Beam test results of irradiated 3D pixel sensors for the CMS-TOTEM Precision Proton Spectrometer

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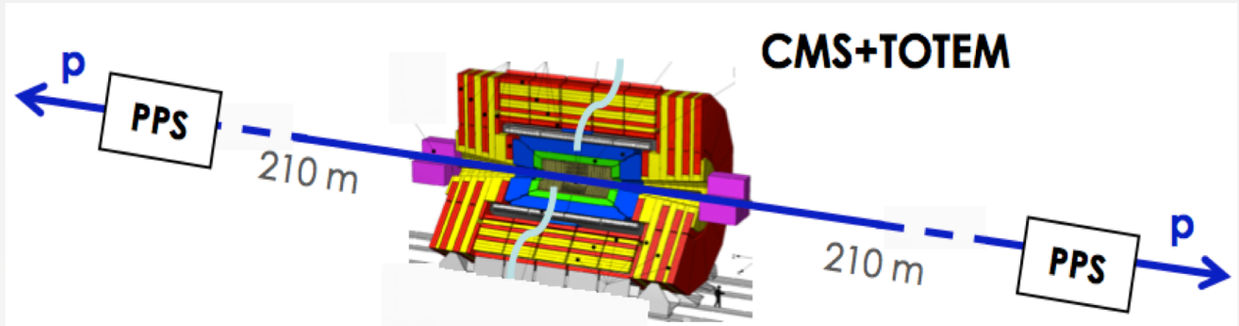
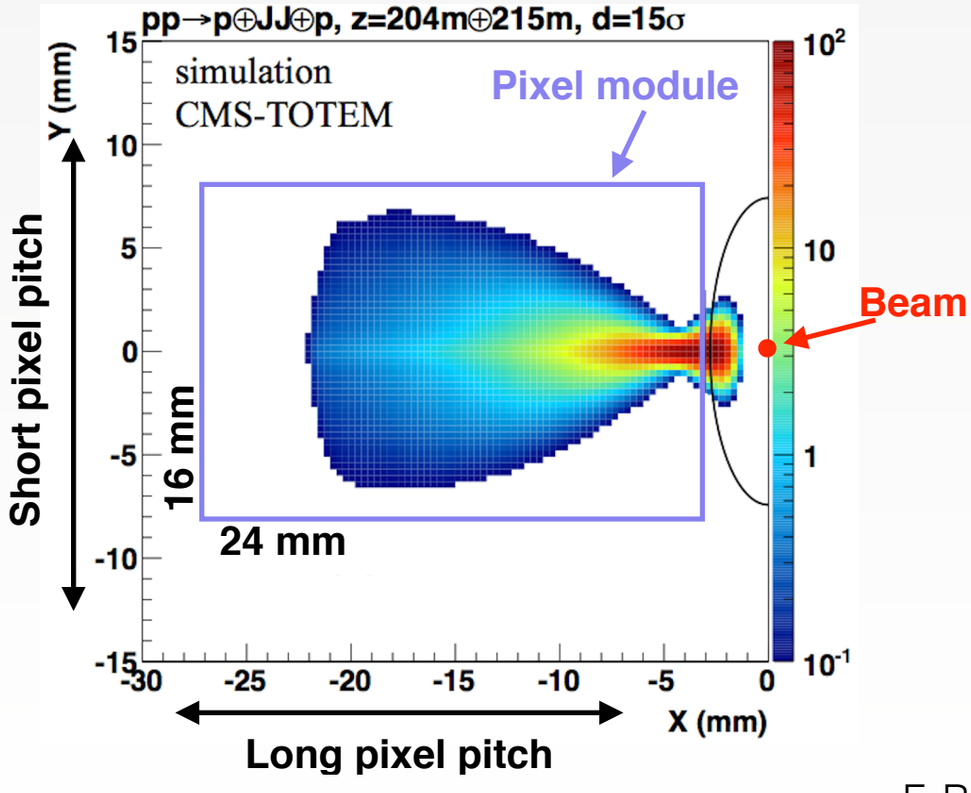
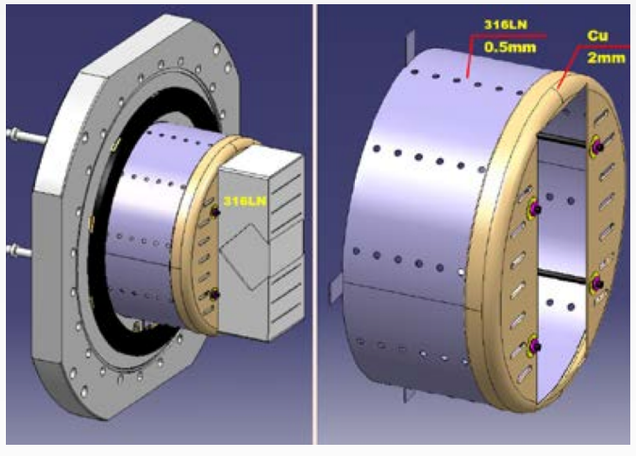
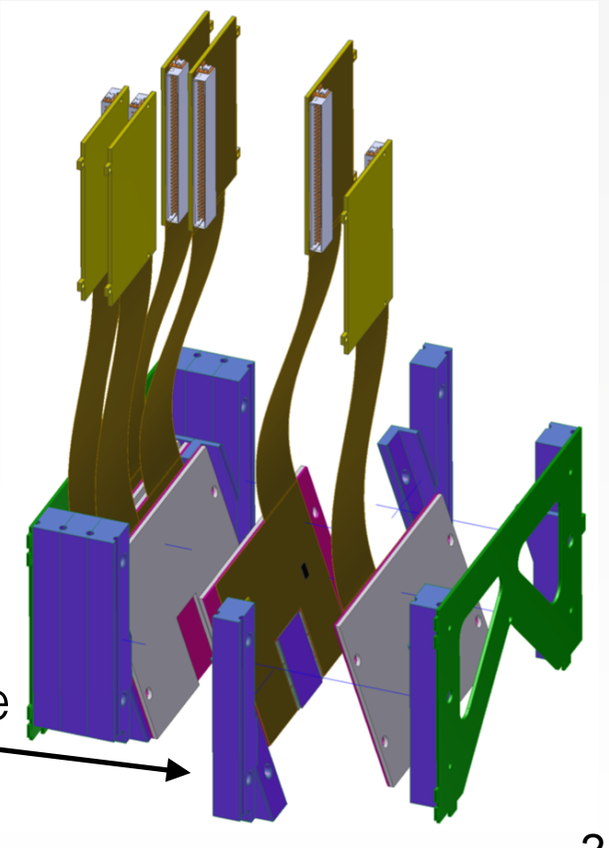
CMS-TOTEM Proton Precision Spectrometer

- The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS) allows measurement of **protons in the very forward region** of both sides of CMS in **standard LHC running conditions**, taking advantage of the machine magnets to bend protons
- Two stations for **tracking and timing detectors** will be installed inside Roman Pots between 205 and 215 m from the CMS/TOTEM IP on both sides
- Requirements for tracking sensors:
  - Good radiation hardness (expected 5×10^{15} p/cm^2)
  - Small insensitive area at the sensor edge
  - Tracking resolution ~10 μm







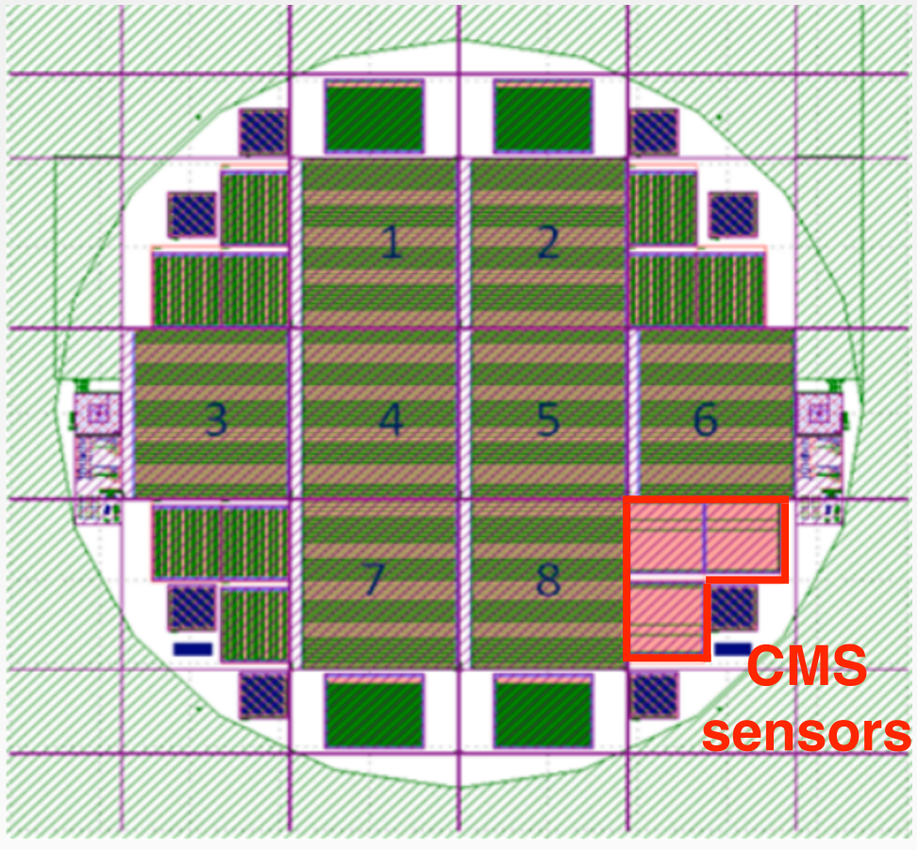


Each station: 6 planes of 3D pixel detectors tilted by 18.4° to improve resolution along long pixel pitch

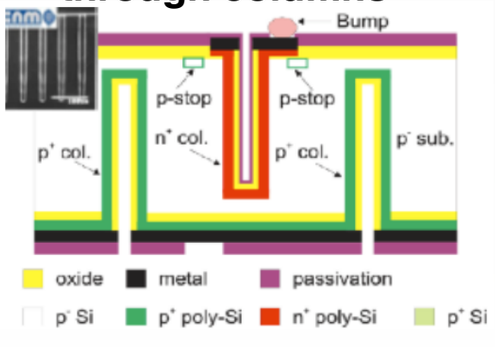
CNM and SINTEF 3D sensors

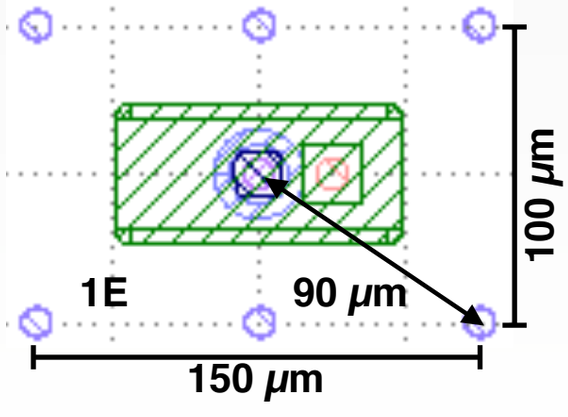
CNM Sensors

Wafer from Atlas IBL production
Wafer thickness = 230 μm
Slim edge of 200 μm (400 μm) on top and bottom (left and right) **with column fence**



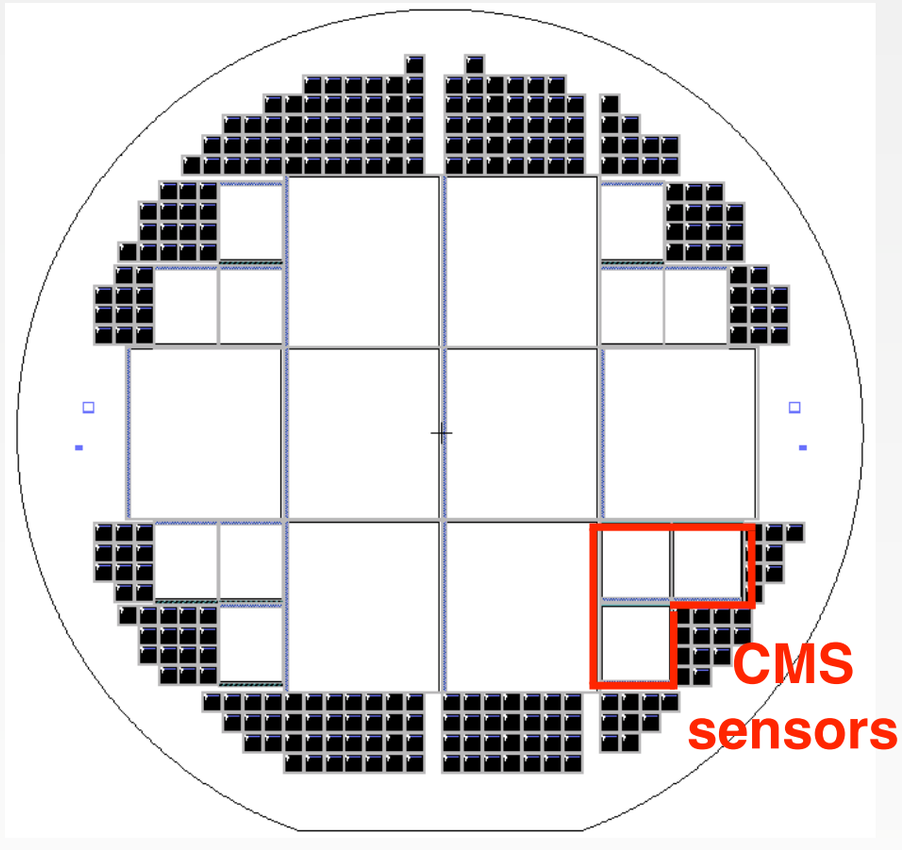
Double-sided not passing through columns



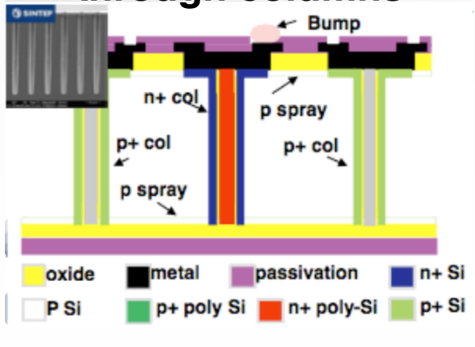


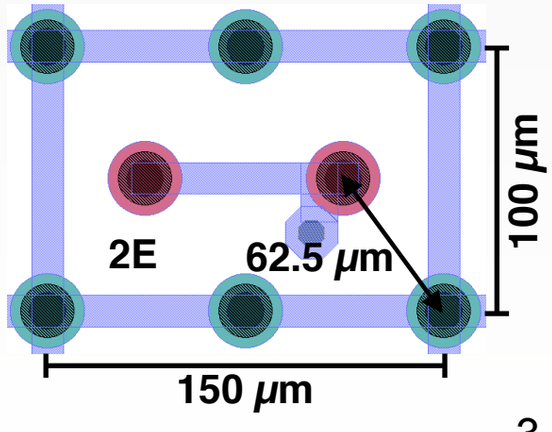
SINTEF Sensors

Wafer thickness = 200 μm
Support wafer not removed
Active edge of 87 μm from the last n+ column on 3 sides, larger on 4th side to host bias pad



Single-sided full passing through columns





3D sensors testing steps

May 2015:

- 8 CNM 1E and 2 SINTEF 2E 3D sensors bump-bonded at IMATEK to the CMS pixel digital ReadOut Chip (ROC) for the Phase I upgrade
- IV curve measurements and ROC optimisation and calibration in Torino

June 2015:

- 4 CNM and 1 SINTEF good-quality detectors tested with 120 GeV protons at Fermi National Accelerator Laboratory (FNAL)

September 2015:

- 5 detectors irradiated with 24 GeV protons at CERN IRRAD Proton Facility, at fluences of $1x10^{15}$ and $3x10^{15}$ n_{eq}/cm^2 (corresponding doses: 52-156 Mrad)

October 2015:

in Torino:

- IV curve measurements
- Setting and calibration of survived ROCs (3 CNM and 1 SINTEF)

November 2015:

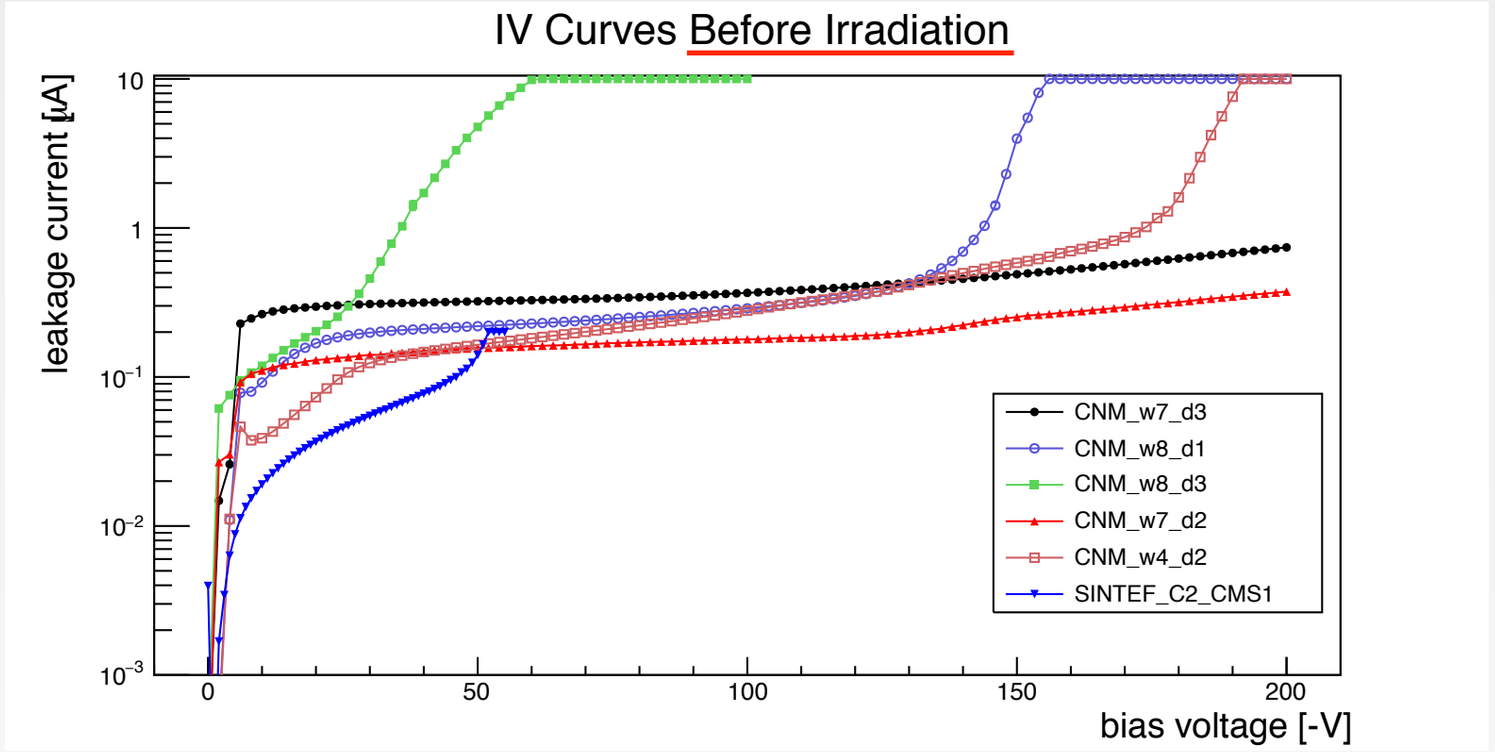
- Irradiated detectors tested on beam at FNAL

IV curves before and after irradiation

Preliminary

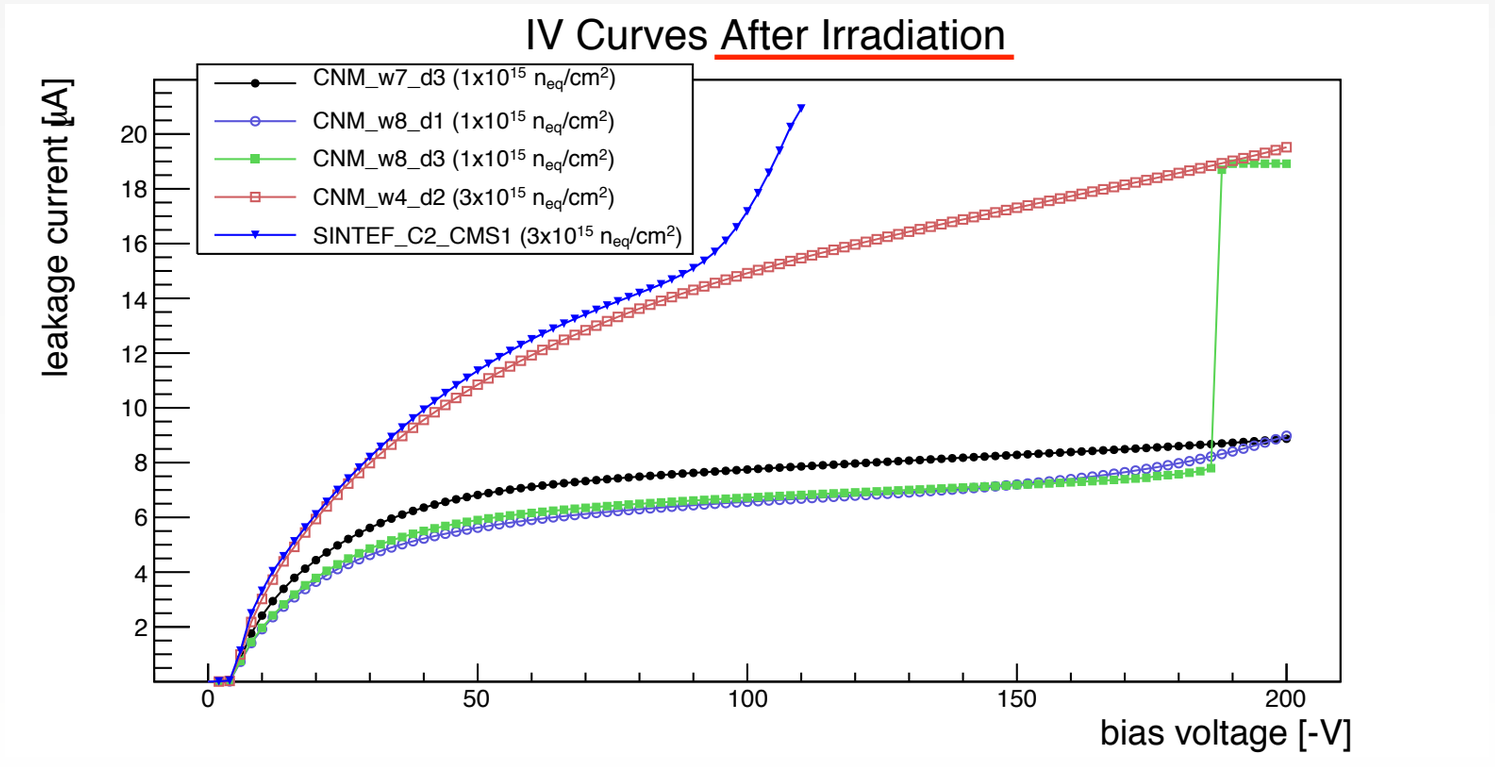
Before irradiation:

- IV measured at **room temperature**
- Apart from 1 sensor with low breakdown, devices show **breakdown above 130 V**, as expected for the CNM 3D

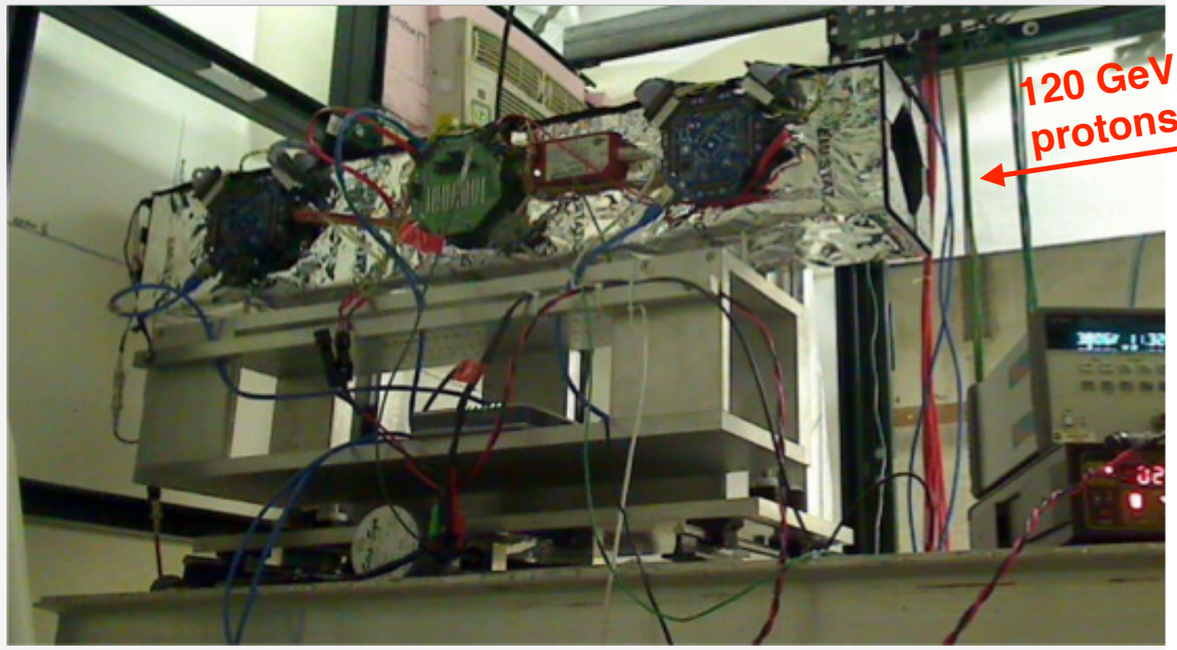


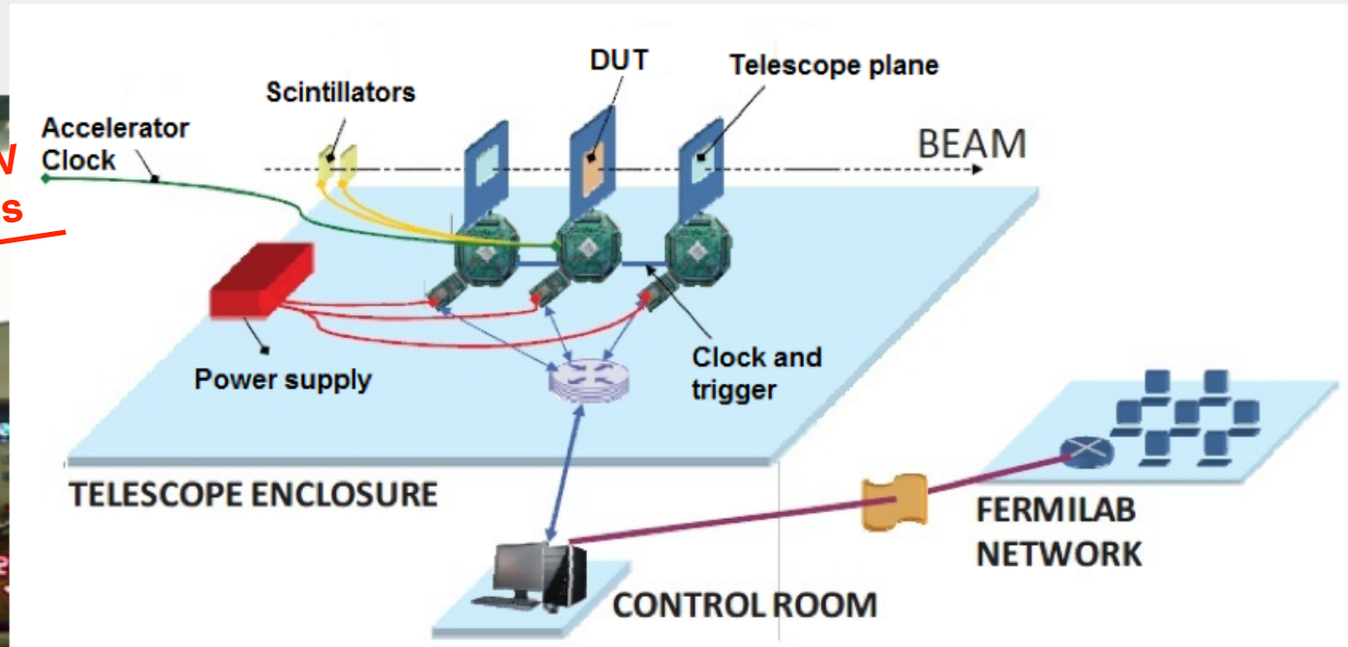
After irradiation:

- IV plotted at **-20°C**, same temperature foreseen in CT-PPS and used at the test beam
- IV curves have been measured with **ROC OFF**
- **Increase of breakdown voltage as expected for this technology**

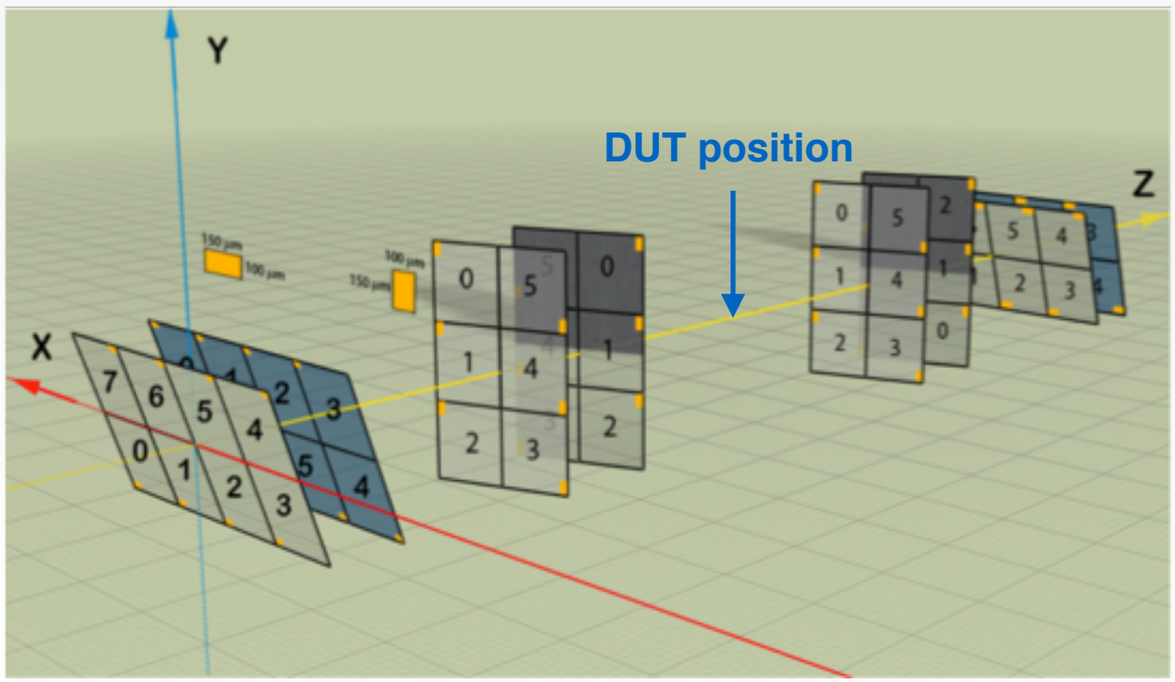


Test beam at FNAL (T992 collaboration)





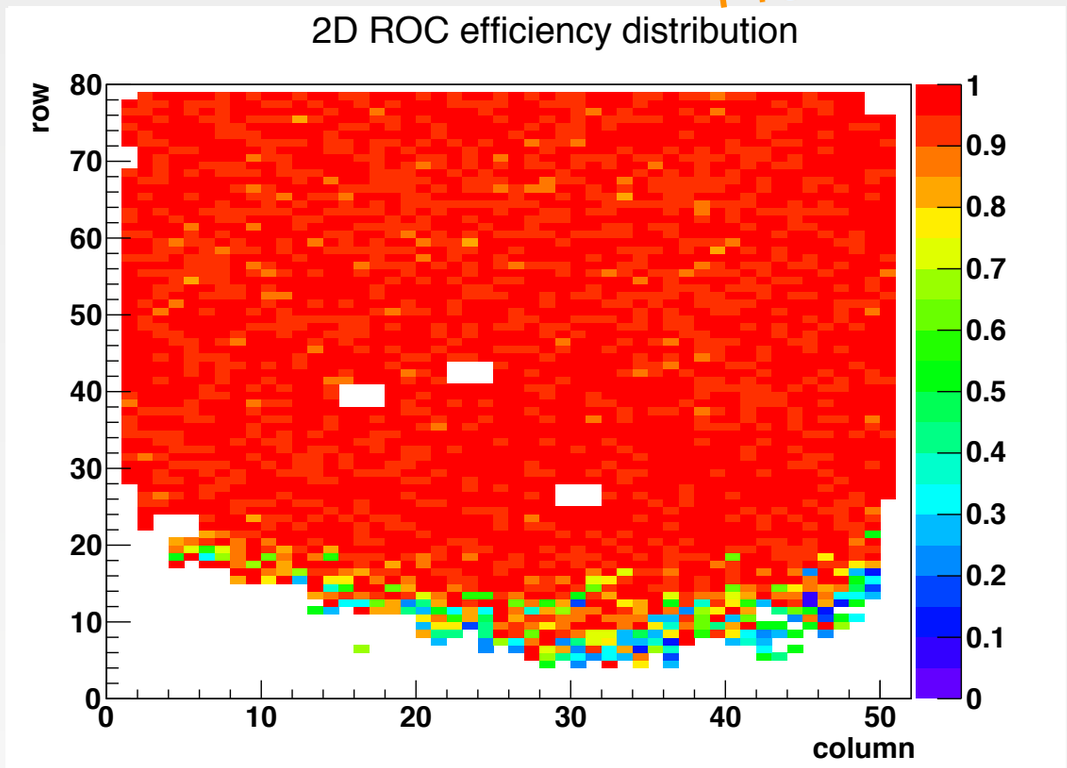
- **8 telescope planes** of CMS pixel modules (pixel size 100x150 μm^2), 4 upstream and 4 downstream with respect to the DUTs
- Telescope planes rotated by 25° with respect to 100 μm pixel pitch direction for increasing **resolution to 8 μm**
- Rotation and cooling systems for the DUTs provided by Purdue
- Alignment and analysis software developed at Milano Bicocca



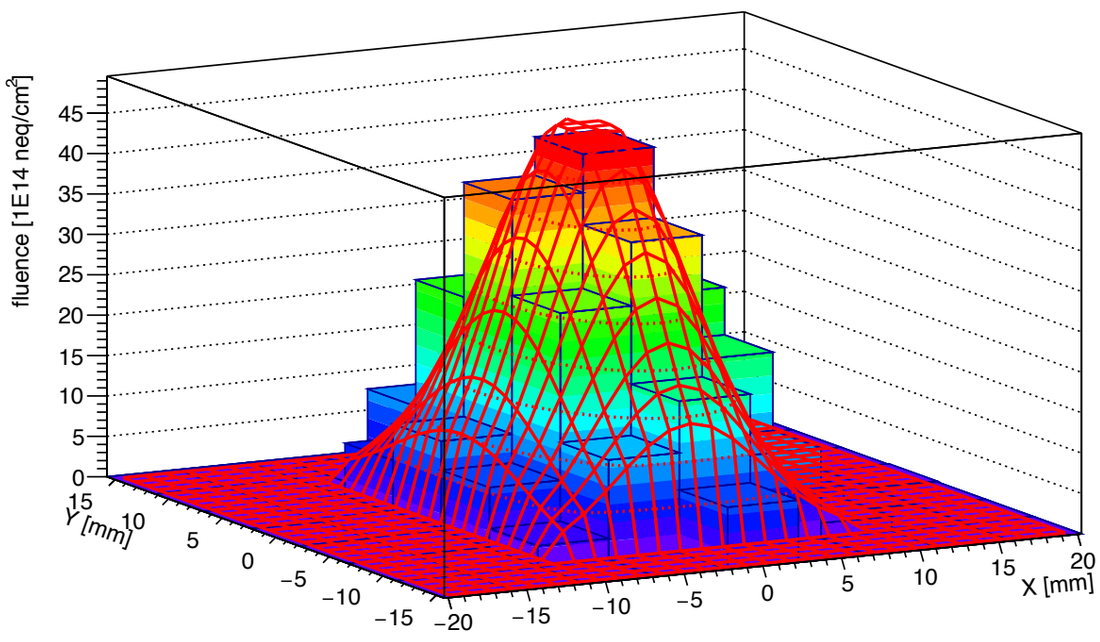
Non uniform irradiation issue

- **Irradiation profile not uniform** on the sensor area.
- Non uniform dose made the optimisation of the ROC problematic, creating **timing issues** and hence inefficient areas. **Problems with the calibration** of ROCs at the test beam may also be related to the same issue → absolute charge value not reliable
- From the charge collected on the whole sensor it is possible to match the irradiation profile to the sensor map
- **Calibration will be repeated** in lab and source measurement will be made to improve the irradiation profile matching
- **Results shown have been obtained by excluding bad pixels and pixels at the edge of the in-time region**

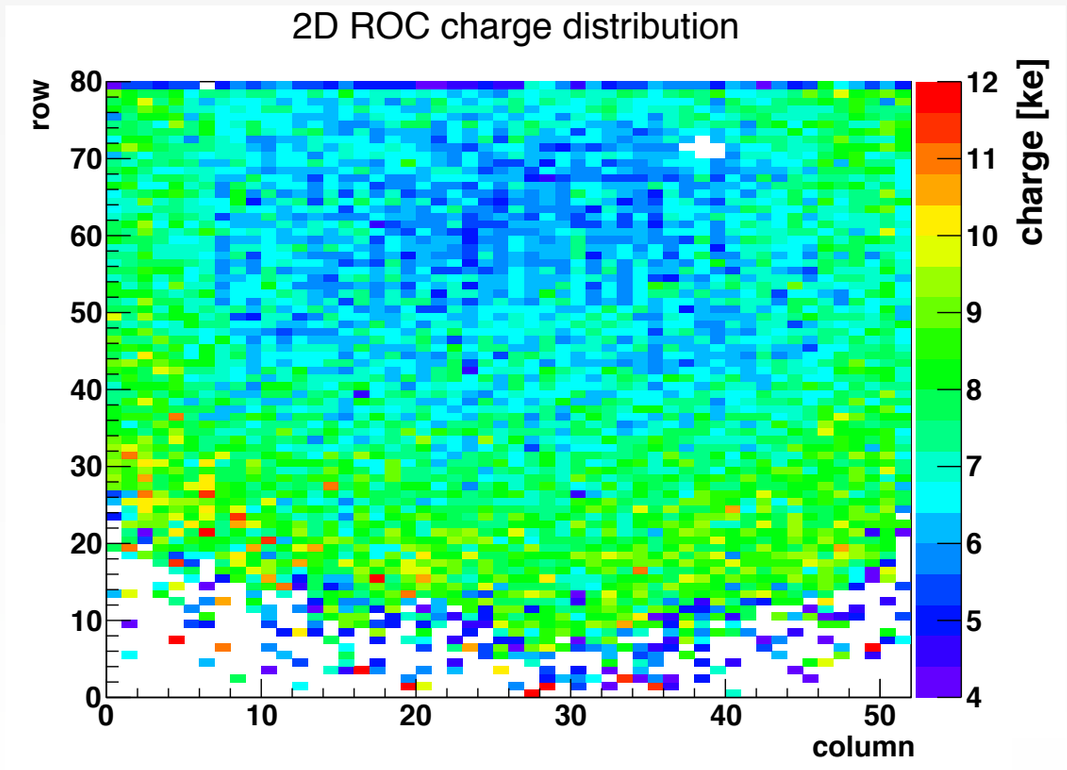
Preliminary



Irradiation profile extracted from IRRAD BPMs



To be normalised to measured dose on reference aluminium foil

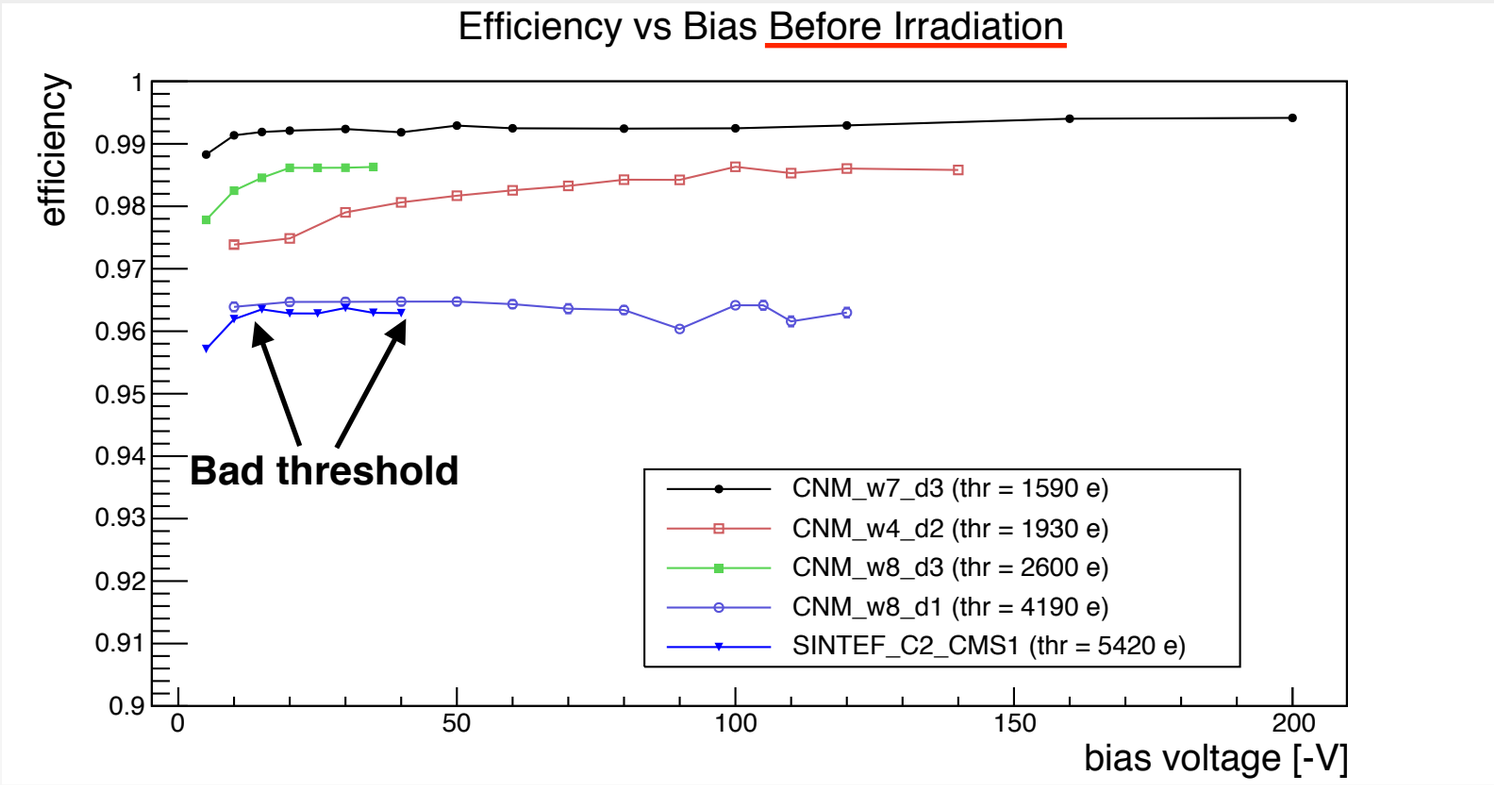


Efficiency vs bias (angle 0°)

Preliminary

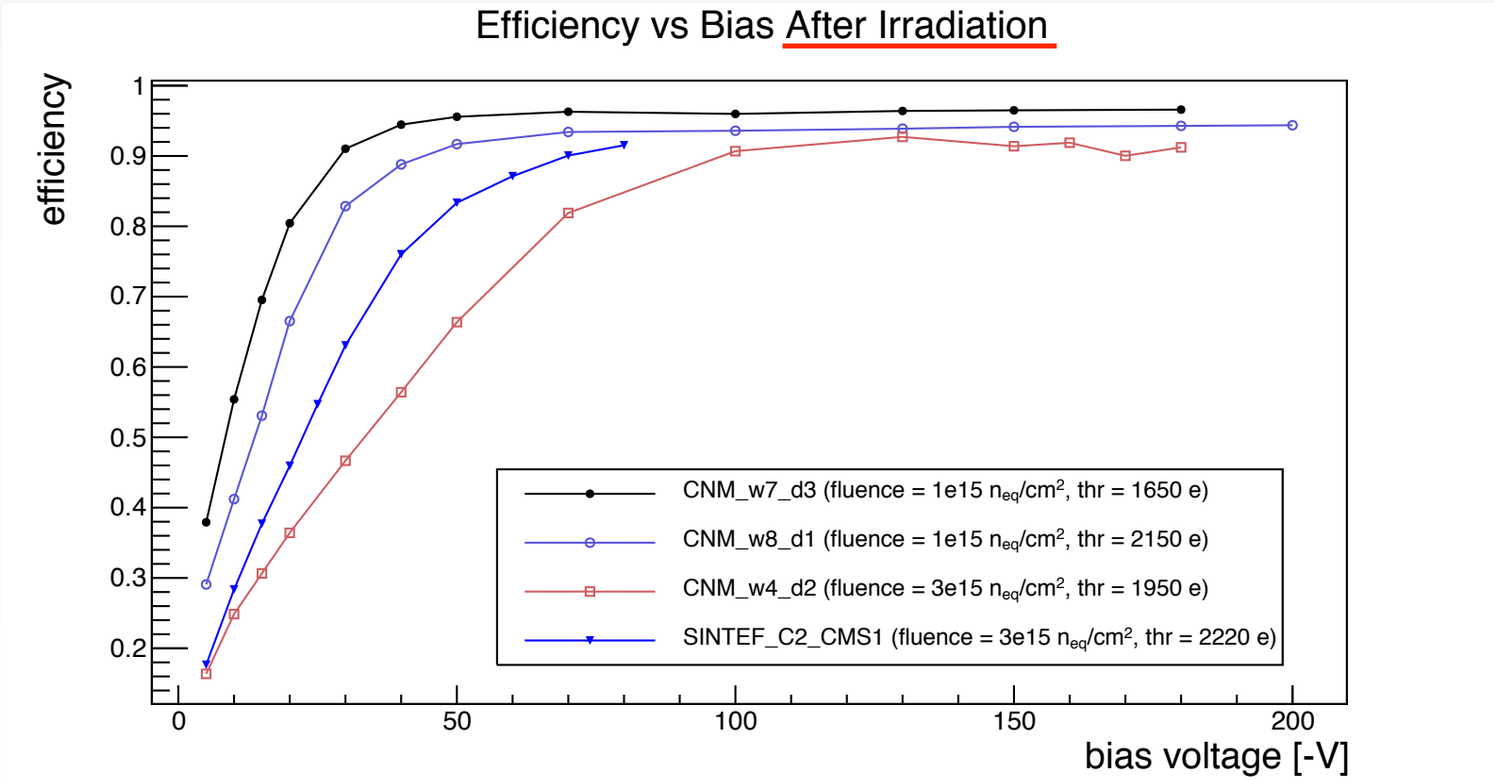
Before irradiation:

- Efficiencies are strongly dependent on the threshold
- Efficiency plateau at 15 V



After irradiation:

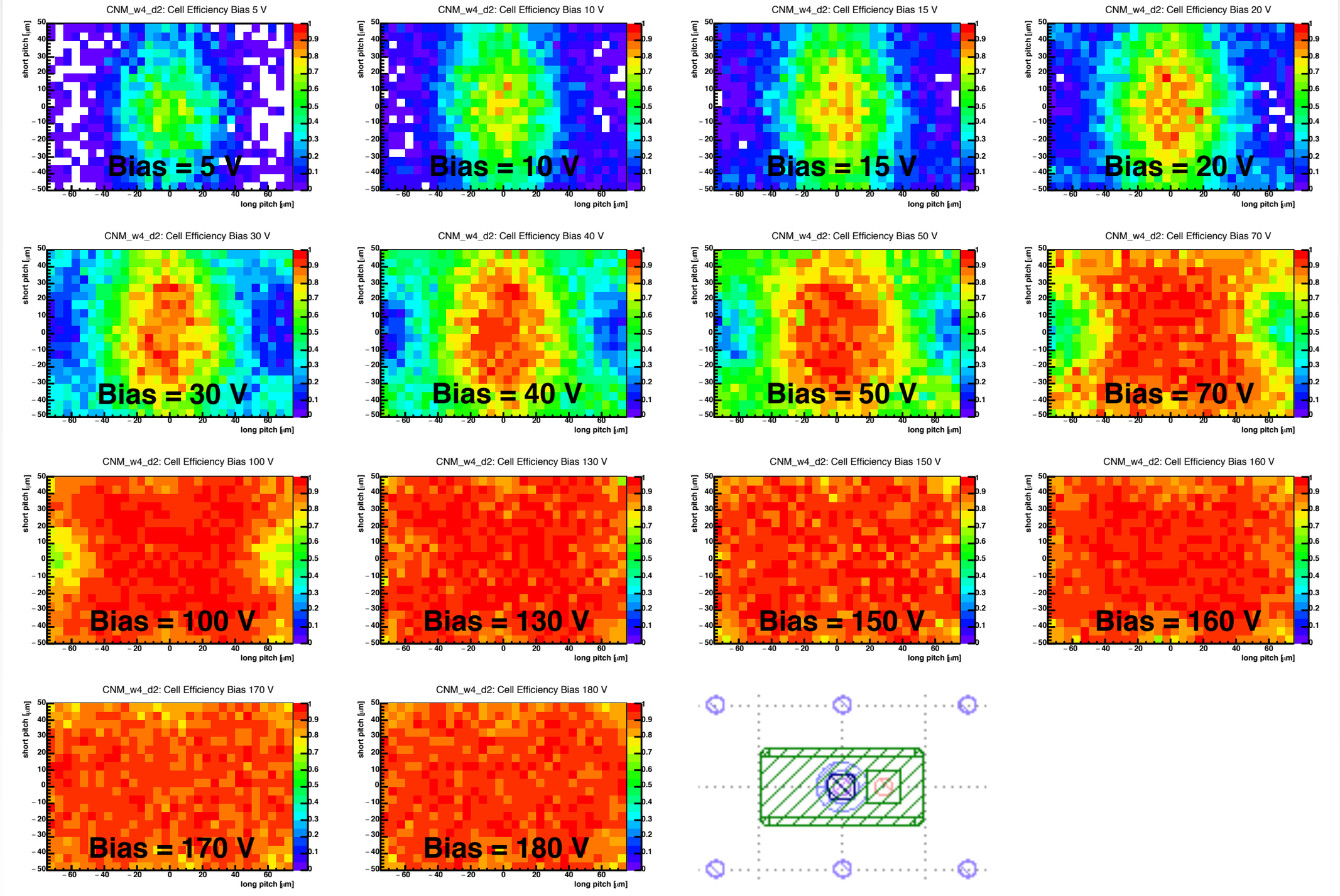
- Efficiency plateau already at ~70 V for less irradiated devices
- **Steeper increase of efficiency with bias for the 2E sensor with respect to the 1E** after $3x10^{15}$ n_{eq}/cm^2
- SINTEF sensor does not reach the plateau before breakdown. A higher breakdown would improve the efficiency



Pixel cell efficiency after irradiation

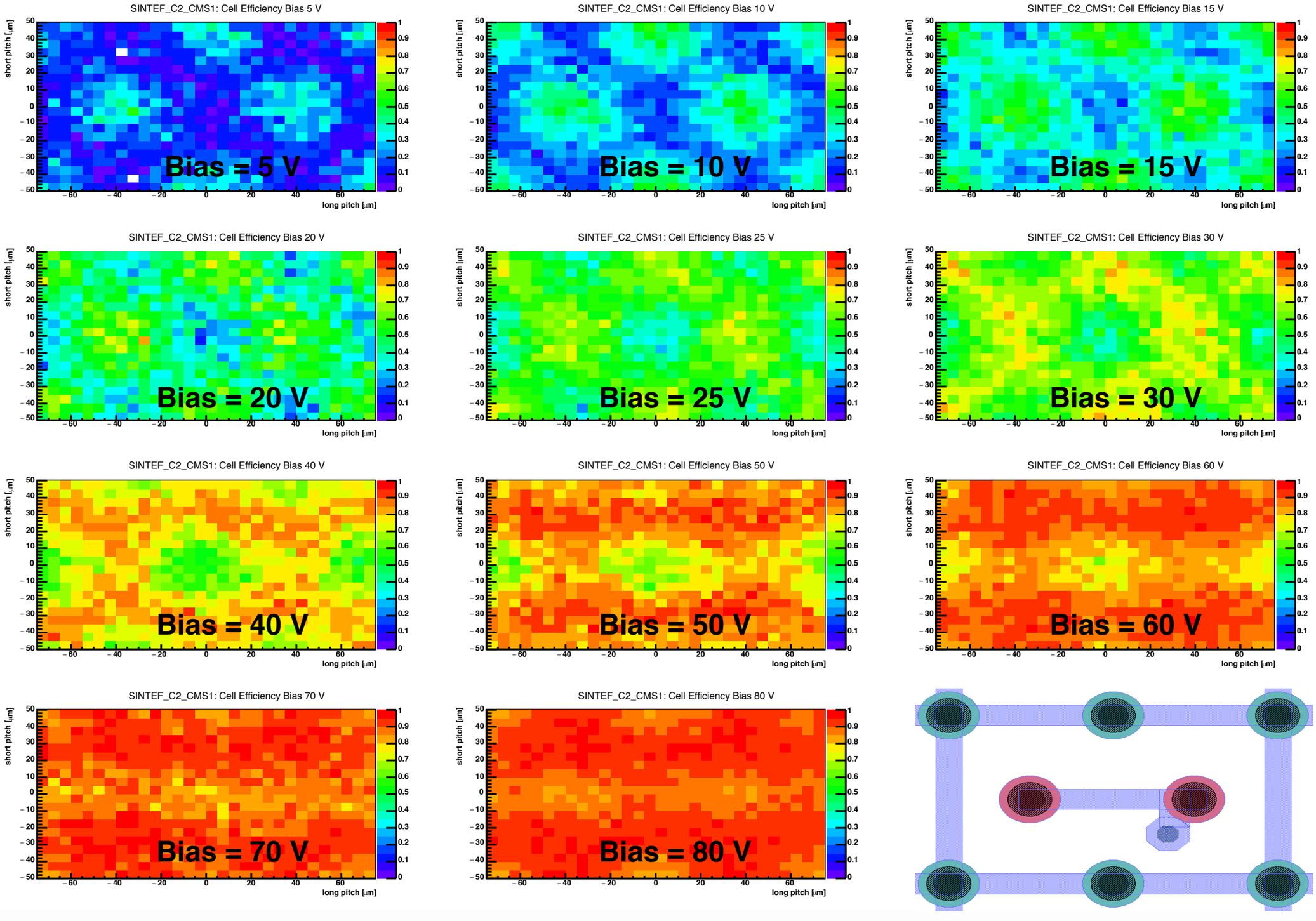
CNM_w4_d2 (3x10^{15} n_{eq}/cm^2, Angle = 0°)

Preliminary



Pixel cell efficiency after irradiation

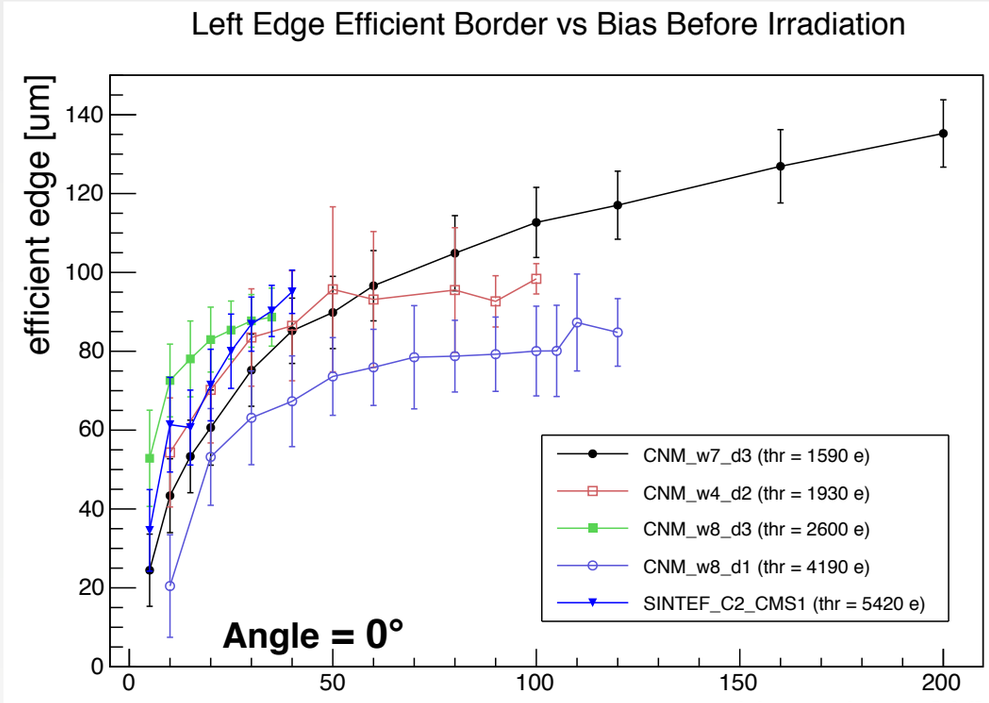
SINTEF_C2_CMS1 (3x10^{15} n_{eq}/cm^2, Angle = 0°)



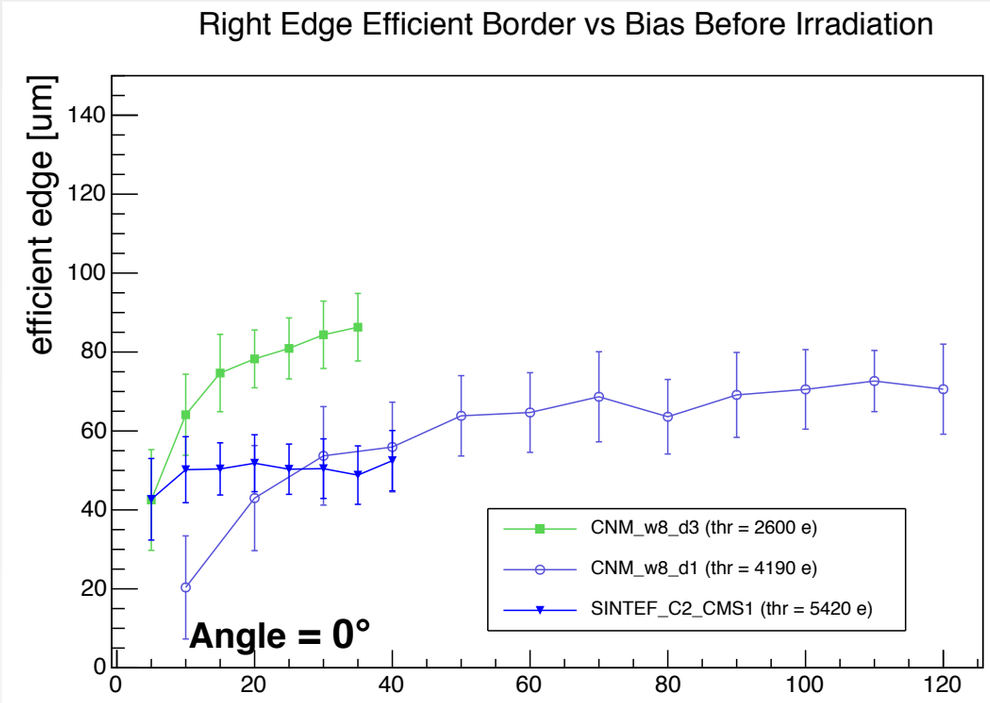
Efficient edge before irradiation

Preliminary

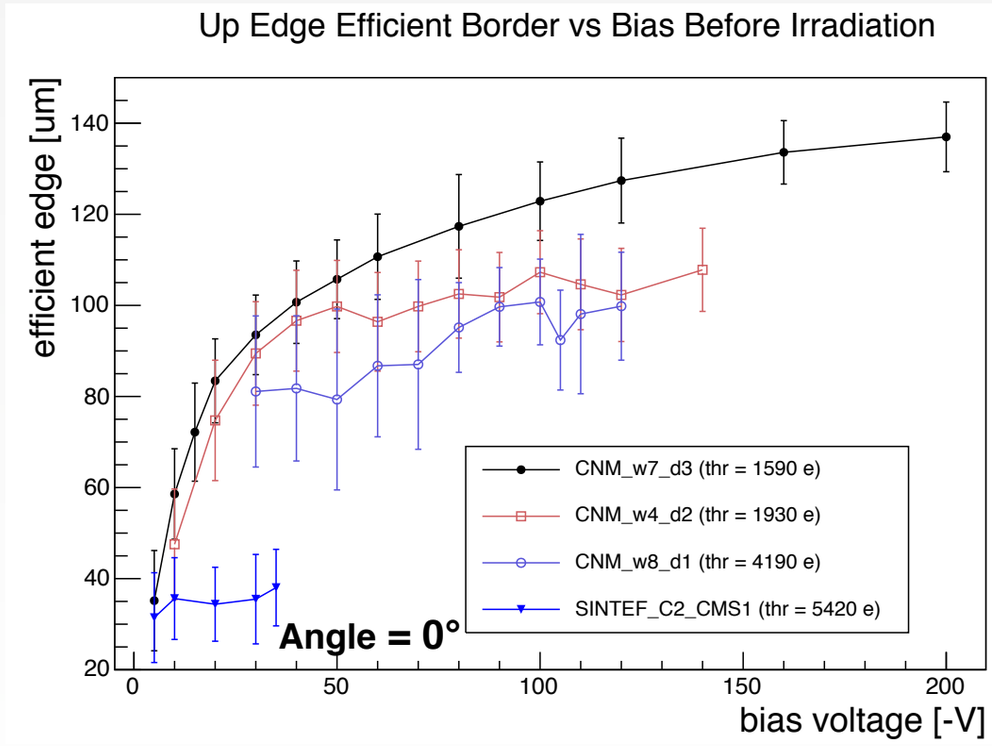
Left Edge



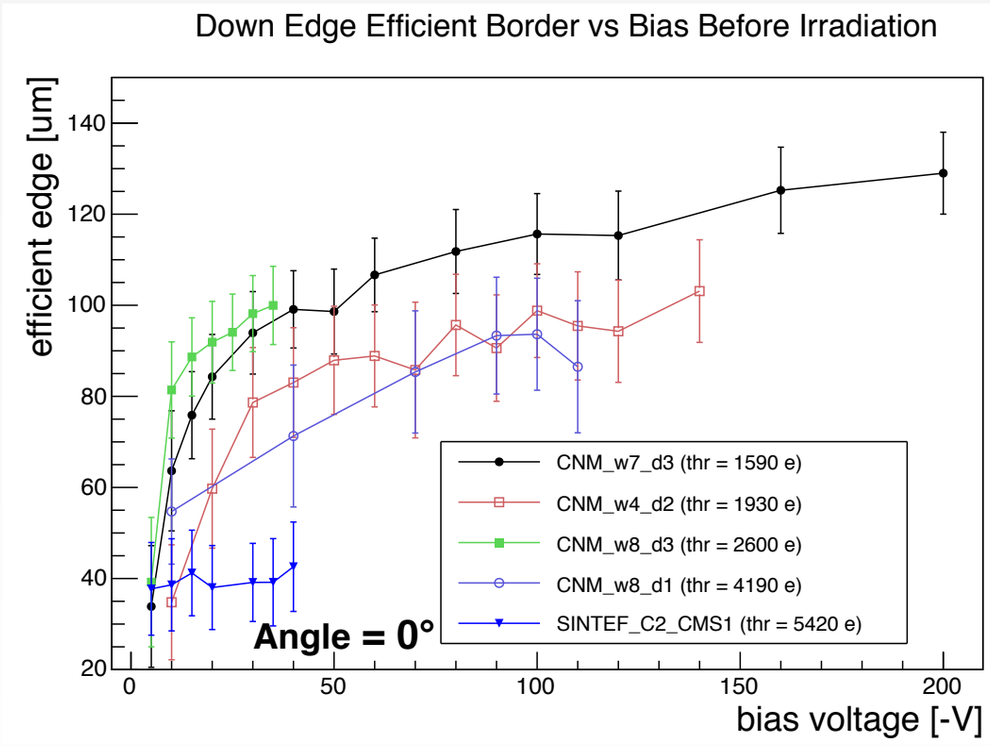
Right Edge



Up Edge



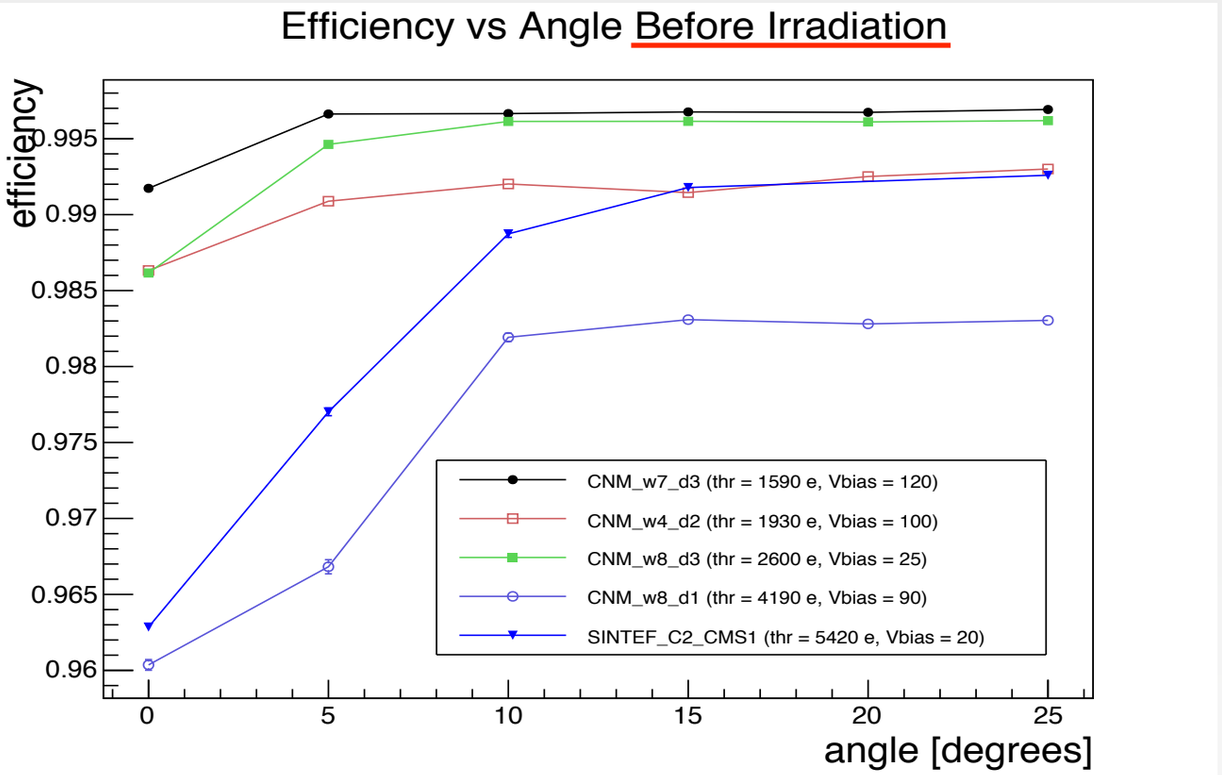
Down Edge

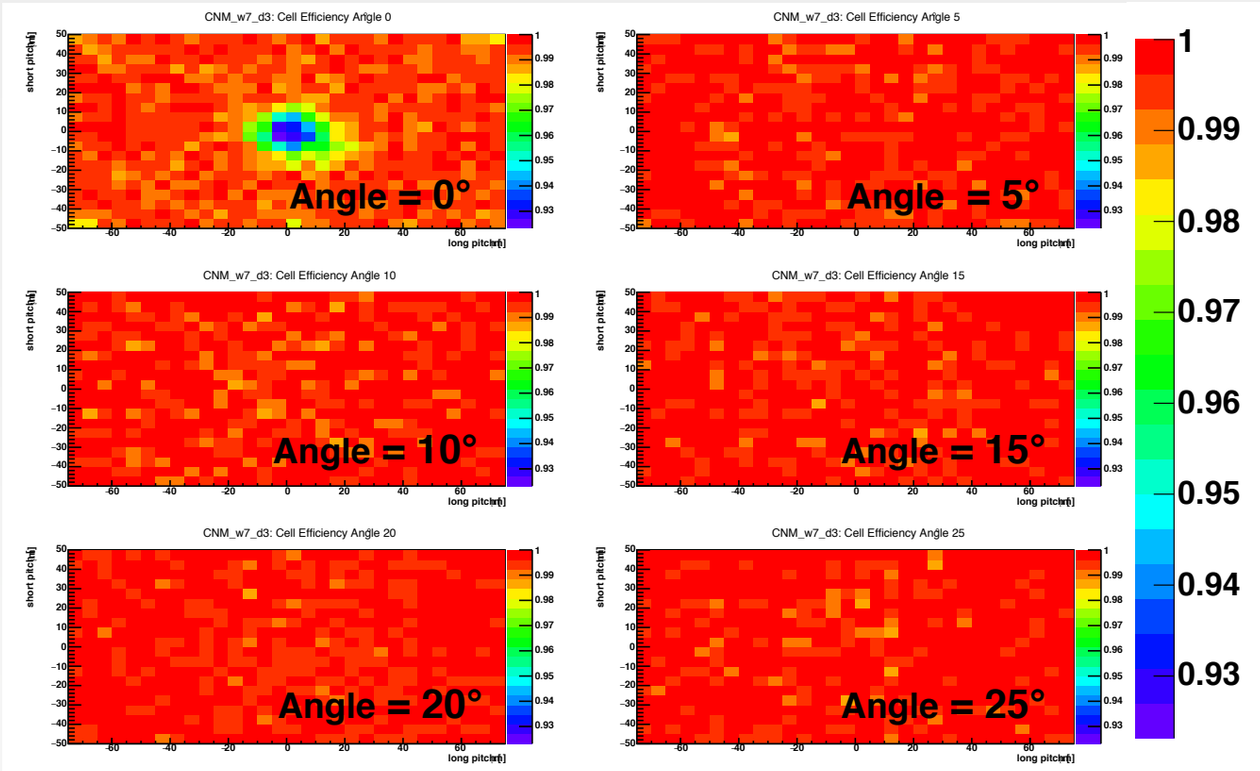


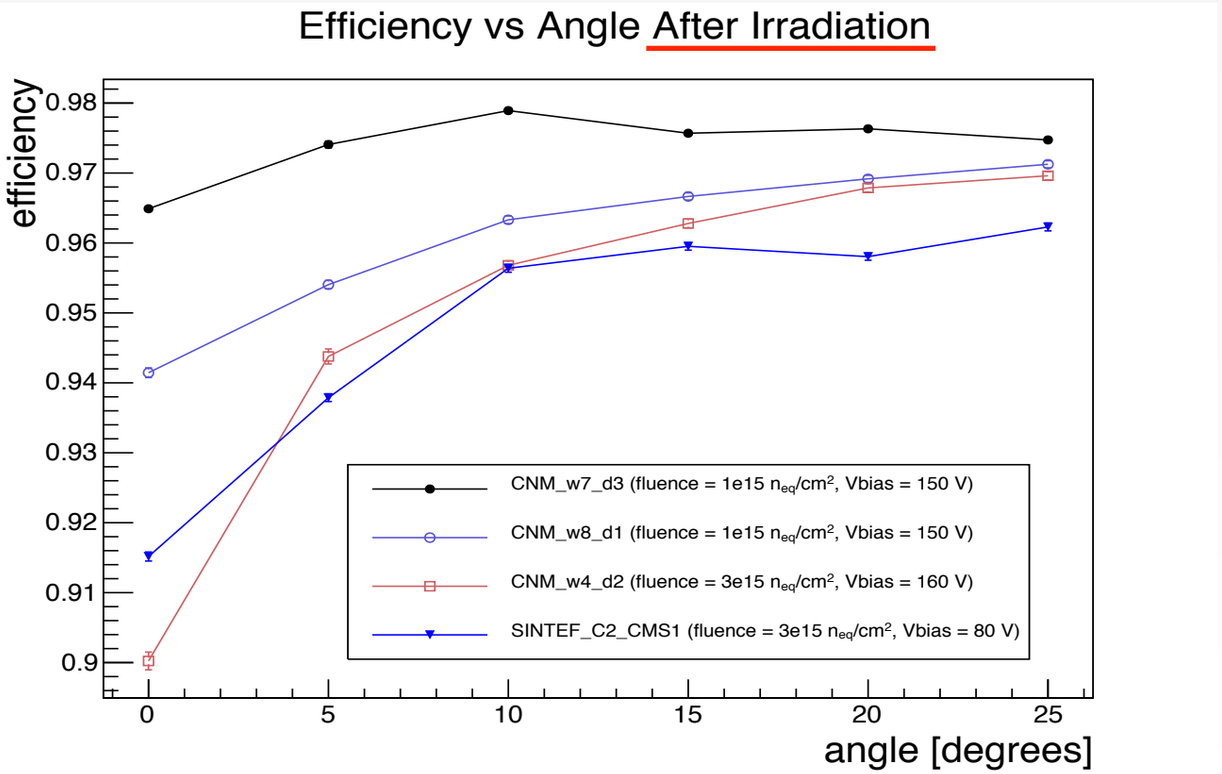
Error bars represent the width of the SCurve when fitting the edge efficiency

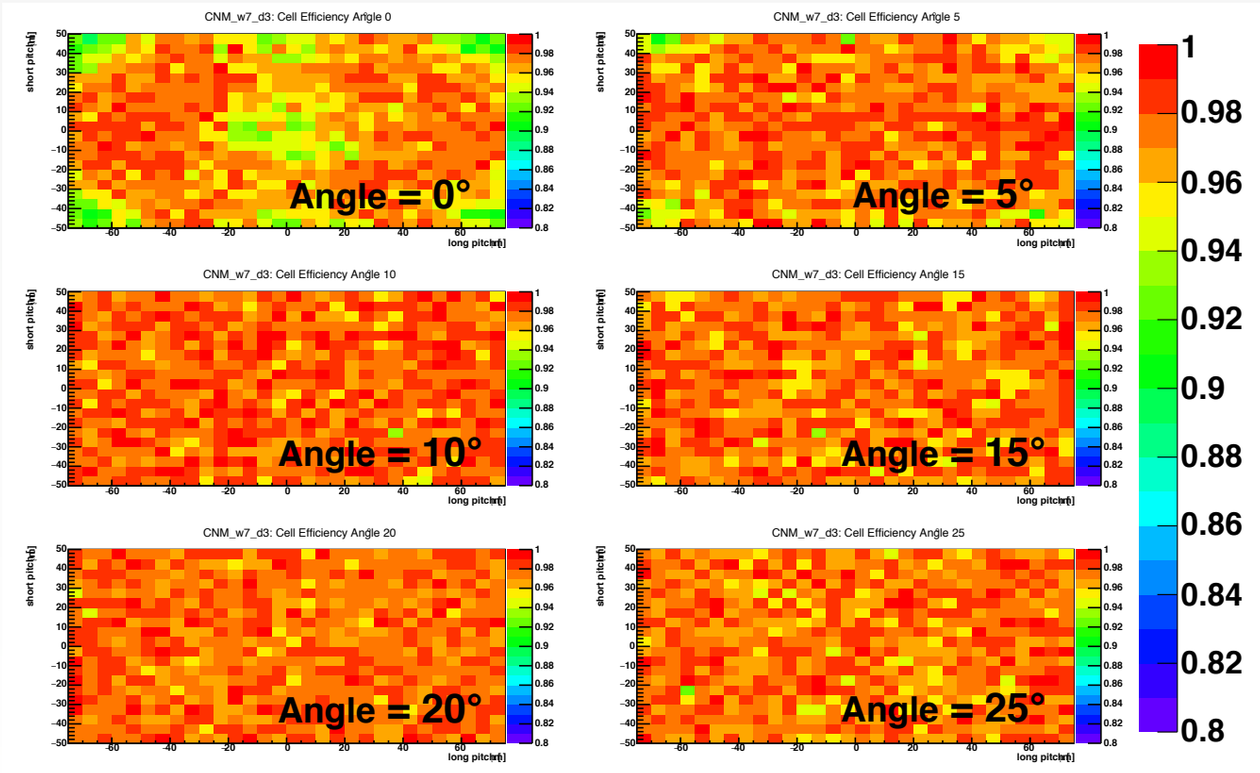
Efficiency vs angle

Preliminary







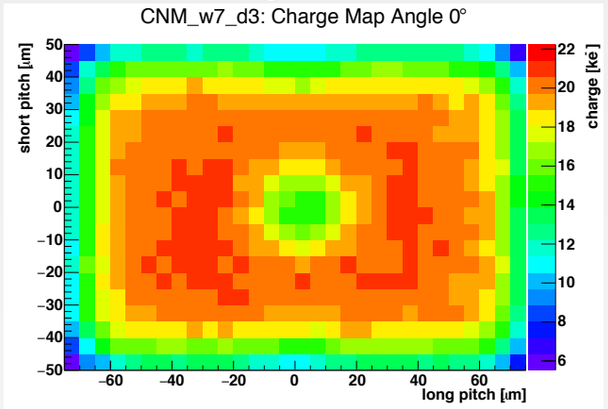


Cell charge vs angle before irradiation

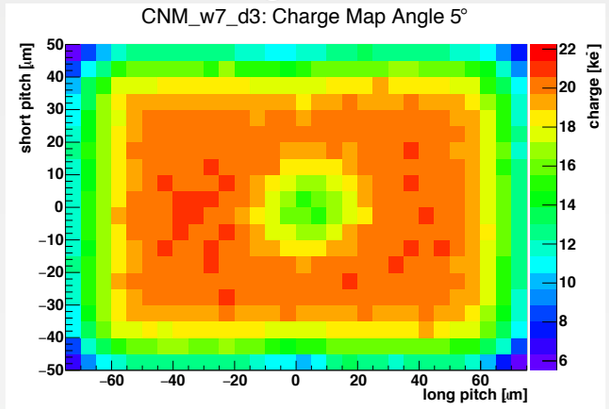
Preliminary

CNM_w7_d3 (Bias = 120 V)

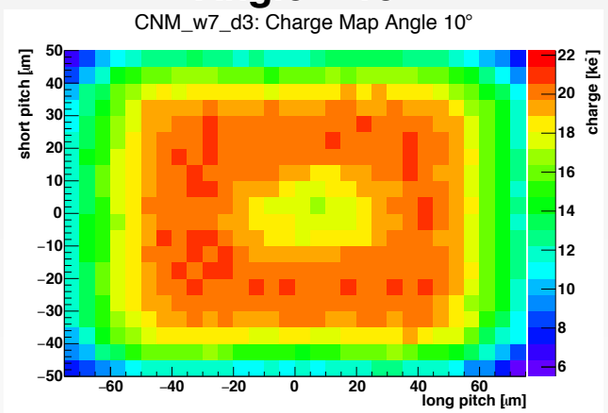
Angle = 0°



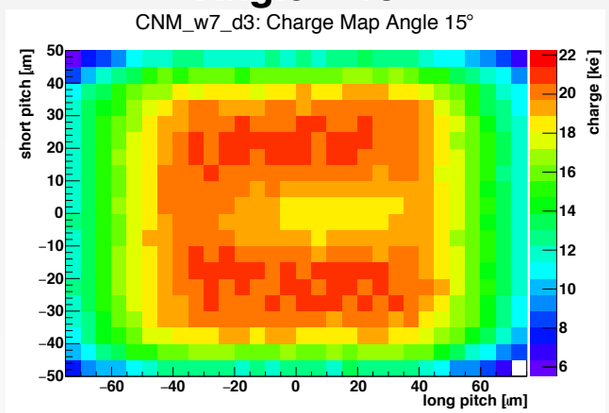
Angle = 5°



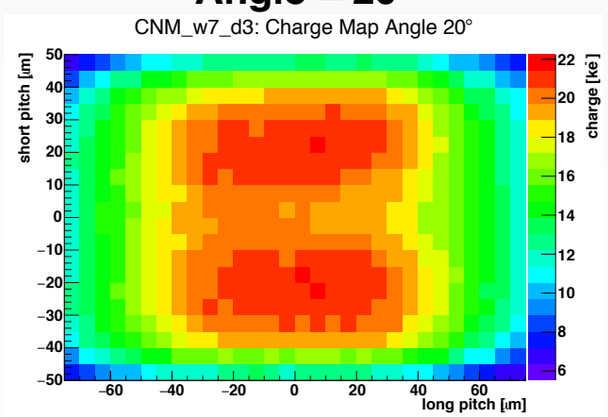
Angle = 10°



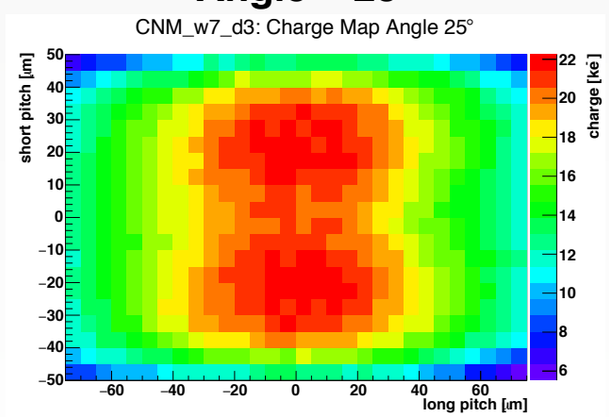
Angle = 15°



Angle = 20°

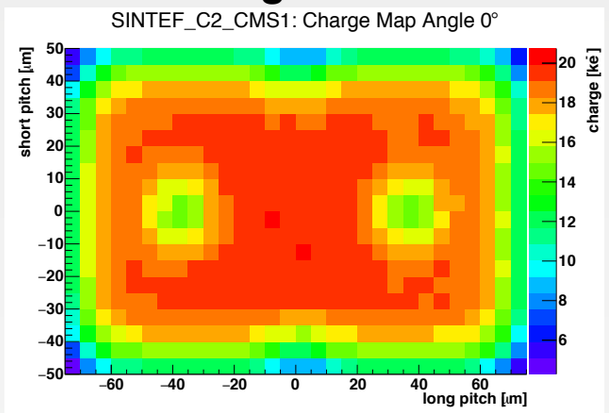


Angle = 25°

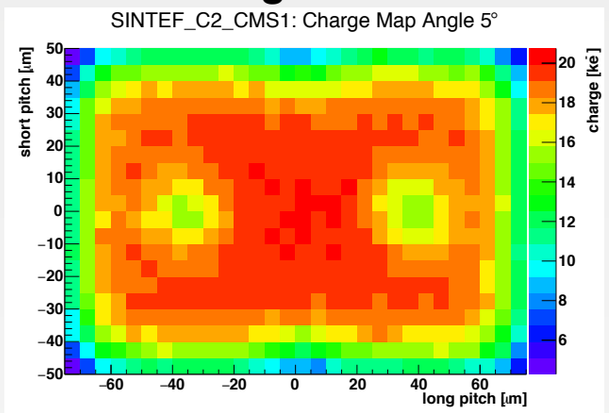


SINTEF_C2_CMS1 (Bias = 20 V)

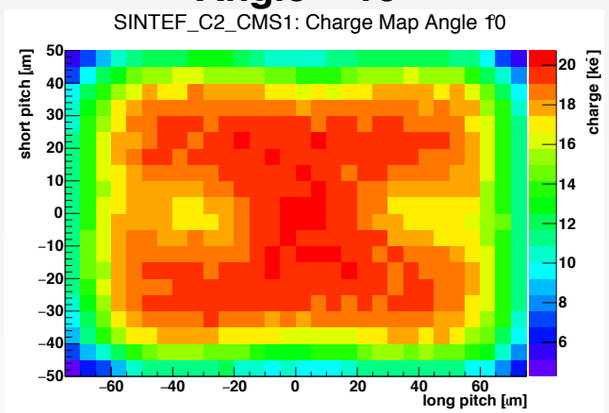
Angle = 0°



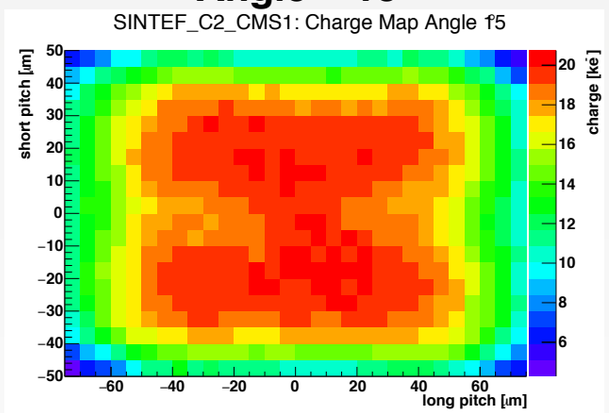
Angle = 5°



Angle = 10°

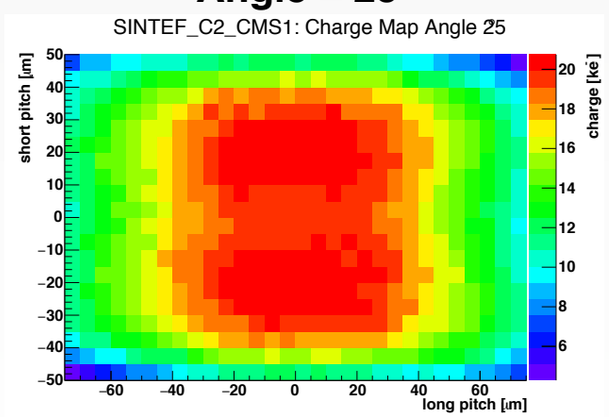


Angle = 15°



Missing measurement at angle = 20°

Angle = 25°

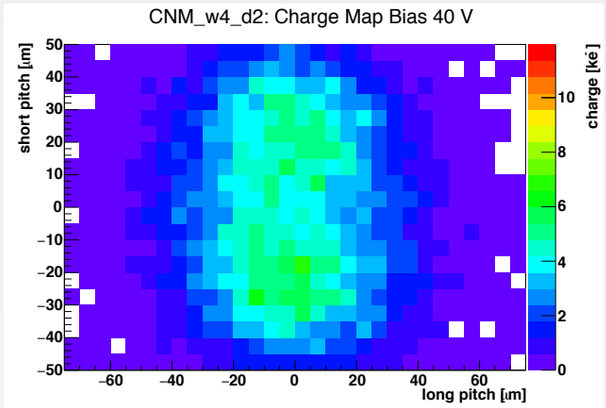


Cell charge vs bias after irradiation

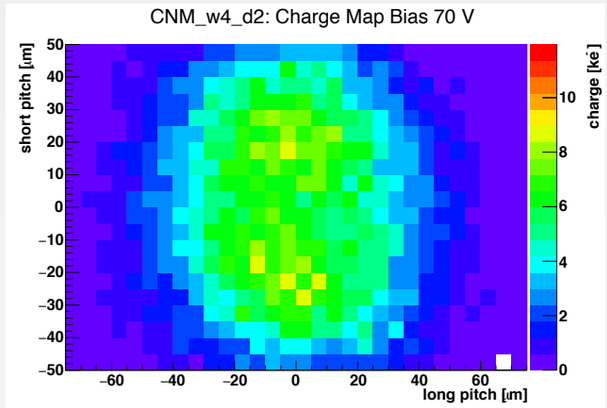
Preliminary

CNM_w4_d2 (3x10^{15} n_{eq}/cm^2, Angle = 0°)

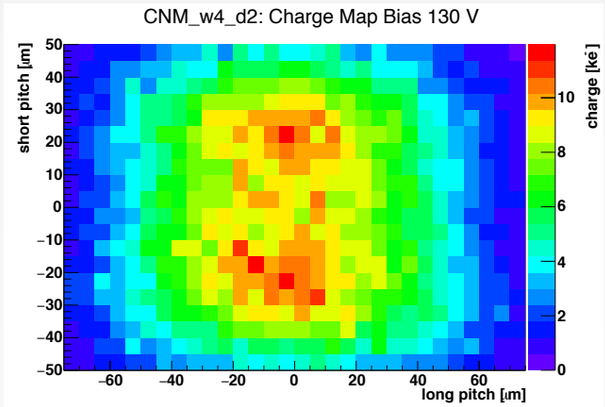
Bias = 40 V



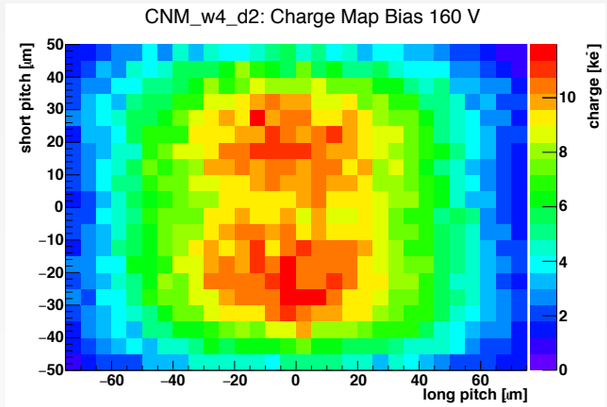
Bias = 70 V



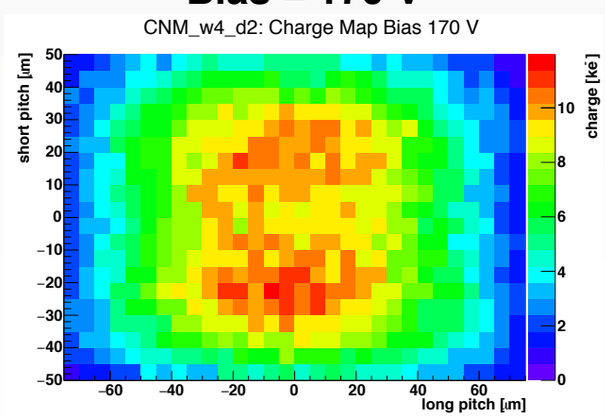
Bias = 130 V



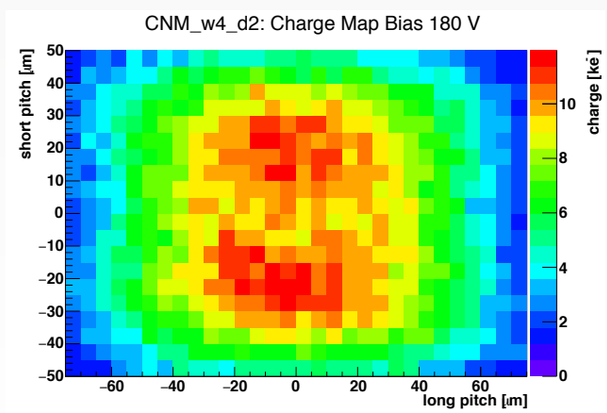
Bias = 160 V



Bias = 170 V

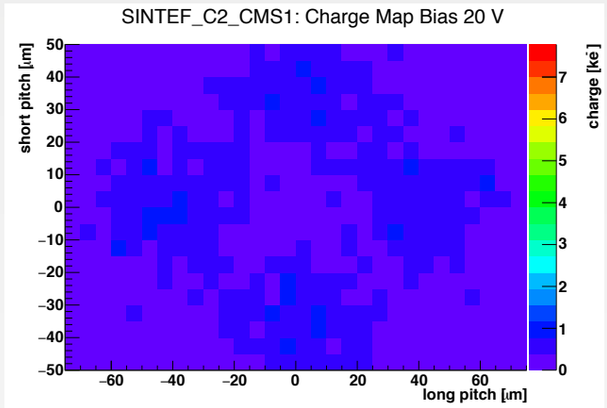


Bias = 180 V

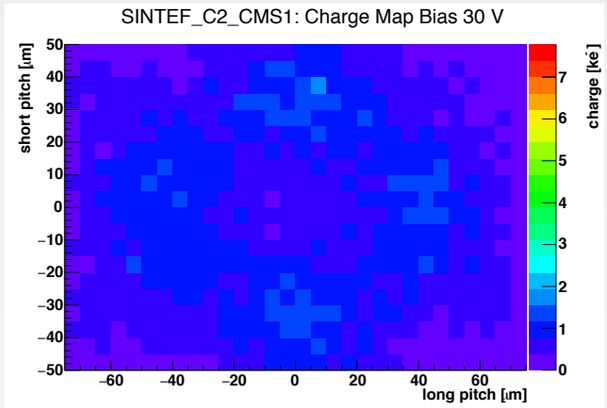


SINTEF_C2_CMS1 (3x10^{15} n_{eq}/cm^2, Angle = 0°)

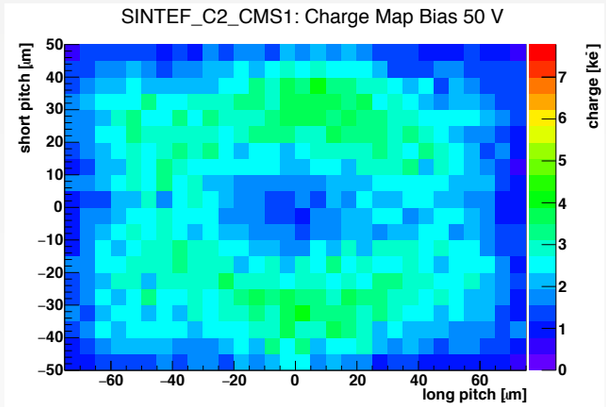
Bias = 20 V



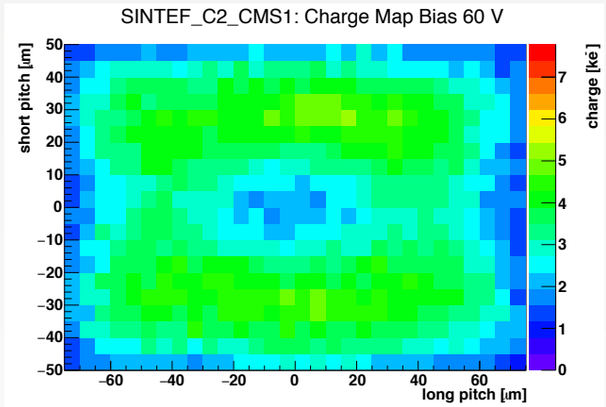
Bias = 30 V



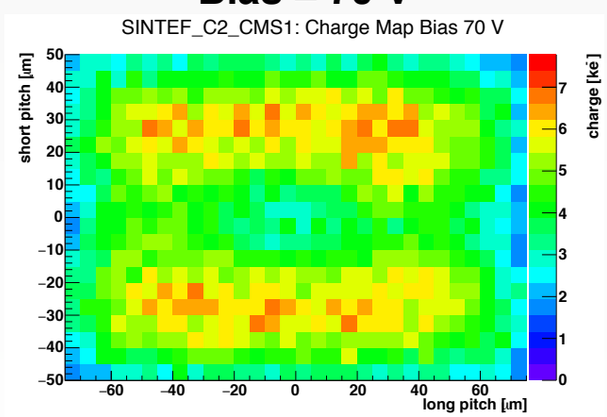
Bias = 50 V



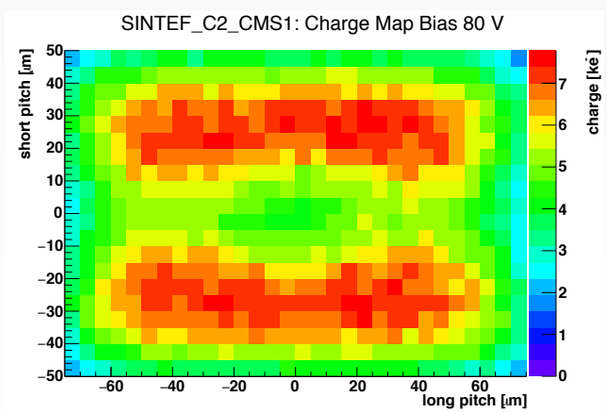
Bias = 60 V



Bias = 70 V



Bias = 80 V



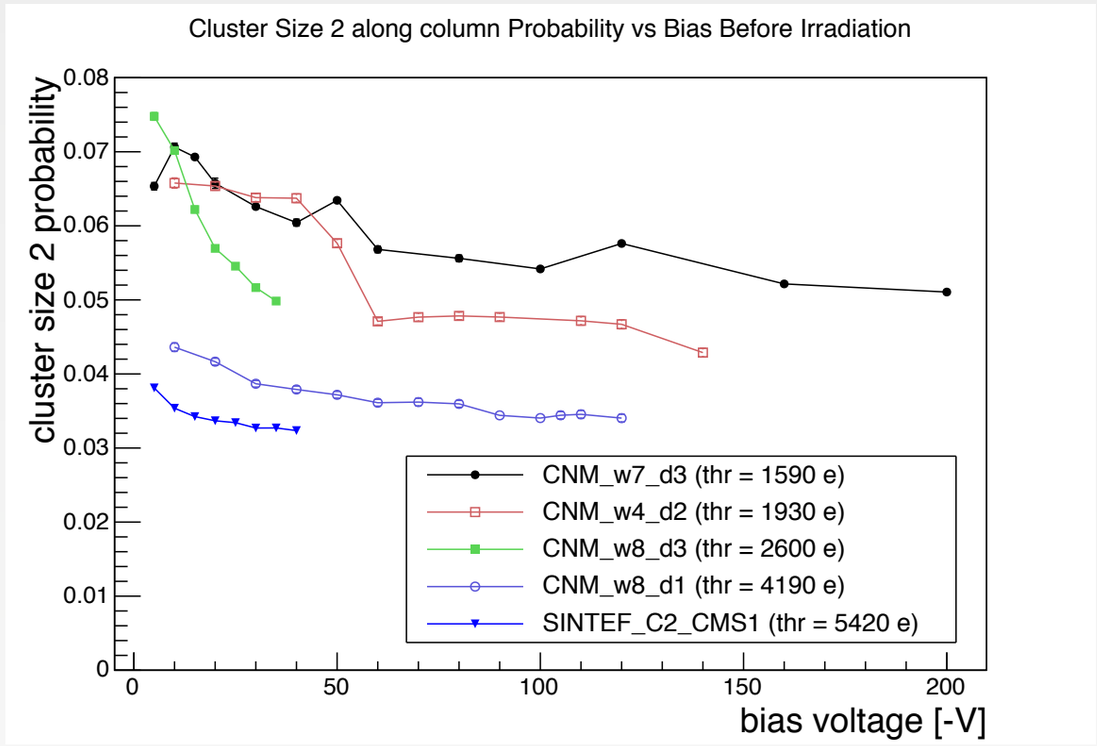
Cluster size 2 before and after irradiation

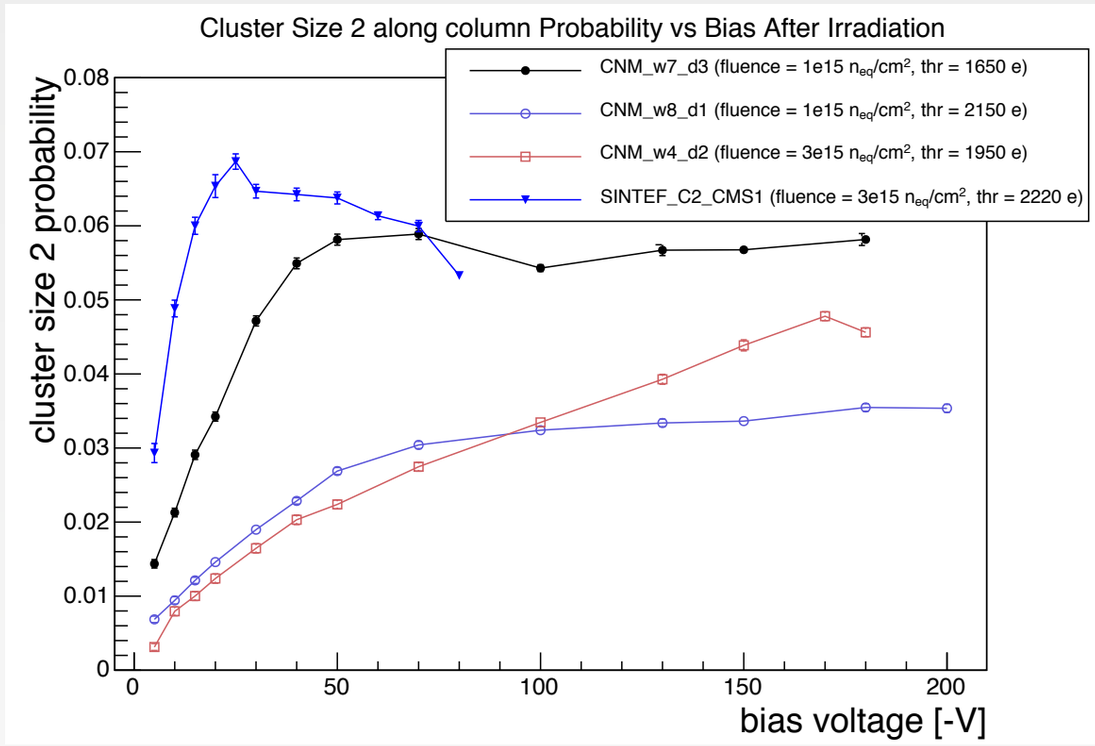
Preliminary

Before Irradiation

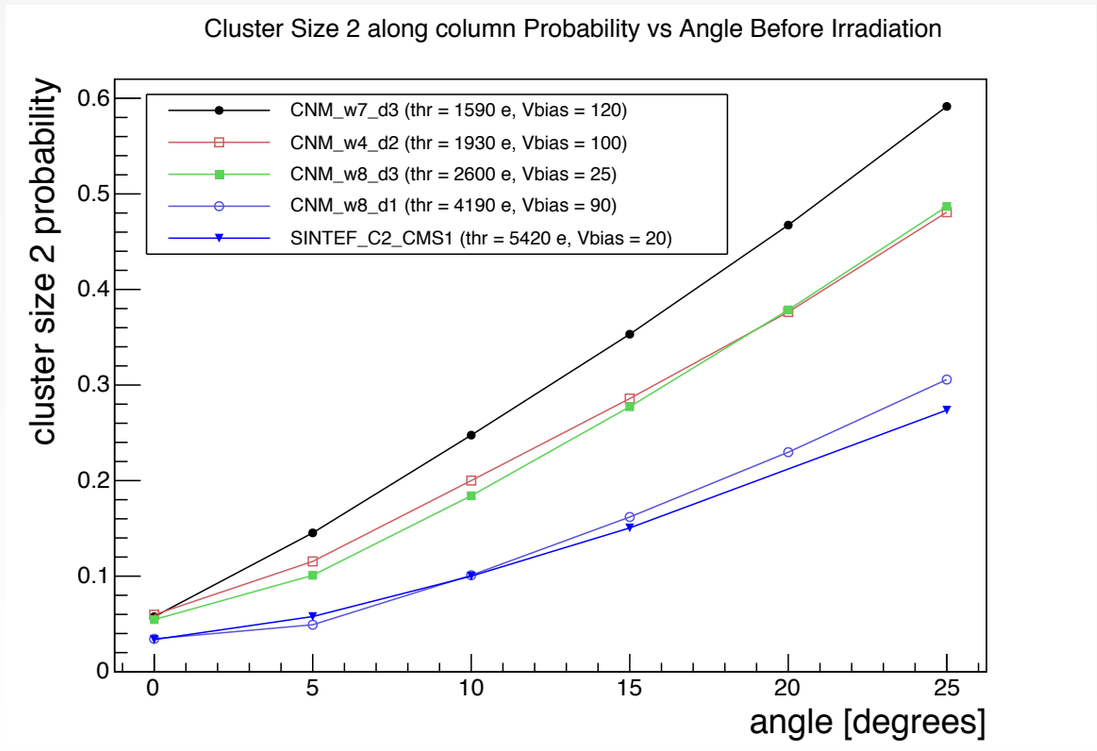
After Irradiation

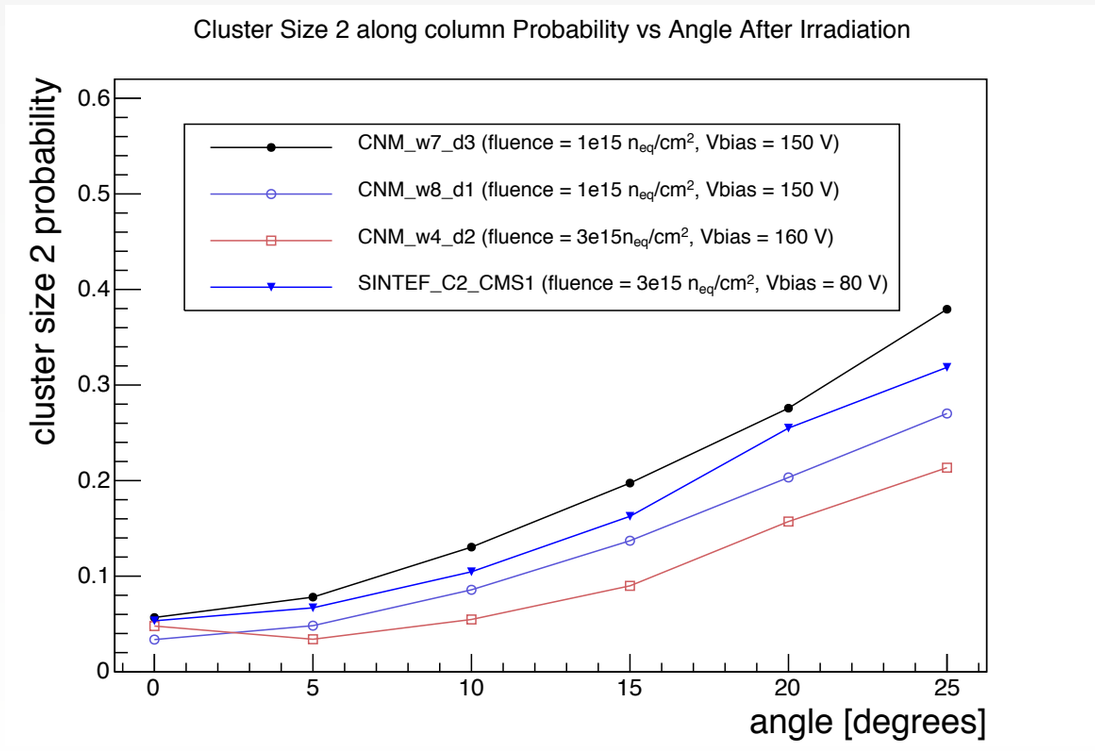
vs Bias





vs Angle





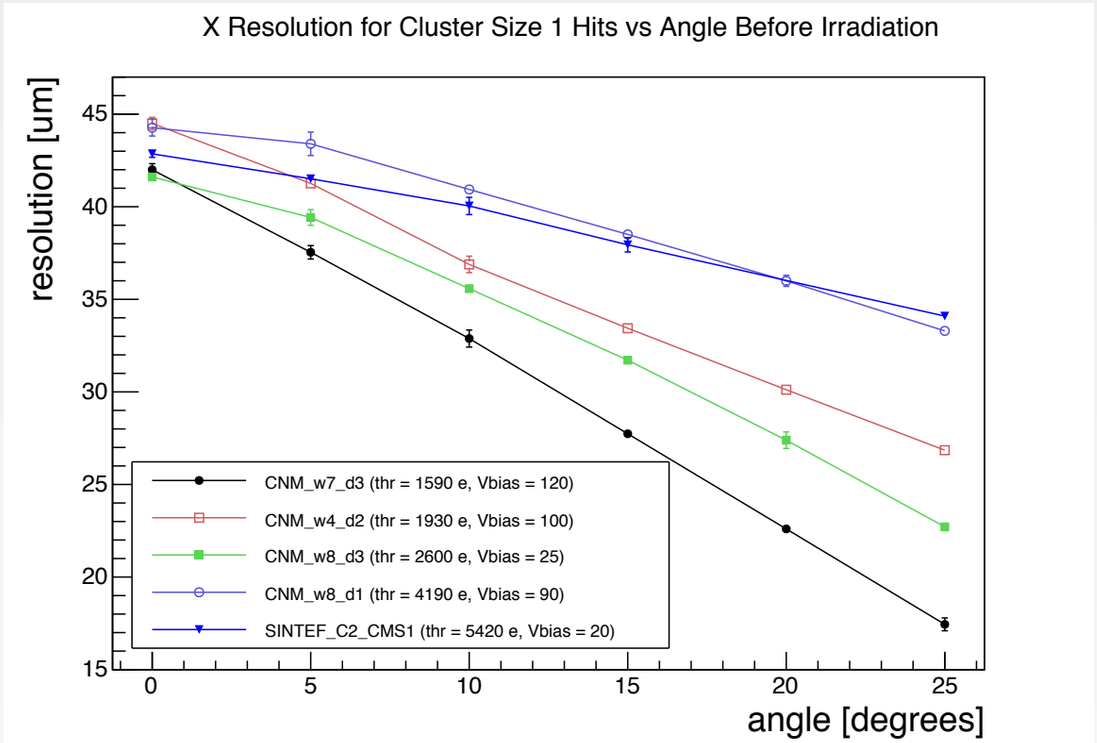
Resolution before and after irradiation

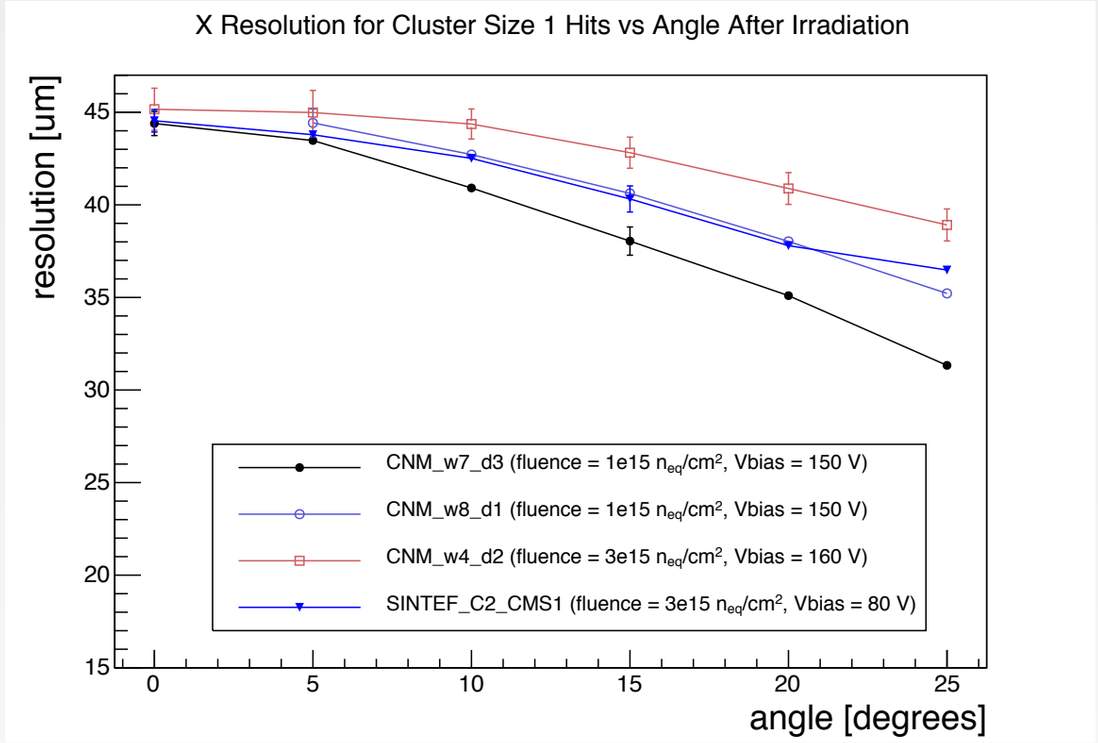
Preliminary

Before Irradiation

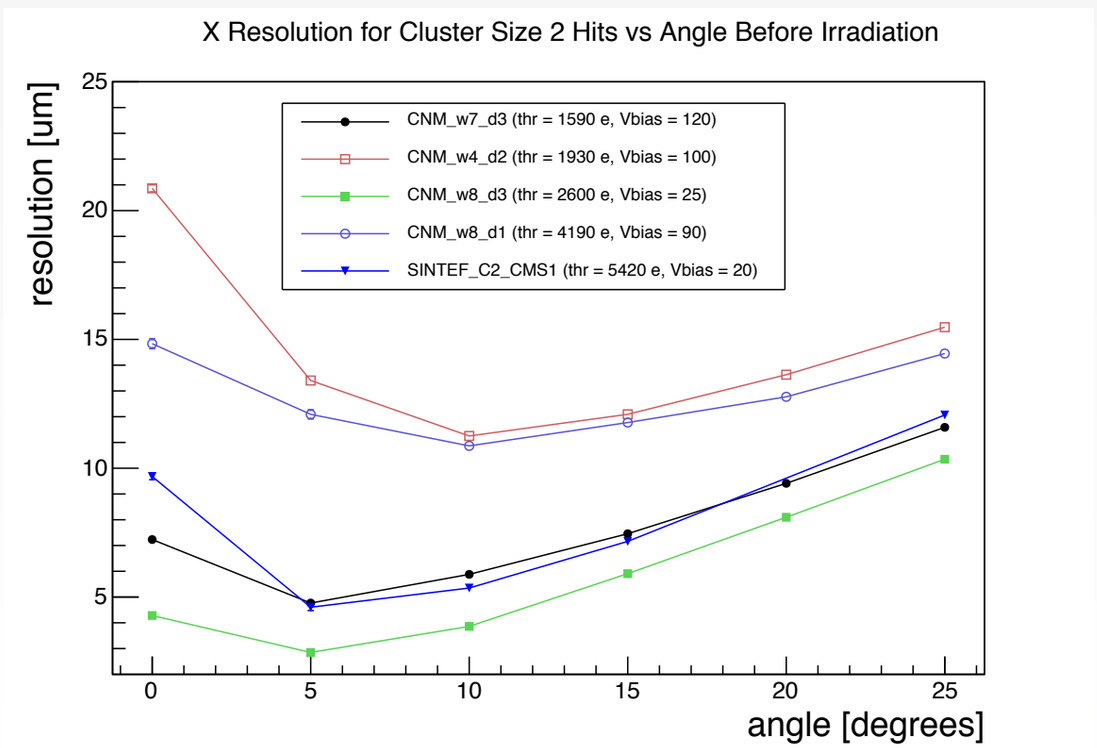
After Irradiation

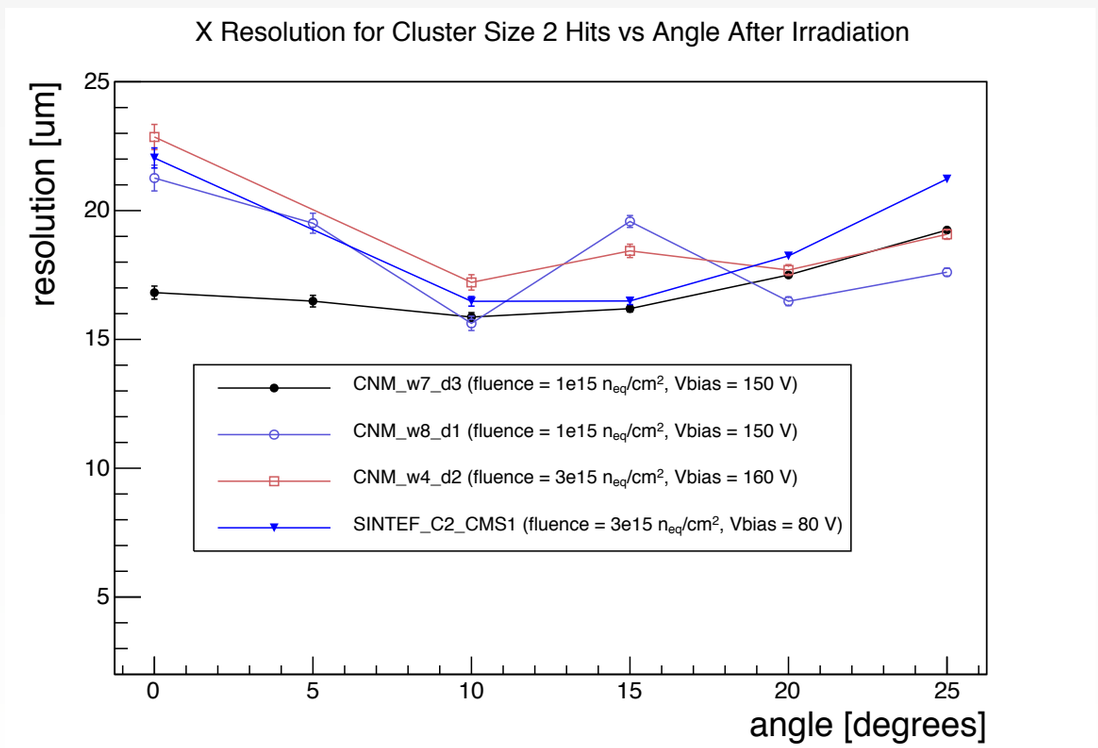
Cluster Size 1





Cluster Size 2





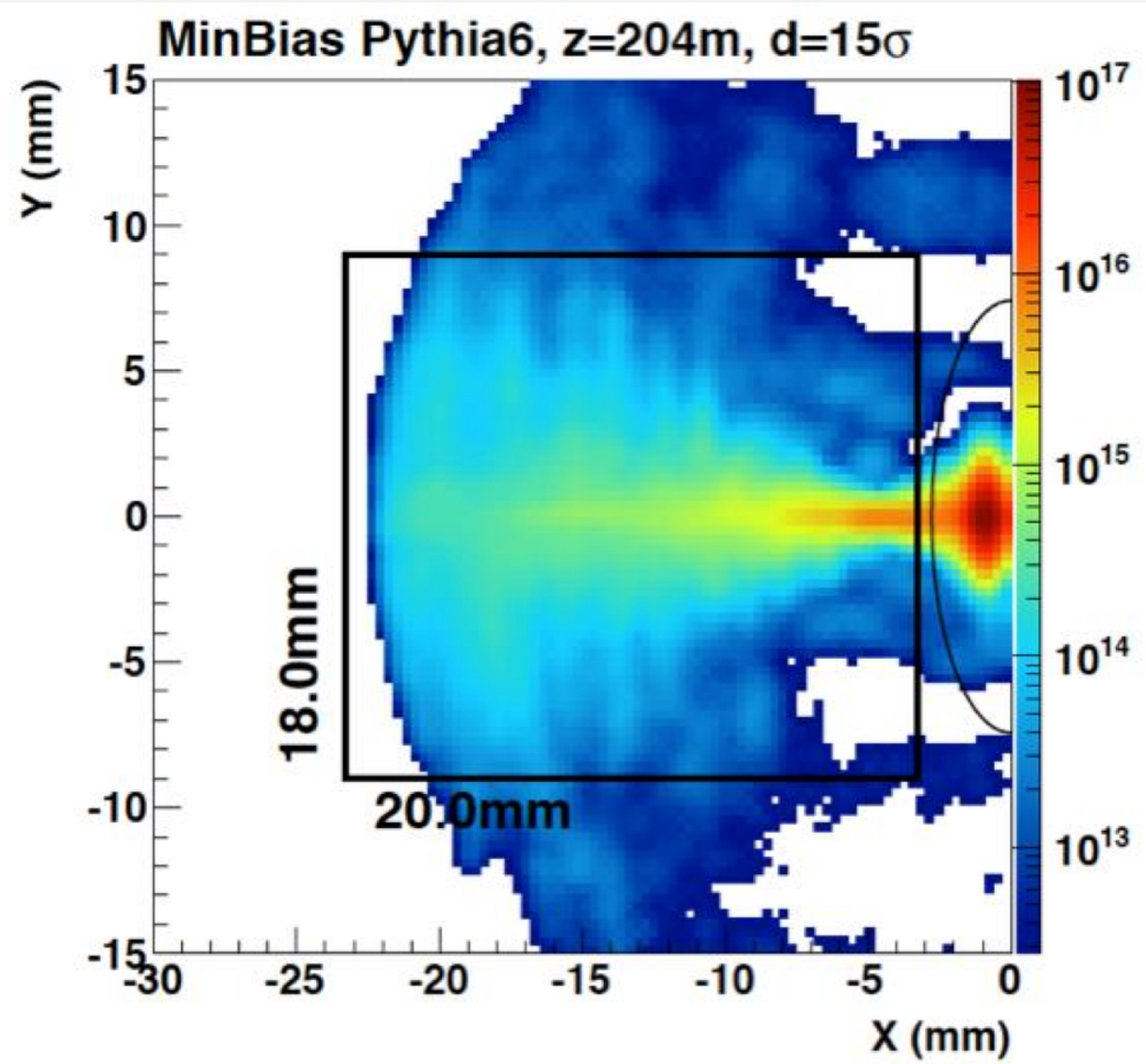
Conclusions

- CNM 1E and SINTEF 2E 3D sensors bump-bonded to CMS digital ROCs have been tested successfully before and after irradiation. Preliminary results have been shown
- Efficiency before irradiation > 99% for an angle of 20°
- Efficiency > 95% for an angle of 20° after irradiation of $1x10^{15}$ and $3x10^{15}$ n_{eq}/cm^2
- Inefficient edge reduction of more than 120 μm for CNM sensors before irradiation
- Edge efficiency compatible with design for SINTEF sensor
- Cluster size 2 probability behaviour as a function of bias and angle as expected before and after irradiation and strongly dependent on the ROC threshold
- Resolutions before irradiation for an angle of 20°: ~25-30 μm for cluster size 1 and ~8-13 μm for cluster size 2
- Resolutions after irradiation for an angle of 20°: ~35-40 μm for cluster size 1 and ~16-18 μm for cluster size 2
- Effort ongoing to match the irradiation profile with the collected charge map to determine the irradiation fluence distribution on ROC
- For the CT-PPS tracking detector 2E pixel sensors with 200 um slim edges are being produced at CNM - first batch of wafers ready for bump-bonding at IZM, second batch almost finished.

Backup

Radiation level

Radiation levels in the detector volume were studied using TOTEM data and simulations

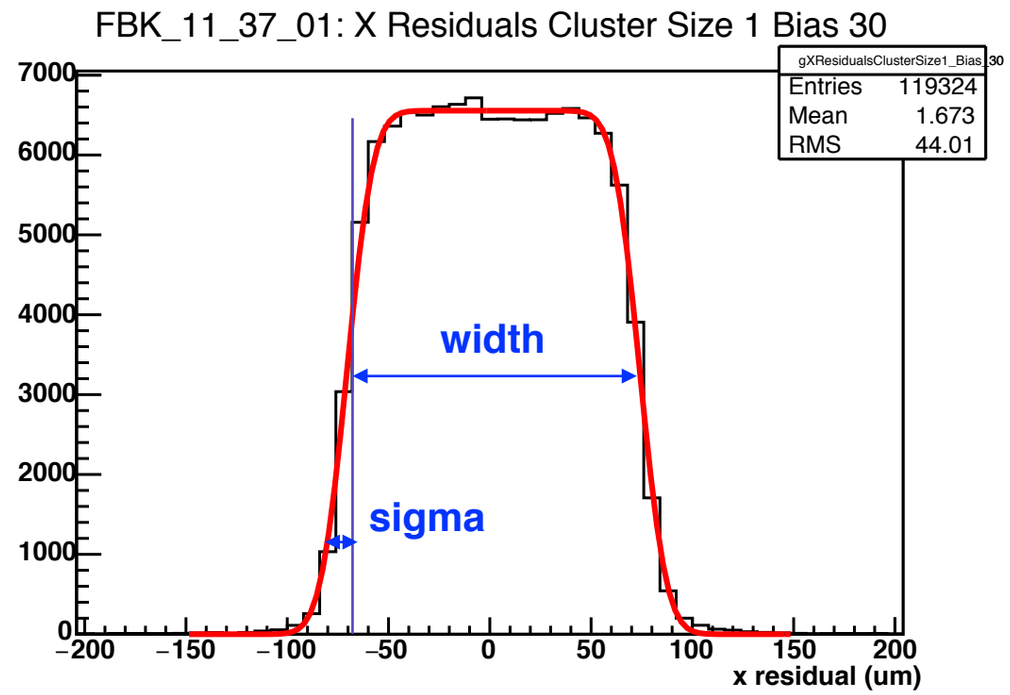


Per 100 fb^{-1}:

- Proton flux up to 5.10^{15} cm^{-2} in the pixel detectors
- 10^{12} neq/cm^2 and 100 Gy in photosensors and readout electronics

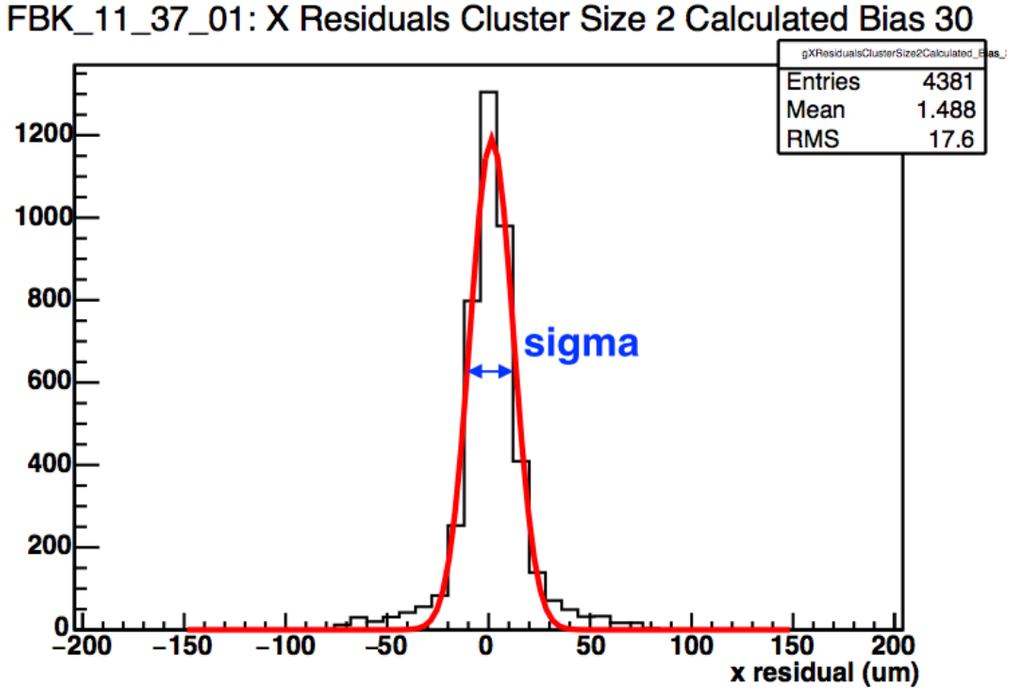
Residuals plots

Preliminary



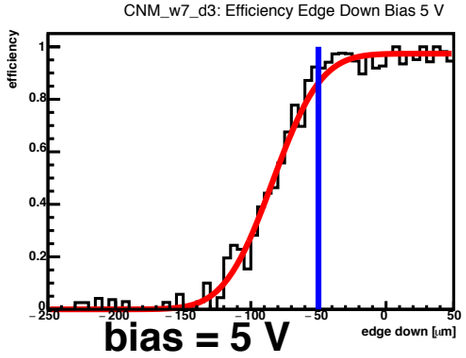
- Residuals cluster size 1 fitted with a square function convoluted with a gaussian.
- Residuals cluster size 2 “Calculated” evaluated by the charge asymmetry and fitted with a gaussian.

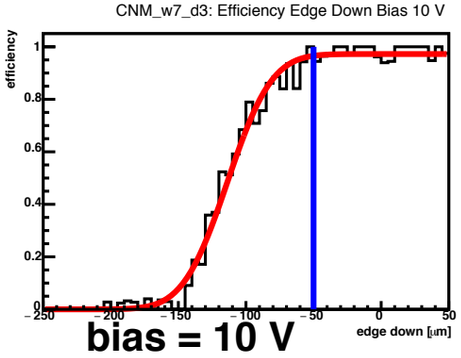
$$\sigma_{CS1} = \sqrt{\left(\frac{width_{CS1}}{\sqrt{12}}\right)^2 + sigma^2_{CS1} - sigma^2_{telescope}}$$

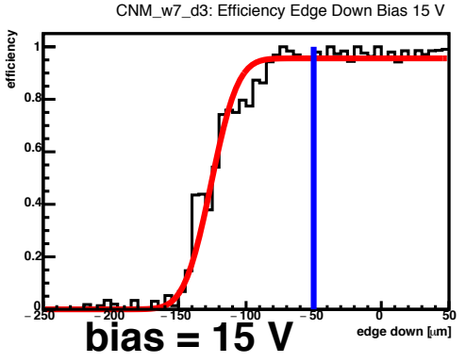


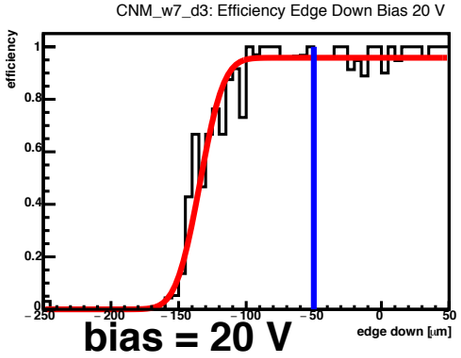
$$\sigma_{CS2} = \sqrt{sigma^2_{CS2} - sigma^2_{telescope}}$$

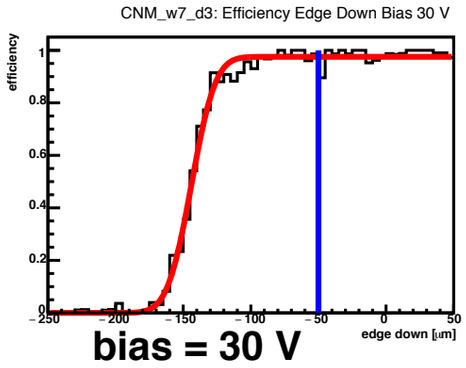
Egde Efficiency fitting

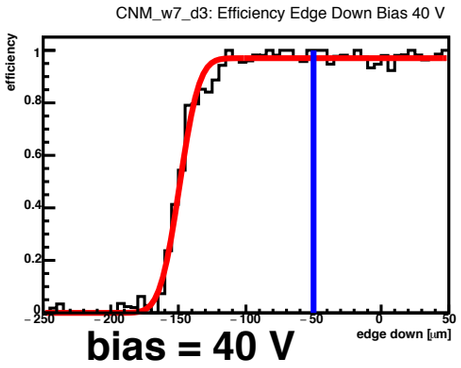


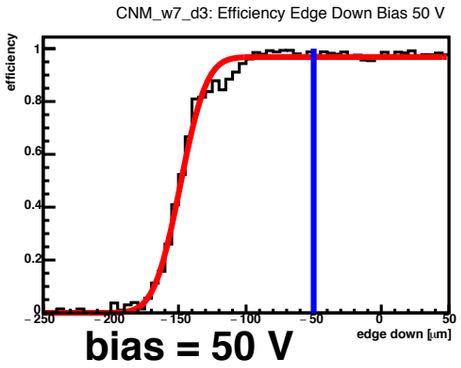


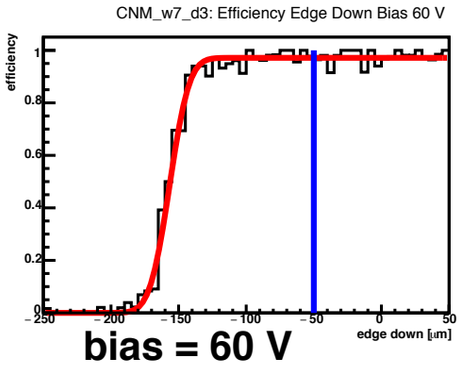


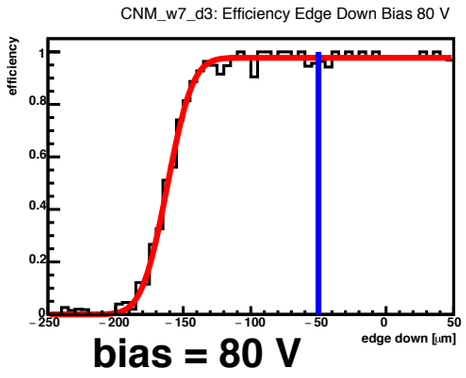


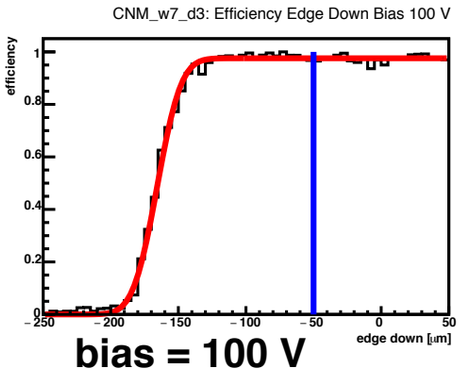


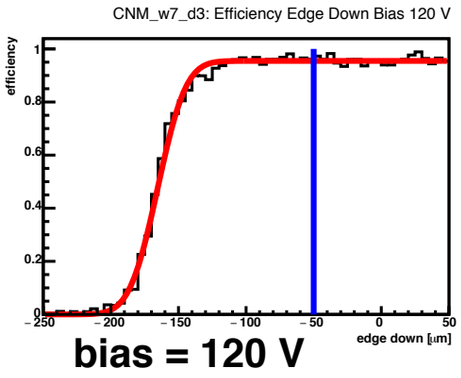


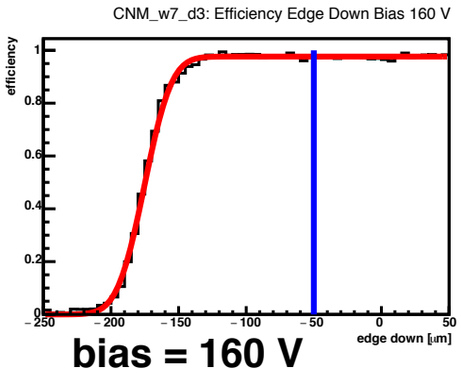


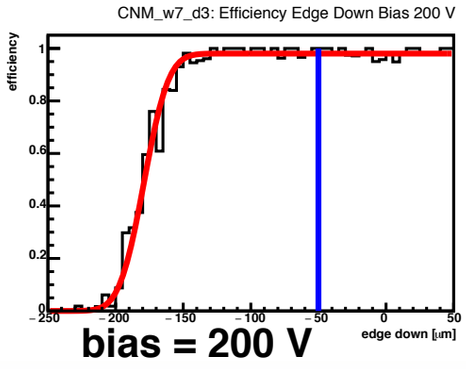












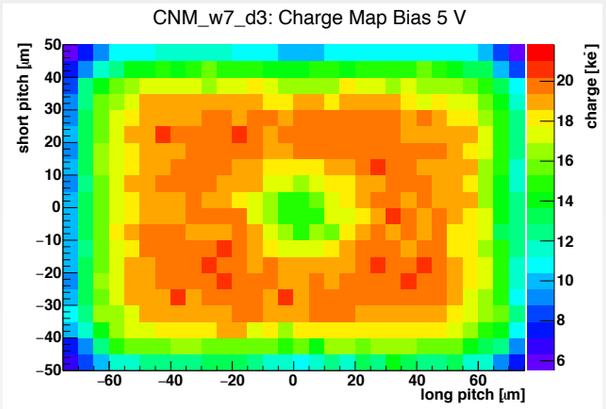
Efficiencies fitted with a SCurve
The vertical blue line indicates the geometrical end of the pixel

Cell charge vs bias before irradiation

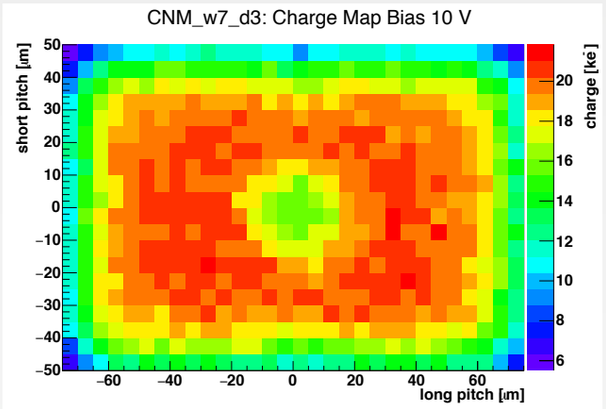
Preliminary

CNM_w7_d3 (Angle = 0°)

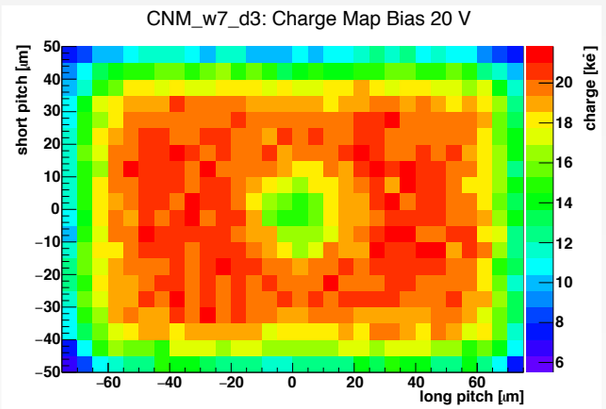
Bias = 5 V



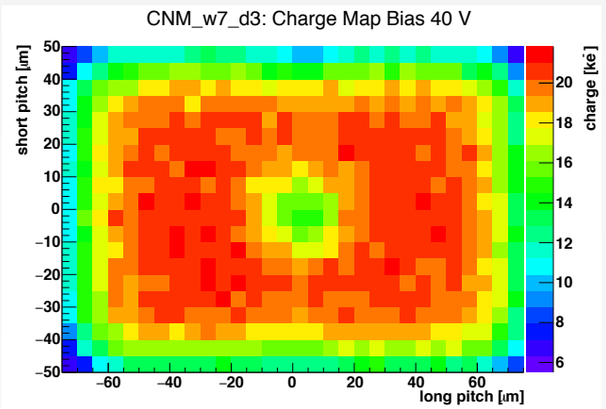
Bias = 10 V



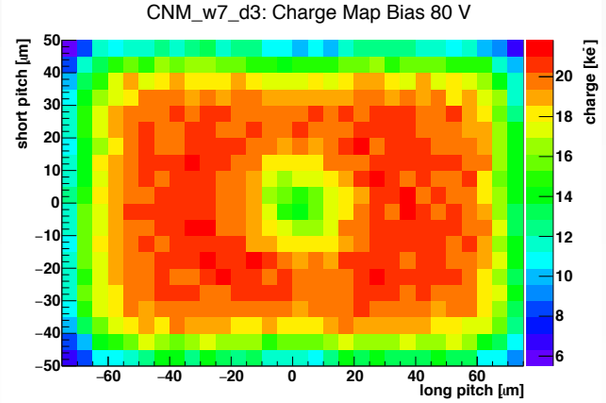
Bias = 20 V



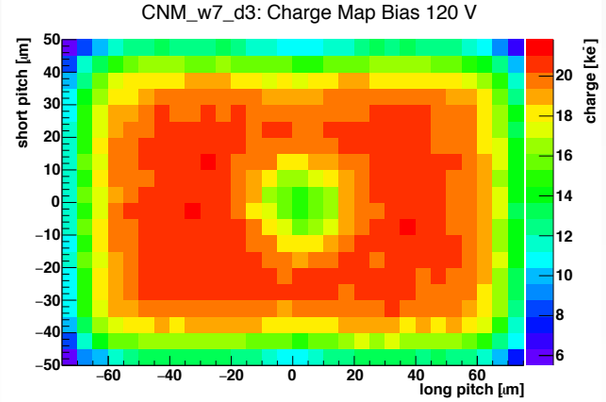
Bias = 40 V



Bias = 80 V

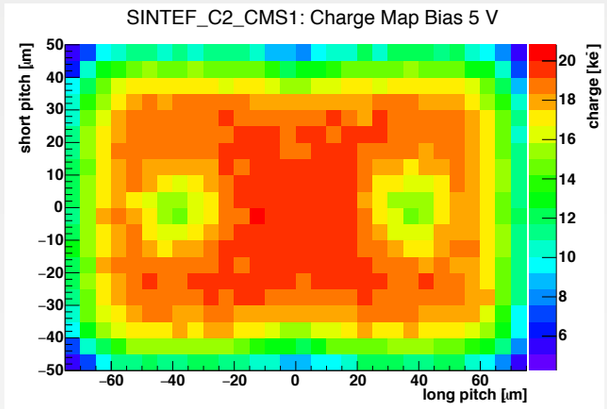


Bias = 120 V

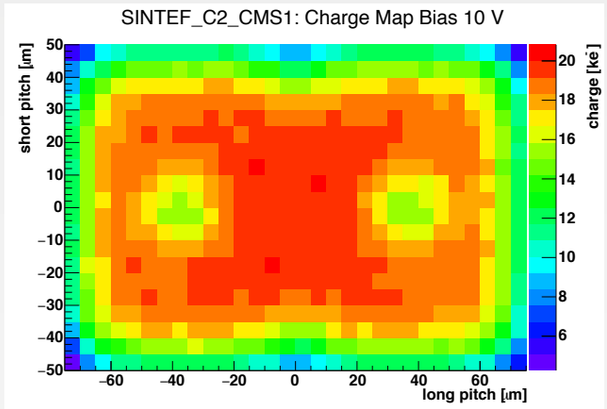


SINTEF_C2_CMS1 (Angle = 0°)

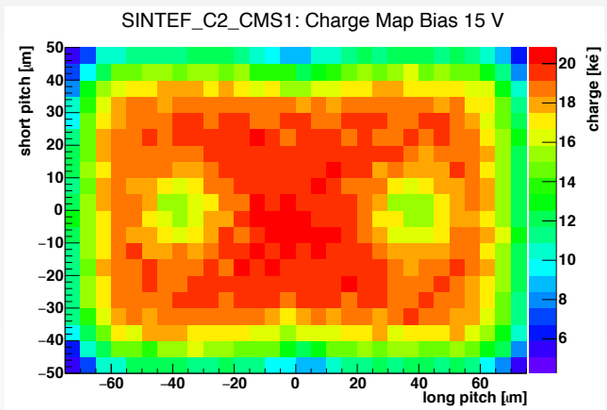
Bias = 5 V



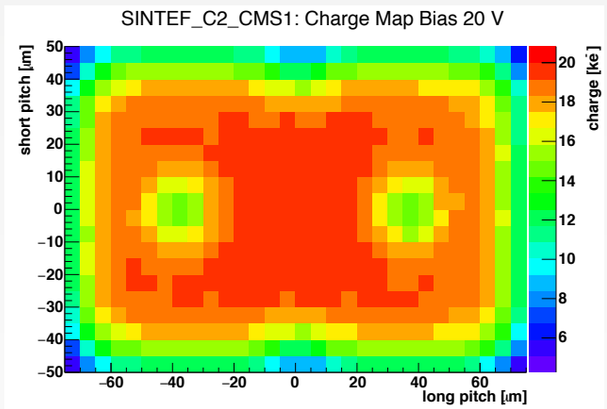
Bias = 10 V



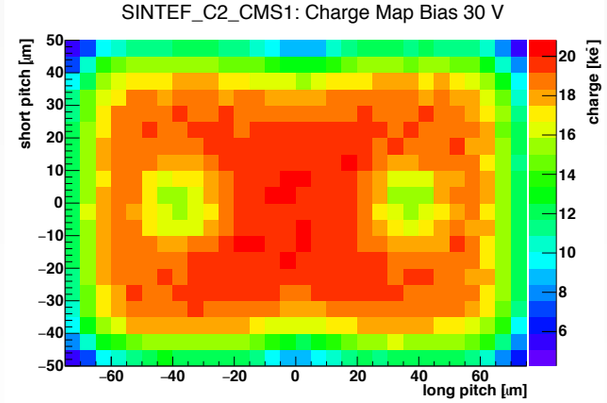
Bias = 15 V



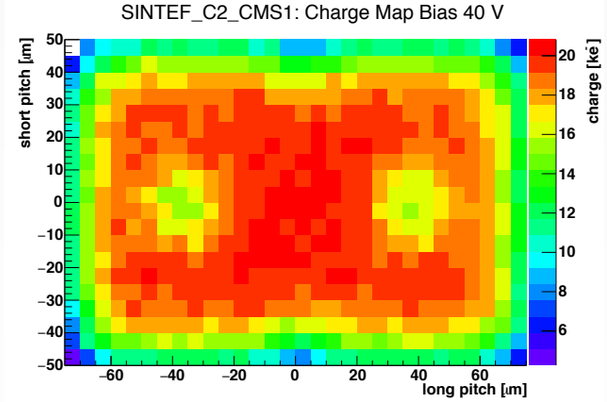
Bias = 20 V



Bias = 30 V



Bias = 40 V

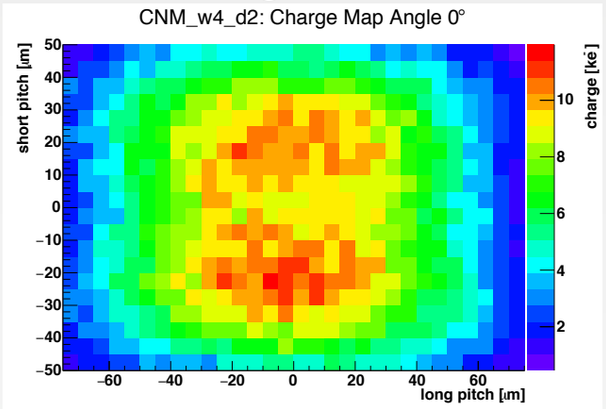


Cell charge vs angle before irradiation

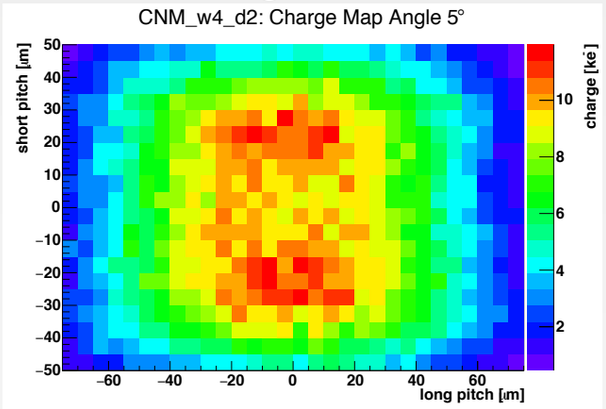
Preliminary

CNM_w4_d2 (3x10^{15} n_{eq}/cm^2, Bias = 160 V)

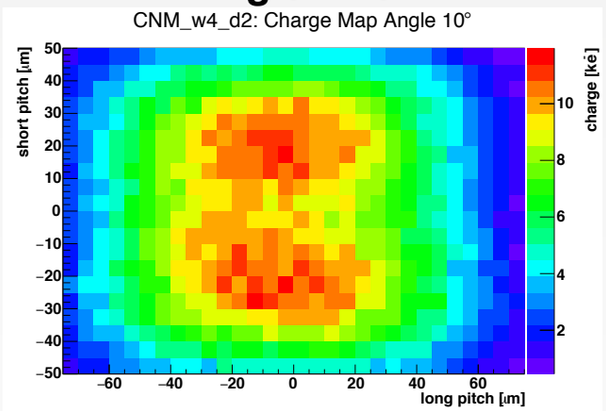
Angle = 0°



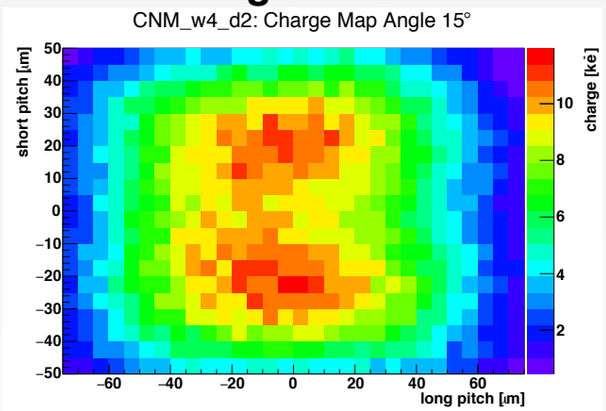
Angle = 5°



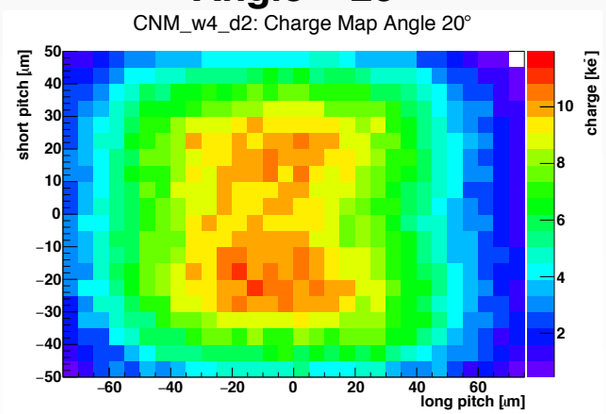
Angle = 10°



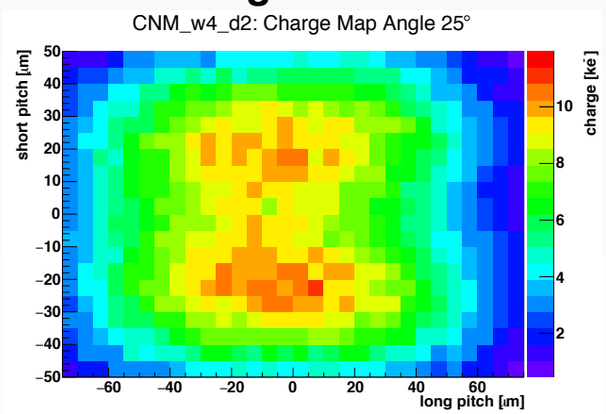
Angle = 15°



Angle = 20°

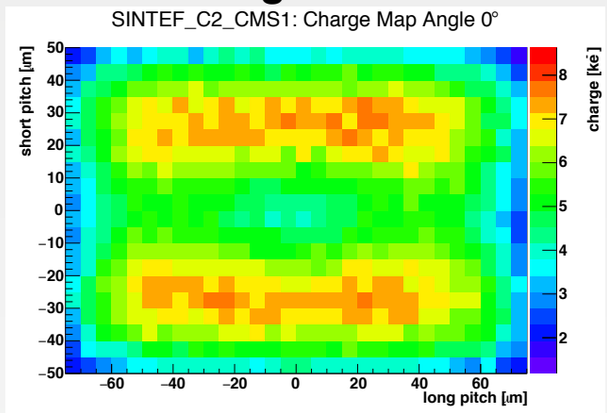


Angle = 25°

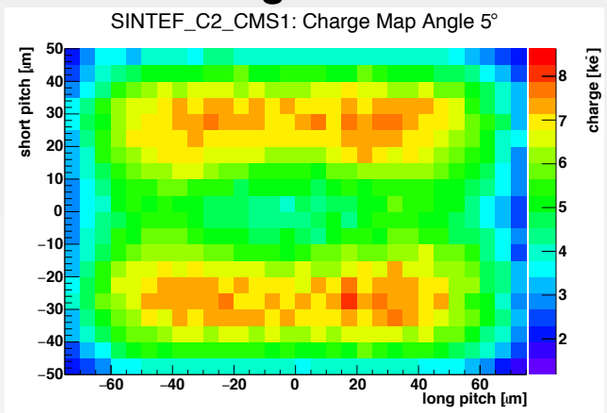


SINTEF_C2_CMS1 (3x10^{15} n_{eq}/cm^2, Bias = 80 V)

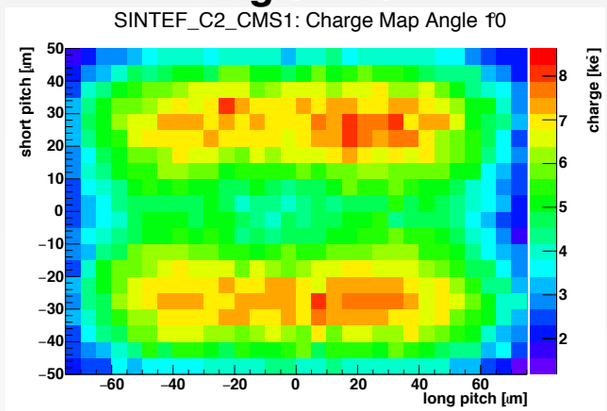
Angle = 0°



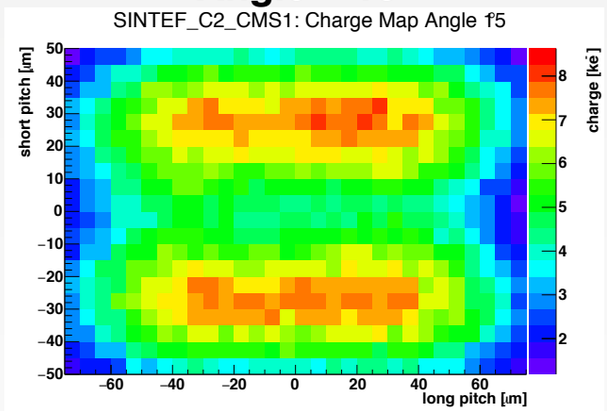
Angle = 5°



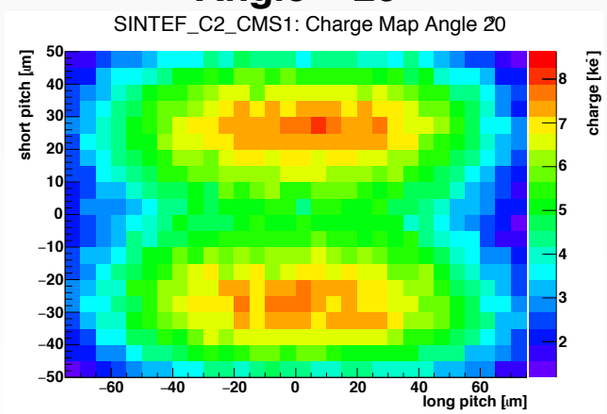
Angle = 10°



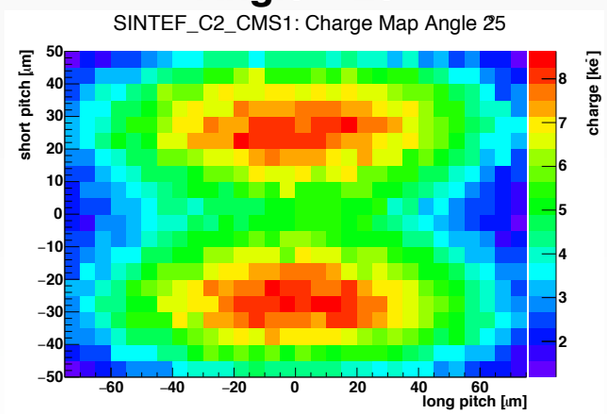
Angle = 15°



Angle = 20°



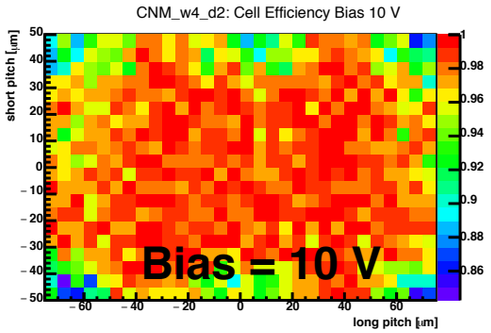
Angle = 25°

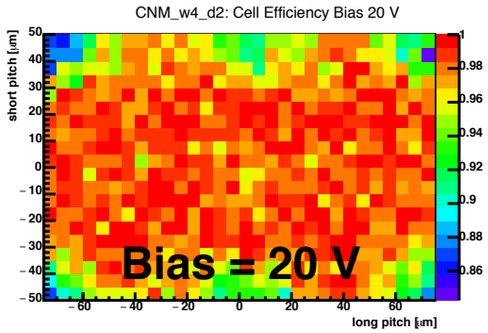


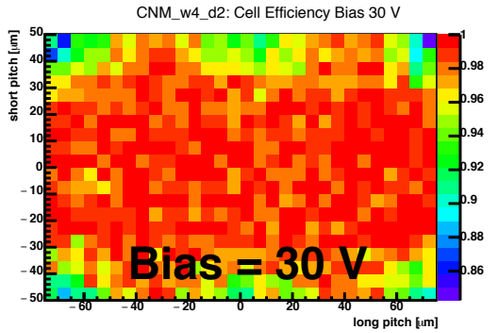
Pixel cell efficiency before irradiation

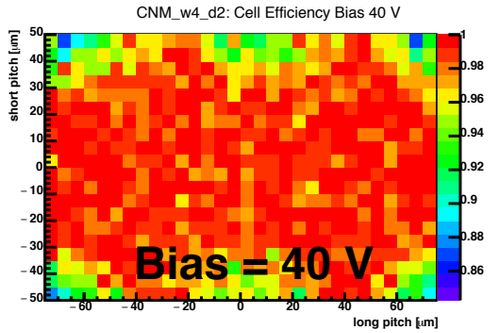
CNM_w4_d2 (Angle = 0°)

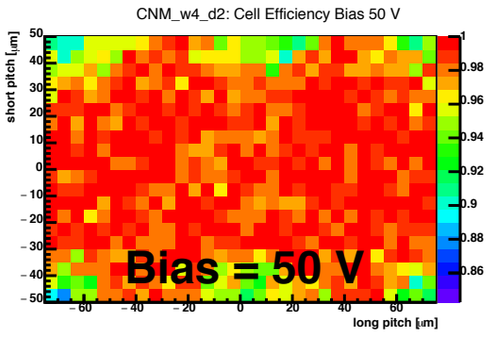
Preliminary

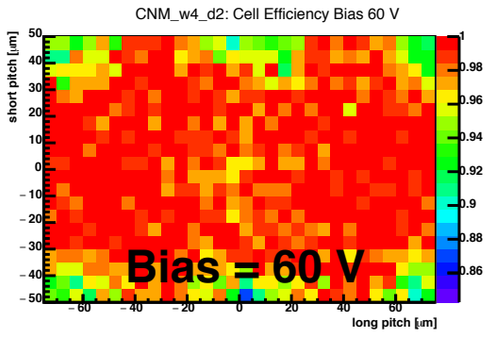


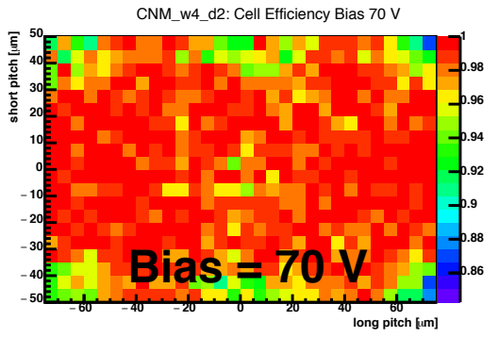


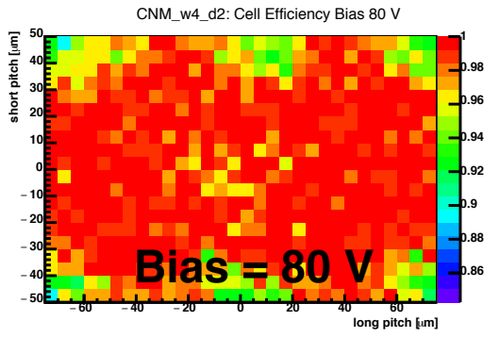


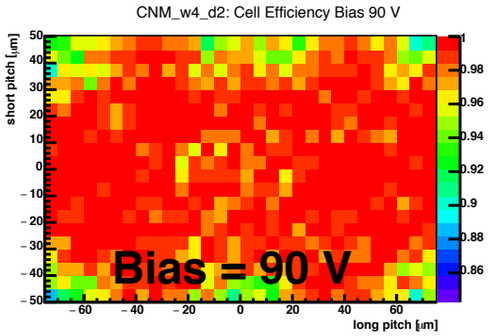


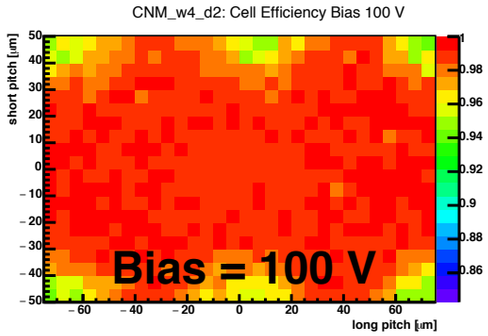


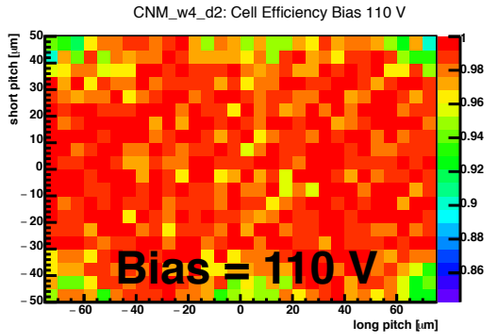


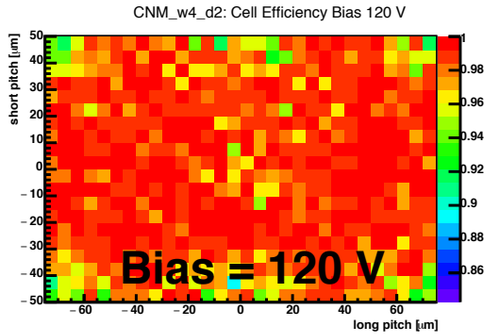


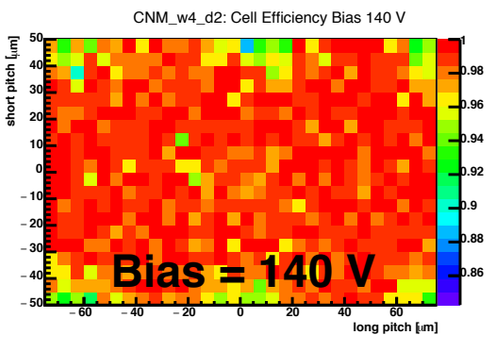








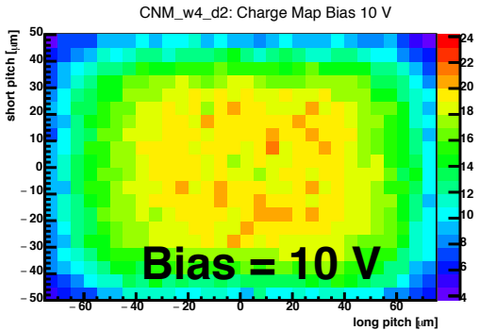


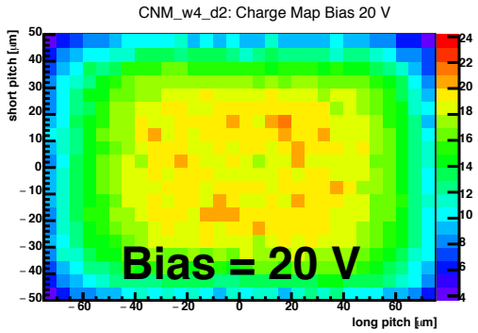


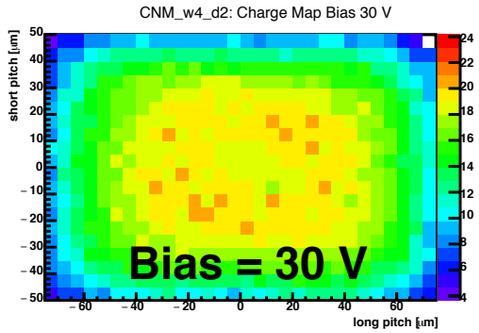
Pixel cell charge before irradiation

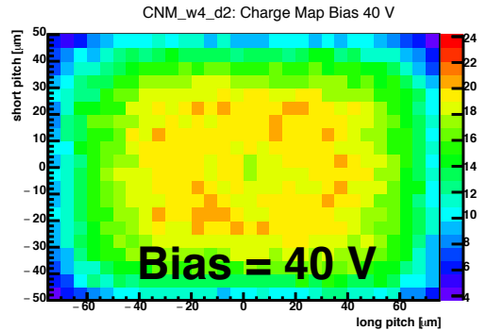
CNM_w4_d2 (Angle = 0°)

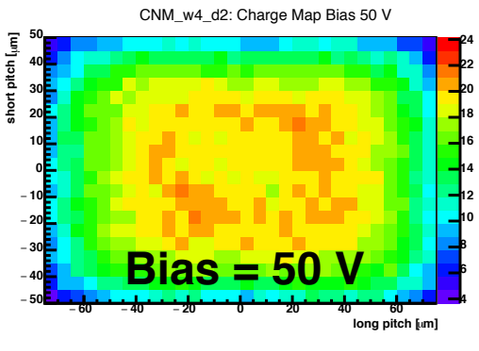
Preliminary

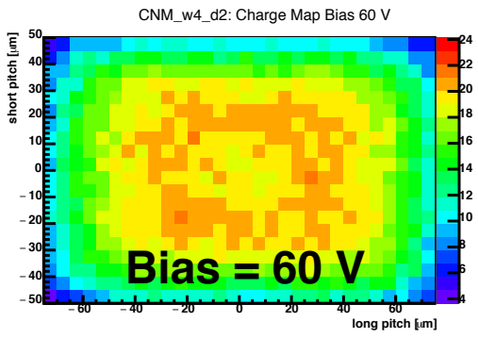


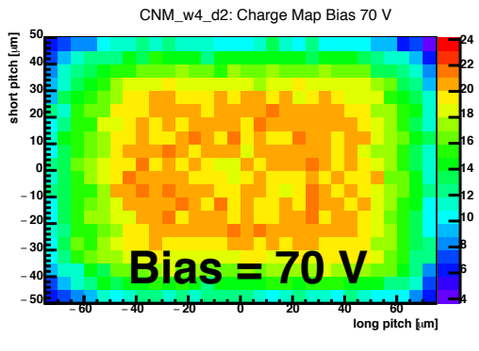


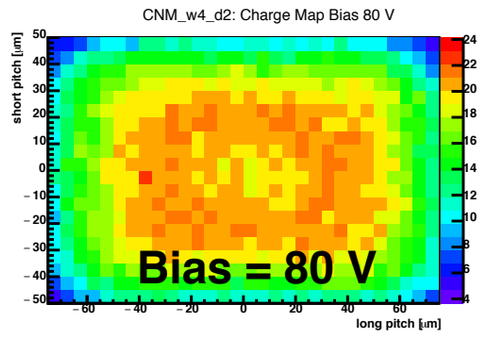


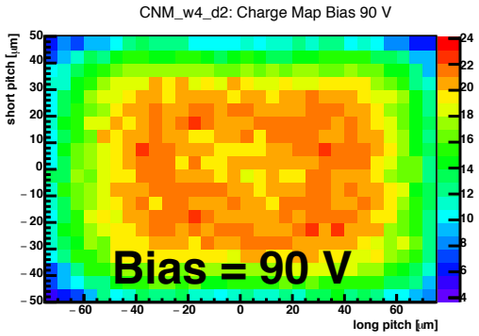


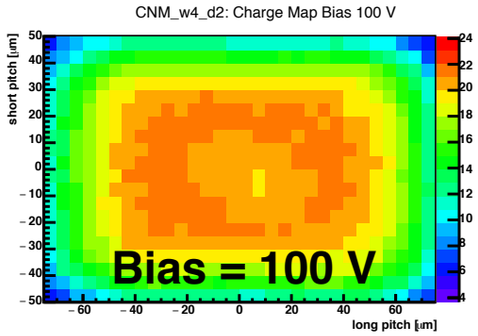


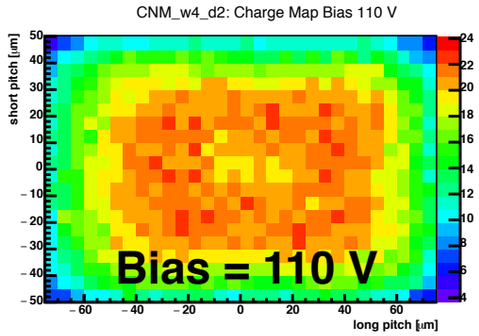


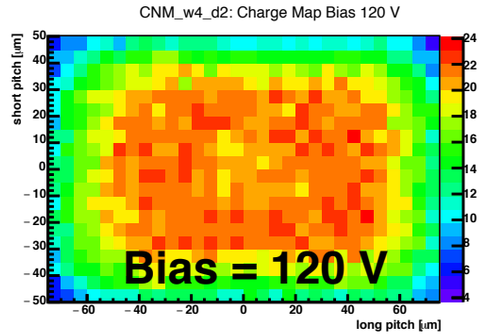


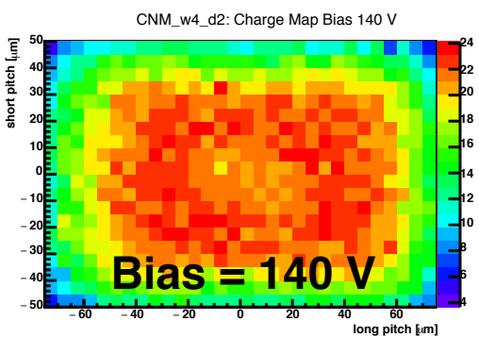








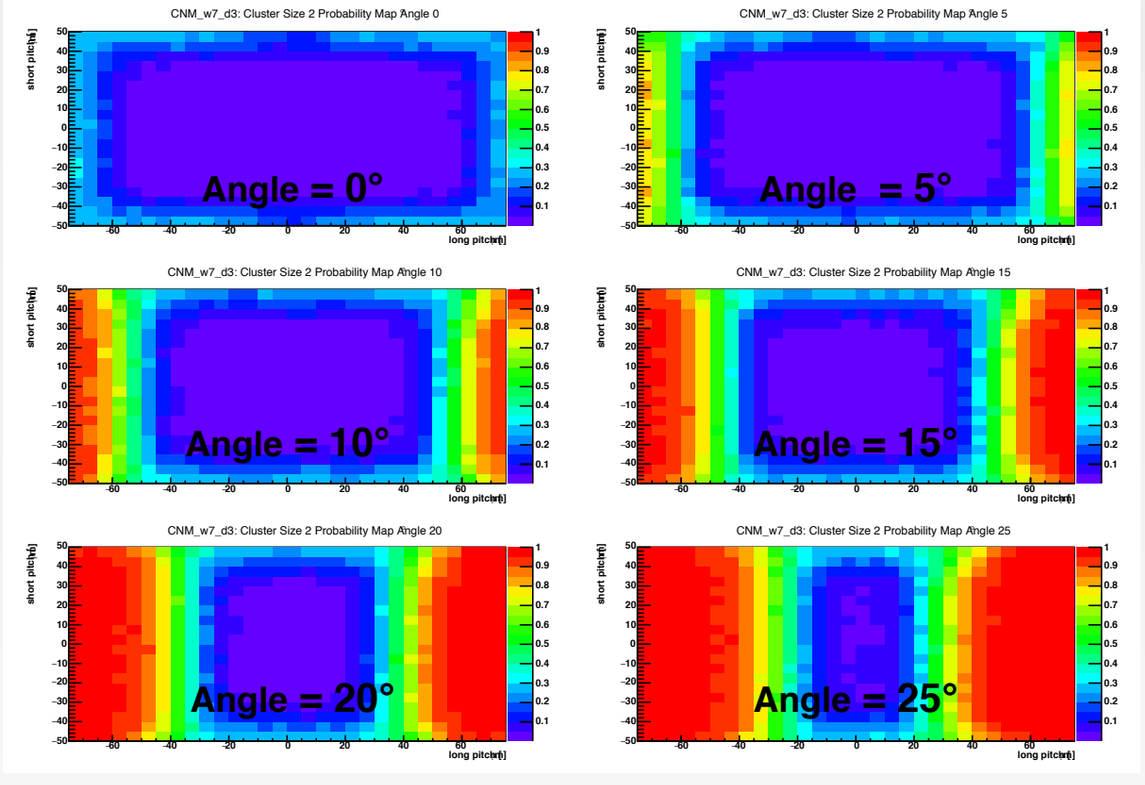




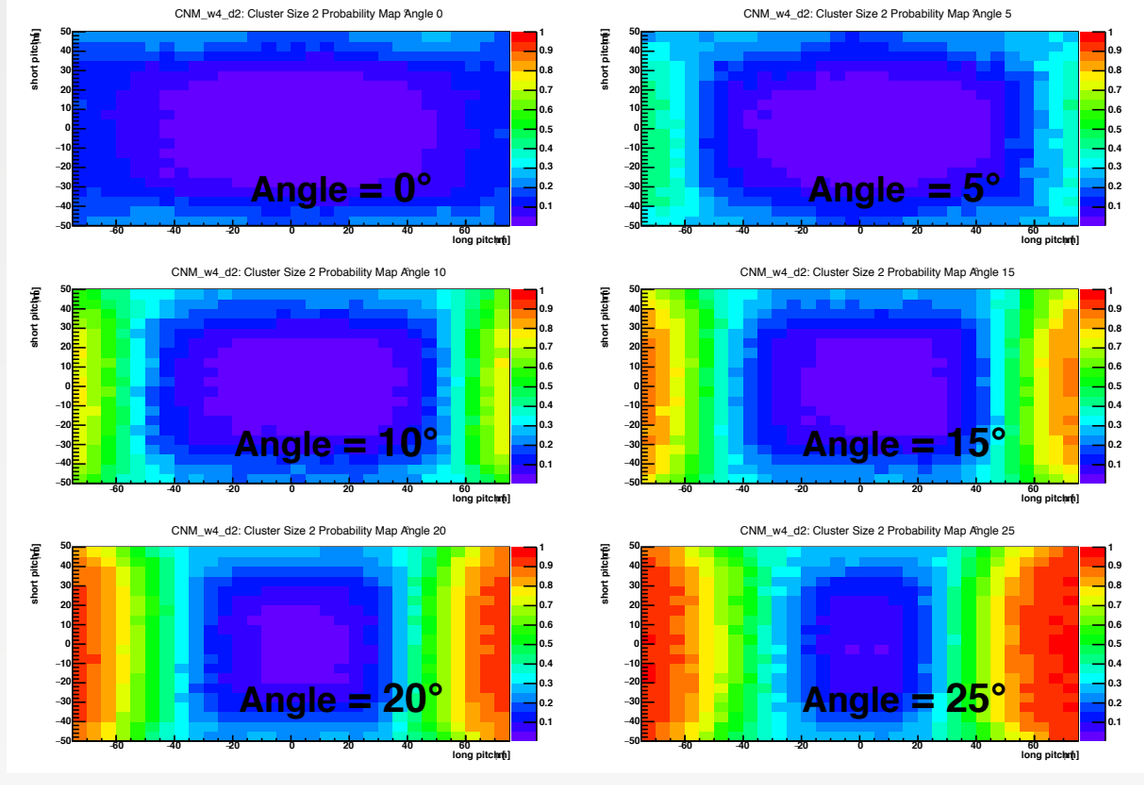
Pixel cell cluster size before irradiation

Preliminary

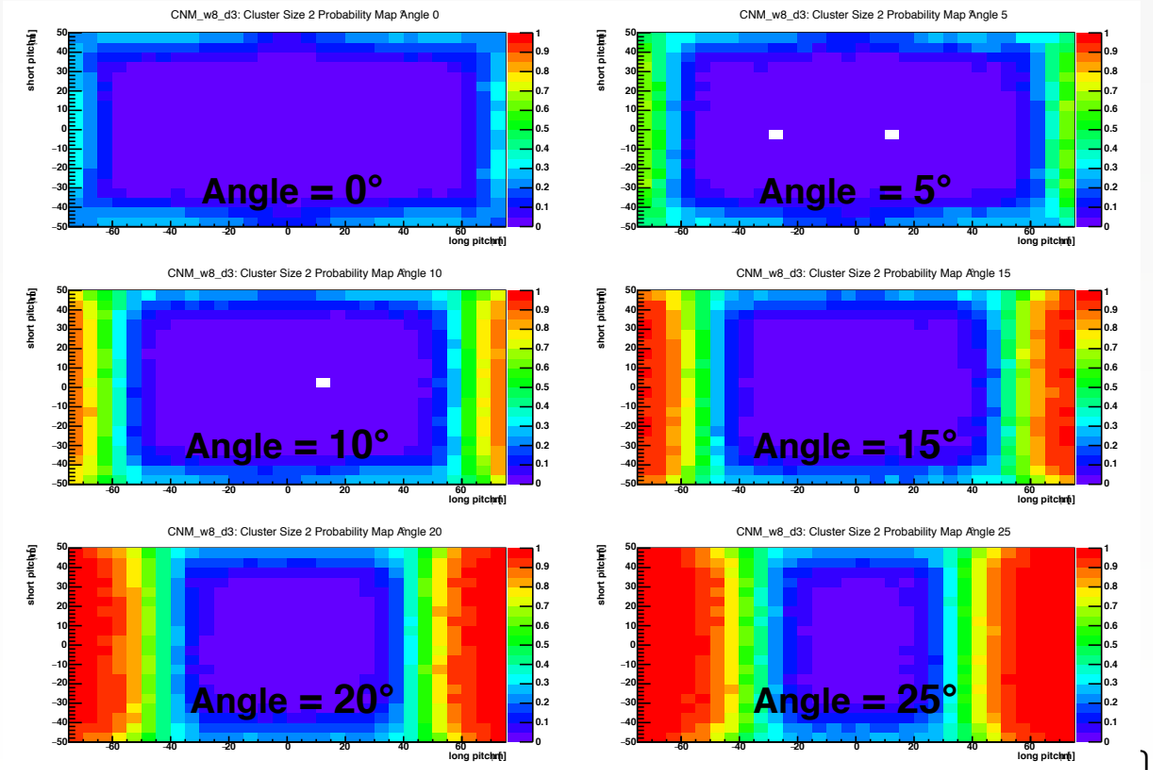
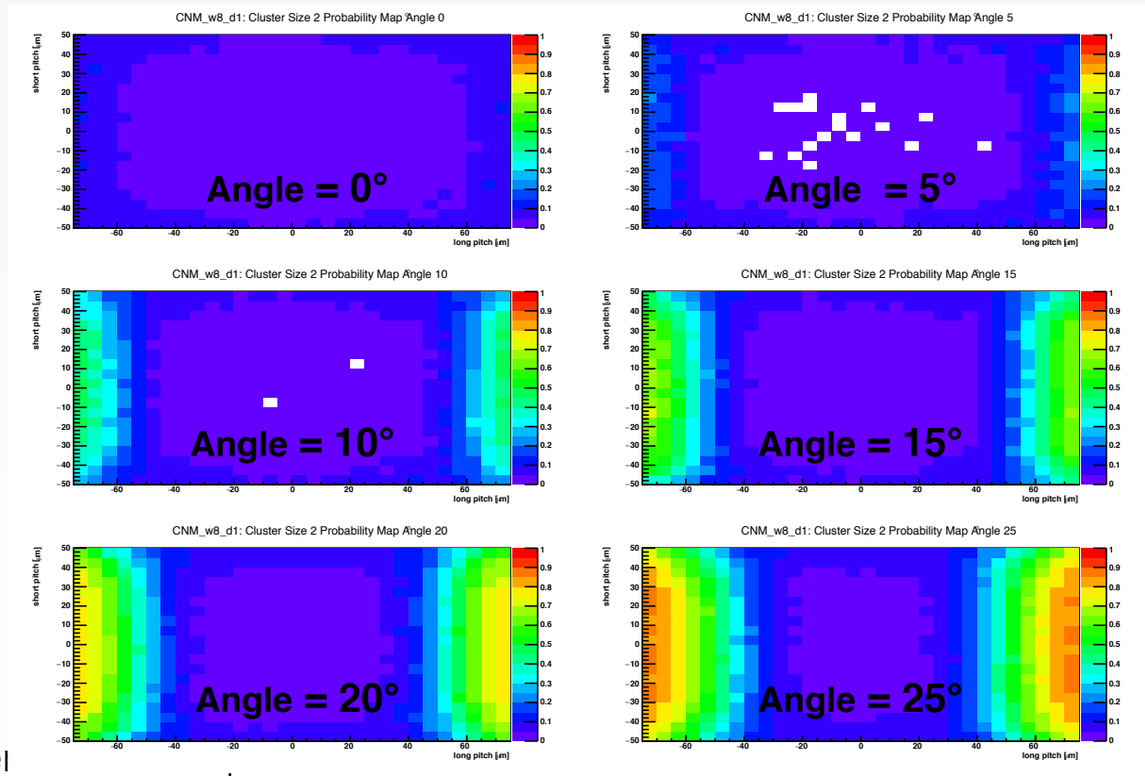
CNM_w7_d3 (Threshold = 1590 e, Bias = 120 V)



CNM_w4_d2 (Threshold = 1930 e, Bias = 100 V)



CNM_w8_d3 (Threshold = 2600 e, Bias = 25 V)



CNM_w8_d1 (Threshold = 4190 e, Bias = 90 V)