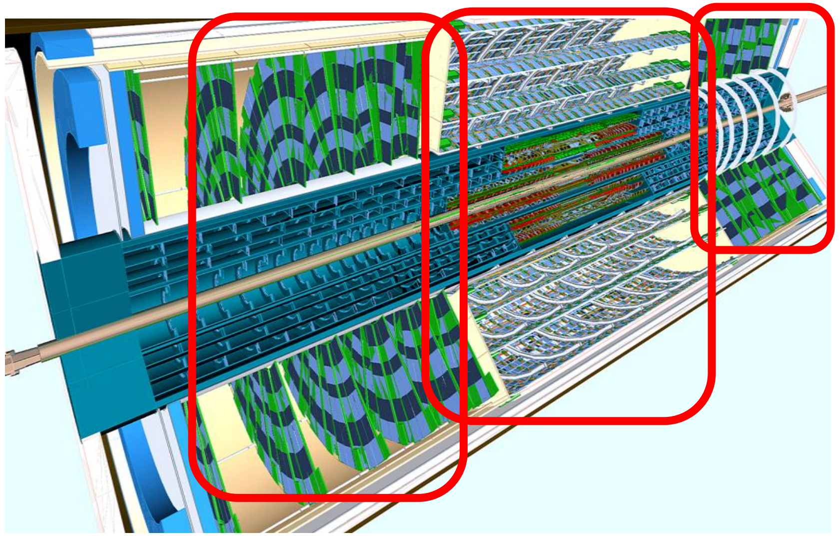
The ITk Detector for the HL-LHC

- For the HL-LHC, the ATLAS tracking system will be replaced with all-silicon detector: the Inner Tracker (ITk)
  - ITk Pixel detector
  - ITk Strip detector
    - 4 concentric cylindrical layers in barrel
    - 6+6 disks in endcaps
    - 17,888 sensors
    - 165 m^2 of silicon
    - 60 million strips
    - Dose: up to 53.2 Mrad
    - Fluence: up to 1.1×10^{15} 1MeV $n_{eq}cm^{-2}$



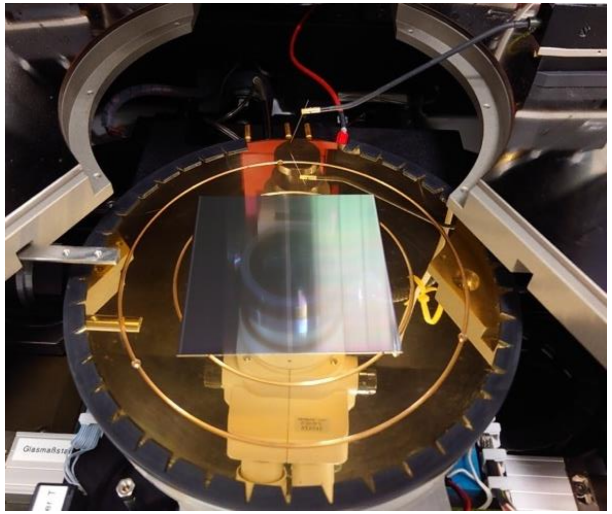
- ITk detector designed to withstand harsh HL-LHC environment
  - 4,000 fb^{-1} over 10 years, $L_{peak}=7.5 \times 10^{34}$ $cm^{-2}s^{-1}$, μ~200

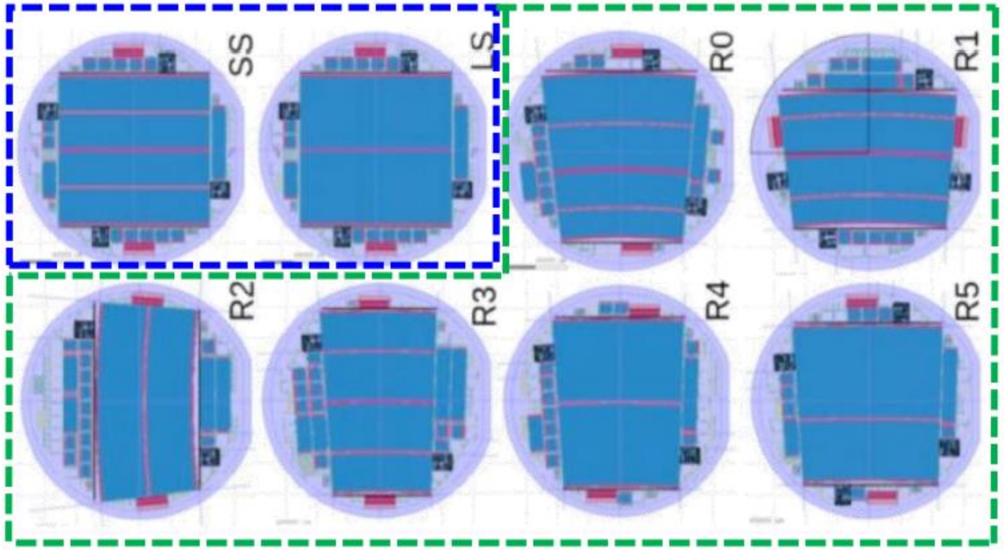
More about
- ITk Pixel in Jo Parker's talk
- ITk Strip in Igor Mandic's talk
- ITk Strip Endcap in Laura Franconi's poster

Si Strip Sensors by HPK

- n^+-on-p, 320 µm thick, single sided microstrips
- AC-coupled strips with polysilicon biasing

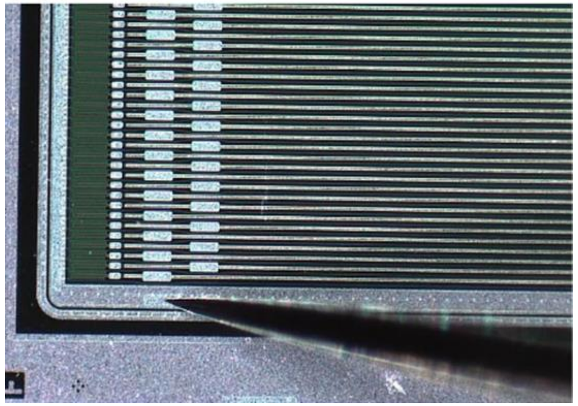
- **Barrel sensors** – square geometry
  - Strip pitch 75.5 µm
  - Short strips (SS) 24.1 mm long
  - Long strips (LS): 48.3 mm long
- **Endcap sensors**: trapezoidal
  - 6 sensor geometries
  - Pitch 70-80 µm
  - Strip length: 15-60 mm depending on radius
- Sensor production of total amount of 20800 sensors started in HPK in 2021 and is scheduled for completion in 2025

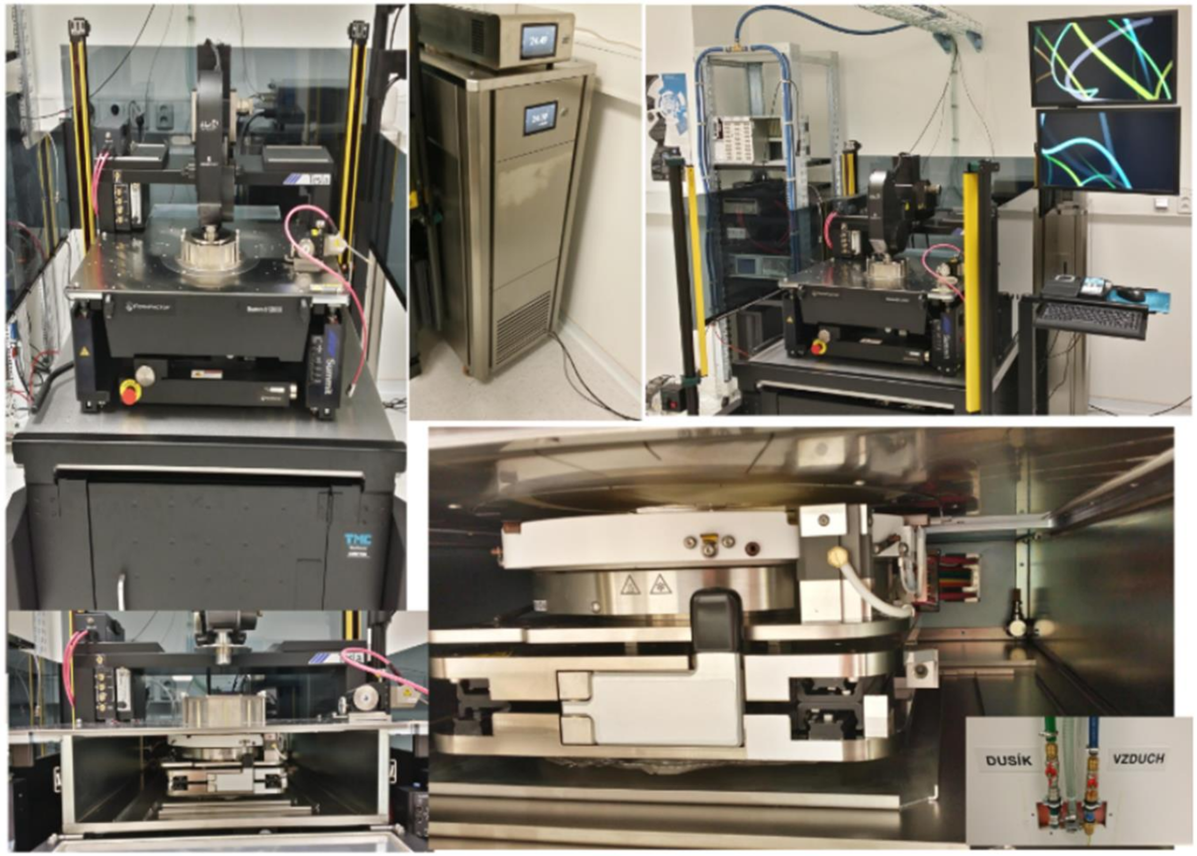




QC main sensor testing

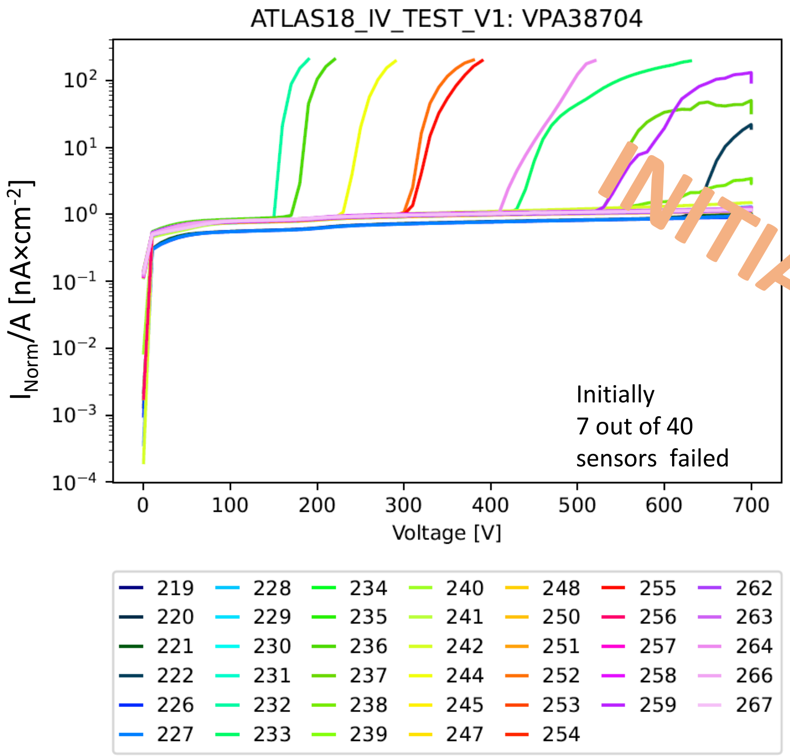
- upon delivery ATLAS performs detailed measurements of sensors to monitor quality of all fabricated devices and to ensure that their characteristics are within specifications defined by ATLAS collaboration
- **QC tests**
  - Mechanical tests (bow and thickness)
  - Current-voltage (IV)
  - Capacitance-voltage (CV)
  - Leakage Current Stability: 5%-10% sampling
  - Full Strip Tests (I_{PIN}, C_{COUPL}, R_{BIAS}/R_{INT}): 2%-10% sampling
- **QC sensor testing sites**
  - KEK/Tsukuba
  - SCIPP
  - U of Cambridge
  - QMUL
  - FZU Prague
  - SFU/TRIUMF
  - Carleton U

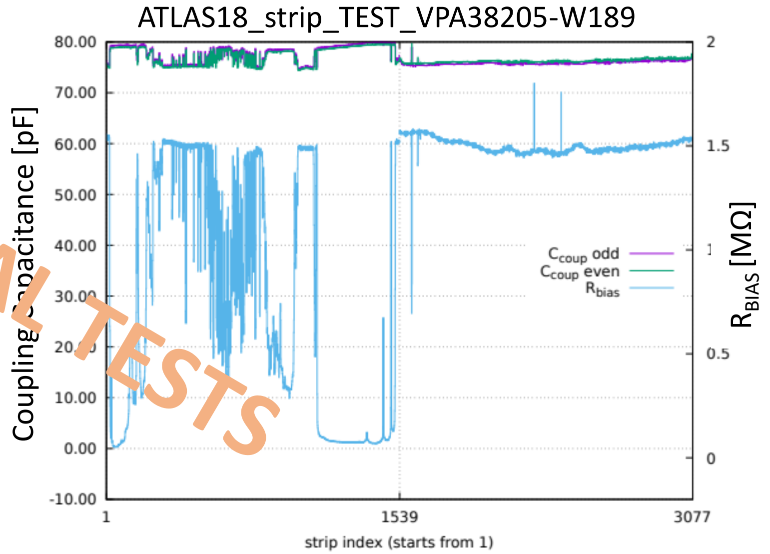


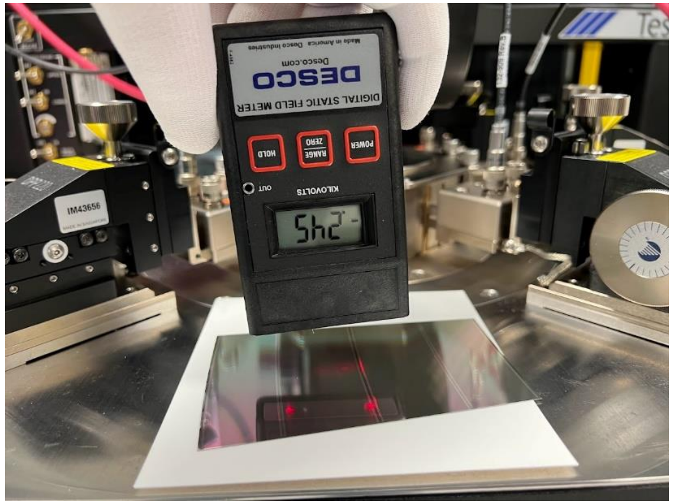


Specific Issues observed in QC testing

- Most sensors show high quality in QC tests
- In several production batches, a number of sensors failed the electrical QC tests:
    1. Early breakdown in IV: Breakdown Voltage (V_{BD}) < 500 V (specs: > 500V)
    2. Areas with low interstrip isolation in full strip tests
    3. Current instabilities during long-term current stability testing and failures in IV after the stability tests





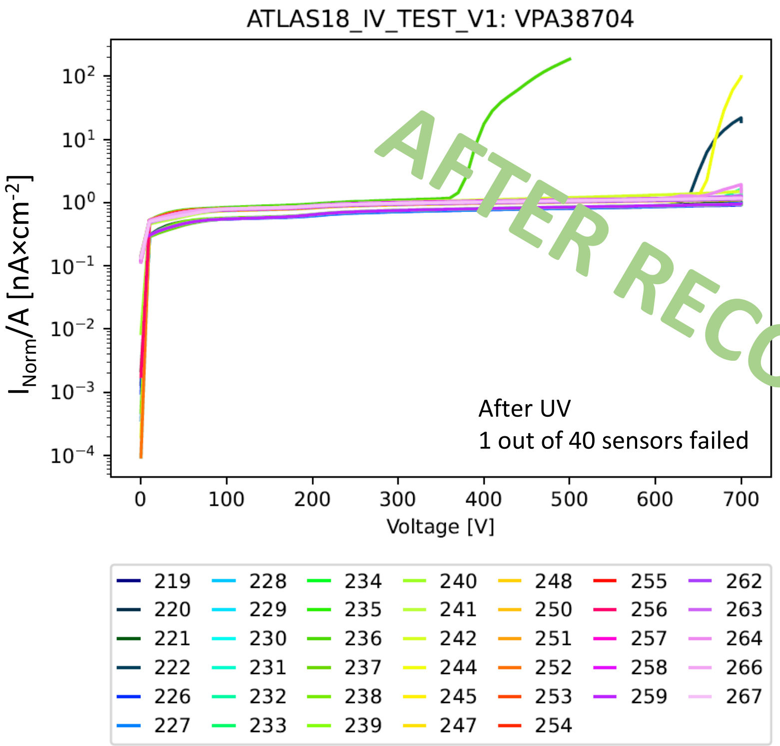


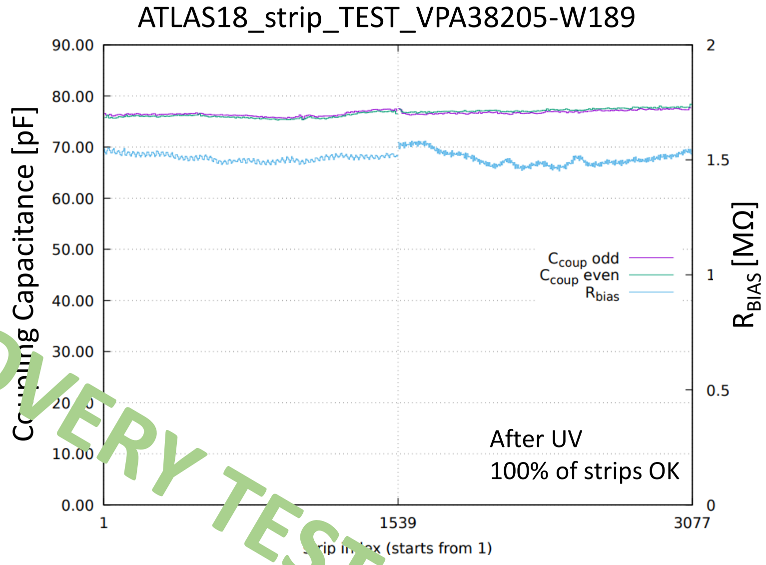
static charge measurement

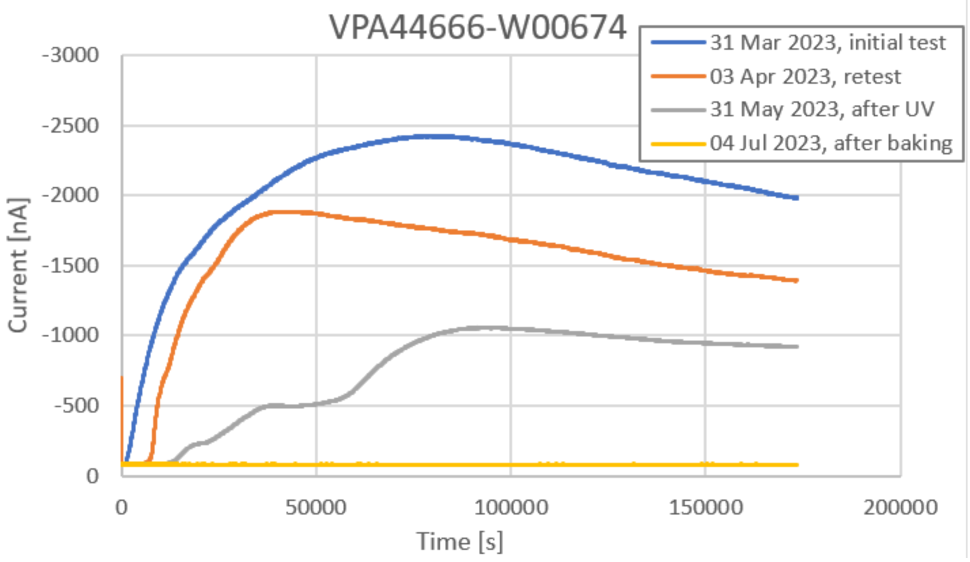
- Strong correlation between observed electrical failures and high electrostatic charge (up to ~ 100's V)
- Electrostatic charge accumulated on the surface of the sensor
    - in the strip area can lead to the loss of interstrip isolation
    - close to the edge and bias ring can cause instability of current or low breakdown voltage

Recovery methods used by the QC sites

- Introduced sensor recovery techniques:
  1. irradiation of the sensor surface with **UV-A** and **UV-C** light
  2. application of the intensive flow of ionized gas
  3. subject the sensors to high-temperature exposure
  4. dry storage over days / weeks







[ATL-COM-ITK-2023-060.pdf]

Sensors affected by static charge in real experiment

- Despite implementation of recovery techniques, it is still possible that some affected sensors won't be identified by the sensor QC testing or that the electrostatic events could occur later during tracker assembly.
- **Hypothesis:**
  - Will the sensor issues caused by static charge be "cured" by ionization in the real experiment? If so, how quickly?
- **Study:**
  - Irradiation of affected sensors by ^{60}Co gamma rays with aim to determine whether it can effectively resolve early breakdown (BD) or low interstrip isolation, and if so, to determine the TID and real experiment duration required for such a cure
- **Plan:**
  - Select 3 sensors with early BD and 3 sensors with low interstrip isolation for the irradiation study
  - Irradiate just 2 (with early BD) + 2 (with low interstrip isolation) sensors to a few consecutive target TIDs
  - 1+1 sensors keep as REFERENCE samples - no irradiation, but transport, storage, and handling identical to irradiated sensors

Samples selected for the study

- 3 sensors with early break-down

	Initial IV test BDV [V]	IV test just before irrad. (2 month in dry storage) BDV [V]
R1-W607	150 V	160 V
R1-W617	150 V	150 V
R1-W650	150 V	200 V

R1-W650: Reference sample

- 3 sensors with low interstrip isolation areas

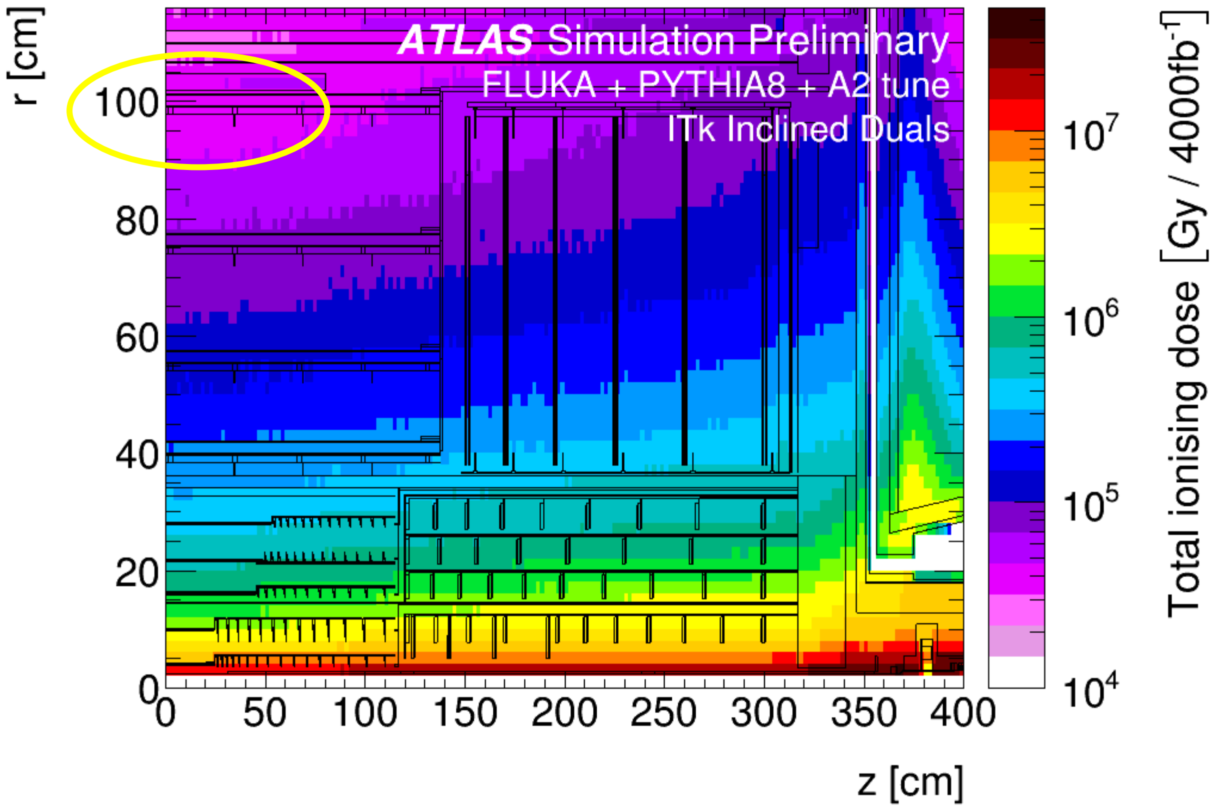
	Initial Full Strip test # of bad strips	Full strip test just before irrad. (2 month in dry storage) # of bad strips
R1-W635	40	40
R1-W620	26	18
R3-W1014	28	24

R1-W620: Reference sample

Estimation of few consecutive target TIDs

- The worst case for curing affected sensors by electrostatic charge are regions where TID is minimal (it will take longer to get sensors cured):
  - Central region of the outermost barrel cylinder, with 5.9 Mrad target dose (including 1.5 safety factor)
  - Targets TIDs planned for this experiment:

Real experiment duration	TID [krad]
1 week	11
1 month	49
6 months	195
1 year	590
2 years	1200
…	

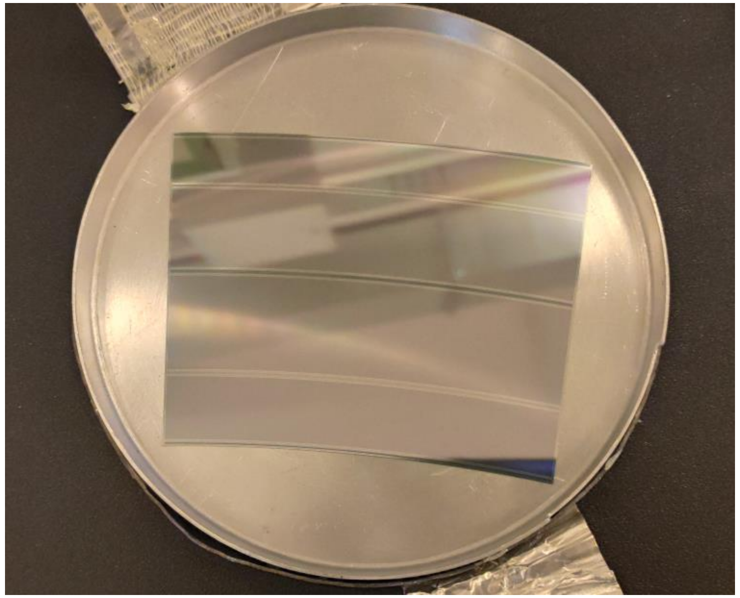


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/RadiationSimulationPublicResults#Phase_II_Upgrade_Mar_2018_AN1

Gamma irradiation

- UJP Praha a.s.: gamma from Co60,
- Sensors irradiated individually in Charge Particle Equilibrium (CPE) box => sensor surface free
- Distance from source: ~28 cm
- Reference samples were physically moved inside the CPE box, taken out, but not subjected to irradiation.

Irrad. campaign	TID [krad]	Dose Rate [krad/min]	Irradiation time [s]
1.	11	1.024	644
2.	1.5	1.026	88
3.	1.5	1.026	88



Results after irradiation of 11krad

	IV just before irrad.: BDV [V]	IV after irrad: BDV [V]
R1-W607	160 V	>600 V*
R1-W617	150 V	>680 V*
R1-W650	200 V	250 V

* The LabVIEW program was interrupted because the current limit of 20uA was reached

Reference sample (R1-W650)

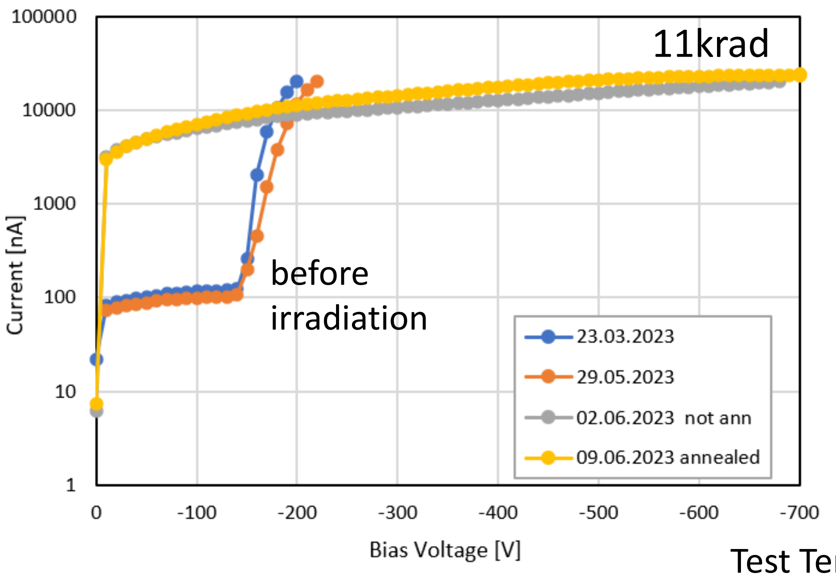
	Full strip test before irrad.: # of bad strips	Full strip test after irrad.: # of bad strips
R1-W635	40	0
R1-W620	18	18
R3-W1014	24	0

Reference sample (R1-W620)

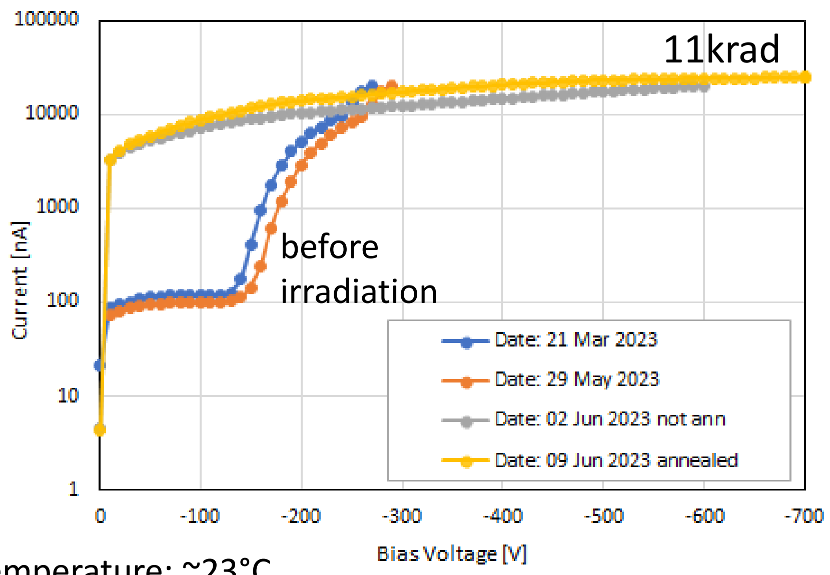
- Gamma irradiated sensors **cured:** BDV increased and low interstrip isolation areas disappeared
- Reference sensor (transported and handled alongside the other sensors, not subjected to irradiation) **not recovered.**
- Gamma irradiation resolved issues successfully during initial planned step of irradiation with 11 krad (~1 week in the real experiment) => further irradiations to higher TIDs were not needed
- Instead, the reference samples were irradiated to an even lower TID of 1.5 krad (~1 day in the real experiment).

IV before and after gamma irradiation

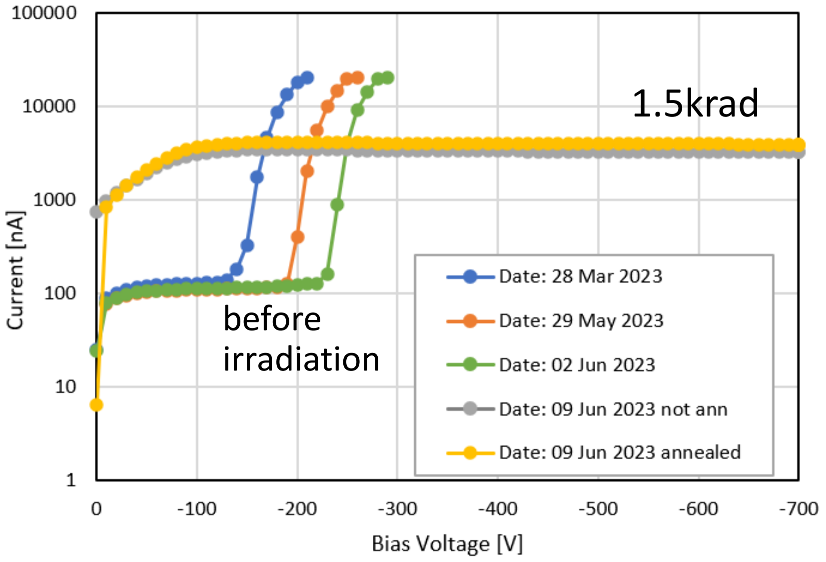
W617



W607



W650 reference sample



Test Temperature: ~23°C

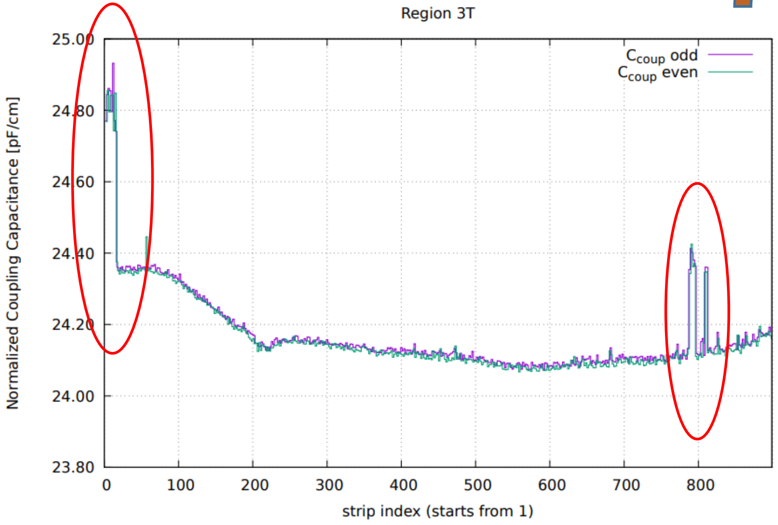
- Early BD of sensors W617 and W607 disappeared after gamma irradiation to 11krad.
- Early BD of reference sample W650 was not resolved (green line). W650 was transported and handled alongside W617 and W607 but not subjected to irradiation.
- After later gamma irradiation of the reference sample W650 to 1.5 krad the early BD disappeared too.
- Annealing at 60°C for 80 minutes does not decrease the current.

R3-W1014: Full Strip Tests

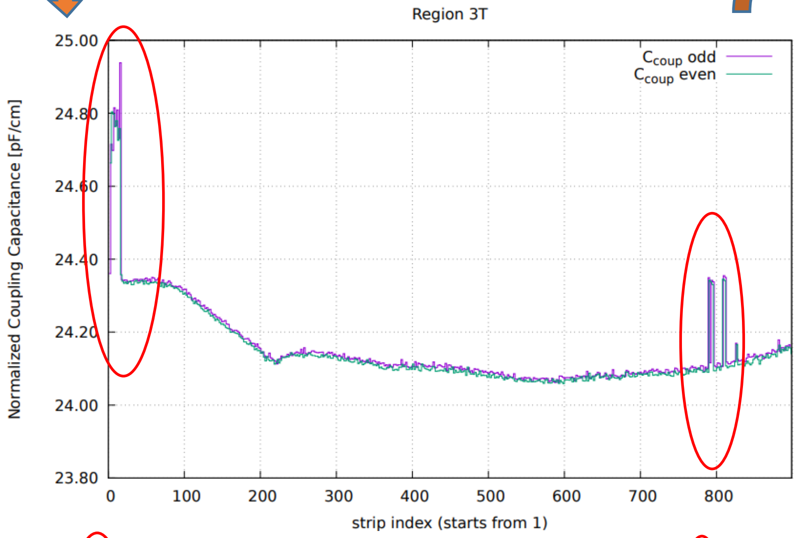
Dry storage

Irradiation

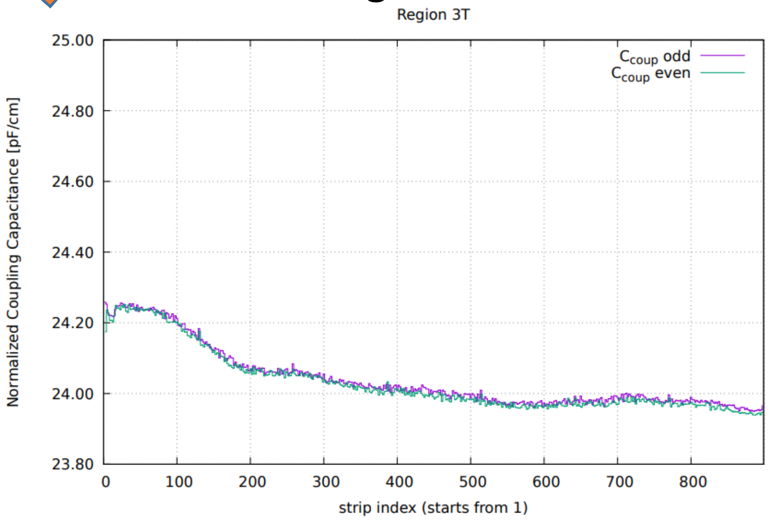
Initial test before irrad.

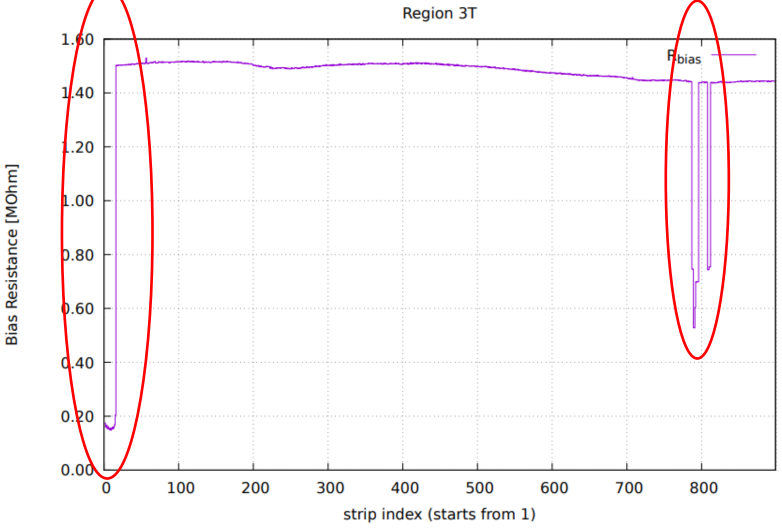


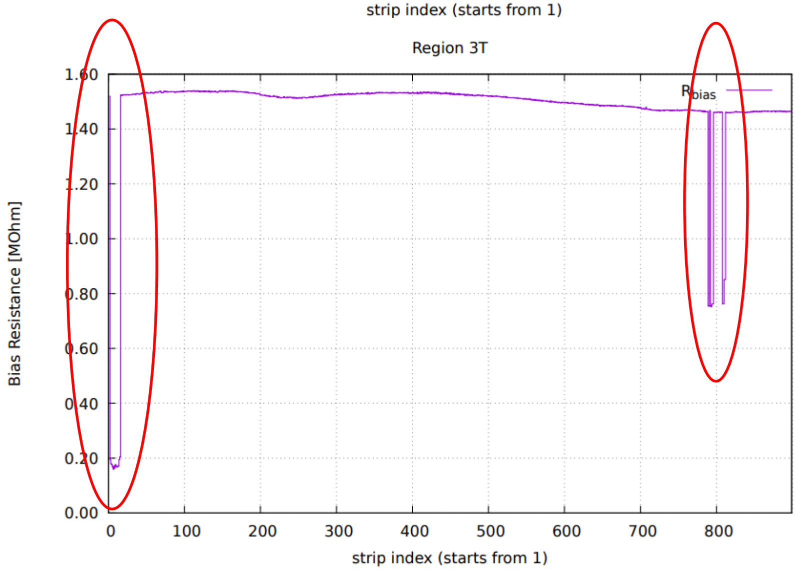
Test right before irrad.

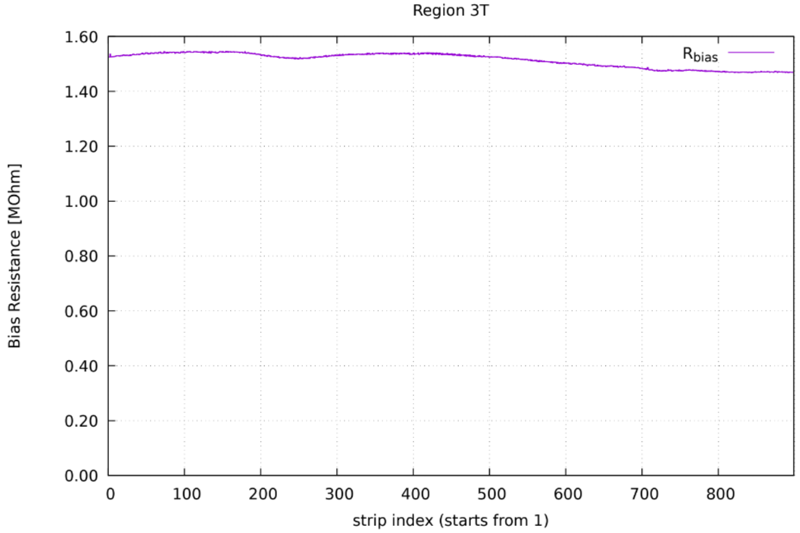


Test after gamma 11krad







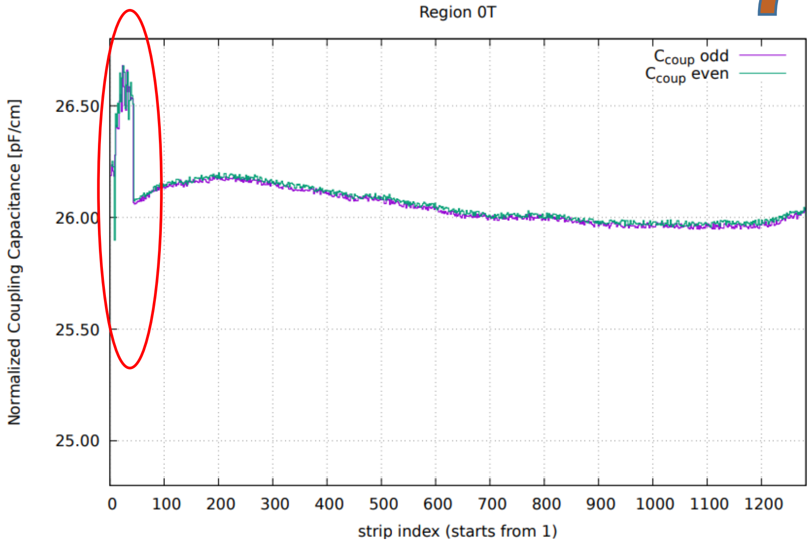


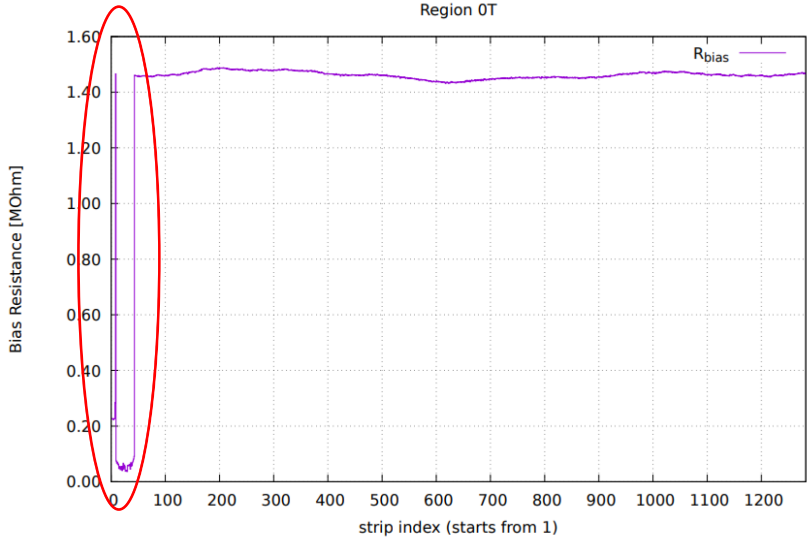
R1-W0635: Full Strip Tests

Dry storage

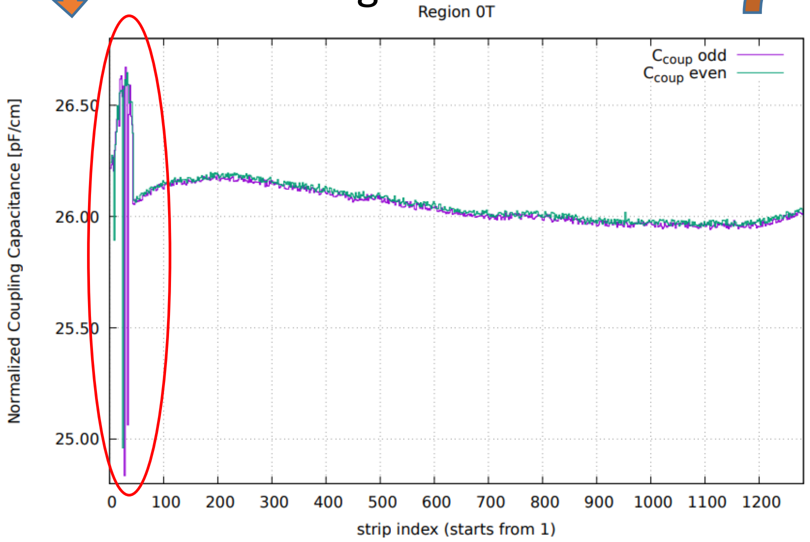
Irradiation

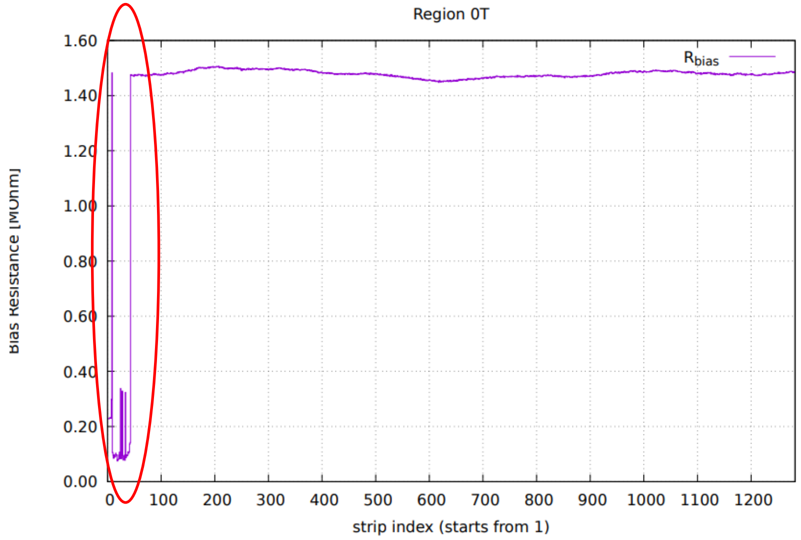
Initial test before irrad.



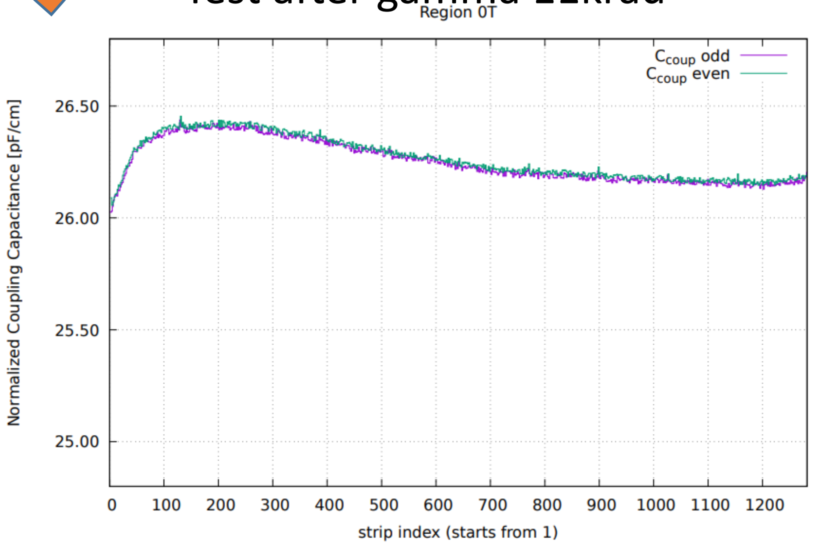


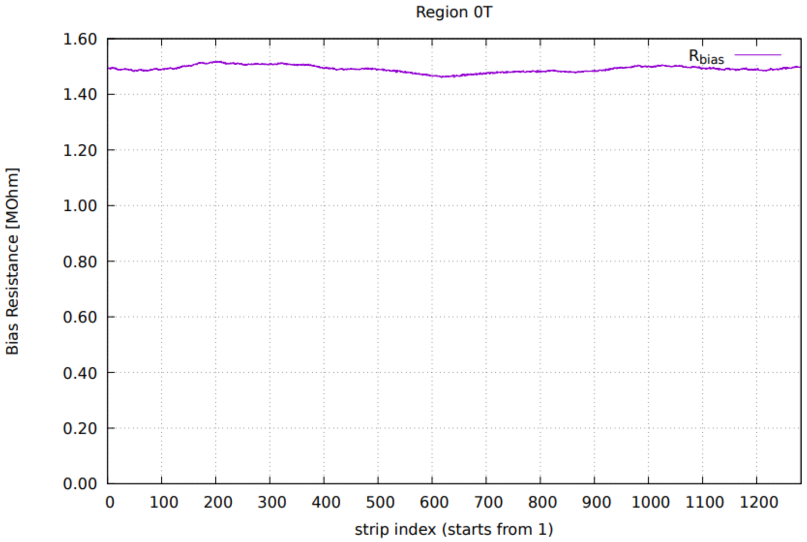
Test right before irrad.





Test after gamma 11krad



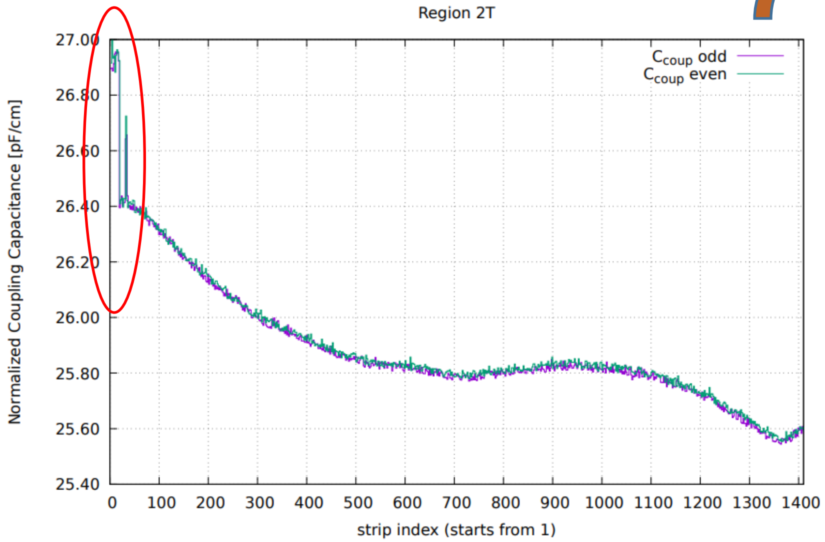


R1-W620: Full Strip Tests - reference sample

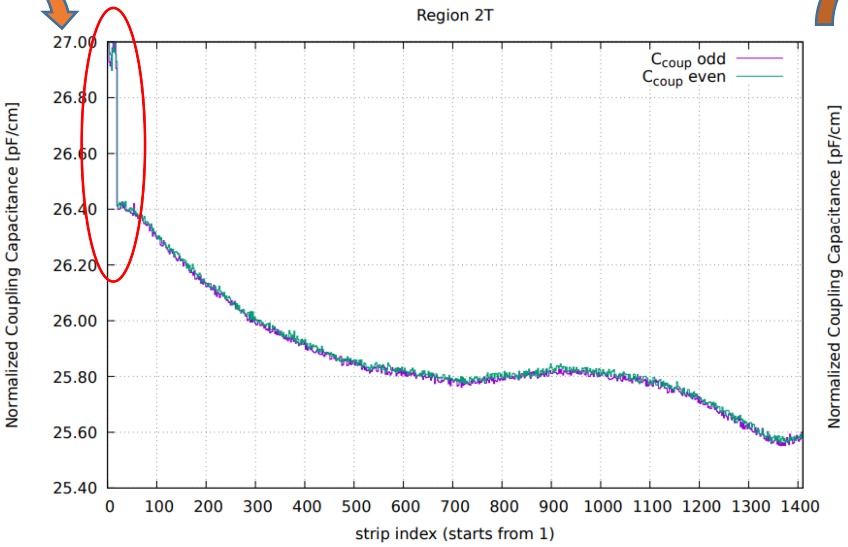
Dry storage

Irradiation

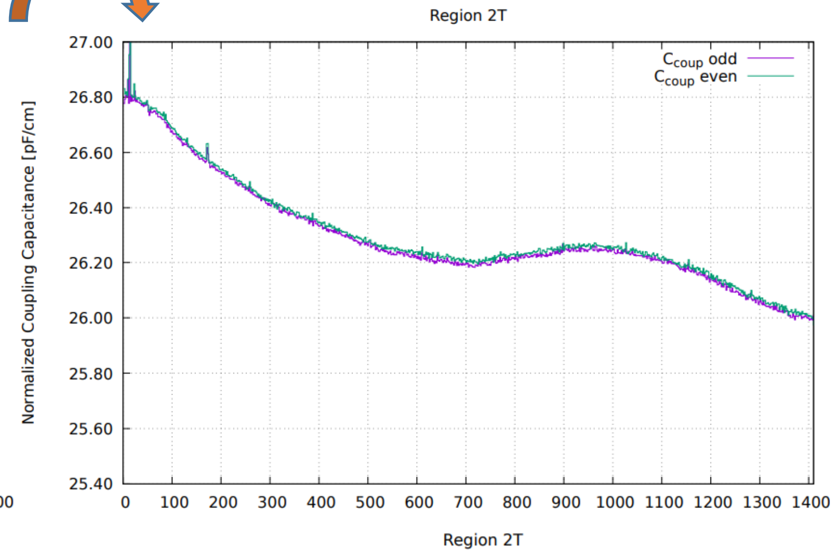
Initial test before irrad.

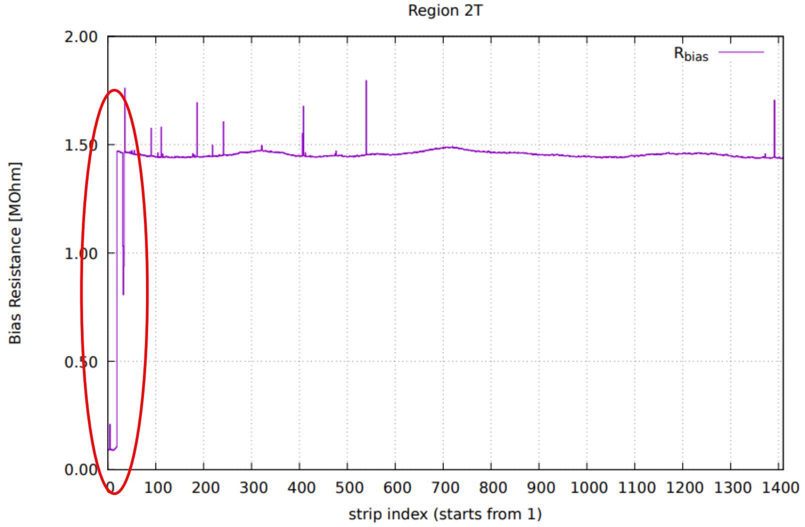


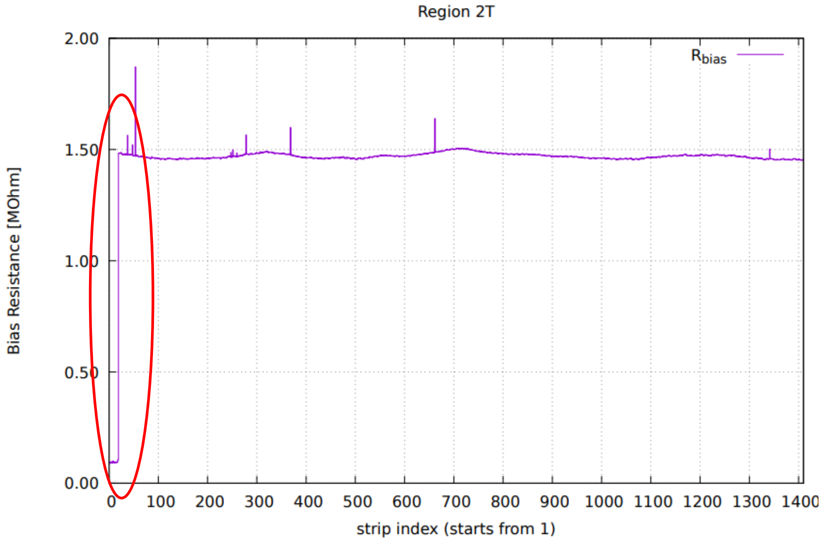
Test after “not irradiation”

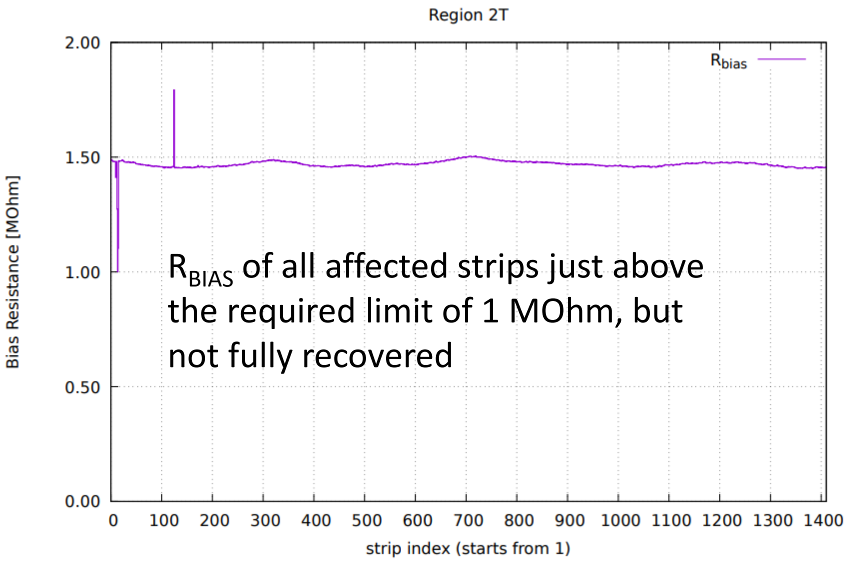


Test after gamma 1.5krad









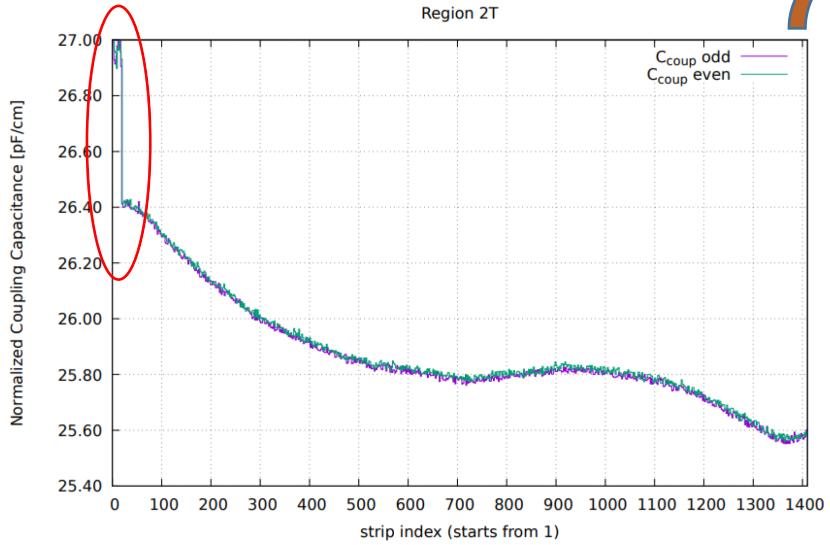
R_{BIAS} of all affected strips just above the required limit of 1 MOhm, but not fully recovered

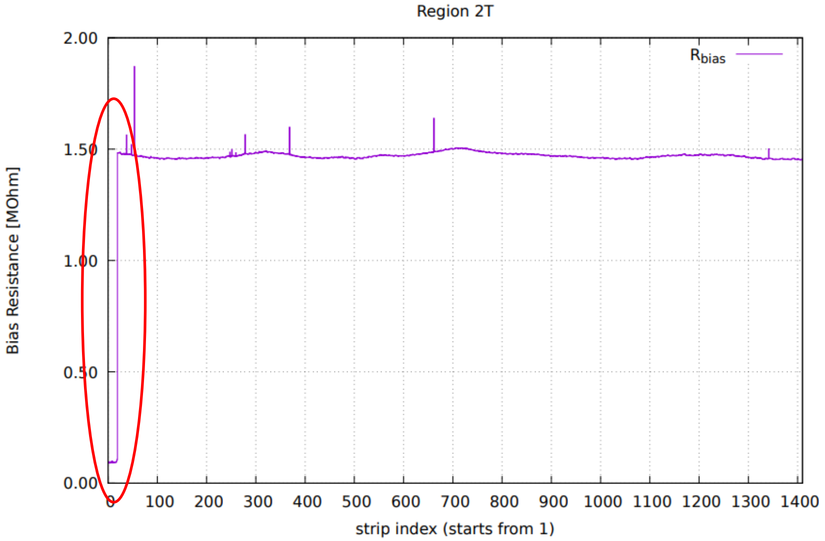
R1-W620: Full Strip Tests – reference sample (2)

Irradiation

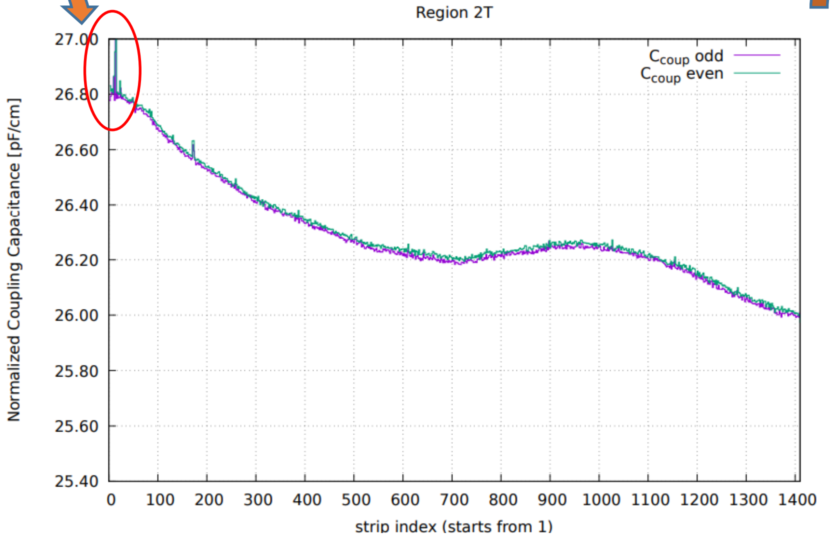
2nd Irradiation

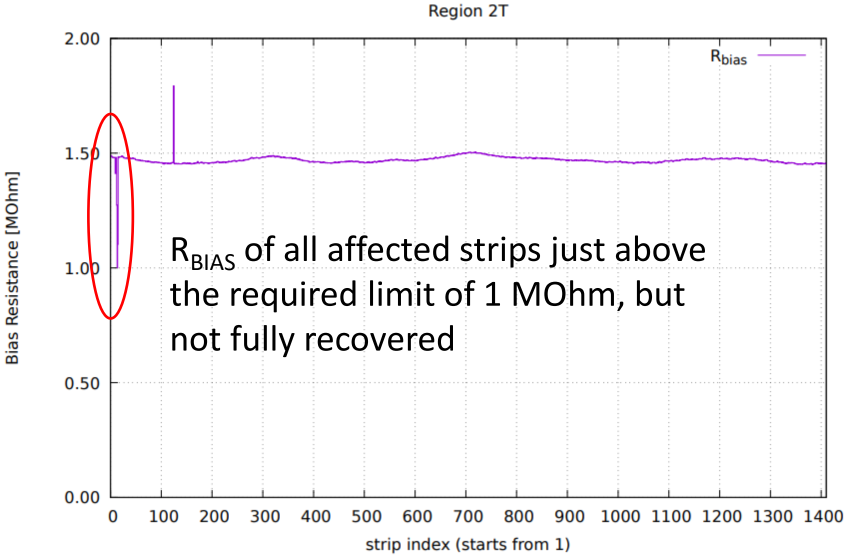
Test right before irrad.





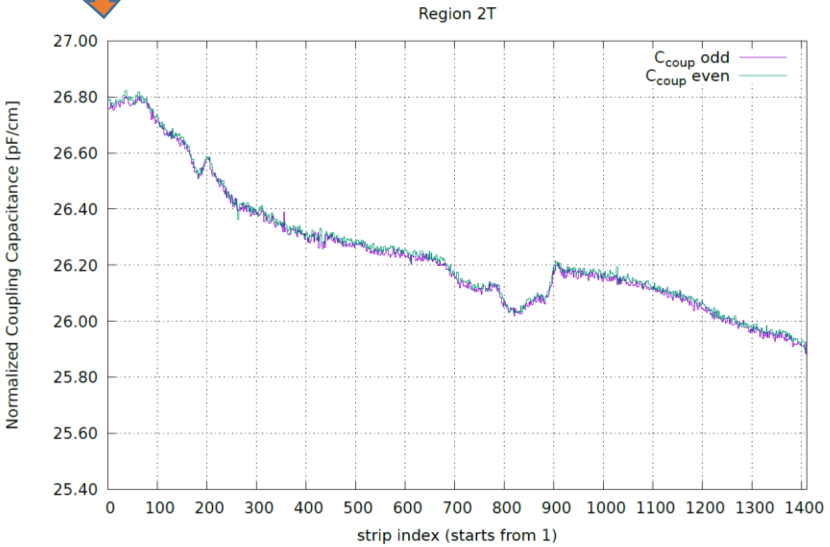
Test after gamma 1.5krad

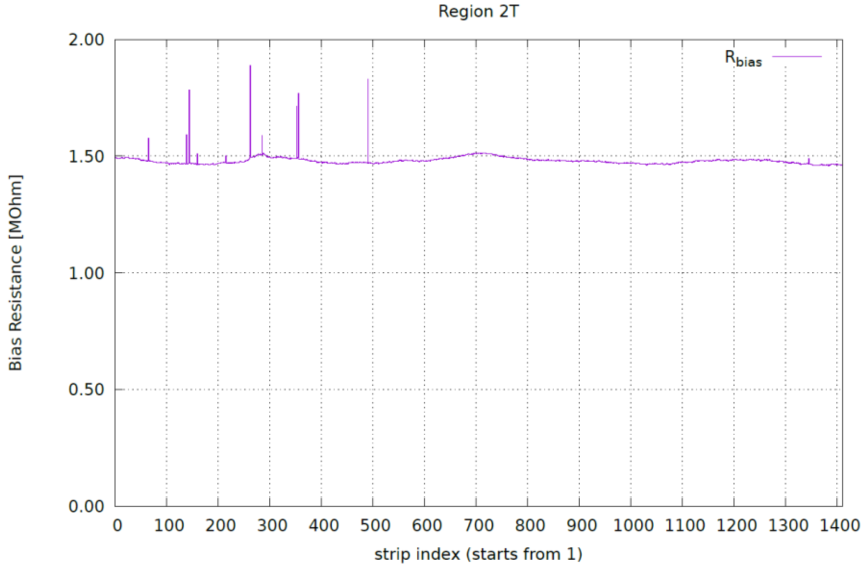




R_{BIAS} of all affected strips just above the required limit of 1 MOhm, but not fully recovered

Test after additional 1.5 krad





Summary

- TID of 11 krad (≈ 1 week in real experiment) successfully resolved early breakdown and low interstrip isolation issues of sensors, related to high electrostatic charge accumulated on the surface of these sensors.
- Even a small TID like 1.5 krad (≈ 1 day in real experiment) resolved the low breakdown voltage and significantly improved also strip test results. R_{BIAS} and C_{COUP} values of all strips were within the specifications.
- Additional TID of 1.5 krad cured the low interstrip isolation issue completely.
- **It implies that the electrostatic sensor issues will be resolved completely within two days of a real experiment operation.**