Test beam results of 3D pixel sensors for the Phase-2 CMS Tracker with the RD53A and CROC readout chips

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Outline

- Introduction to the High-Luminosity Upgrade for the CMS Inner Tracker
- Layout of 3D pixel sensors
- Read-out chips: CROC and RD53A
- Irradiation and test beam
- Test beam results
- Conclusions

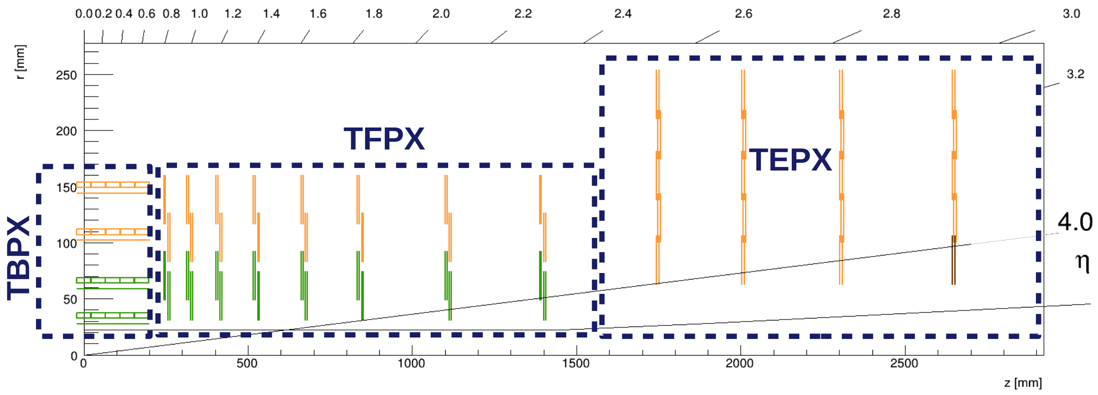
The CMS Inner Tracker upgrade for the High-Luminosity LHC

- The **High-Luminosity LHC** environment
  - Instantaneous luminosity peaks at **7.5x10^{34} cm^{2}/s**
  - **200 collisions per bunch crossing**

Baseline scenario
with replacement after ~6 years of operation

Runs 4+5	
1E16 1MeV neq	Grad
1.88	1.03

- CMS needs an upgrade to cope with such conditions. The silicon tracker will be completely replaced to sustain the foreseen radiation levels, especially in the innermost layer of the Inner Tracker (IT) →

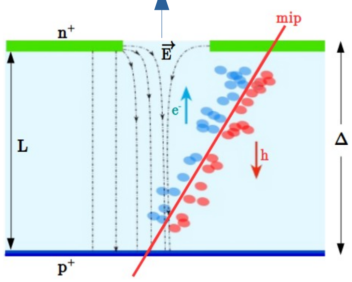


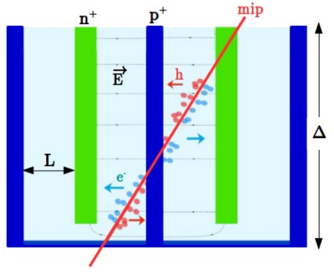
High-Luminosity upgrade of the CMS IT layout

- Tracking coverage extended up to **|η| = 4.0**
- **Tracker Barrel Pixel (TBPX)**: 4 layers
- **Tracker Forward Pixel (TFPX)**: 8 small disks per side
- **Tracker Endcap Pixel (TEPX)**: 4 large disks per side
- **Hybrid modules** with **1x2** and **2x2 readout chips**

Have a look at Massimiliano Antonello's presentation on planar sensor results

- **Active thickness**: 285µm → **150µm to reduce power dissipation**
- **Pixel pitch**: 100x150µm^{2} → **25x100µm^{2} to reduce pixel occupancy**
- Two sensor technologies: **planar pixels + 3D pixels in the innermost layer**
  - 3D pixel sensors are more radiation tolerant
  - Simulations for TBPX L1 show thermal runaway issues in planar sensors

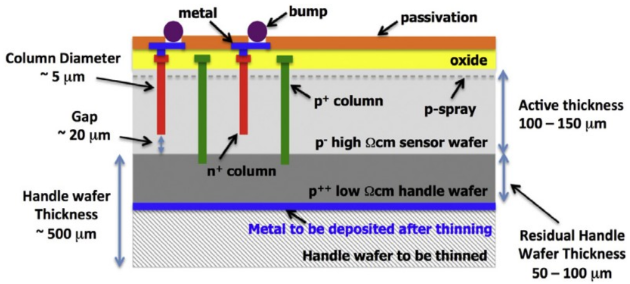


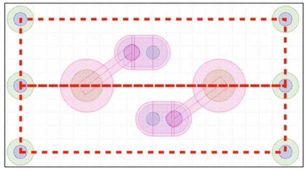


CNM and FBK 3D pixel sensors

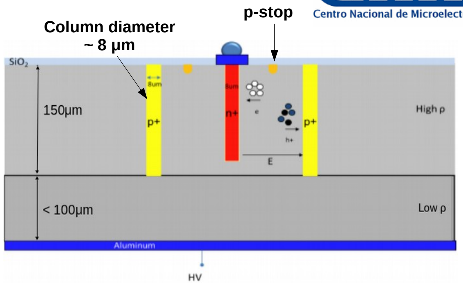
- Two manufacturers involved in the production of this sensor technology for the CMS Inner Tracker Upgrade:

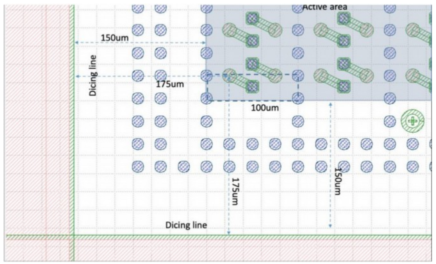
FBK -Fondazione Bruno Kessler- (Trento, Italy) in collaboration with **INFN**





CNM -Centro Nacional de Microelectrónica- (Barcelona, Spain)

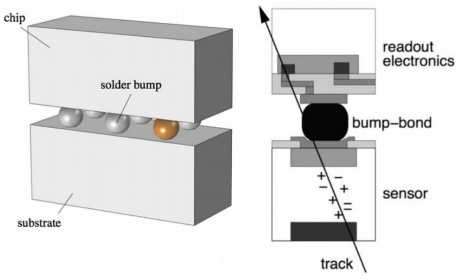




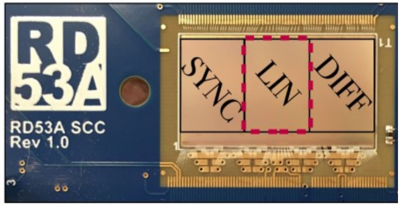
- Low resistivity silicon layer bonded to high resistivity substrate using the ***D****irect* ***W****afer* ***B****onding* (**DWB**) technique: **Si-on-Si**
  - The total thickness after thinning is 250μm with **150μm of active thickness**.
- Columnar implants penetrate the substrate from the same face: **single-side** ***D****eep* ***R****eactive* ***I****on* ***E****tching* (**DRIE**) **process**
  - **p⁺ columns** in contact with the backside of the sensor
  - **n⁺ columns** connected through the bump bonding pads to the readout chip → **~115μm in FBK** and **~130μm in CNM**
  - They have a **5μm diameter in FBK** and **8μm diameter in CNM**. They are filled with polysilicon.
- The bias voltage is applied to the ohmic contact from the sensor backside.

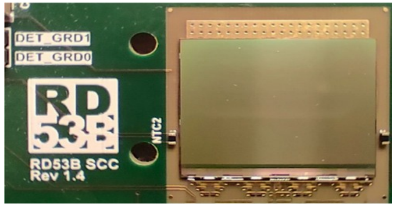
The CMS Read-Out Chip: CROC

- The read-out chip (ROC) is connected to the sensor with the bump-bonding technique.
- The read-out chip design has been carried out by the **RD53 Collaboration**
  - 65nm CMOS technology
  - 50x50μm^2 pixel matrix → diagonal sensor-chip mapping
  - Digital readout with Time-Over-Threshold
  - Serial powering via on-chip shunt-LDO regulators → Have a look at Antonio Cassese's presentation!

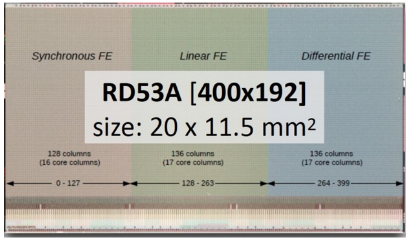


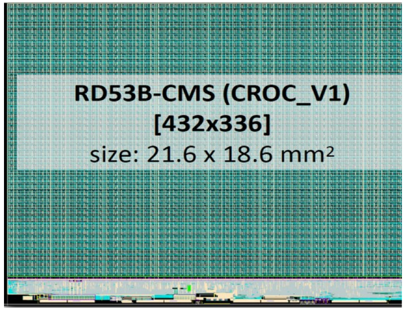
- **RD53A** was the first prototype common for ATLAS and CMS → R&D purposes (until beginning of 2022)
  - **Three analog front-ends:** **synchronous**, **linear** and **differential**
  - 76800 pixel channels → **26112 in the linear front-end**
  - 192 rows x 400 columns → **192 rows x 136 columns**





- CMS' choice was to have a ROC with **only linear front-end**: **CROC**
  - Currently available for sensor R&D purposes
  - Final version foreseen for the second half of 2023
  - **145152 pixel channels** → **336 rows x 432 columns**





- In order to operate the modules, a calibration is needed: **Tuning to a threshold of 1000e-** is feasible before and after irradiation, although with a higher noise in the latter.

Irradiation and test beam

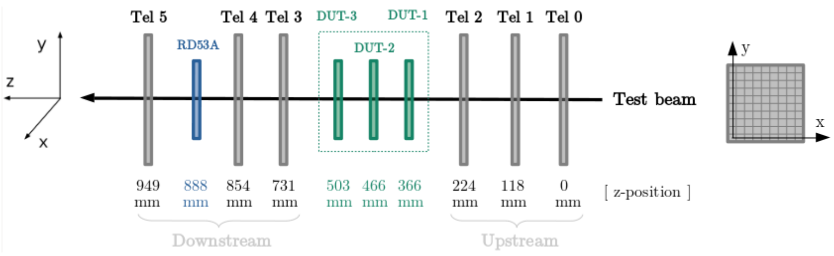
- **Data taking @ DESY and CERN SPS test beam areas**:
  - DESY: 5.2 GeV electron/positron beam
  - CERN: 120 GeV pion beam

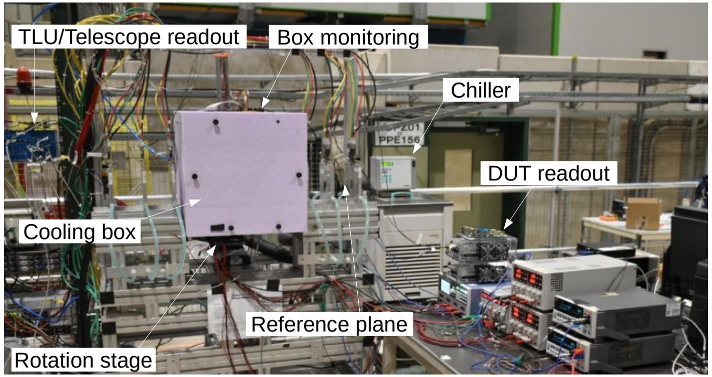
- Setup: **EUDET-type telescope**
  - Two arms: downstream and upstream
  - 5-6 Mimosa26 planes with square pixels of 18.4 µm pitch
  - Mimosa26 resolution around 2 µm on each coordinate
  - Telescope resolution depending on the DUT position
  - 576 rows x 1152 columns

- The **D**evices **U**nder **T**est (**DUTs**) are placed inside a cooling box in the middle of the telescope.

- **Irradiation** of 3D pixel modules @ several facilities:
  - **CERN PS**: 24 GeV protons
  - **Karlsruhe Institute of Technology (KIT)**: 25 MeV protons
  - **Fermilab Irradiation Test Area (ITA)**: 400 MeV protons
  - **Institut Pluridisciplinaire Hubert Curien (IPHC)**: 23 MeV protons

Setup at the SPS test beam area





→ The results shown in this presentation correspond to modules irradiated in these two facilities

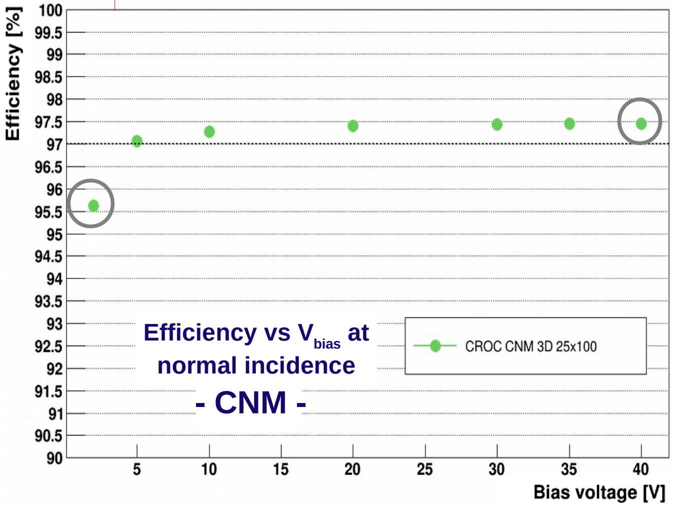
CERN PS: **TID ≃ 0.5 GRad per $1x10^{16} n_{eq}/cm^2$**

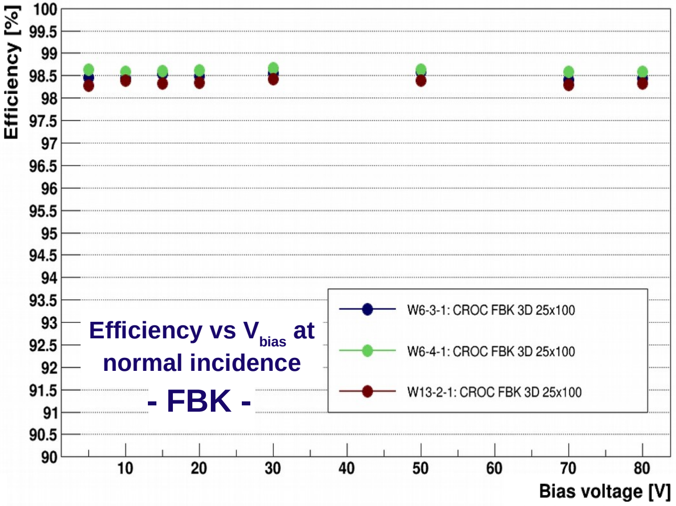
KIT: **TID ≃ 1.5 GRad per $1x10^{16} n_{eq}/cm^2$**

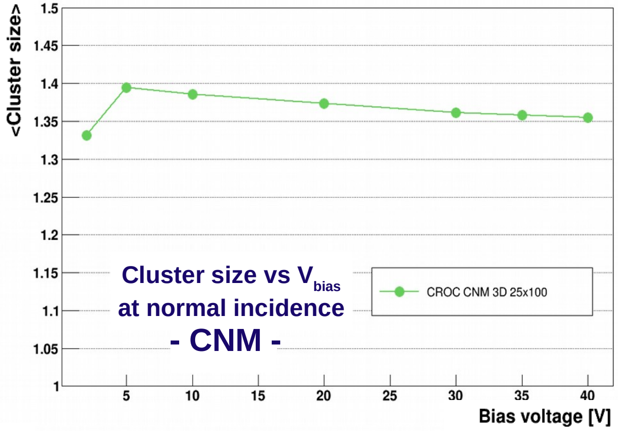
Results: fresh CROC 3D modules

- **Efficiency as a function of bias voltage at normal incidence**: **higher than 97% after full depletion** (already at 5V)
  - The columns are passive material and give rise to inefficiencies → it can be recovered by tilting the modules
  - Less than 1% of masked (stuck+noisy) channels → noisy = occupancy higher than 2×10^{-5}
  - The modules were tuned to average thresholds of 1000-1200e-

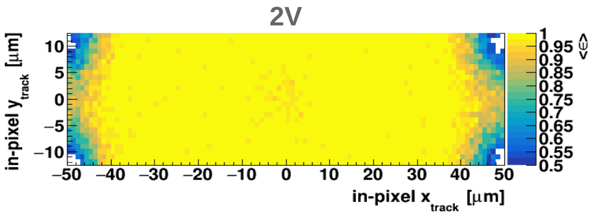
►Slightly lower efficiency in CNM modules due to larger column radius

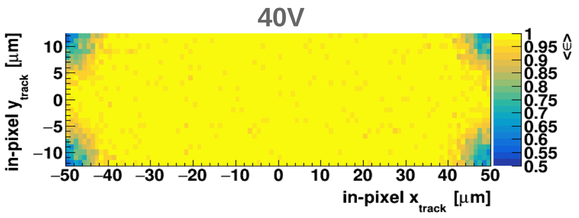


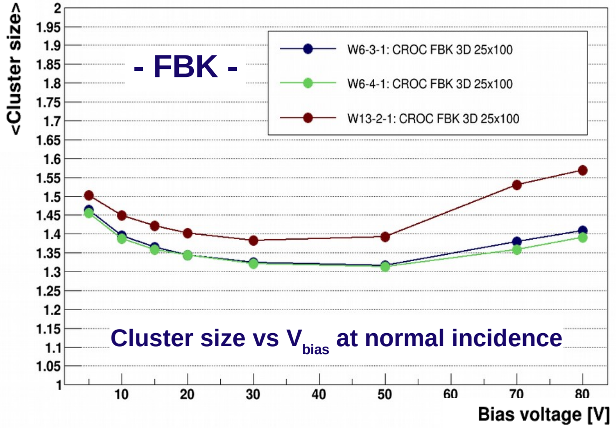




Efficiency map in the pixel cell

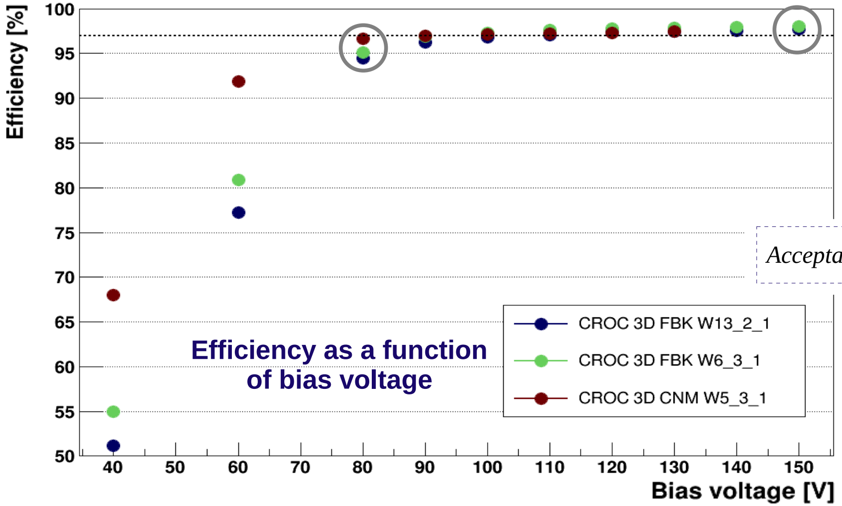






Results (I): CROC 3D modules irradiated at $1x10^{16} n_{eq}/cm^2$

- **Efficiency as a function of bias voltage at normal incidence**: **higher than 97% for all the modules after full depletion**.
  - The modules were tuned to average thresholds of 1000e- at T≃-30º
  - The **efficiency plateau starts at around 90V** → operation range: around 40V for CNM modules and 50V for FBK modules.
  - The acceptance can be introduced to consider the effect of the masked pixels on the hit detection efficiency:

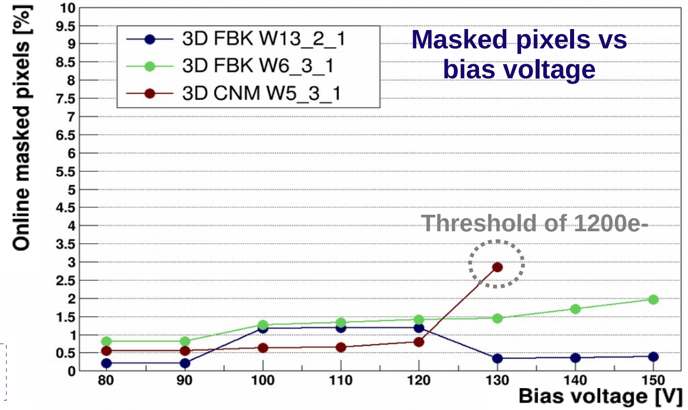


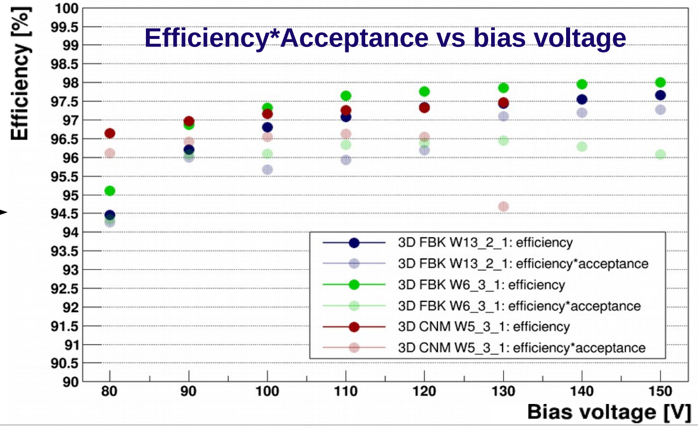
$$Acceptance = 1 - \frac{Number\ of\ masked\ pixels}{Number\ of\ pixels}$$

- **Noisy and stuck pixels masked during tuning**
- FBK modules show stable noise up to 150V
- CNM module shows a steep increase at 130V

Thr=1000e- → 9% masked pixels
Thr=1200e- → 3% masked pixels

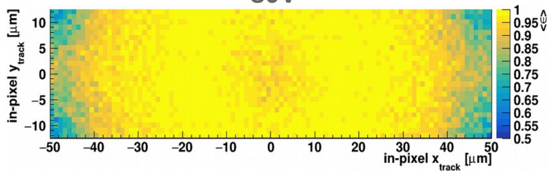
noisy = occupancy higher than $2x10^{-5}$



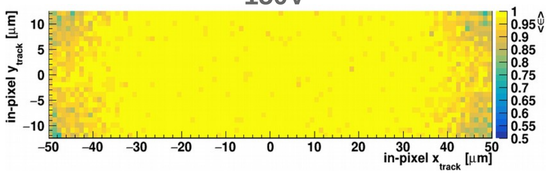


Efficiency map in the pixel cell

80V



150V



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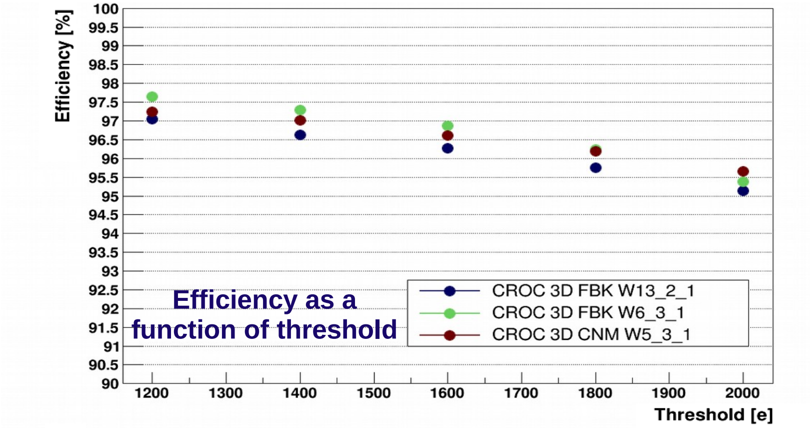
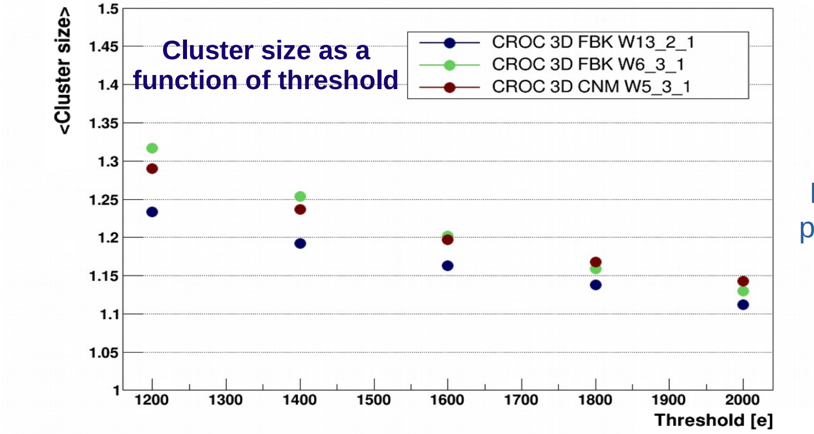
Results (II): CROC 3D modules irradiated at $1x10^{16} n_{eq}/cm^2$

- **Efficiency and cluster size as a function of threshold**
  - **Efficiency loss of around 2.5% when doubling the threshold**
  - Charge sharing is reduced as the threshold increases → impact on the spatial resolution



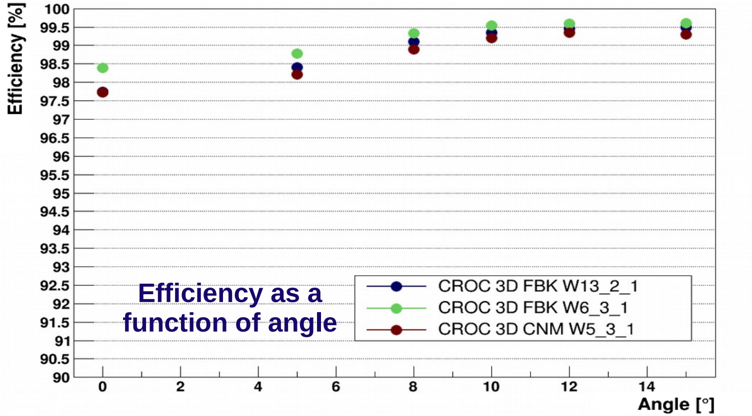


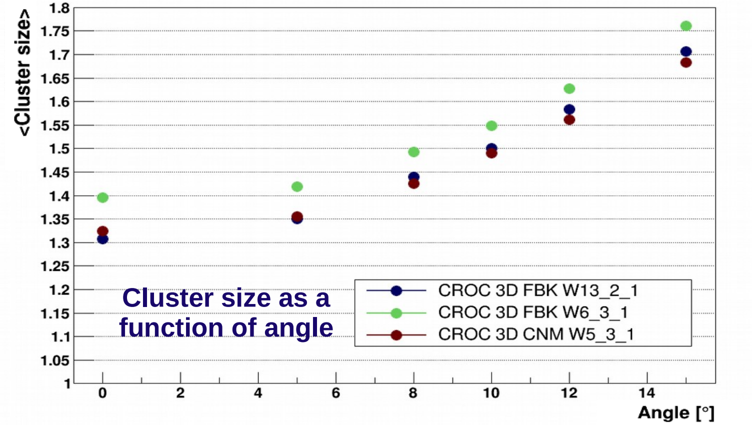
Both threshold and angular scan were performed without any noise mask at 120V

T ≃ -30º

Have a look at Martina Manoni's presentation for resolution studies!

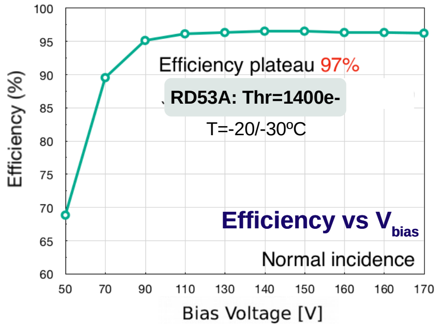
- **Efficiency and cluster size as a function of angle**
  - Rotation around the short pixel pitch: 25μm
  - FBK modules tuned to 1000e- and CNM module to 1200e-
  - **Efficiency higher than 99% at angles larger than 8º**

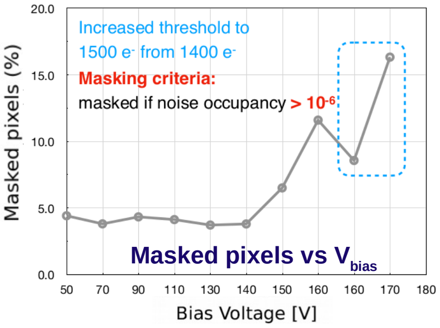


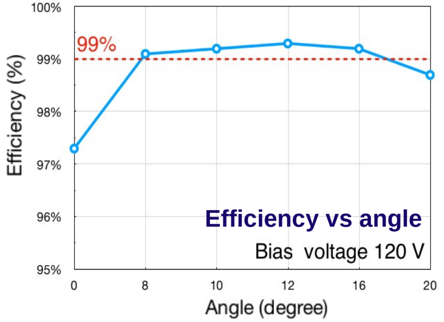


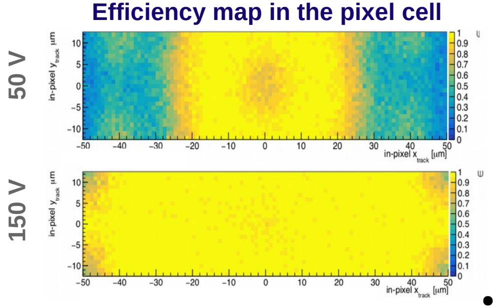
Results: RD53A 3D modules irradiated at 1.5-1.8x$10^{16}$$n_{eq}$/cm^2

Φ = 1.5x$10^{16}$$n_{eq}$/cm^2

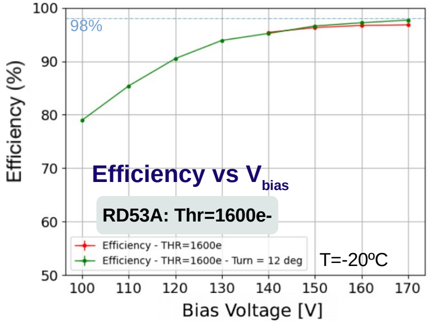


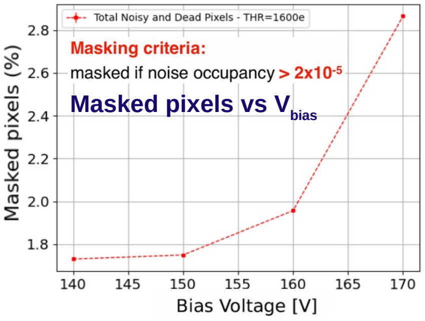


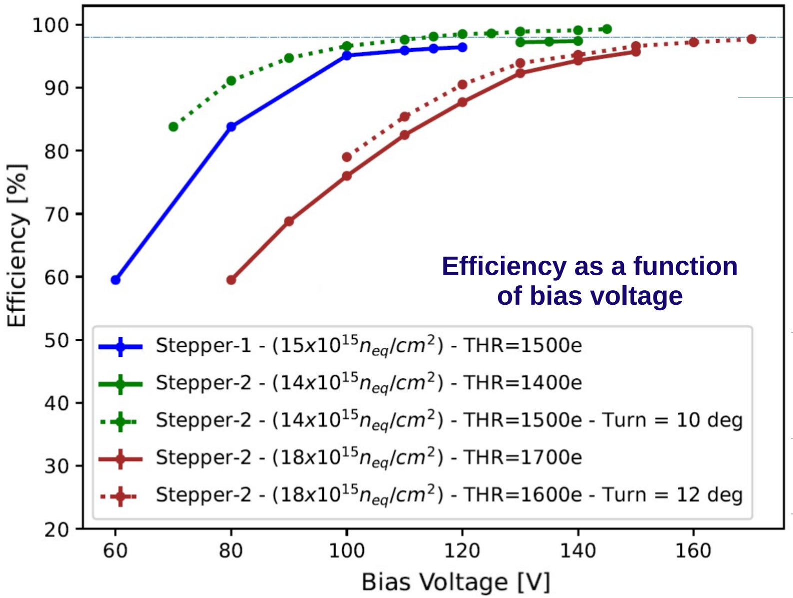




Φ = 1.8x$10^{16}$$n_{eq}$/cm^2







Test beam performed at DESY

Irradiation at KIT

TID ≃ 2GRad

TID ≃ 3GRad

- **Hit detection efficiency as a function of bias voltage and angle**
  - Only FBK modules
    - Thr=1400-1500e- at a fluence of 1.5x$10^{16}$$n_{eq}$/cm^2
    - Thr=1600-1700e- at a fluence of 1.8x$10^{16}$$n_{eq}$/cm^2
  - Normal incidence: **97% hit efficiency** reached at both fluences.
  - Tilted module
    - **99% hit efficiency** reached at **Φ≃1.5x$10^{16}$$n_{eq}$/cm^2** and **$V_{bias}$≃130V**
    - **98% hit efficiency** reached at **Φ≃1.8x$10^{16}$$n_{eq}$/cm^2** and **$V_{bias}$≃170V**
  - **Sudden increase in the number of noisy pixels** before (or near) reaching the depletion voltage → 130-170V depending on the module

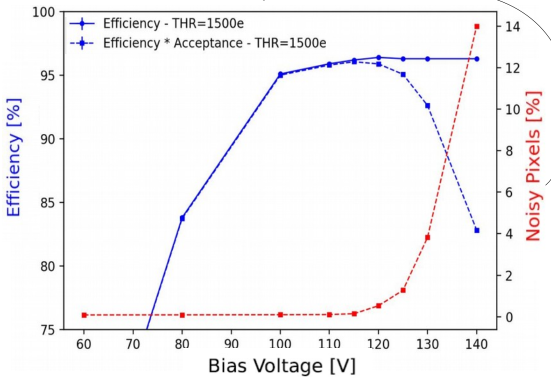
Noisy behaviour in RD53A 3D modules irradiated at $\Phi > 1x10^{16} n_{eq}/cm^2$

Efficiency and masked pixels as a function of bias voltage

Noisy pixels defined with a cut at $2x10^{-5}$ occupancy (1% of the L1 occupancy)

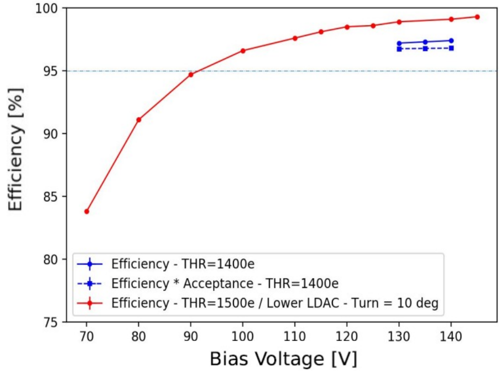
- RD53A FBK Stepper-1 irradiated at $1.5x10^{16} n_{eq}/cm^2$ -

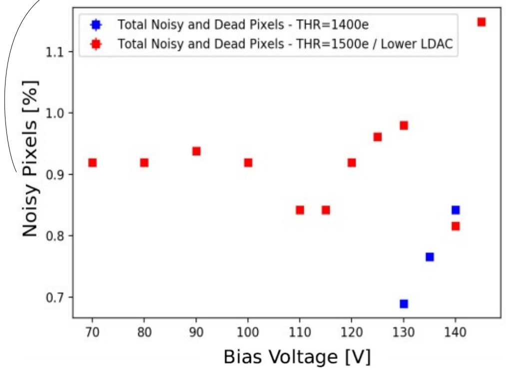
~20 dead pixels not included



- RD53A FBK Stepper-2 irradiated at $1.4x10^{16} n_{eq}/cm^2$ -

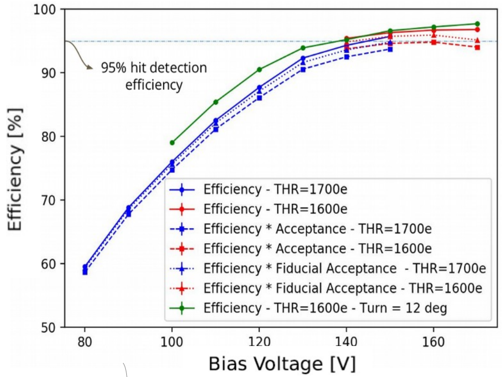
~60 dead pixels included

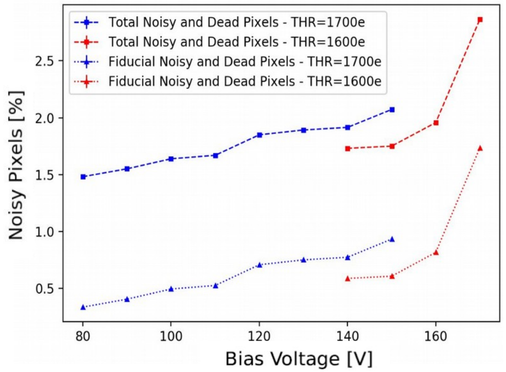




- **The increase in the number of noisy channels correlates with fluence and bias voltage**
- **More noise observed in Stepper-1 (130µm n^+ column) than in Stepper-2 (115µm n^+ column)**
  - Stepper-1 irradiated at $1.5x10^{16} n_{eq}/cm^2$: ~14% at V_{bias} = 140V
  - Stepper-2 irradiated at $1.4x10^{16} n_{eq}/cm^2$: ~1% at V_{bias} = 140V
  - Stepper-2 irradiated at $1.8x10^{16} n_{eq}/cm^2$: below 1% up to V_{bias} = 160V
- The CROC CNM (130µm n^+ column) irradiated at $1x10^{16} n_{eq}/cm^2$ seems to behave similar to Stepper-1
- The cause is still under investigation:
  - 3D geometry producing electric field peaks that generate avalanche? Relation to the n^+ column length?

- RD53A FBK Stepper-2 irradiated at $1.8x10^{16} n_{eq}/cm^2$ -





Fiducial acceptance: excluding the noisy pixels corresponding to a damaged region where the pixels were already noisy at very low bias voltages

Conclusions

- 3D pixel sensors have been chosen by CMS as the baseline technology for the innermost layer of the TBPX.
- CROC 3D modules have been irradiated to $1x10^{16} n_{eq}/cm^2$ for the first time and show excellent performance.
- RD53A 3D modules iradiated to $1.5x10^{16} n_{eq}/cm^2$ and $1.8x10^{16} n_{eq}/cm^2$ fullfil the CMS requirements.
    - 97% efficiency at normal incidence and 99% when the modules are tilted
    - Comfortable margin of operation without the risk of thermal runaway
    - Noisy channels below 2%
- The noisy behaviour present at high bias voltages and high fluences is still under investigation.
- Irradiation of CROC 3D modules to higher fluences is foreseen for 2023.

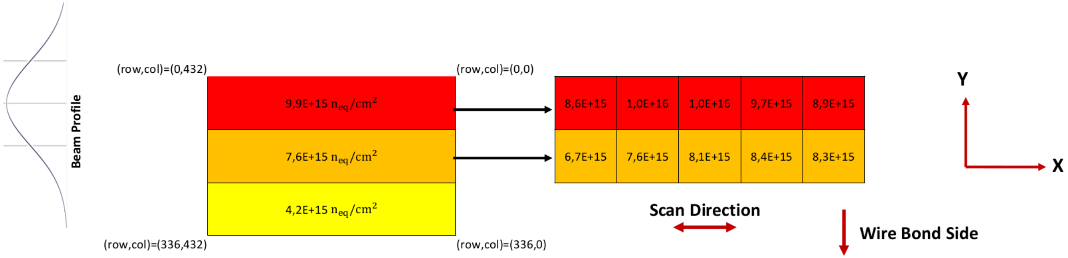
BACKUP

Irradiation and test beam (II)

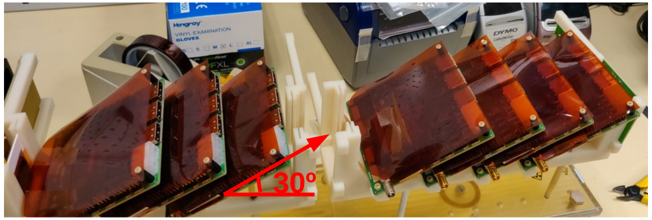
- **First CROC modules have been irradiated at the CERN IRRAD facility**
  - Tilted by 30º to achieve a uniform irradiation along columns
  - Horizontal scan to achieve a uniform irradiation along rows
  - In the backside of some modules there was an **Al-foil** that is used **to estimate the fluence from spectroscopy**:
    - Cut into small pieces
    - Measure activity of each small piece

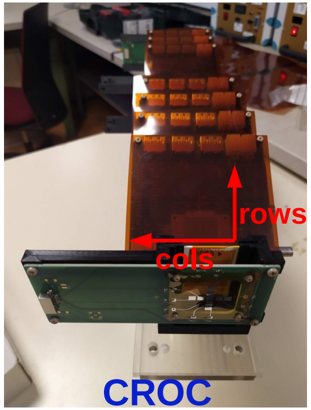
    } Fluence estimation in different regions (rows and columns)

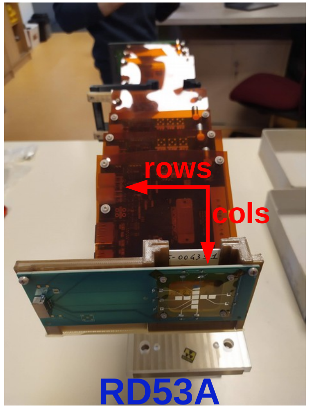
- The spectroscopy results are consistent among the Al-foils of different modules with a 7% error on fluence.
  - Not perfectly centered along Y (vertical direction)
  - Uniform irradiation along X (scanning direction)
  - Focus on the **region of interest**: **~1x10^{16}n$_{eq}$/cm^2** ⟶ **TID ≃ 0.5GRad**

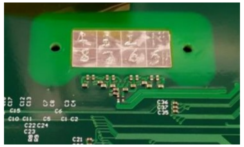


Last irradiation campaigns of RD53A and CROC at IRRAD (CERN)



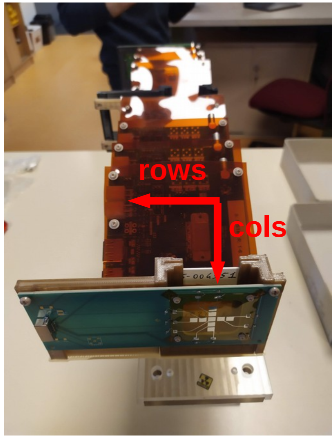


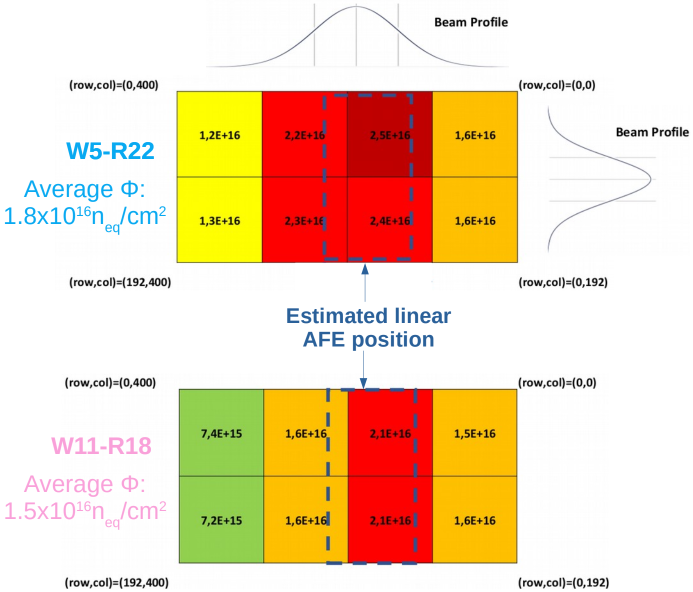




RD53A FBK 3D modules irradiated at 2.0-2.5x$10^{16}n_{eq}/cm^2$ (I)

- The irradiation campaign that was carried out in May/June at CERN-PS with a 24GeV proton beam gave rise to **modules non-uniformly irradiated**.
- The aluminium foils placed behind the modules were used to estimate the fluence in different regions.





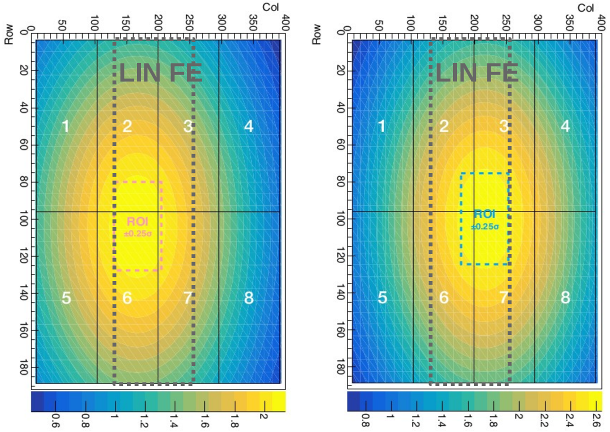
Need of analyzing the data per regions of fluence !!

Dosimetry evaluation

- Cut the Al-foil placed on the sensor surface during the irradiation in 8 small pieces.
- Measure activity of each small piece.
- Fit with bivariate Normal distribution to get an approximate irradiation profile.
- Define a **region of interest (ROI)** irradiated as uniform as possible:

W5-R22: **(2.6±0.09)x$10^{16}n_{eq}/cm^2$**

W11-R18: **(2.1±0.08)x$10^{16}n_{eq}/cm^2$**



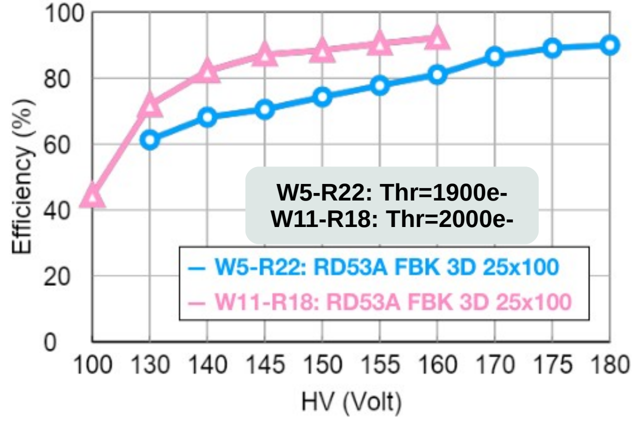
Irradiation profiles on sensor surface

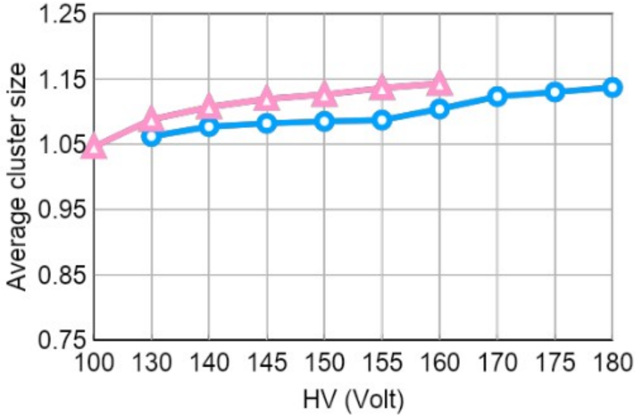
RD53A FBK 3D modules irradiated at 2.0-2.5x10^{16}n$_{eq}$/cm^{2} (II)

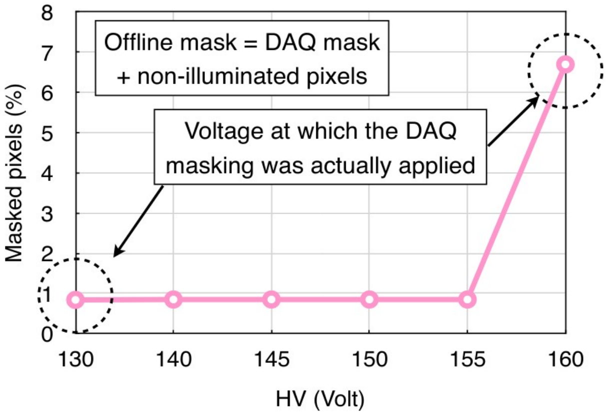
- The **ROI irradiated at ~2.1x10^{16}n$_{eq}$/cm^{2}** reaches **~92% efficiency at 160V with ~7% of masked pixels**.
- The **ROI irradiated at ~2.6x10^{16}n$_{eq}$/cm^{2}** reaches **~90% efficiency at 180V with ~1% of masked pixels**.

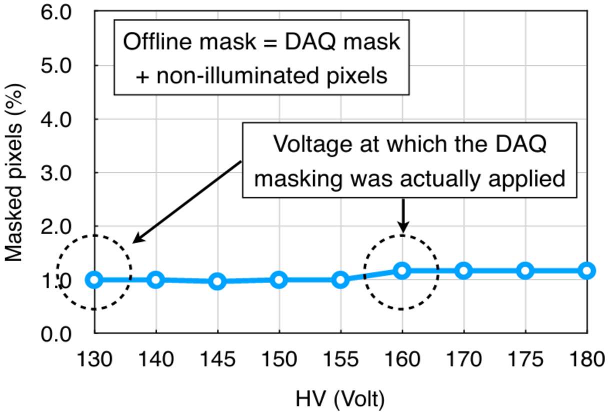
Preliminary results!

Fluences in chosen ROI
- **W5-R22**: **(2.6±0.09)x10^{16}n$_{eq}$/cm^{2}**
- **W11-R18**: **(2.1±0.08)x10^{16}n$_{eq}$/cm^{2}**









- **Online masked pixels**: noisy and stuck pixels masked before the data taking
  - Noisy pixel: occupancy higher than 2x10^{-5}
  - Masking applied only at 130V and 160V
- **Offline masked pixels:** non-illuminated pixels during the data taking