BTTB 2023 – Edinburgh

Test Beam Results on 3D Pixel Sensors for the CMS Tracker Upgrade at the High-Luminosity LHC

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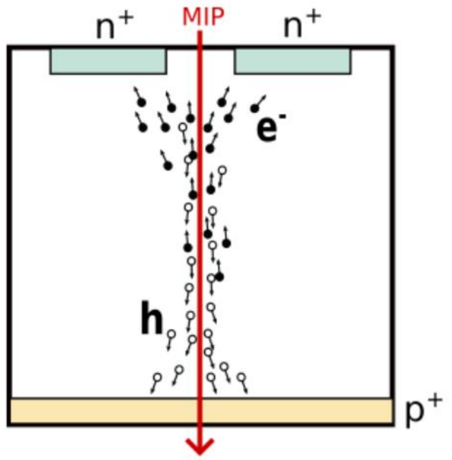
High Luminosity LHC and the CMS Pixel Upgrade

- In the High-Luminosity LHC (HL-LHC), the luminosity will reach $7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ → 200 collisions per bunch-crossing
- The CMS experiment needs to be upgraded significantly for HL-LHC
- The silicon tracker of the CMS experiment will be completely replaced
  - Outer Tracker (OT) → Strip Detectors
  - **Inner Tracker (IT)** → Pixel detectors (this Talk)
    - $4.9\ \mathrm{m}^2$ of pixel surface and 2×10^9 channels
    - Tracking coverage up to $|\eta| = 4$

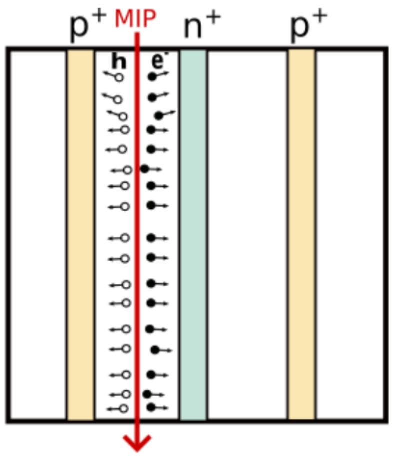
- Two types of sensors will be used in the Inner Tracker:
  - Standard "planar" pixel sensors and **3D** pixel sensors → Higher **radiation resistance** (this Talk)
  - In 3D sensors the drift path is perpendicular to the active thickness and 1/3 shorter
  - 3D sensors will be installed only in the innermost layer (only 30 mm from the beam line!)

- **Active thickness** (for both 3D and planar pixel sensors): $150\ \mu\mathrm{m}$
- **Pixel size** (pitch): $25 \times 100\ \mu\mathrm{m}^2$ (6x smaller w.r.t. the present CMS tracker)

Planar Pixel Sensor

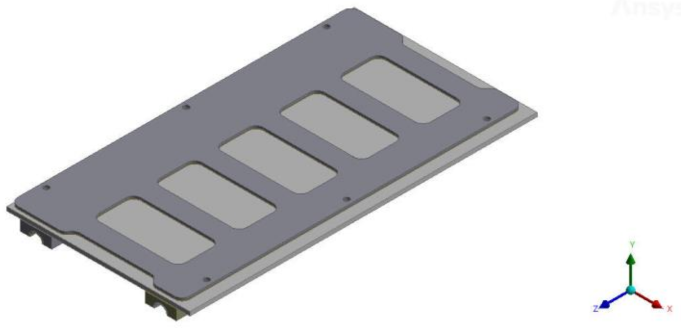


3D Pixel Sensor

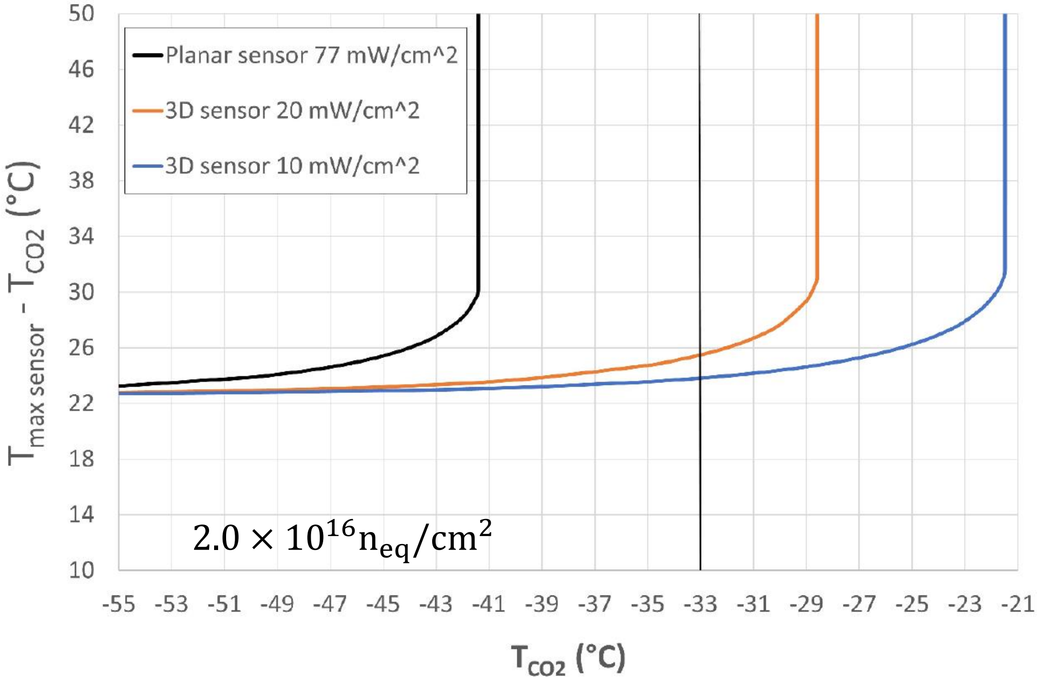


Thermal Simulations

- Thermal properties of the innermost tracker layer were simulated for planar and 3D sensors
- The tracker will have a CO_2 cooling set at -33 °C
- In the innermost tracker layer, planar sensors would go in thermal runaway after large fluences
  - After $2.0 \times 10^{16} n_{eq}/cm^2$, CO_2 should reach at -45 °C to prevent it!
  - With 3D sensors, there is a margin of about of about 10 °C
  - In the second tracker layer planar sensors are a safe choice due to the lower fluences
- Thermal performance of 3D sensors good enough to select lighter design for cooling plate and mechanics (orange curve)

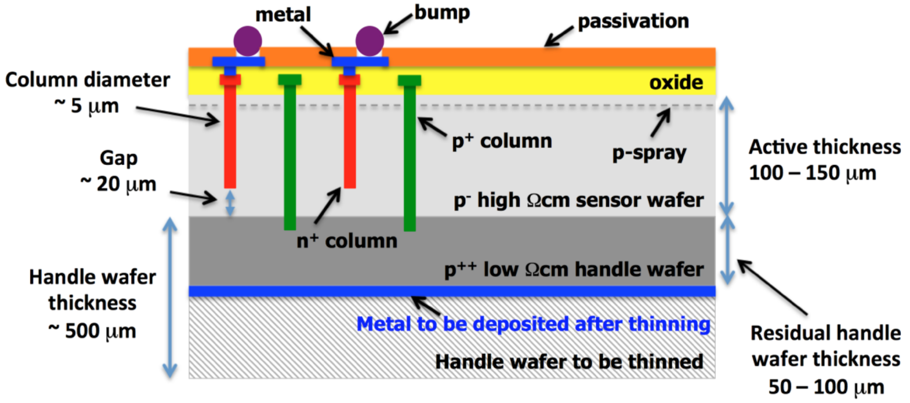


Baseline "5 windows" cooling plate

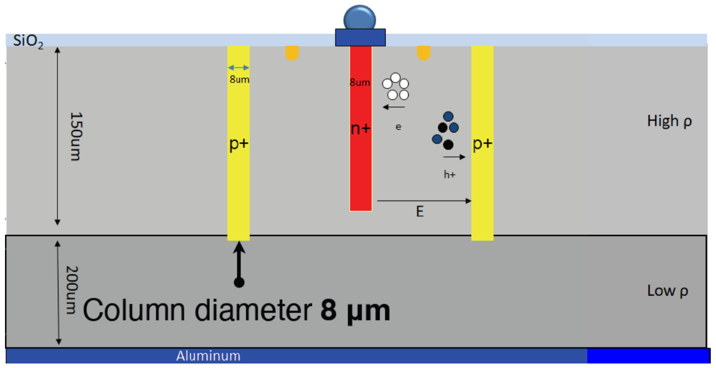


CMS 3D Sensors

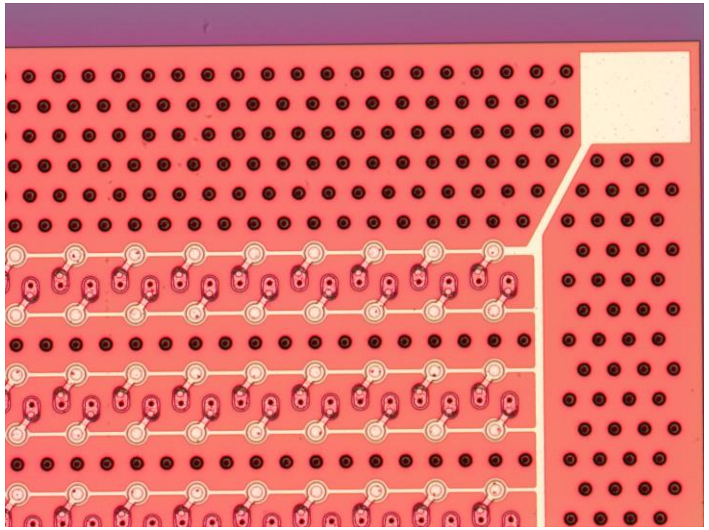
- **FBK** (Trento, Italy), in collaboration with **INFN**, and **CNM** (Barcelona, Spain) were involved in the R&D of 3D sensors
- A low resistivity CZ silicon layer is bonded to a high resistivity FZ substrate (**D**irect **W**afer **B**ond, **Si**licon-**Si**licon)
  - Total sensor thickness around $250\ \mu m$ (with $150\ \mu m$ active thickness)
  - The bias voltage is applied to the ohmic contact, on the backside of the sensor
- Columnar implants penetrate deep into the substrate from the same silicon face (**D**eep **R**eactive **I**on **E**tching)
  - p^+ columns reach the backside of the sensor, hence the bias voltage
  - n^+ columns are connected to the readout chip (and they are 115 μm long for FBK and 130 μm for CNM)
  - The columns are filled with polysilicon; the column diameter is 5 μm in FBK and 8 μm in CNM



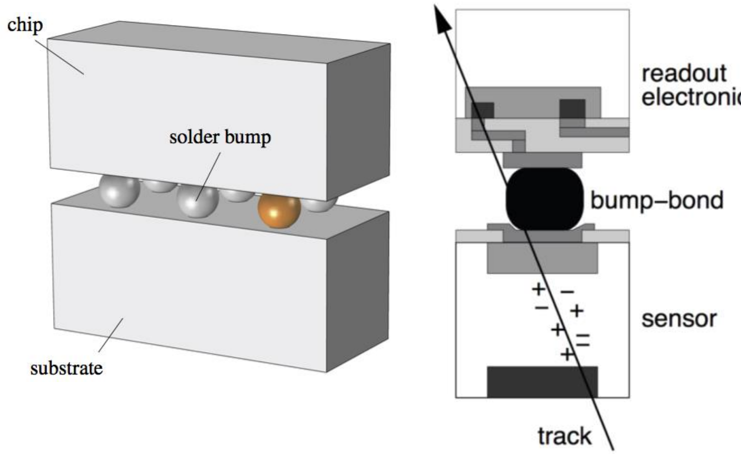
Side view of an FBK 3D sensor



Side view of a CNM 3D sensor
(before thinning the support wafer)



The CMS Read-Out Chip: CROC



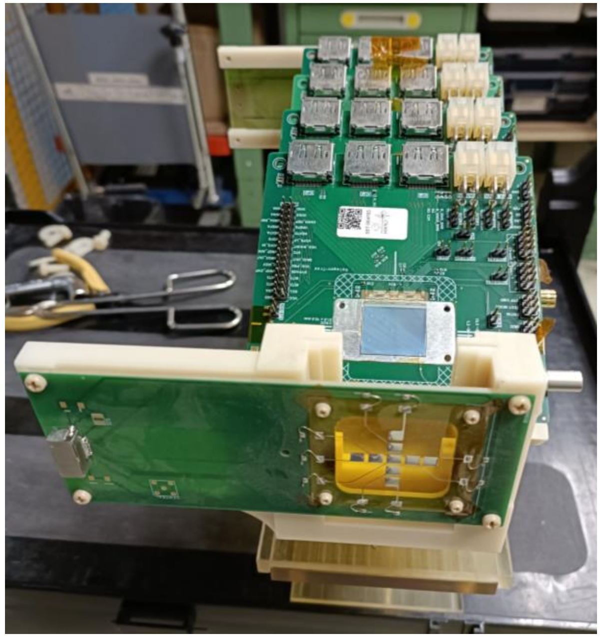
Bump Bonding

- The ReadOut Chip (ROC) is coupled to the sensor (bump-bonding)
  - Sensor + ROC → Pixel module
- The CMS ROC (**CROC**) was designed by the RD53 Collaboration
  - Joint ATLAS-CMS effort established in 2013 to develop readout chips for the HL-LHC pixel detectors
  - **RD53A** was the first prototype, used for sensor R&D until the beginning of 2022
    - $76800\ (50 \times 50\ \mu\mathrm{m}^2)$ pixel channels
- The CROC was available for testing late 2021
  - Extensively used for sensor R&D: first test beams with CROC modules in 2022
  - Final version submitted in October 2023 (CROCv2)
  - $145152\ (50 \times 50\ \mu\mathrm{m}^2)$ pixel channels
- Various calibrations are needed to operate the pixel modules
  - The pixels channels can be tuned to average thresholds around $1000\ \mathrm{e}^-$ before irradiation
  - After irradiation, we aim to similar values (although with a higher noise)

CROC module mounted into a single chip card

CROC Module Irradiation Campaigns

Irradiation support with four CROC modules installed

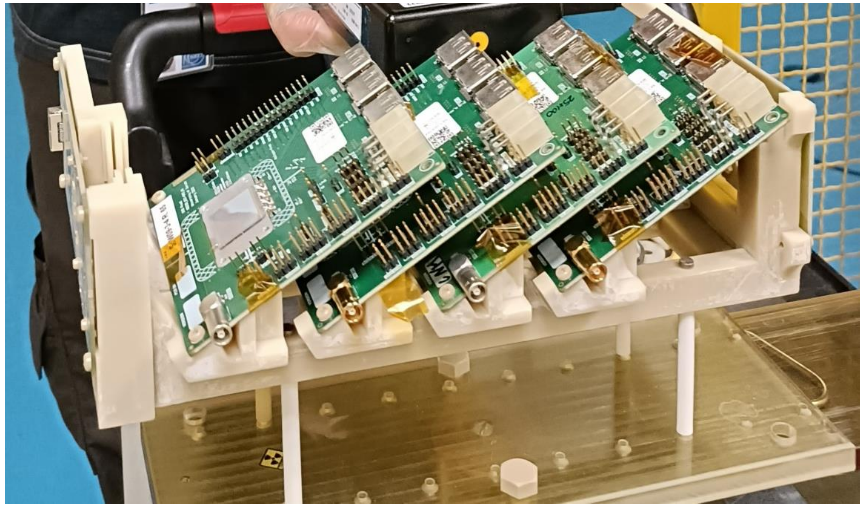


- Four irradiation campaigns were performed at the **IRRAD** facility at CERN
  - **24 GeV** protons → Total Ionizing Dose $\mathrm{TID} = 0.5\ \mathrm{GRad\ per}\ 10^{16}\mathrm{n_{eq}/cm^2}$
- Seven CROC modules can be irradiated at the same time
  - Tilted by $30°$ to achieve a uniform vertical irradiation
  - Horizontal scanning (scan span: $26\ \mathrm{mm}$) to achieve a uniform horizonal irradiation
- Aluminum foils were used to estimate the received fluence with spectroscopy
  - The foils are divided into 20 smaller pieces (about $5 \times 5\ \mathrm{mm}^2$)
  - Can be used to estimate the fluence in different (row and column) regions of the modules
- Irradiations were performed also at KIT, with **23 MeV** protons → $\mathrm{TID} = 1.5\ \mathrm{GRad\ per}\ 10^{16}\mathrm{n_{eq}/cm^2}$

Aluminum foil placed in the backside of the module, divided into 20 smaller pieces

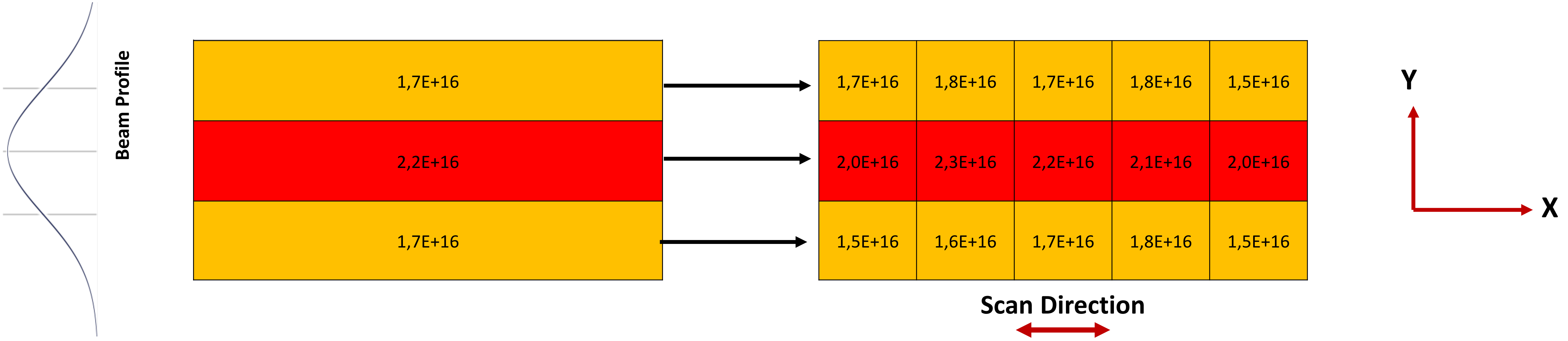
More uniform irradiations but larger TID

30°



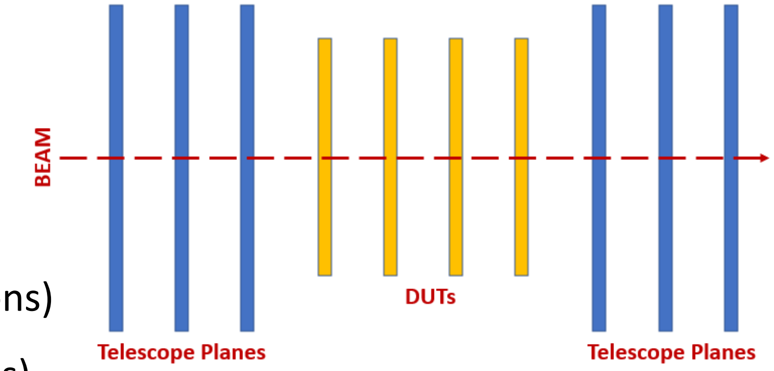
SPS Irradiation Measurements

The measured fluences (n_{eq}/cm^2) are reported in each rectangle for the corresponding sample



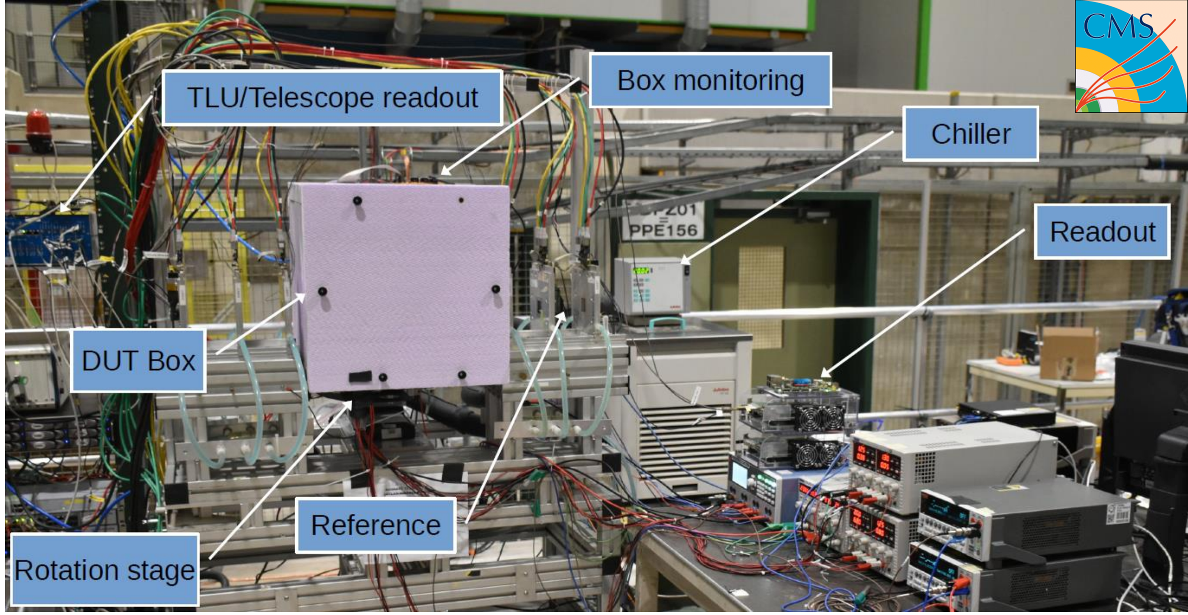
- Example of the spectroscopy of one aluminum foil (2023 campaign)
  - Three strips subsequently cut into smaller squares
  - Irradiation **centered** along **Y** and **uniform** along **X** (the direction of the scanning)
  - Region of Interest (**ROI**) can be defined for data analysis
- The spectroscopy results are **consistent** between the aluminum foils of different modules
  - 7% error on fluence, as estimated by IRRAD
- The innermost tracker layer should be replaced after an expected fluence $> \mathbf{1.5 \times 10^{16}\ n_{eq}/cm^2}$

Test Beams



- Test Beam Facilities:
  - CERN **SPS** (120 GeV pions)
  - **DESY** (5.2 GeV electrons)
- EUDET telescope
  - Six pixel planes equipped with MIMOSA26 sensors ($18\ \mu m$ pitch)
  - Two arms: upstream and downstream triplets
  - $2\ \mu m$ resolution in each coordinate
- The Device Under Tests (**DUTs**) are kept inside a cooling box between the arms
  - Heat exchangers close do the DUTs
  - Stable air temperature around $-30\ ^{\circ}C$
- A rotation and translation stage allows to set the DUTs at different positions/angles
- In DESY we only used the upstream arm with irradiated modules
  - Beam degradation due to the cooling box
- "Corryvreckan" software was used for data analysis:

  https://project-corryvreckan.web.cern.ch/project-corryvreckan/

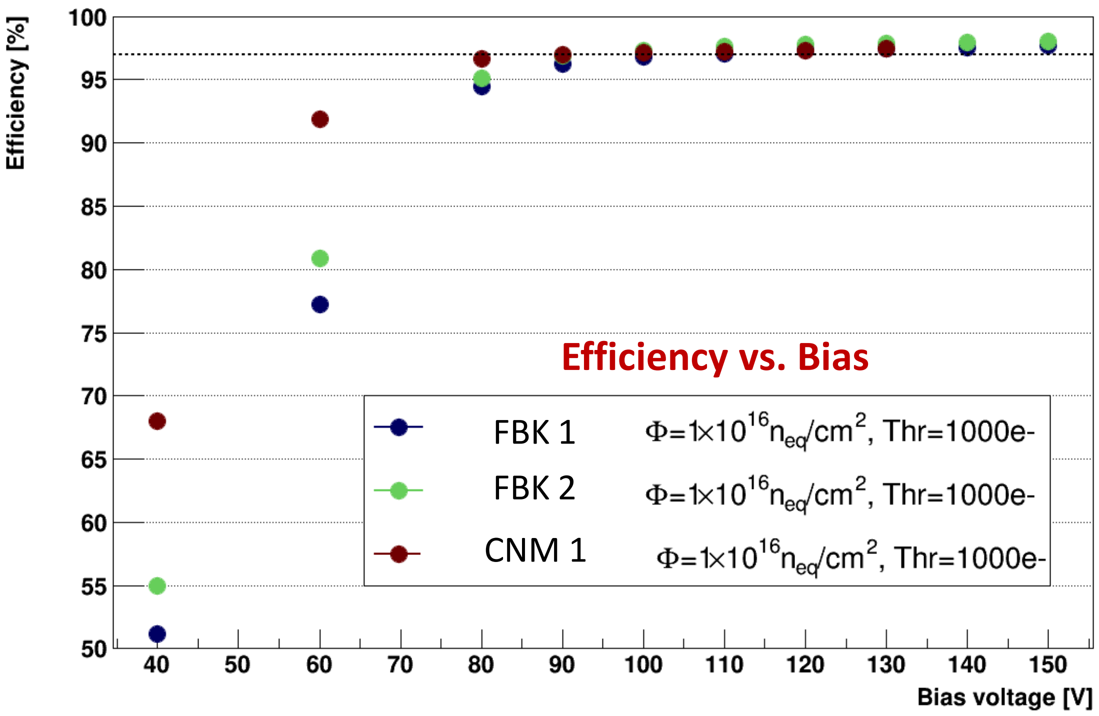


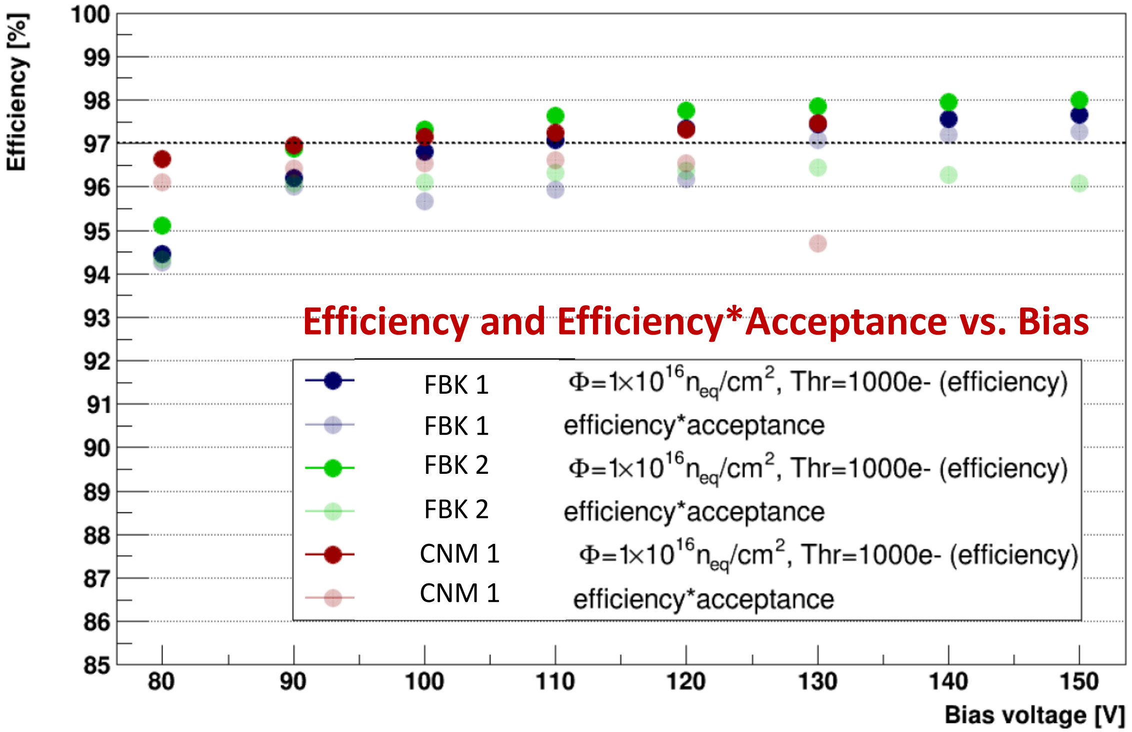
SPS Test Beam

DESY Test Beam

Irradiated 3D Modules $(1.0 \times 10^{16} n_{eq}/cm^2)$

Irradiated at IRRAD
Tested at SPS



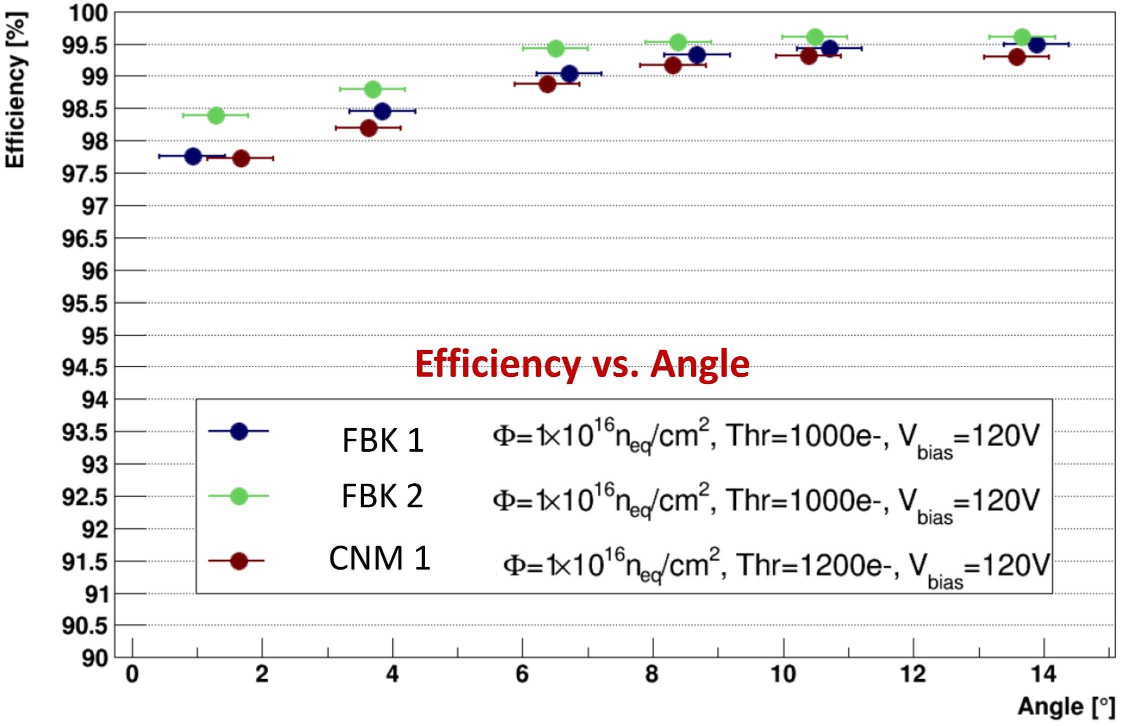


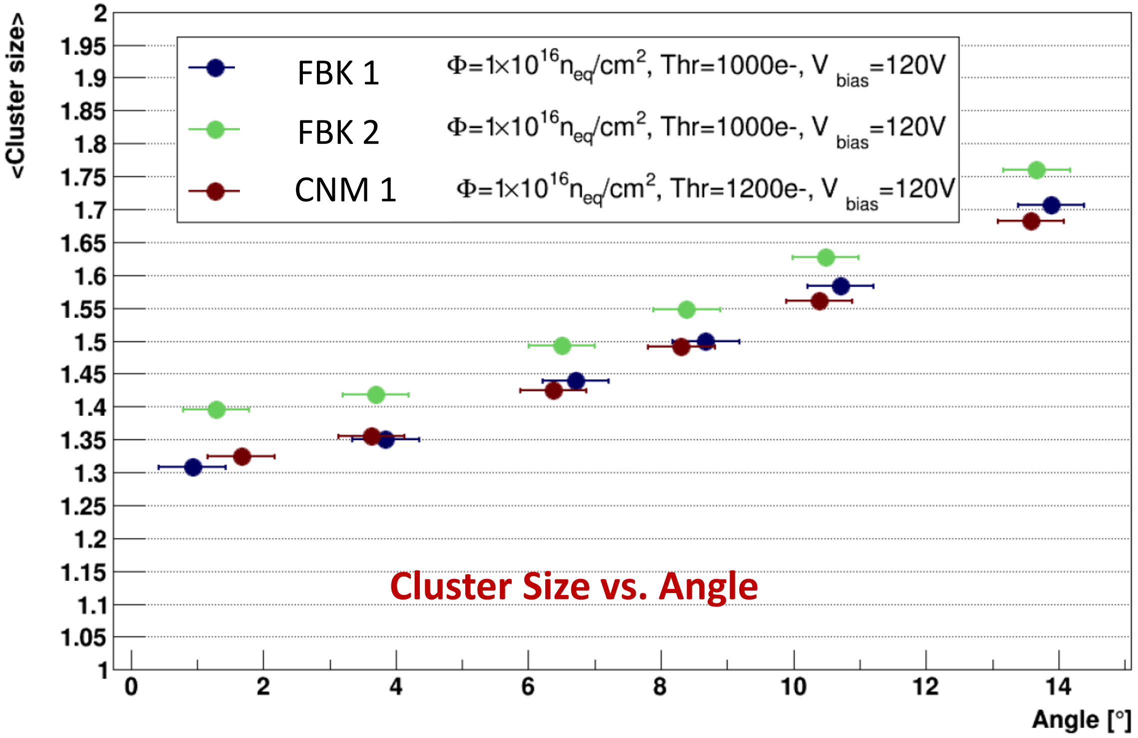
- Hit Efficiency vs. Bias Voltage for the irradiated 3D modules (two FBK, one CNM)
  - The efficiency is calculated inside a **ROI** of uniform Fluence $(\mathbf{1.0 \times 10^{16}\ n_{eq}/cm^2})$
  - The modules were tuned to an average threshold of $\mathbf{1000\ e^-}$
- FBK (CNM) sensors show stable noise behaviour up to $150\ \mathrm{V}$ $(130\ \mathrm{V})$: above that, the noise steeply increases
  - The acceptance is introduced to present a more coherent hit detection efficiency considering the effect of masked pixels
- Hit Efficiency plateau is $\sim \mathbf{50\ V}$ wide and starts around $\mathbf{90\ V}$ $\rightarrow$ Maximum value of $\sim \mathbf{98\%}$ at $\mathbf{130\ V}$

$$\text{Acceptance} = 1 - \frac{\text{Number of Masked Channels}}{\text{Number of Channels}}$$

Irradiated 3D Modules $(1.0 \times 10^{16} n_{eq}/cm^2)$

Irradiated at IRRAD
Tested at SPS

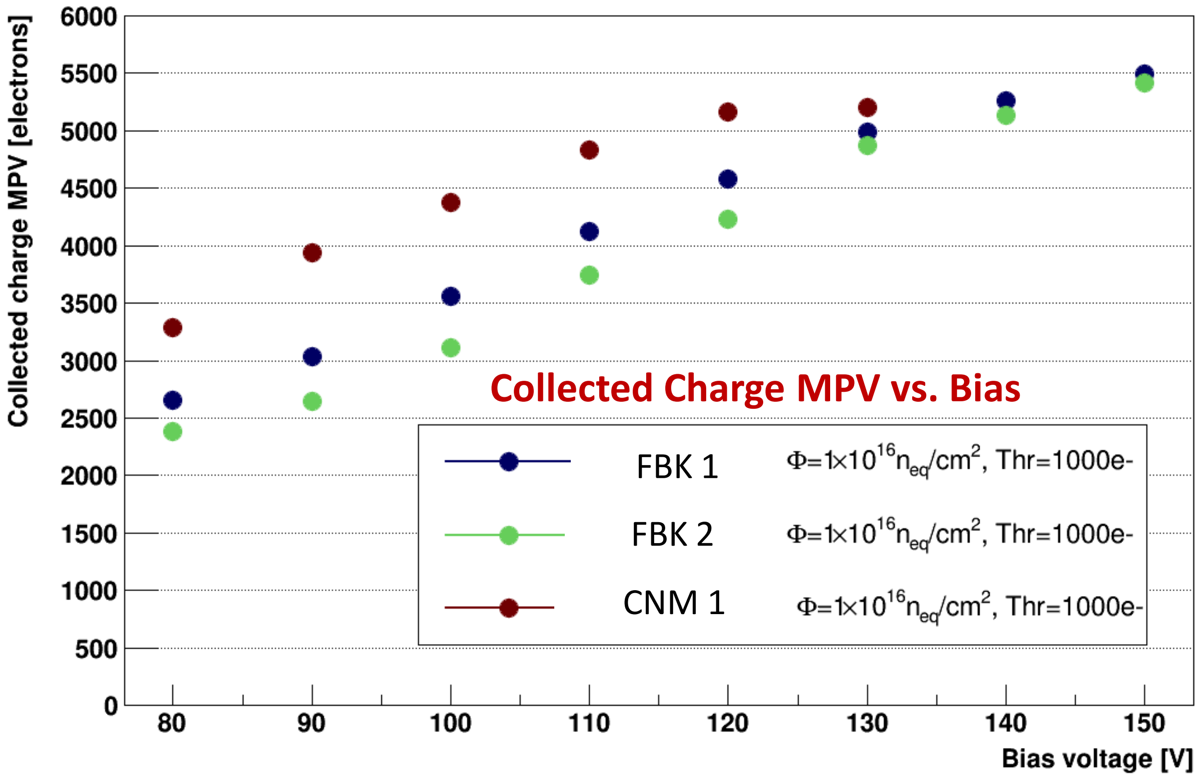


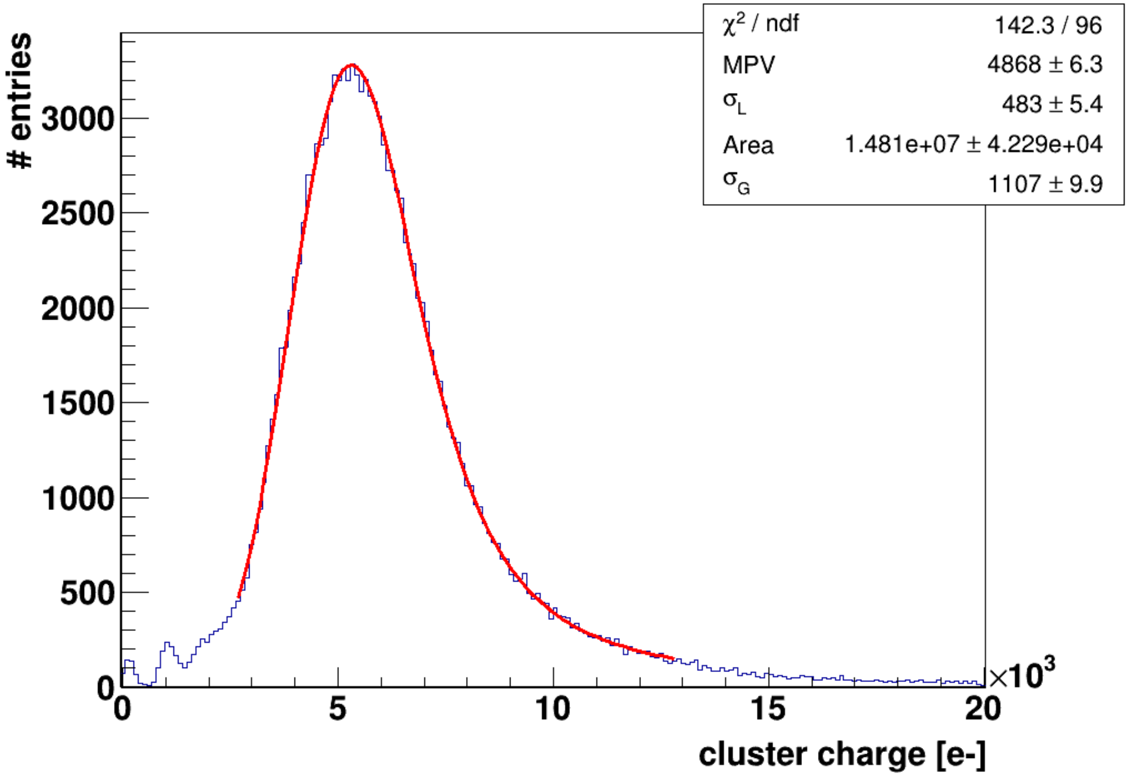


- Since the columns are made by passive material, 3D sensors have intrinsic inefficiencies with orthogonal beam incidence
  - By rotating the DUTs the inefficiencies are recovered since incident particles always escape the passive material
- With a rotation angle as small as $8°$, a hit-detection efficiency of $\mathbf{99\%}$ is reached at $\mathbf{120\ V}$
- The average cluster size increases with the rotation angle (as expected) improving the resolution

Irradiated 3D Modules $(1.0 \times 10^{16} n_{eq}/cm^2)$

Irradiated at IRRAD
Tested at SPS

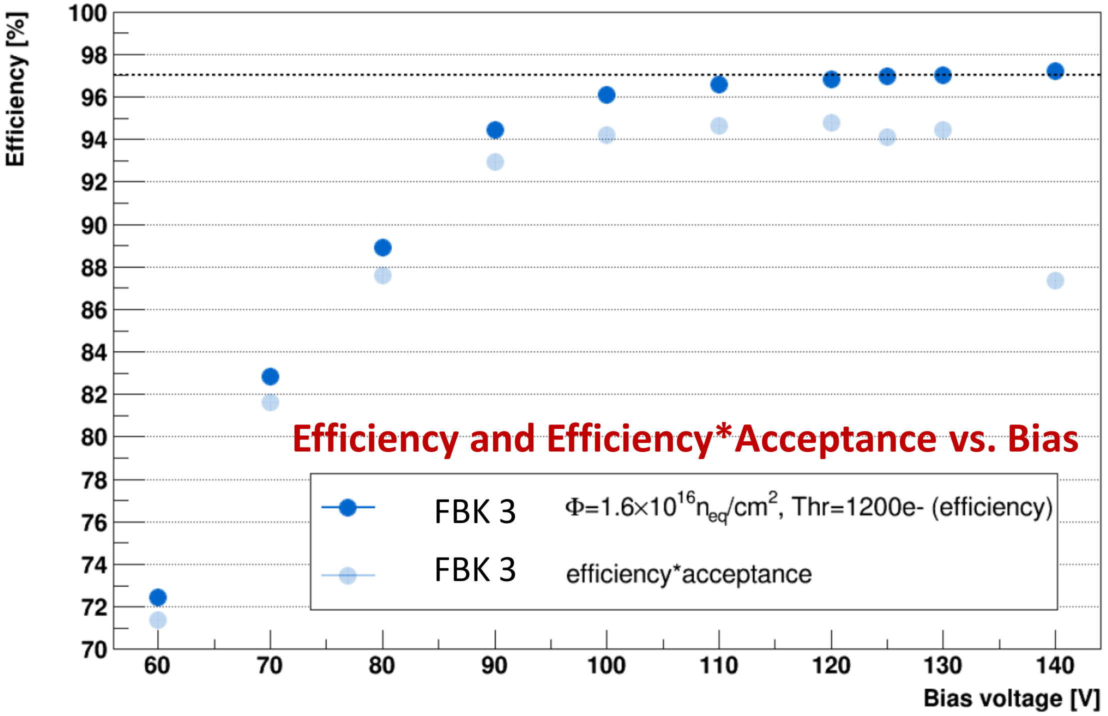


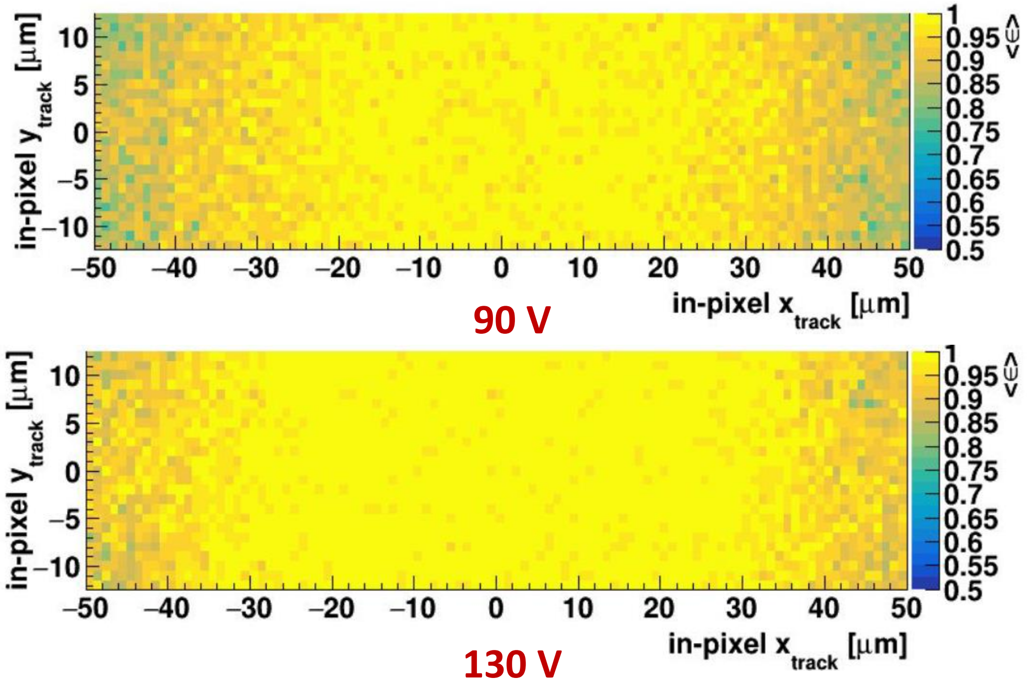


- The collected (cluster) charge distribution is fitted with a Landau distribution convoluted with a Gaussian distribution
- The MPV increases with the bias voltage (as the sensor depletes more)
- The maximum MPV is around 5500 electrons, about 50% less with respect to non-irradiated DUTs

Irradiated 3D Modules $(1.6 \times 10^{16} \mathrm{n_{eq}/cm^2})$

Irradiated at KIT
Tested at DESY



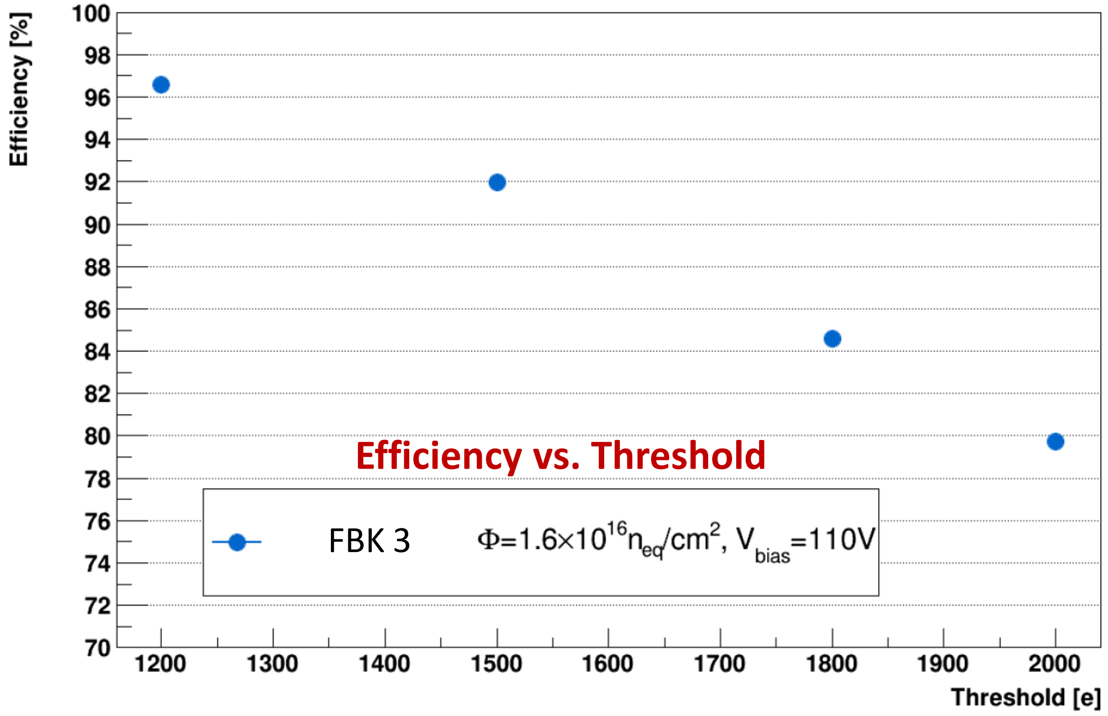


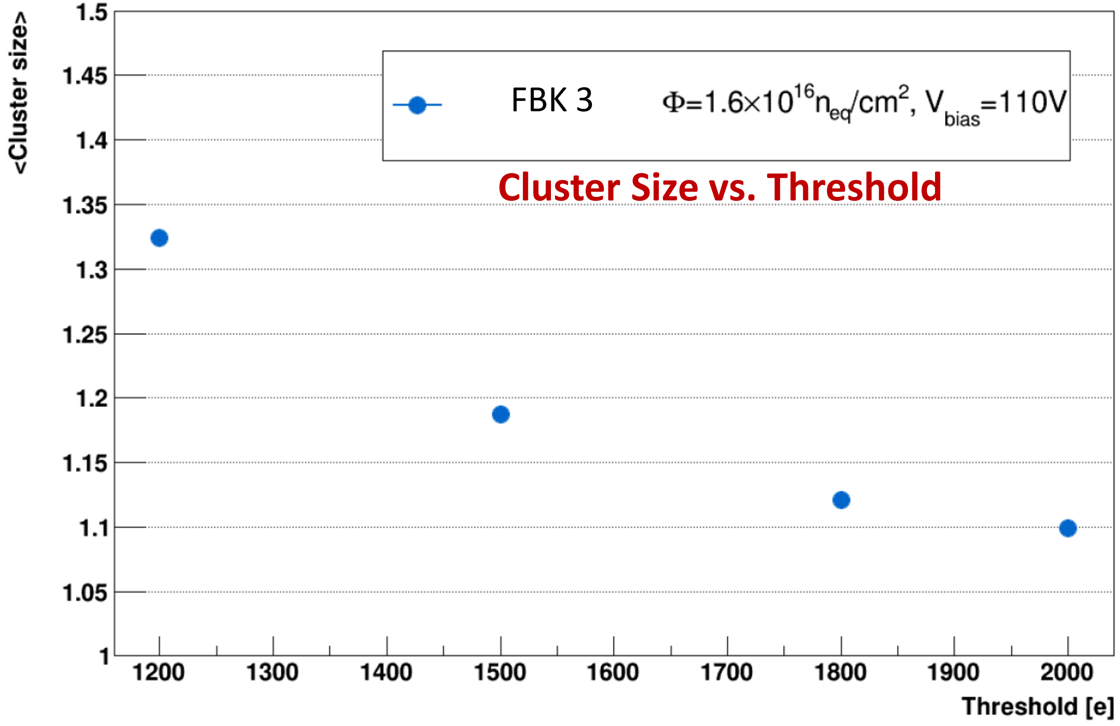
In-Pixel Efficiency

- Hit Efficiency vs. Bias Voltage for an irradiated 3D FBK module, with orthogonal beam incidence
  - The Fluence is **uniform** in this case ($\mathbf{1.6 \times 10^{16}\ n_{eq}/cm^2}$) and the module was tuned to an average threshold of $\mathbf{1200\ e^-}$
- Hit Efficiency plateau is $\sim \mathbf{30\ V}$ wide and starts around $\mathbf{110\ V}$ $\rightarrow$ Maximum value of $\sim \mathbf{97\%}$ at $\mathbf{130\ V}$
- By looking inside a pixel cell, inefficiencies at the corners of the cell are recovered by increasing the bias voltage

Irradiated 3D Modules ($1.6 \times 10^{16} n_{eq}/cm^2$)

Irradiated at KIT
Tested at DESY

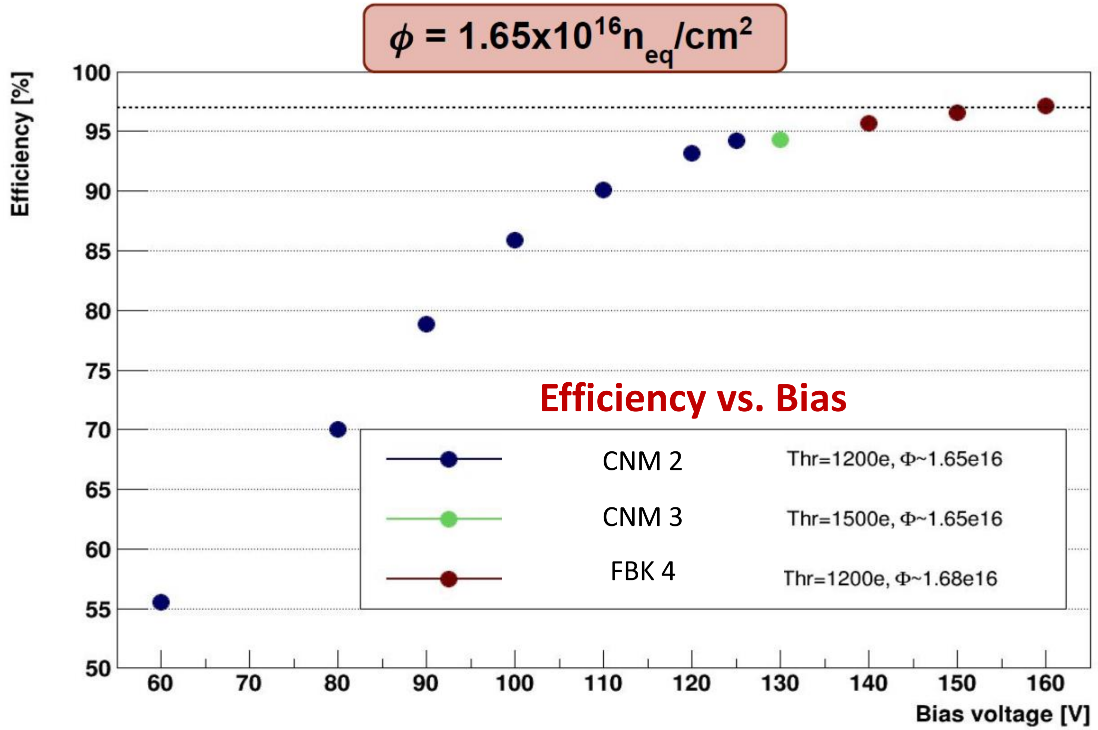


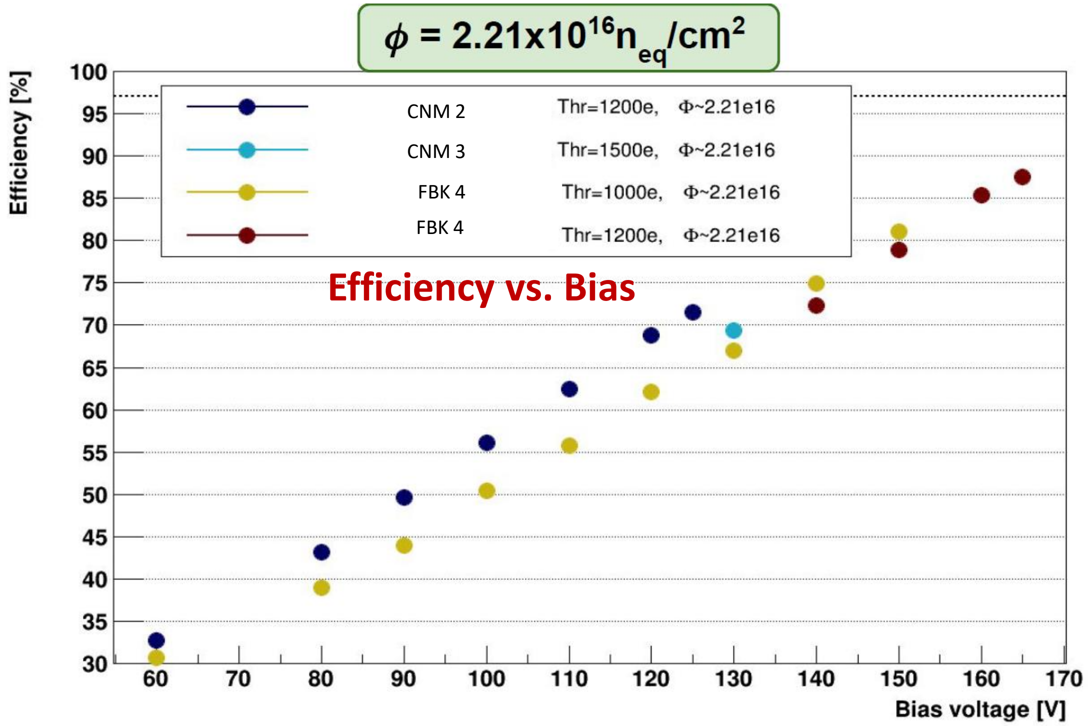


- Hit Efficiency vs. Average Pixel Threshold of the module → $\mathbf{16\%}$ efficiency drop when doubling the threshold
  - The higher the Fluence, the higher the effect (about $\mathbf{2\%}$ with $1.0 \times 10^{16}\ n_{eq}/cm^2$)
- The charge sharing (hence the cluster size) decreases as the threshold increases
  - The resolution is also affected

Irradiated 3D Modules $(> 1.7 \times 10^{16} n_{eq}/cm^2)$

Irradiated at IRRAD
Tested at SPS





- Hit Efficiency vs. Bias Voltage for three (heavily) irradiated modules (one FBK, two CNM), with orthogonal beam incidence
  - Given the (relatively high) Fluence gradient, two ROIs were selected: one at $\mathbf{1.7 \times 10^{16}\ n_{eq}/cm^2}$ and one $\mathbf{2.2 \times 10^{16}\ n_{eq}/cm^2}$
- Focusing on the ROI with the lower Fluence, for the FBK sensor the plateau starts around $\sim \mathbf{130\ V}$ and is $\sim \mathbf{30\ V}$ wide
  - After $\mathbf{160\ V}$ noise steeply increases
  - Maximum value of $\sim \mathbf{97\%}$ at $\mathbf{150\ V}$
- At $\mathbf{2.2 \times 10^{16}\ n_{eq}/cm^2}$ the efficiency is lower (but still $\sim \mathbf{90\%}$): sensors in the innermost layer will be replaced earlier

Conclusions

- CMS decided to install **3D sensors** in the innermost tracker layer
  - Higher radiation resistance and better thermal performance (planar sensors would go in thermal runaway)

- **3D CROC** modules irradiated up to $\mathbf{1.6 \times 10^{16}\ n_{eq}cm^{-2}}$ show excellent performances
  - Hit efficiency plateau is $\sim \mathbf{30\ V}$ wide (before noisy behaviour) and starts around $\mathbf{110\ V}$ after a Fluence of $\mathbf{1.6 \times 10^{16}\ n_{eq}cm^{-2}}$
  - Hit efficiency plateau is $\sim \mathbf{50\ V}$ wide (before noisy behaviour) and starts around $\mathbf{90\ V}$ after a Fluence of $\mathbf{1.0 \times 10^{16}\ n_{eq}cm^{-2}}$
  - After a Fluence of $\mathbf{2.2 \times 10^{16}\ n_{eq}cm^{-2}}$ the 3D modules are still working, albeit with a reduced performance
  - The innermost tracker layer should be replaced after an expected fluence of $> \mathbf{1.5 \times 10^{16}\ n_{eq}/cm^{2}}$

- Results are compatible with those obtained with the 3D sensors coupled to the previous version of the chip, RD53A