

The CT-PPS tracking system with 3D pixel detectors

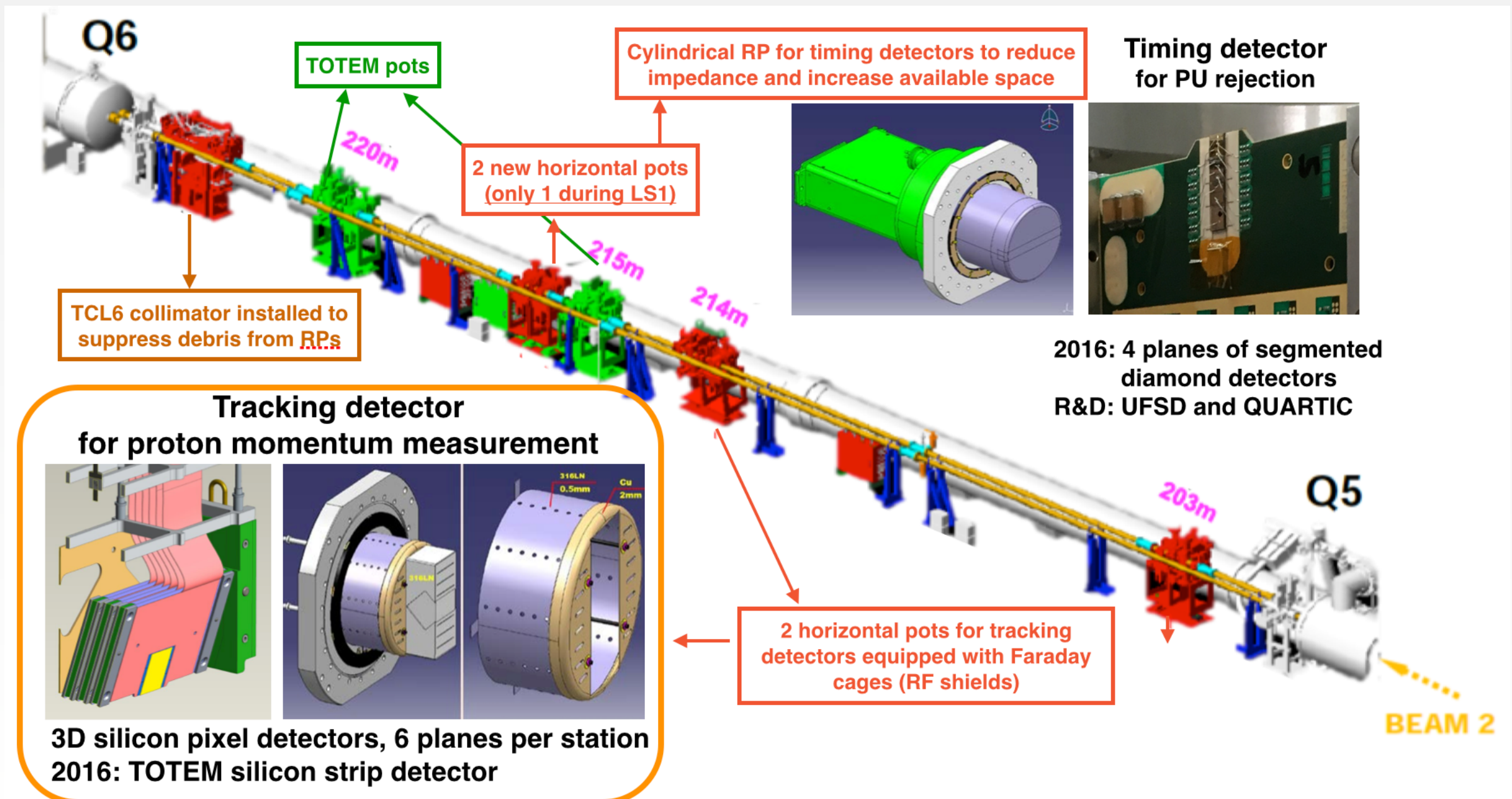
Fabio Ravera
on behalf of the CMS and TOTEM Collaborations

QCD at LHC: forward physics
and UPC collisions of heavy ions

Trento, 27 September 2016

CMS-TOTEM Precision Proton 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
- **Tracking and timing detectors** will be installed in Roman pots between 205 and 215 m from the CMS/TOTEM IP, two stations for each detector on both sides



Tracking system

- **Requirements:**

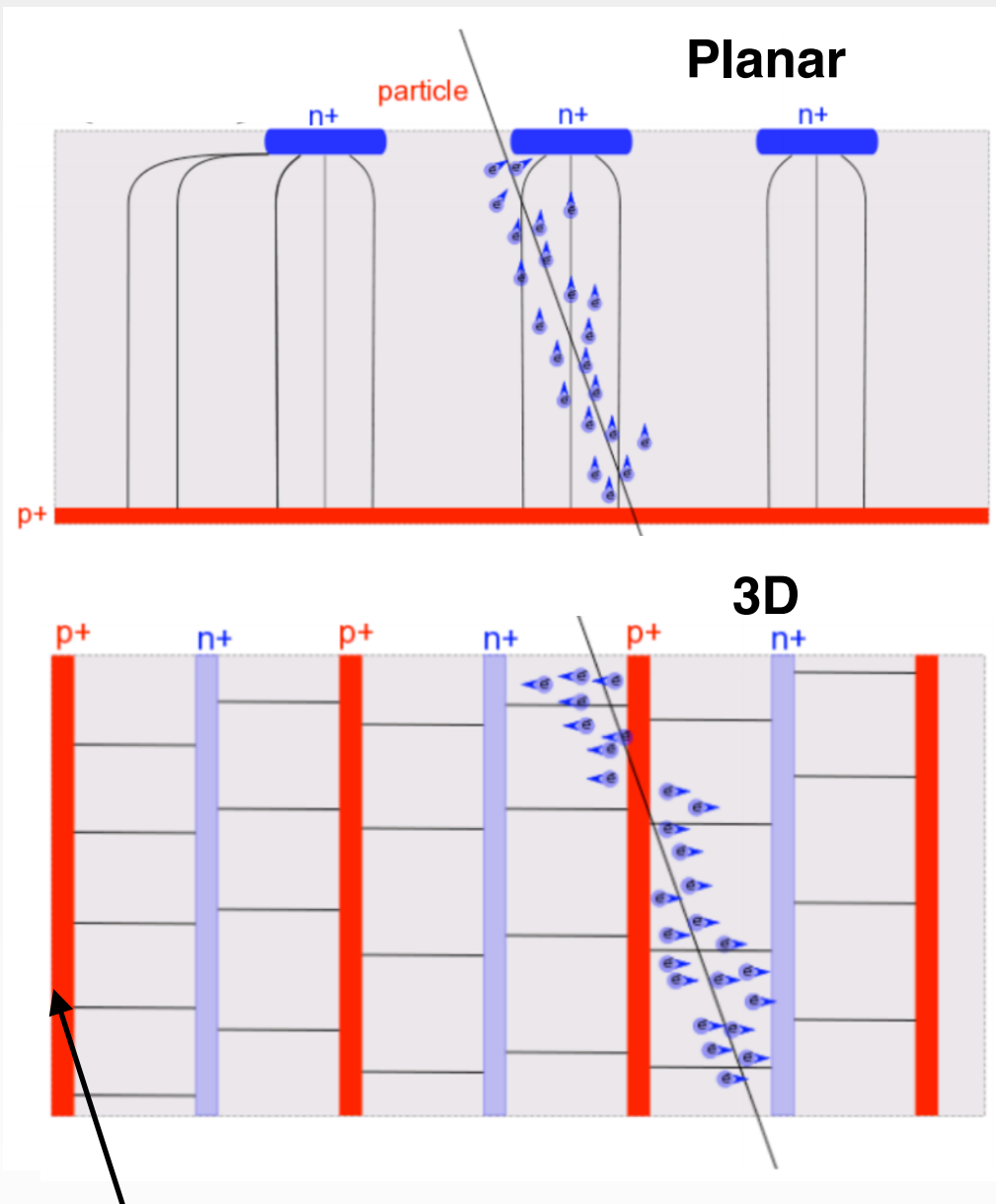
- **Sustain high radiation levels:** for 100 fb^{-1} , proton flux up to $5 \times 10^{15}/\text{cm}^2$ in tracking detectors.
- **Small inefficient area at the edge of the sensor** toward the beam.
- **Tracking resolution of $\sim 10 \text{ }\mu\text{m}$.**

- **Baseline design:**

- **3D sensor** technology chosen for its intrinsic high **radiation hardness** and the possibility to implement **slim edges**.
- **Two stations per side, each with 6 detector planes tilted by 18.4°** to increase the cluster size and **improve resolution**.
- **Readout chip and front-end electronics as for CMS Phase I pixel upgrade.**
- Mechanics and cooling adapted from TOTEM tracking system.

3D silicon sensors

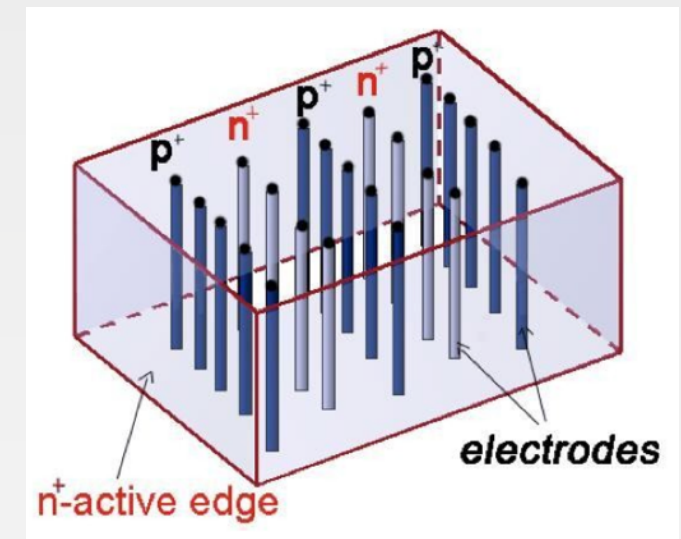
3D sensors have electrodes that are etched perpendicular through the silicon bulk with the Deep Reactive Ion Etching.



Possibility to effectively implement active or slim edges.

The architecture decouples substrate thickness and electrode distance.

Columns have radius of $\sim 5 \mu\text{m}$ and the distance between electrodes varies from $100 \mu\text{m}$ to $50 \mu\text{m}$ depending on the number of readout electrodes per pixel cell



Advantages of 3D structures in comparison with standard planar sensors:

- Lower depletion voltage.
- Faster charge collection.
- Higher radiation hardness.

Disadvantages:

- Complex technology.
- Higher capacitance.

3D sensors for CT-PPS

3D sensors produced in the double-sided not-fully passing through technology by CNM

Baseline design:

- **2E pixel** configuration (2 readout columns)
 - 200 μm **slim edges**
 - 2x3 sensors (6 ROCs each)
- 1E and 2x2 sensors as backup solution

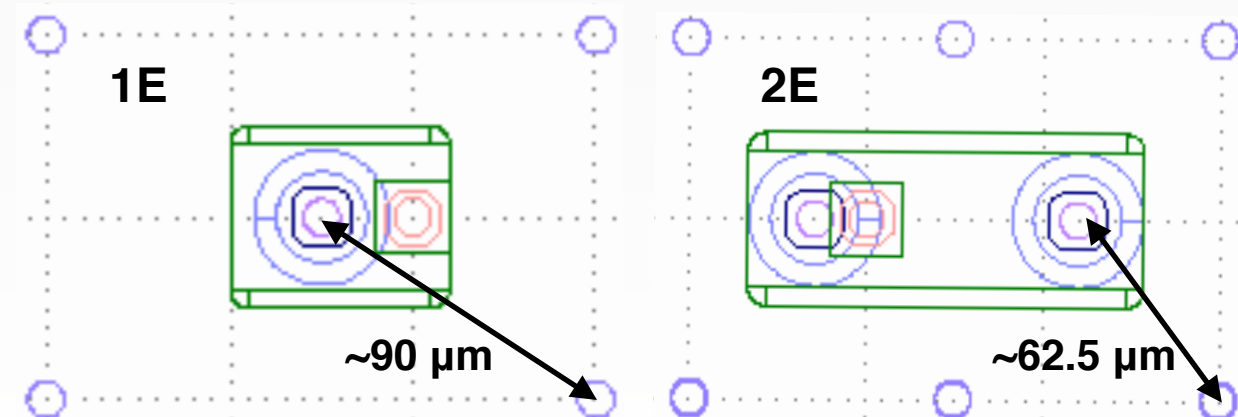
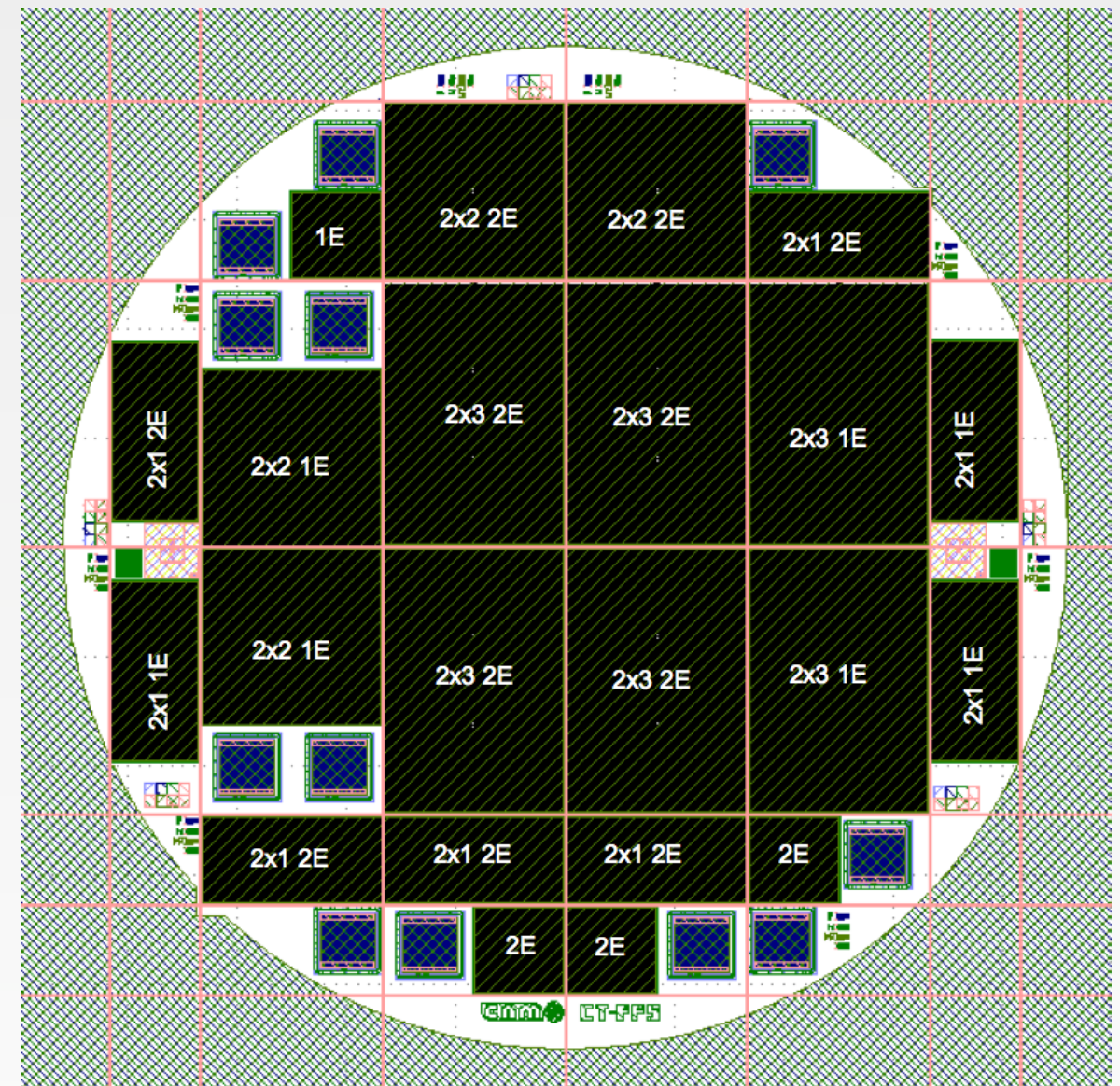
First batch of 3D sensors completed in December 2015.

In general good quality sensors but low yield, in particular of the class A ones.

Second batch production completed in May.

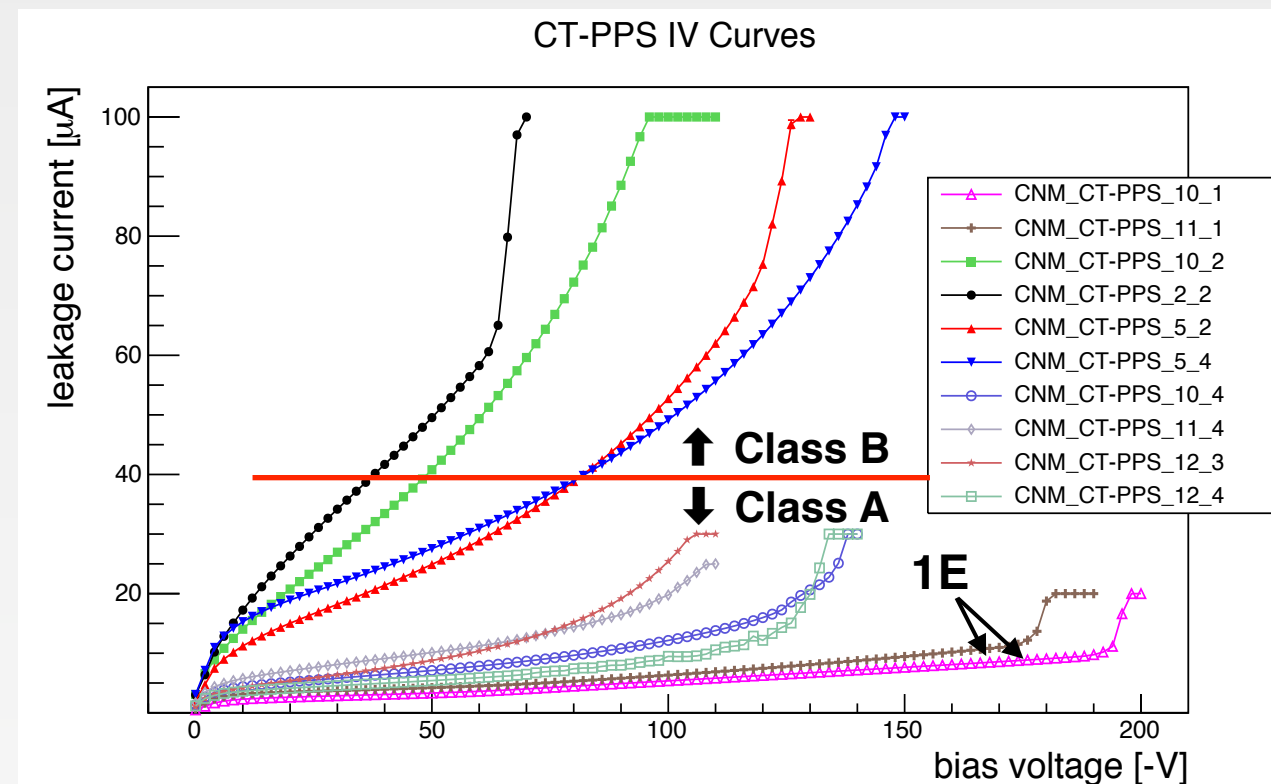
A problem, probably with the p-stop implantation, caused values of breakdown voltage too low to allow using the sensors. In order to recover the production a low-dose neutron irradiation is under study.

24 wafers produced at CNM



Module production and tests

- 3D sensor IV curves measured at CNM on wafer using a temporary metal deposition. Sensor classification and selection based on these results.
- Bump-bonding at IZM to the PSI46dig ReadOut Chip, same ROC as the CMS Phase I pixel detector upgrade.
- A total of 46 modules already available and under test, remaining modules in production
- Temporary wire-bonding and gel-pak film gluing on flex hybrid for the module testing and bump-bonding validation with X-ray.
- Precision gluing to final flex hybrid with TPG dissipative layer.
- Module test and calibration in the final assembly.
- Mounting of the 6 plane package.
- Test at H8 SPS beam-line for final validation inside a Roman Pot with cooling and secondary vacuum.



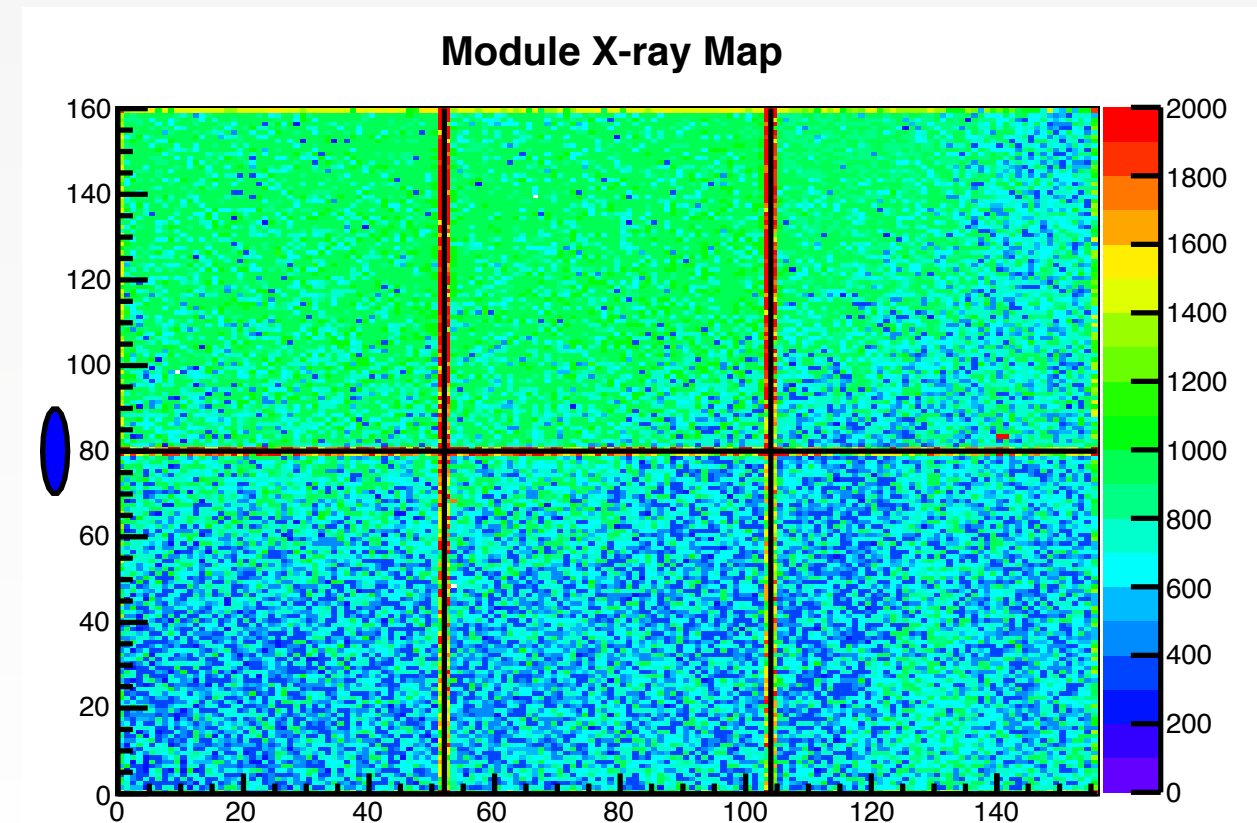
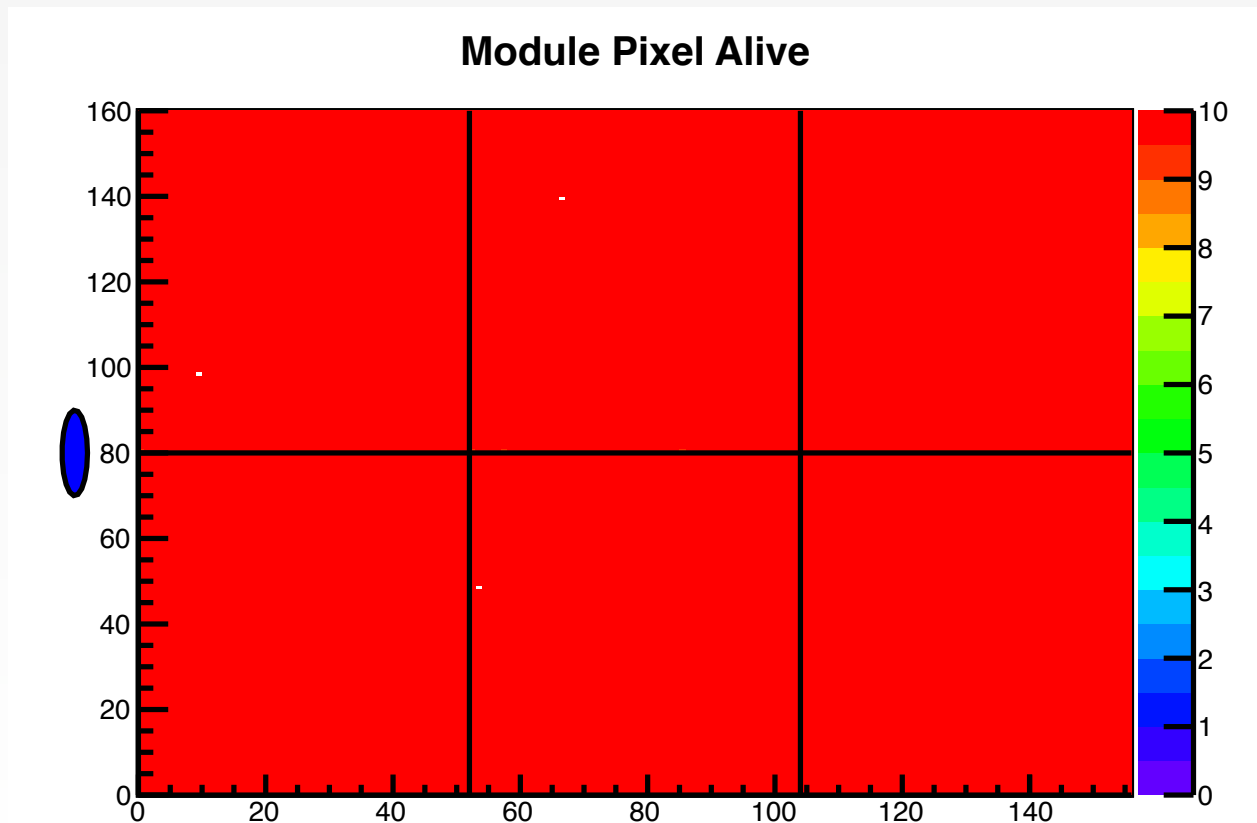
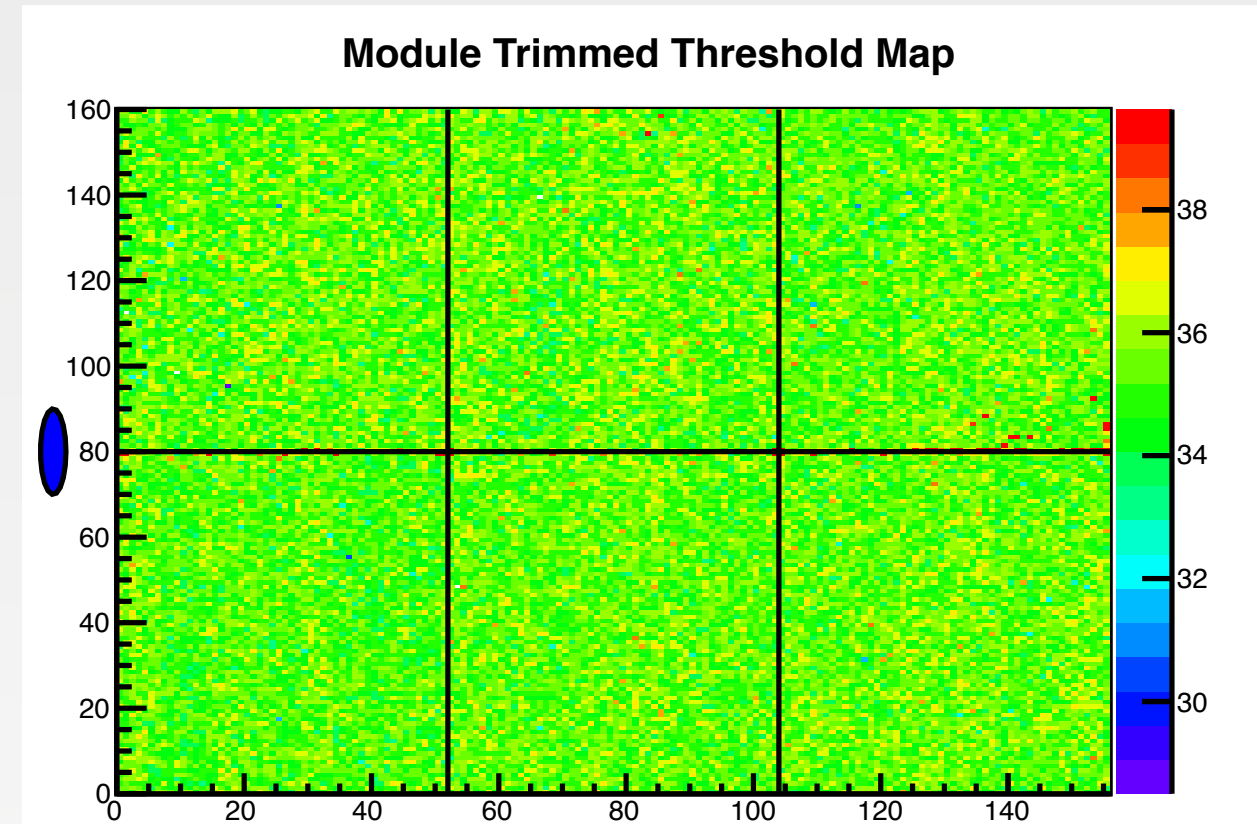
Module testing

Detectors characterised and optimised in Torino and Genova laboratory:

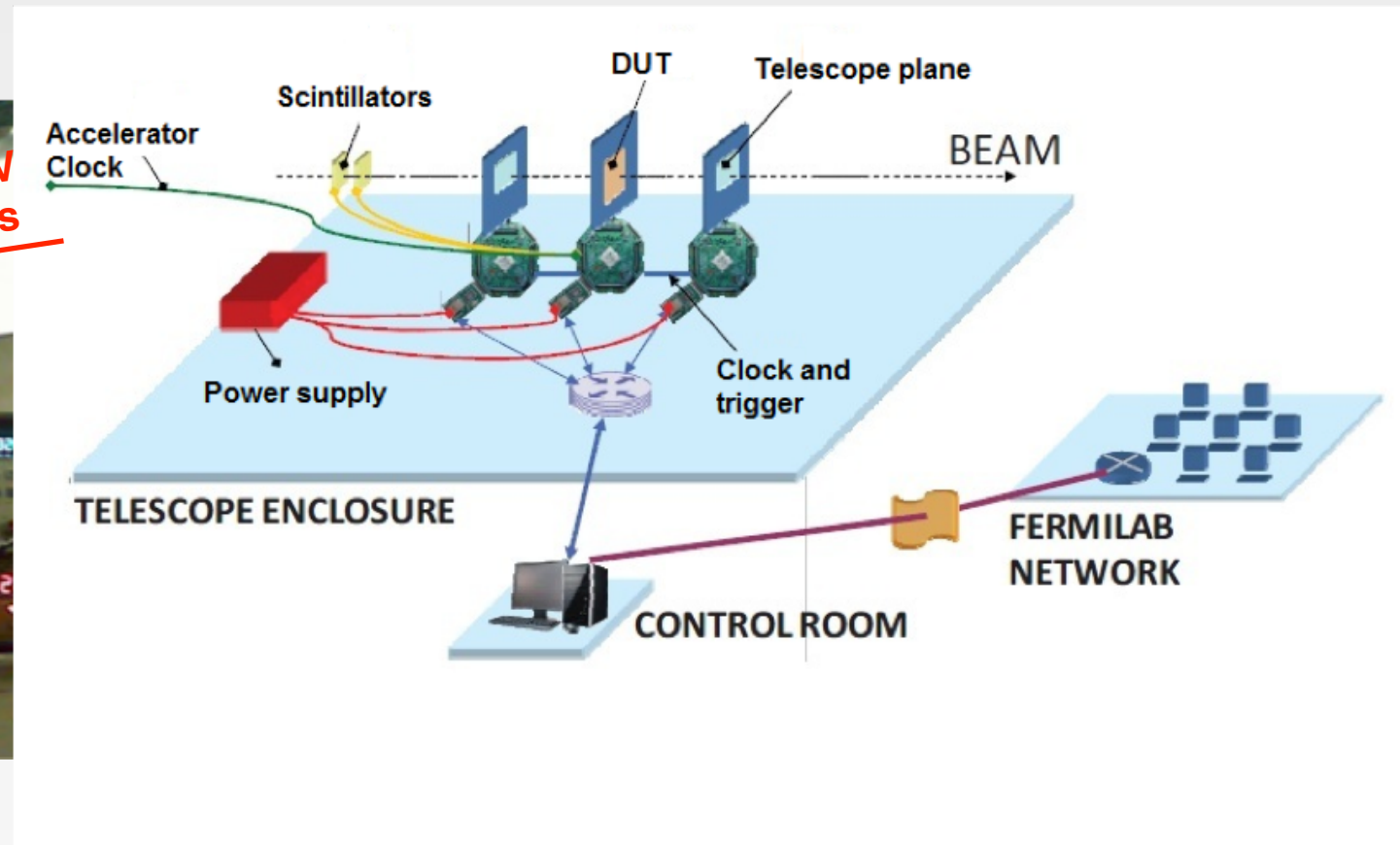
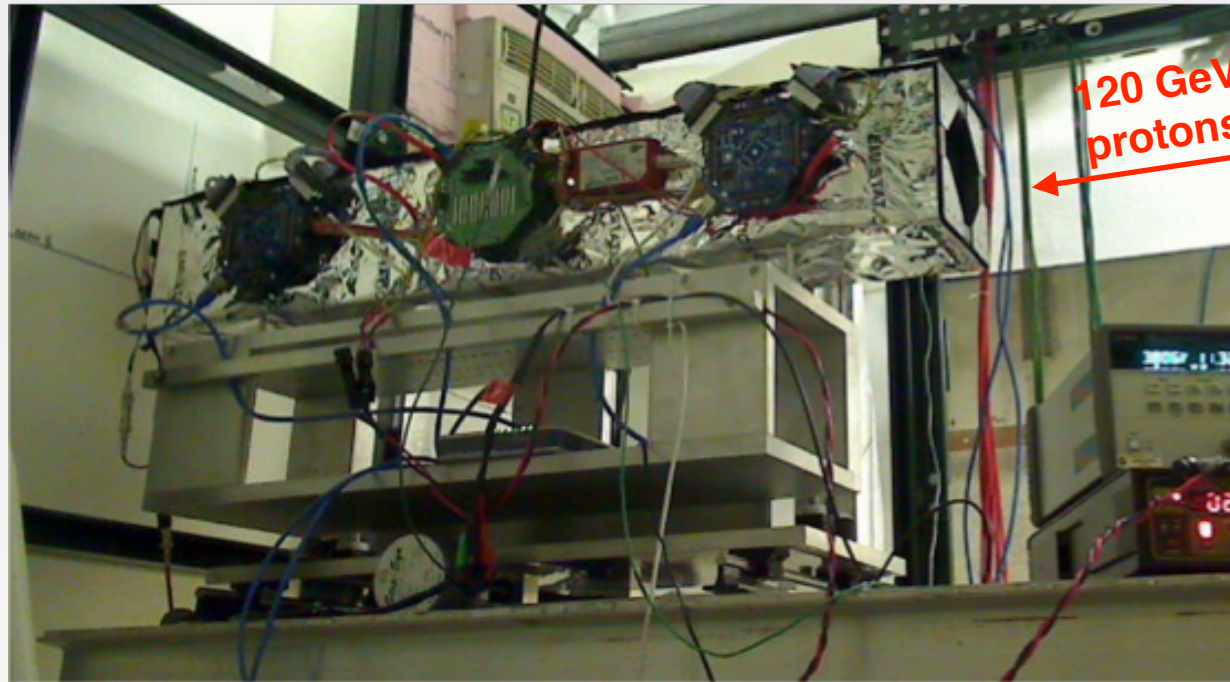
- IV curve
- ROC calibration and optimisation
- Threshold trimming to ~ 1800 e⁻
- X-ray to check bump-bonding quality

No damage due to flip-chip observed, based on sensor IV curve comparison and ROC performance before and after bump-bonding

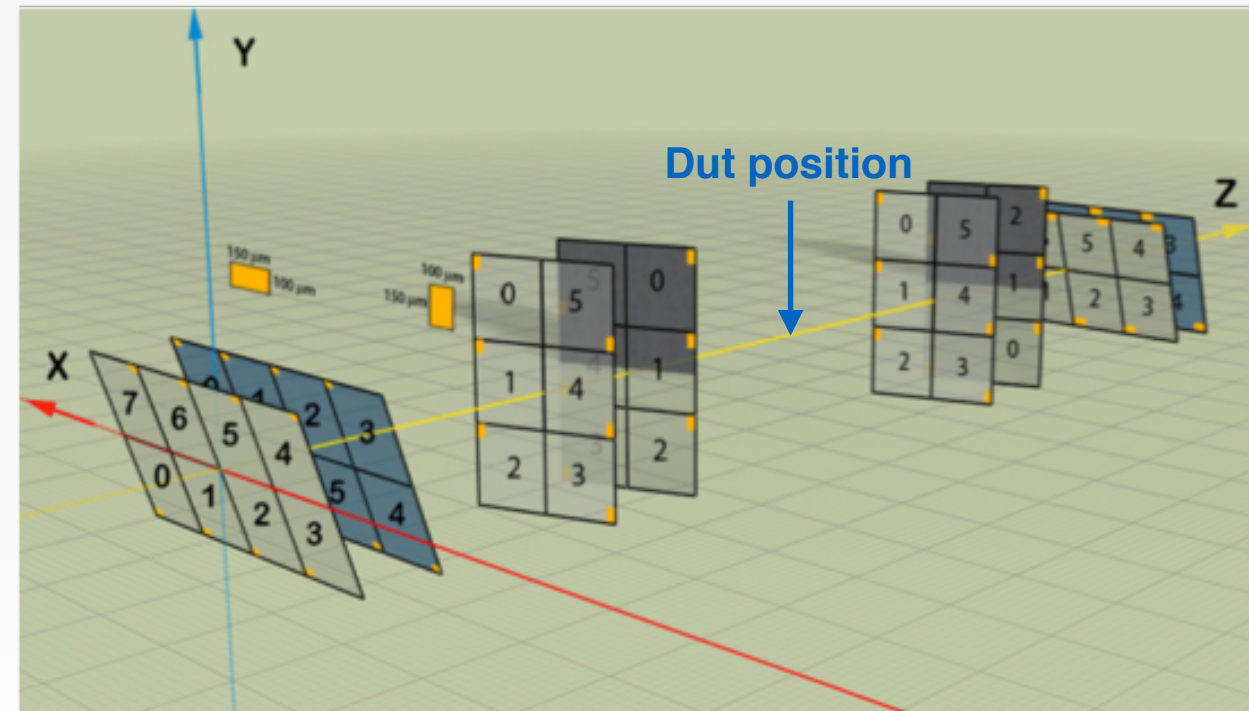
Good quality of bump-bonding checked with X-ray test.



Testbeam at FNAL (T992 collaboration)



- **8 telescope planes** of CMS pixel modules (pixel size $100 \times 150 \mu\text{m}^2$), 4 upstream and 4 downstream with respect to the DUTs
- Telescope planes rotated of 25° with respect to $100 \mu\text{m}$ pixel pitch direction for improving **resolution to $8 \mu\text{m}$**
- Rotation and cooling systems for the DUTs provided by Purdue
- Alignment and analysis software developed at Milano Bicocca



Beam test - Efficiency

Preliminary

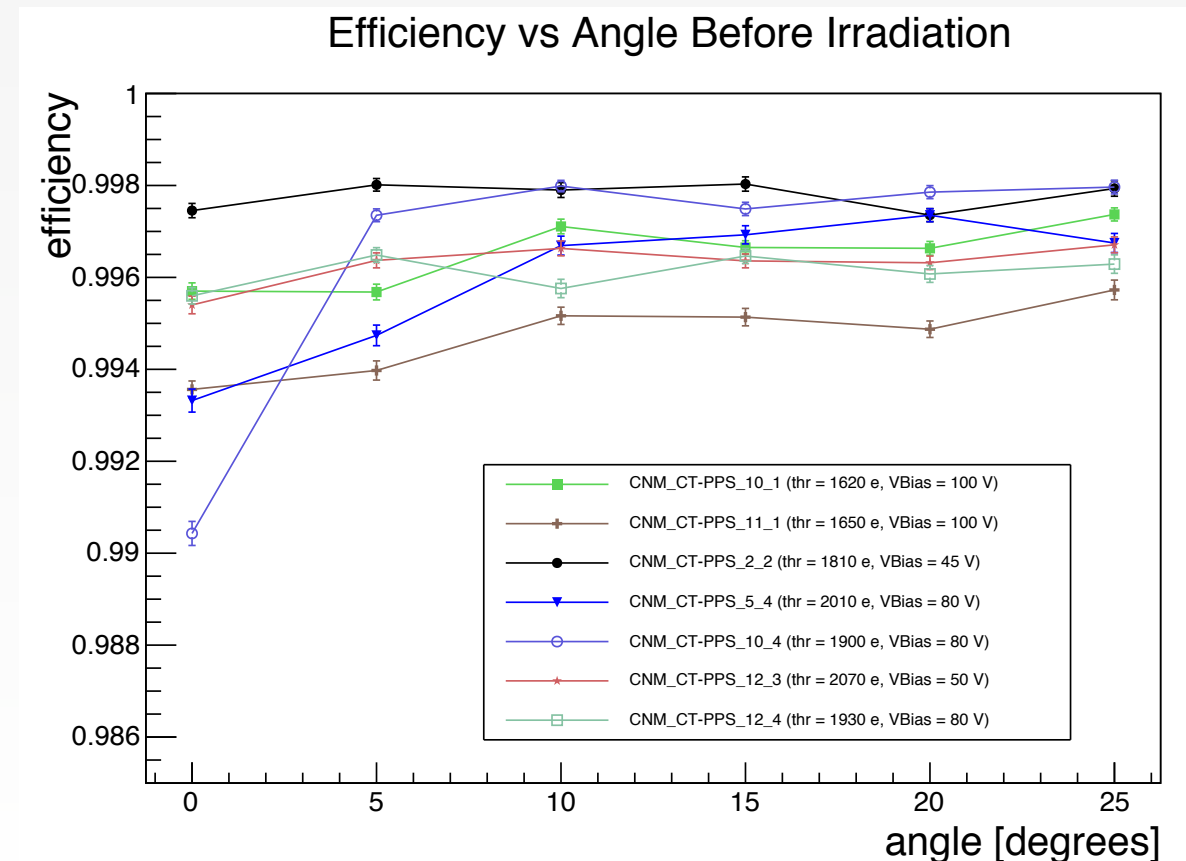
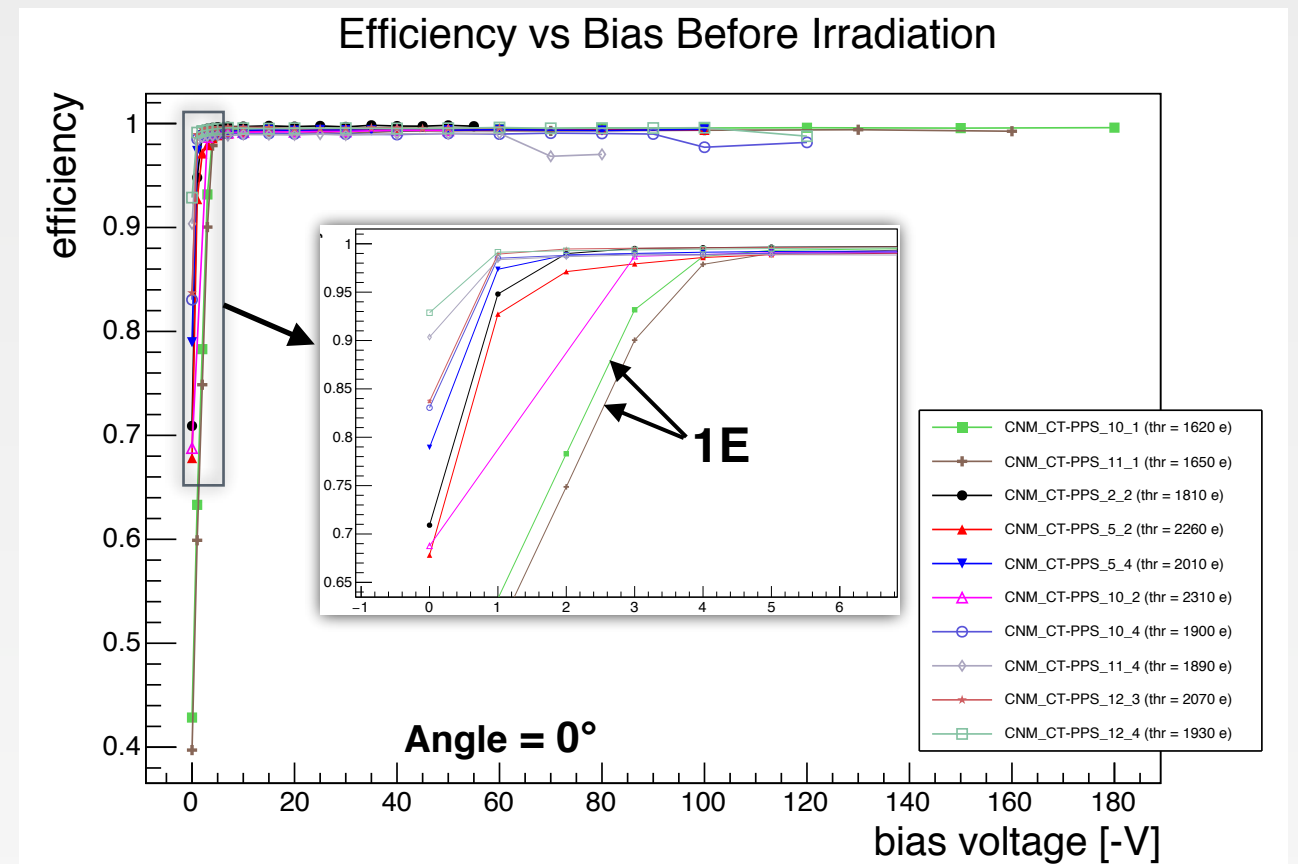
10 single-ROC sensors (**2 1E and 8 2E**) bump-bonded in March at IZM to the CMS Phase I ROC have been **tested at FNAL with 120 GeV protons**.

Sensors selected both of class A and B.

2E (1E) sensors reach the full efficiency already at bias voltages of ~ 3 V (5 V). No difference in efficiency is seen between class A and B sensors.

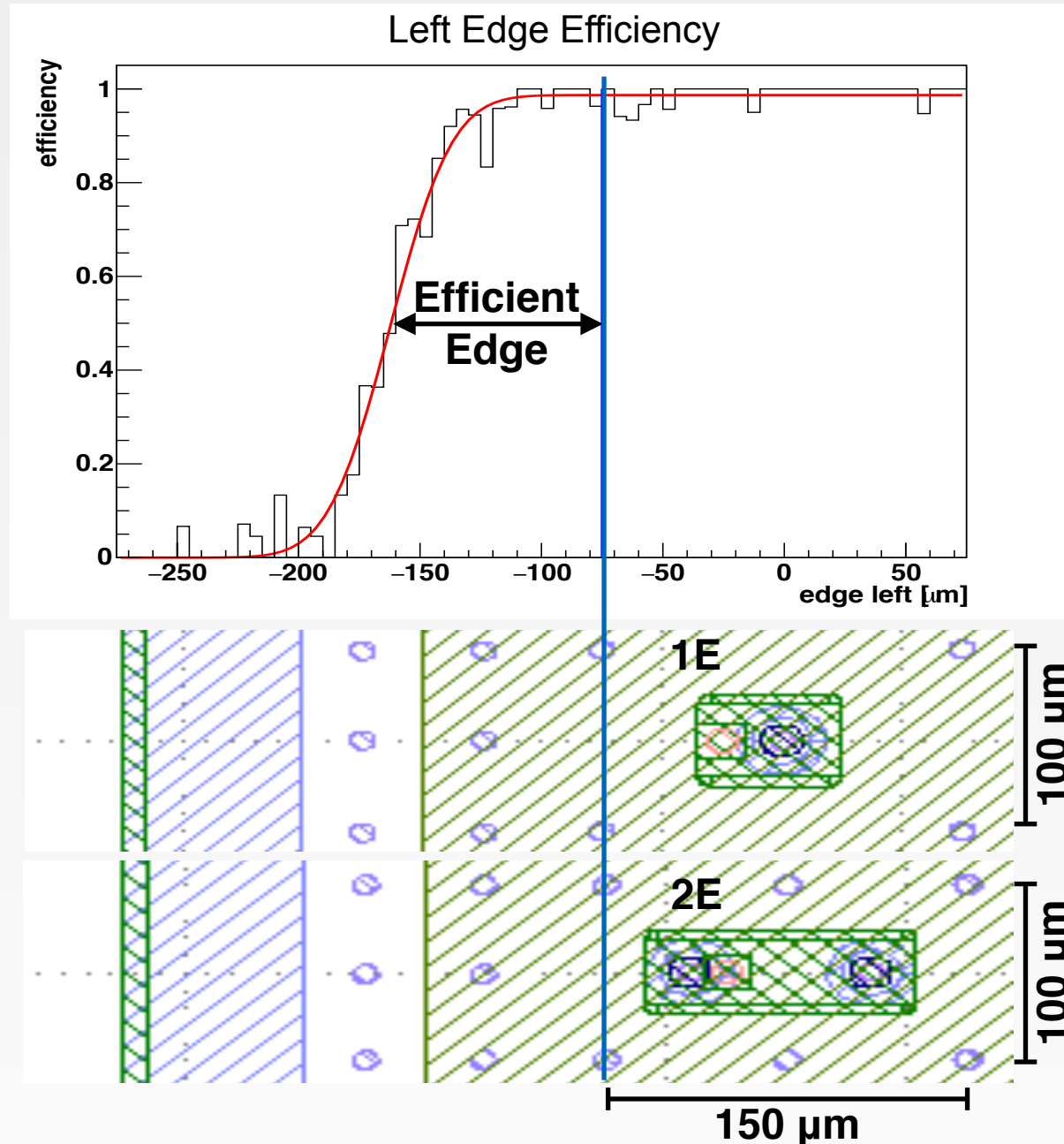
Thanks to the not-fully passing-through columns, high efficiency is obtained even without rotating the sensors.

Efficiency greater than 99.4% at 20° .
(CT-PPS tracking detector angle = 18.4°)

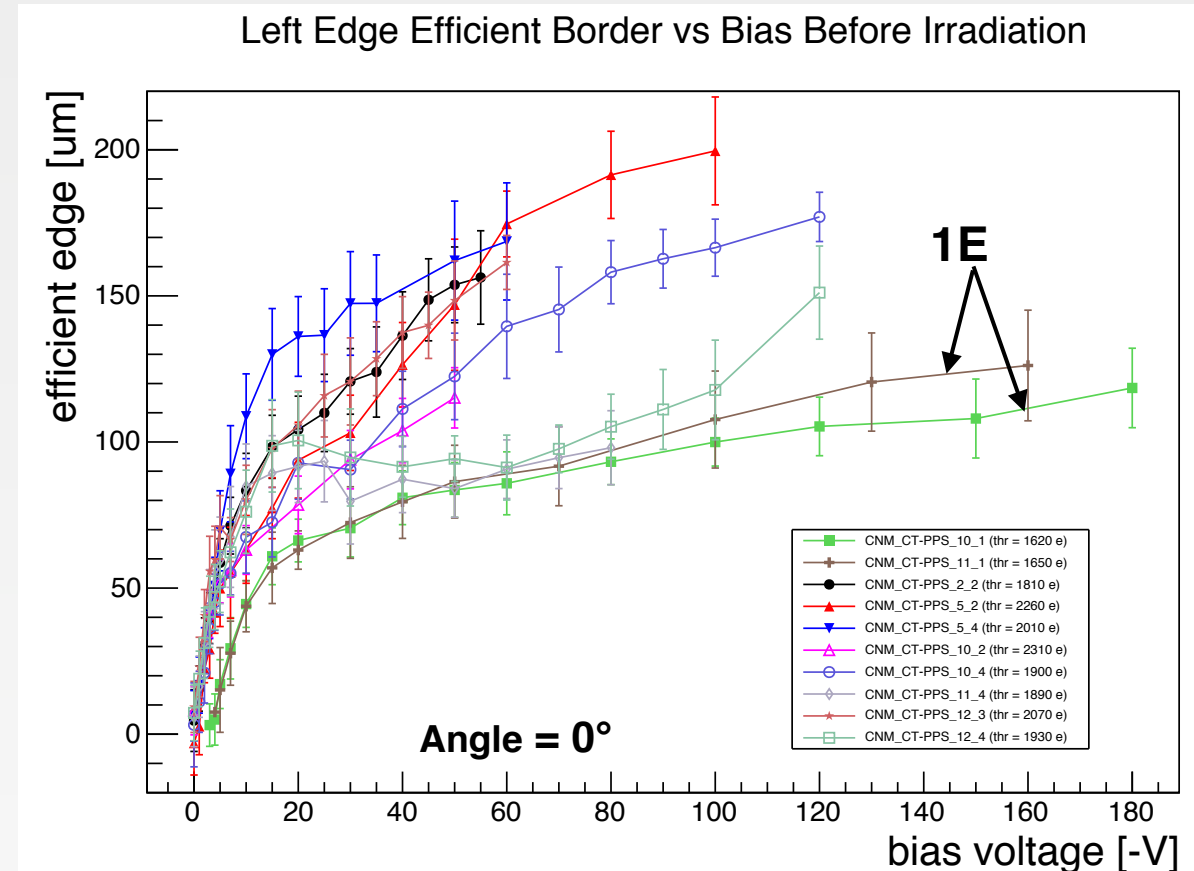


Beam test - Edge efficiency vs bias

Preliminary



Efficiency at the edge of the sensor fitted with a S-curve. Error bars represent the width of the S-curve.



At a bias voltage of 40 V up to 150 μm can be gained at the edge of the sensor with the 2E layout.

2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n⁺-electrode closer to the sensor edge.

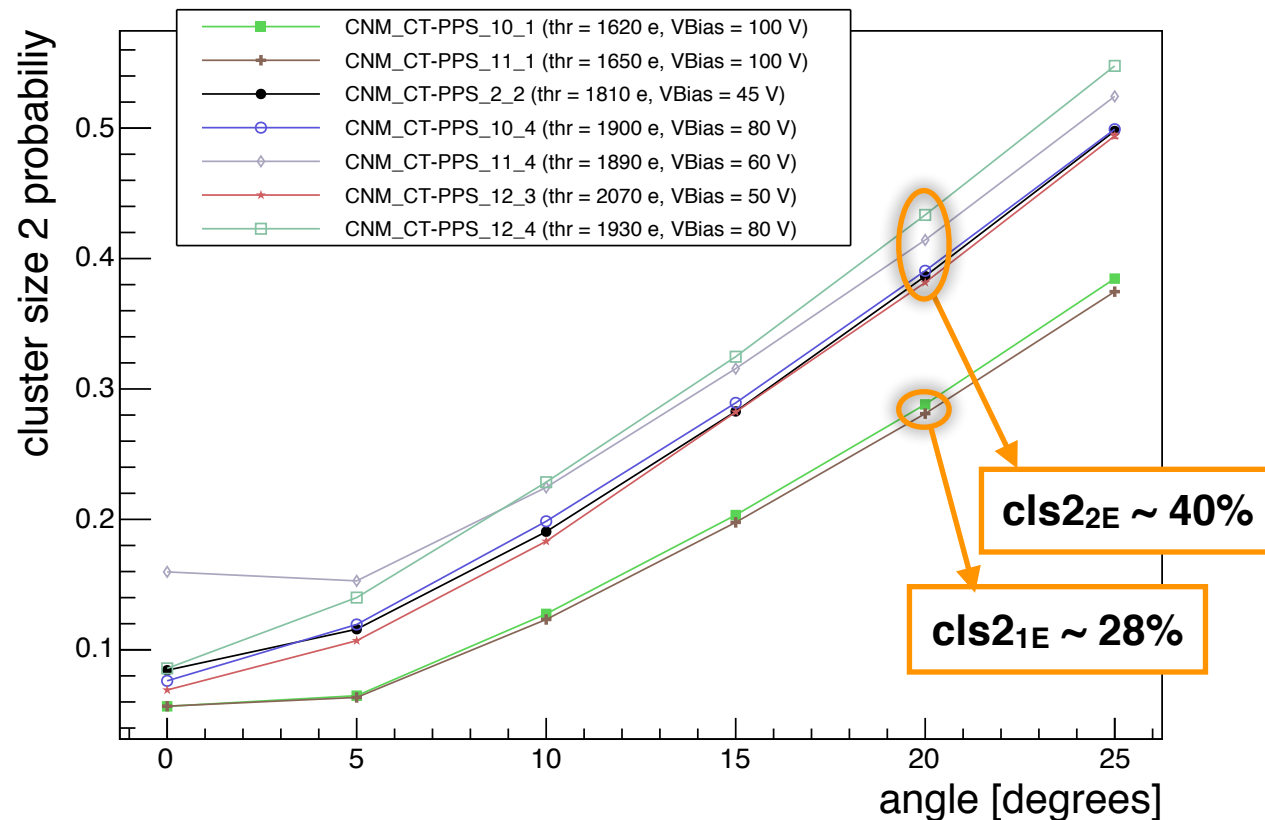
Beam test - Resolution vs angle

Preliminary

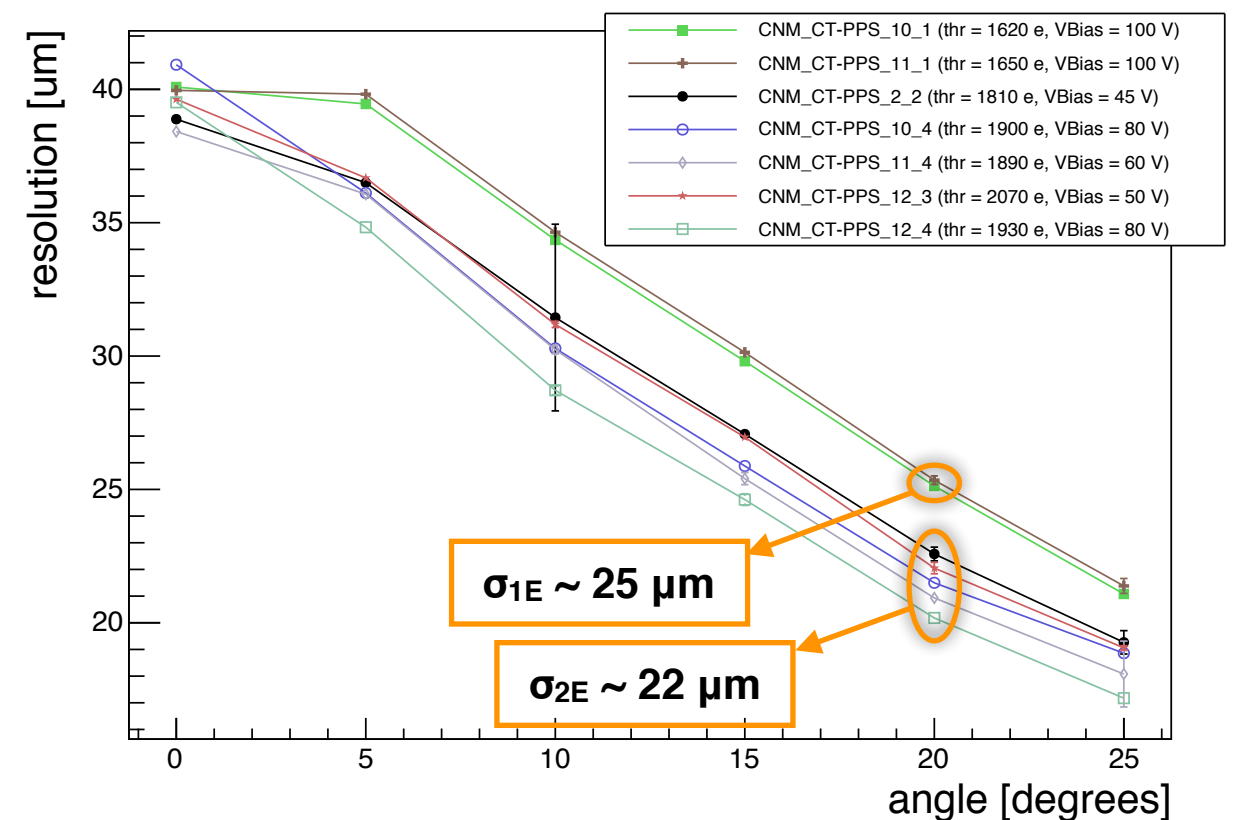
Detector resolution is evaluated by fitting residuals separately for cluster size 1 and 2. After subtracting the telescope resolution, the **global resolution is obtained as average of the two values weighted by the cluster size probability**.

Since electrodes are closer to the pixel geometrical edge, **2E sensors have more clusters of size 2 and therefore a better resolution with respect to 1E ones**.

Cluster Size 2 vs Angle Before Irradiation



X Resolution Weighted vs Angle Before Irradiation



Considering a resolution per single plane between 20 and 25 μm , **the target resolution of $\sim 10 \mu\text{m}$ can be achieved**.

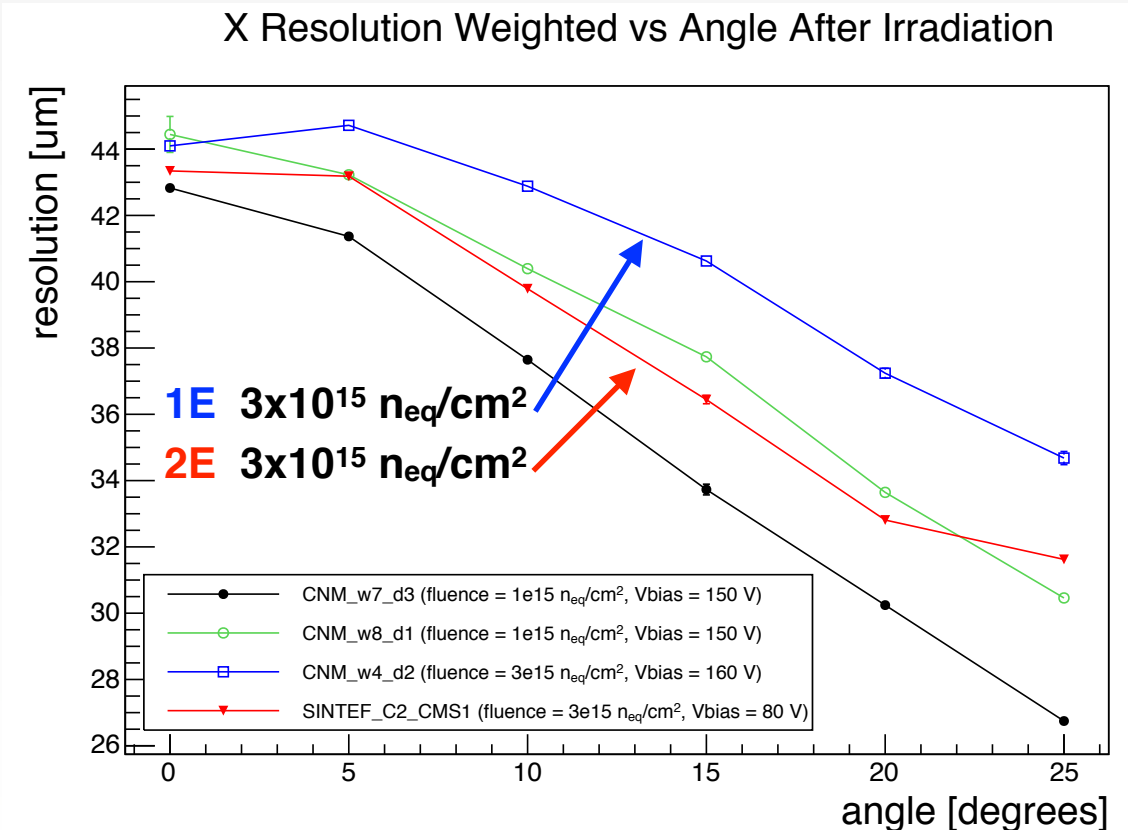
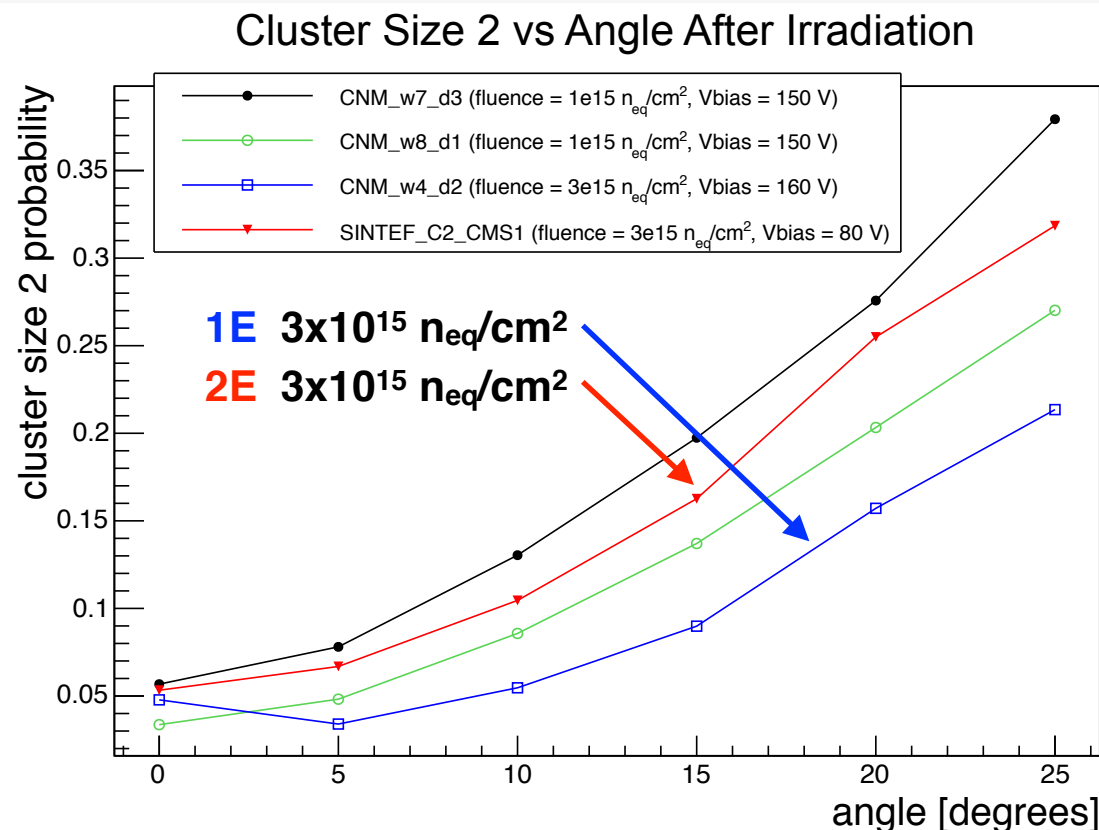
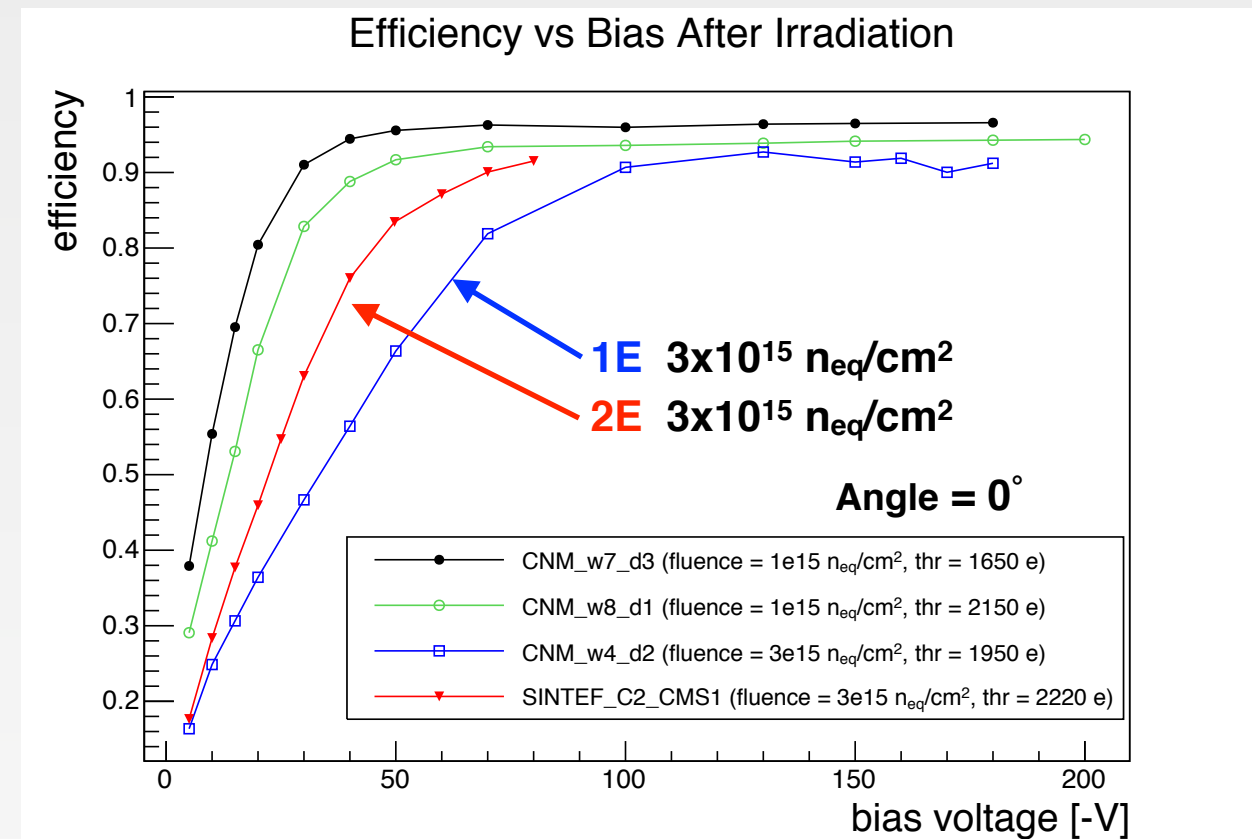
Performance after irradiation

Preliminary

It is foreseen that **the detector will be irradiated during its life up to 5×10^{15} p/cm²** which corresponds to $\sim 1 \times 10^{15}$ n_{eq}/cm².

3 1E CNM + 1 2E SINTEF sensors were irradiated at the CERN IRRAD Proton Facility with 24 GeV protons to fluences of 1×10^{15} and 3×10^{15} n_{eq}/cm² and tested in a beam at FNAL.

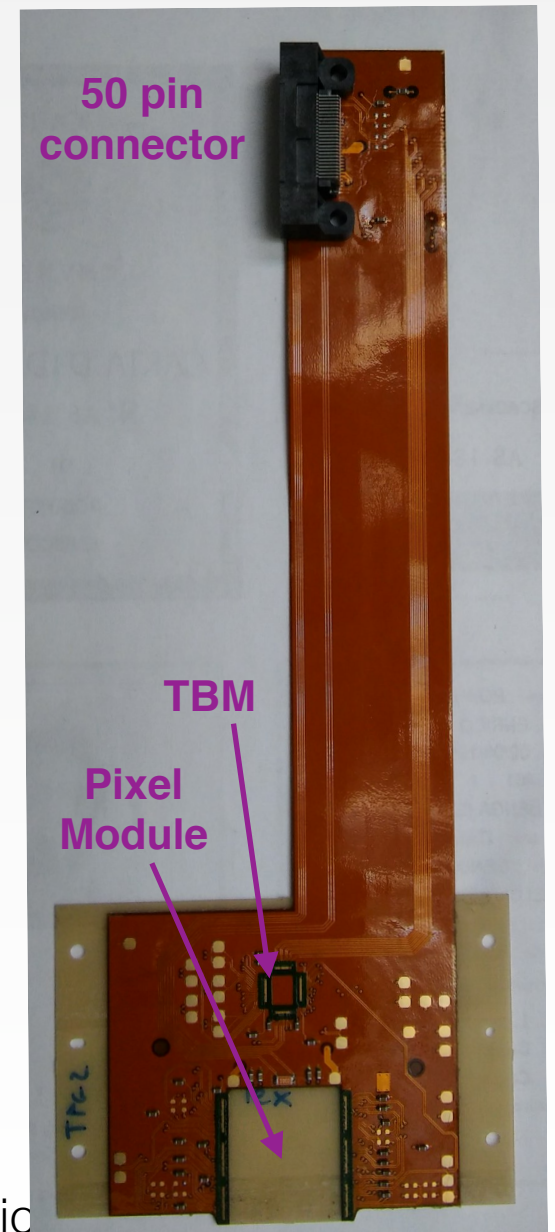
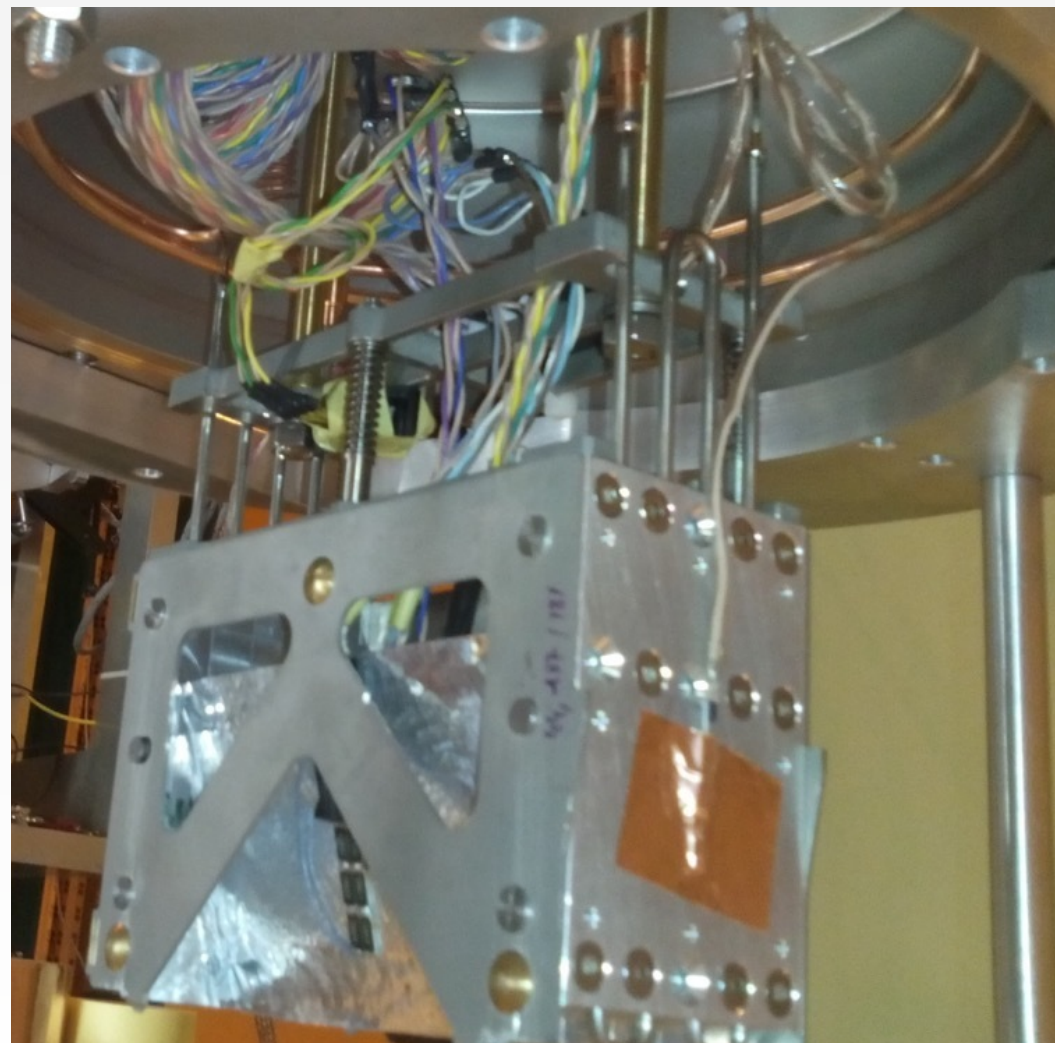
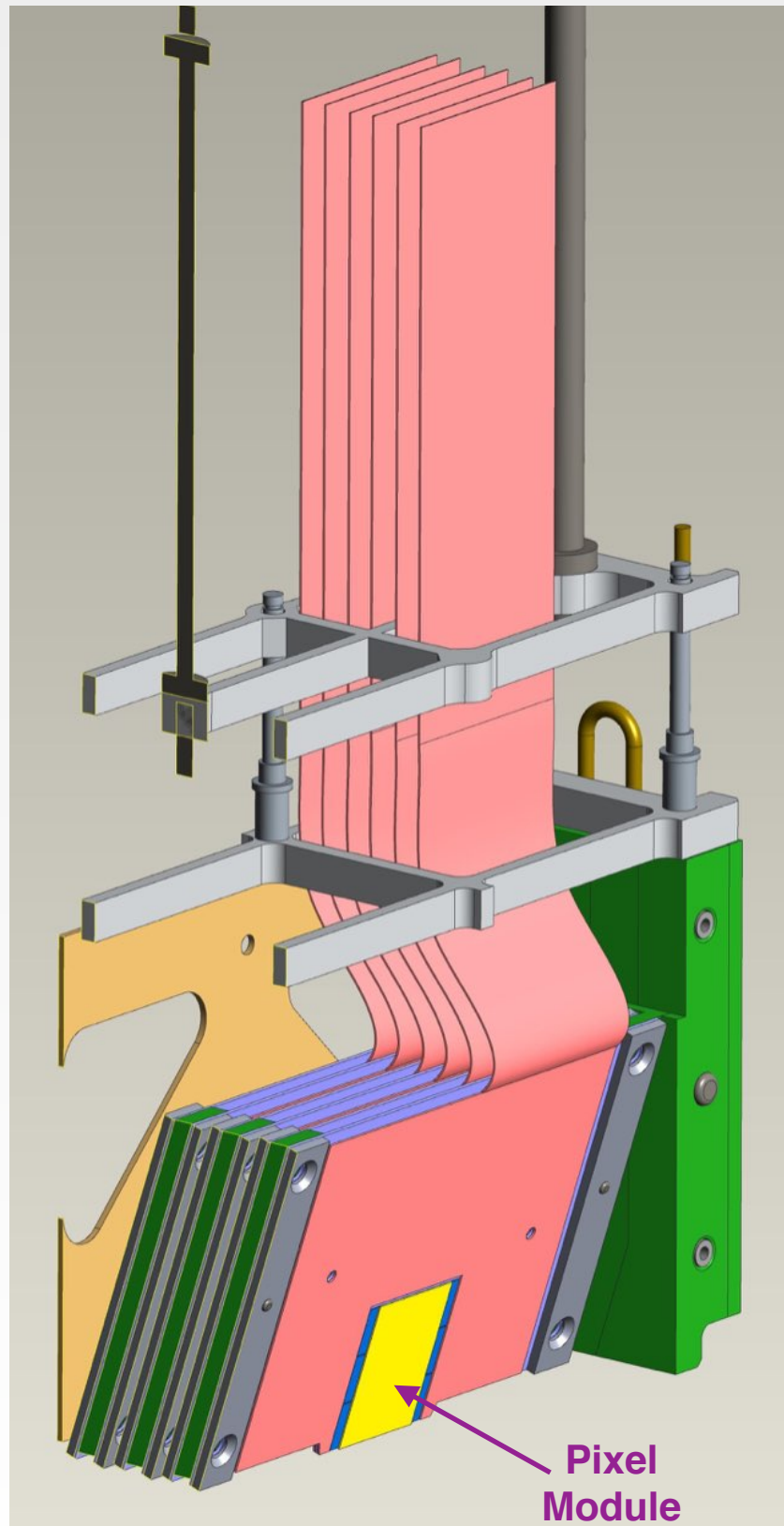
Results show the advantage of the 2E configuration after irradiation.



Tracking detector - Mechanics

- 6 detector planes per pot.
- New Al support structures produced in Genova.
- Detector heat dissipation provided by a TPG layer encapsulated in a thin aluminium layer connected to a cooling system identical to the TOTEM one.
- **Cooling tests showed heat dissipation according to requirements.**

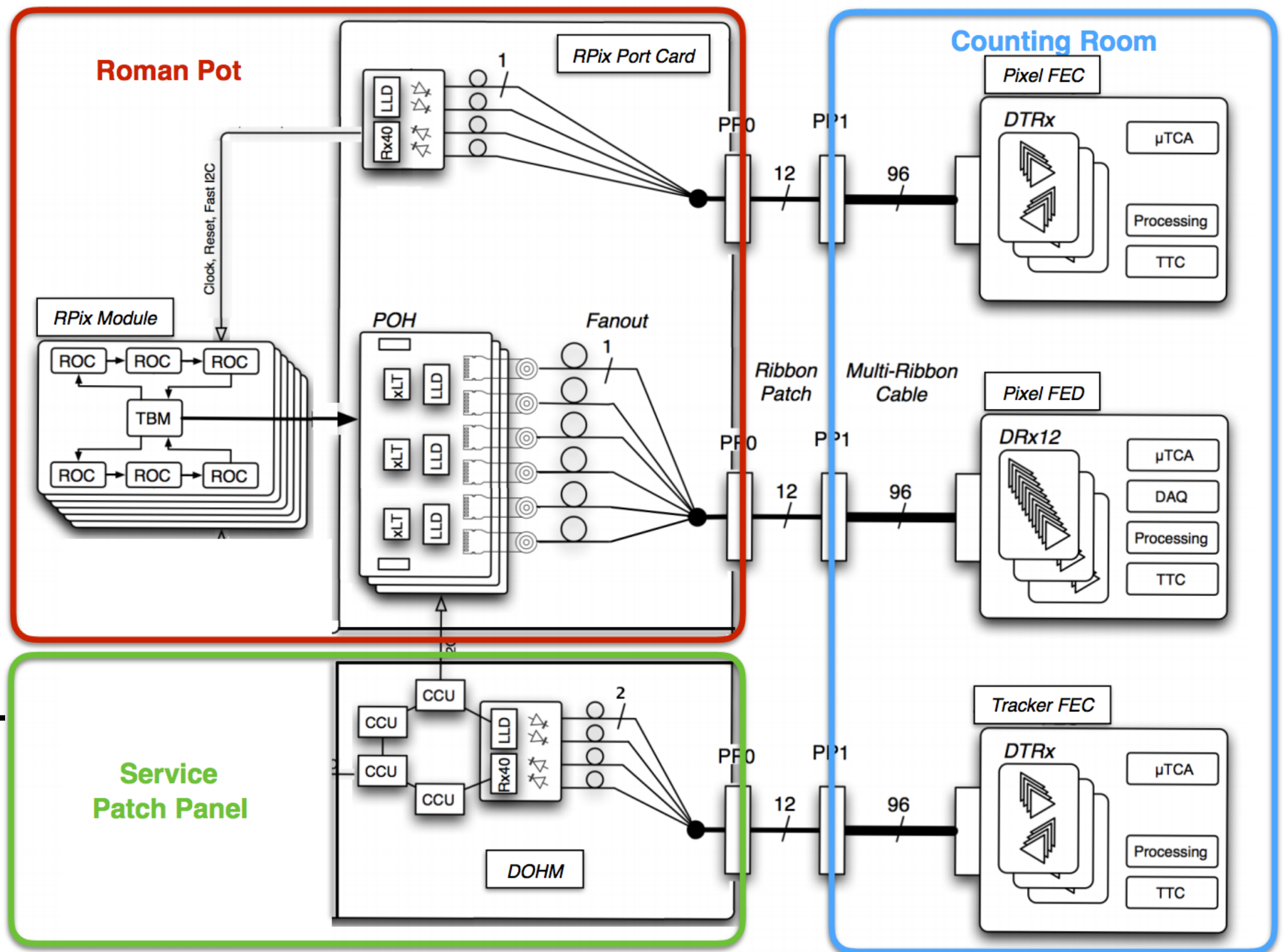
Cooling test setup



Tracking detector - Electronics

CT-PPS custom design

Already used for
TOTEM Strips



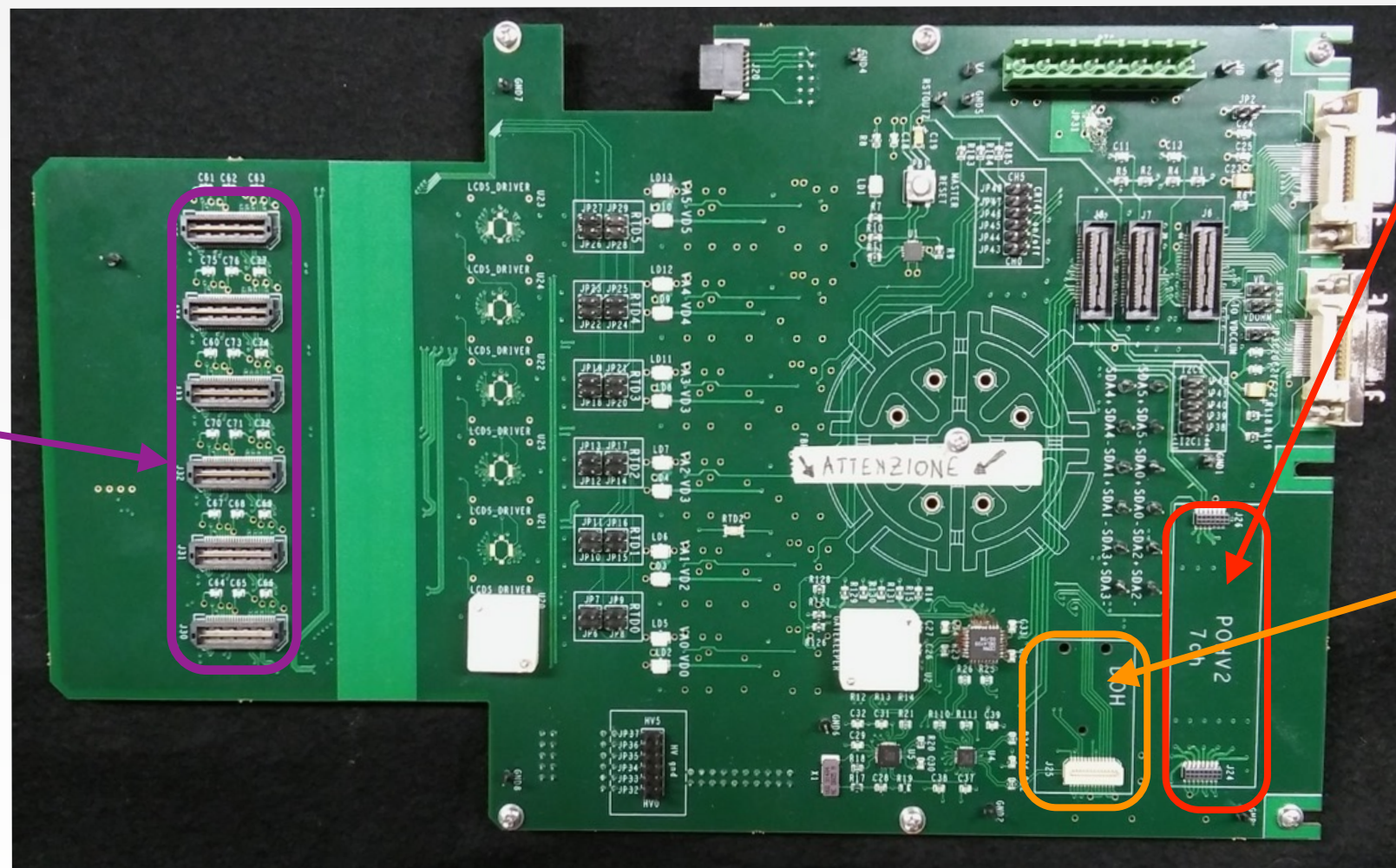
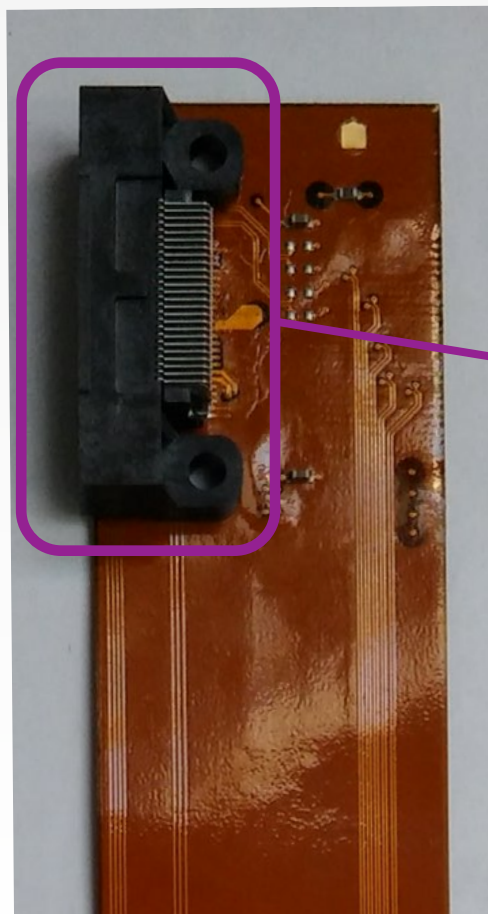
From CMS Phase I pixel Upgrade

Tracking detector - Electronics

- **RPix Port Card** is custom designed for CT-PPS to interface the tracking station to the readout electronics.
- Concept: TOTEM boards (to fit the RP space constraints) with components as in FPIX readout.
- **Prototype Port Card produced and under test at Genova with good results up to now.**
- Launch of the production of the 4 + spare boards expected by the end of the October.

RPix Port Card

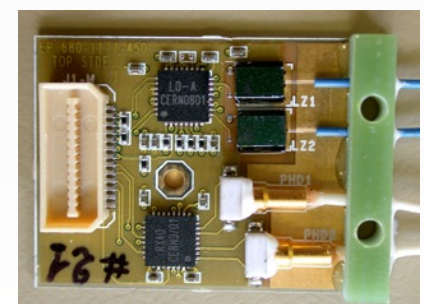
Connectors for flex hybrid boards



Pixel Opto-Hybrid



Digital Opto-Hybrid



Summary

- **During the end-of-the-year LHC shutdown 3D pixel detectors will be installed in the CT-PPS tracking Roman Pots, replacing the TOTEM strip detectors that are being used for 2016 data taking.**
- **Very good results were obtained at beam tests on single-ROC sensors**, both of class A and B.
- **Results, both before and after irradiation, prefer the 2E layout.**
- **Genova and Torino laboratories have started the qualification of the final modules.**
- **Tracker mechanics and cooling successfully tested**, remaining structures are in production
- **Production of final flex hybrid started**, expected to be finalised in October.
- **RPix Port Card prototype is under tests, no issue seen so far.** 4 + spares production expected to be launched at the end of October.

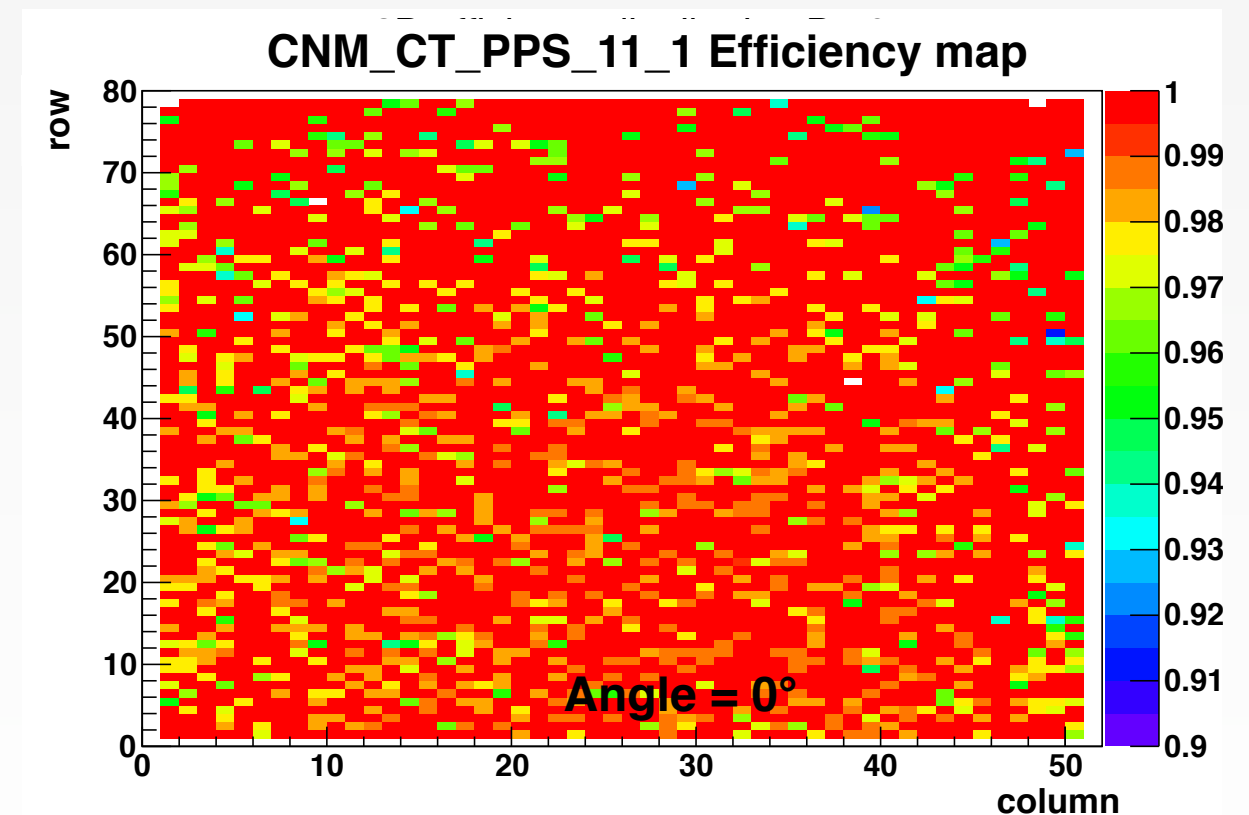
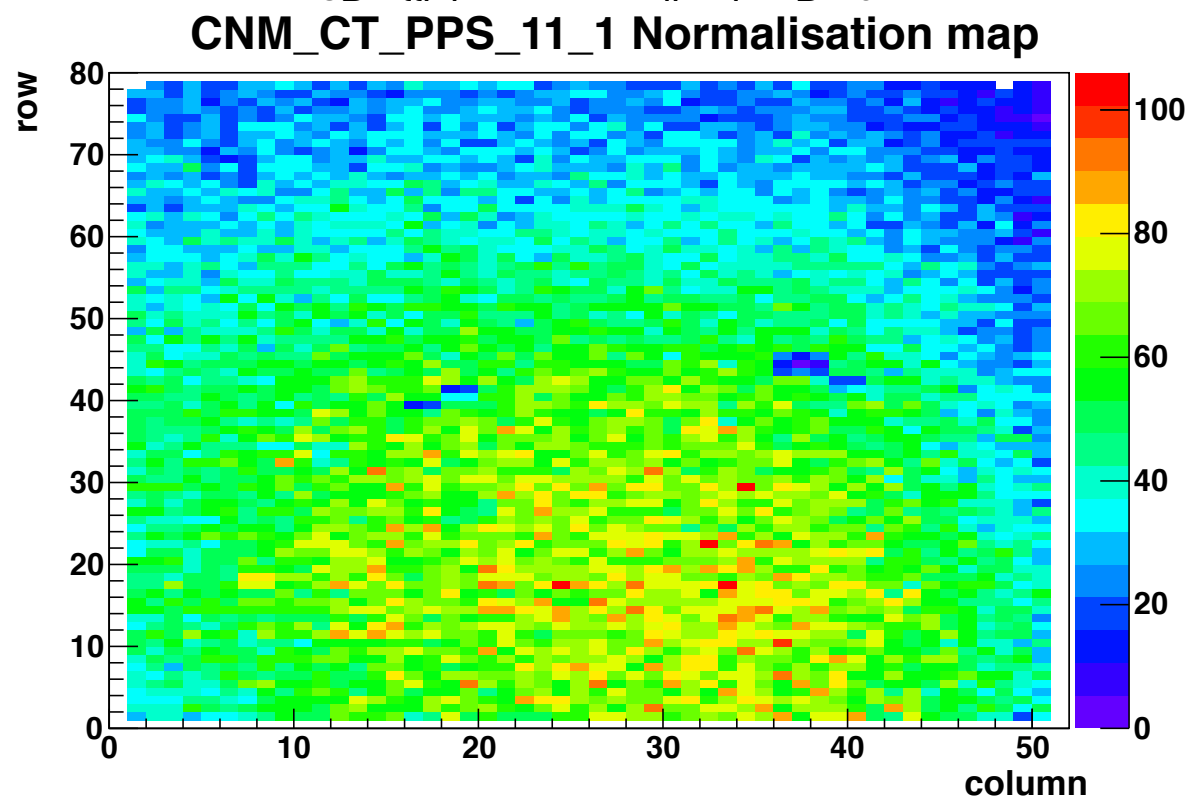
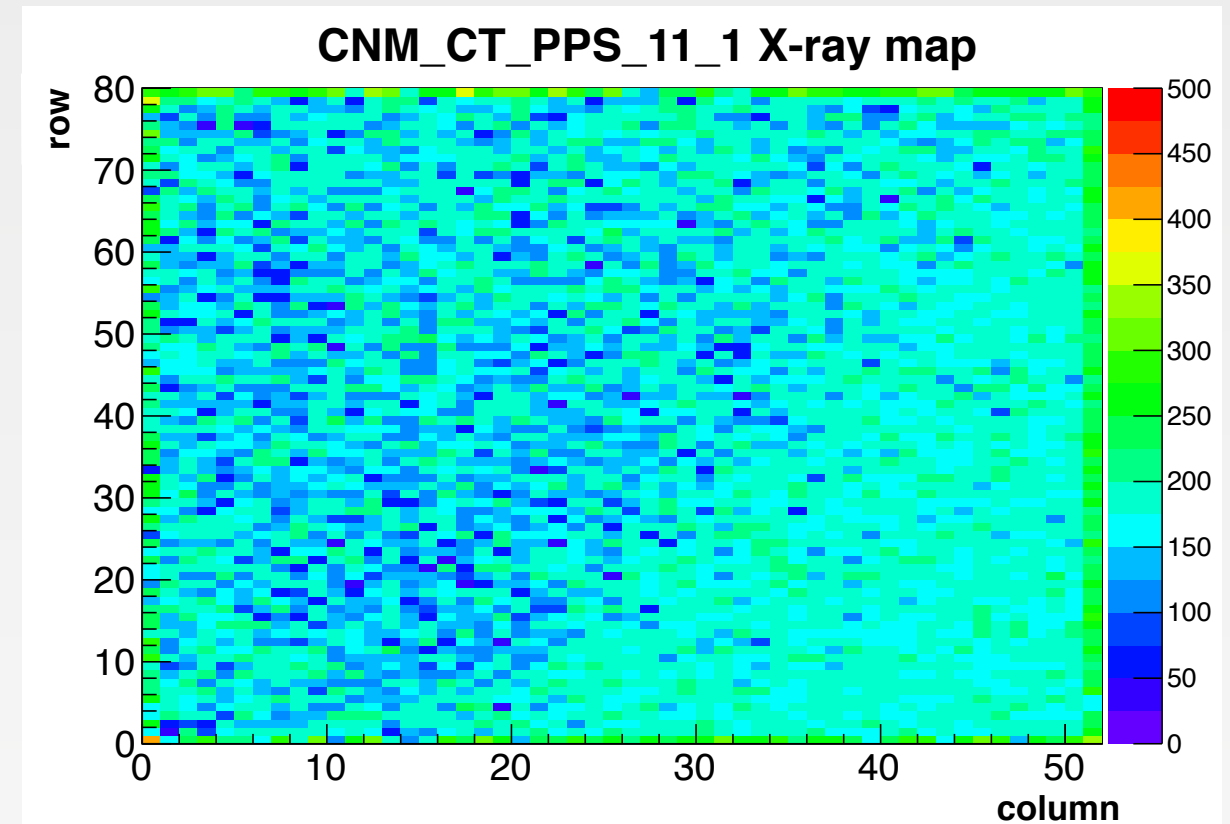
Acknowledgements

- The CT-PPS Tracking Group: R. Arcidiacono, M. Arneodo, M. Bozzo, N. Cartiglia, S. Cerchi, A. Falchi, F. Ferro, M.M. Obertino, E. Robutti, M. Ruspa, K. Shchelina, V. Sola, A. Solano, S. Tosi
- Fermilab T-992 collaboration: K.T. Arndt, G. Bolla, D. Bortoletto, M. Boscardin, M. Bubna, J. Chramowicz, M. Costa, J.P. Cumalat, G.-F. Dalla Betta, M. Dinardo, F. Ferro, A. Godshalk, M.D. Krohn, A. Kumar, S. Kwan, M.T. Jones, C.M. Lei, D. Menasce, L. Moroni, M.M. Obertino, L. Perera, A. Prosser, E. Robutti, R.A. Rivera, X. Shi, A. Solano, L. Uplegger, C. Vernieri, L. Vigani, S. Wagner
- CNM group: G. Pellegrini, M. Baselga, D. Quirion
- SINTEF group: T.-E. Hansen, A. Kok, O. Koybasi, M. Povoli, A. Summanwar
- Irradiation at the CERN IRRAD Proton Facility: F. Ravotti, A. Junkes

Backup

X-ray vs efficiency on single ROC

- Comparison of X-ray map and efficiency measured at the test beam for the same single-ROC sensor.
- **No X-ray pattern observed in the efficiency map.**



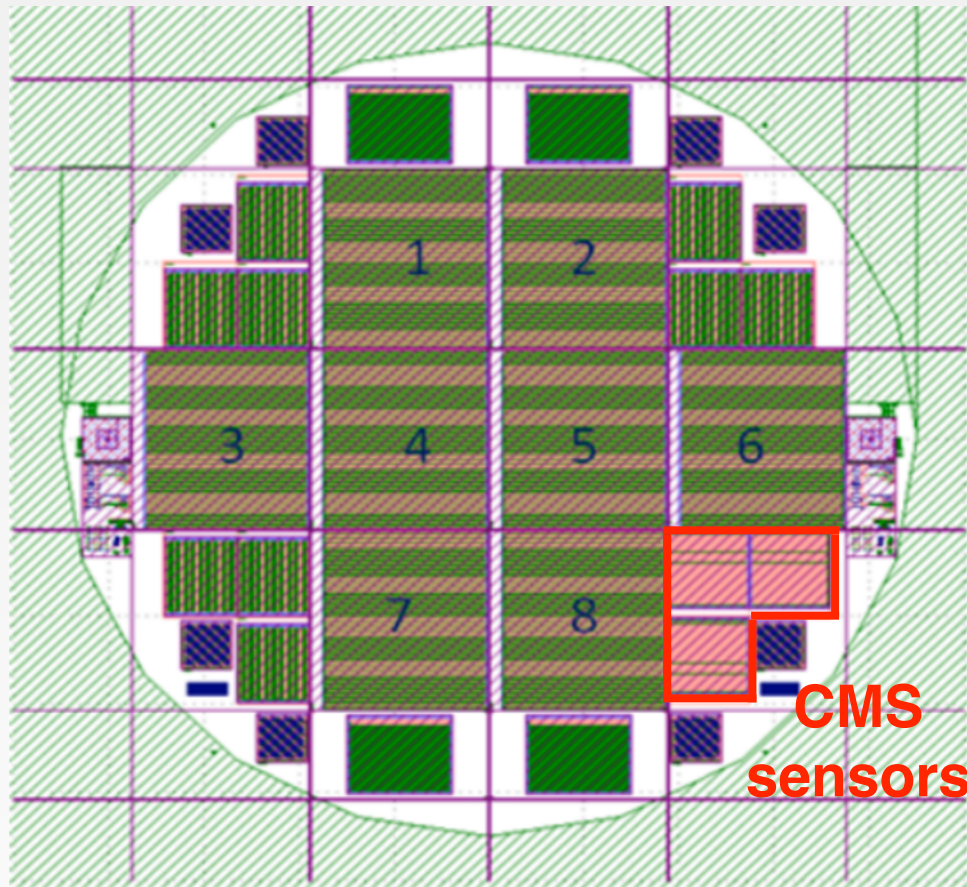
Tested CNM and SINTEF 3D sensors

CNM Sensors

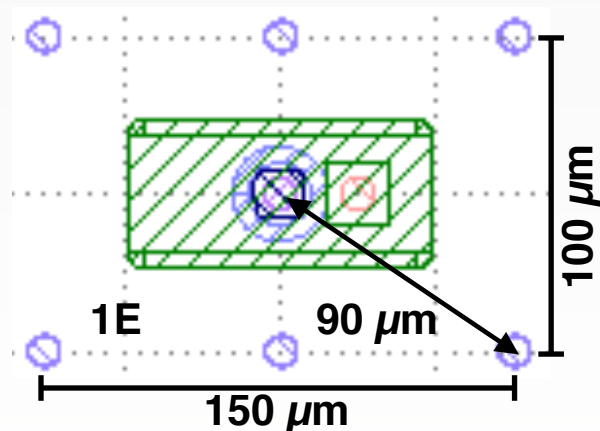
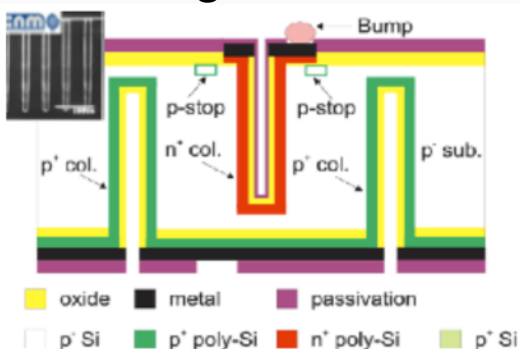
Wafer from Atlas IBL production

Wafer thickness = 230 μm

Slim edge with column fence of 200 μm
(400 μm) on top e bottom (left and right)



Double side not passing through columns

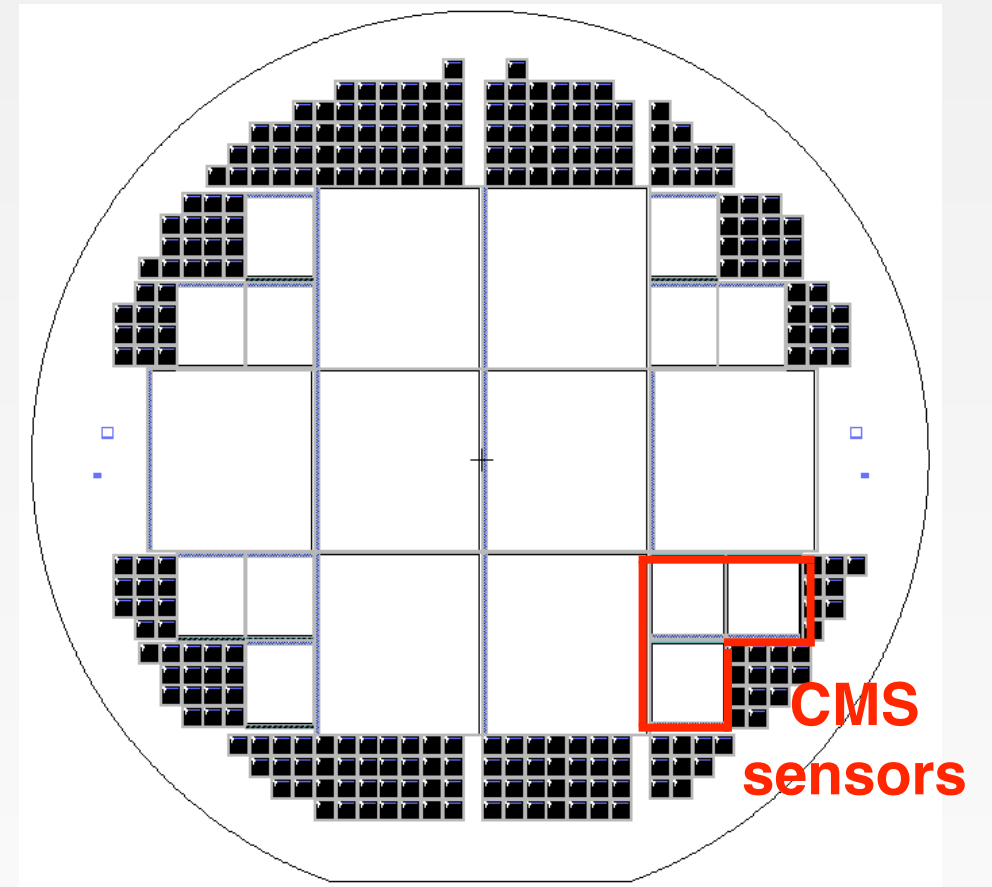


SINTEF Sensors

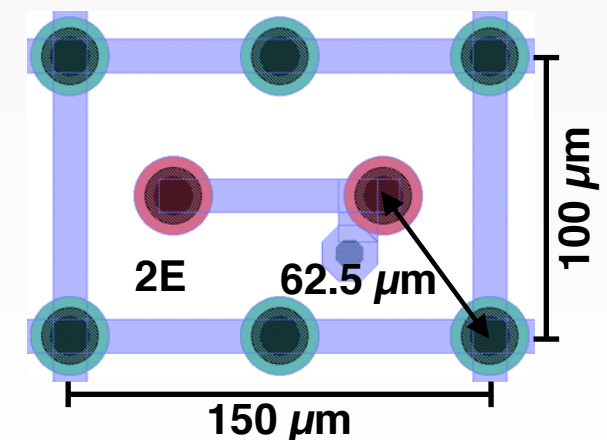
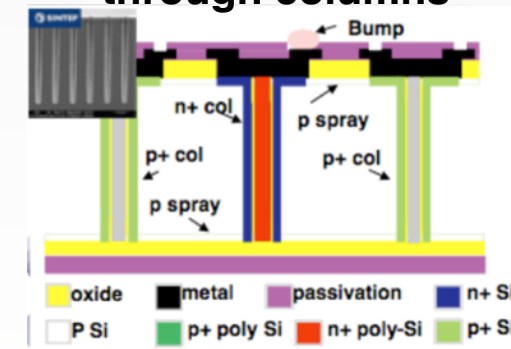
Wafer thickness = 200 μm

Support wafer not removed

Active edge 87 μm larger than the last n+ column on 3 edges, much larger to host bias pad on left edge

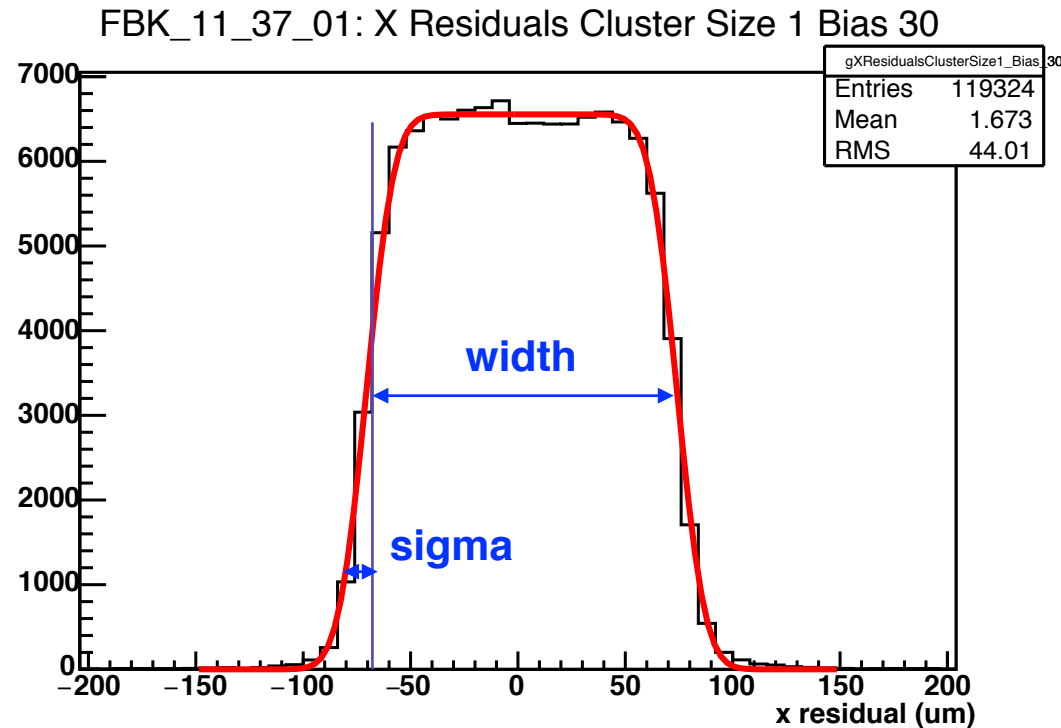


Single sided full passing through columns



Residuals plots

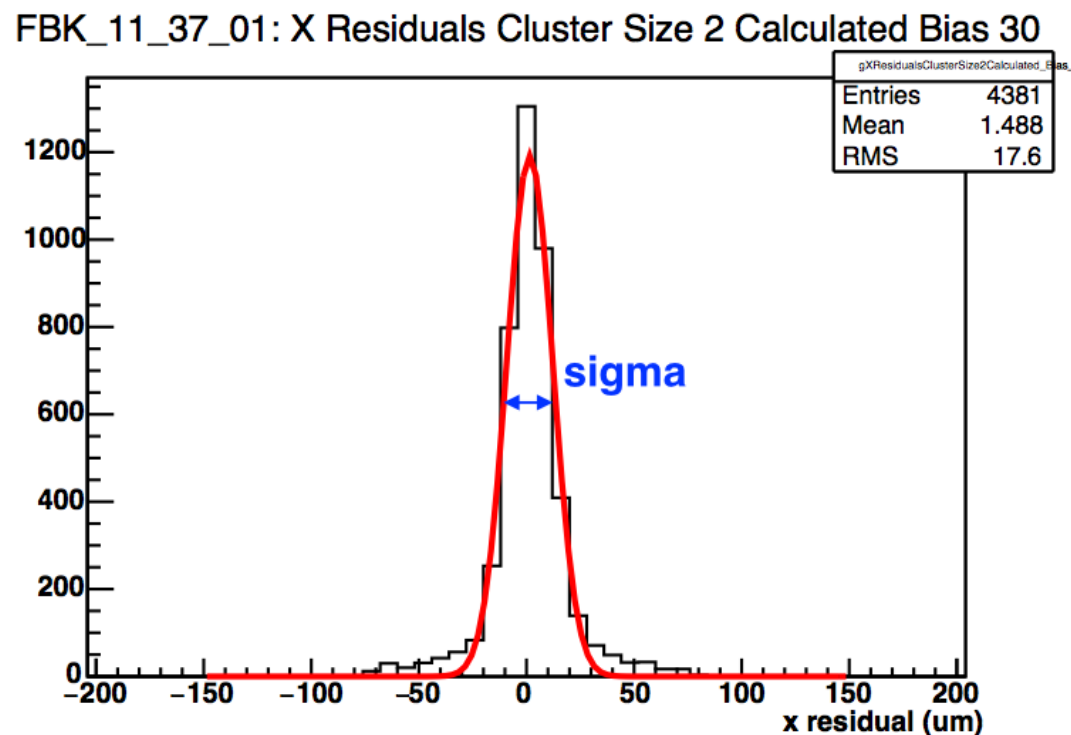
Preliminary



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

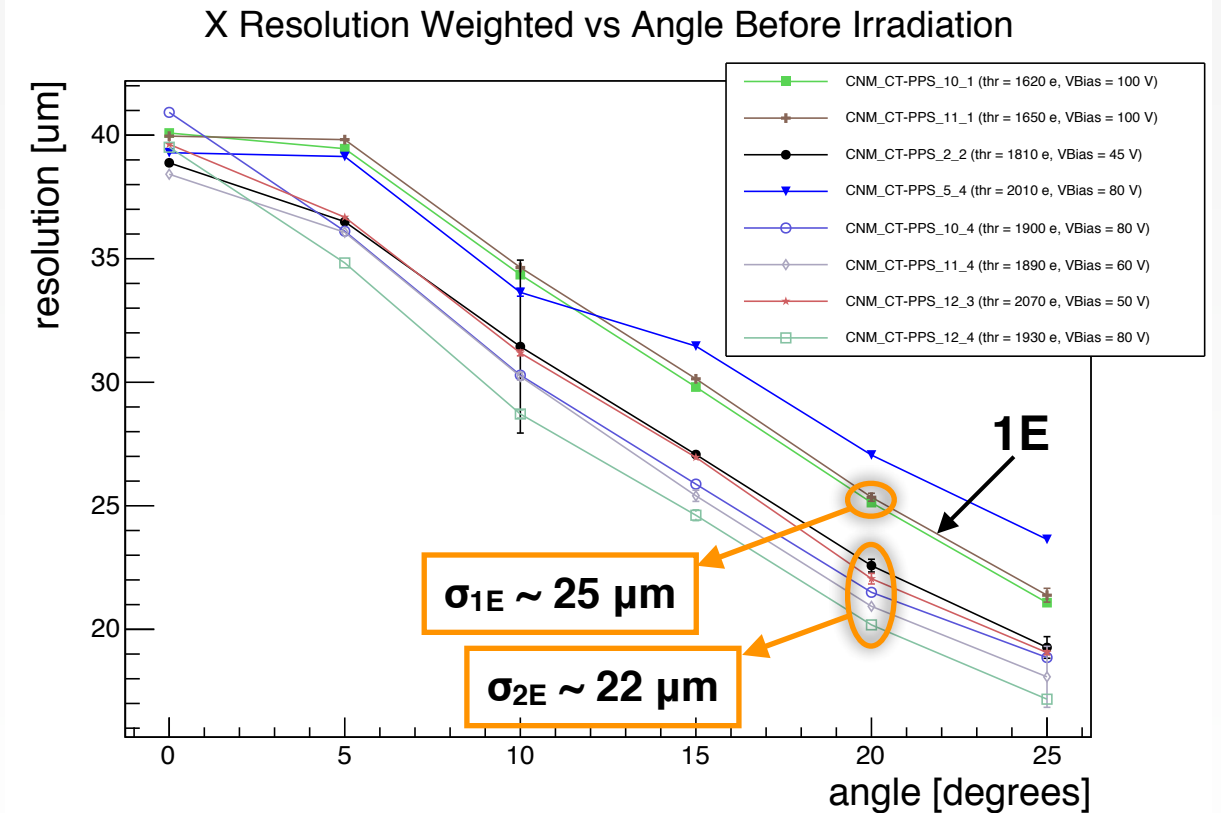
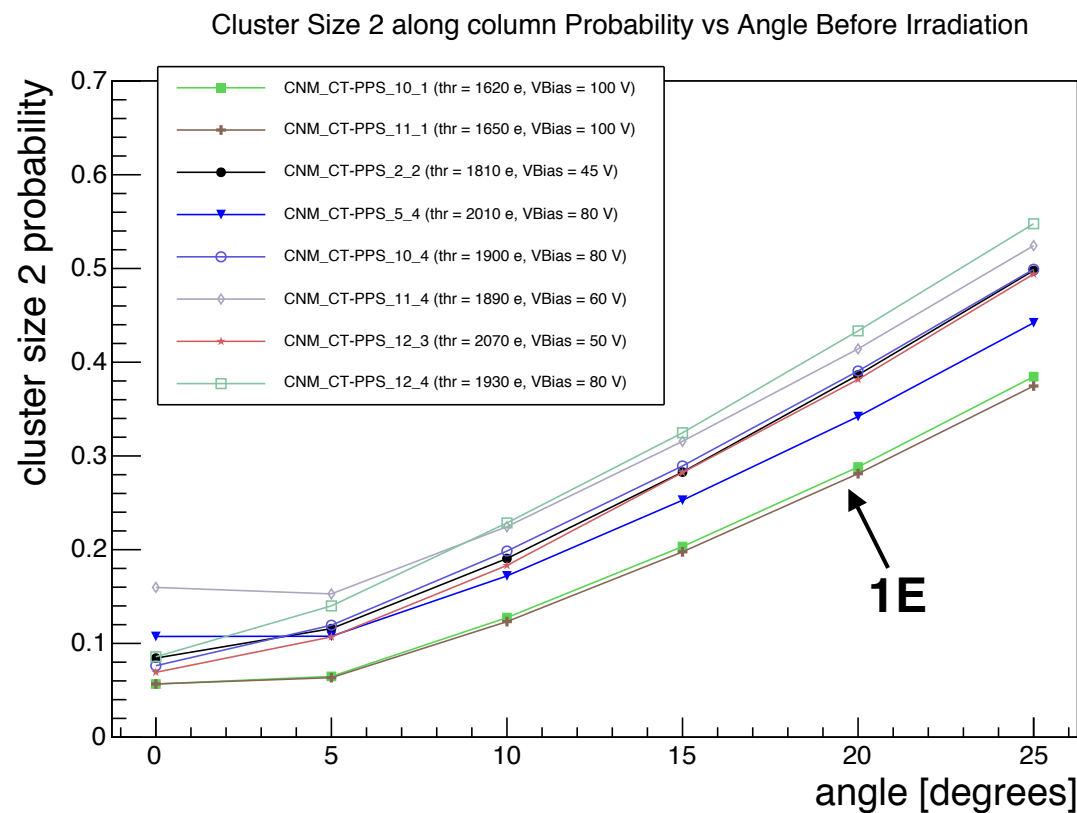
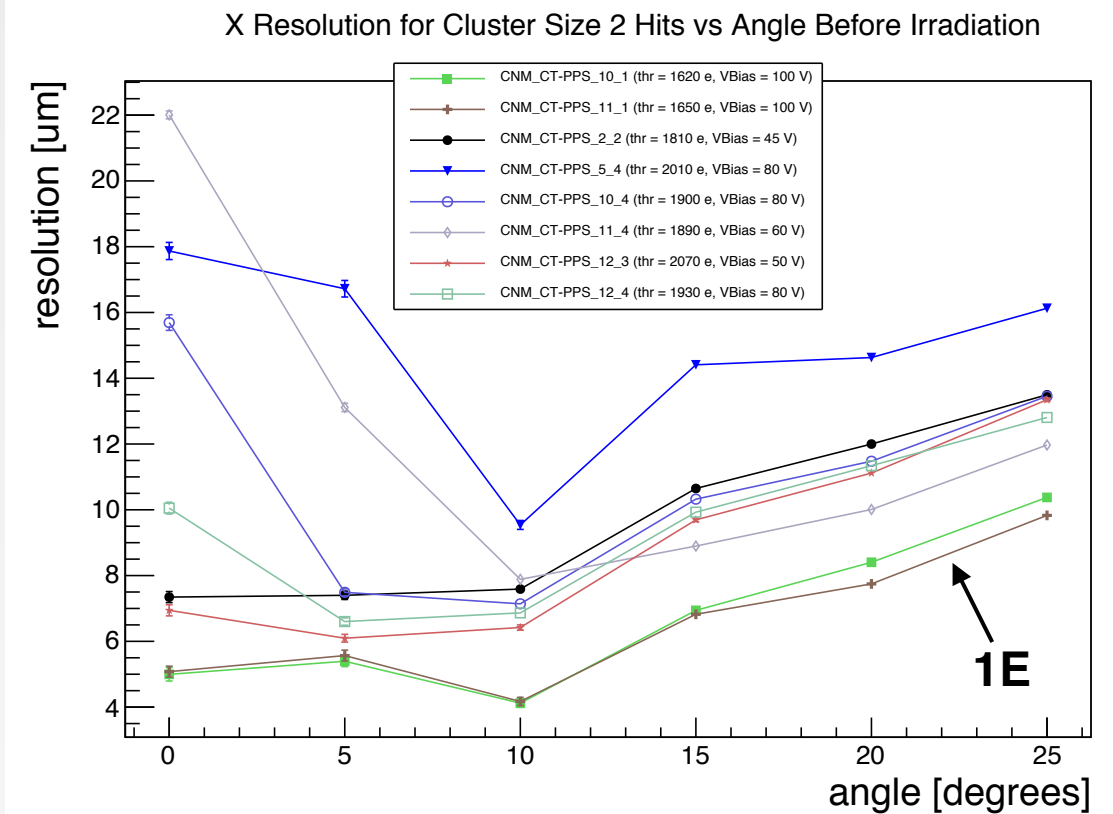
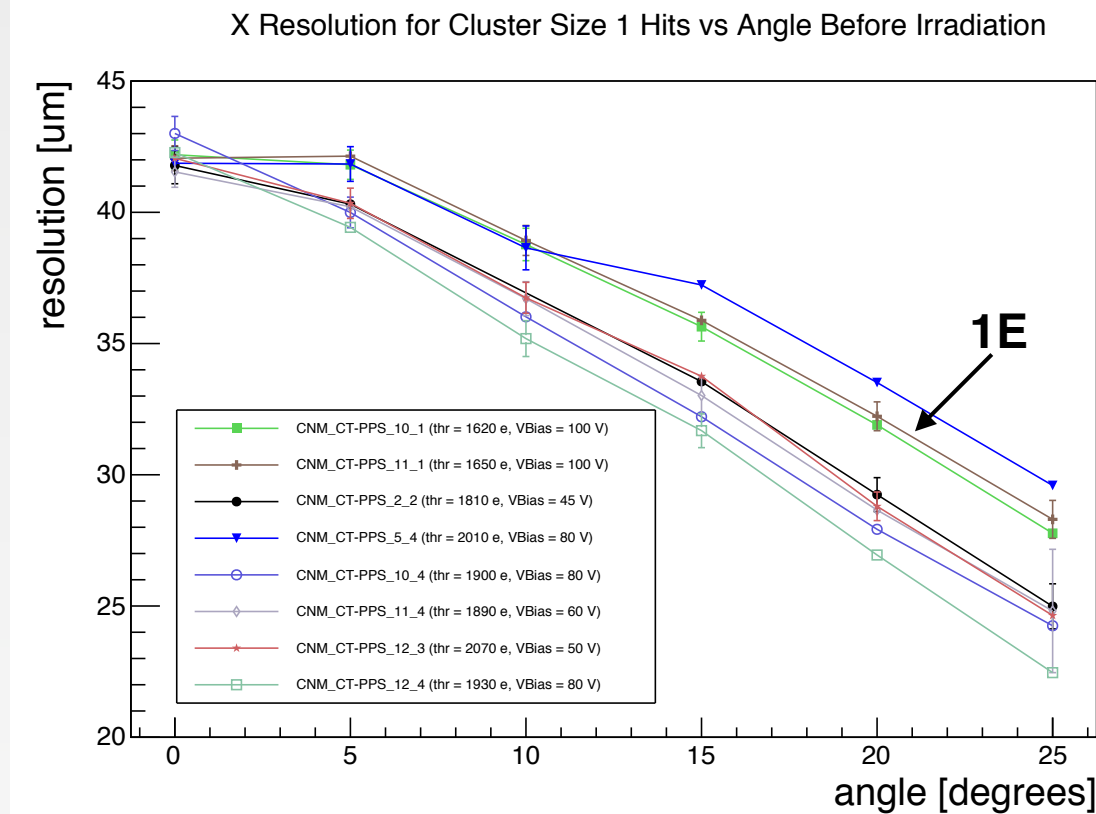
$$\sigma_{CS1} = \sqrt{\left(\frac{width_{CS1}}{\sqrt{12}}\right)^2 + \sigma_{CS1}^2 - \sigma_{telescope}^2}$$

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



Resolution vs angle

Preliminary



Specifications to qualify the devices

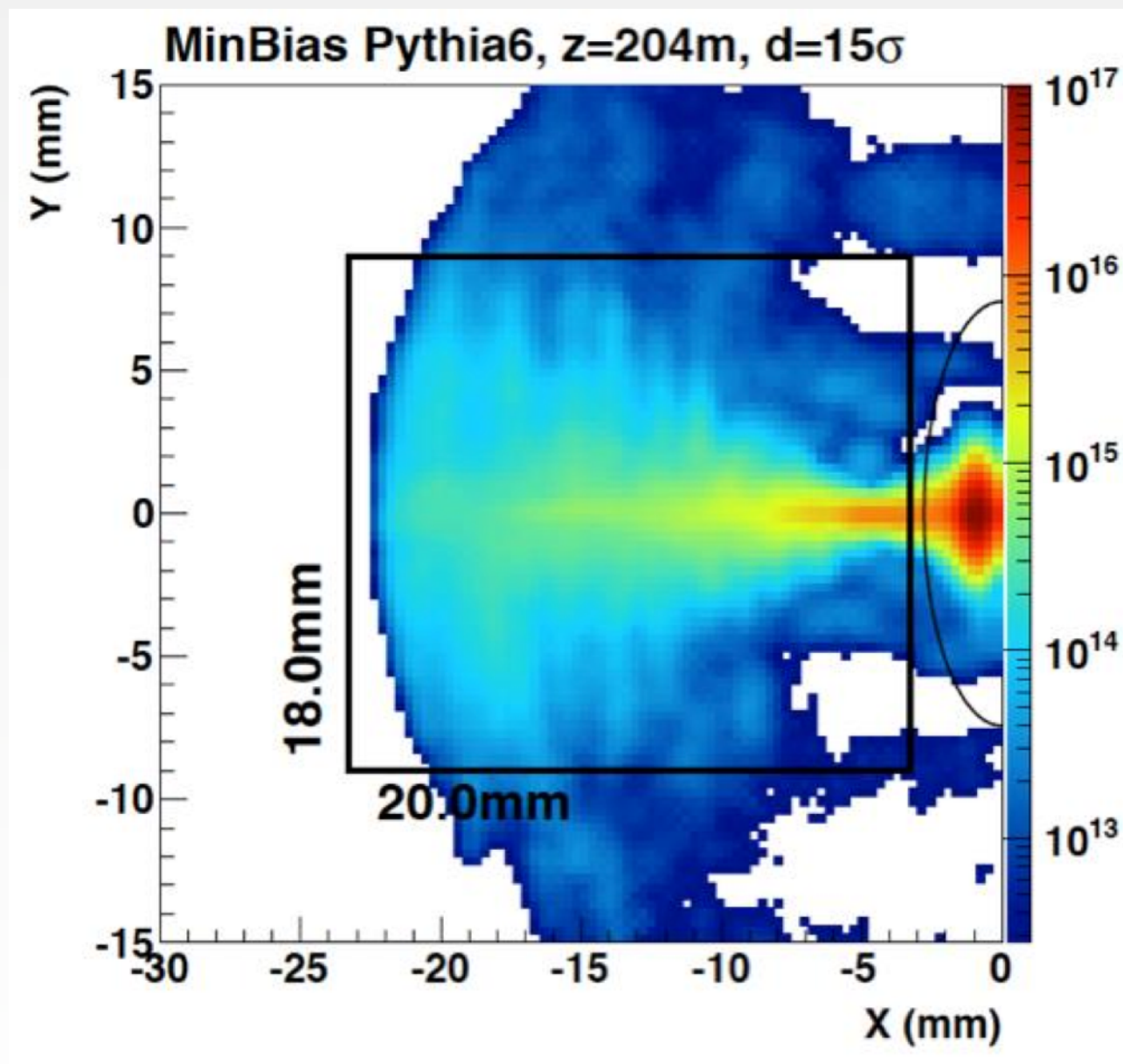
Define: $V_{op} = V_{depl} + 10V$ where V_{depl} and V_{op} are respectively the full depletion and operation voltages.

The following specifications, taken at room temperature (20-24 °C), qualify a device as functioning correctly:

- **$V_{depl} < 20 V$**
- Breakdown voltage: **$V_{bd} > 35 V$**
- **$[I(25V)/I(20V)] < 2$**
- Current at operation voltage:
 - Class A** $I(V_{operation}) < 2\mu A$ per tile \rightarrow very good
 - Class B** $2\mu A < I(V_{operation}) < 10\mu A$ per tile \rightarrow good enough
 - Class C** $I(V_{operation}) > 10\mu A$ per tile

Radiation level

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



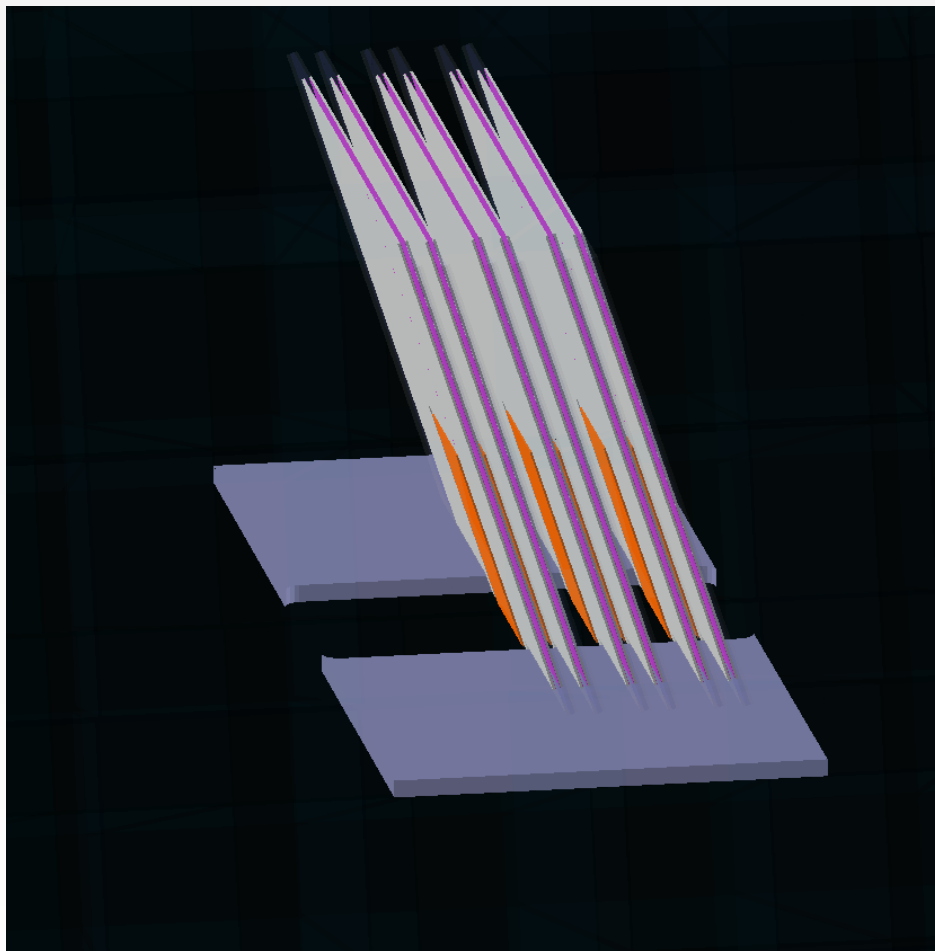
Per 100 fb^{-1} :

- Proton flux up to $5 \times 10^{15} \text{ cm}^{-2}$ in the pixel detectors
- 10^{12} neq/cm^2 and 100 Gy in photosensors and readout electronics

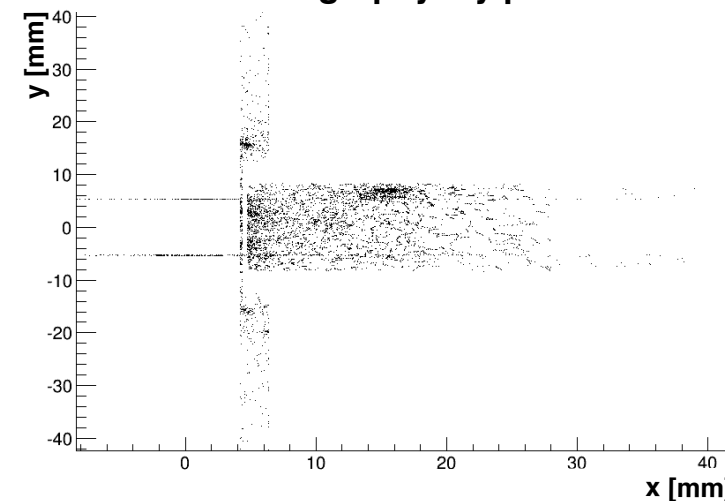
Tracker simulation

- **Final module geometry description implemented into Geant4.** “Fireworks” and “radiography” showed expected behaviour.
- **Simulation included in CMSSW.**
- **Simplified 3D sensor digitisation introduced** considering only geometrical effects, electric field effects is being added.

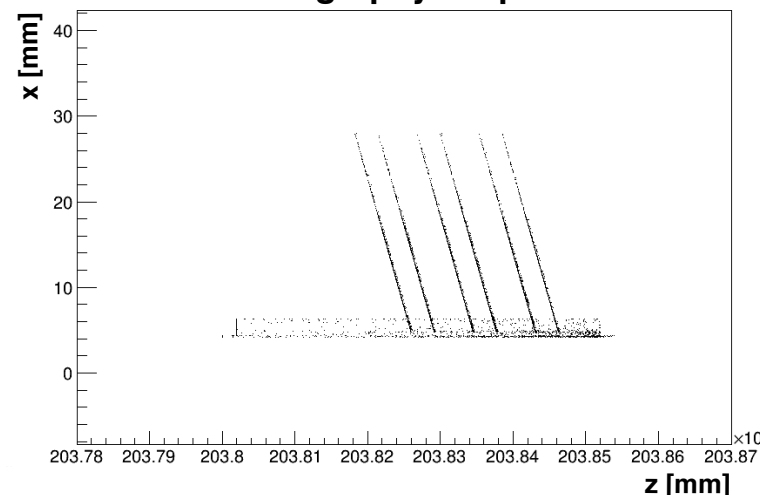
Fireworks



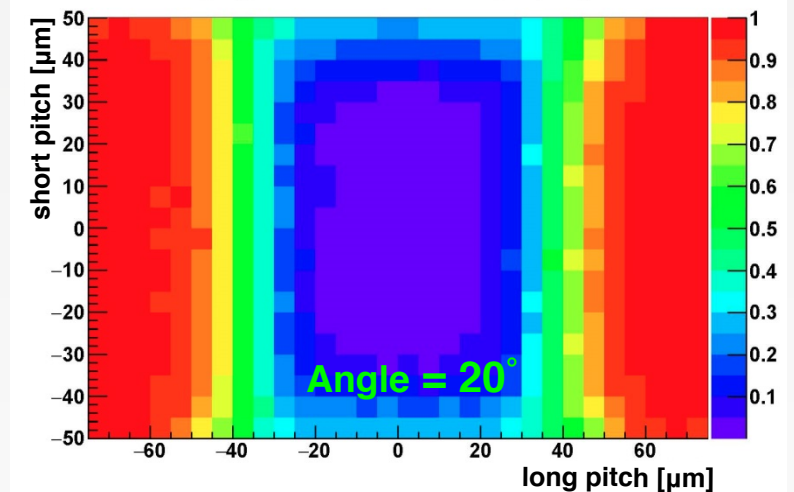
Radiography x-y plane



Radiography z-x plane



Cluster size 2 probability map - test beam



Cluster size 2 probability map - simulation

