Power dissipation and hit efficiency of CNM 3D pixel sensors irradiated to 1.6e16 neq/cm^2

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ATLAS - ITk

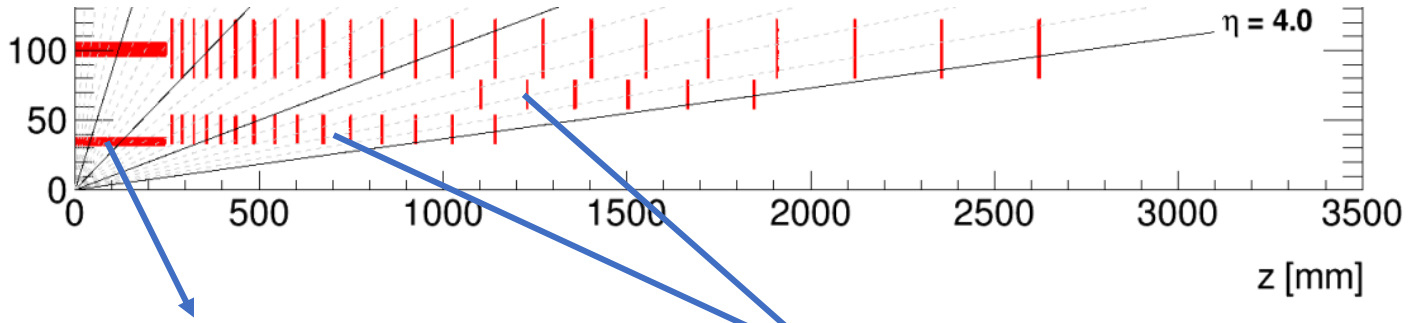
The Large Hadron Collider (LHC) will be upgrade to be able to reach about seven times its current nominal instantaneous luminosity.

The expected particle fluence will be 1.7e16neq/cm^2 in the innermost layer.

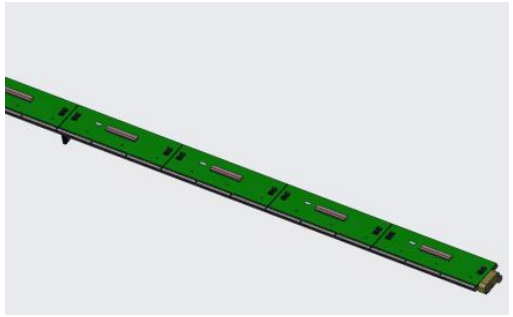
3D pixel sensors have been chosen for the innermost pixel layer of Inner Tracker (ITk) because of their high-radiation tolerance.

3D pixel silicon sensors in the ITk:

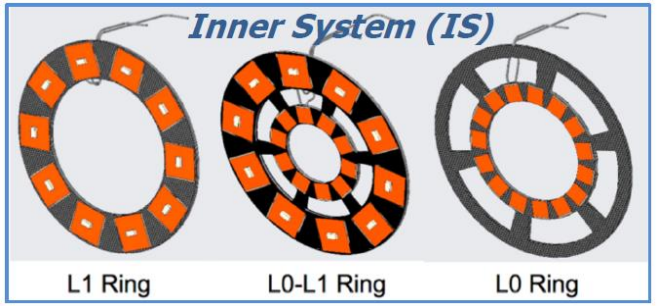
- Barrel: pixel cell 25x100 µm^2 1E
- Rings: pixel cell 50x50 µm^2 1E



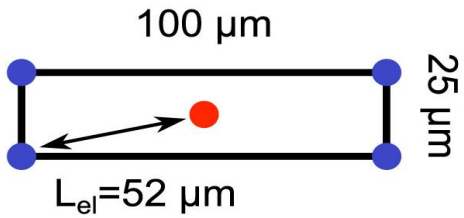
Barrel - staves



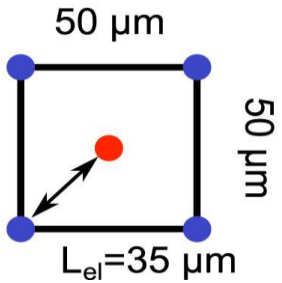
Ring



25×100 µm^2, 1E



50×50 µm^2, 1E



RD53A run at CNM

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

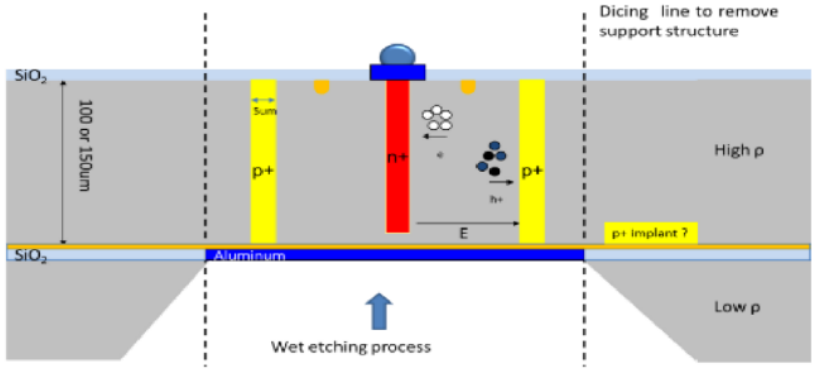
- Single sided process
  - Both p- and n-columns etched from the front
  - p-stop insulation
- Silicon on Isulator (SOI) wafers 150 µm active thickness with 300µm handle wafer

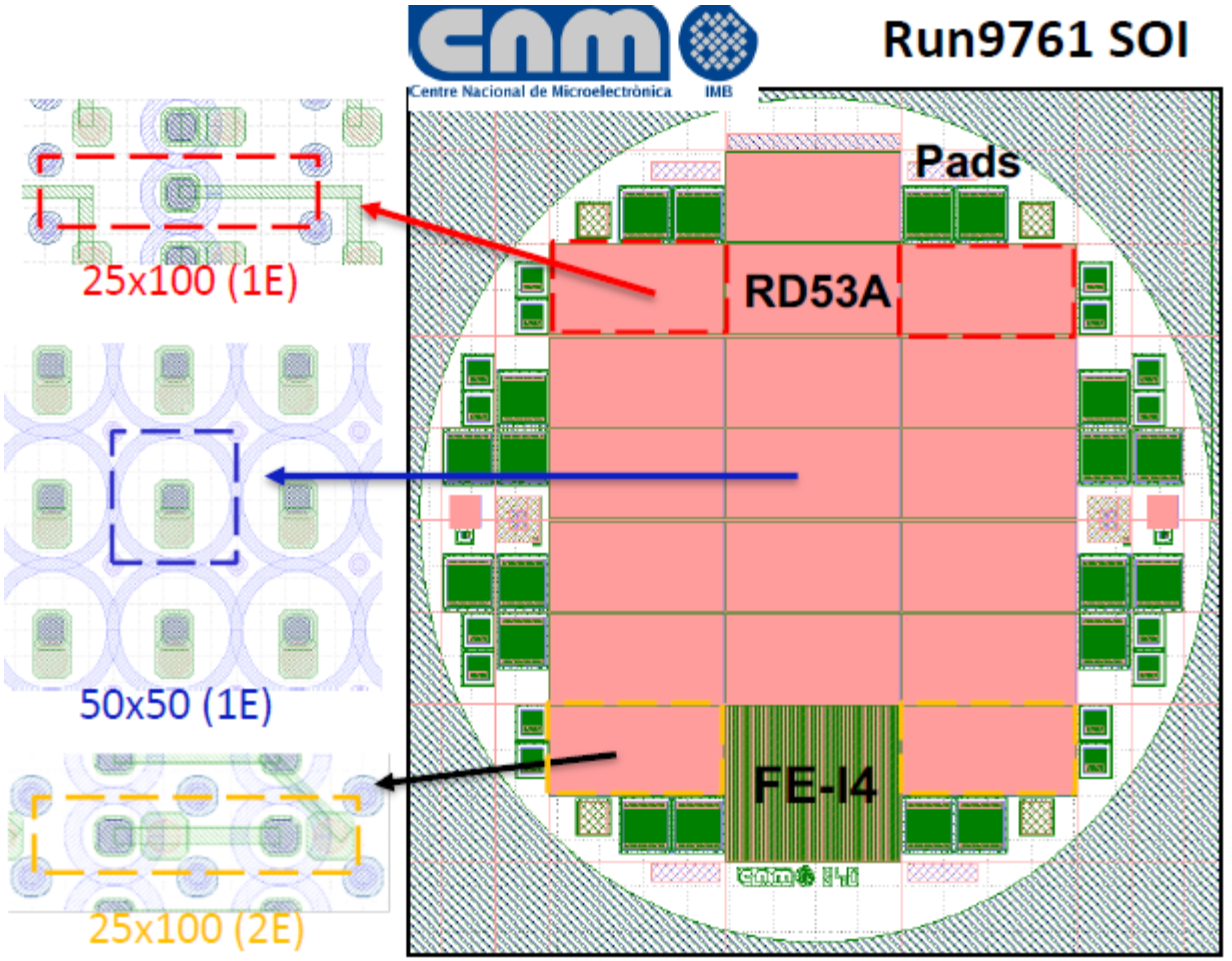
The mask includes:

- 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.





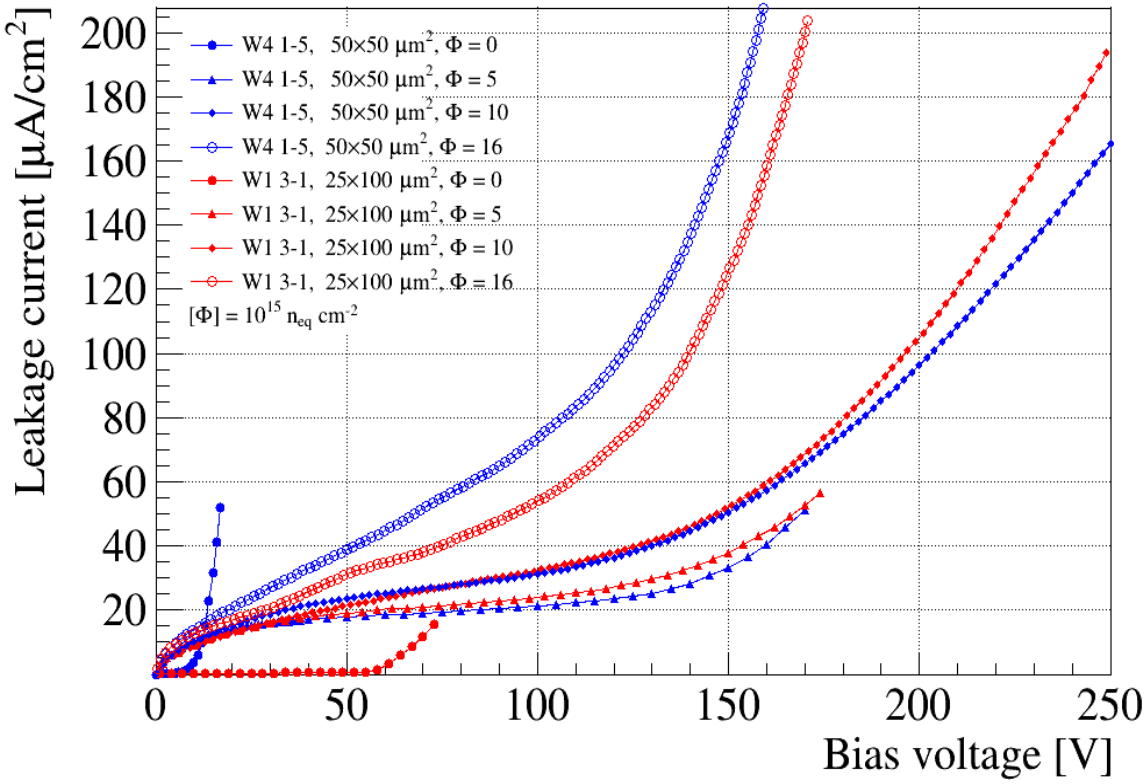
RD53A module

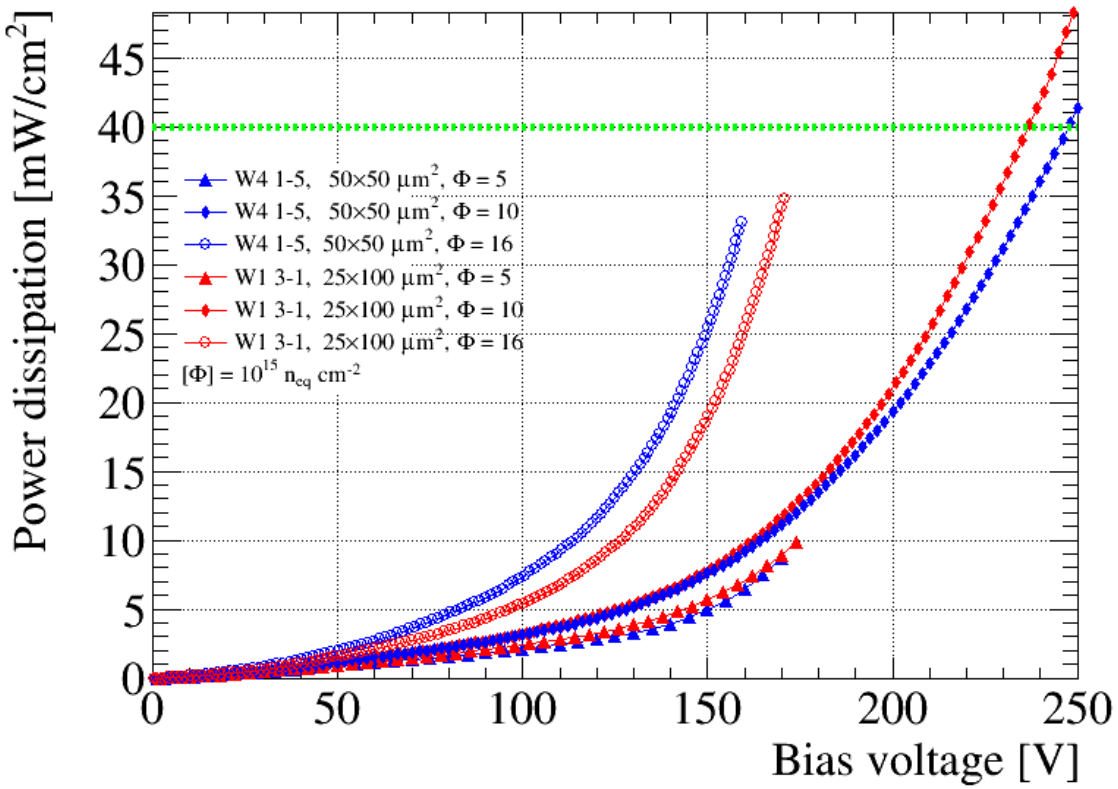
- Under-Bump Metallization (UBM) were performed at CNM.
- Flip-chip was carried out at IFAE.
- 50x50 was fully connected while the 25x100 had large disconnected areas on the right and left sides
- Both sensors were uniformly irradiated with proton beams in different facilities up to 1.6e16 neq/cm^2:

Sensor name	W4 1-5	W1 3-1
Pitch [μm^2]	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]	420	420
Total		
Φ [n_{eq}/cm^2]	1.6×10^{16}	1.6×10^{16}
TID [Mrad]	1520	1835

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

Sensor IV - Power dissipation

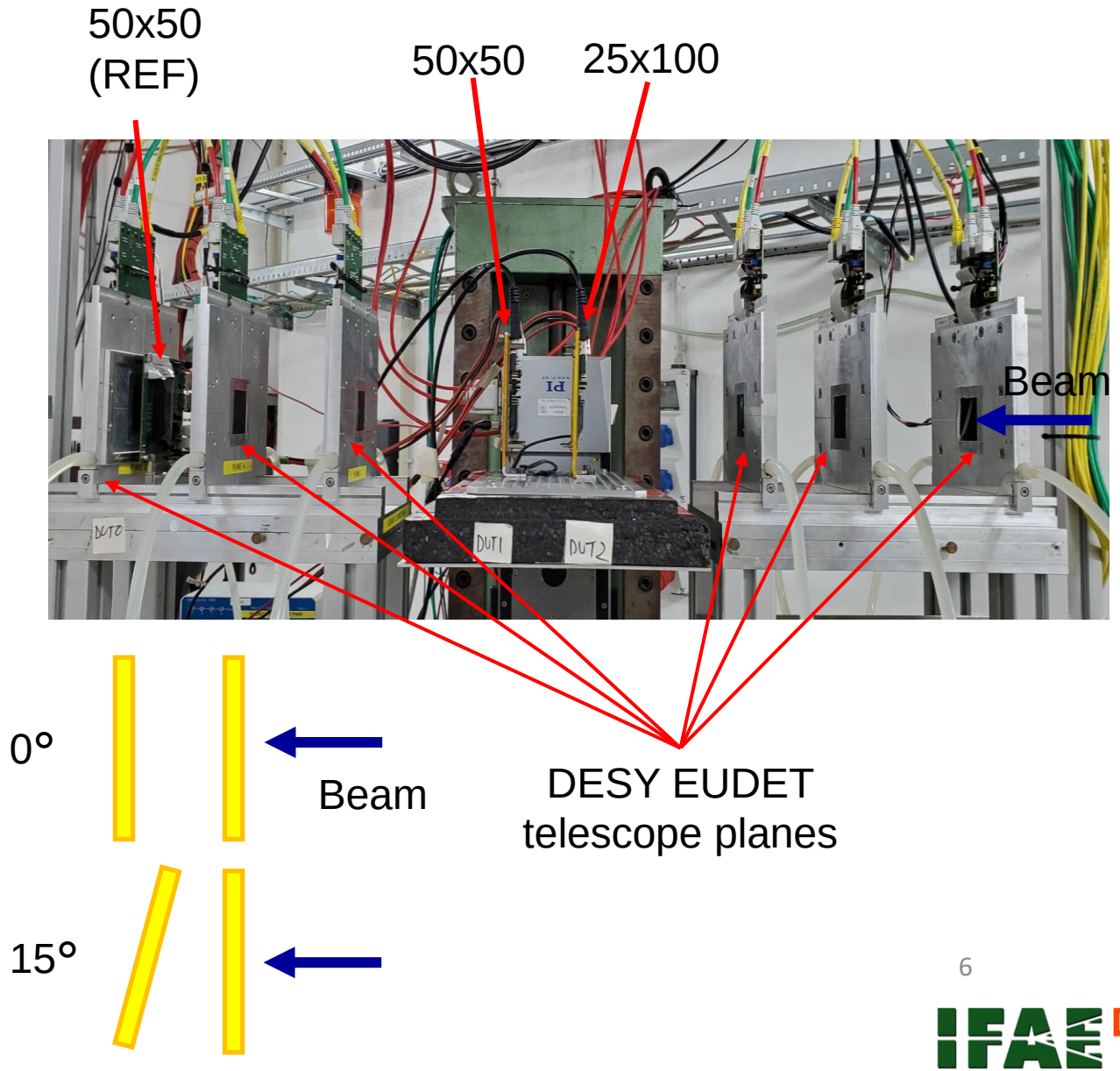




- Irradiated modules were measured at -25° in a climate chamber.
- Not irradiated modules were measured at room temperature.
- For ATLAS specifications, the Power Dissipation must be lower than 40 mW/cm^2.
- After irradiation to 1.6e16 neq/cm^2. These sensors can be operated up to 160V.

DESY setup – December 2021

- EUDET telescope: 6 MIMOSA pixel detectors for tracking.
- We use a 50x50 non-irradiated RD53A planar sensor as timing reference.
- We use dry ice to reduce the leakage current on the modules.
  - Box temperature: -48ºC
- We used EUTELESCOPE to reconstruct the particle tracks and TBMon2 to calculated the efficiency.
- 50x50 was measured at 0º (normal to the incident beam direction) and at 15º
- 25x100 was measured only at 0°.



Threshold scan after tuning

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

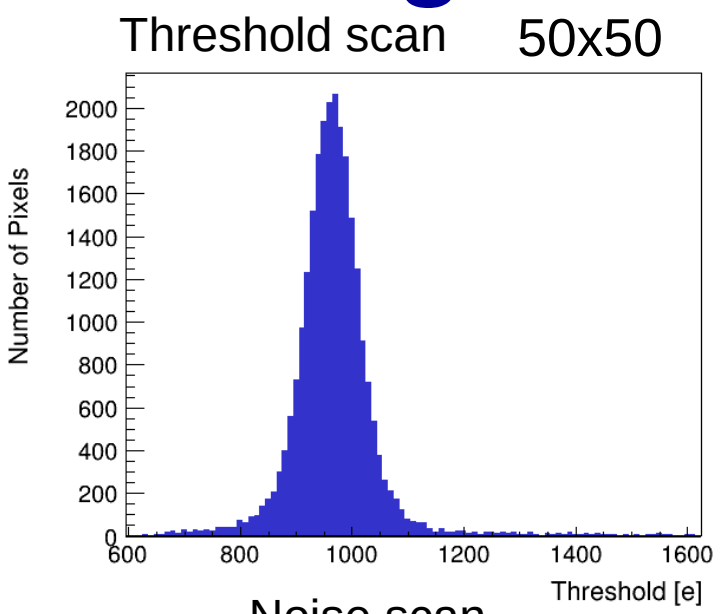
The Lin FE was very noisy and could not be tuned, we measured only the Diff FE (selected for the final ALTAS ITkPix chip)

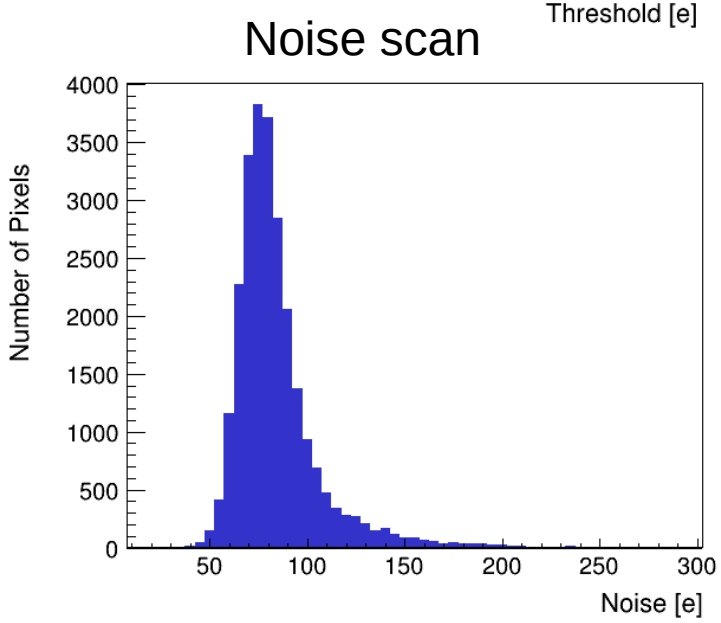
50x50:

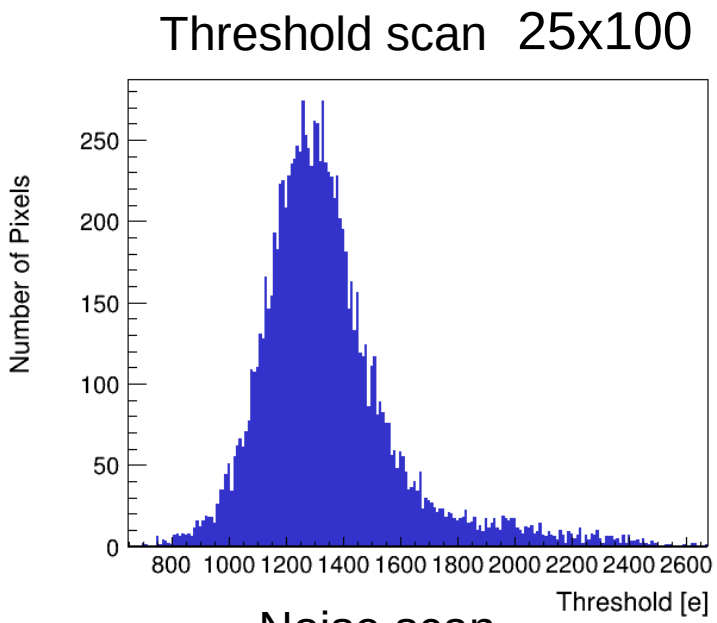
- Threshold value around 1000 e.
- The noise is lower than 100 e.

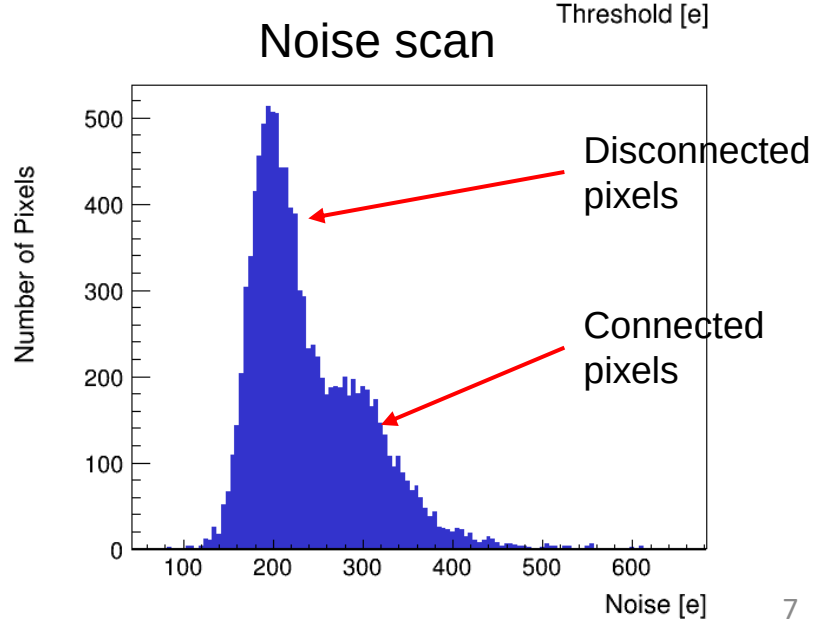
25x100

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





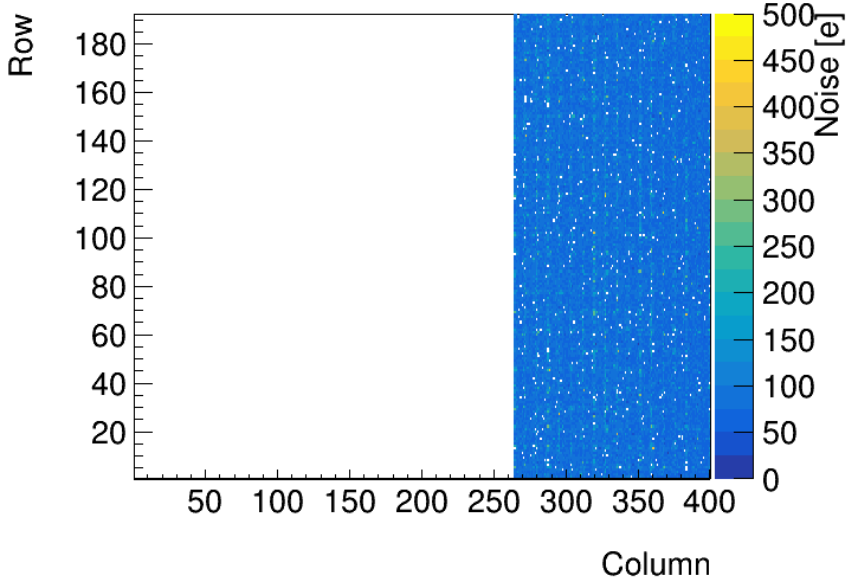


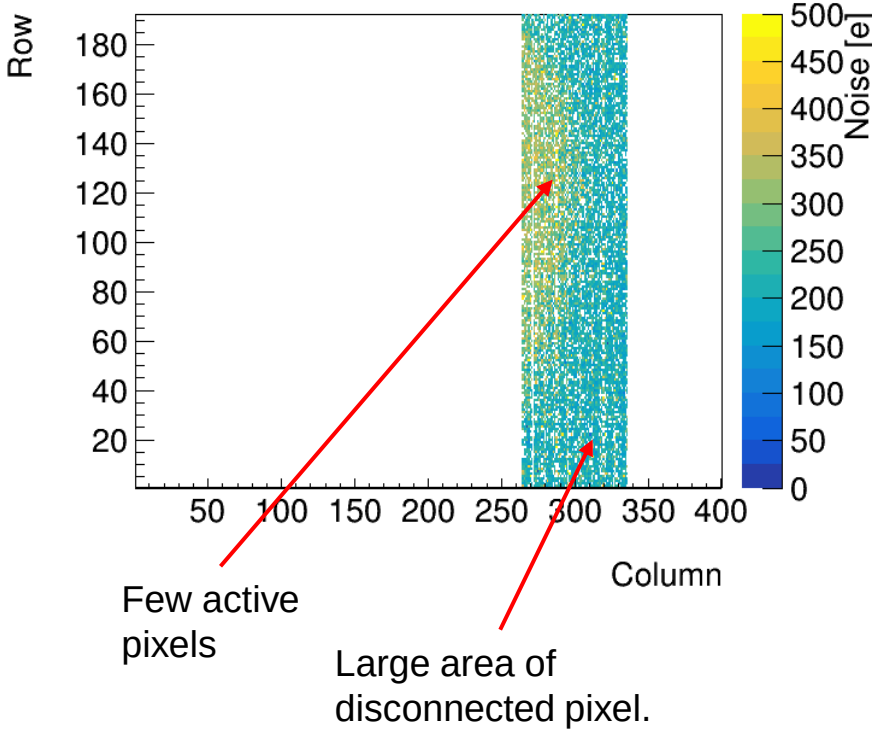


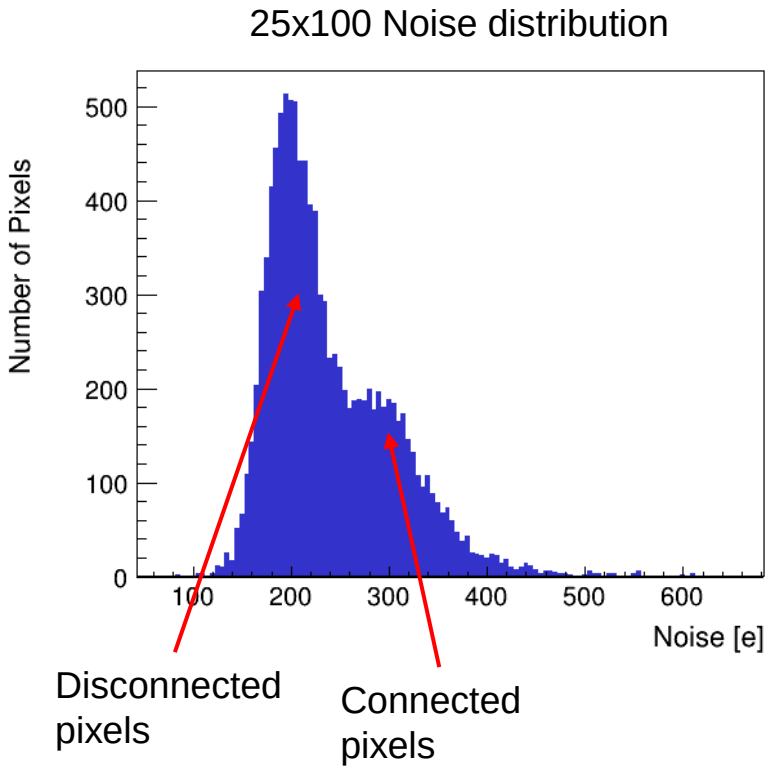
25x100 1E – disconnected areas

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

- 1k noise pixels were masked in the 25x100 around the active area (19%).
- 62 noise pixels were masked in the 50x50 in the diffFE (0.25%)



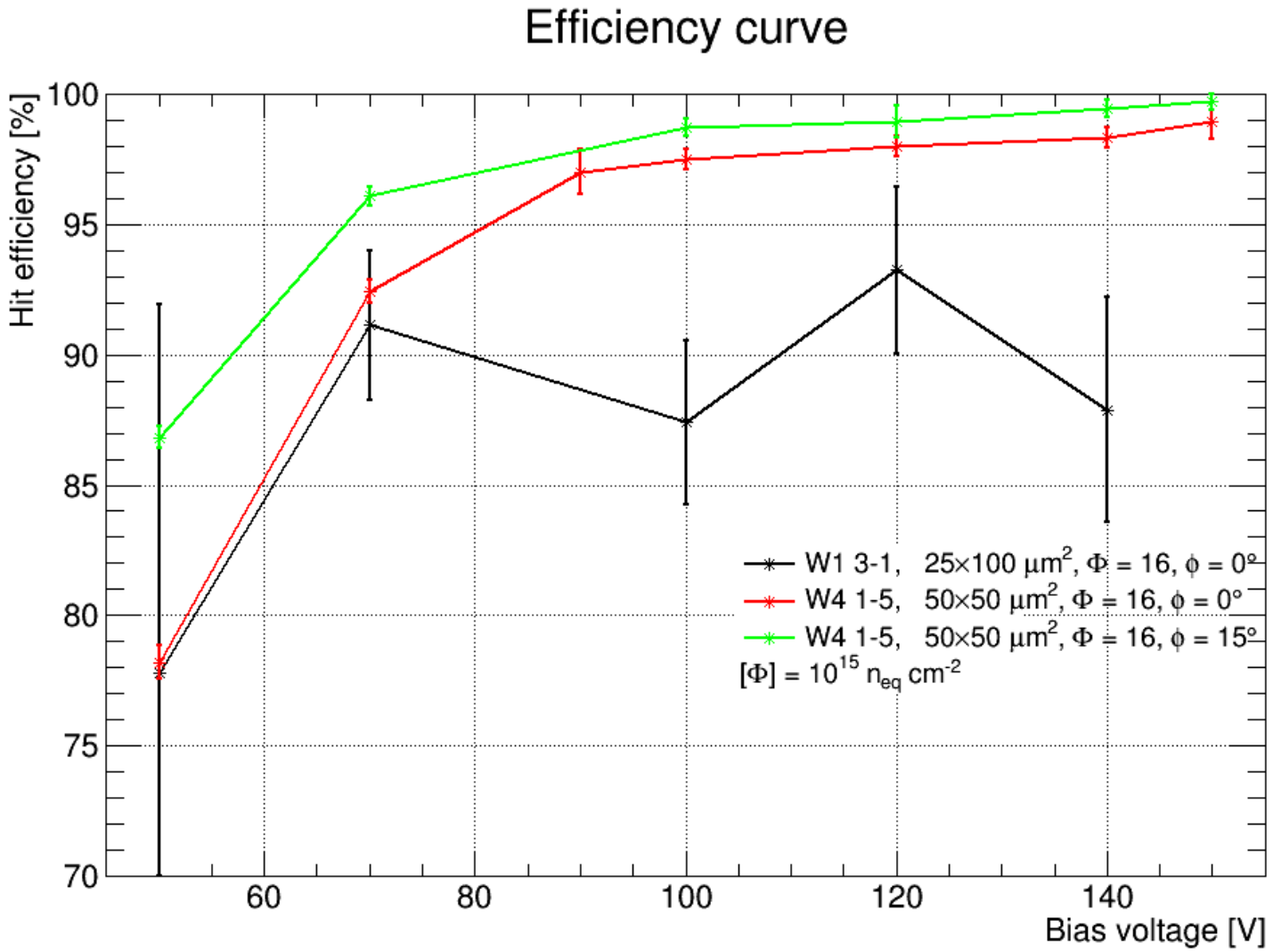




Efficiency vs bias voltage plot

- Tilted 50x50 (green curve) reach an efficiency higher than 97% at 80V.
- At 100V, the 50x50 (red curve) reach an efficiency higher than 97%.

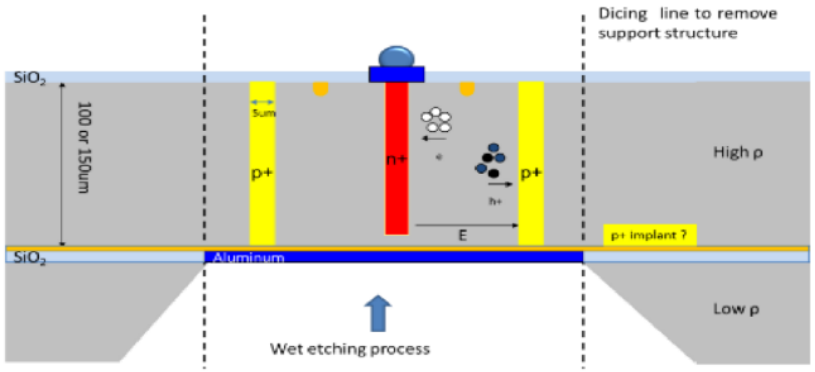
- 25x100 efficiency oscillates around 90%.
  - Very low statistic (large disconnected area and very few pixels analyzed)
  - Larger Total Ionization Dose (TID) and more noise in the front-end
  - Larger threshold (and tails)



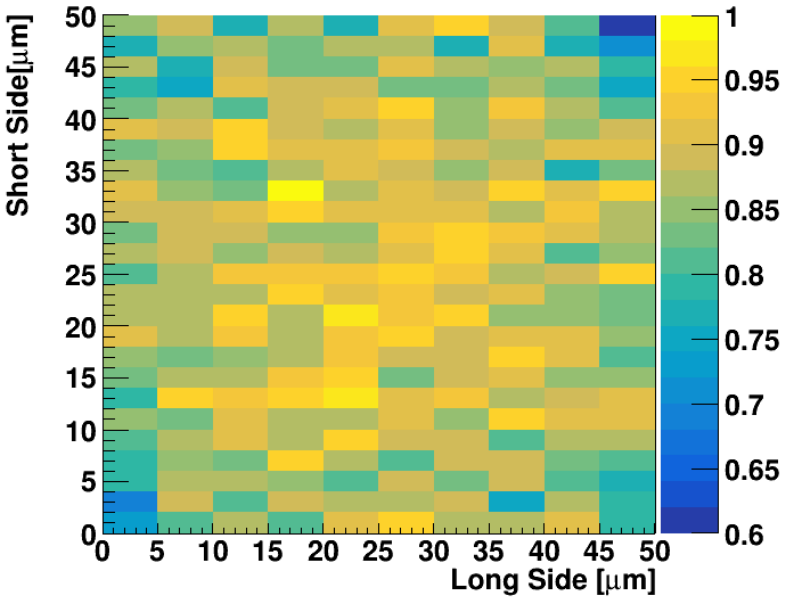
Efficiency pixel map 50x50 at 70V

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

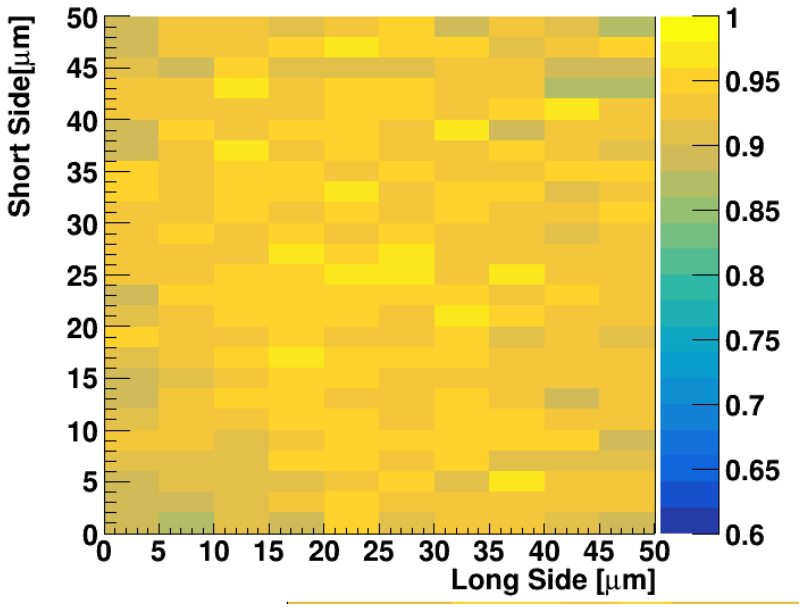
Efficiency in the corners for the tilted one is higher and uniform.

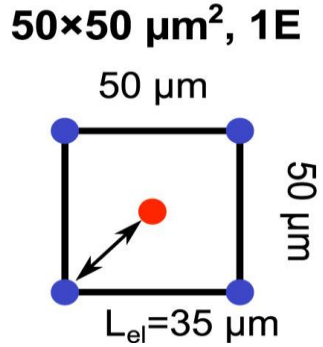


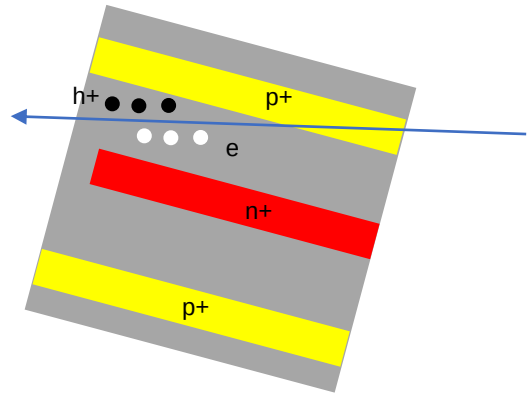
Not tilted



Tilted





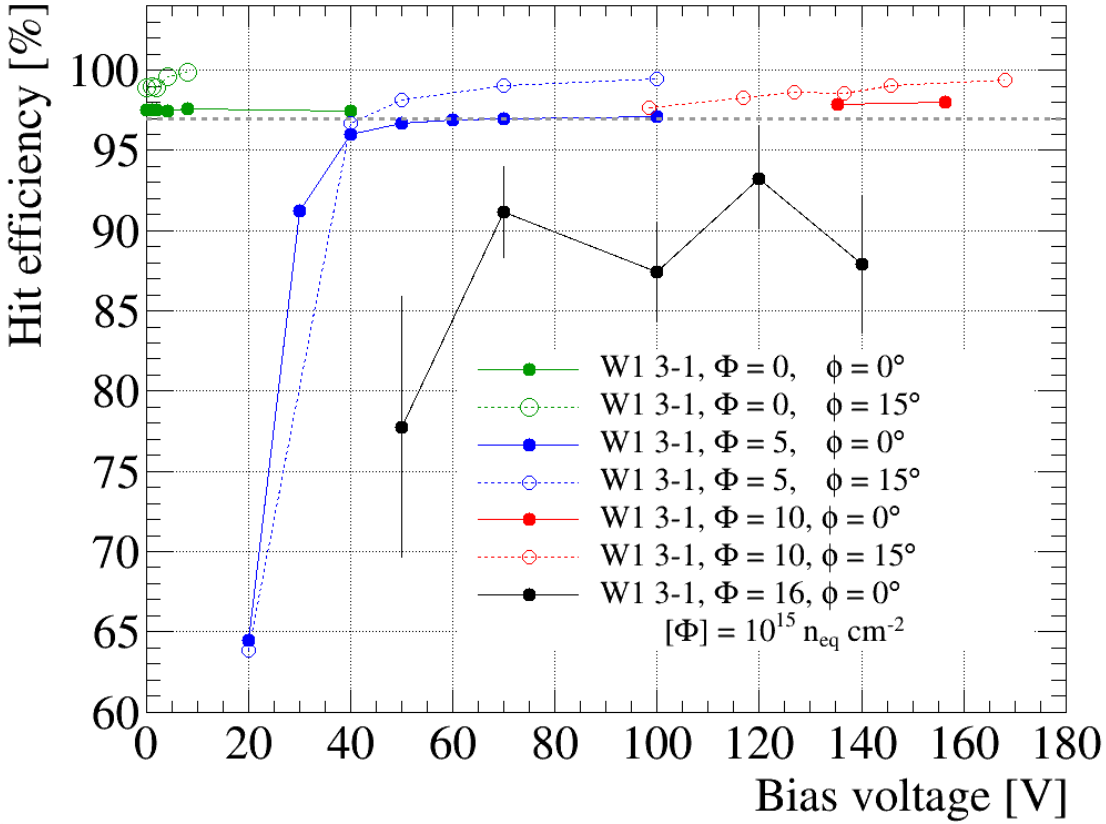


15º tilted scheme

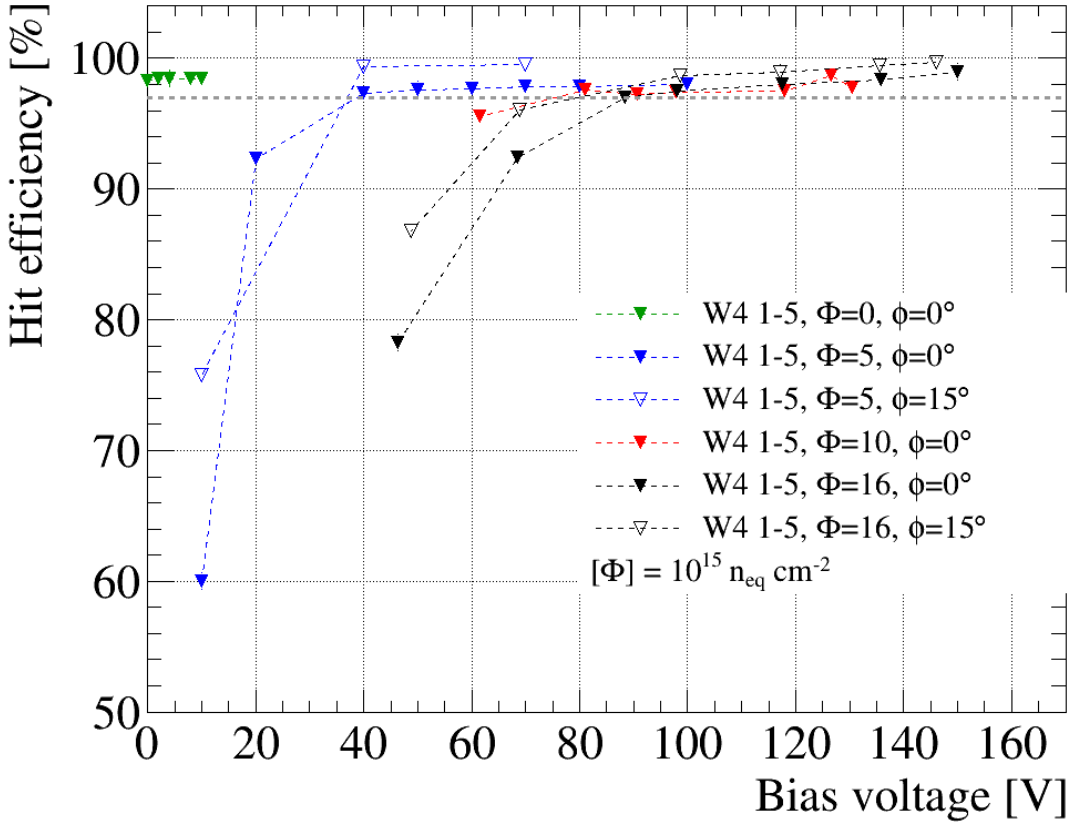
Efficiency vs bias voltage plot

Overview of the hit efficiency after each irradiation step.

25x100



50x50



Conclusion

I presented efficiency results of two 3D irradiated pixel sensors, 25x100 and 50x50, both irradiated to 1.6e16 neq/cm^2.

- The 50x50 not-tilted reaches 97% efficiency with just 100 V.
- The 50x50 tilted 15° reaches 97% efficiency at 80 V.
- 25x100 sensor presents a large disconnected area and a large noise in the chip. Efficiency oscillated around 90%.

The power dissipation of both sensor is below 40 mW/cm^2 up to 160 V.

- Power dissipation for the 50x50 is around 7 mW/cm^2 at 100 V, when it reaches the 97% hit efficiency.
- Power dissipation for the 25x100 is around 5 mW/cm^2 at 90 V, when it reaches the 90% hit efficiency.

Outlook

New Silicon-on-Silicon (SiSi) 25x100 1E device already mounted on a pcb for future tests.

Two SiSi modules have been irradiated at Fermilab, waiting for cooling down.

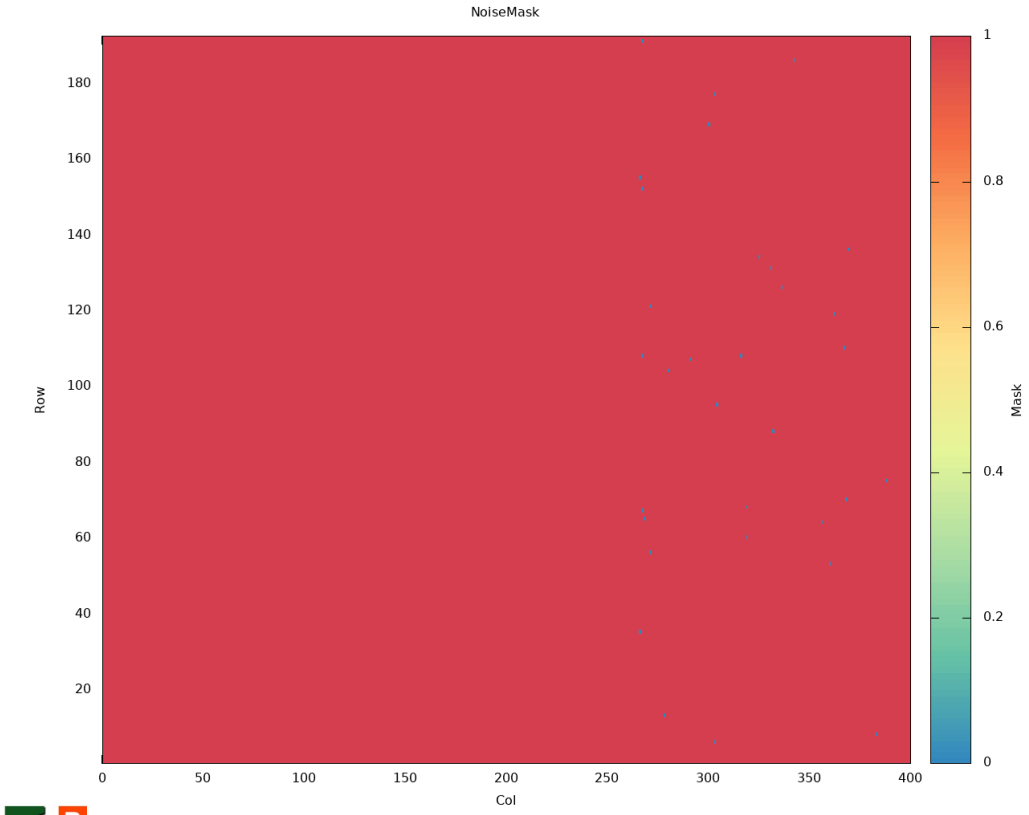
New SiSi pre-production at CNM in progress and expected for December.

Thanks for your attention

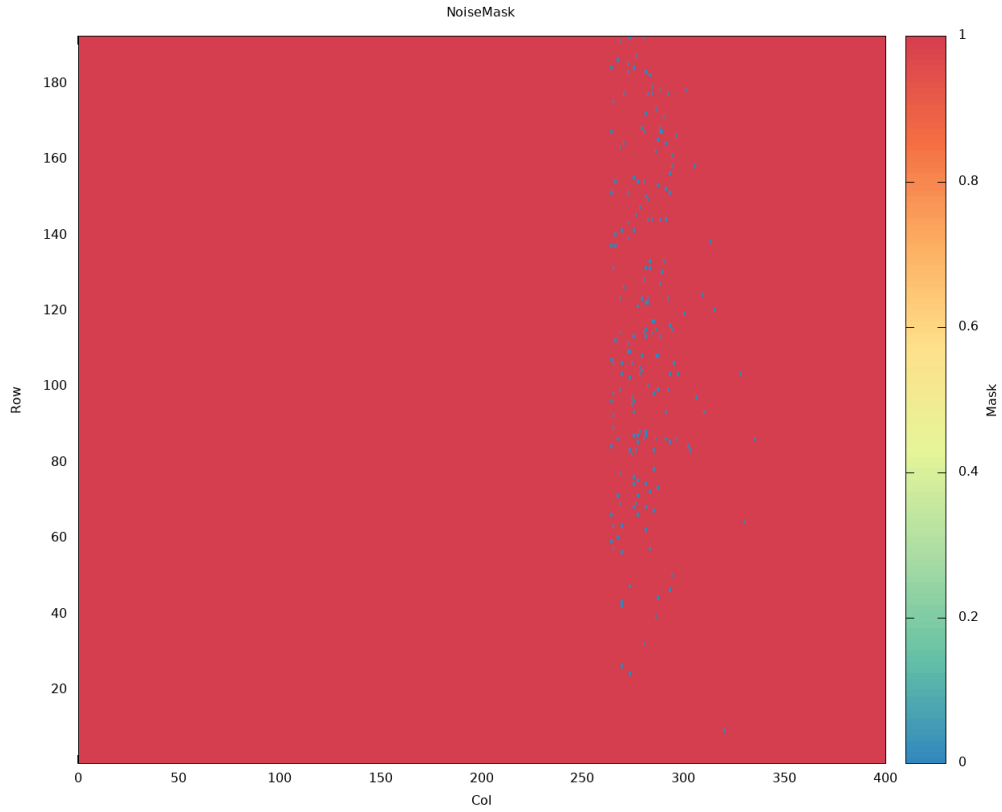
Tuning: noise mask

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

50x50



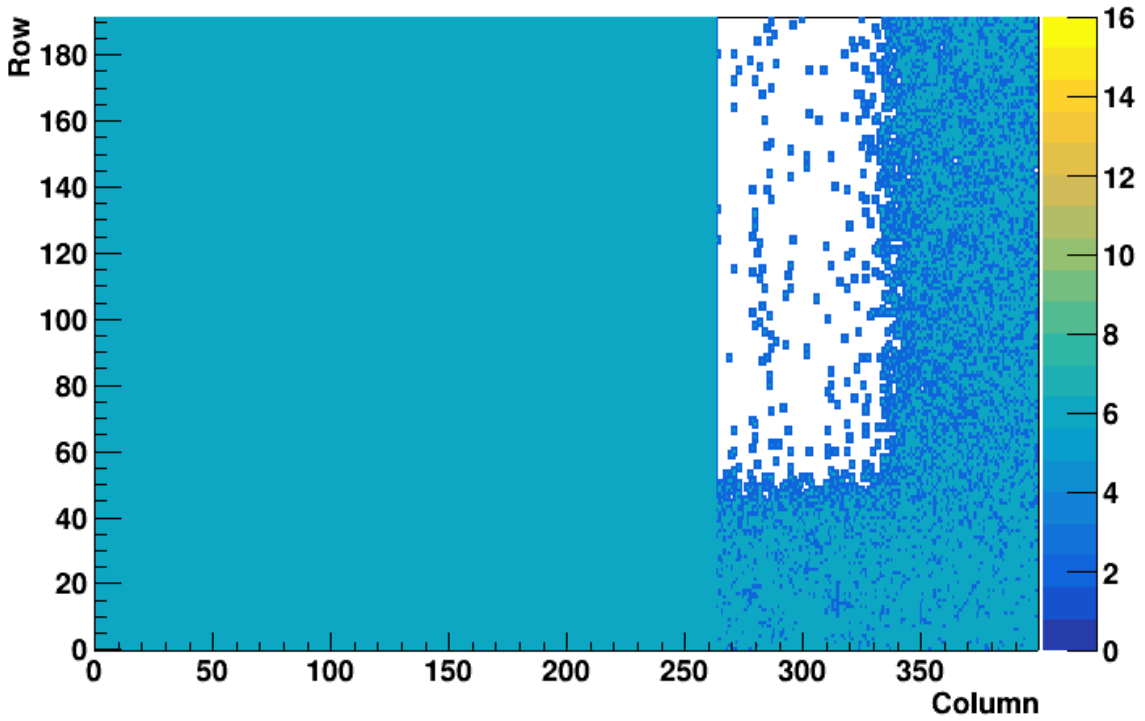
25x100



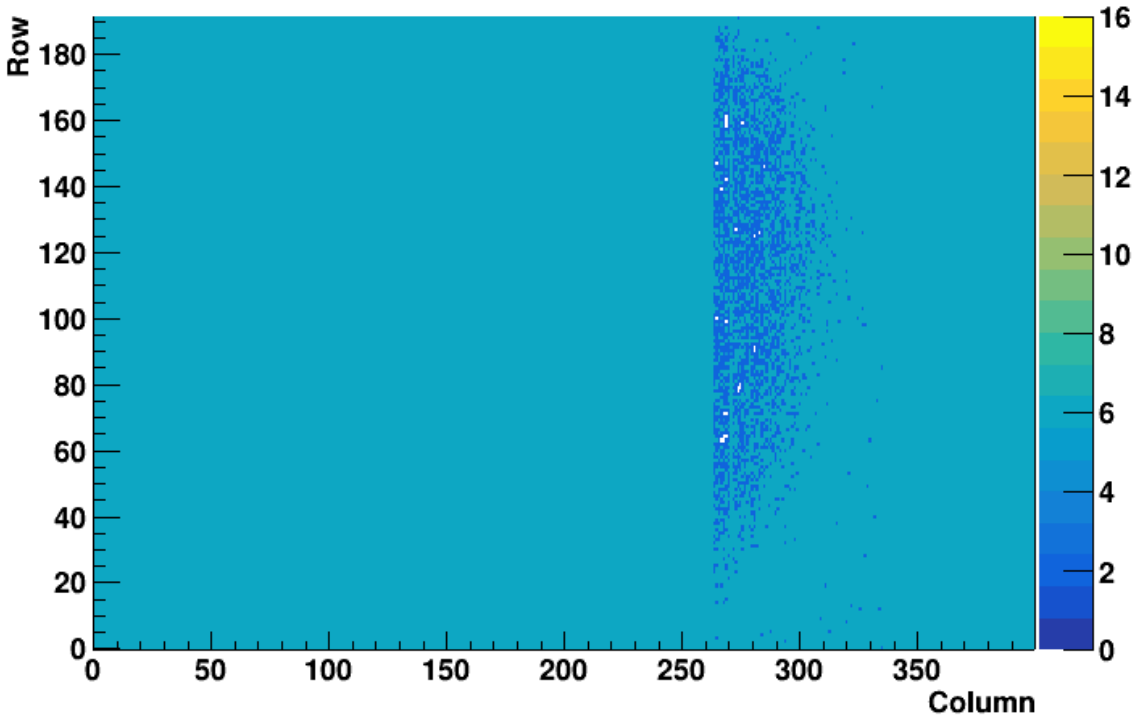
Masked pixel map at 100V

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

50x50



25x100

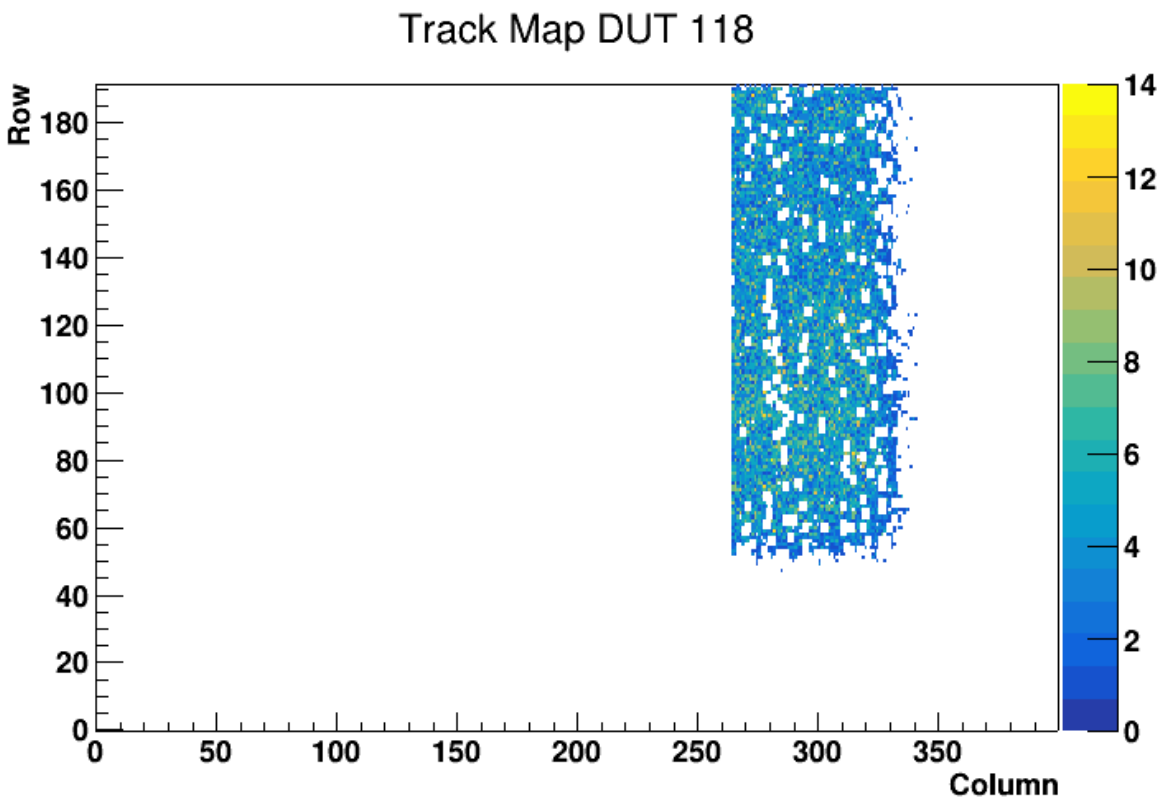


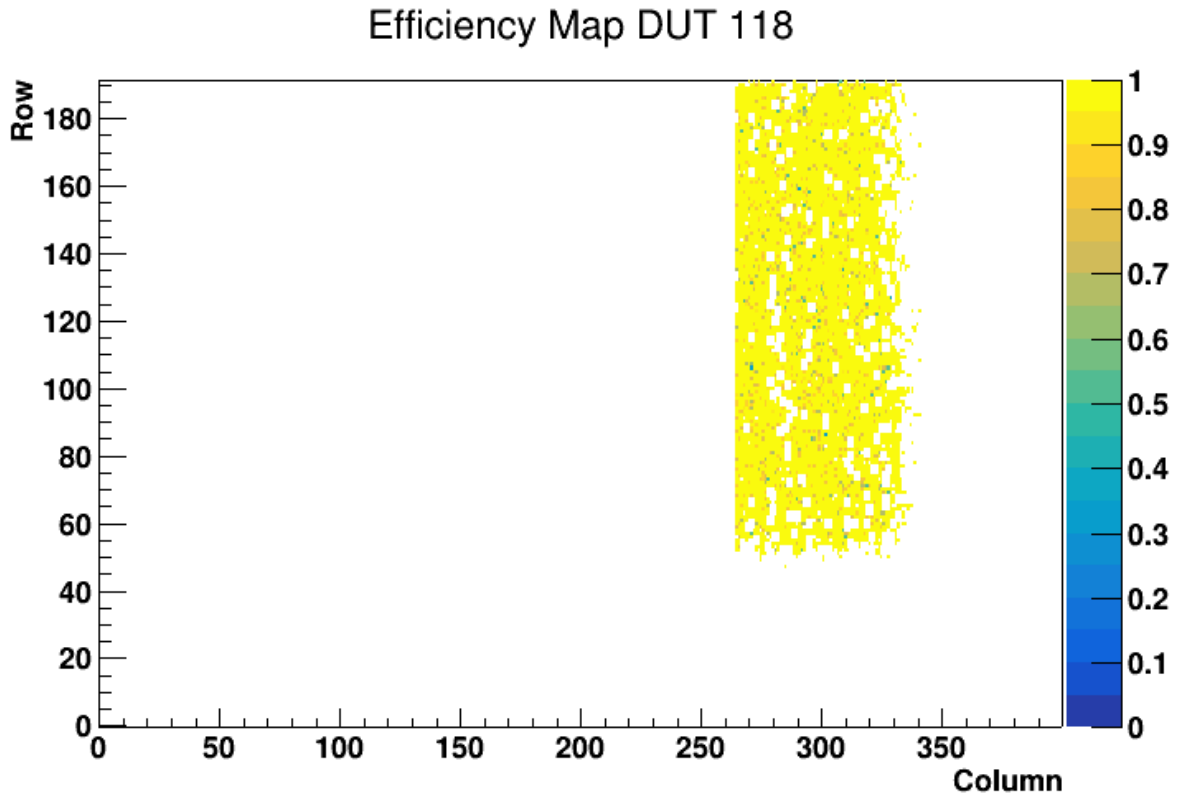
Area of the 25x100 is very small because of a large disconnected area

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.

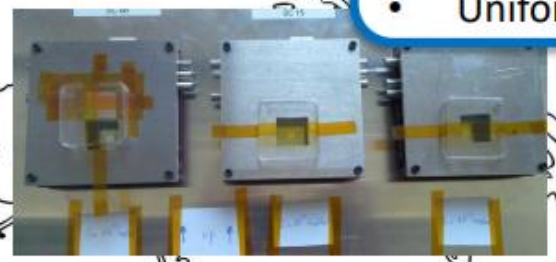




This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

AIDA 2020

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



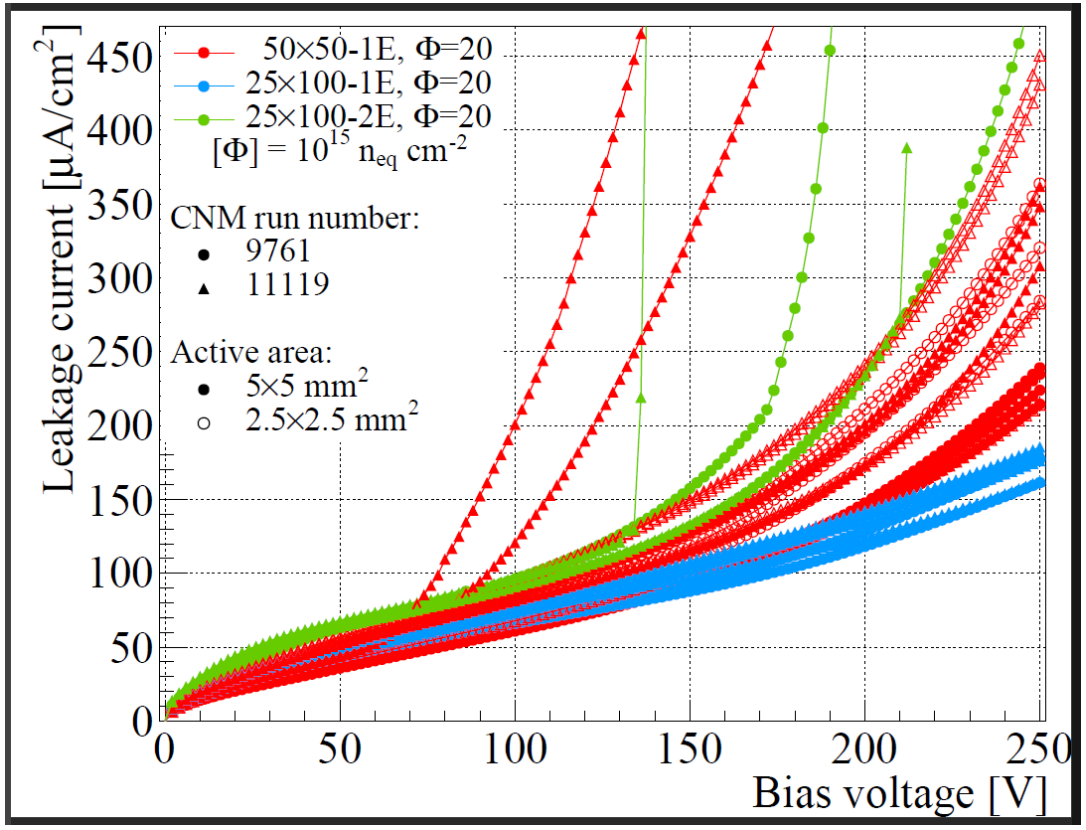
Birmingham, UK
- 27 MeV (up to 37 MeV) protons
- Large TID: ~650 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C

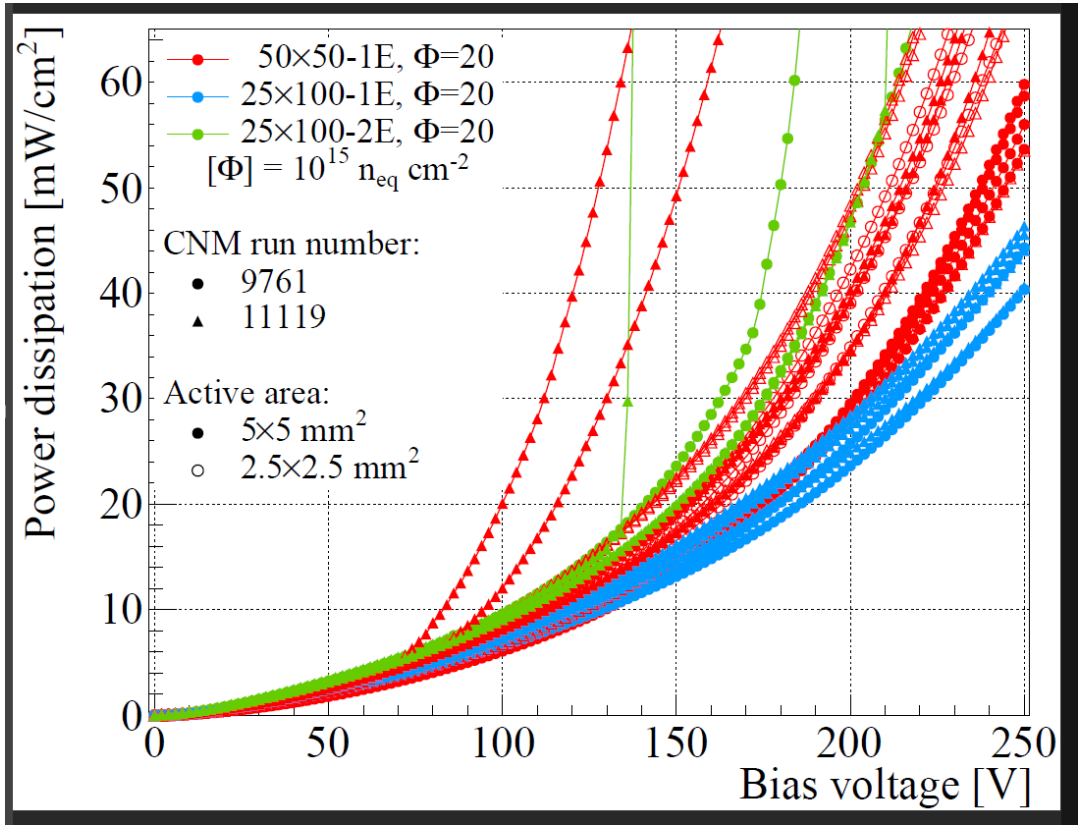
CYRIC, Japan
- 70 MeV protons
- Large TID: ~350 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C

TRIGA reactor at JSI, Slovenia
- Reactor neutrons
- Negligible TID
- Uniform irradiation
- Tantalum in the chip gets activated

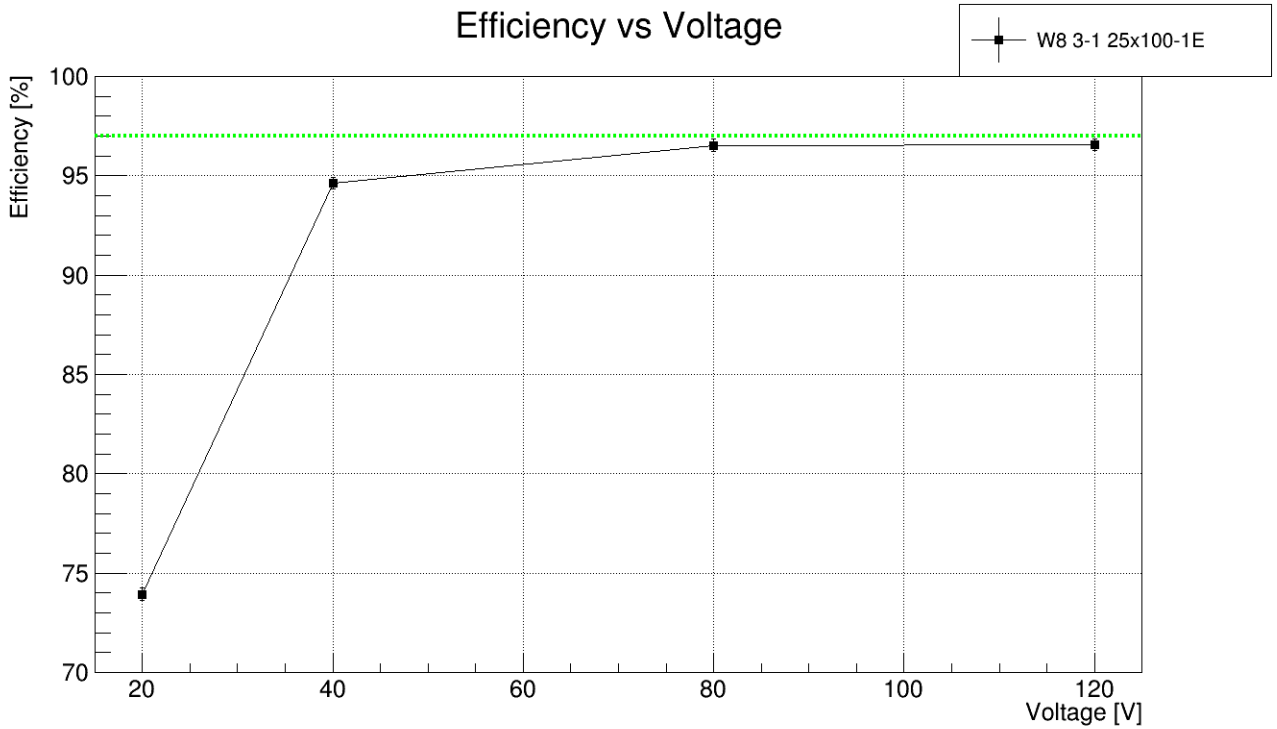
Thanks to: Koji Nakamura, Vladimir Cintro, Laura Gonella & Amelia Hunter, Felix Bögelspacher & Alexander Dierlamm

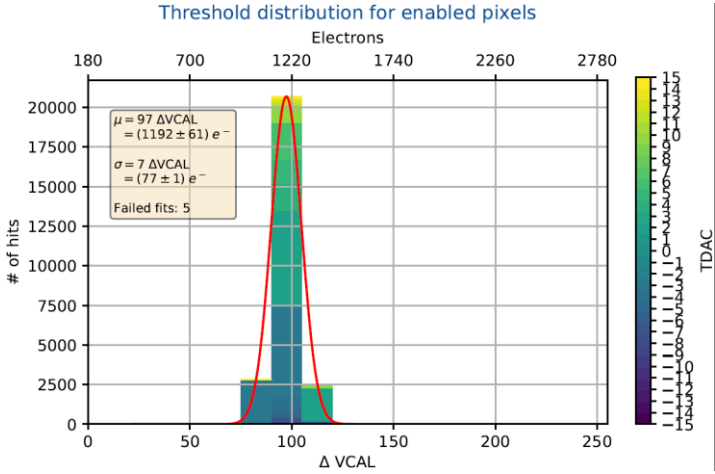
Diodes IV and Pow

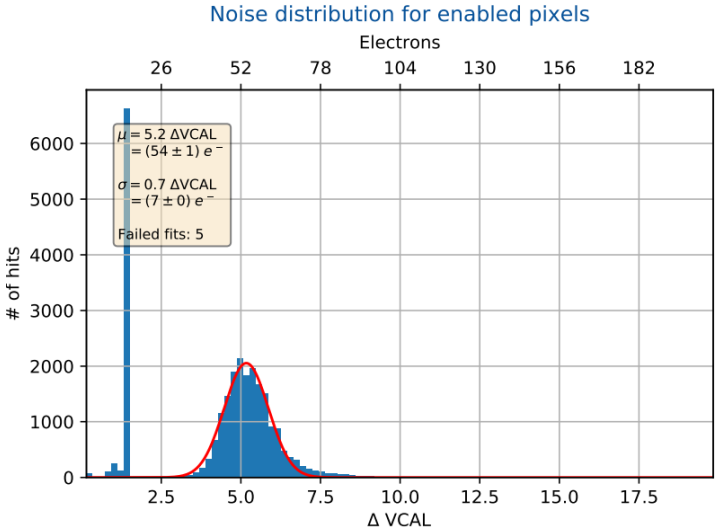




SiSi 25x100-1E irradiated at 1e16 neq/cm^2





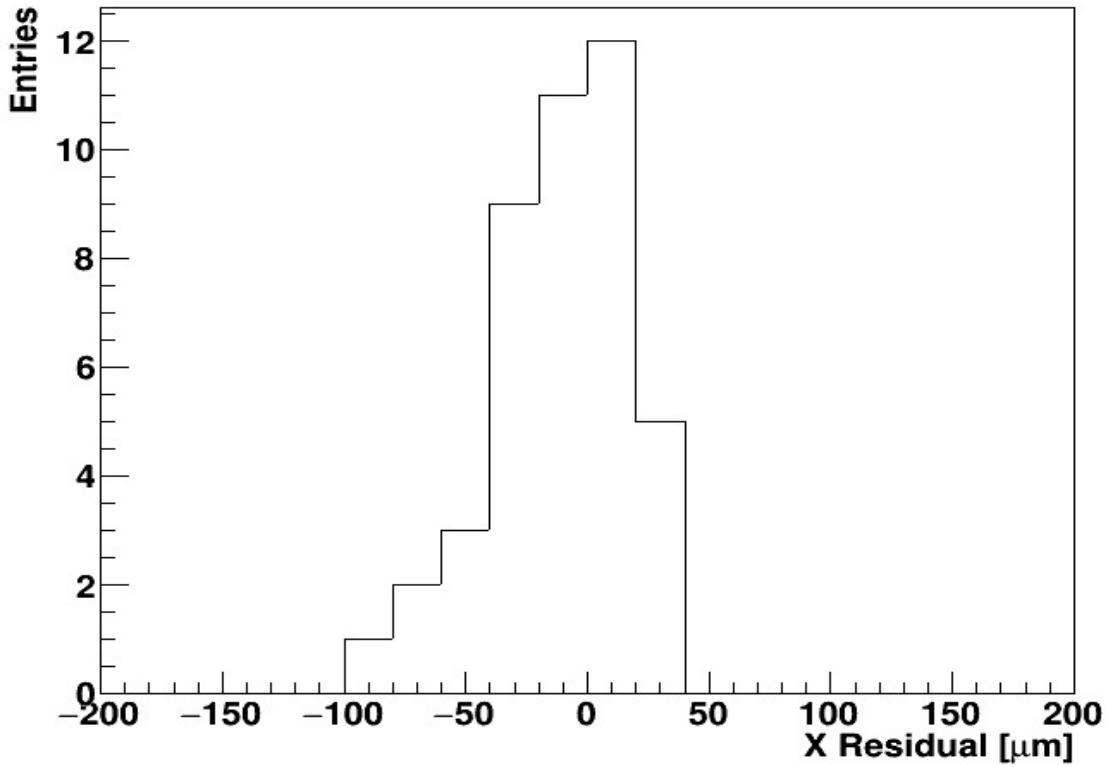


Sensor were uniformly irradiated with a 70MeV proton beams in CYRIC

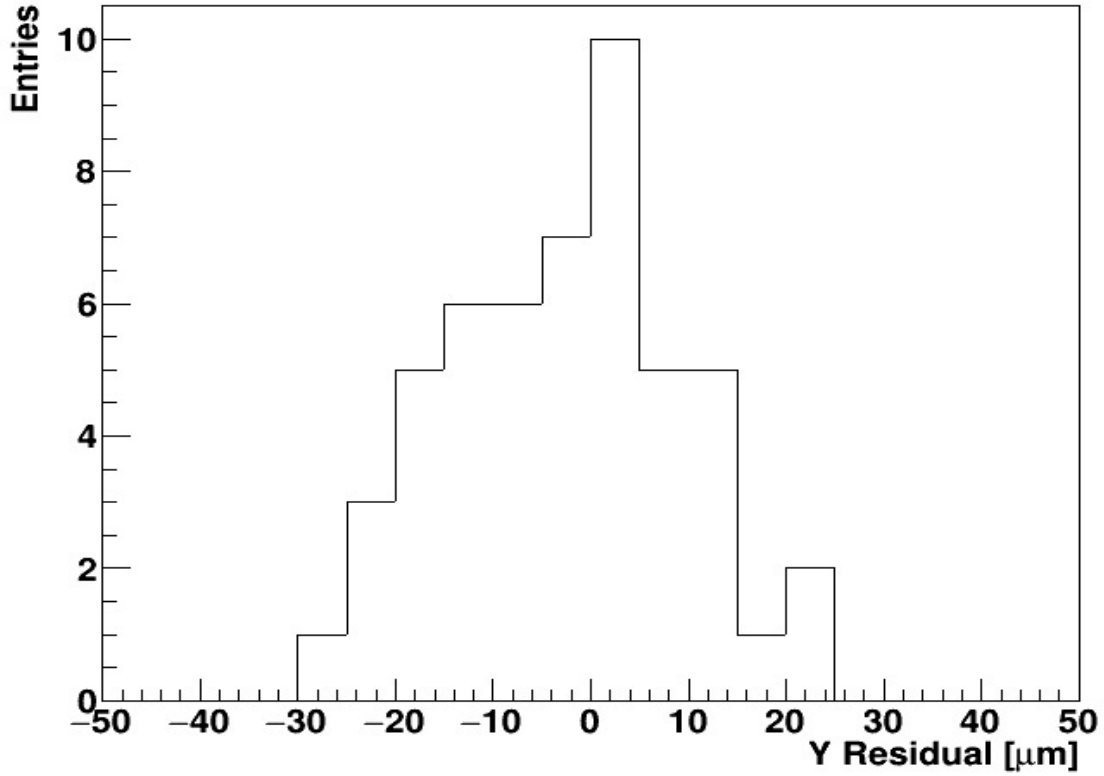
Residual plot 25x100

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

X axis



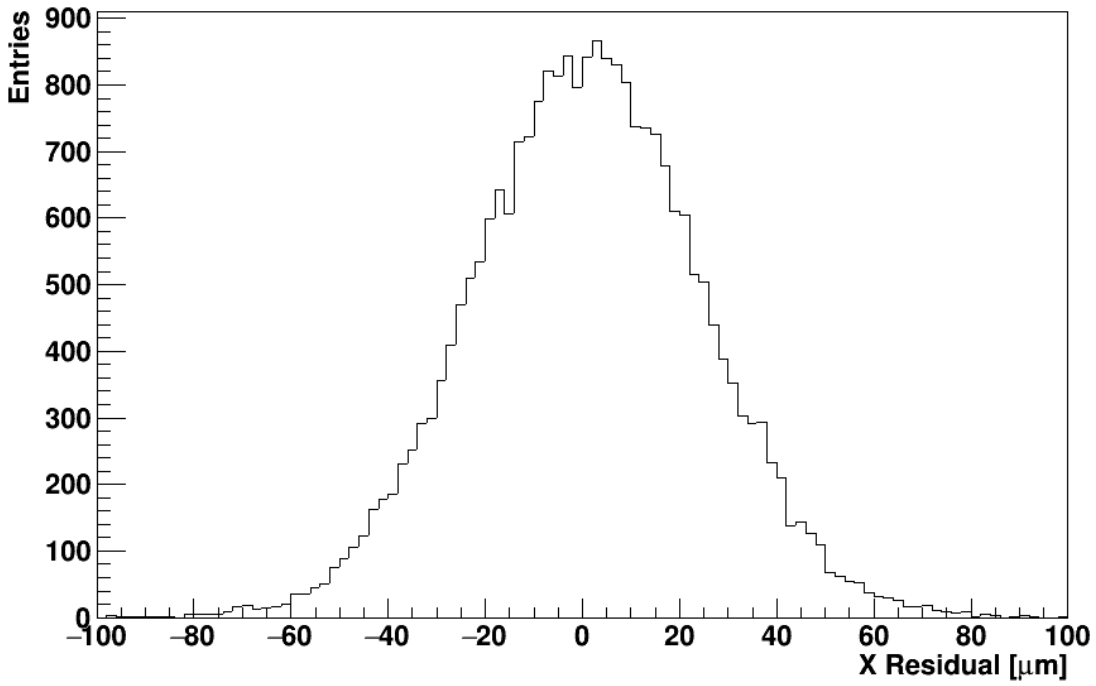
Y axis



Residual plot 50x50

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

X axis



Y axis