Outlook of the irradiated 3D pixel sensors characterization for the ATLAS ITk

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14-04-2023

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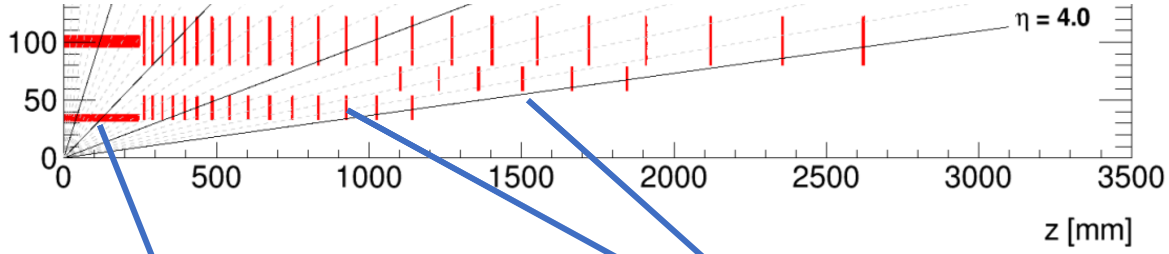
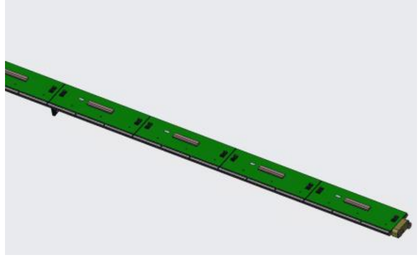
ATLAS - ITk

- The LHC next upgrade is the High-Luminosity LHC (HL-LHC) planned to start operation in 2029. ATLAS will replace its current tracker with a full silicon system called ITk.
- The hybrid pixel detectors of the innermost layer of the ITk will be exposed to a particle fluence of about $1.7 \times 10^{16}\ n_{eq}/cm^2$.
- 3D pixel sensors have been chosen for the innermost pixel layer of ITk because of their high-radiation tolerance.

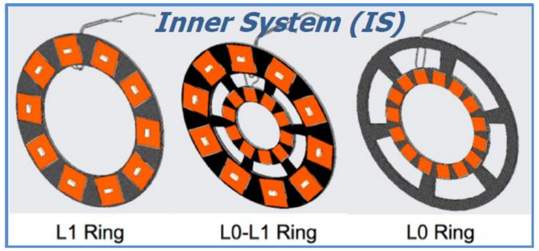
- **Sensors for innermost layer of ATLAS ITk (L0, R0 and R0.5)**
  - 3D silicon pixel sensors (50x50 µm^2 1E and 25x100 µm^2 1E cells).
  - 150 µm active thickness with 300 µm handle wafer.
  - Single side and SiSi technology
  - Sensor fabrication sites:
    - FBK (Trento-Italy); SINTEF (Norway); CNM (Barcelona-Spain)



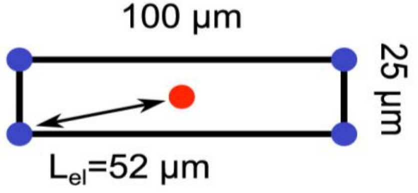
Barrel - staves



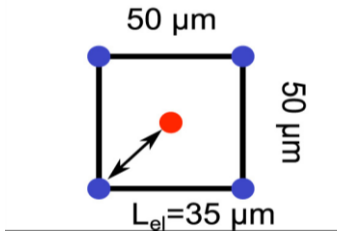
Ring



25×100 µm², 1E



50×50 µm², 1E



3D pixel sensors

In 3D pixel sensors, electrodes are etched deep in the silicon. Deposited charge does not depend on the distance (L) between electrodes.

Damage by radiation

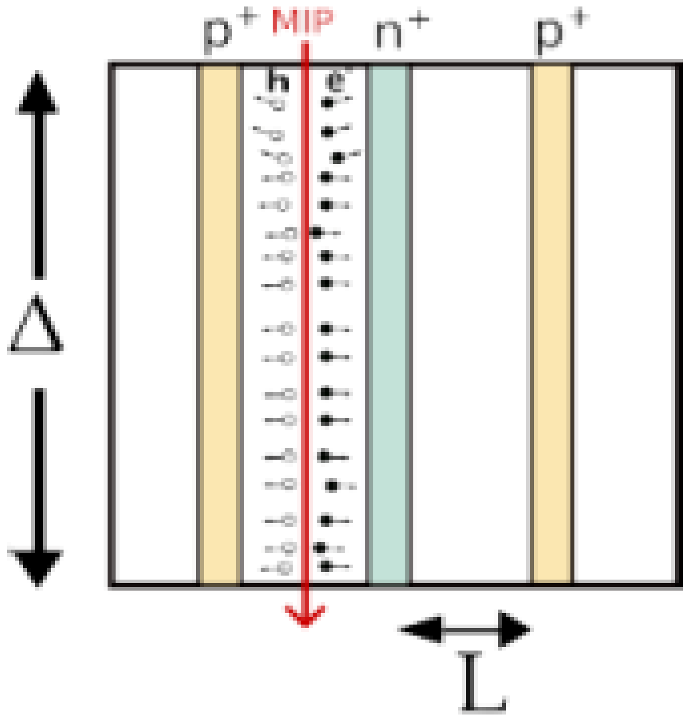
- Changing of a doping concentration
  - Change of the depleted zone.
- Damage in the silicon structure
  - Probability to trap electrons affecting the signal.

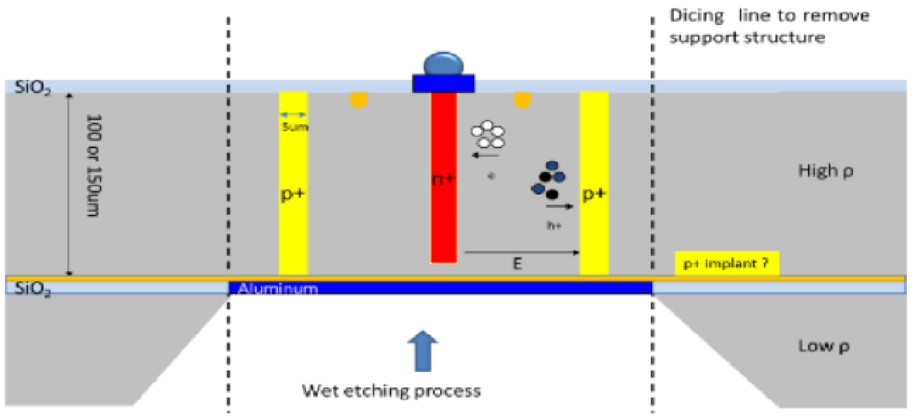
Due to the less distance (L) between electrodes

- Less voltage to fully depleted.
- Lower probability of trapping.

First 3D pixel sensor compatible with the RD53A chip manufactured at CNM.

- Single sided process
  - Both p- and n-columns etched from the front.
  - p-stop isolation.
- Silicon on Insulator (SOI) wafers 150 µm active thickness with 300µm handle wafer.
- *Future productions:* Silicon on Silicon (SiSi)





Sensor studies

Measuring the performance of sensors at different bias voltages after being irradiated and determinate if they meet the requirements for ATLAS ITk in terms of:

- **Leakage current**
    - Depleted voltage and breakdown
- **Power dissipation**
    - Related to the temperature of the bare module
- **Detection efficiency**

Sensors tested in this presentation are:

- 50x50 µm² 1E pixel cell.
- 25x100 µm² 1E pixel cell.
- Both were flip-chipped to RD53A chip and mounted in a single chip card for testing.
- 50x50 was fully connected while the 25x100 had large disconnected areas on the right and left sides.

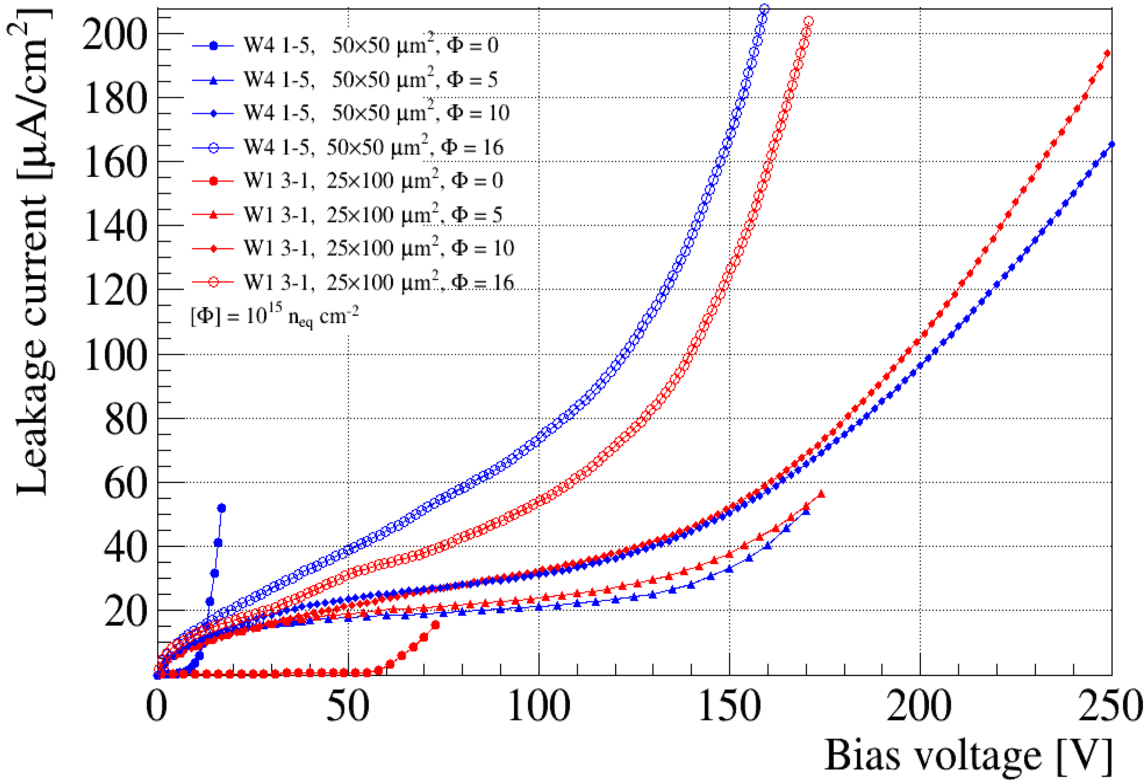
Irradiation history:

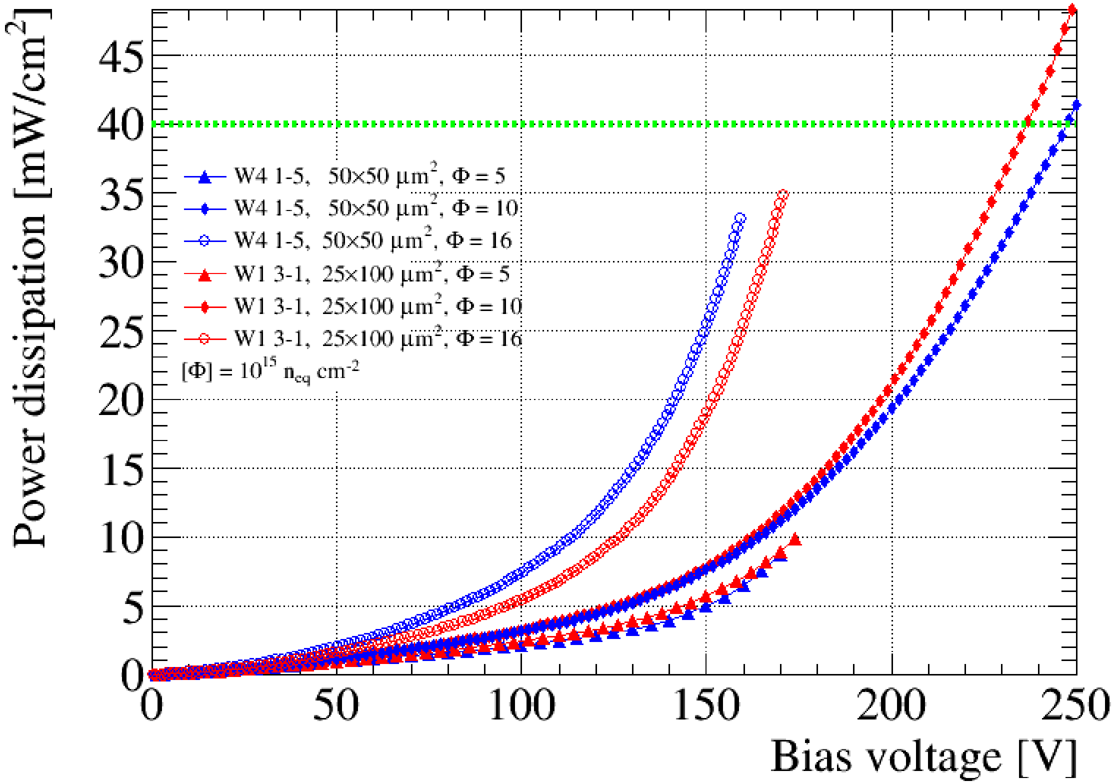
Both sensors were irradiated with proton beams in different facilities up to 1.6e16 n_{eq}/cm^2

Sensor name	W4 1-5	W1 3-1
Pitch [µm²]	50 × 50	25 × 100
First irradiation step		
Faciliy	KIT	KIT
Φ [n_{eq}/cm^2]	5.0×10^{15}	5.1×10^{15}
TID [Mrad]	750	750
Second irradiation step		
Faciliy	CYRIC	BU
Φ [n_{eq}/cm^2]	4.8×10^{15}	5.0×10^{15}
TID [Mrad]	350	665
Third irradiation step		
Faciliy	CYRIC	CYRIC
Φ [n_{eq}/cm^2]	6×10^{15}	6×10^{15}
TID [Mrad]	350	350
Total		
Φ [n_{eq}/cm^2]	1.6×10^{16}	1.6×10^{16}
TID [Mrad]	1450	1765

Table shows the Total Ionization Dose (TID) and the particle fluence at different radiation steps.

Sensor IV and Power dissipation





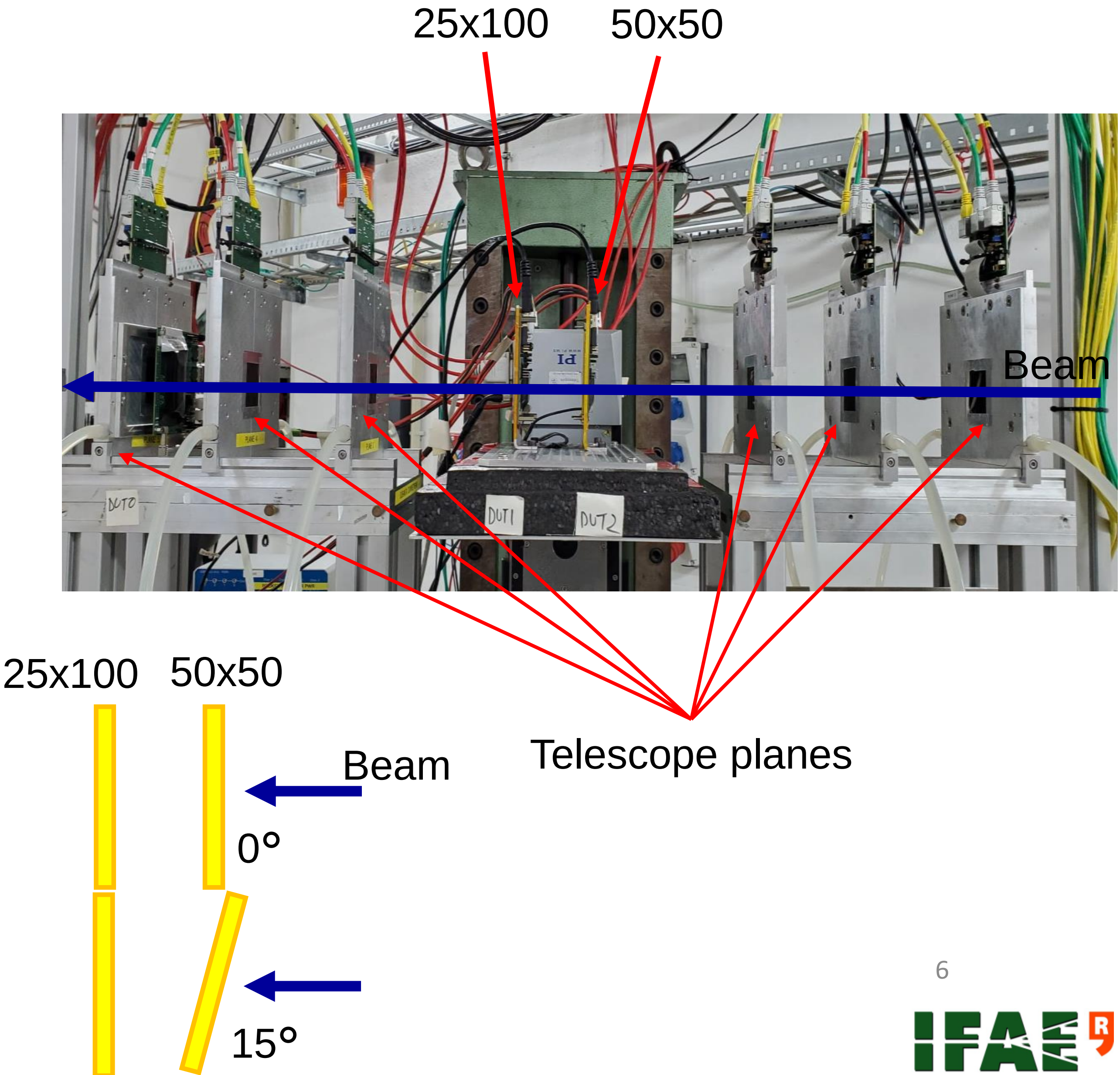
QA/QC requirements for sensors after irradiation during operation:

- Power consumption at -25°C: < 40 mW/cm²
- Maximum current at -25°C < 0.20 mA/cm²
- Maximum operation voltage: 250V
- After irradiate the sensors at 1.6e16 n_{eq}/cm^2. They can be operated up to 160V.

Sensor detection efficiency

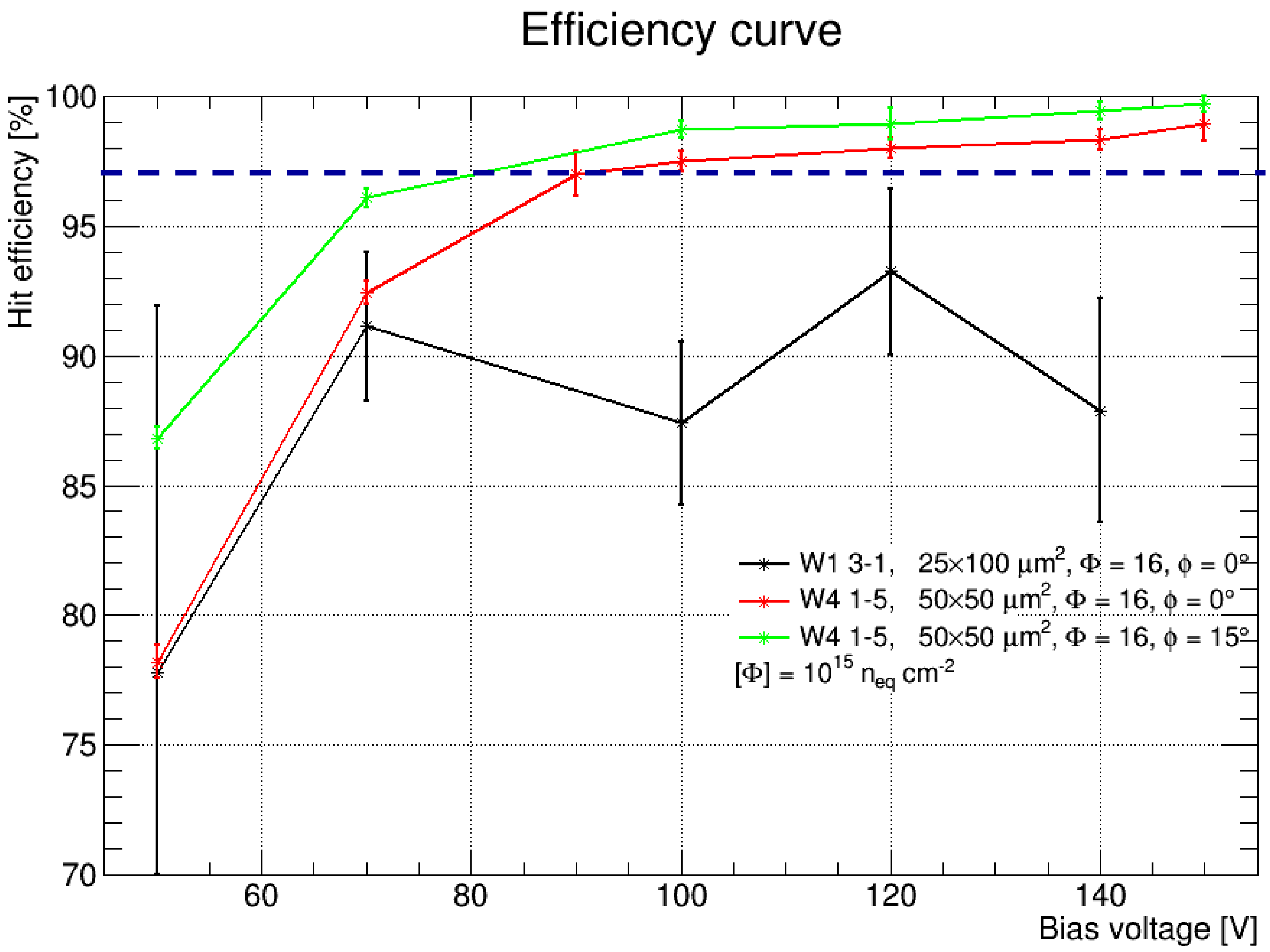
To study the hit efficiency of the sensor, it is necessary to carry out a test beam experiment.

- **Test beam**
  - Using an electron accelerator beam to study the hit efficiency of the sensors.
  - Using the telescopes to reconstruct particle trajectory.
  - Measuring the hit of the particle in the sensor
    - Hit in the sensor: efficiency increase.
    - No Hit in the sensor: efficiency decrease.
- **50x50** was measured at 0º (normal to the incident beam direction) and at 15º (because the columns)
- **25x100** was measured only at 0°.
- **<u>It is necessary to reach an efficiency higher than the 97% to meet ATLAS ITk specifications.</u>**



Efficiency vs bias voltage plot

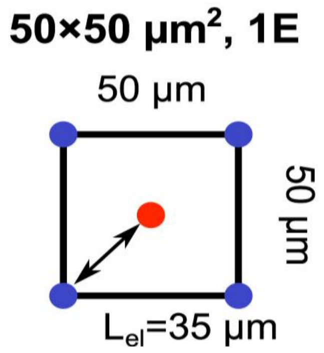
- At 100V, the 50x50 (red curve) reach an efficiency higher than 97%.
- Tilted 50x50 (green curve) reach an efficiency higher than 97% at 80V.
- 25x100 efficiency oscillates around 90%.
  - Very low statistic (large disconnected area and very few pixels analyzed)
  - Larger Total Ionization Dose (TID) and more noise in the front-end.
  - Larger threshold (and tails)



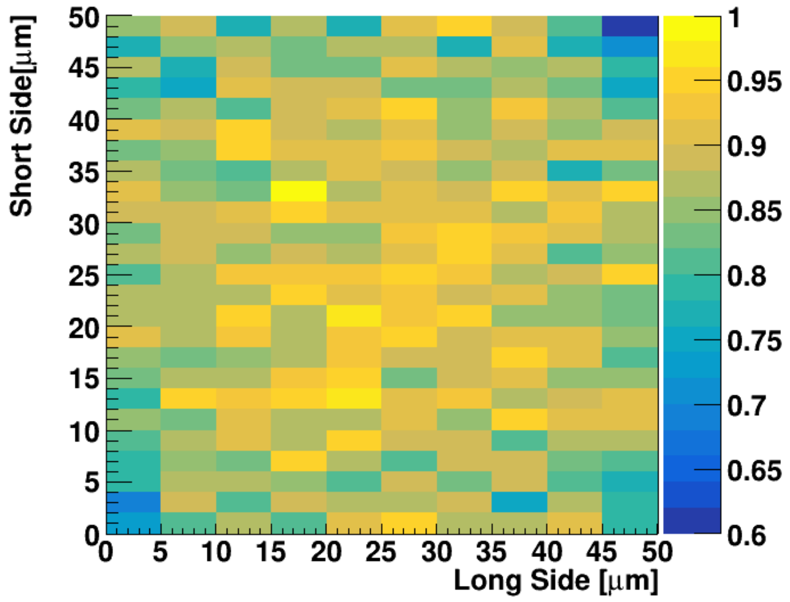
Efficiency pixel map 50x50 at 70V

Efficiency pixel map for the same sensor (50x50) normal (left) and tilted 15º (right) at the same scale.

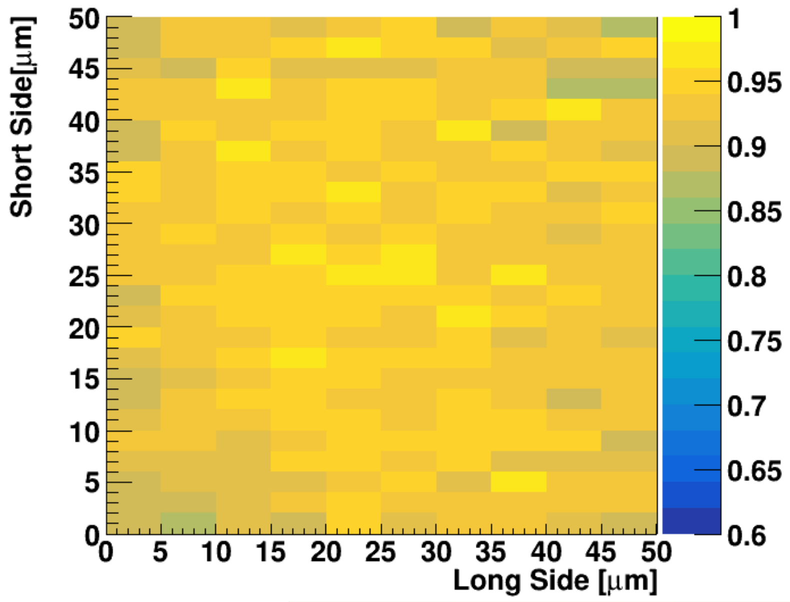
Efficiency in the corners, for the tilted one, is higher and more uniforms. Because the particle that passing through the columns do not deposit charge.

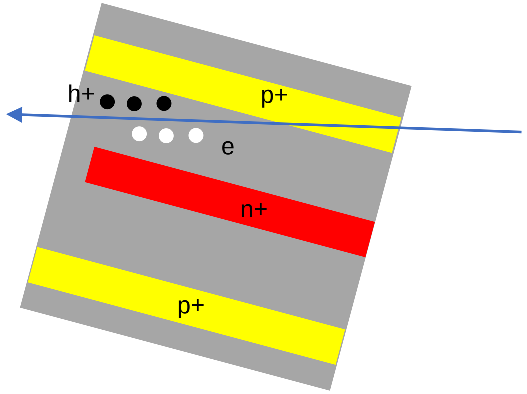


Not tilted



Tilted





15º tilted scheme

Conclusion

An outlook of the characterization procedure for 3D pixel sensors for the ATLAS ITk was presented

Although sensor technology used in this study was not the final choice by ATLAS ITk, the full performance procedure after irradiation was carried out.

Next steps

New Silicon-on-Silicon (SiSi) 25x100 1E device already mounted in a SCC and irradiated is waiting for being tested at CERN.

Set of SiSi devices at Fermilab already irradiated, waiting for shipping to CERN.

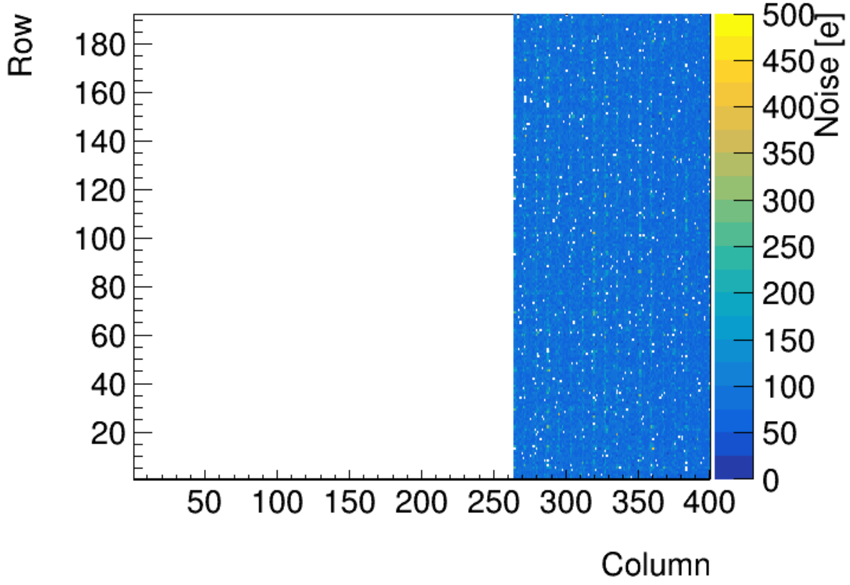
New SiSi pre-production at CNM in process.

Thanks

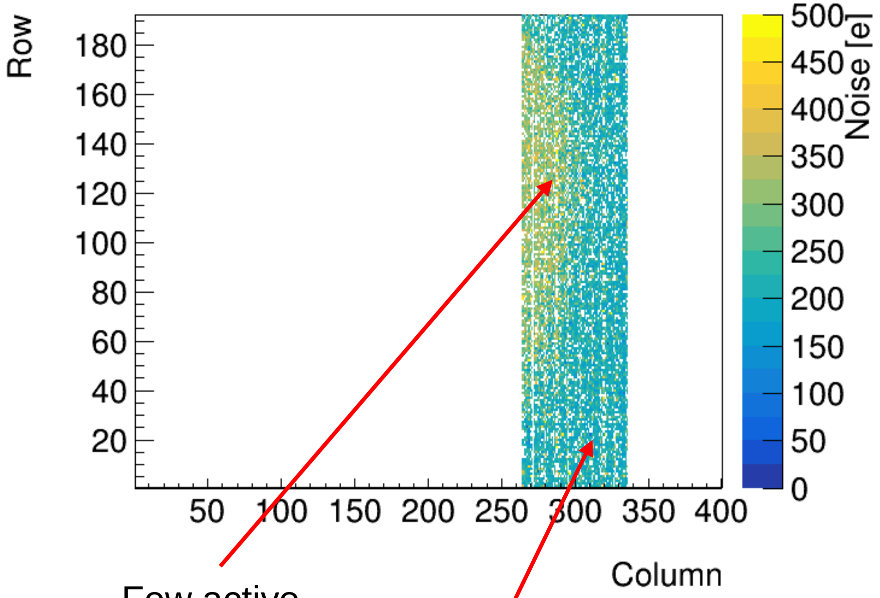
25x100 1E – disconnected areas

The noise scan of the 25x100 shows different noise distributions for the connected and disconnected pixels.

50x50 Noise Map



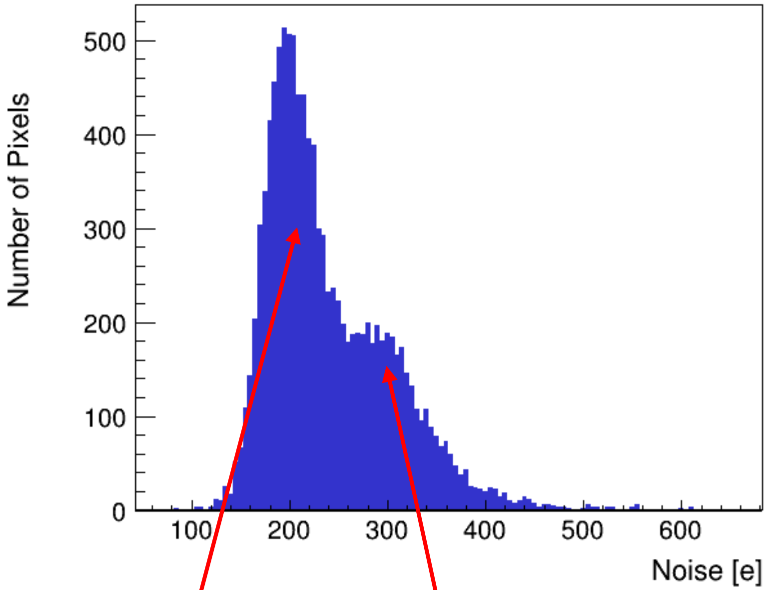
25x100 Noise Map



Few active pixels

Large area of disconnected pixel.

25x100 Noise distribution



Disconnected pixels

Connected pixels

Threshold scan after tuning

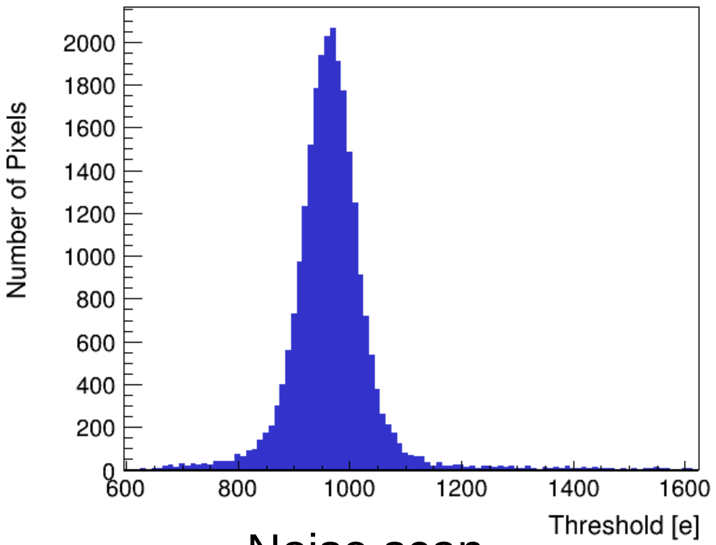
The RD53A chip prototype chip is made of 3 different analog FE parts.

The Lin FE was very noisy and could not be tuned, we measured only the Diff FE (selected for the final ALTAS ITkPix chip)

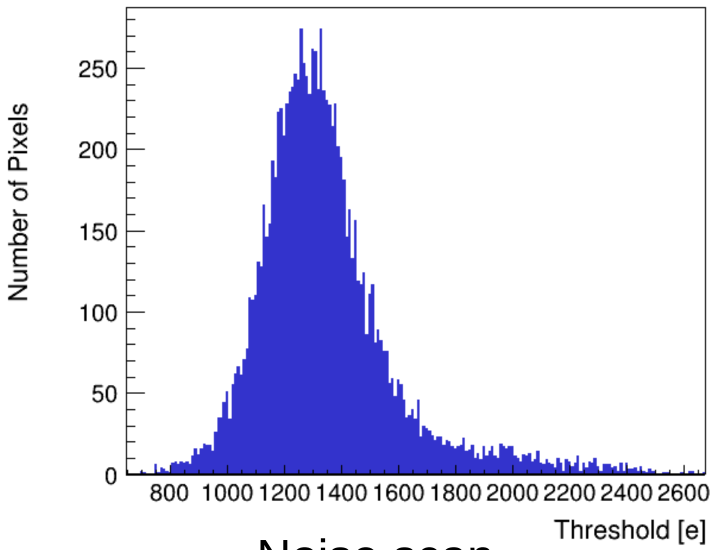
50x50:
- Threshold value around 1000 e.
- The noise is lower than 100 e.

25x100
- Threshold value around 1300 e.
- Large threshold range and tail.
- Two noise distributions for connected (around 300e) and disconnected (200e) pixels.

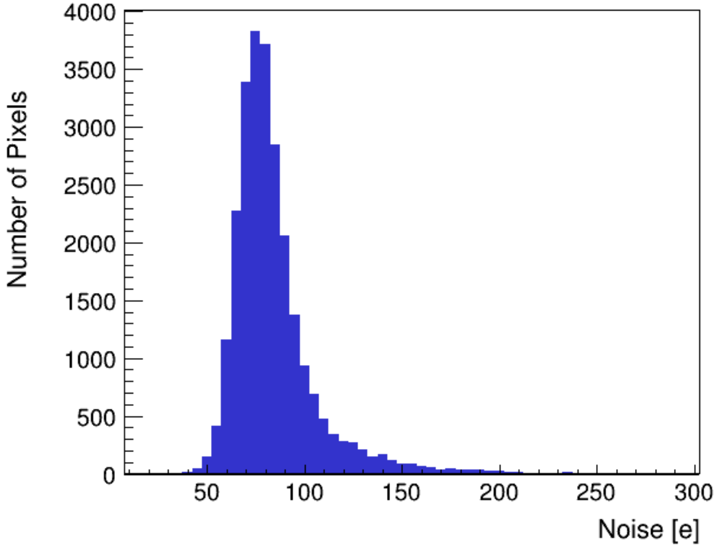
Threshold scan 50x50



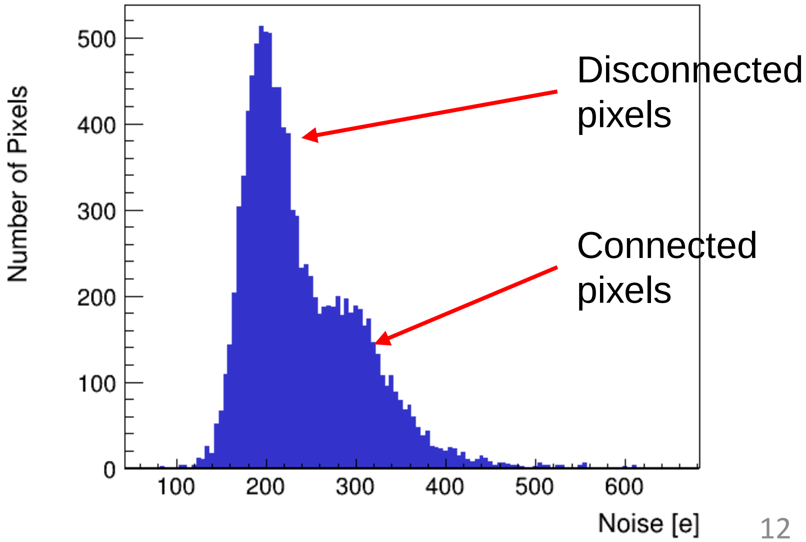
Threshold scan 25x100



Noise scan



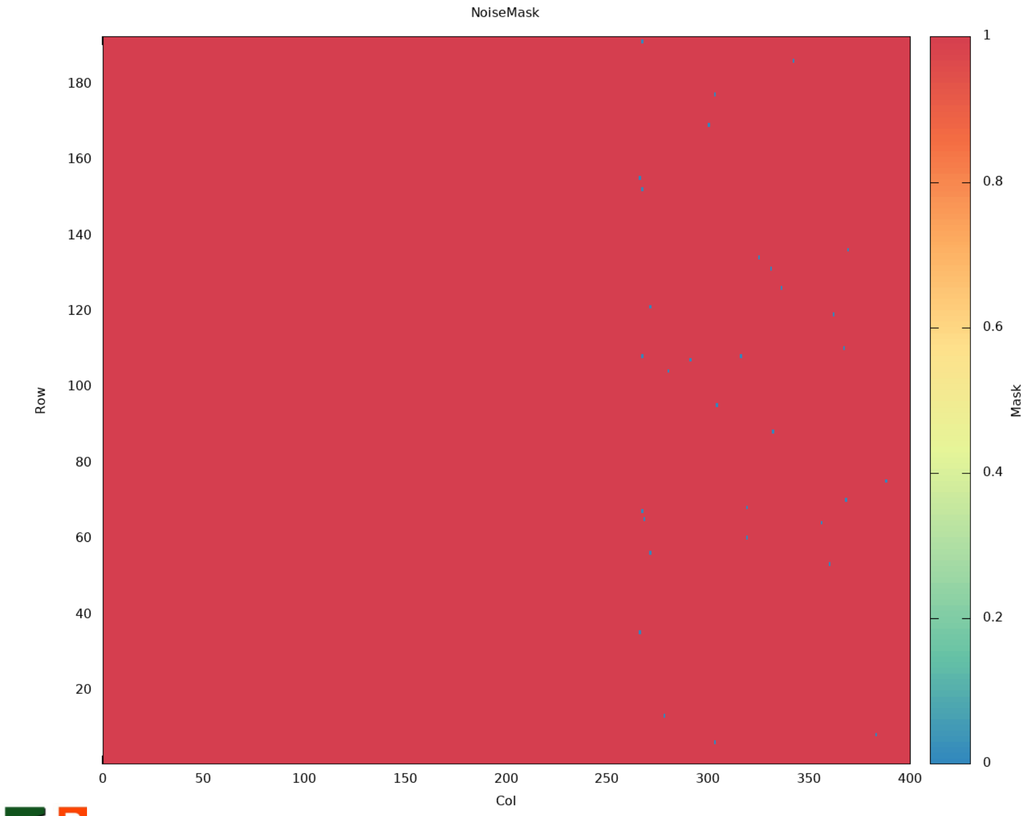
Noise scan



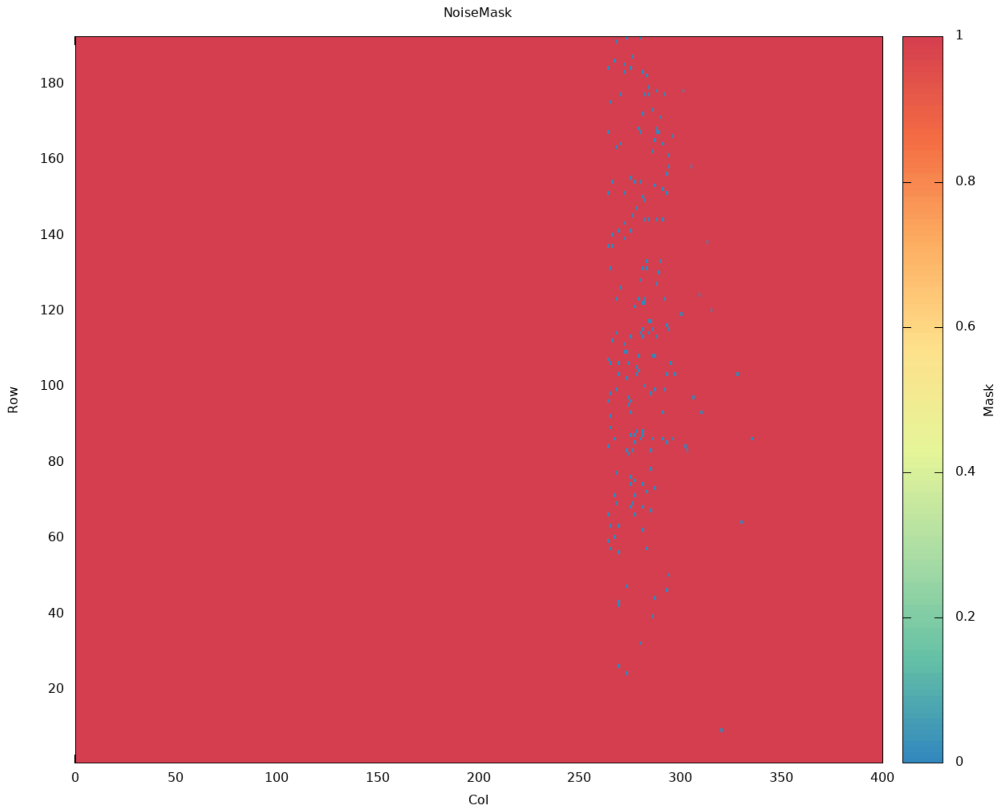
Tuning: noise mask

Very few pixels are masked in the 50x50 while the 25x100 was much more noisy probably due to the disconnected pixels.

50x50



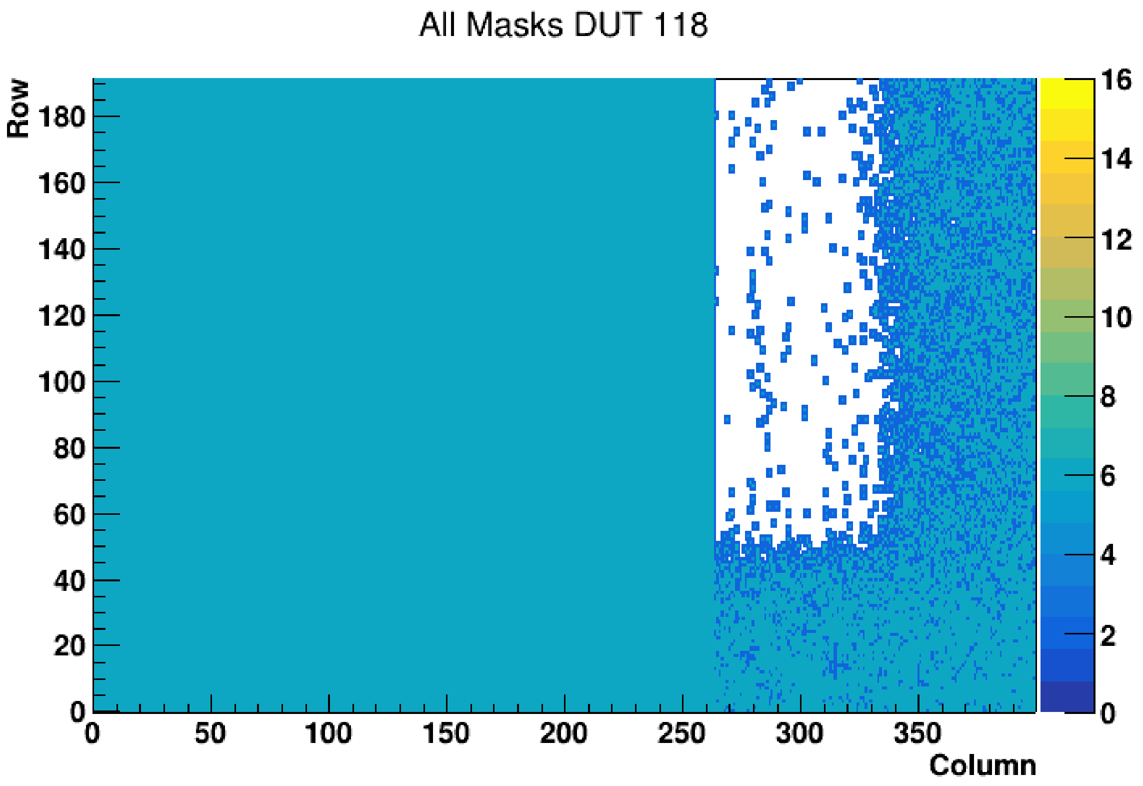
25x100



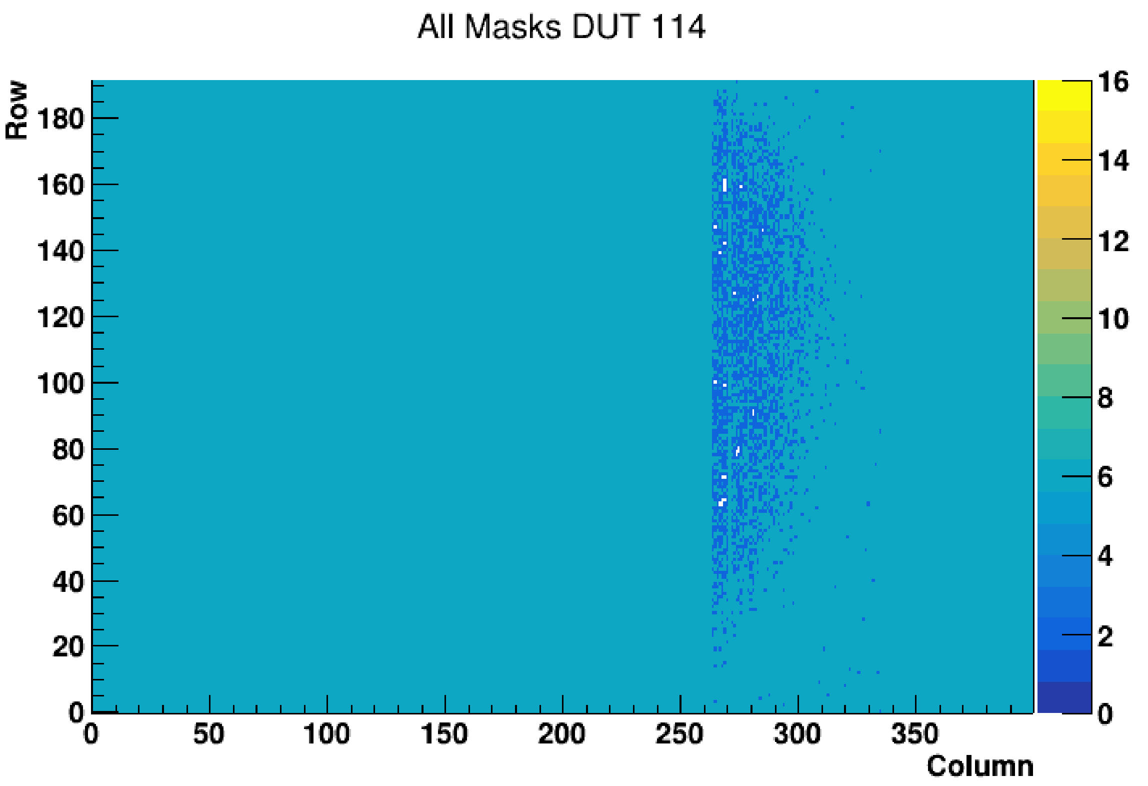
Masked pixel map at 100V

Sensor mask map shows the areas (white areas) where the reconstruction software considerer active for the track reconstruction.

50x50



25x100

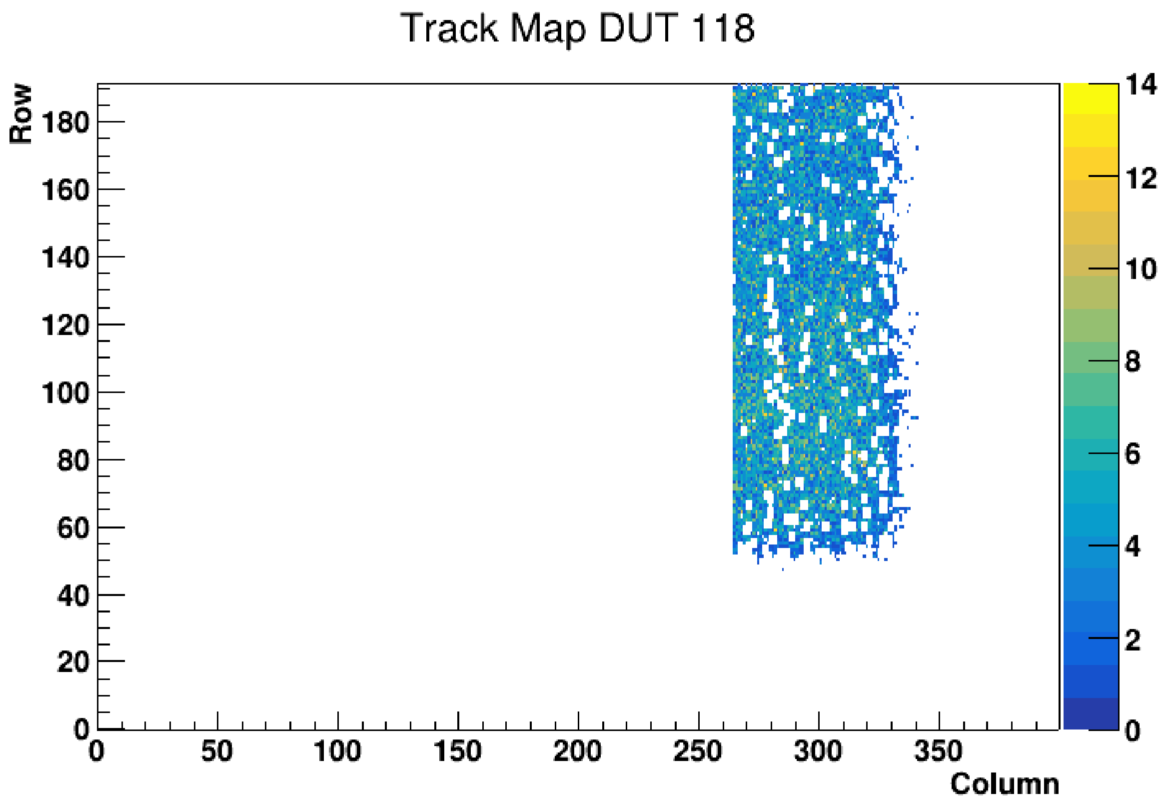


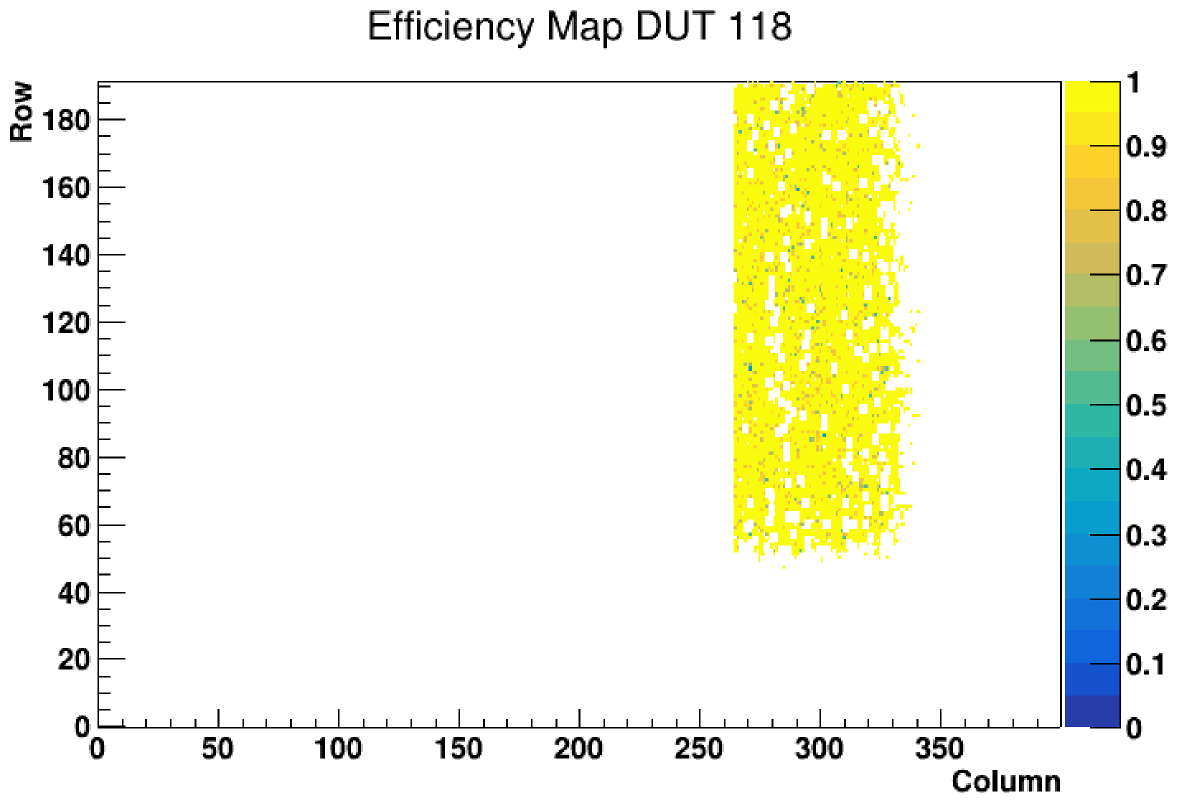
Area of the 25x100 is very small because of a large disconnected area

Full sensor hit map and Efficiency 50x50 at 100V

The left plot shows the area where the tracks are reconstructed (trigger window)

On the right plot the efficiency map is shown.

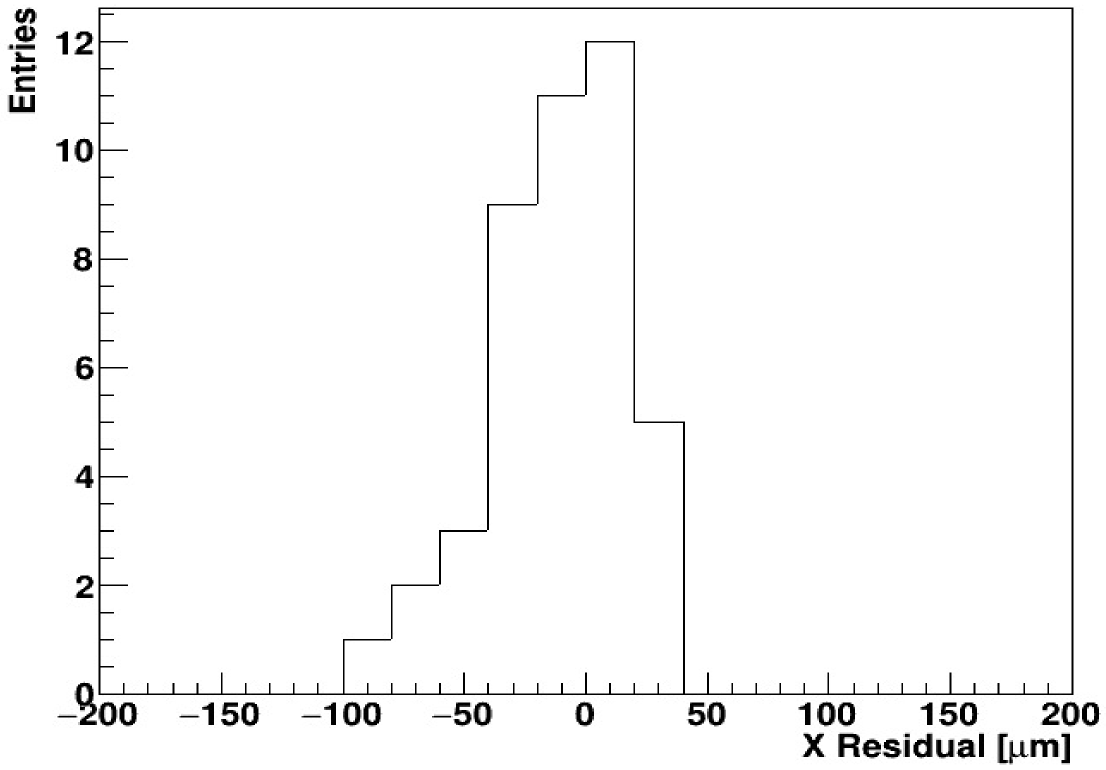




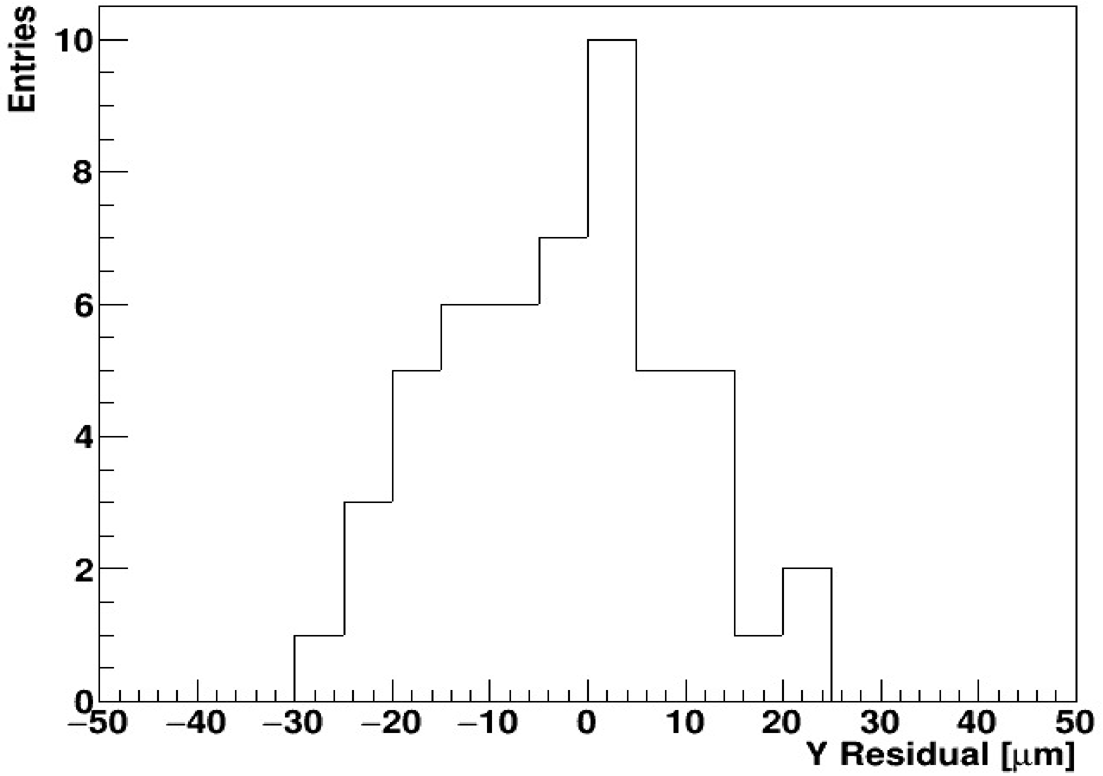
Residual plot 25x100

Residual distributions as expected from the pixel size and the multiple scattering at DESY

X axis



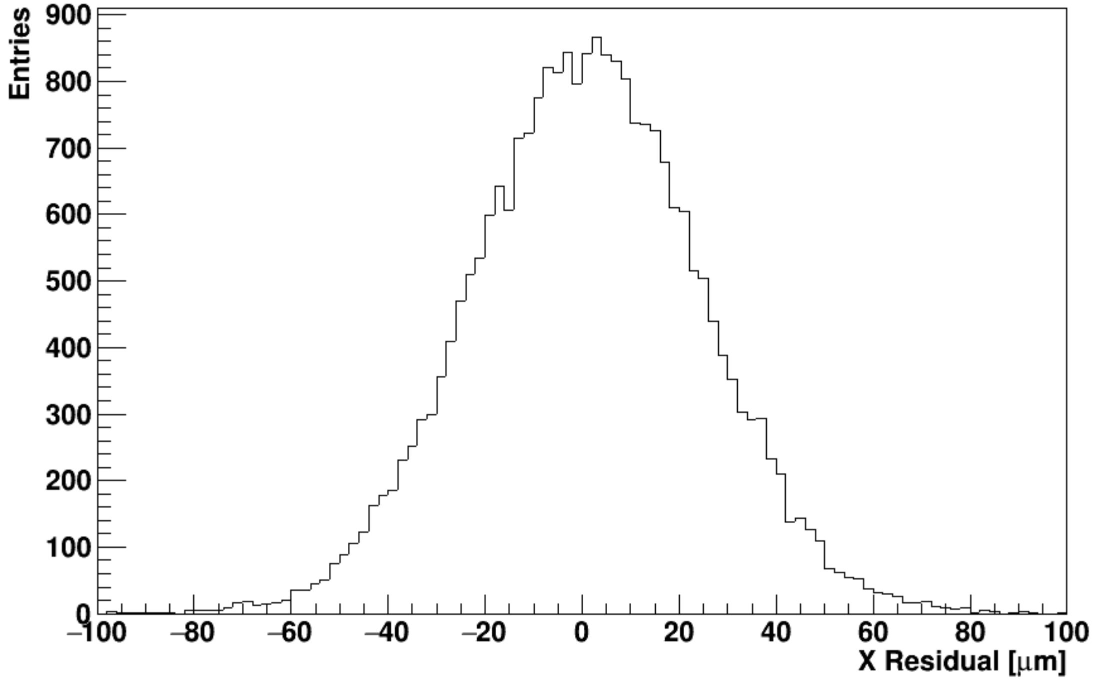
Y axis



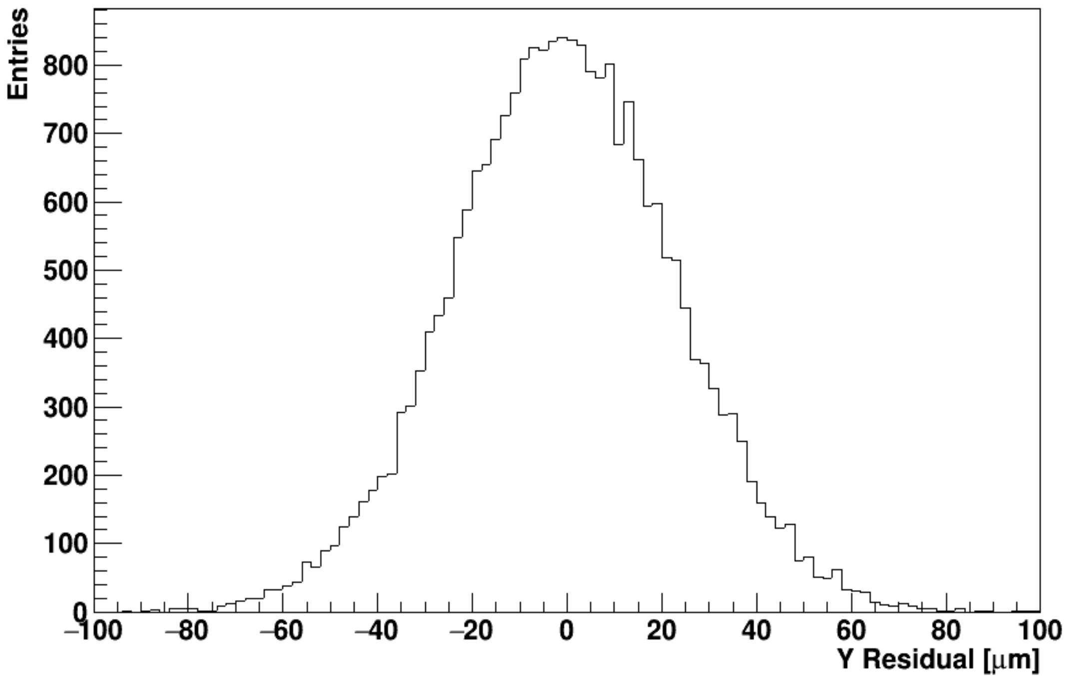
Residual plot 50x50

Residual distributions as expected from the pixel size and the multiple scattering at DESY

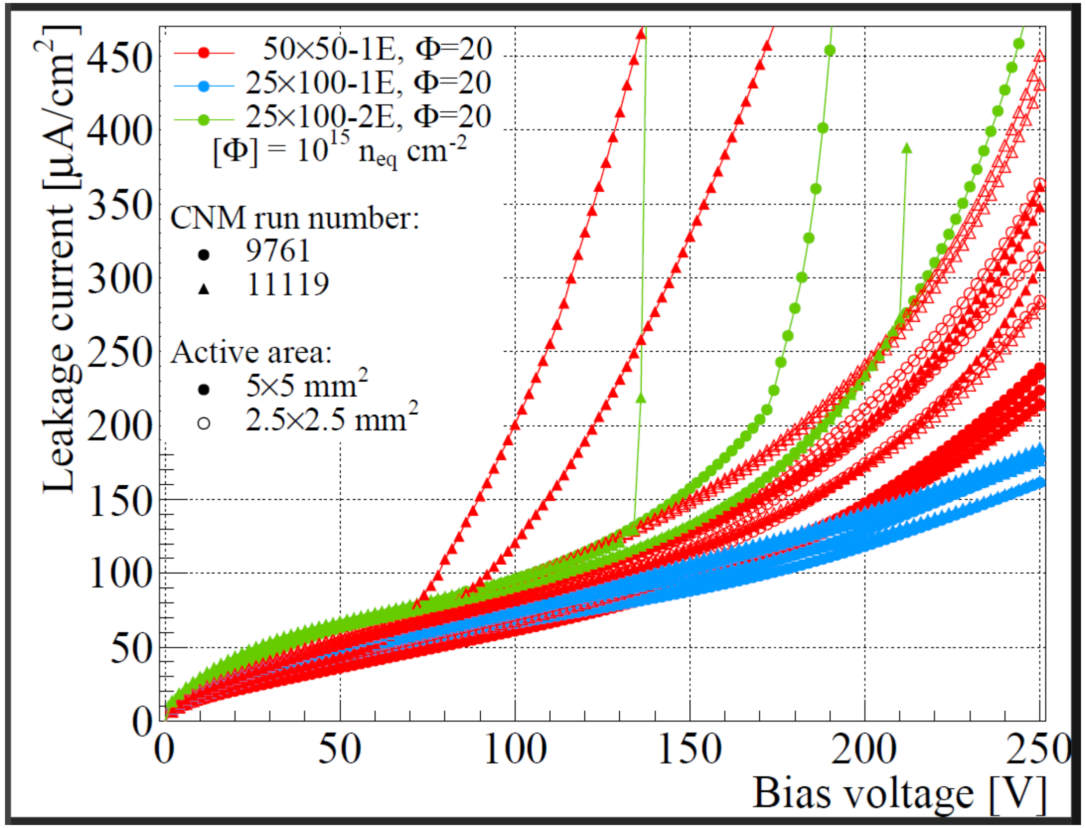
X axis

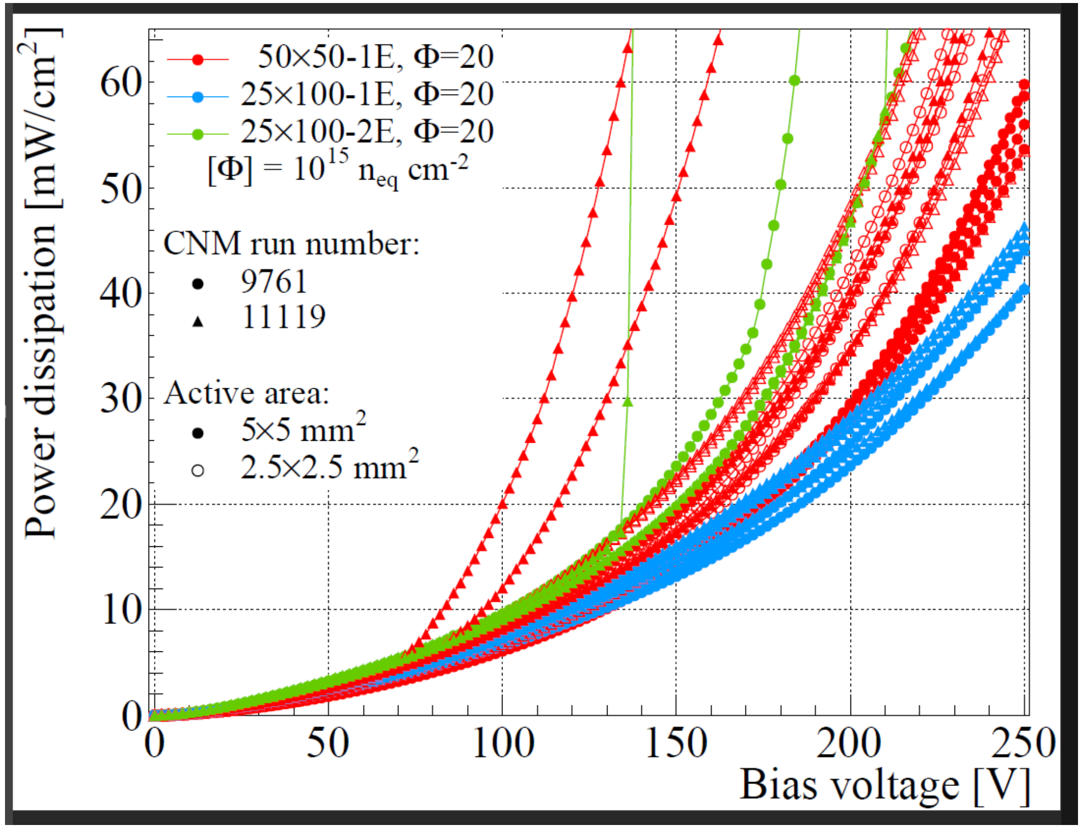


Y axis



Diodes IV and Pow

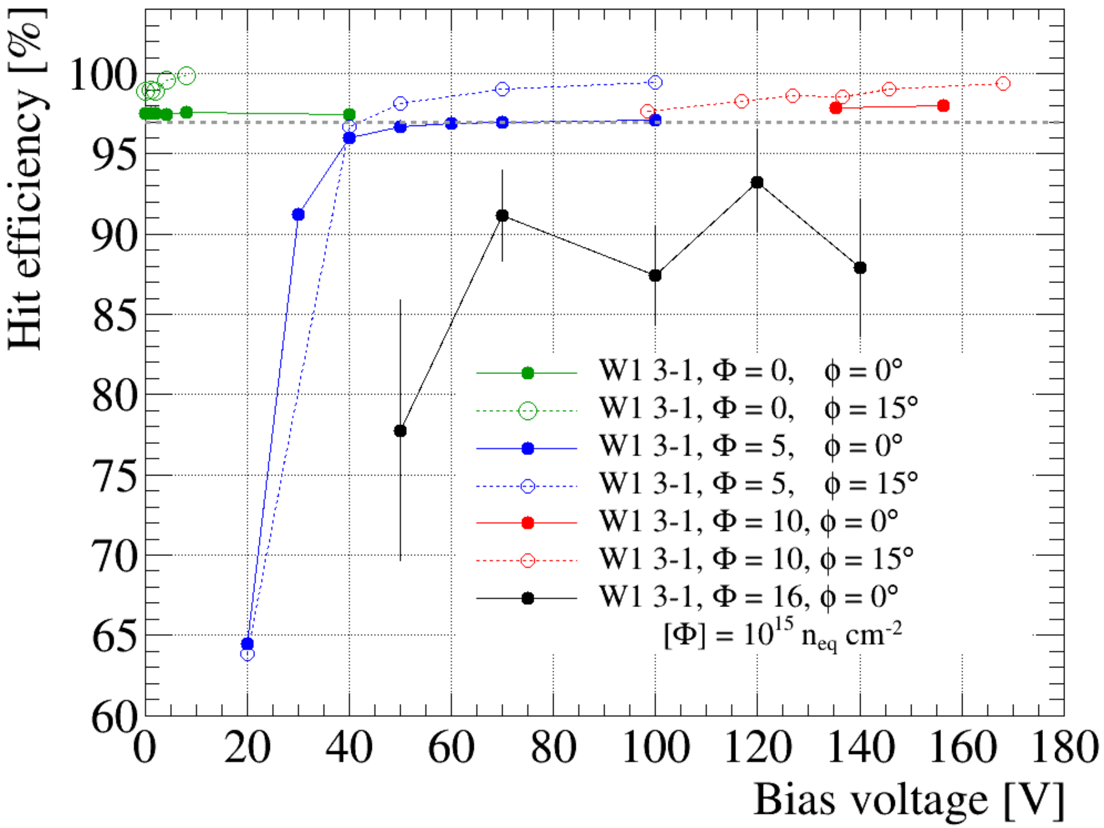




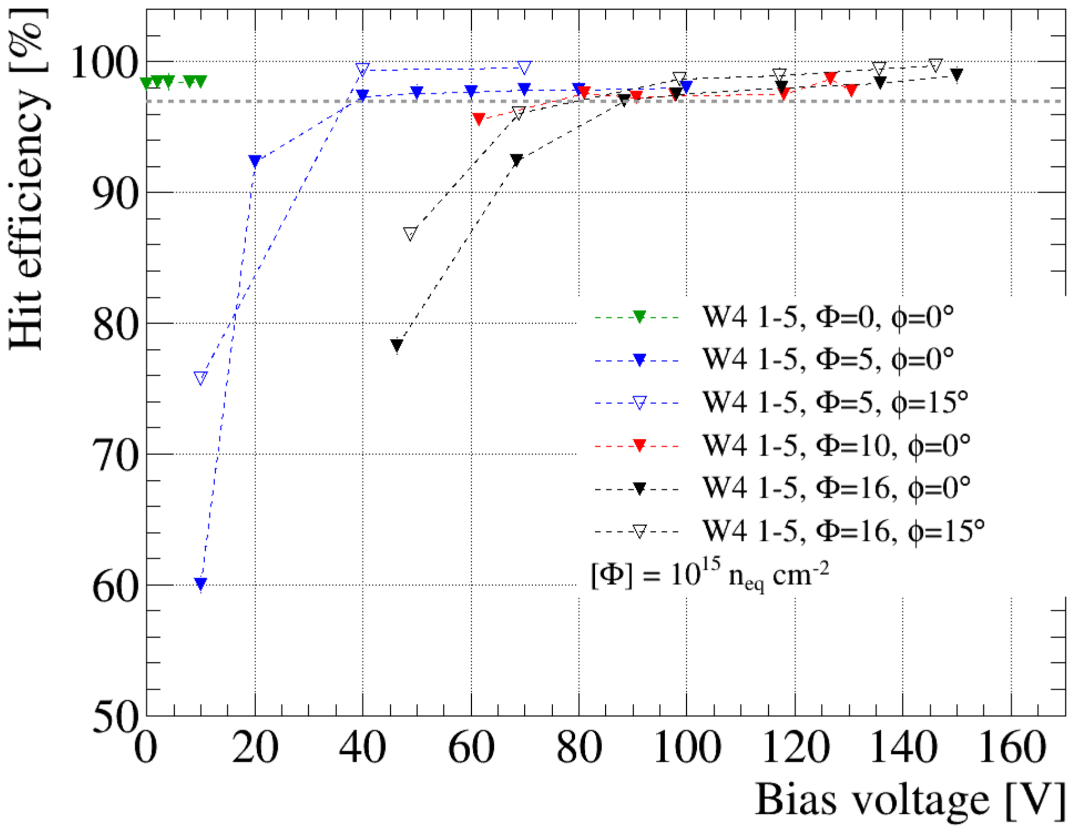
Efficiency vs bias voltage plot

Hit efficiency plot at different irradiation levels.

25x100



50x50



RD53A run at CNM

First 3D sensor pixel compatible with the RD53A chip manufactured at CNM.

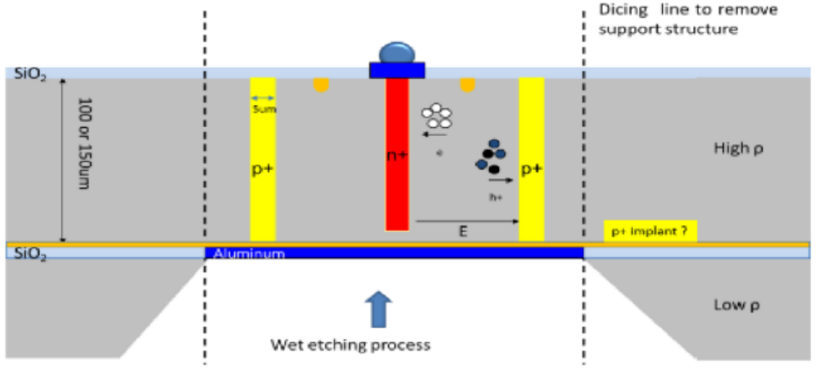
- Single sided process
  - Both p- and n-columns etched from the front
  - p-stop insulation
- Silicon on Isulator (SOI) wafers 150 µm active thickness with 300µm handle wafer
- Under-bond metallization were performed at CNM
- Flip-chip was carried out at IFAE.

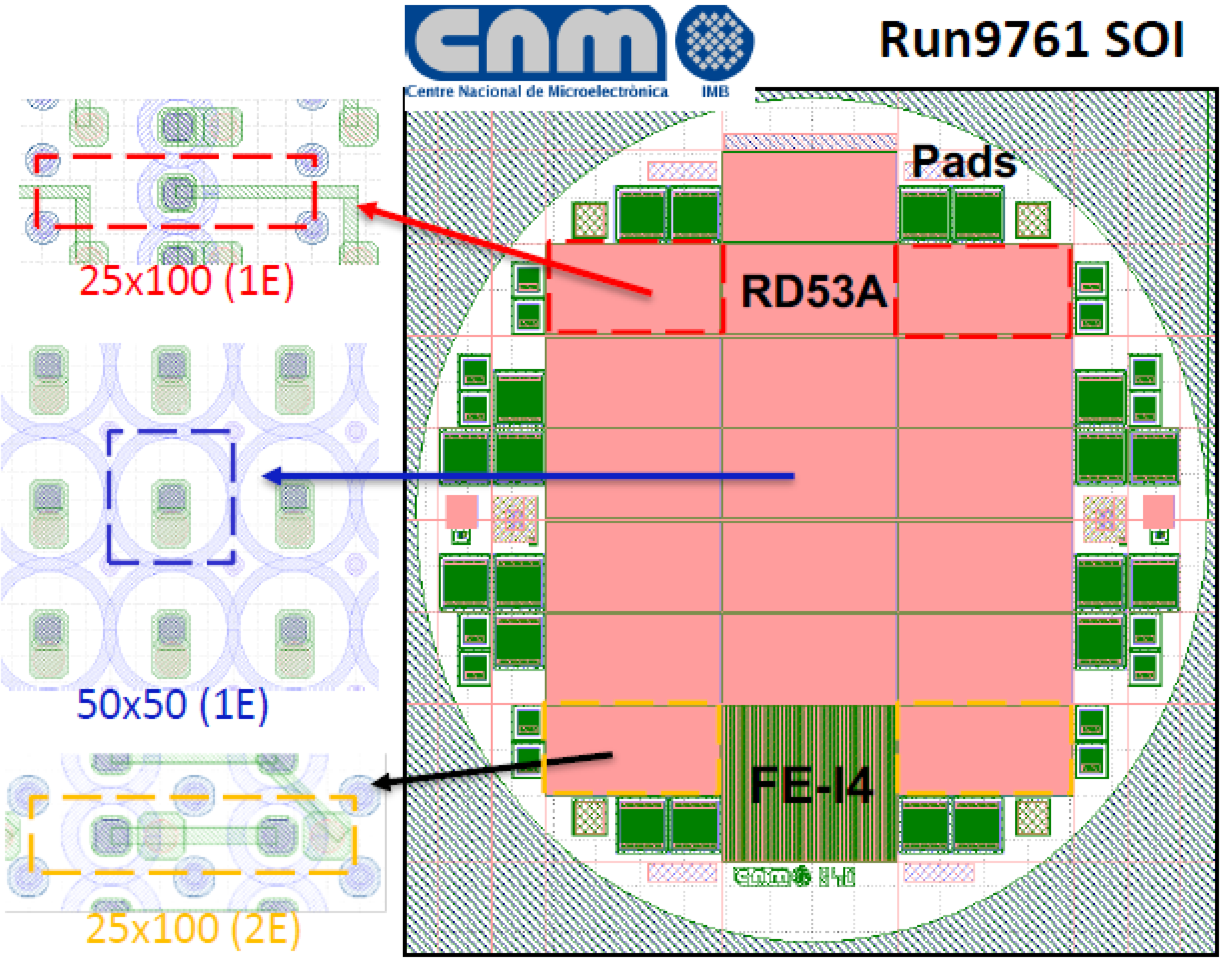
The mask includes:

- 14x RD53A 50x50 µm² 1E
- 2x RD53A 25x100 µm² 1E
- 2x RD53A 25x100 µm² 2E
- 1x FE-I4 50x50 µm 1E
- Pad diodes of 50x50 µm²
- Pad diodes 25x100 µm²

Sensors tested in this presentation are:

- 50x50 µm² 1E pixels
- 25x100 µm² 1E pixels.



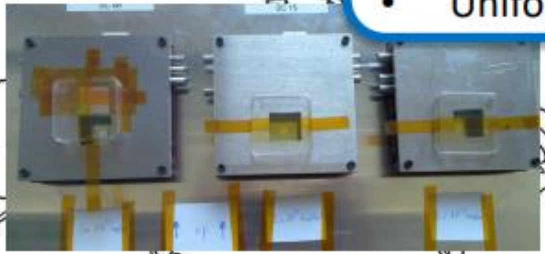


This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

AIDA 2020

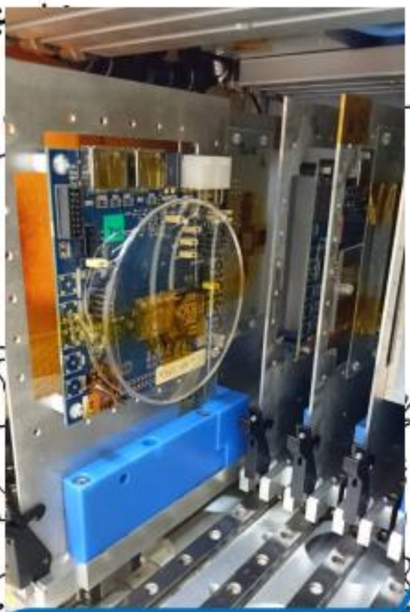
KIT, Germany

- 23 MeV protons
- Large TID: ~750 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C



Birmingham, UK

- 27 MeV (up to 37 MeV) protons
- Large TID: ~650 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C



CYRIC, Japan

- 70 MeV protons
- Large TID: ~350 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C

TRIGA reactor at JSI, Slovenia

- Reactor neutrons
- Negligible TID
- Uniform irradiation
- Tantalum in the chip gets activated

Thanks to: Koji Nakamura, Vladimir Cintro, Laura Gonella & Amelia Hunter, Felix Bögelspacher & Alexander Dierlamm