Results on FBK 3D pixel detectors for CMS

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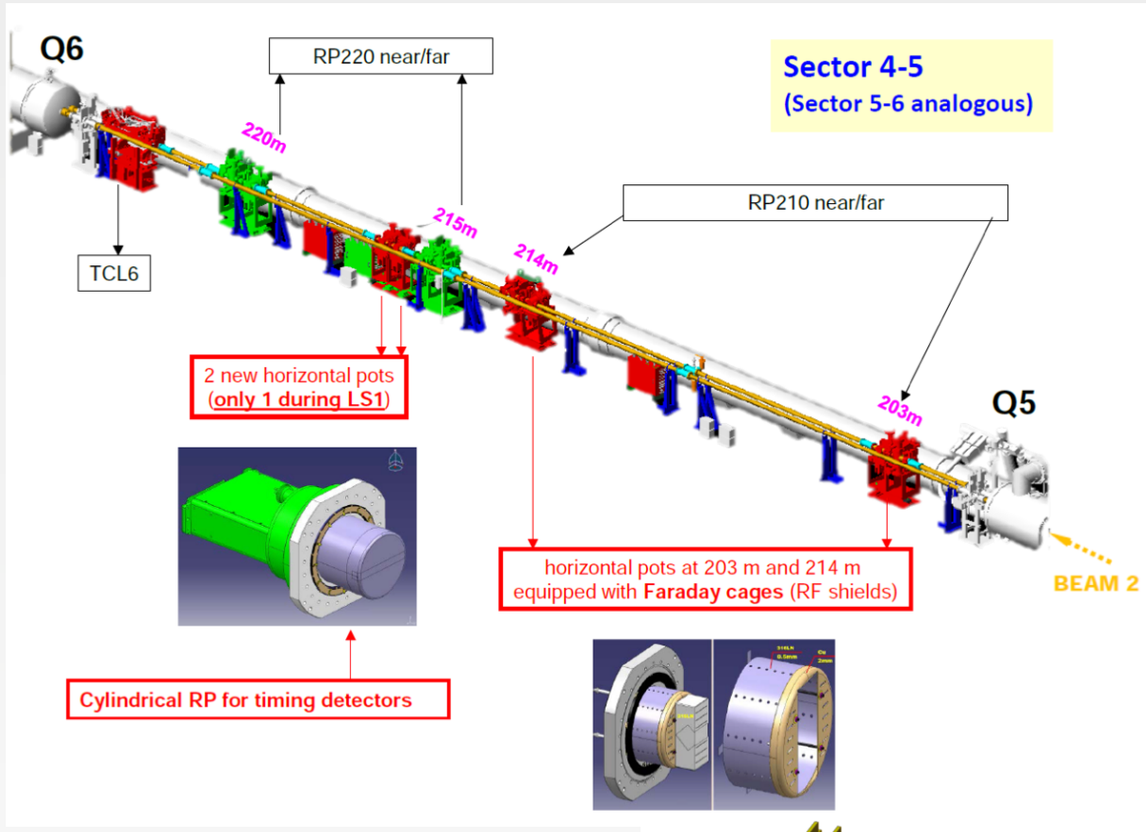
CMS-TOTEM Proton Precision Spectrometer

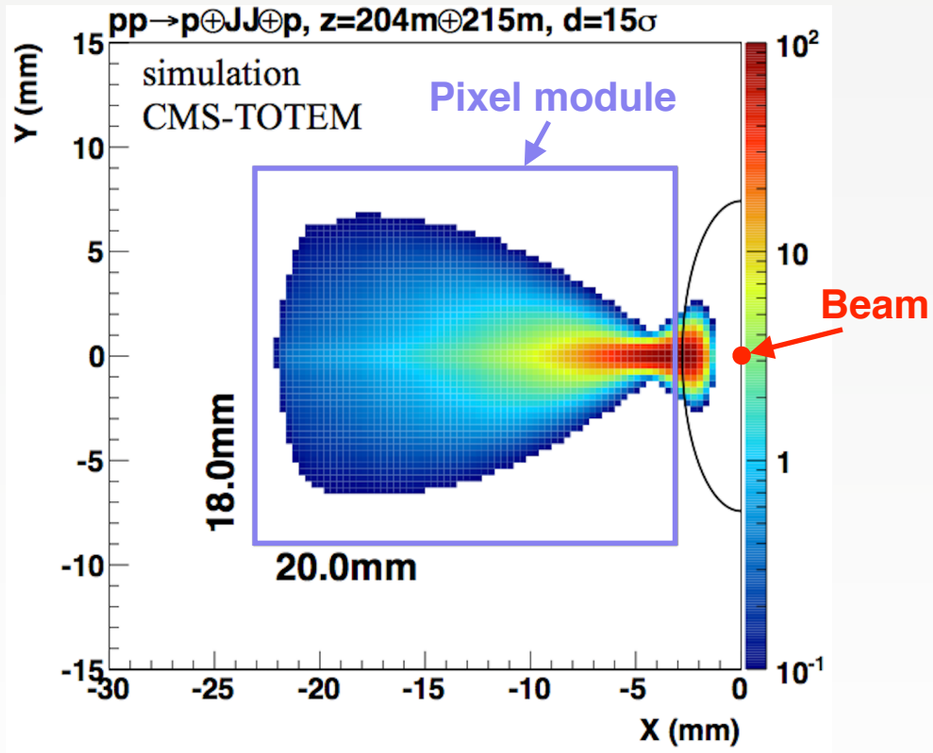
In 2016 tracking detectors will be installed at ~220 m from the CMS-TOTEM common Interaction Point.

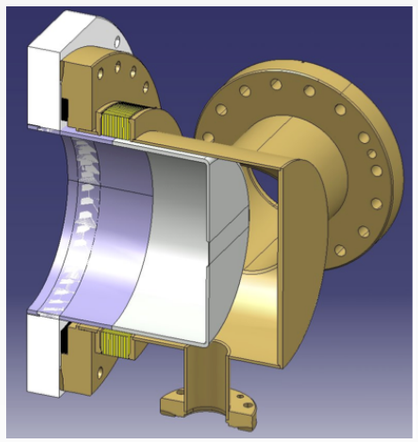
Goal: study of diffractive p-p interactions at LHC.

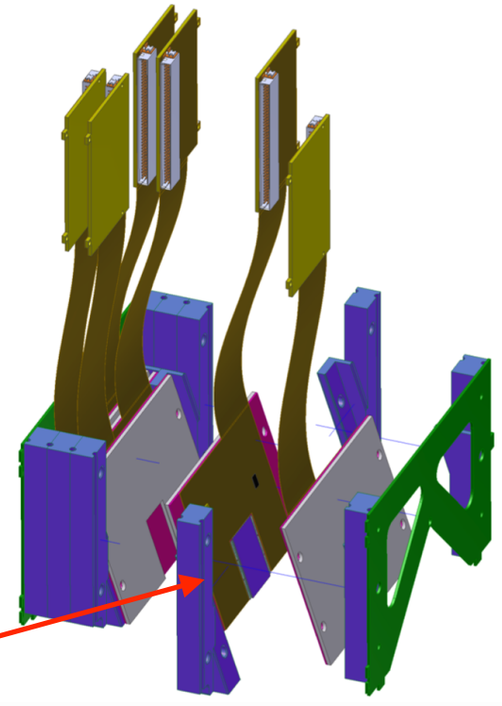
Requirements for tracking sensors:

- Good radiation hardness (expected 5x10^{15} p/cm^2).
- Small insensitive area at the sensor edge.







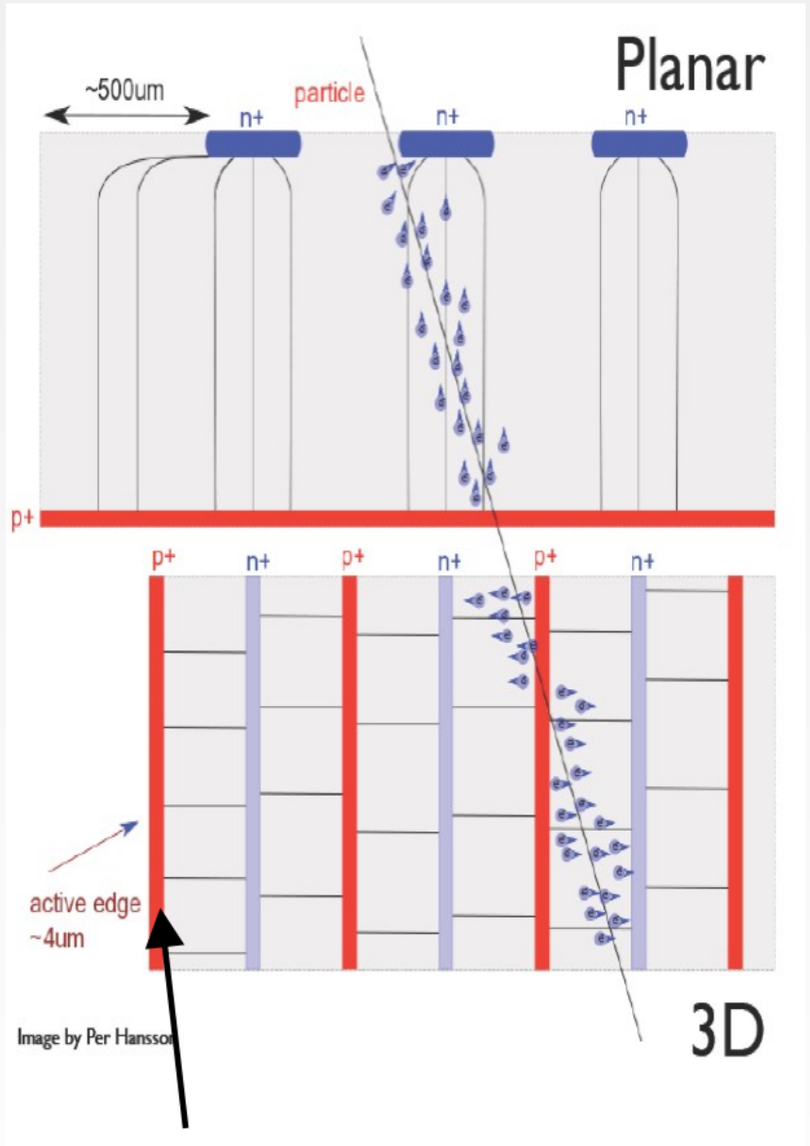


Sensor tilt compatible

3D sensors fulfil both these requirements

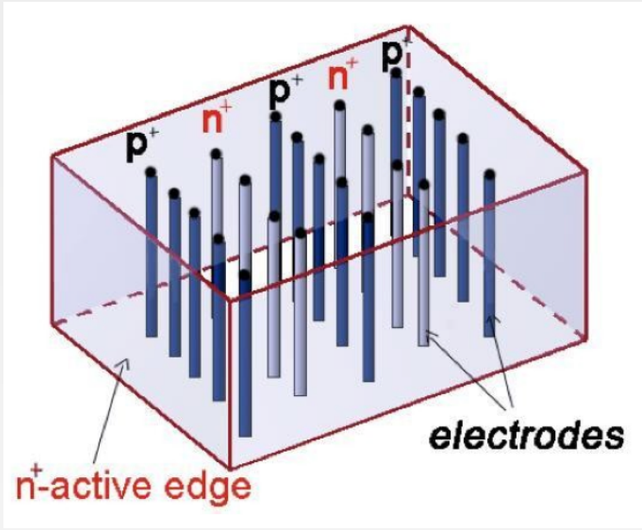
3D silicon sensors

3D silicon detectors were proposed in 1997 by Parker, Kenney and Segal.



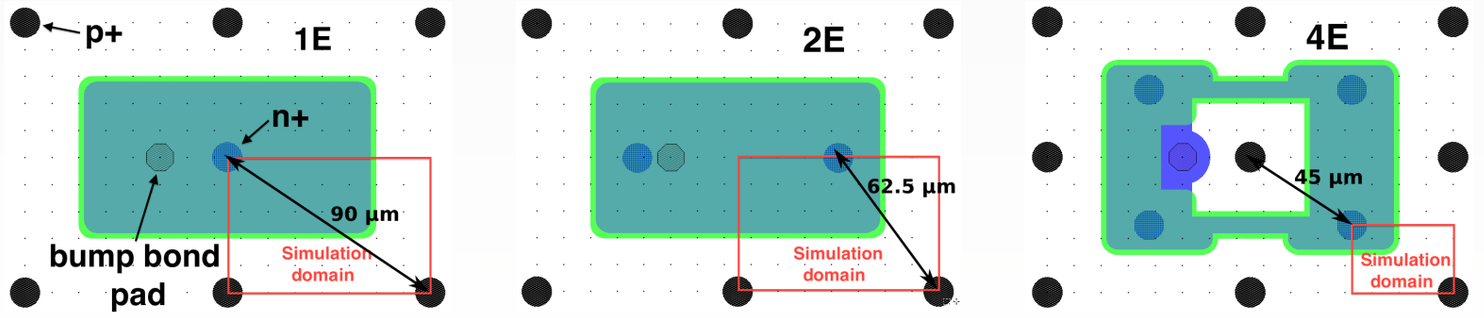
Possibility to implement active edges.

3D sensors have electrodes that are etched perpendicular through the silicon bulk.



The architecture decouples substrate thickness and electrode distance. The result is the same charge deposit of a planar silicon sensor of the same thickness but electrode distances strongly reduced.

Columns have radius of ~ 5 µm and the distance between electrodes varies from 100 µm to 50 µm depending on the pixel configuration.

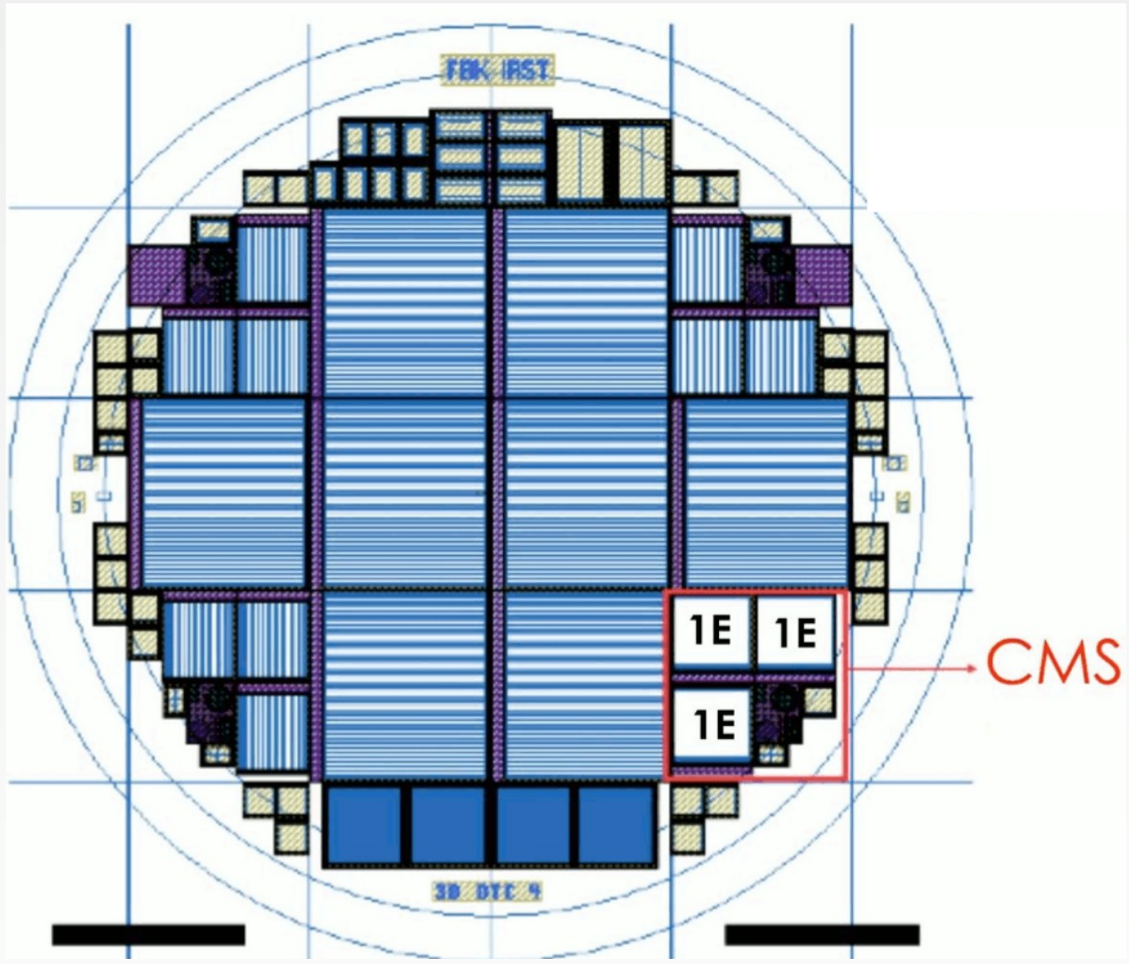


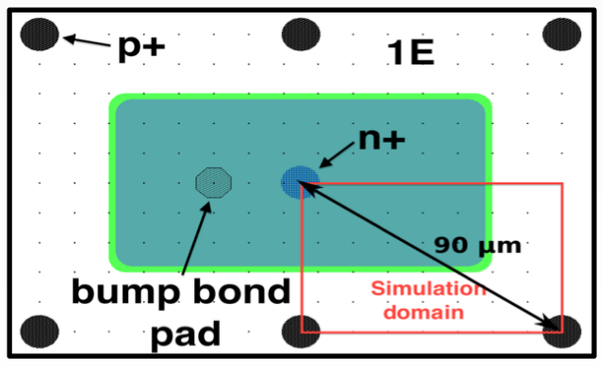
Tested FBK 3D sensors

Wafer from Atlas IBL production

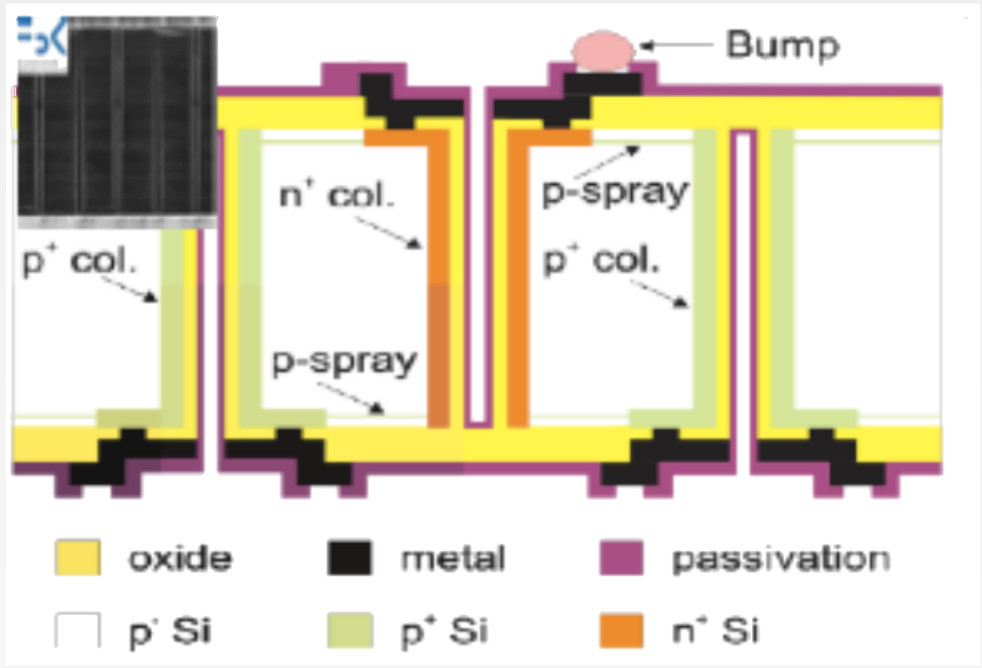
Wafer thickness = 230 μm

Slim edge = 200 *μ*m





Double-Sided Full 3D



Columns etched in the substrate determine a geometrical inefficiency for tracks entering the detector perpendicularly to the surface. Tilting the detector is necessary for increasing the efficiency.

FBK 3D testing steps

March 2014:

- 10 FBK 3D sensors bump-bonded to the CMS pixel digital ReadOut Chip (ROC).
- IV curve measurements and ROC optimisation and calibration in Torino.

April 2014:

- 7 good quality detectors tested with 120 GeV protons at Fermi National Accelerator Laboratory (FNAL).

June 2014:

- 8 detectors irradiated with 23 MeV protons at Karlsruhe Institute of Technology (KIT) within the AIDA project, at fluences of 1-3-6-10x10^{15} n_{eq}/cm^2 (corresponding dose: 150-450-900-1500 Mrad).

July 2014:

at Torino laboratory:

- IV curve measurements
- Setting and calibration of survived ROCs (1-3x10^{15} n_{eq}/cm^2)

August 2014:

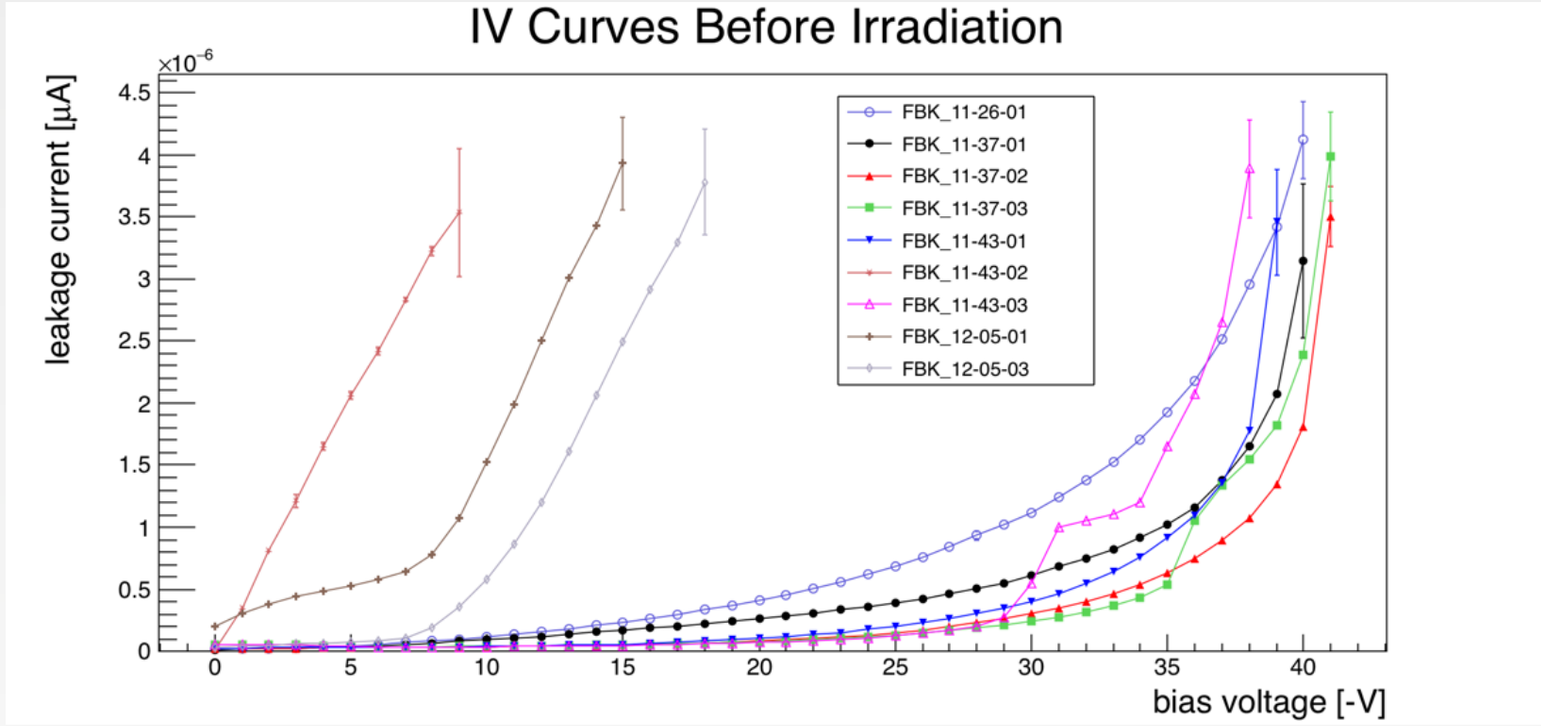
- Irradiated detectors tested on beam at FNAL.

IV curves before and after irradiation

Preliminary

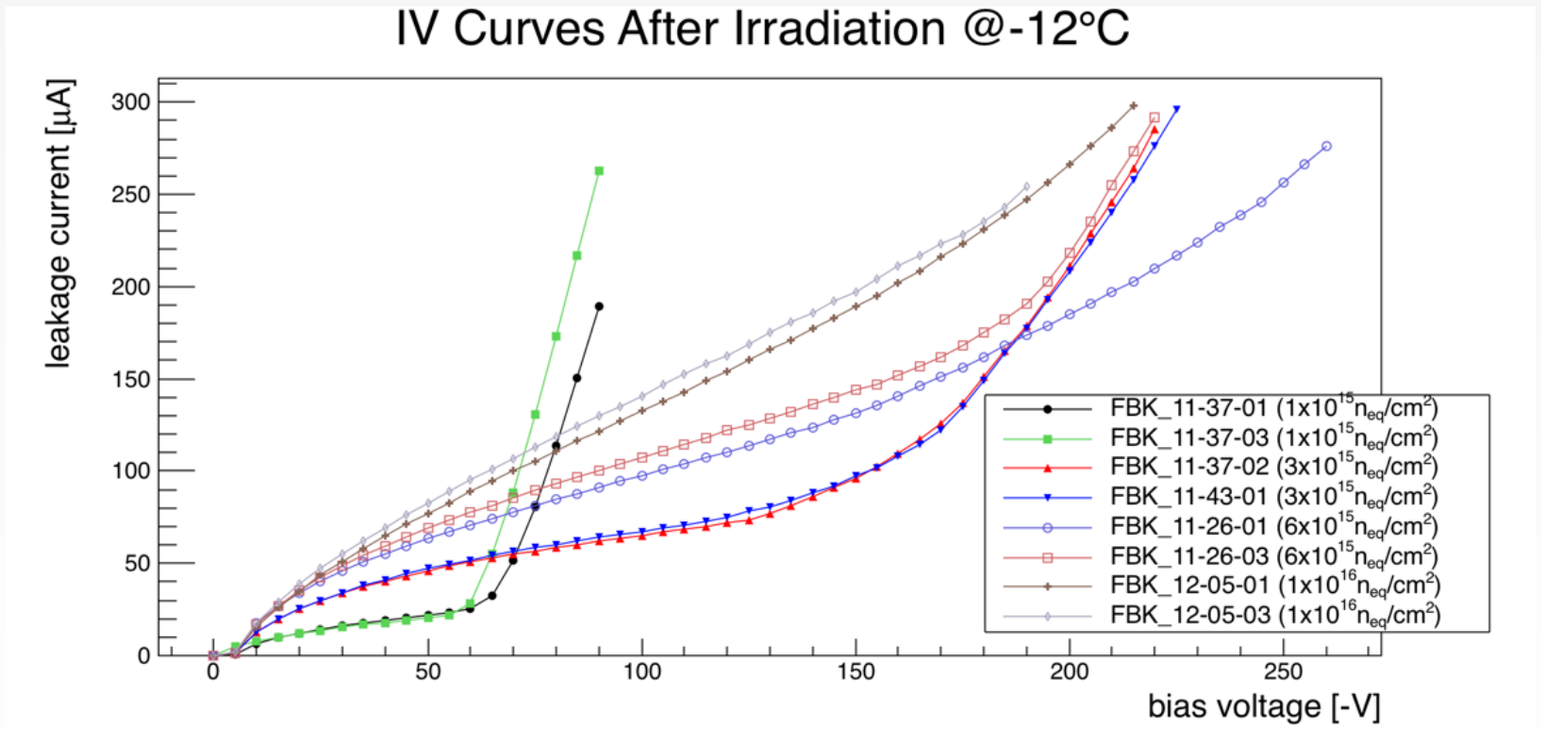
Before irradiation:

- IV measured at room temperature.
- 7 sensors show a breakdown voltage higher than 30 V as expected.

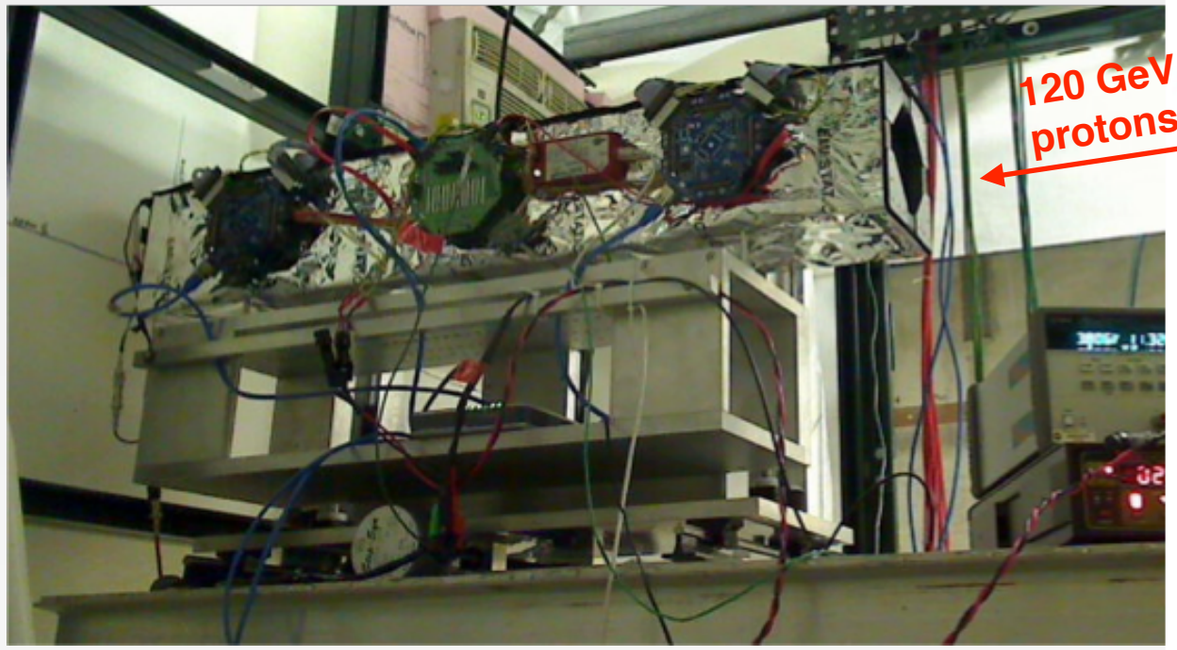


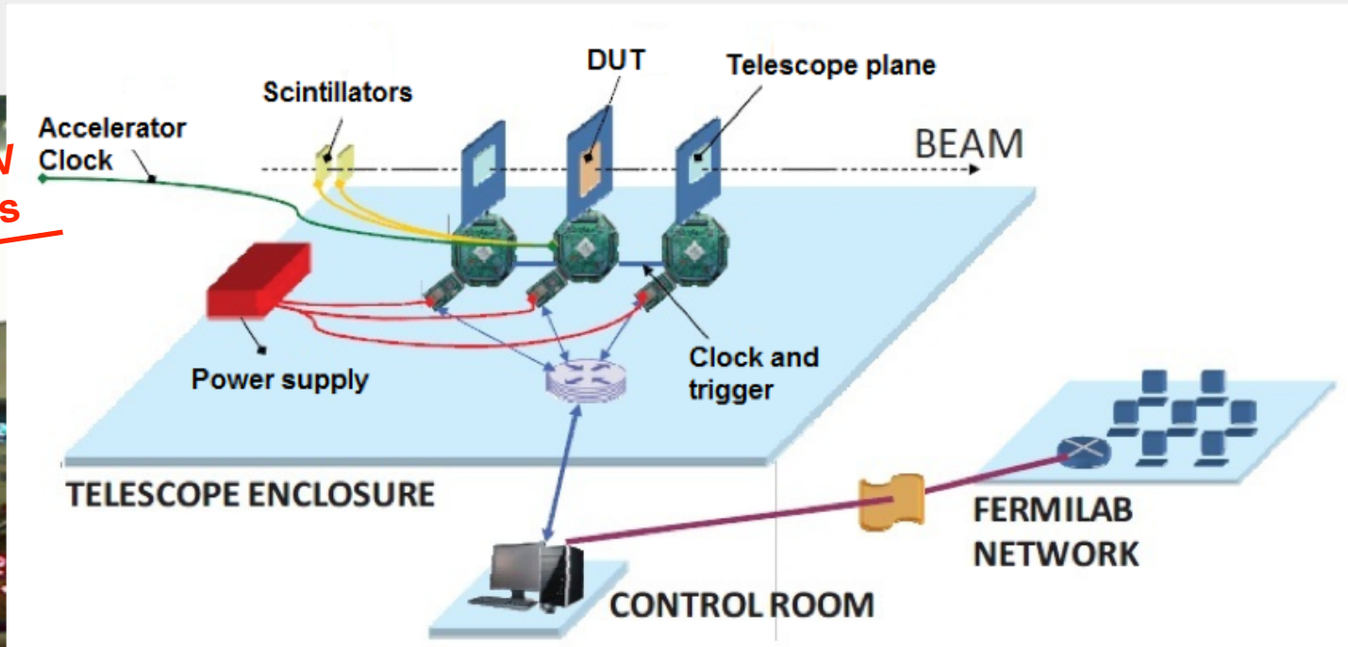
After irradiation:

- IV measured at -12˚C, same temperature used at the testbeam.
- Increase of breakdown voltage due to charge created by the irradiation on the sensor surface.
- Leakage currents are in agreement with the Atlas IBL 3D ones.

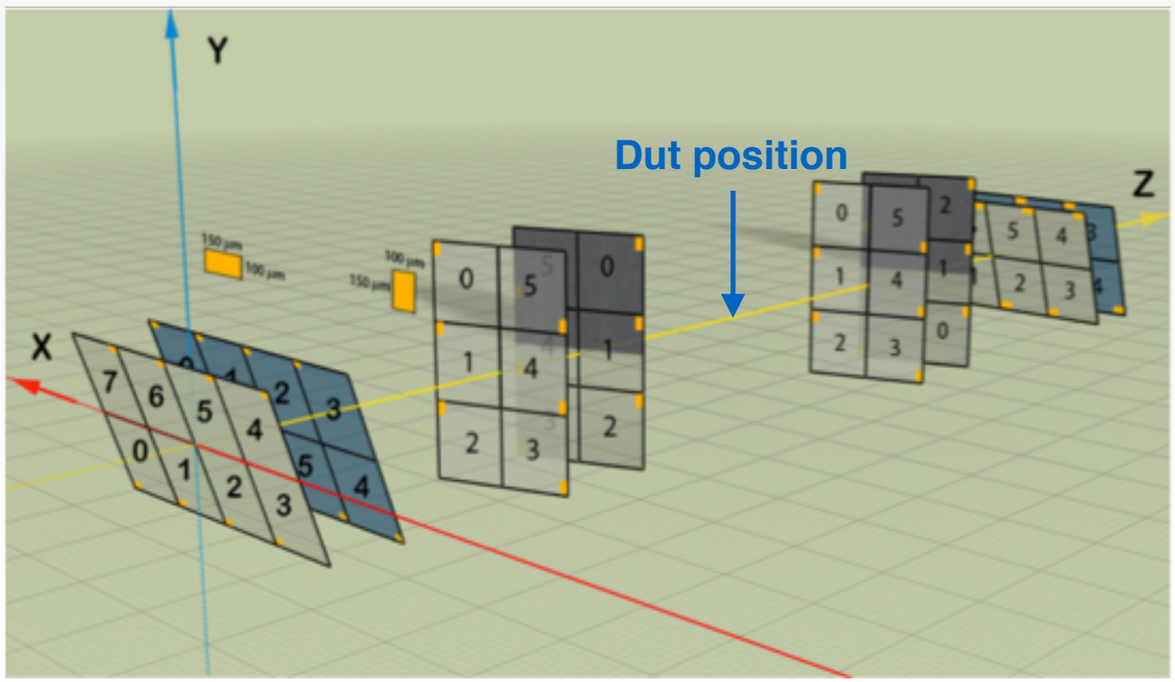


Testbeam at FNAL (T992 collaboration)





- 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 of 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



Efficiency vs bias (angle 0˚)

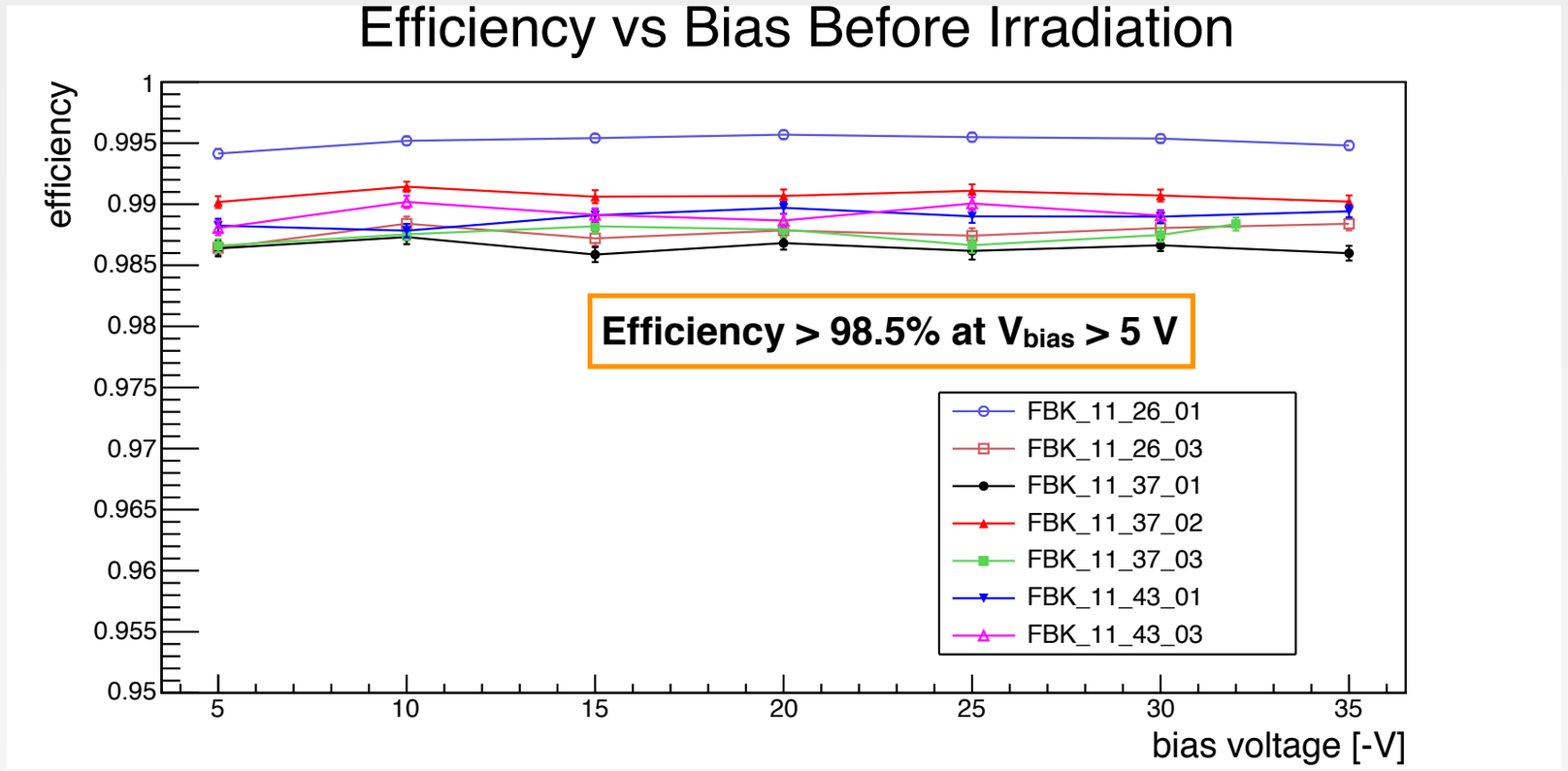
Preliminary

Testing procedure:

- Threshold scan
- Bias Scan
- Angle Scan

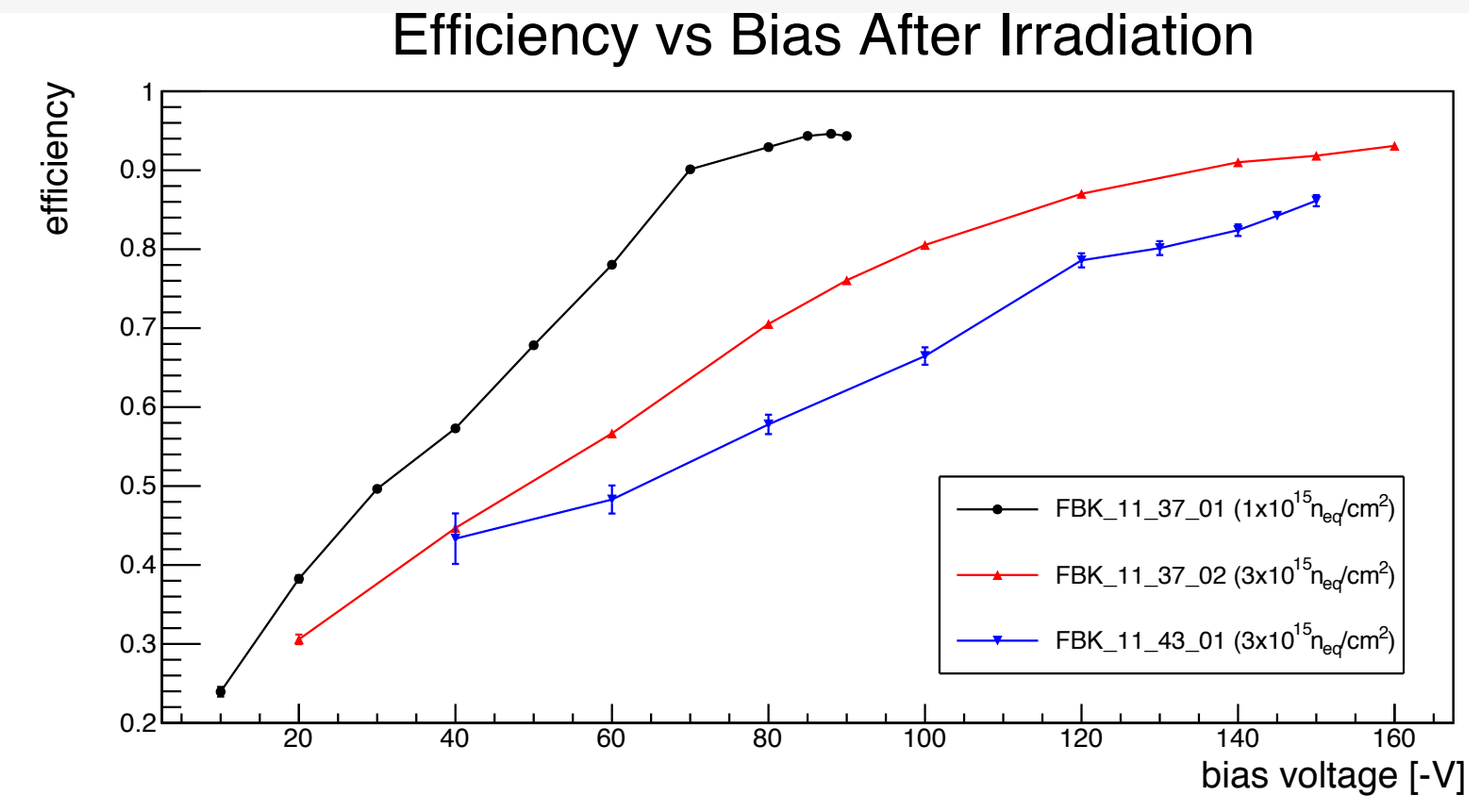
Before irradiation:

- Threshold between ~2500-3000 e^-
- Efficiency saturation already at 5 V
- Bias voltage between 25 V and 30 V chosen for angle scan



After irradiation:

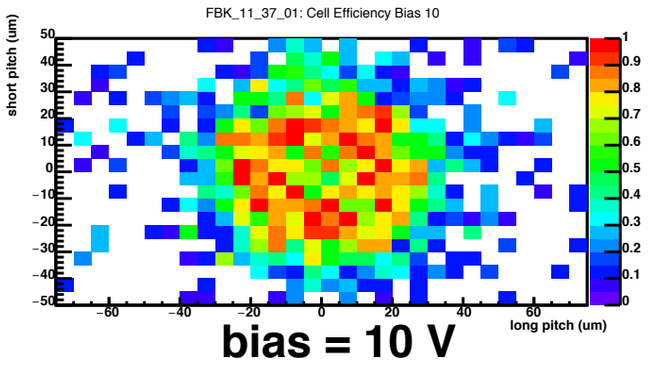
- Threshold ~3000 e^- for FBK_11_37_01 and FBK_11_37_02.
- Threshold ~4700 e^- for FBK_11_43_01 due to ROC problems.
- Sensors forced into breakdown region to try to reach full depletion

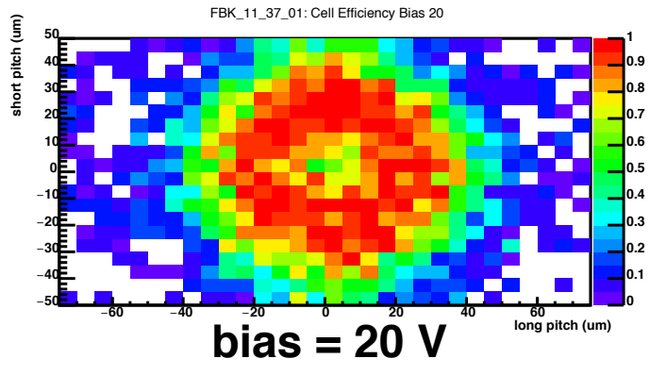


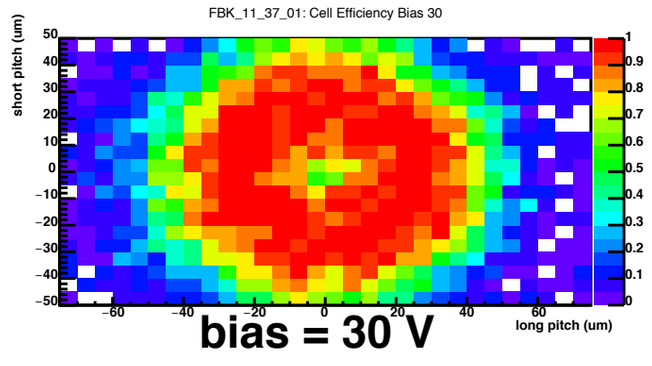
Pixel cell efficiency after irradiation

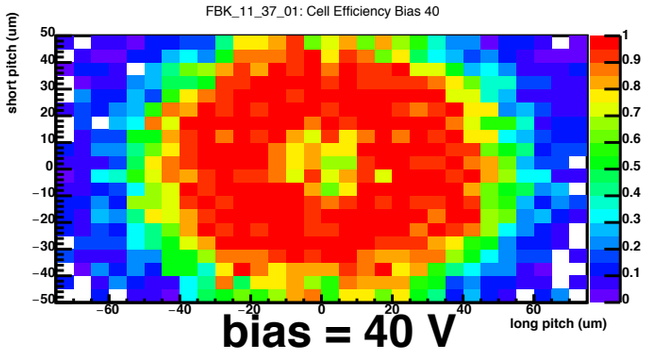
FBK_11_37_01 ($1x10^{15}$ n_{eq}/cm^2)

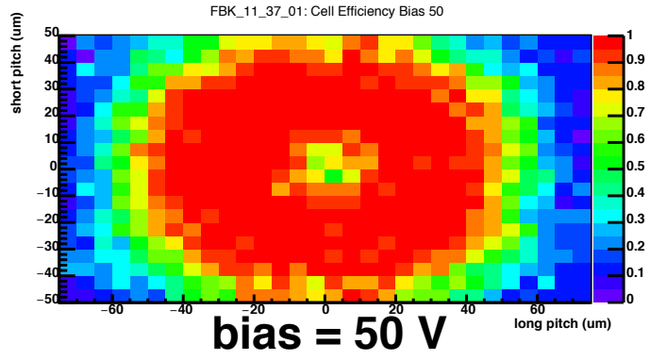
Preliminary

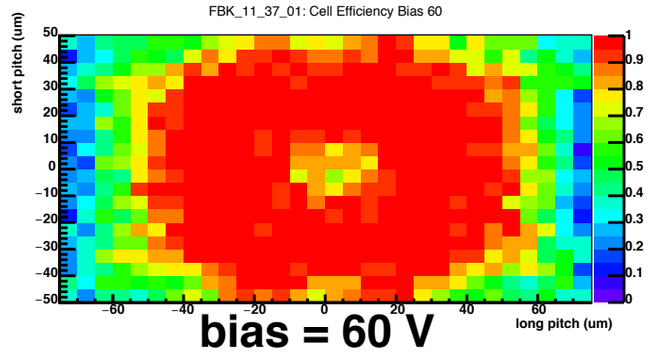


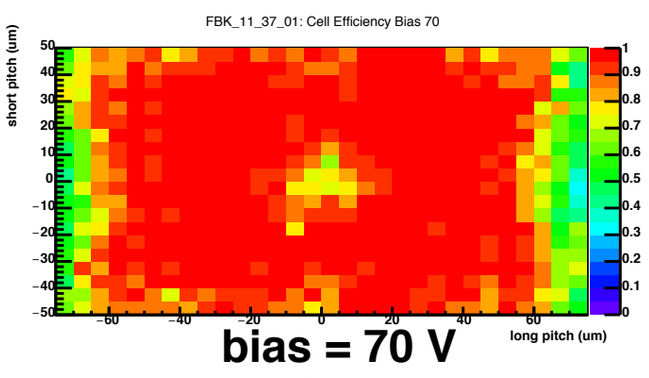


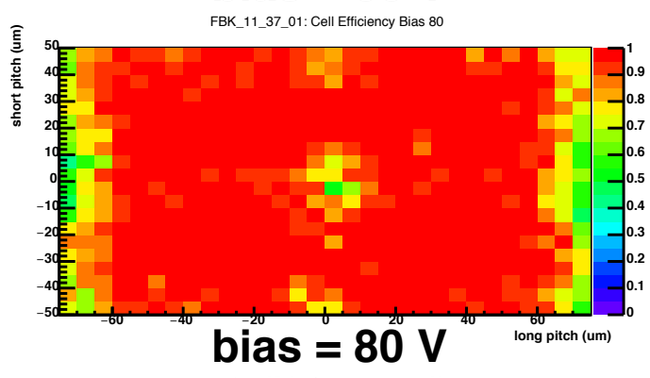


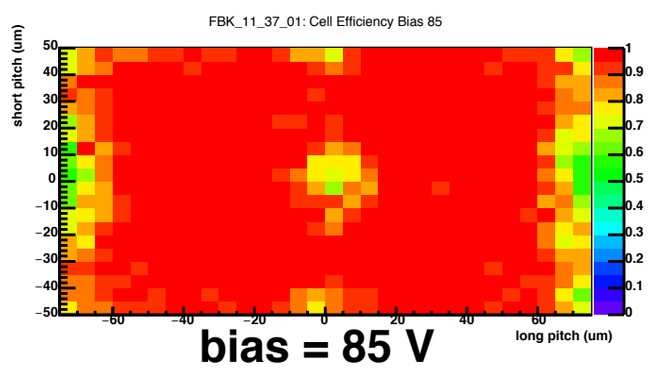


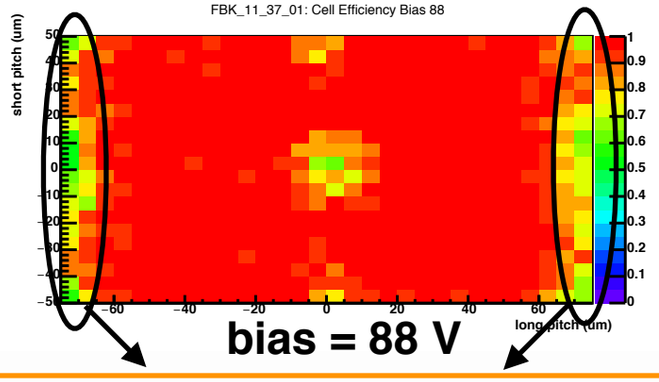


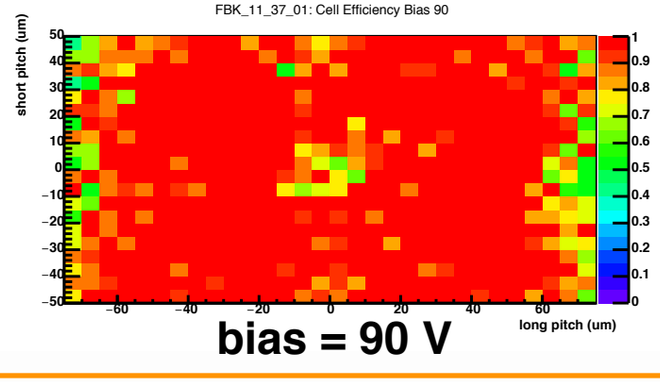


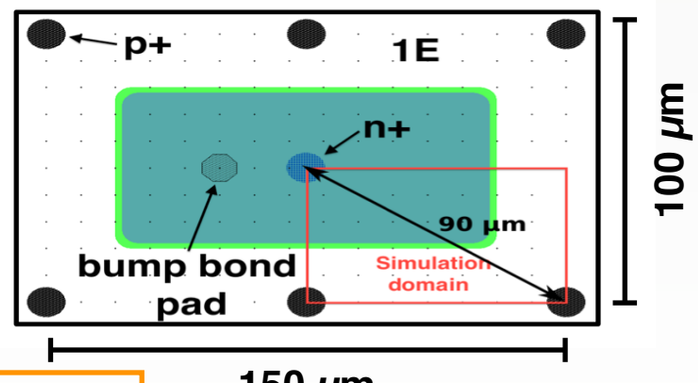








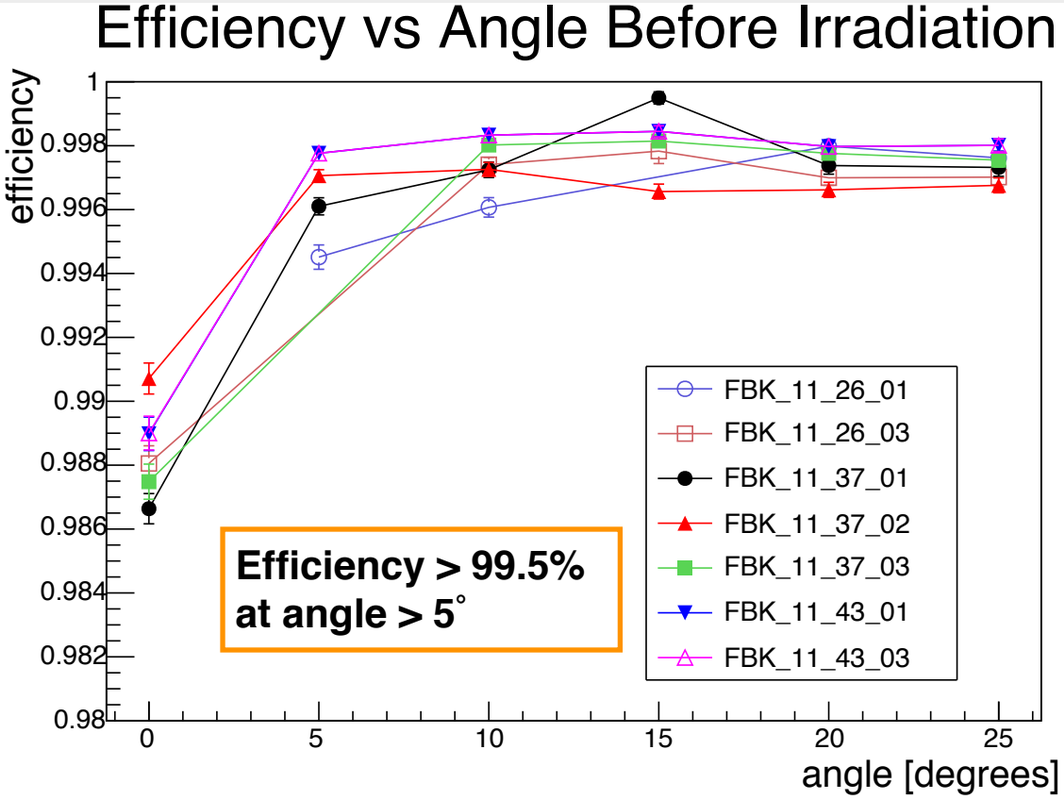


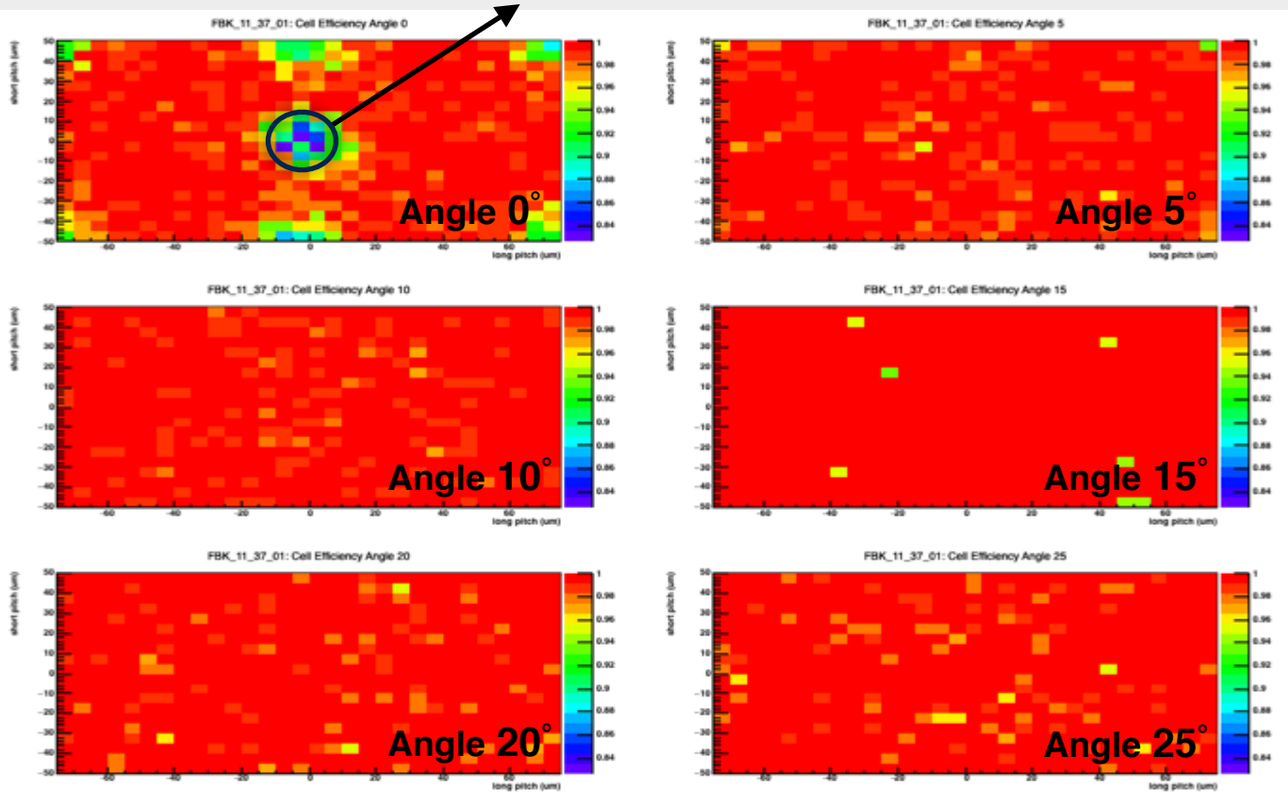


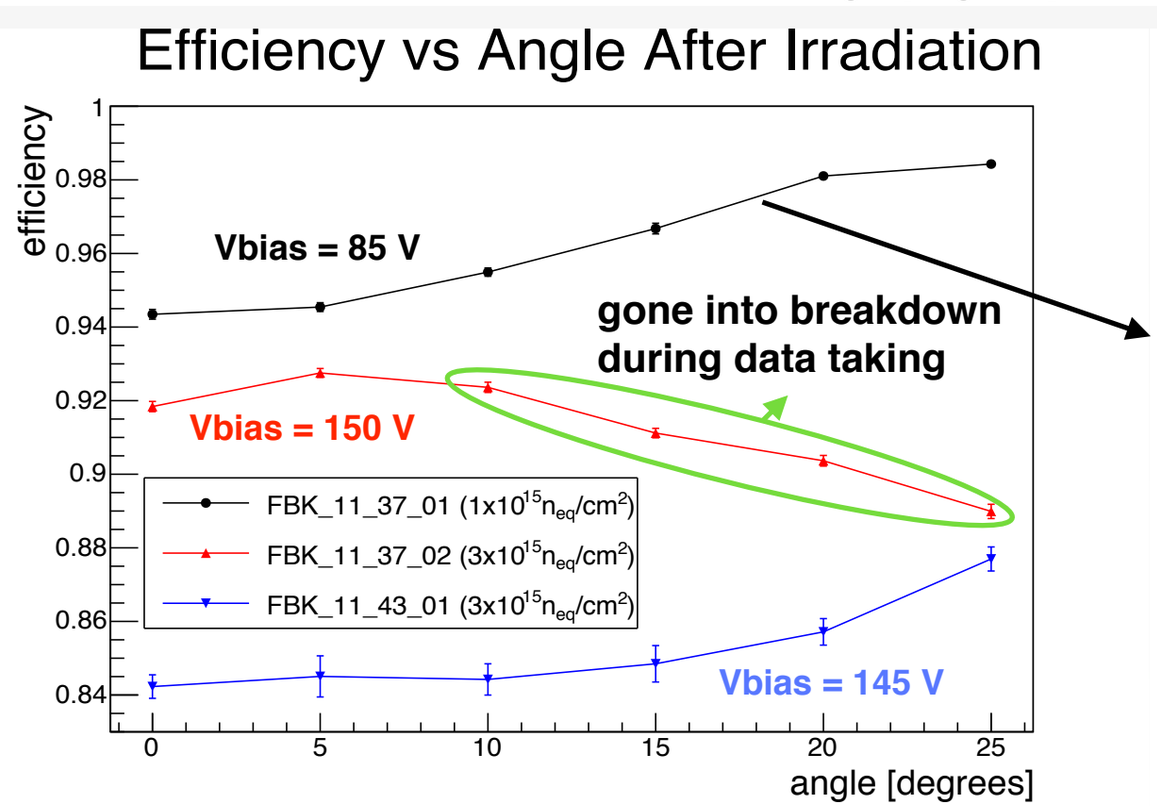
1 readout column not enough to fully collect charge in the side regions

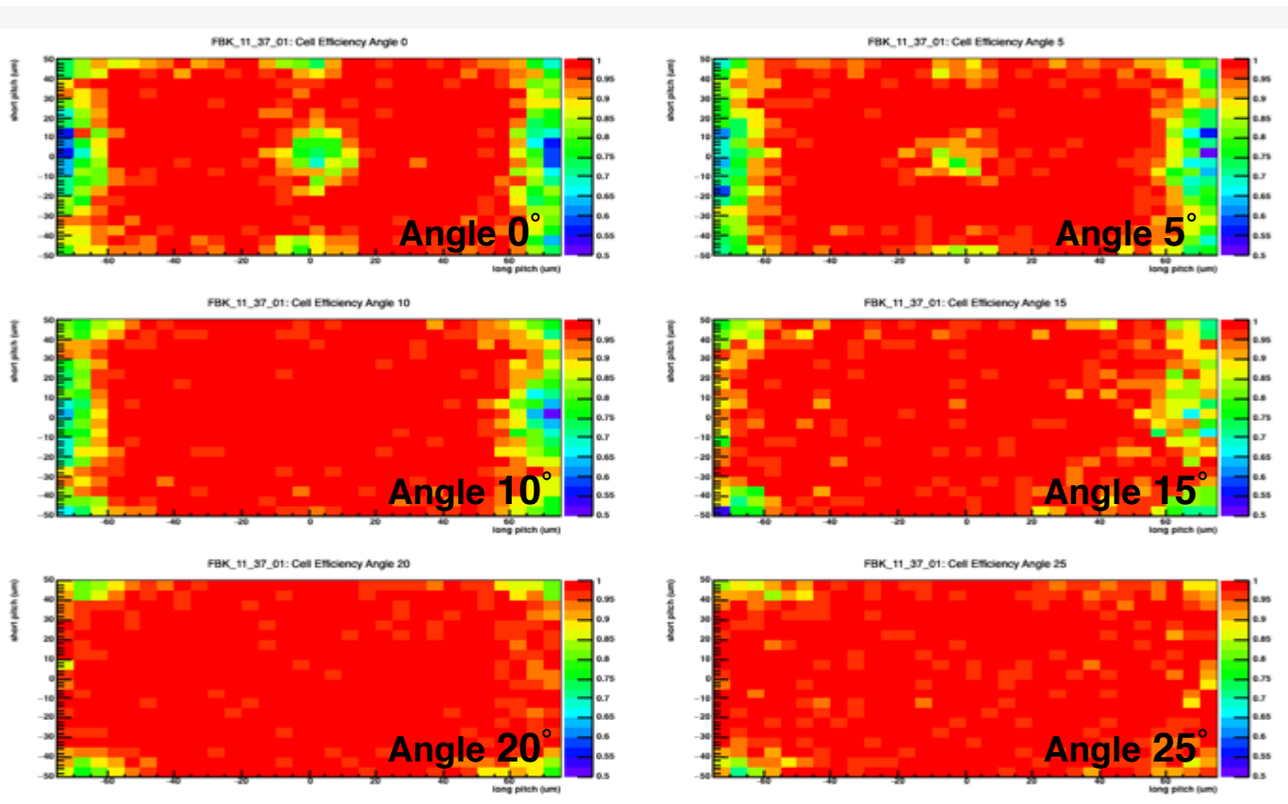
Efficiency vs angle

Preliminary





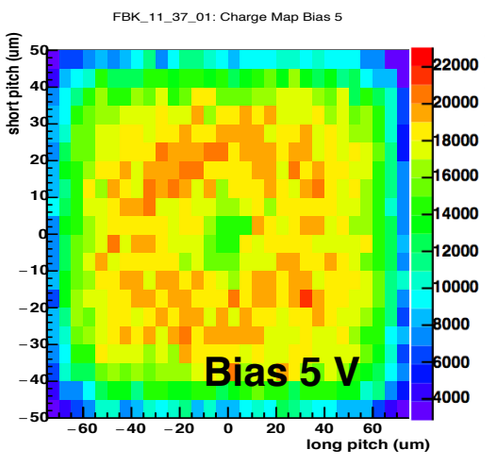


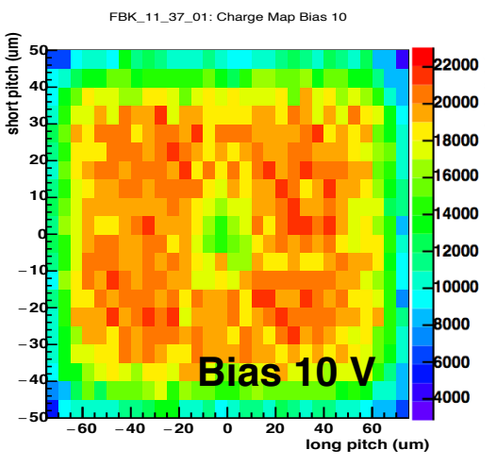


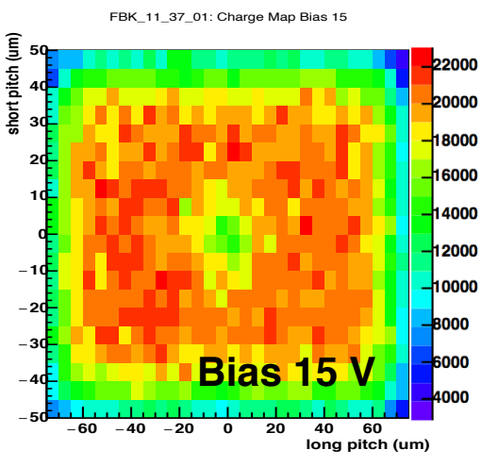
Cell charge before irradiation

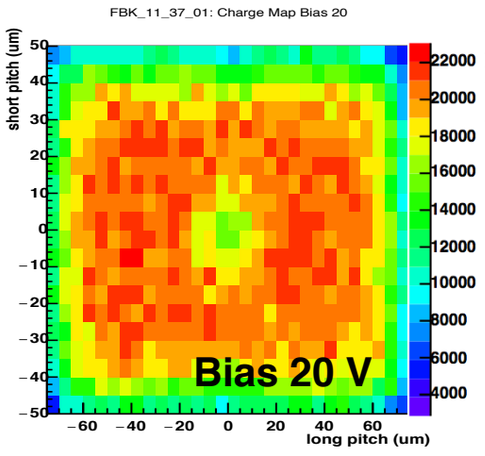
Preliminary

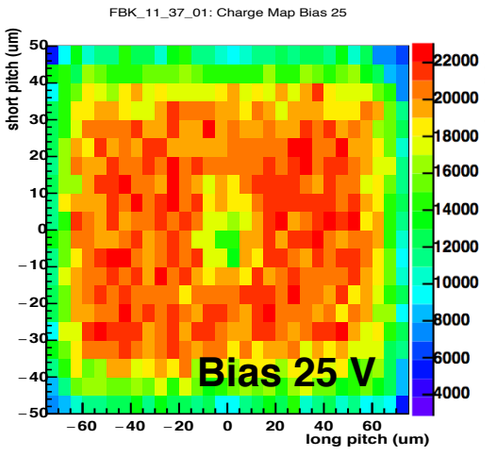
Charge vs bias (angle 0°)

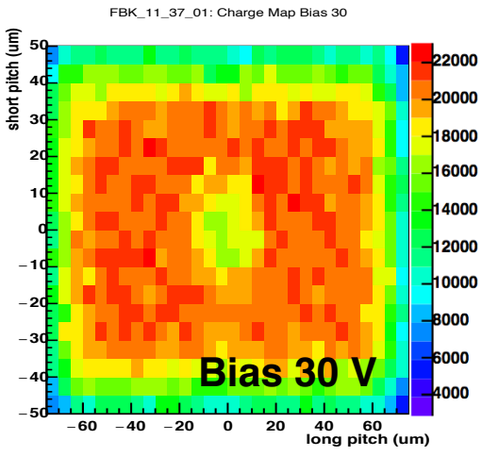


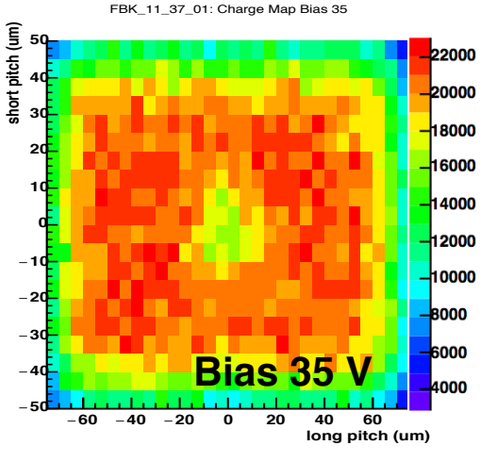






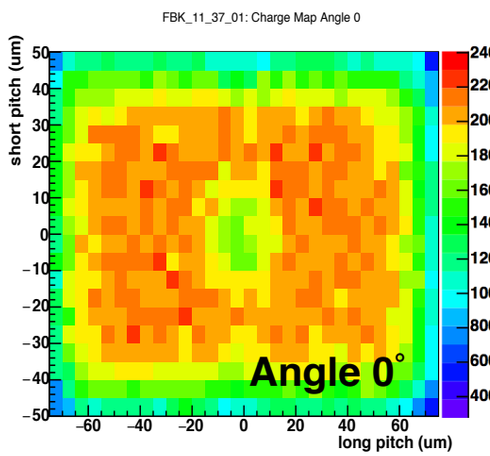


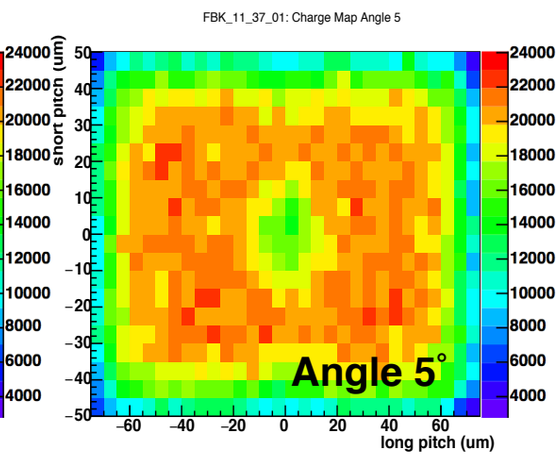


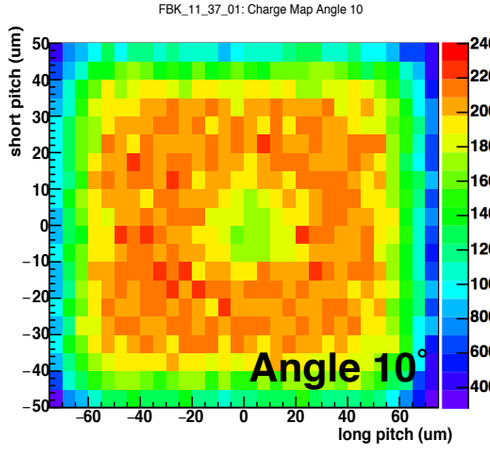


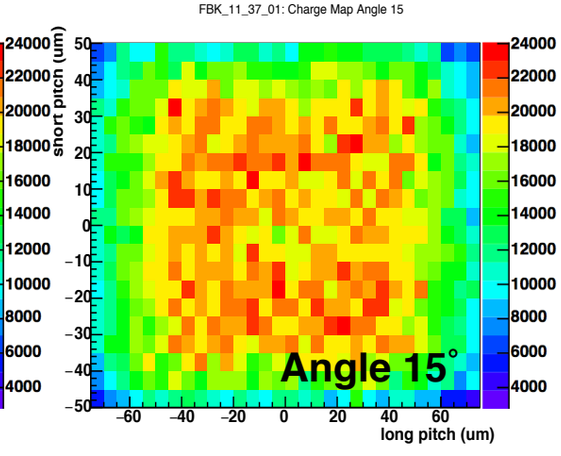
- Full charge collected already at 15 V.
- Reduction of the collected charge due to hollow readout column recovered completely at 20°.

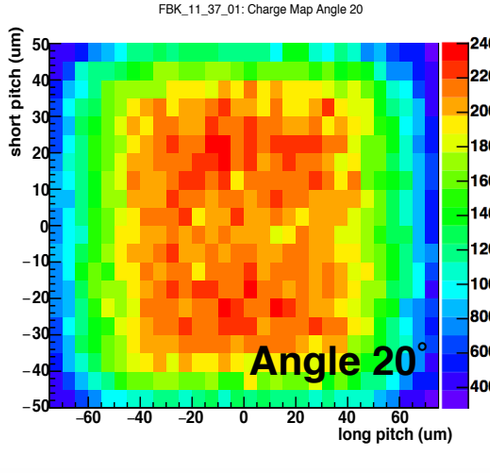
Charge vs angle (bias 30V)

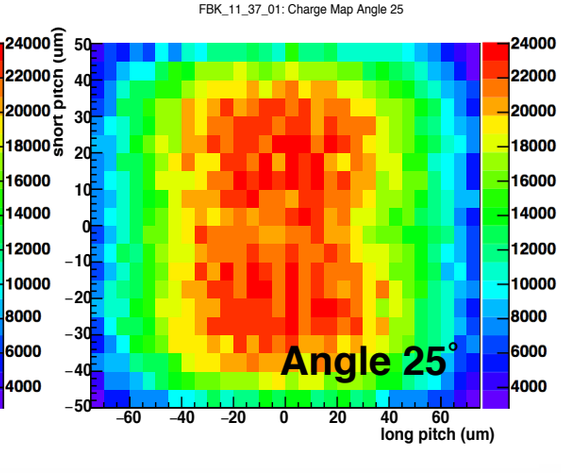










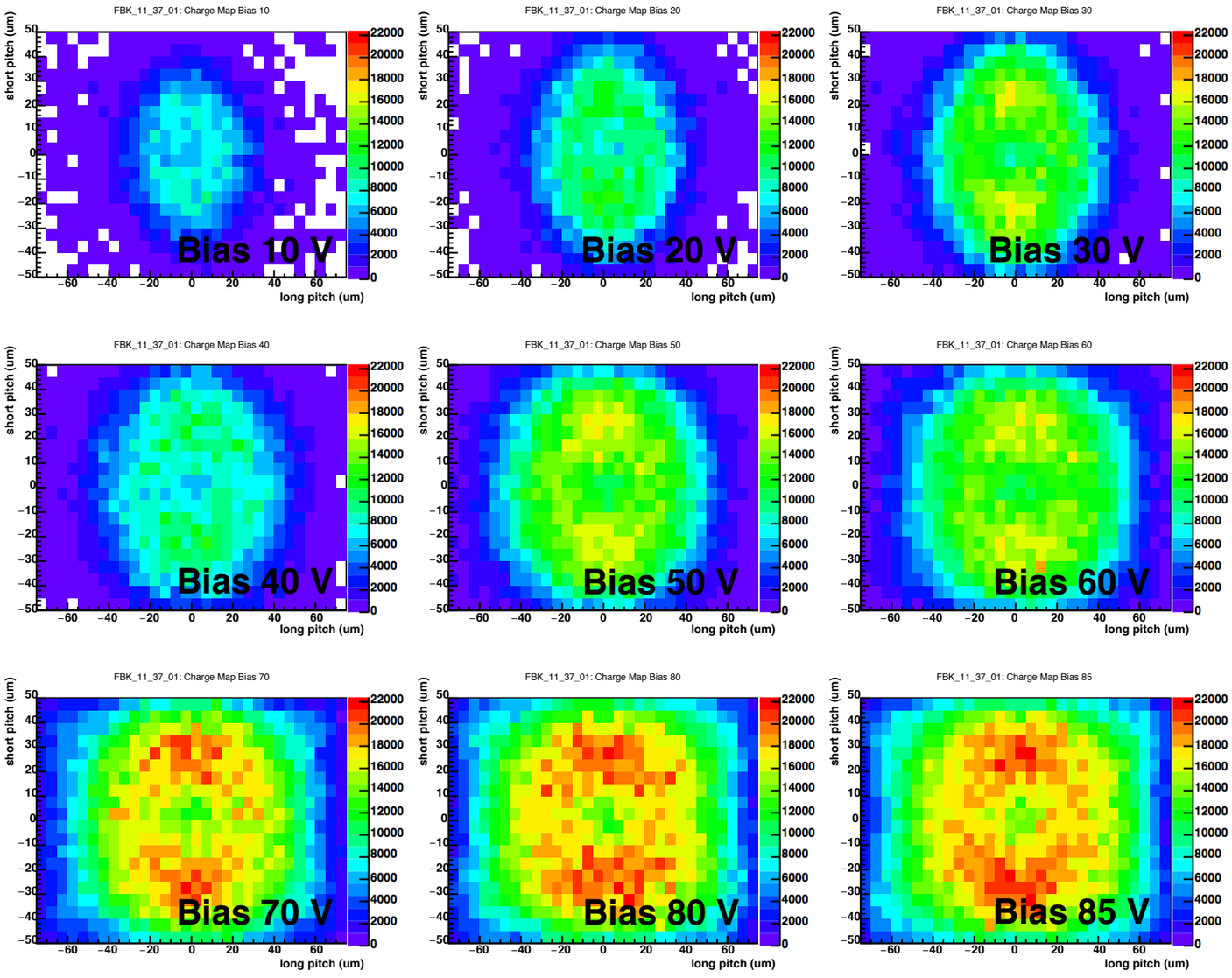


Cell charge after irradiation

FBK_11_37_01 (1x10^{15} n$_{eq}$/cm^2)

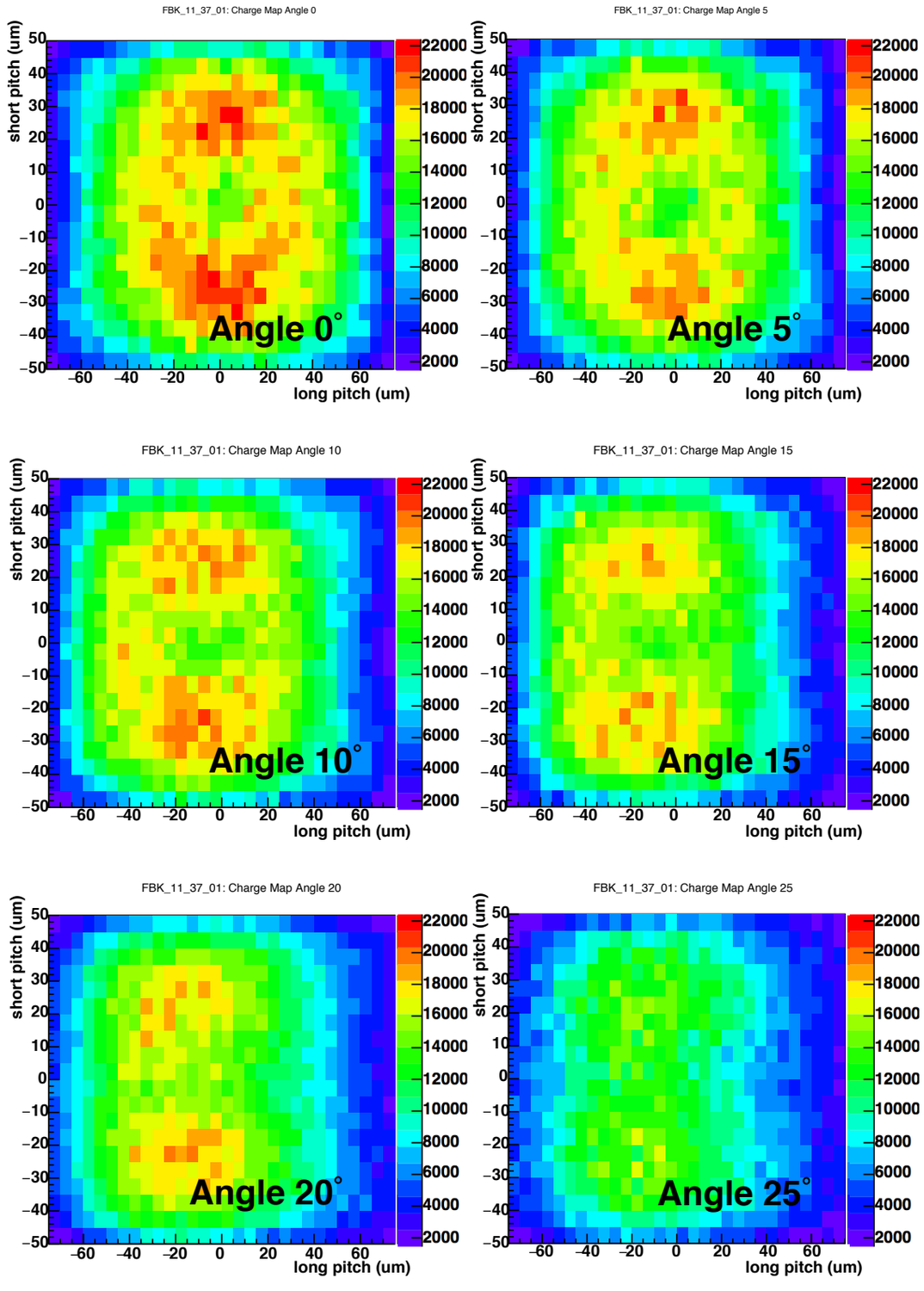
Preliminary

Charge vs bias (angle 0°)



- At lower biases detectors are not fully depleted.
- Left-right asymmetry in the collected charge after tilting the detectors.

Charge vs angle (bias 85 V)

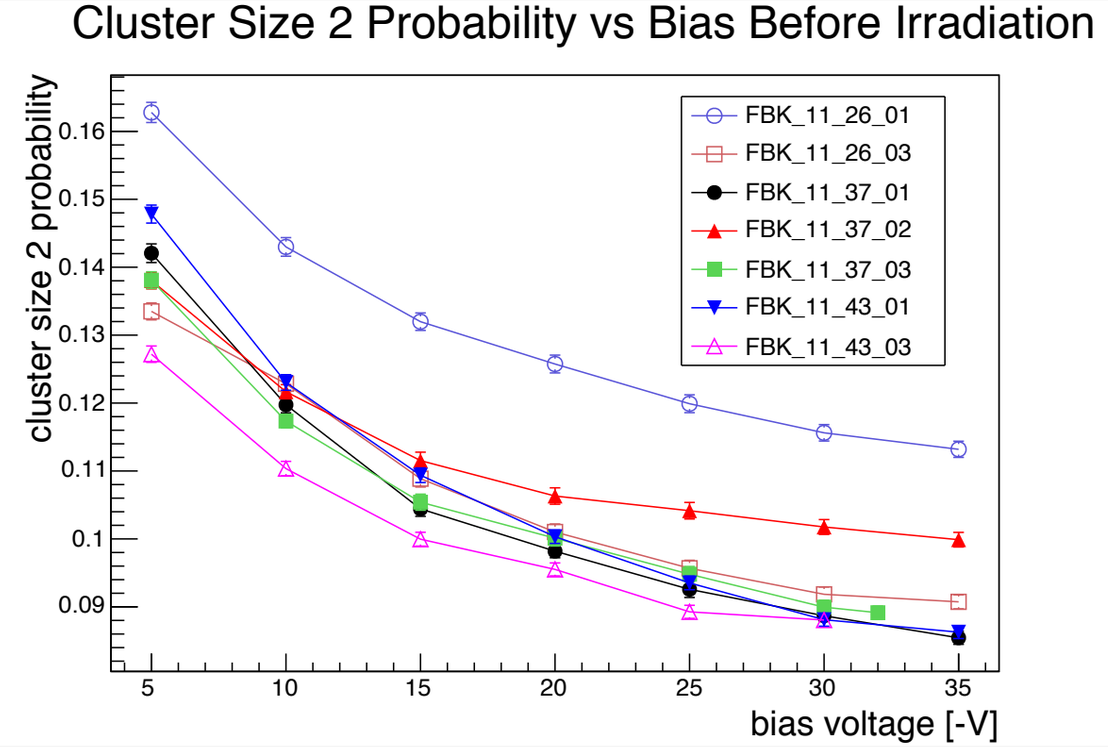


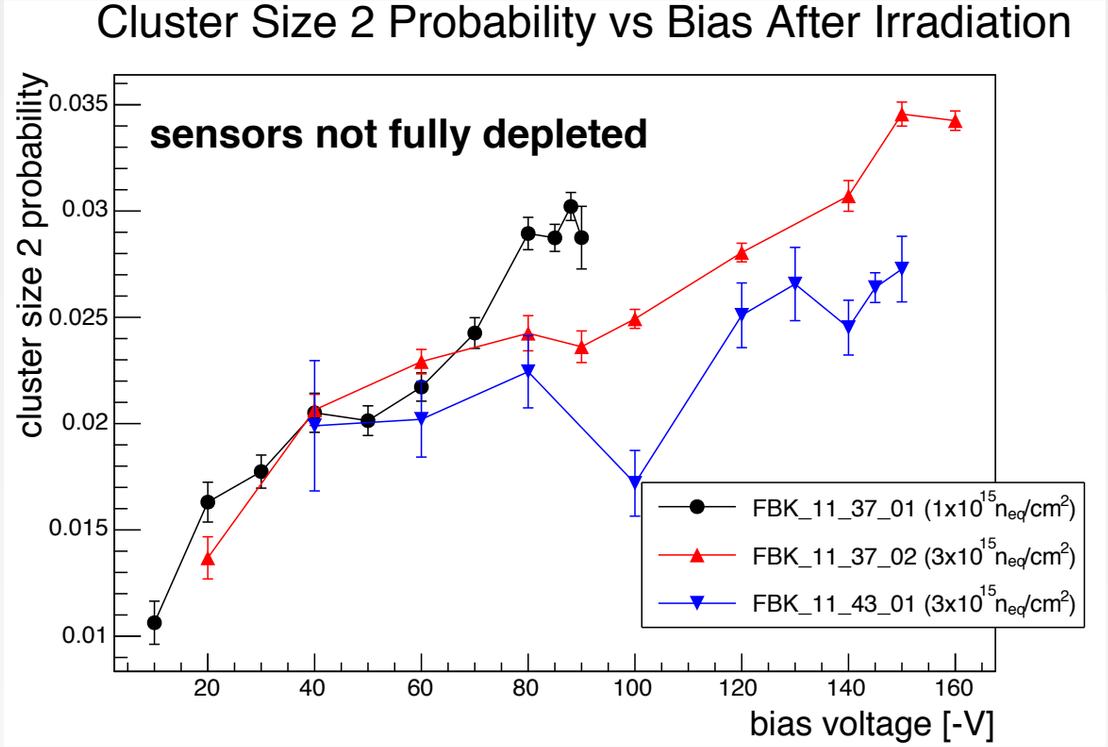
Cluster size before and after irradiation

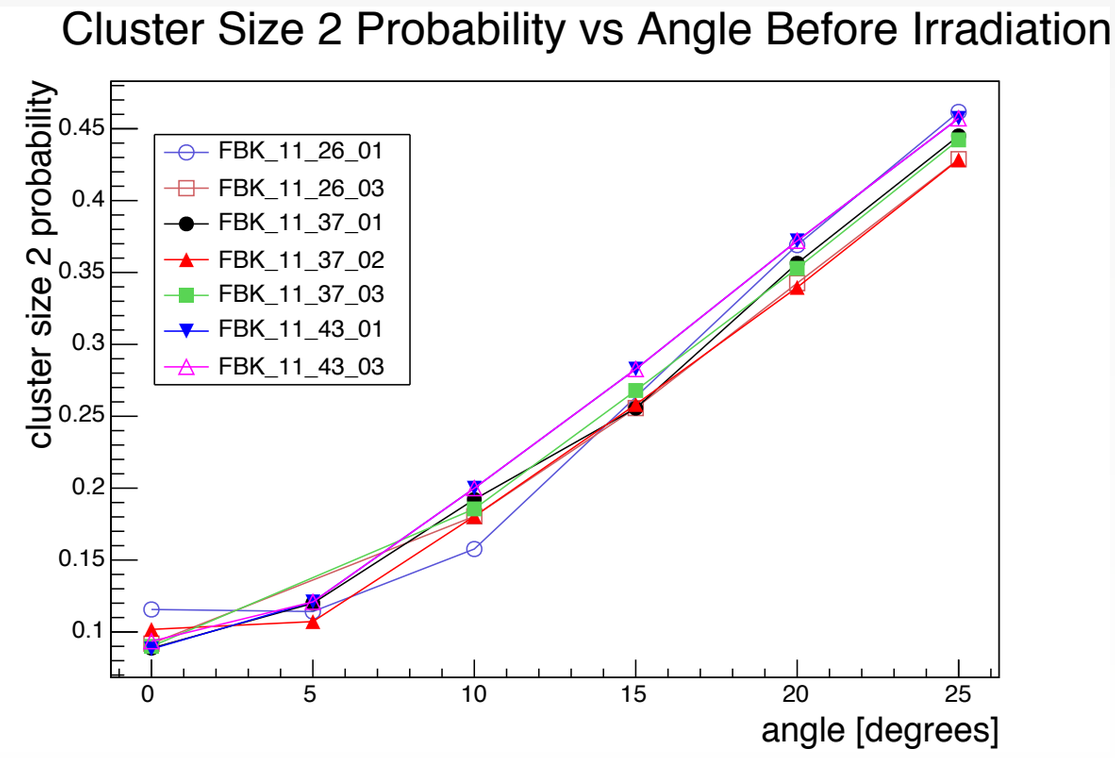
Before Irradiation

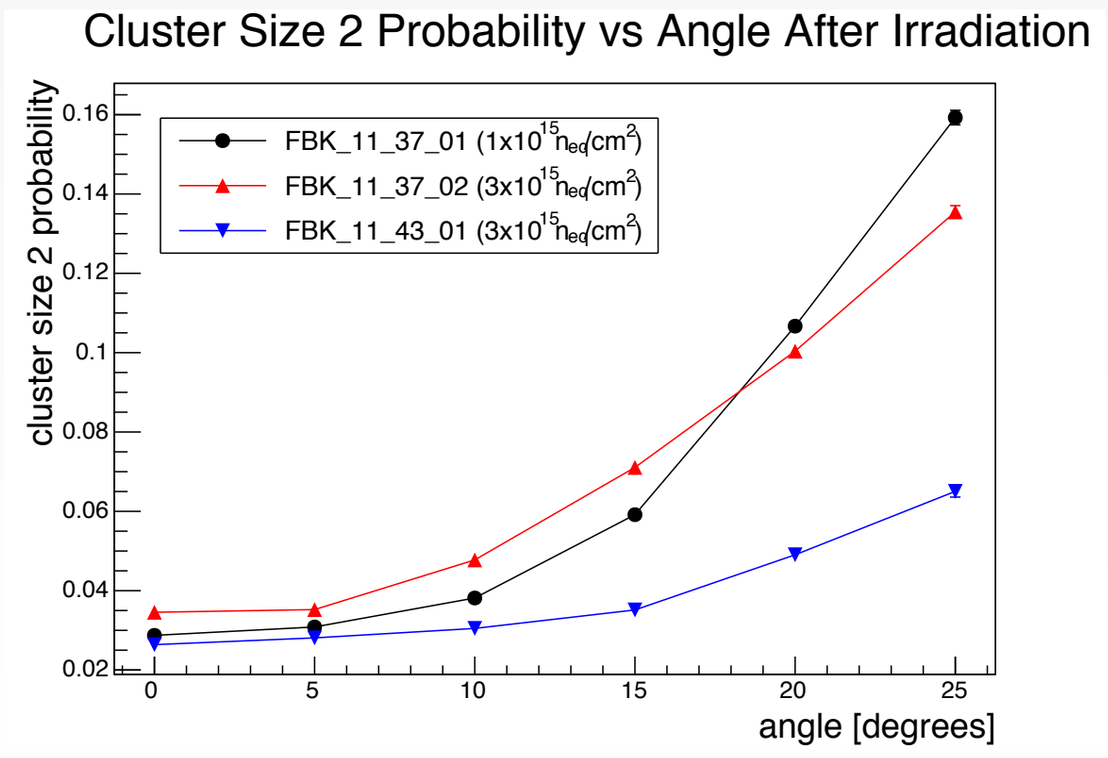
After Irradiation

Preliminary



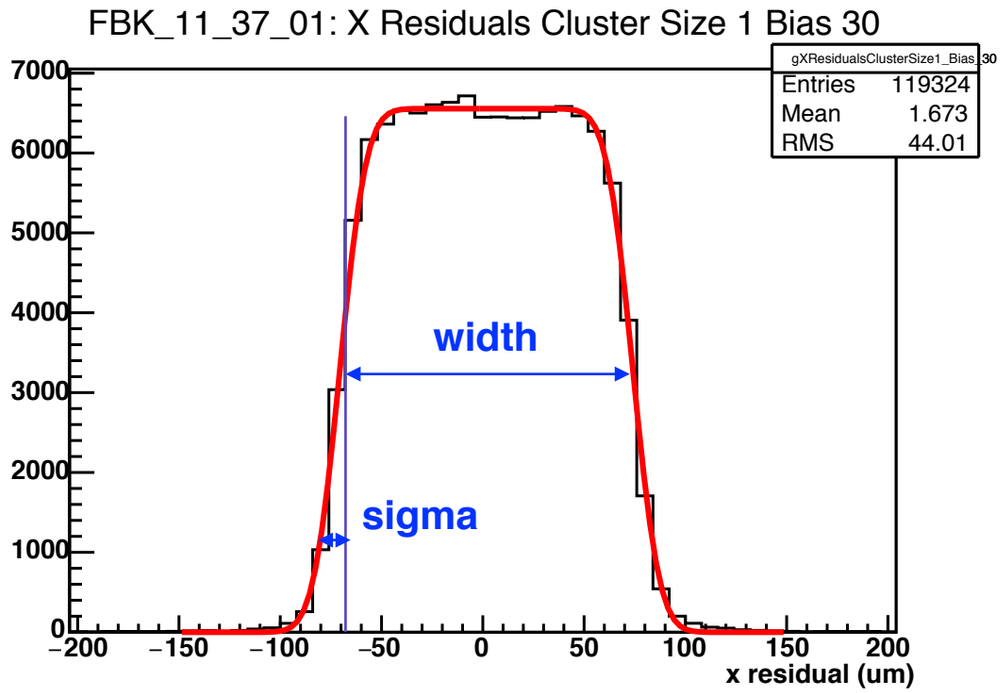




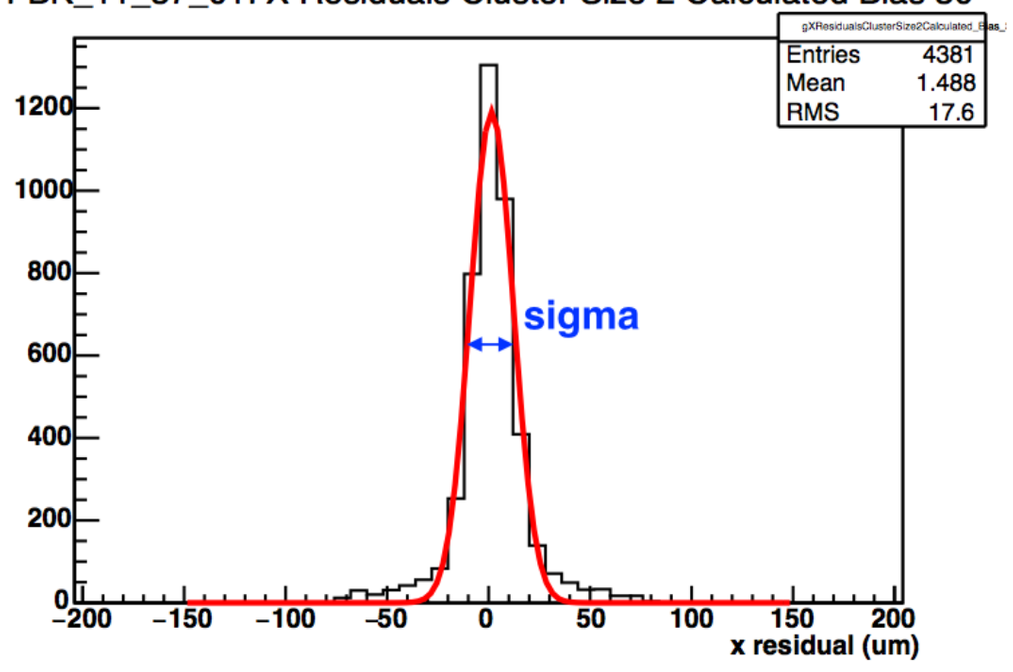


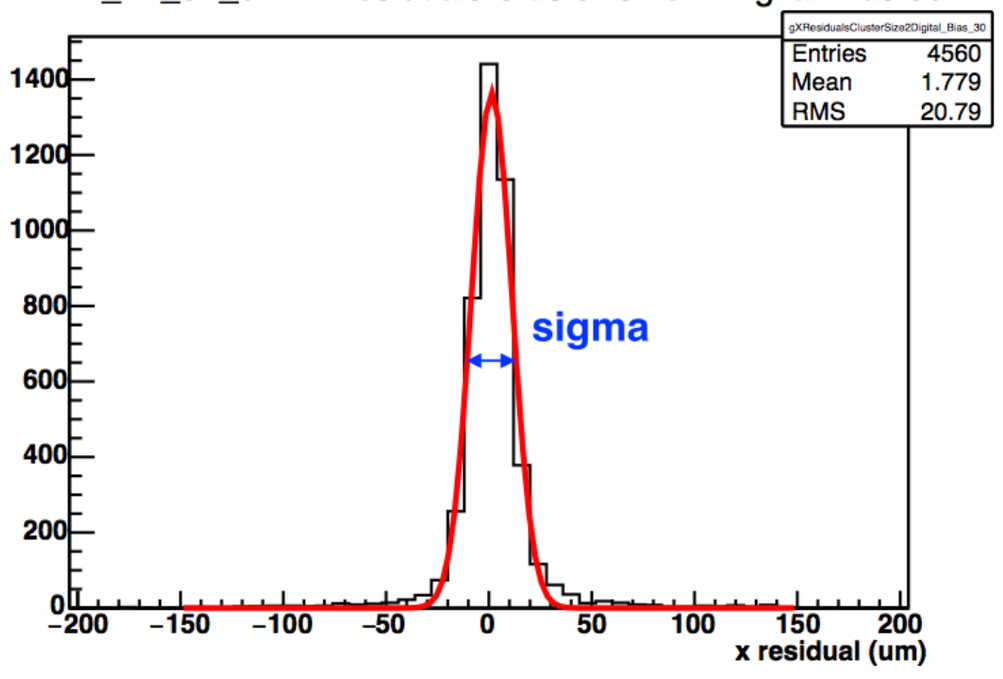
Residuals plots

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.
- Residuals cluster size 2 “Digital” evaluated assuming that the particle crosses the sensor exactly of to the border of the two hit pixels and fitted with a gaussian.



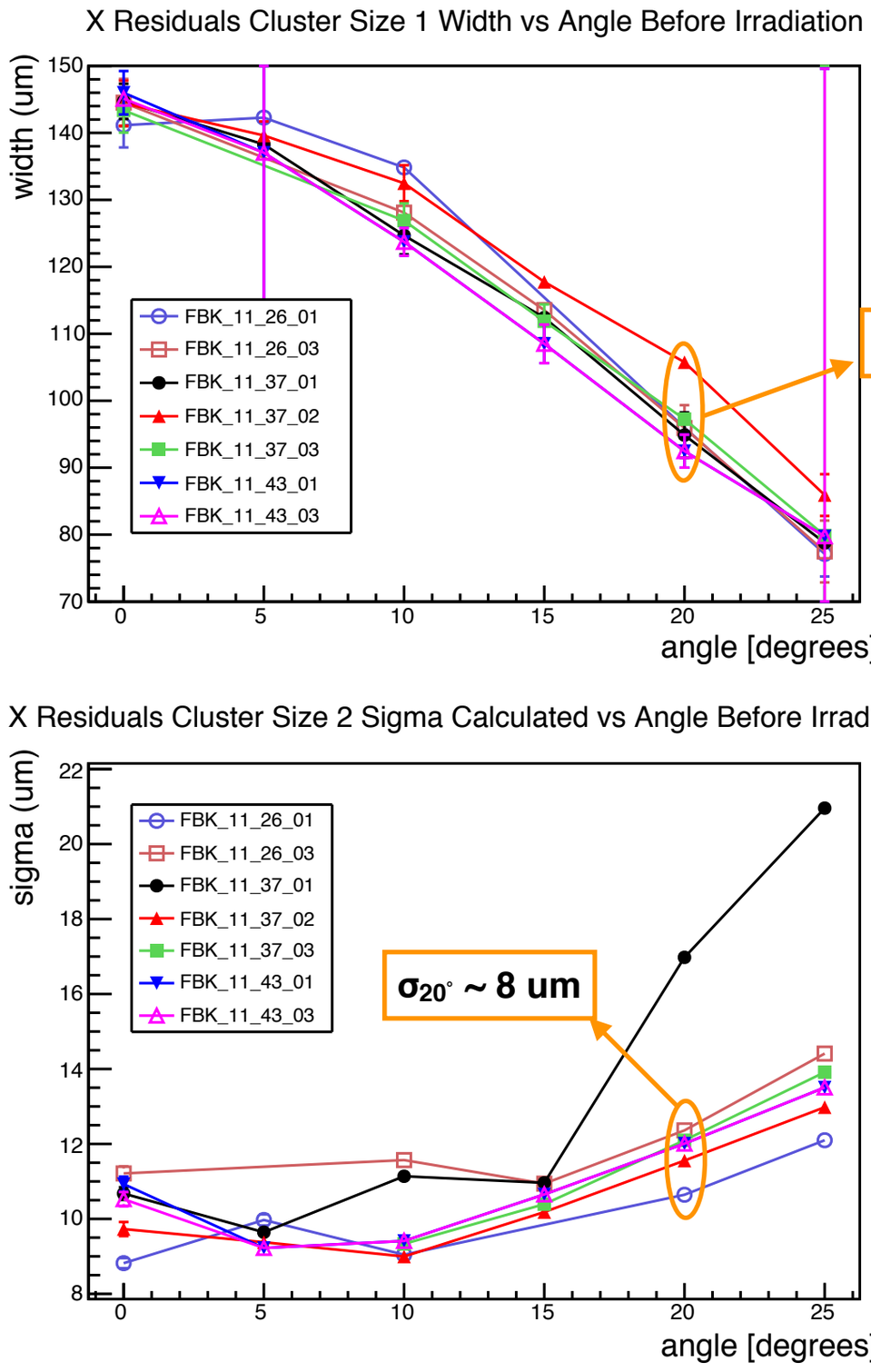


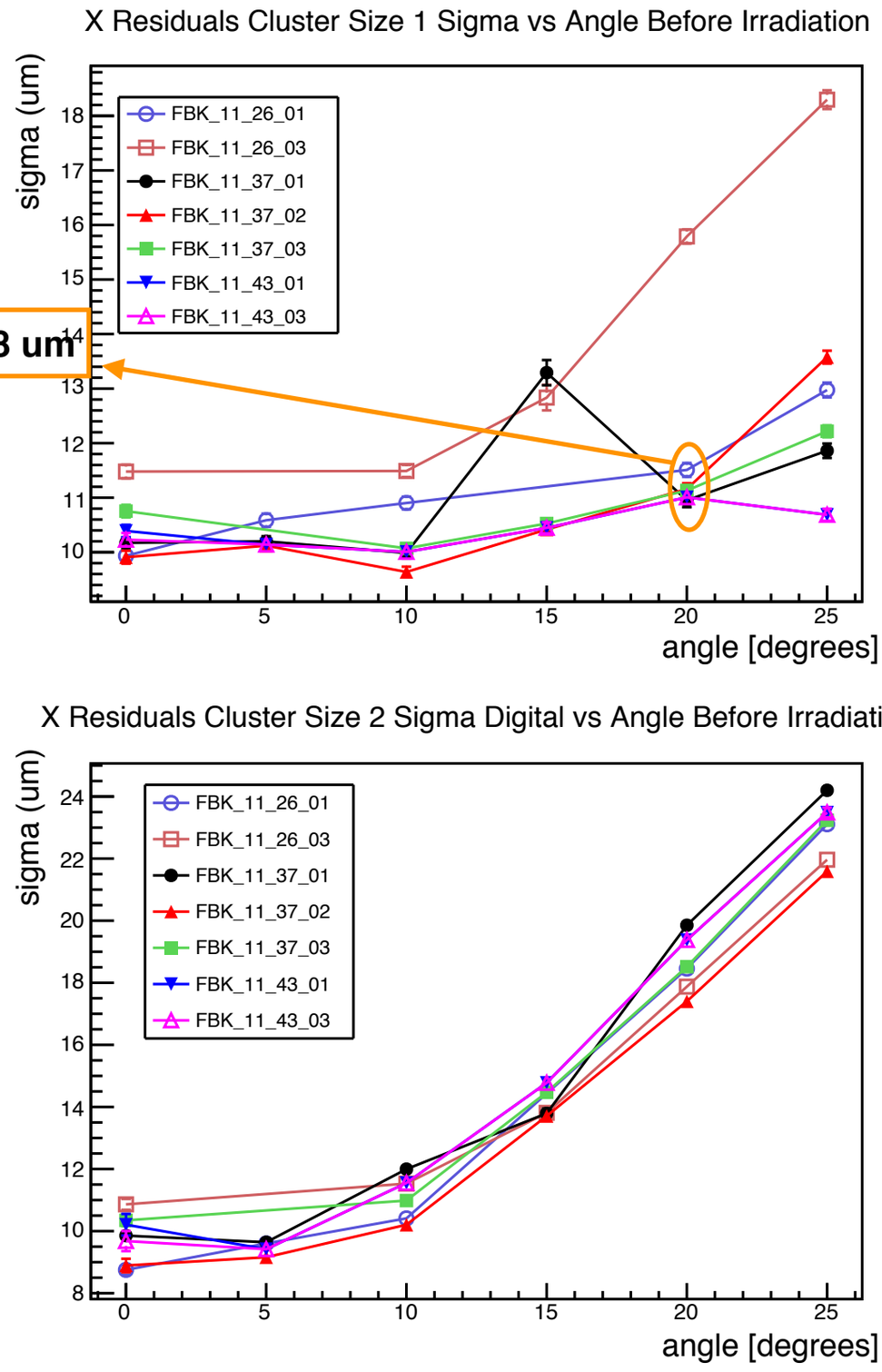
$$\sigma_{CS1} = \sqrt{\left(\frac{width_{CS1}}{\sqrt{12}}\right)^2 + sigma^2_{CS1} - sigma^2_{telescope}}$$

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

Resolution before irradiation

Preliminary

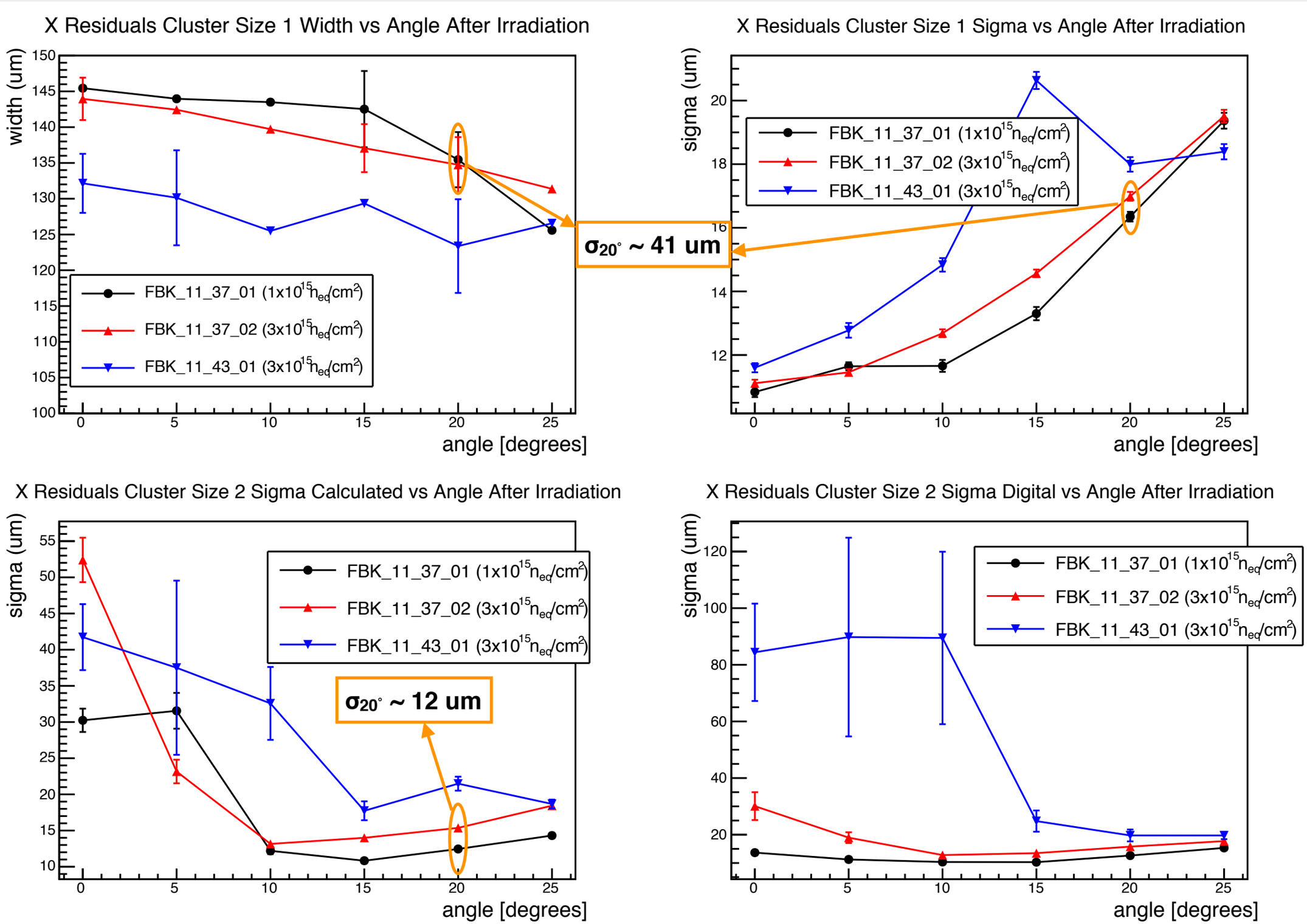




$\sigma_{20^\circ} \sim 28$ um

Resolution after irradiation

Preliminary



Conclusions

- FBK 1E 3D sensors bump-bonded to the CMS digital ROCs have been tested successfully before and after irradiation. Preliminary results have been shown.
- Efficiency before irradiation > 99.5% at angle > 5°.
- Efficiency after irradiation > 98% at 20° after irradiation of $1x10^{15}$ n_{eq}/cm^2 .
- Cluster size 2 probability behaviour as a function of bias and angle as expected before irradiation. Low statistic after irradiation due to not full depletion of the pixel borders.
- Resolutions before irradiation at 20°: ~28 μm for cluster size 1 and ~8 μm for cluster size 2.
- All the limitations in terms of efficiency and resolution are expected to be overcome using sensors with more than one readout column in each pixel.

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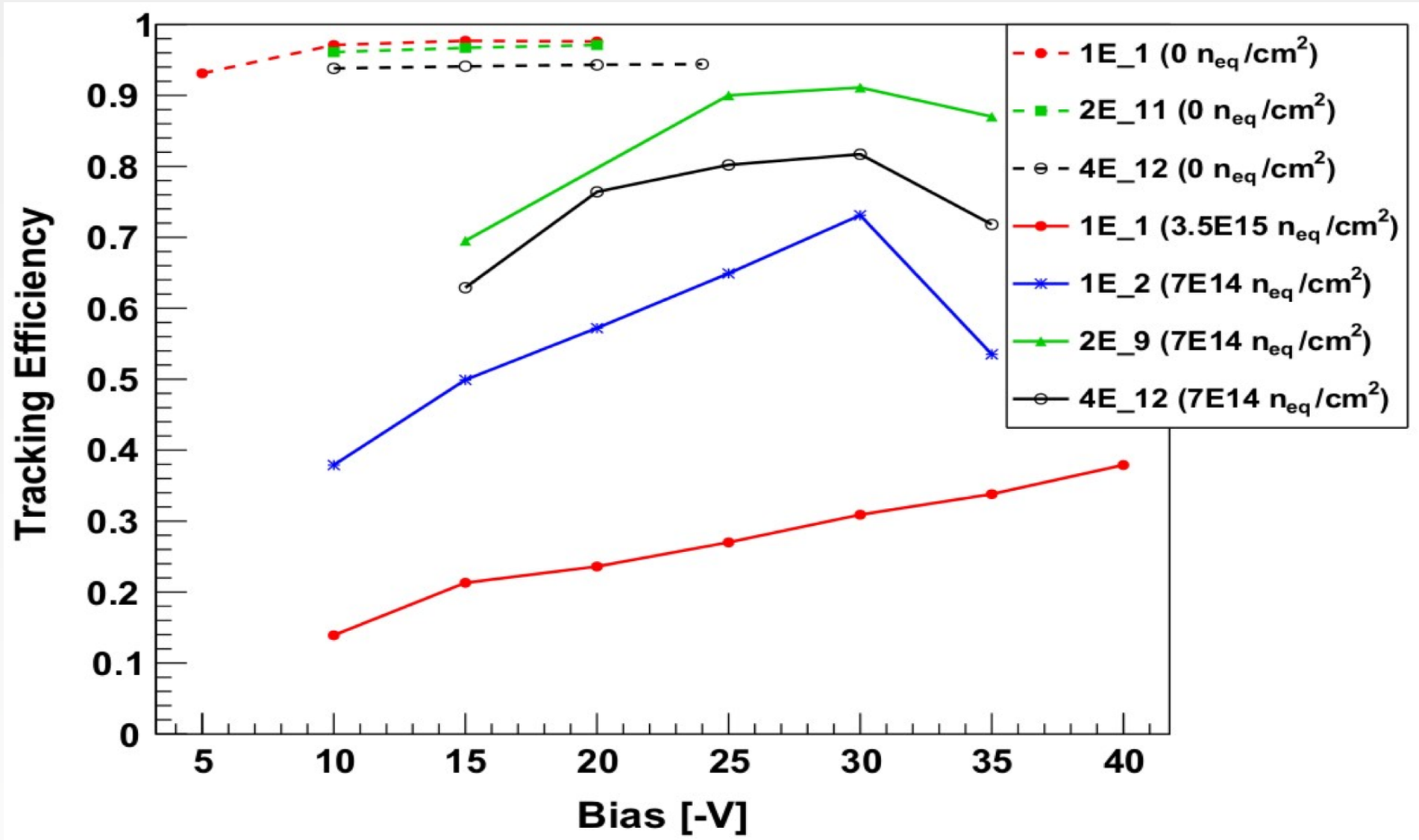
Backup Slides

FBK 3D + CMS analog chip efficiency

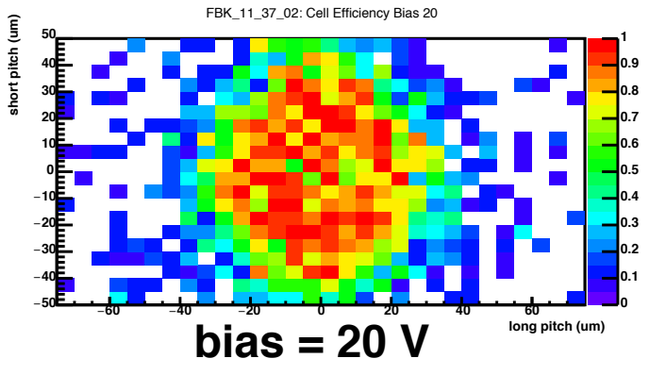


A. Krzywda et al., NIM A 763 (2014) 404–411

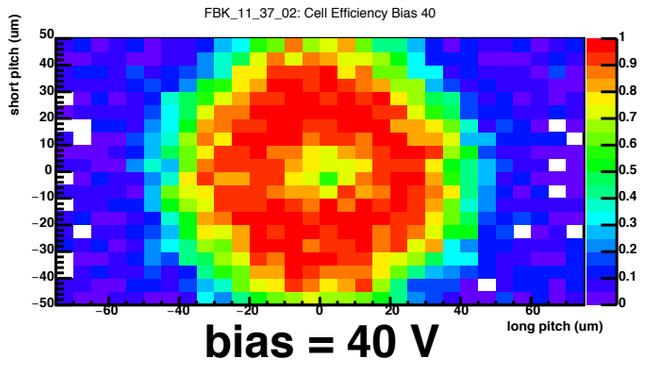
Pixel cell efficiency after irradiation

FBK_11_37_02 (3x10^{15} n_{eq}/cm^2)

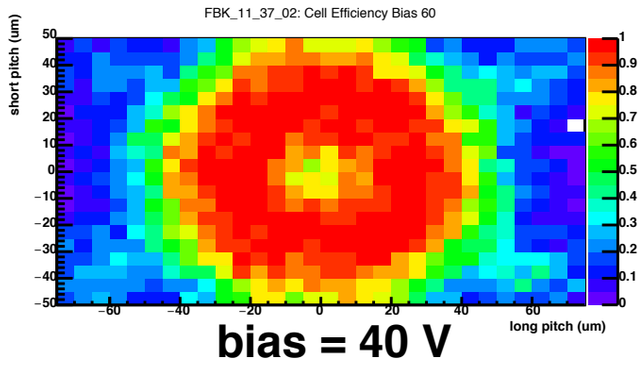
Preliminary



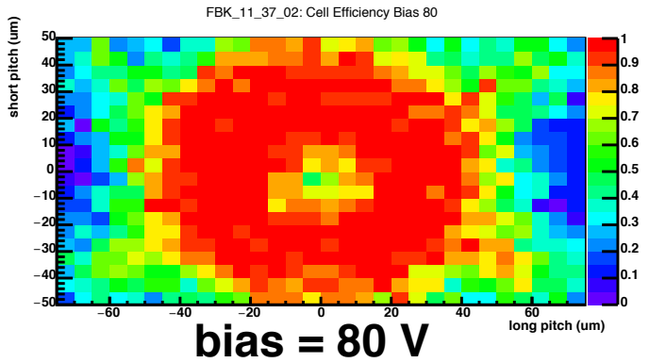
bias = 20 V



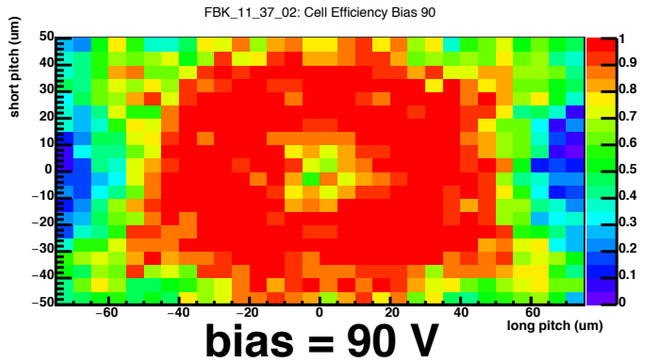
bias = 40 V



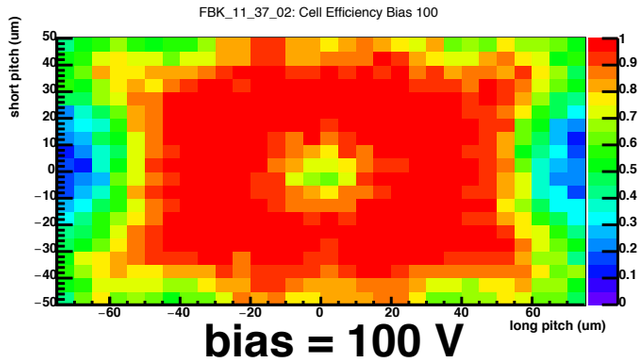
bias = 40 V



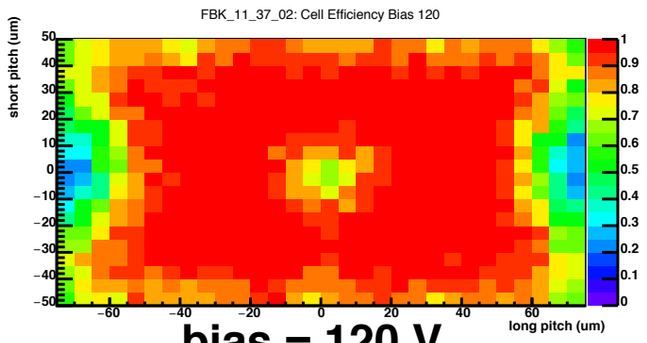
bias = 80 V



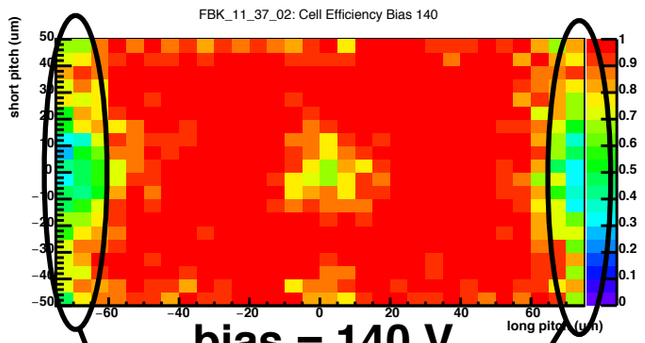
bias = 90 V



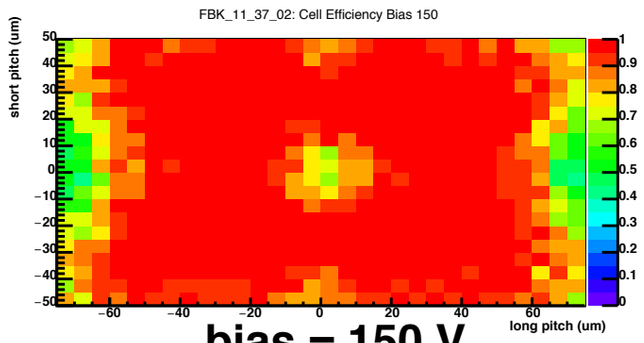
bias = 100 V



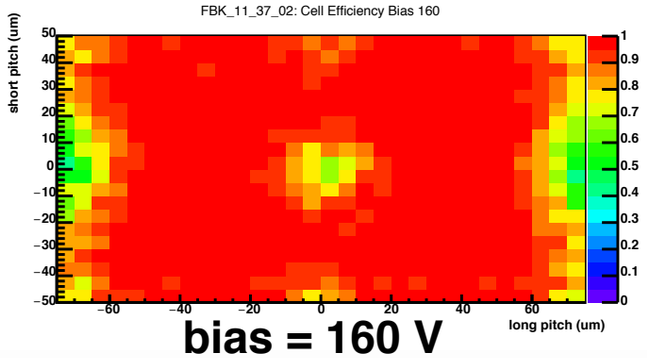
bias = 120 V



bias = 140 V

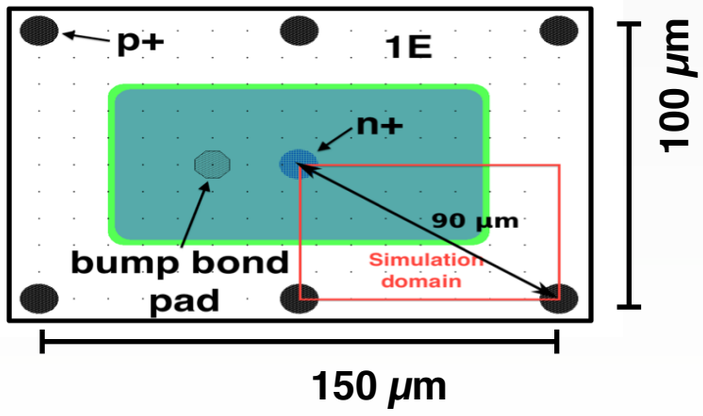


bias = 150 V



bias = 160 V

1 readout column not enough to fully collect charge in the side region

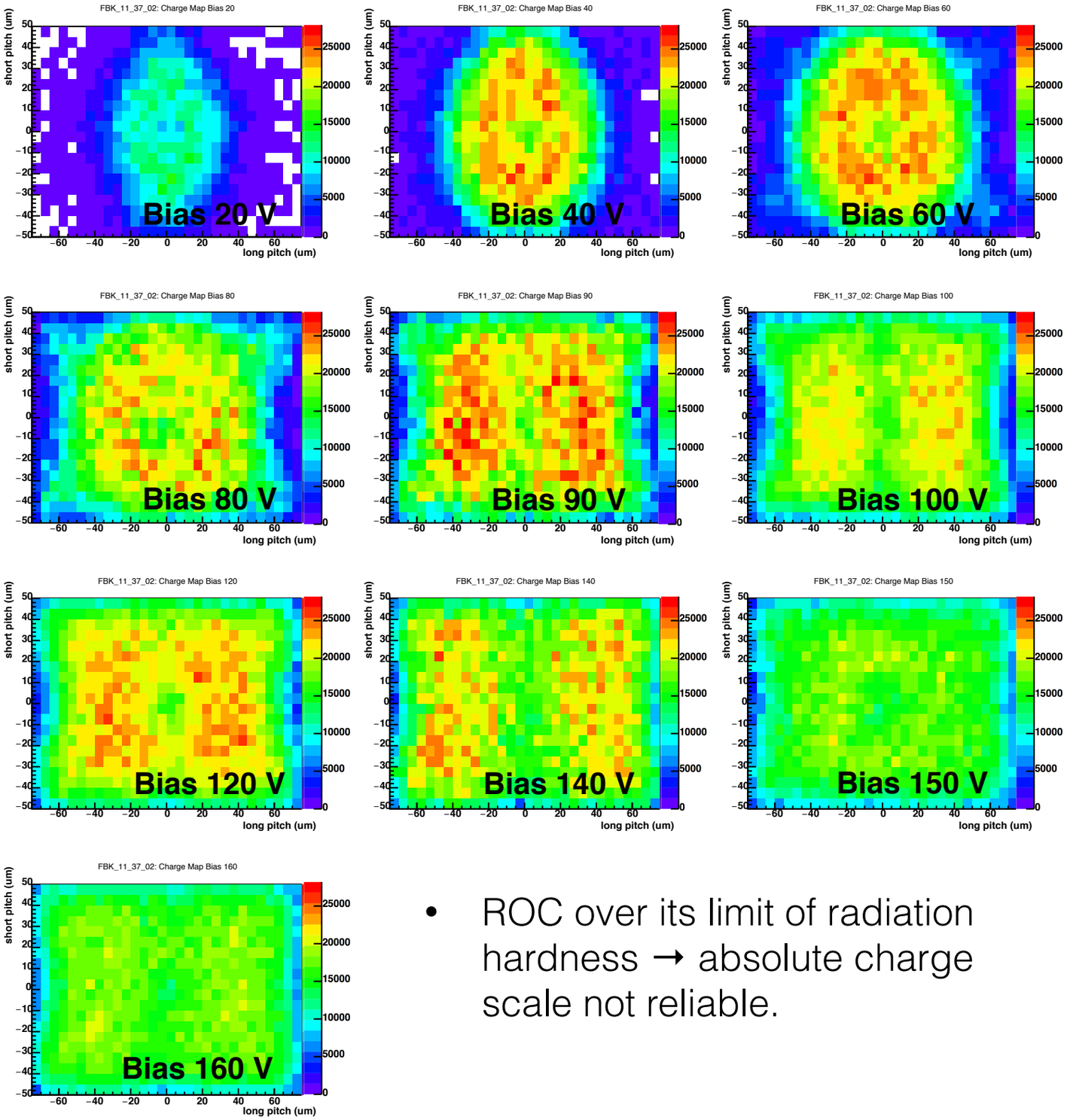


Cell charge after irradiation

FBK_11_37_02 (3x10^{15} n$_{eq}$/cm^2)

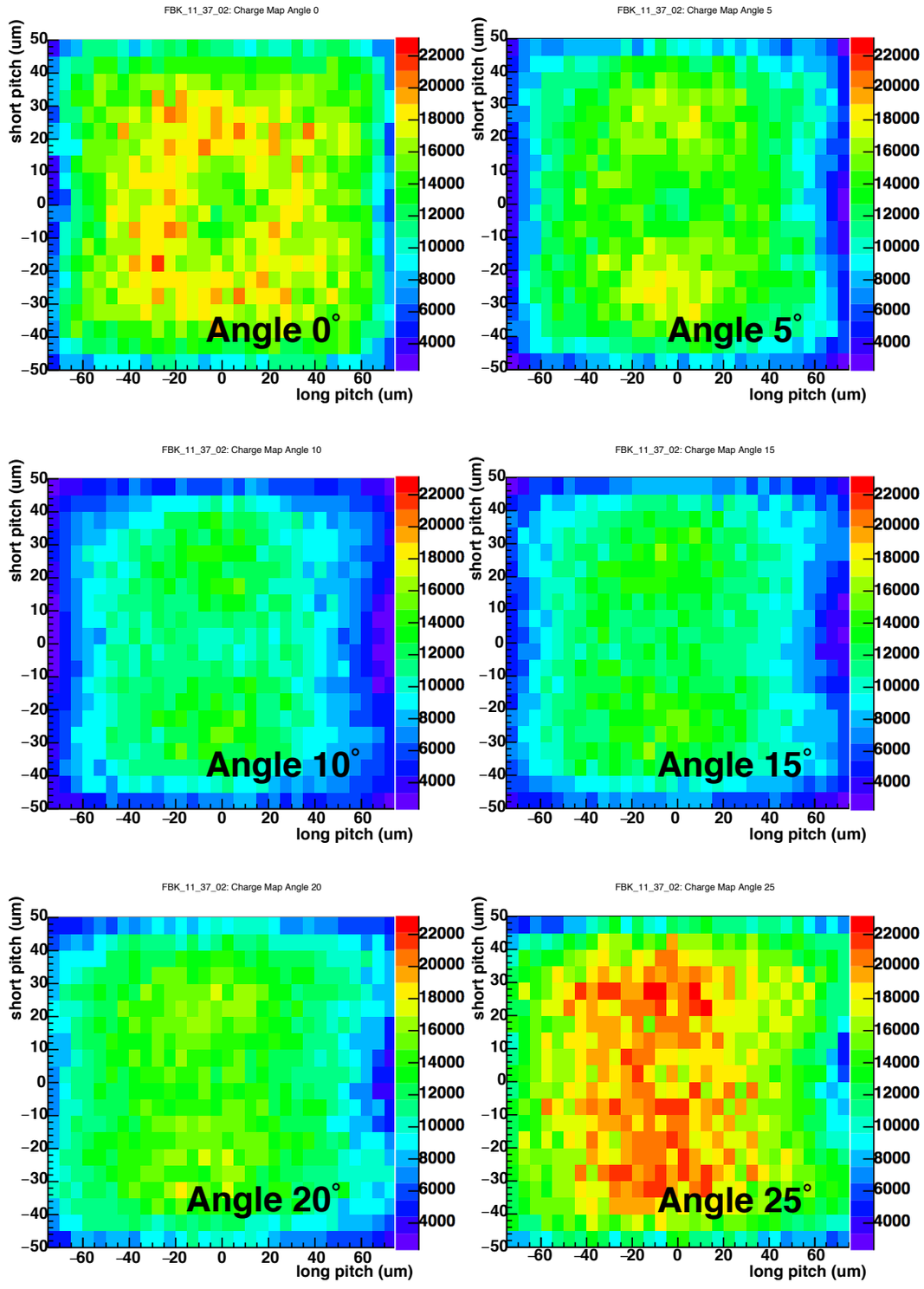
Preliminary

Charge vs bias (angle 0°)



- ROC over its limit of radiation hardness → absolute charge scale not reliable.

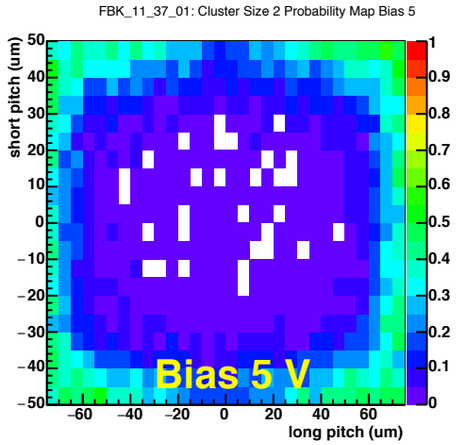
Charge vs angle (bias 150 V)

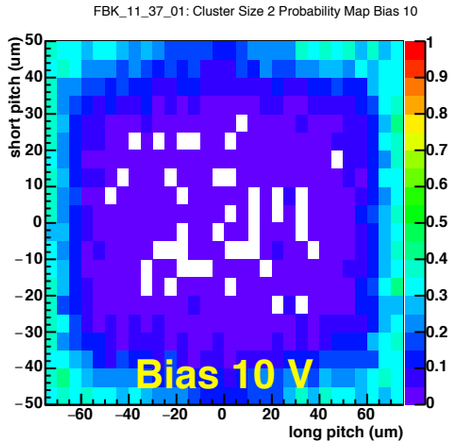


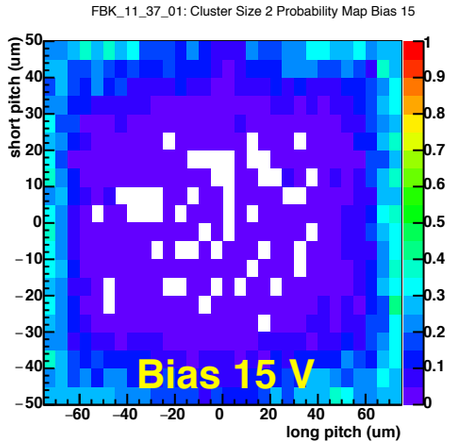
Cell cluster size before irradiation

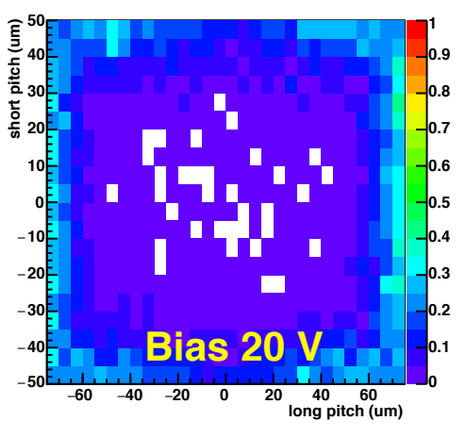
Preliminary

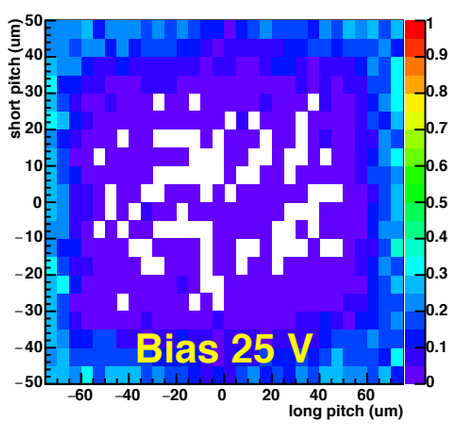
Cluster size 2 probability vs bias

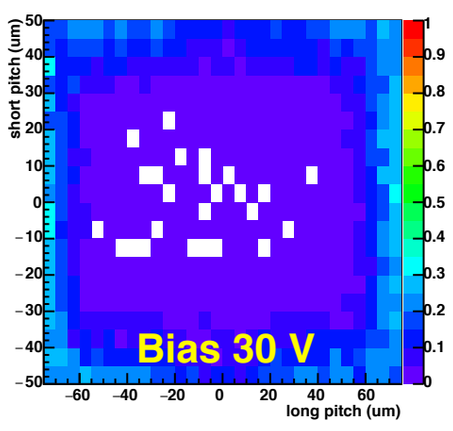


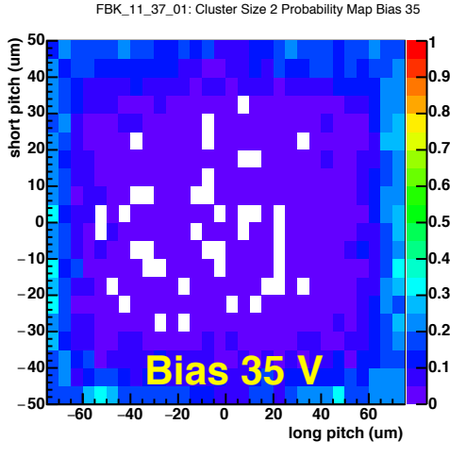






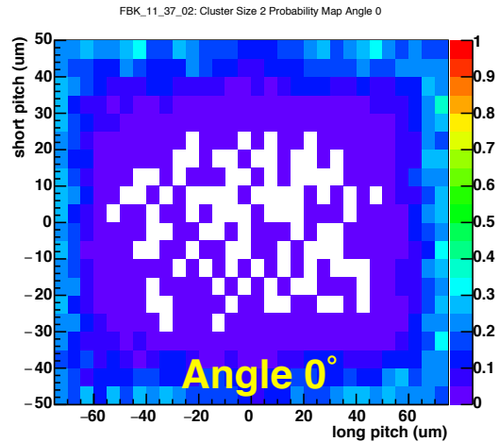


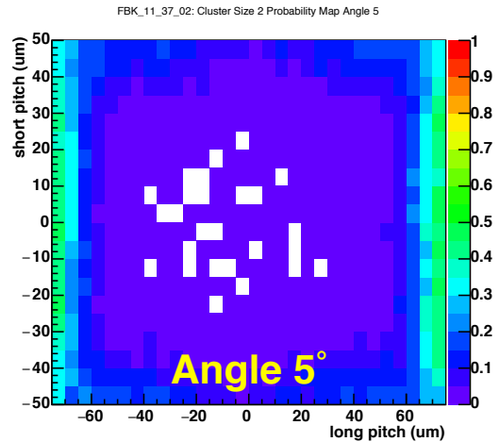


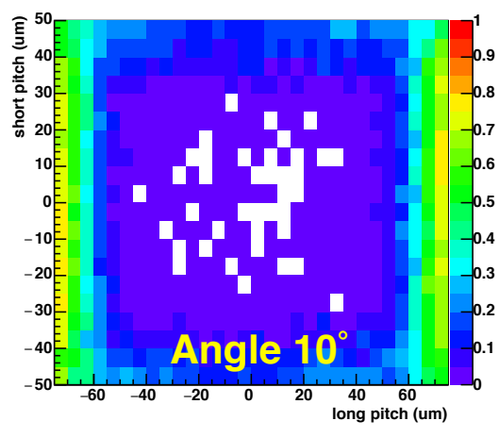


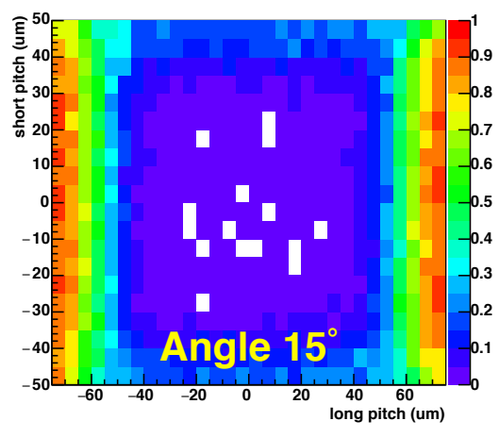
- Low bias → Cluster size 2 at the pixel border where electric field is lower.
- Sensor tilted with respect to a vertical axis → increase of cluster size 2 for geometrical reasons.

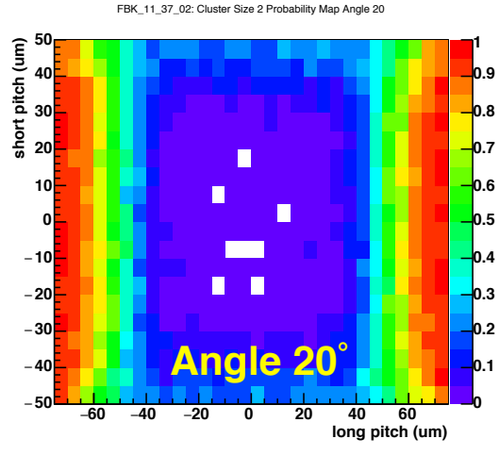
Cluster size 2 probability vs angle

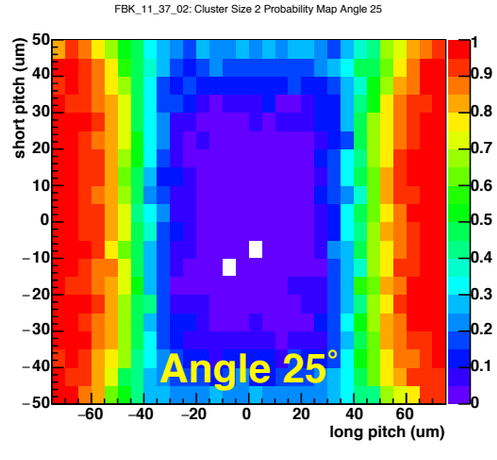








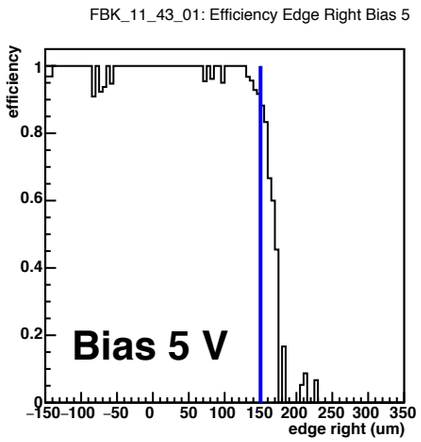


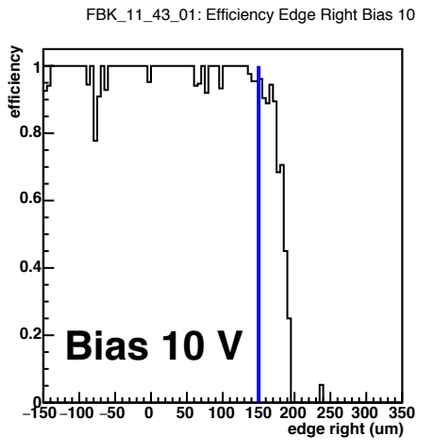


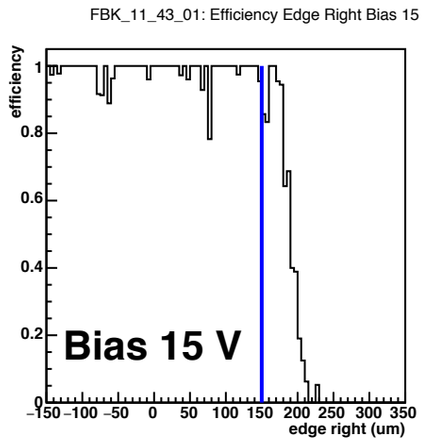
Edge efficiency before irradiation

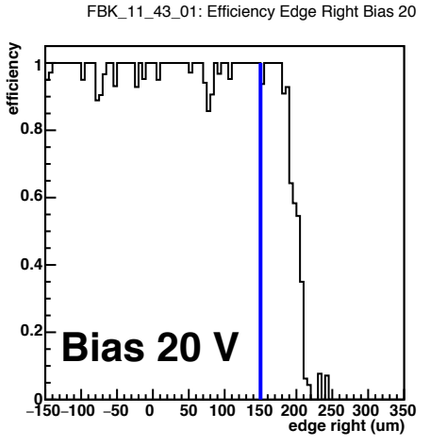
Preliminary

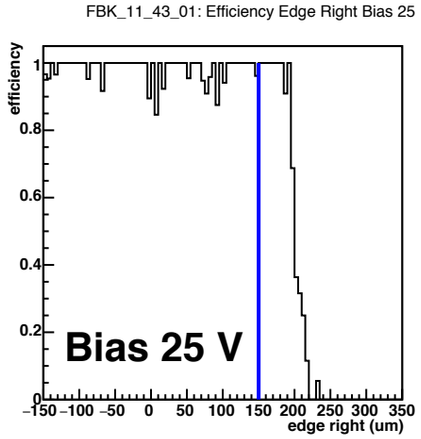
Edge efficiency vs bias (angle 0°)

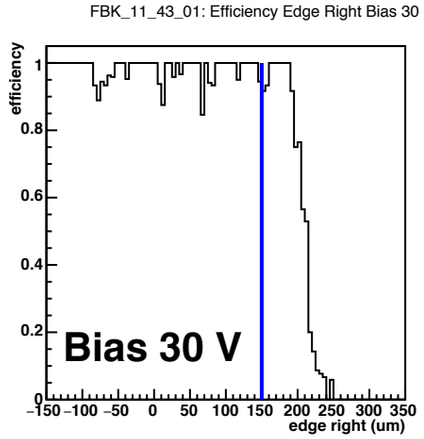


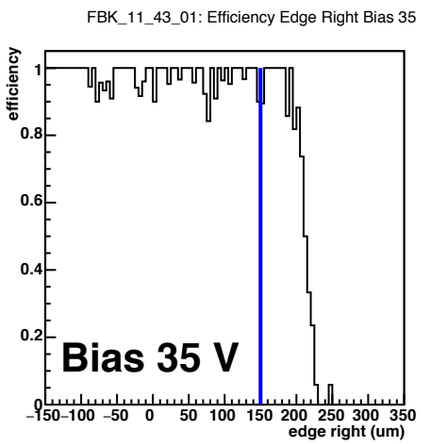






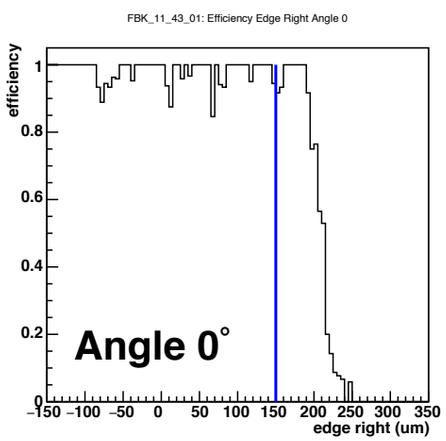


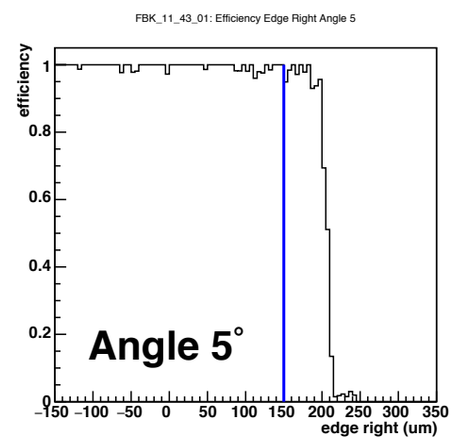


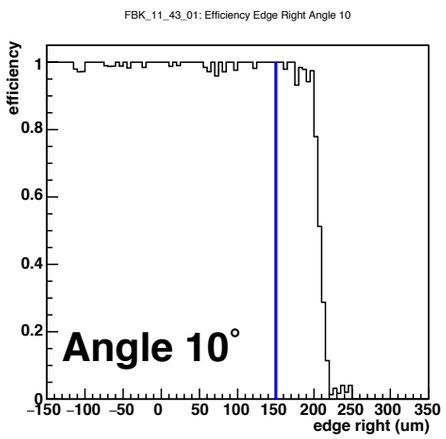


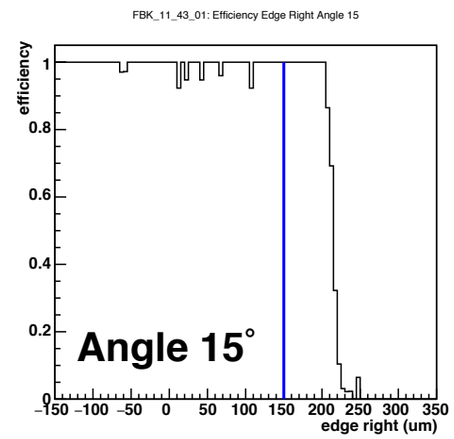
- Edge of the pixel: blue line
- Edge on the sensor: right limit of the histogram

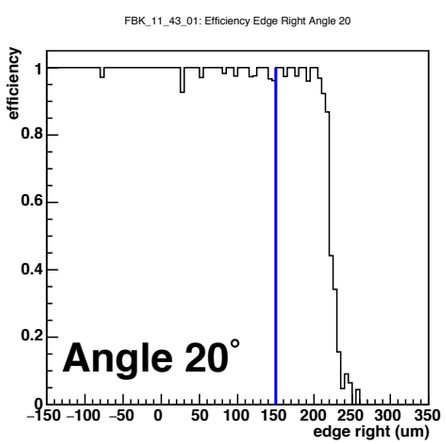
Edge efficiency vs angle (bias 30 V)

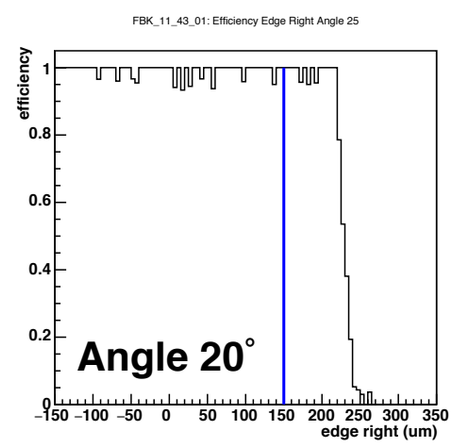












At operating voltage and angle of 20°: extra ~70 μm of active area at sensor edge