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Results on 3D Pixel Sensors for the CMS Upgrade at the HL-LHC

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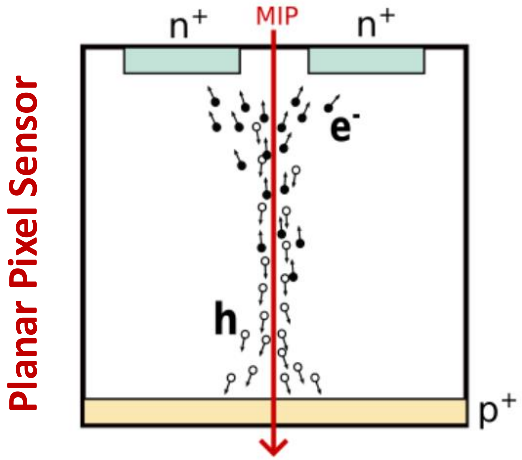
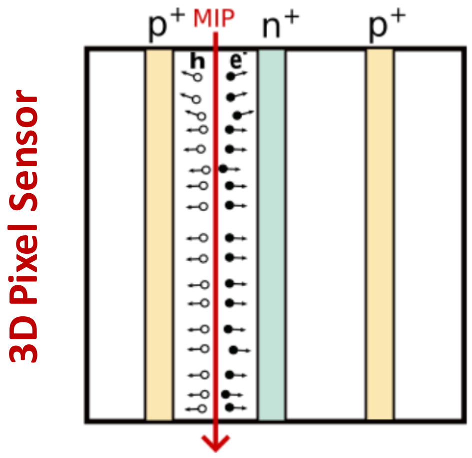
High Luminosity LHC and the CMS Pixel Upgrade

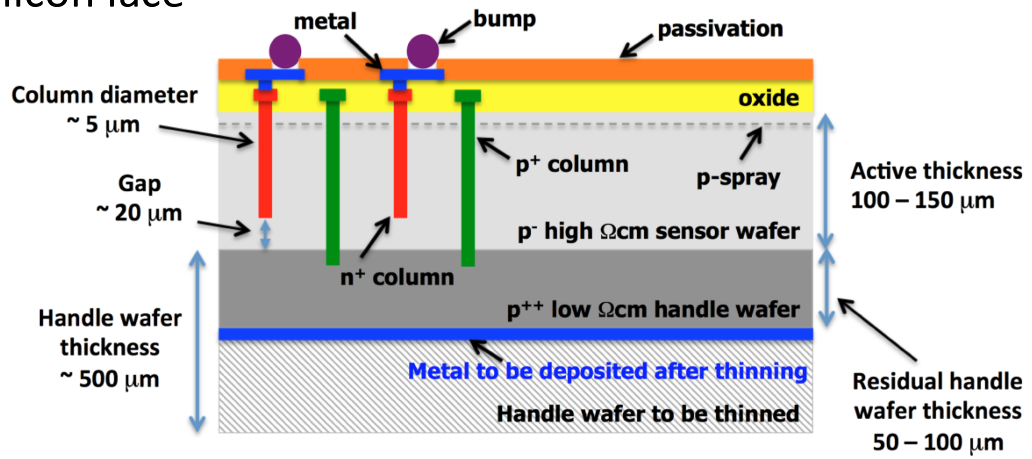
- The silicon tracker of the CMS experiment will be completely replaced for the HL-LHC
    - **Inner Tracker (IT)** → Pixel detectors (Anna Macchiolo's Talk)
- Two types of sensors are considered for the new tracker:
    - Standard "planar" pixel sensors
    - **3D** pixel sensors → Higher **radiation resistance** (this Talk)
        - New technology for CMS IT: will be installed only in the innermost layer (only 30 mm from the beam line!)
- In 3D sensors the drift path is perpendicular to the active thickness
    - Short drift distance of charge carriers: $\sim 50\ \mu\mathrm{m}$ (vs. $150\ \mu\mathrm{m}$ for planar)
- 3D sensors have many advantages with respect to planar sensors:
    - Smaller bias voltages needed to deplete the sensor
    - Reduced trapping probability in irradiated sensors
- **Active thickness** (for both 3D and planar pixel sensors): $150\ \mu\mathrm{m}$
- **Pixel size** (pitch): $25 \times 100\ \mu\mathrm{m}^2$ (six times smaller w.r.t. the present CMS tracker)





FBK 3D Sensors

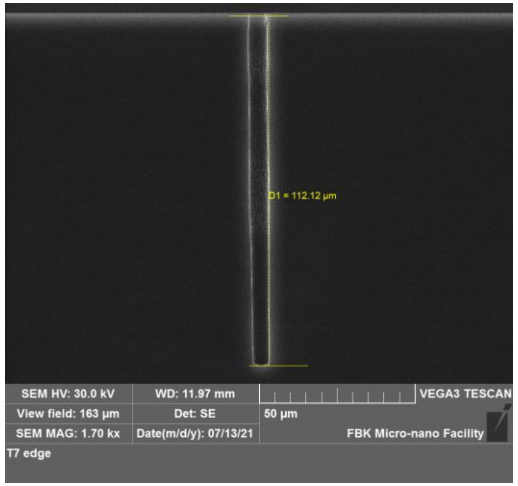
- FBK (Trento, Italy), in collaboration with INFN, is one the two producers of 3D sensors
- A low resistivity CZ silicon layer is bonded to the high resistivity FZ substrate (Silicon-Silicon)
  - Mechanical support for the silicon wafer during production
  - Ohmic contact for the $p - n$ junction
  - "Direct Wafer Bonding" (**DWB**) technique
  - Thinned and metallized at bump-bonding vendor → Total sensor thickness around $250\ \mu\text{m}$ (with $150\ \mu\text{m}$ 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
  - **$5\ \mu\text{m}$ diameter** holes in silicon
  - The columns are doped differently: p^+ and n^+
  - p^+ columns reach the backside of the sensor, hence the bias voltage
  - n^+ columns are connected to the readout chip
  - The columns are filled with polysilicon



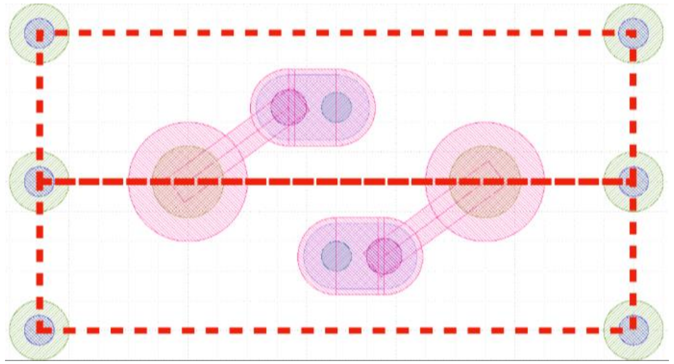
Side view of an FBK 3D sensor

FBK 3D Sensors

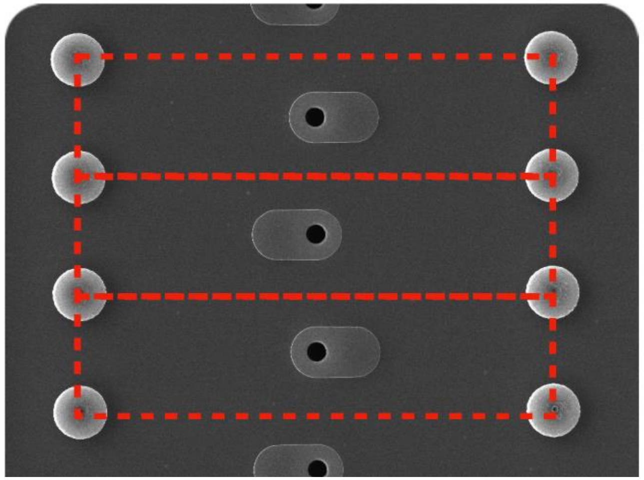
- The n^+ columns in FBK 3D sensors are 115 ± 5 μm long
  - The p^+ columns are at least 150 μm long to reach the backside of the sensor
- A pixel "cell" is delimited by p^+ columns
  - n^+ column is in the center of the $25 \times 100\ \mu m^2$ cell…
  - …and connected to the readout chip (through bump-bonding)
  - The chip has a $50 \times 50\ \mu m^2$ pixel matrix



Side view of an n^+ column

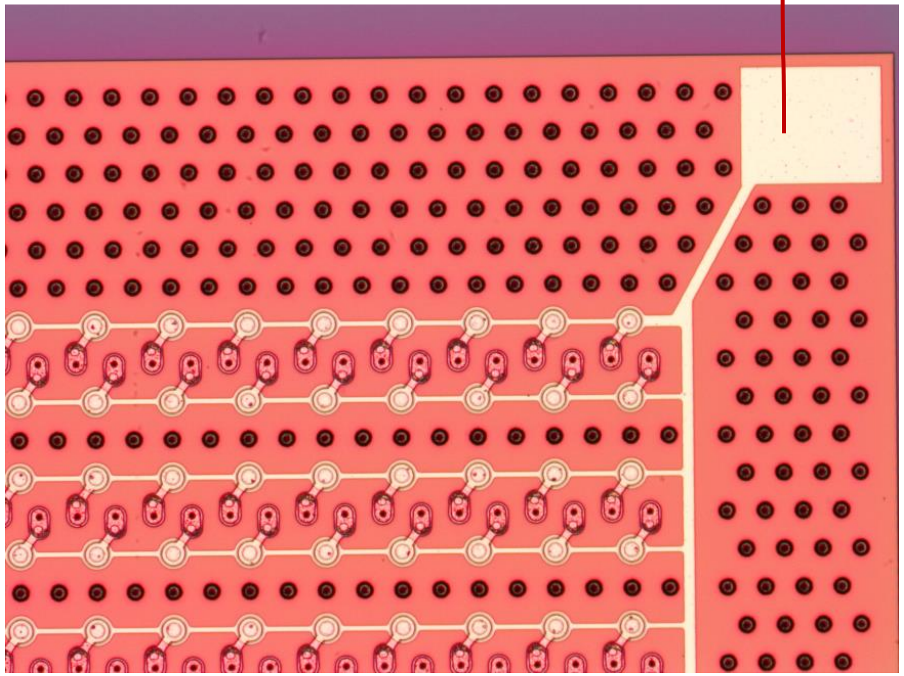


Schematics of two adjacent $25 \times 100\ \mu m^2$ pixel cells



Three $25 \times 100\ \mu m^2$ pixel cells
n^+ column still to be filled with polysilicon

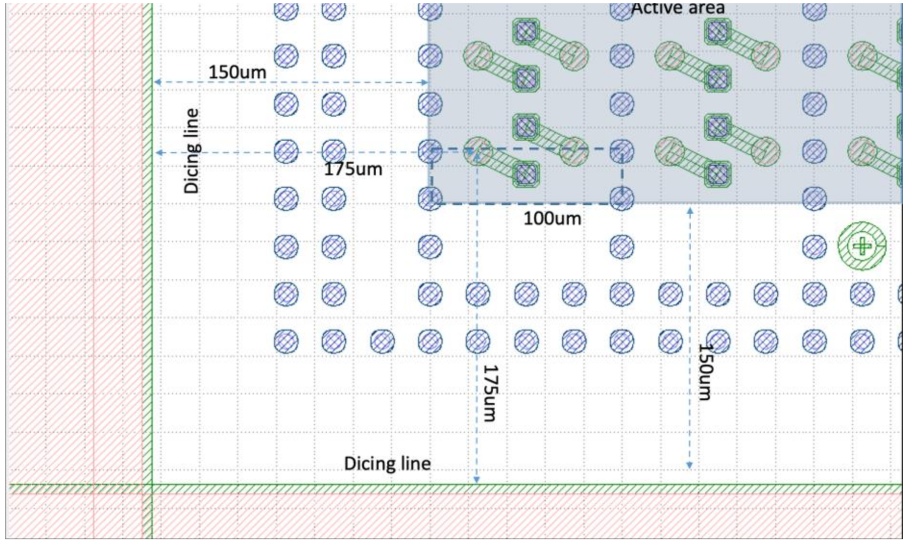
Temporary Metal



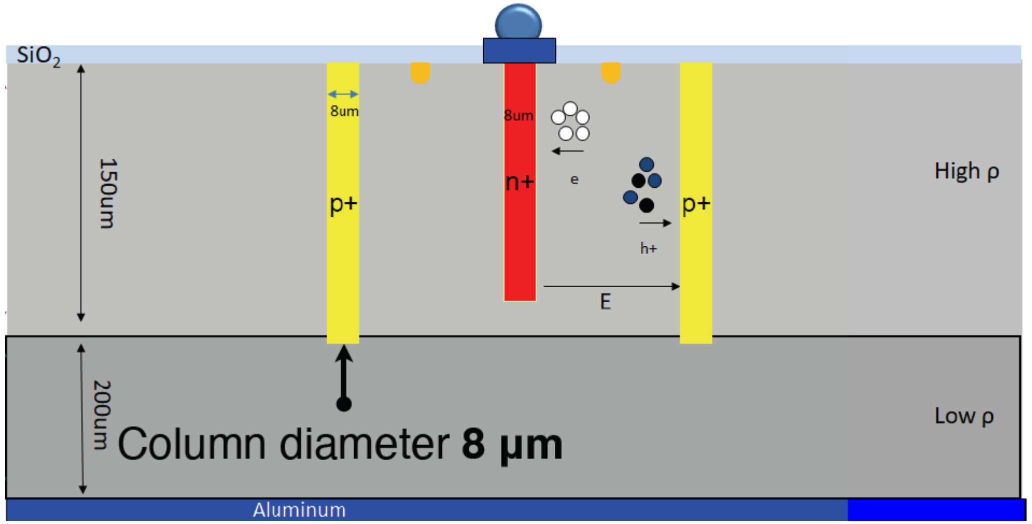
CNM 3D Sensors

- CNM (Barcelona, Spain) is the other foundry that produces 3D sensors
- Very similar construction w.r.t. FBK (DWB, single sided process …)
  - Same active thickness and same total thickness after thinning

- The main differences are:
  - Larger column diameter: **8 µm**
  - Longer n^+ columns: about **130 µm** (in present samples)
  - p-stop instead of p-spray isolation technique

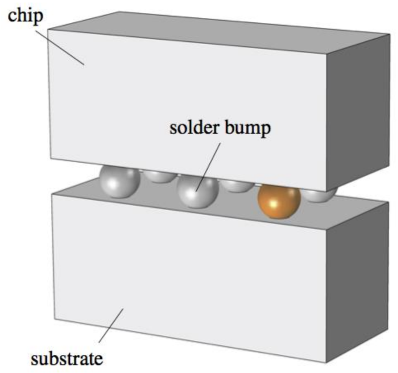


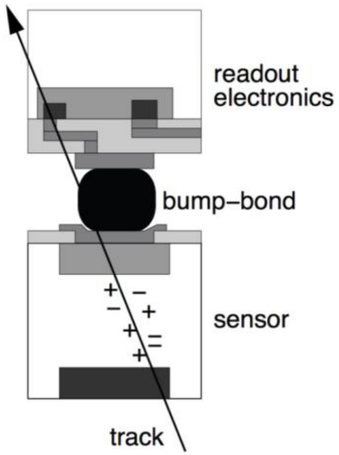
Schematics of a CNM 3D sensor periphery



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

The CMS Read-Out Chip: CROC





Bump Bonding

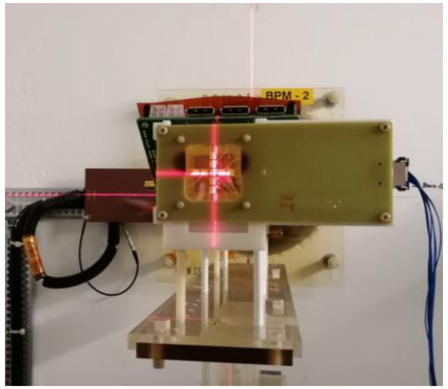
- The ReadOut Chip (ROC) is coupled to the sensor…
  - … with the bump-bonding technique
  - Sensor + ROC → Pixel module
- The **CROC** is being designed by the RD53 Collaboration
  - Joint ATLAS-CMS effort established in 2013 to develop readout chips for the HL-LHC pixel detectors
  - **RD53A** was the first prototype, used for sensor R&D until the beginning of 2022
    - 76800 ($50 \times 50\ \mu m^2$) pixel channels (the analog front-end chose by CMS is 1/3 of the pixel matrix)
- The CROC was available for testing late 2021
  - Now used for sensor R&D: first test beams with CROC modules in 2022
  - 145152 ($50 \times 50\ \mu m^2$) pixel channels
- Various calibrations are needed to operate the pixel modules
  - The pixels channels can be tuned to average thresholds around $1000e^{-}$ before irradiation
  - After irradiation, we aim to similar values (although with a higher noise)

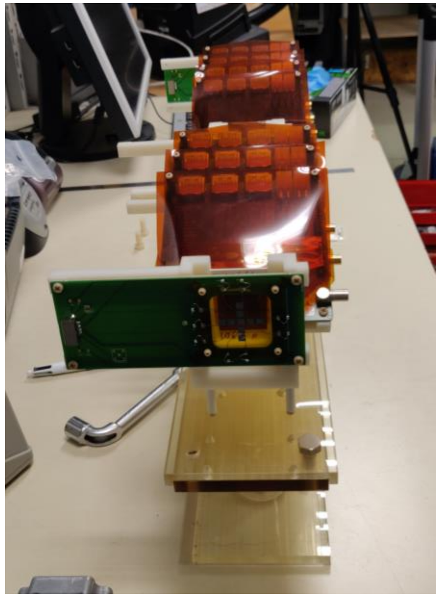
CROC module mounted into a single chip card

CROC Modules Irradiation Campaign

24 GeV Proton Irradiation

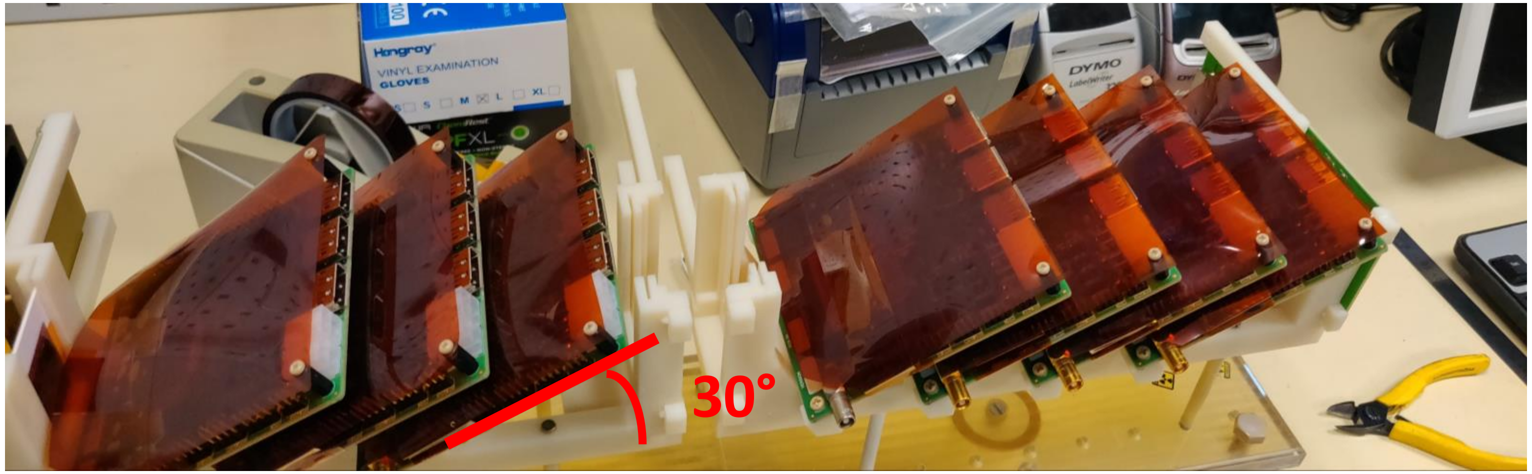
- We had CROC module irradiation campaign at the **IRRAD** facility at CERN (31/08/22 - 07/10/22)
- Seven CROC modules: three FBK 3D, one CNM 3D and three HPK Planar (all coated with parylene)
  - Tilted by $30°$ to achieve a uniform vertical irradiation
  - Horizontal scanning (scan span: $26\ \mathrm{mm}$) to achieve a uniform horizonal irradiation
- Behind four CROC modules we placed aluminum foils
  - 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





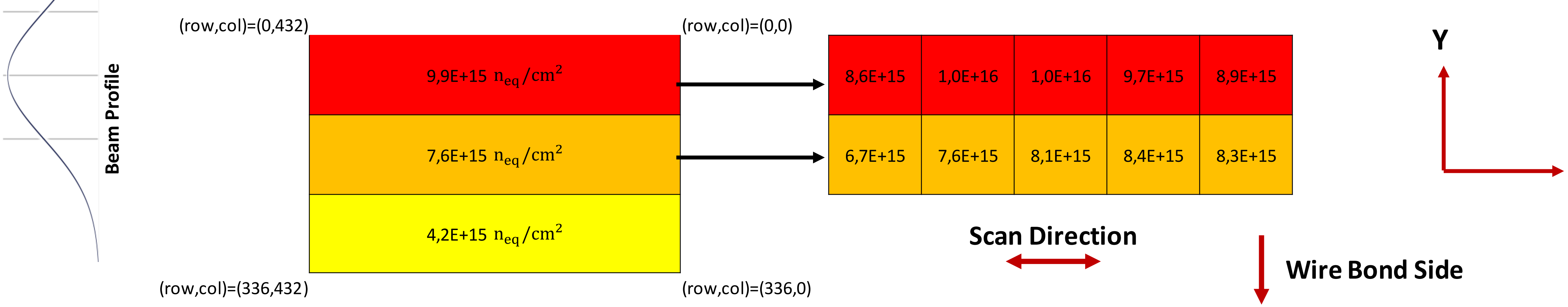
Irradiation support with the seven CROC modules installed

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



CROC Modules Irradiation Campaign

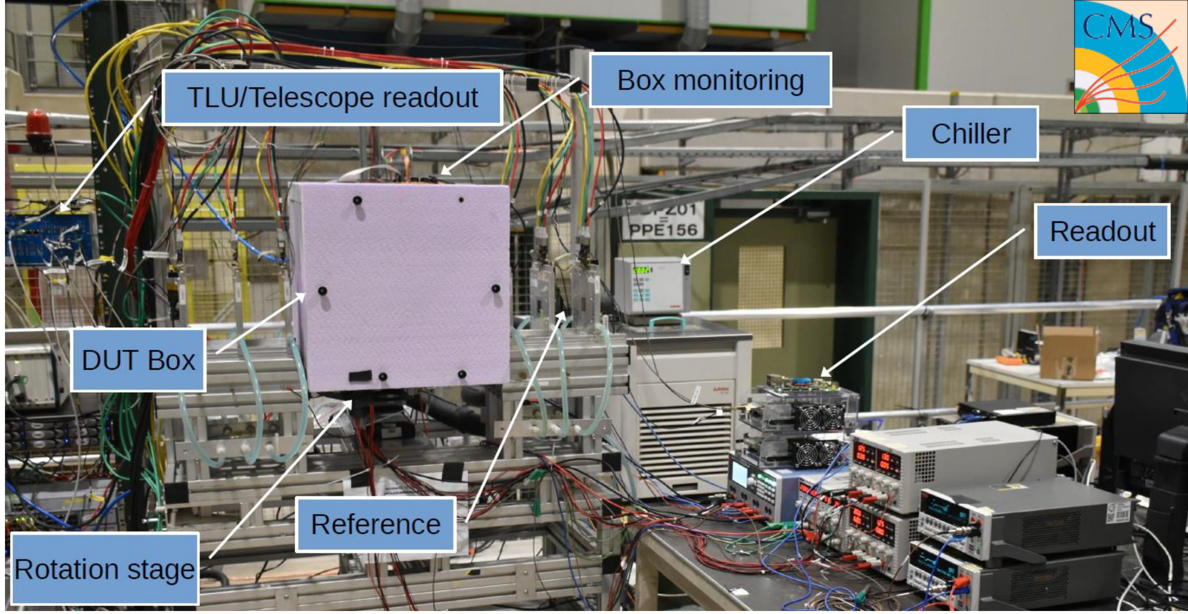
The measured fluences are reported in each rectangle for the corresponding sample

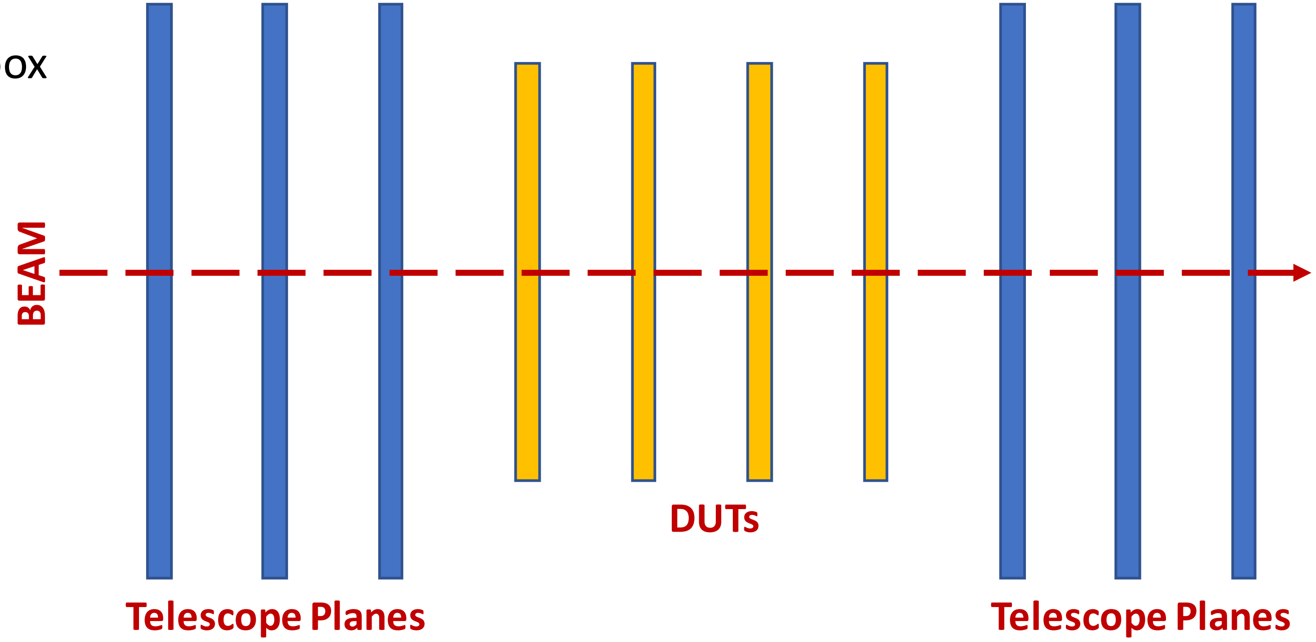


- Fluences are obtained from the spectroscopy of aluminum foils: the aluminum foil of each module is cut into smaller samples
    - **Not** perfectly **centered** along **Y**
    - **Uniform** irradiation along **X** (the direction of the scanning)
    - In any case we have a large area of the CROC module irradiated at about $\mathbf{10 \times 10^{15}\ n_{eq}/cm^2}$
        - This will be our Region of Interest (**ROI**) in the following
- 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 of $\mathbf{15 \times 10^{15}\ n_{eq}/cm^2}$

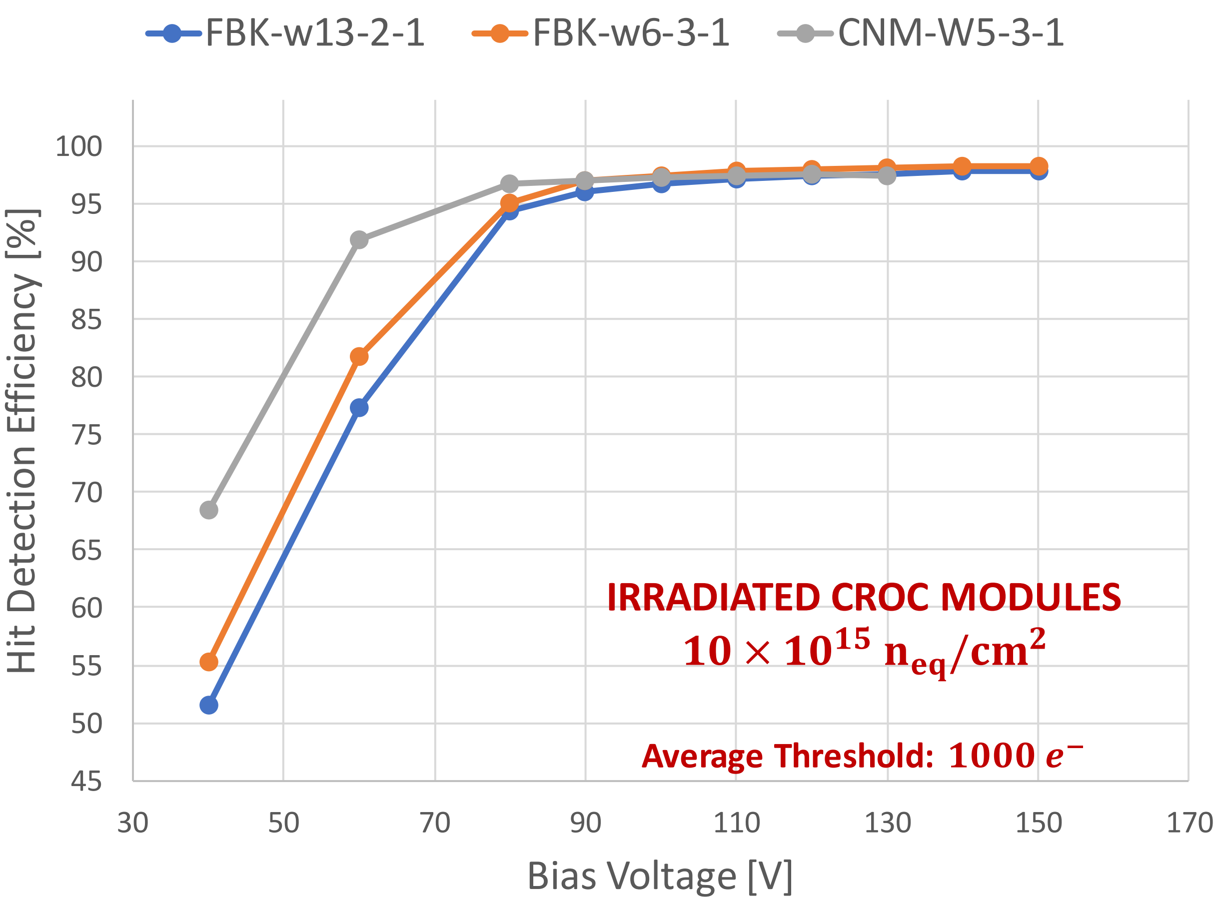
SPS Test Beam

- Test beam at CERN SPS: 02/11/2022 – 09/11/2022
  - 120 GeV pions
- EUDET telescope
  - Six pixel planes equipped with MIMOSA26 sensors ($18\ \mu m$ pitch)
    - One plane was not working
  - $2\ \mu m$ resolution in each coordinate
- Four Device Under Tests (**DUTs**) are kept inside a cooling box
  - Placed in the middle of the telescope
  - Heat exchangers close do the DUTs
  - Stable air temperature around $-30\ °C$
- Three of the four DUTs can be rotated
  - Using a rotation stage inside the cooling box





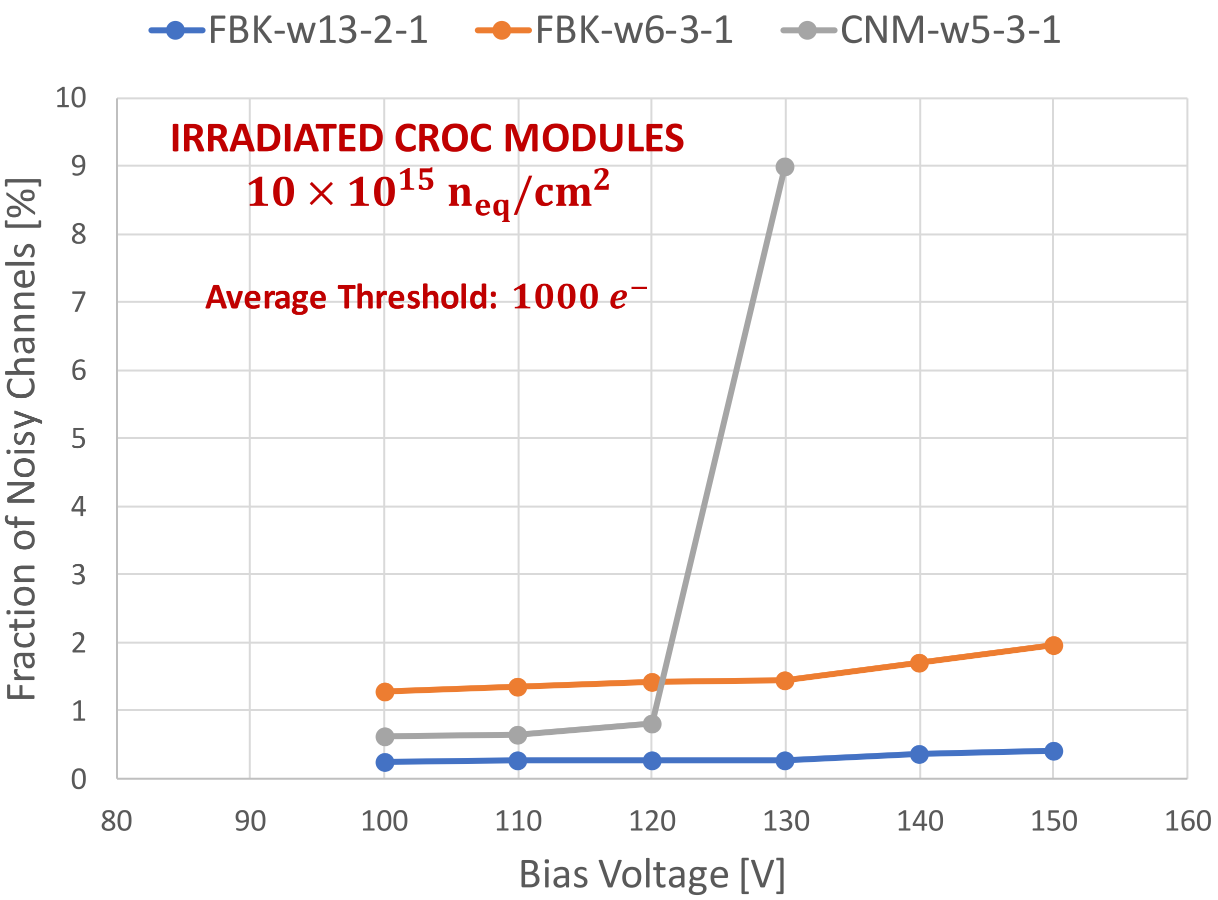
Efficiency Studies



The wZ-X-Y notation indicates the X-Y position of the sensor in the wafer Z of the production (either FBK or CNM)

- Efficiency vs. Bias Voltage for the irradiated 3D modules
  - Two FBK 3D, one CNM 3D
  - The efficiency is calculated inside a **ROI** of uniform fluence
  - Estimated **fluence** inside the ROI: $\mathbf{10 \times 10^{15}\ n_{eq}/cm^2}$
  - The modules were tuned to an average threshold of $\mathbf{1000\ e^-}$
- Efficiency plateau is $\sim \mathbf{50\ V}$ wide and starts around $\mathbf{90\ V}$
  - Maximum value of $\sim \mathbf{98\%}$ at $\mathbf{130\ V}$
  - The columns are made by passive material → Inefficiencies
  - By rotating the DUTs the inefficiencies are recovered…
  - …since incident particles always escape the passive material

Noise Studies

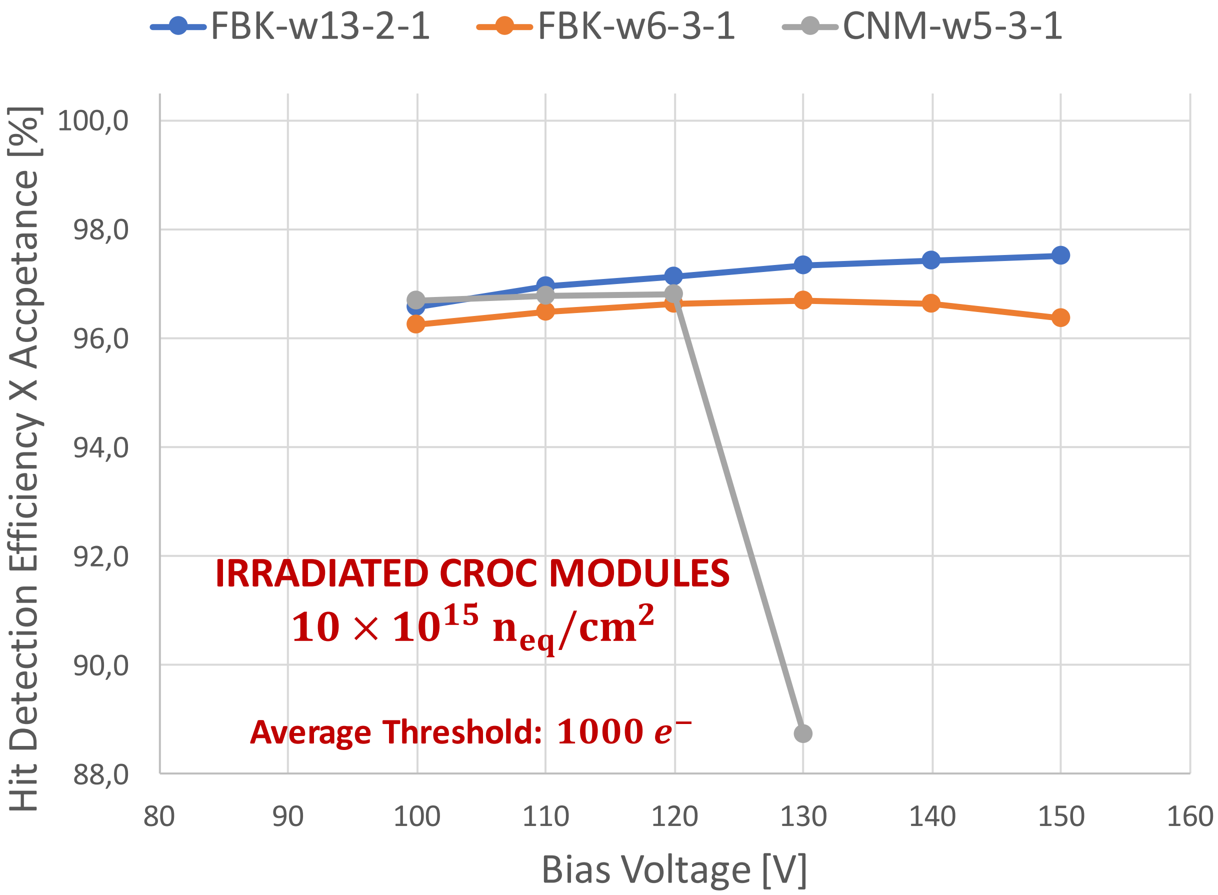


- Noisy Channels vs. Bias Voltage for the irradiated 3D modules
  - The two FBK modules are stable up to $150\ \mathrm{V}$
  - Steep increase at $130\ \mathrm{V}$ for the CNM module
  - The cause is still under investigation
    - A similar behavior was observed with FBK 3D RD53A modules irradiated to higher fluences ($> 15 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$)
  - In any case the module can be operated between $90\ \mathrm{V}$ and $130\ \mathrm{V}$ with full efficiency
- Increasing the threshold of the CNM module to $1200\ \mathrm{e^-}$ the noisy channels decrease to 2% at $130\ \mathrm{V}$

Efficiency Studies with Acceptance

In order to present a more coherent hit detection efficiency, we can define the **acceptance** as:

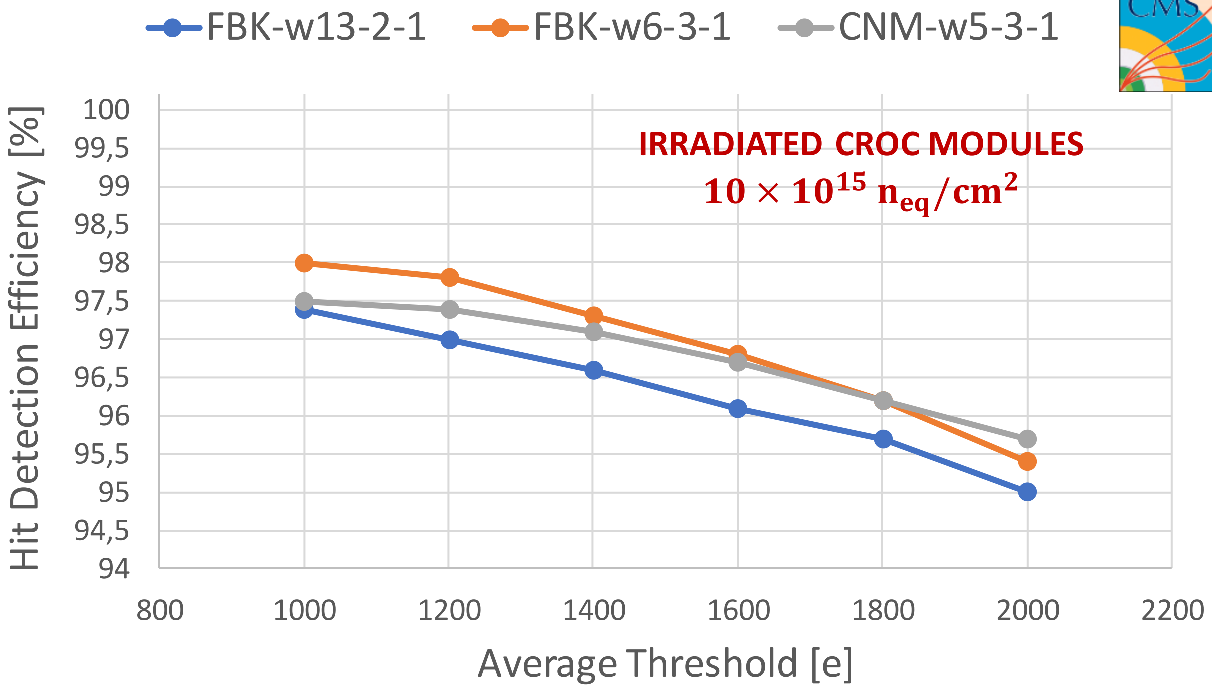
$$\text{Acceptance} = 1 - \frac{\text{Number of Noisy and Dead Channels}}{\text{Number of Channels}}$$



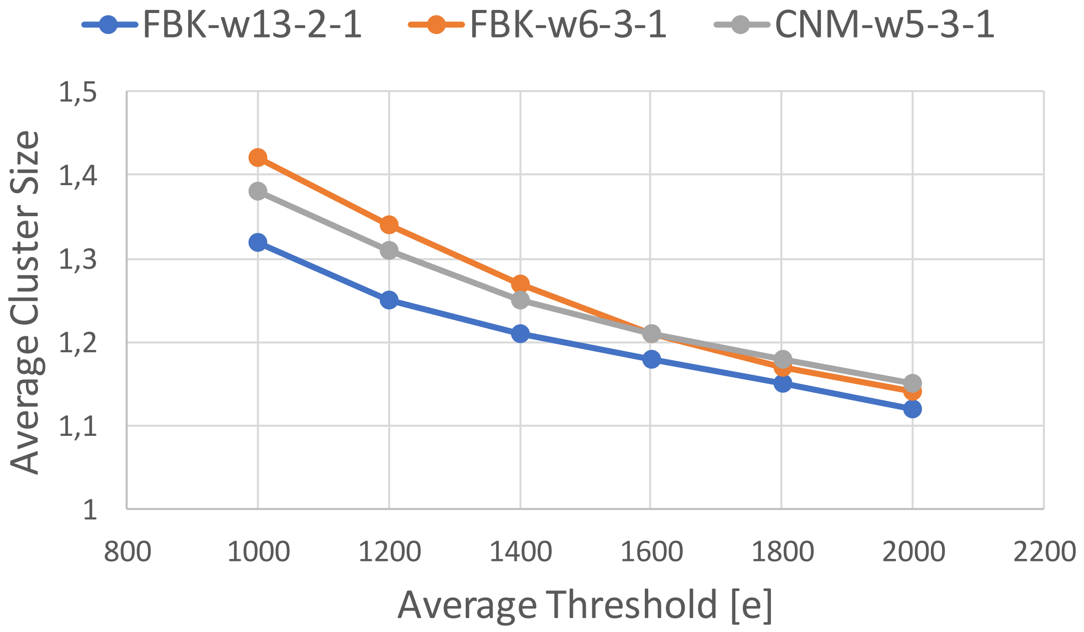
- Efficiency × Acceptance vs. Bias Voltage for the three modules
  - $1000\ e^-$ threshold
  - In this way we consider the number of noisy channels
  - The effect is more pronounced for the CNM module…
  - …due to the higher number of noisy channels at 130 V

Threshold Studies

- Efficiency vs. Average Threshold for the irradiated 3D modules
  - Bias voltage of $120\ \mathrm{V}$ for the three modules
  - Doubling the threshold, the efficiency drops by only 2.5%
  - Hit efficiency at 95% in the worst case, with $2000\ e^{-}$ threshold

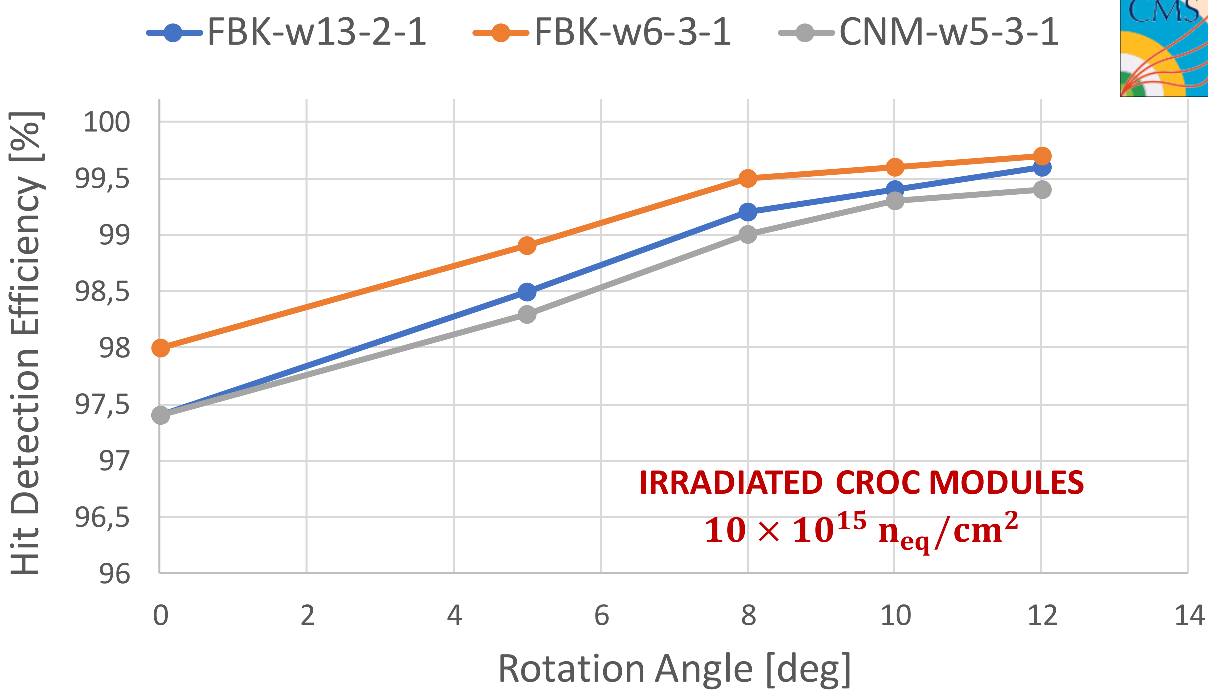


- Average Cluster Size vs. Average Threshold
  - Charge sharing significantly reduced by raising the threshold
  - Could have an impact worsening the spatial resolution

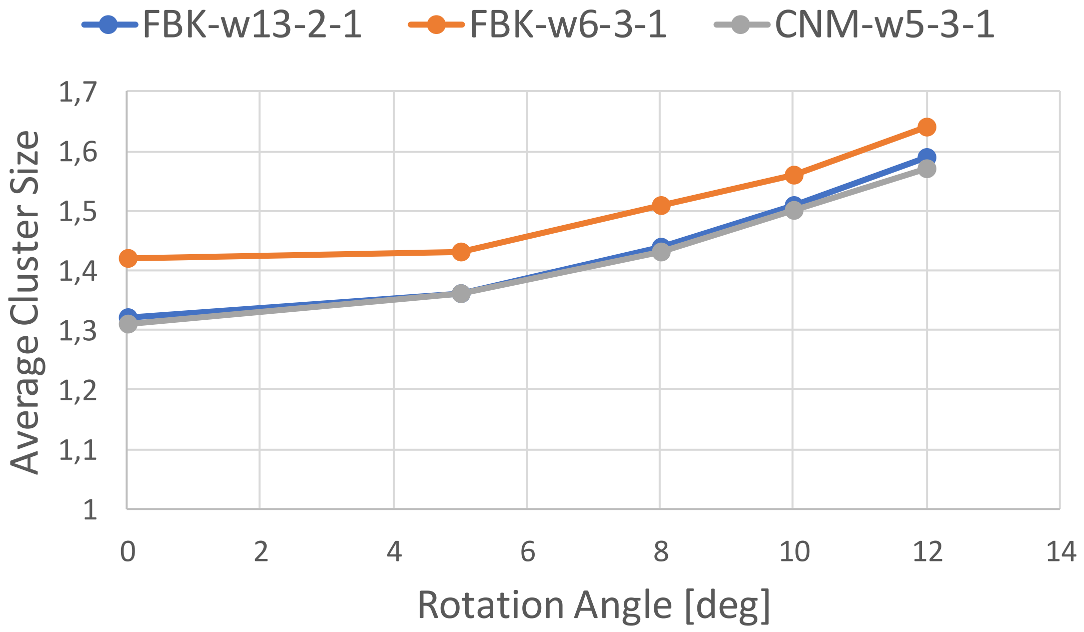


Angle Studies

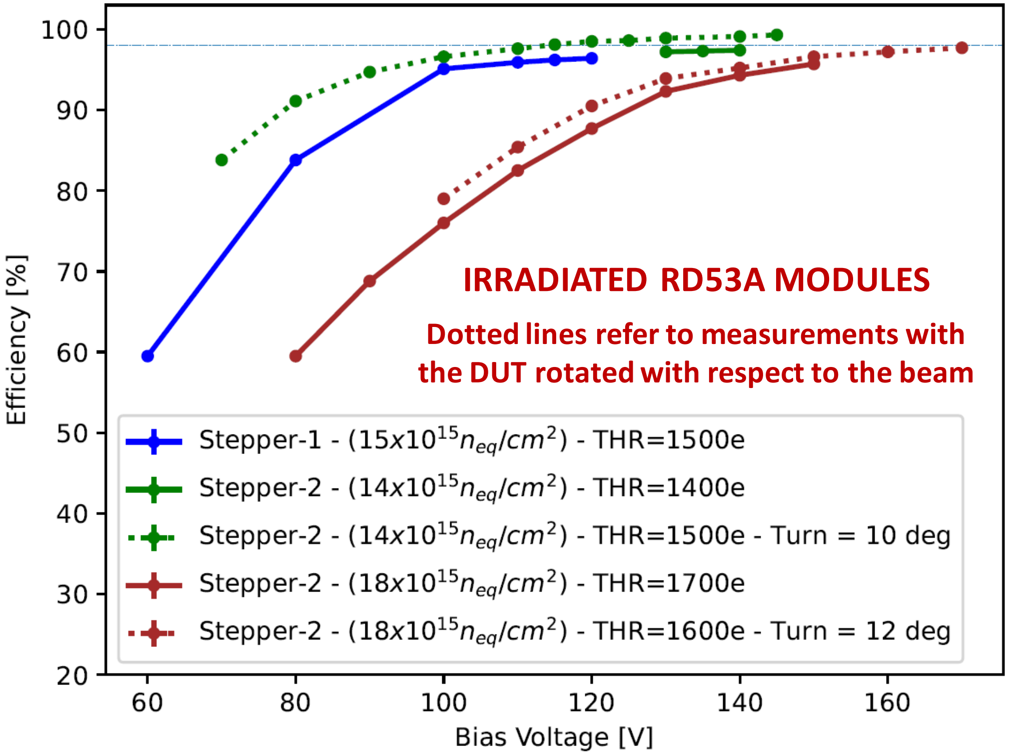
- With a rotation stage, the DUTs can be rotated w.r.t. beam
  - Rotation around the $25\ \mu m$ pitch
- Efficiency vs. Rotation Angle for the irradiated 3D modules
  - Bias voltage of $120\ V$ for the three modules
  - Average threshold of $\mathbf{1000}\ \boldsymbol{e^-}$ for the two **FBK** modules…
  - … and $\mathbf{1200\ e^-}$ for the **CNM** module
- **Efficiency** $> 99\%$ is achieved for an **angle** $> 8°$



- Average Cluster Size vs. Rotation Angle
  - Cluster size increases with angle as expected
  - Resolution studies are being performed



FBK 3D RD53A Irradiated Modules



- In order to reach an efficiency $> 98\%$:
  - $V_{bias} > 110$ V after a fluence of $\mathbf{15 \times 10^{15}\ n_{eq} cm^{-2}}$
  - $V_{bias} > 160$ V after a fluence of $\mathbf{18 \times 10^{15}\ n_{eq} cm^{-2}}$

- Two **FBK 3D RD53A** productions: **Stepper-1** (2019) and **Stepper-2** (2020)
  - Step-And-Repeat photolithography technology
  - The pixel design is the same, but in Stepper-1 the n^+ columns were longer
    - 130 μm (instead of 115 μm, FBK new default, also used for CROC modules)

- Three **irradiated** FBK 3D RD53A pixel modules were tested in 2021
  - DESY test beam
  - The irradiations were performed at **KIT** (23 MeV protons)
  - The irradiations (up to $18 \times 10^{15}\ n_{eq}/cm^2$) were always **uniform**

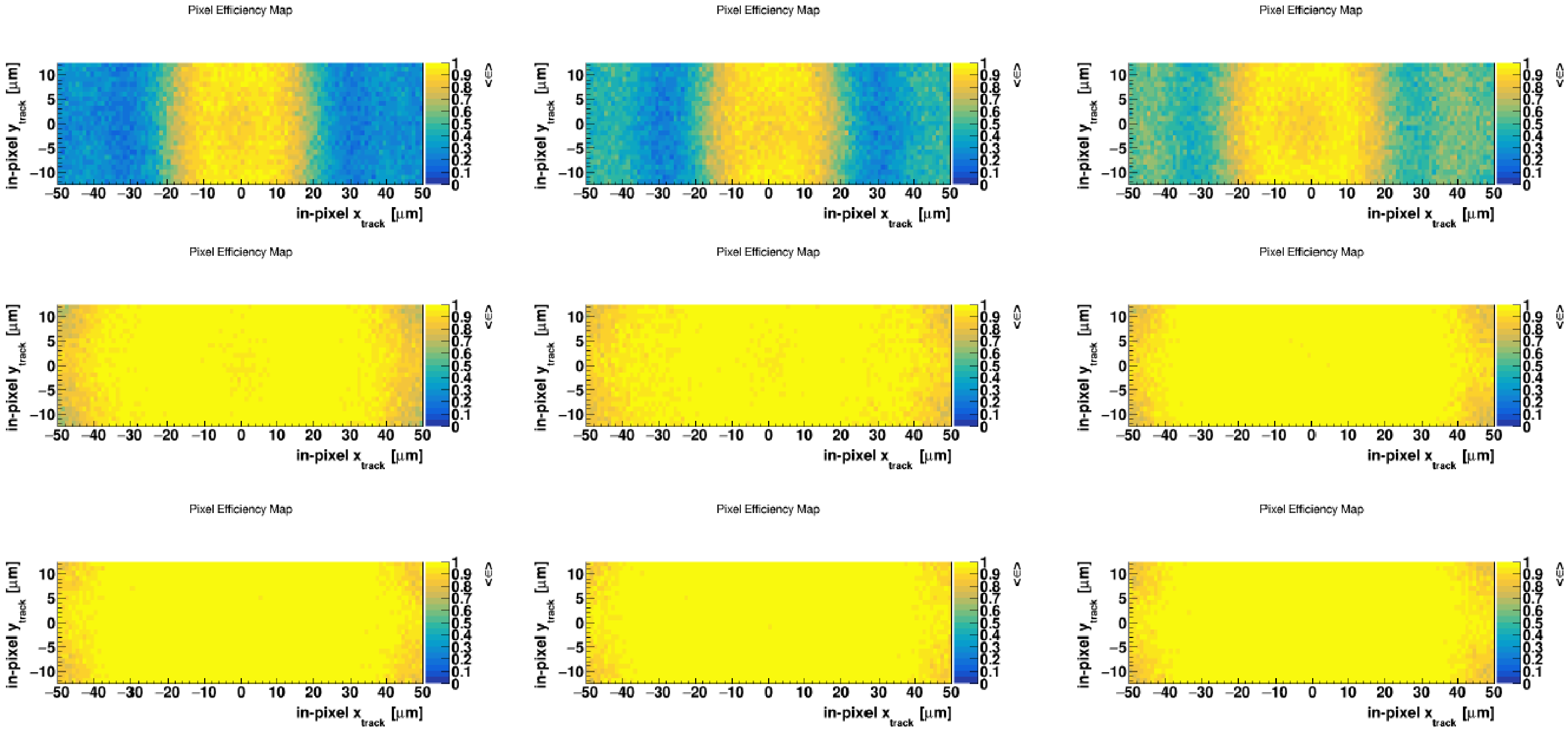
- A sudden increase in the number of noisy channels was observed…
  - …at high bias voltages ($> 130 - 170$ V, depending on the module)
  - The problem was more severe with **Stepper-1** modules

Conclusions

- **3D CROC** modules irradiated to $\mathbf{10 \times 10^{15}\ n_{eq}cm^{-2}}$ show excellent performances
  - First results with irradiated CROC modules
  - Efficiency plateau is $\sim \mathbf{50\ V}$ wide and starts around $\mathbf{90\ V}$
- **FBK 3D RD53A** modules irradiated up to $\mathbf{18 \times 10^{15}\ n_{eq}cm^{-2}}$ also showed good performances
  - The noisy channels behavior is still under study and being compared with irradiated 3D CROC modules
- New irradiation of CROC modules (with 3D and planar sensors) are foreseen for 2023…
  - … aiming a fluence of at least $15 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$
  - The innermost tracker layer should be replaced after an expected fluence of $\mathbf{15 \times 10^{15}\ n_{eq}/cm^{2}}$
- The presented results will contribute to the optimization of the pixel detectors to be installed in CMS
  - 3D pixel modules will be installed in the innermost layer of the future CMS tracker

Backup

	W13-2-1	W6-3-1	W5-3-1
40V			
80V			
120V			



Backup

W13-2-1 | W6-3-1 | W5-3-1

40V

80V

120V