The CT-PPS tracking system with 3D pixel detectors

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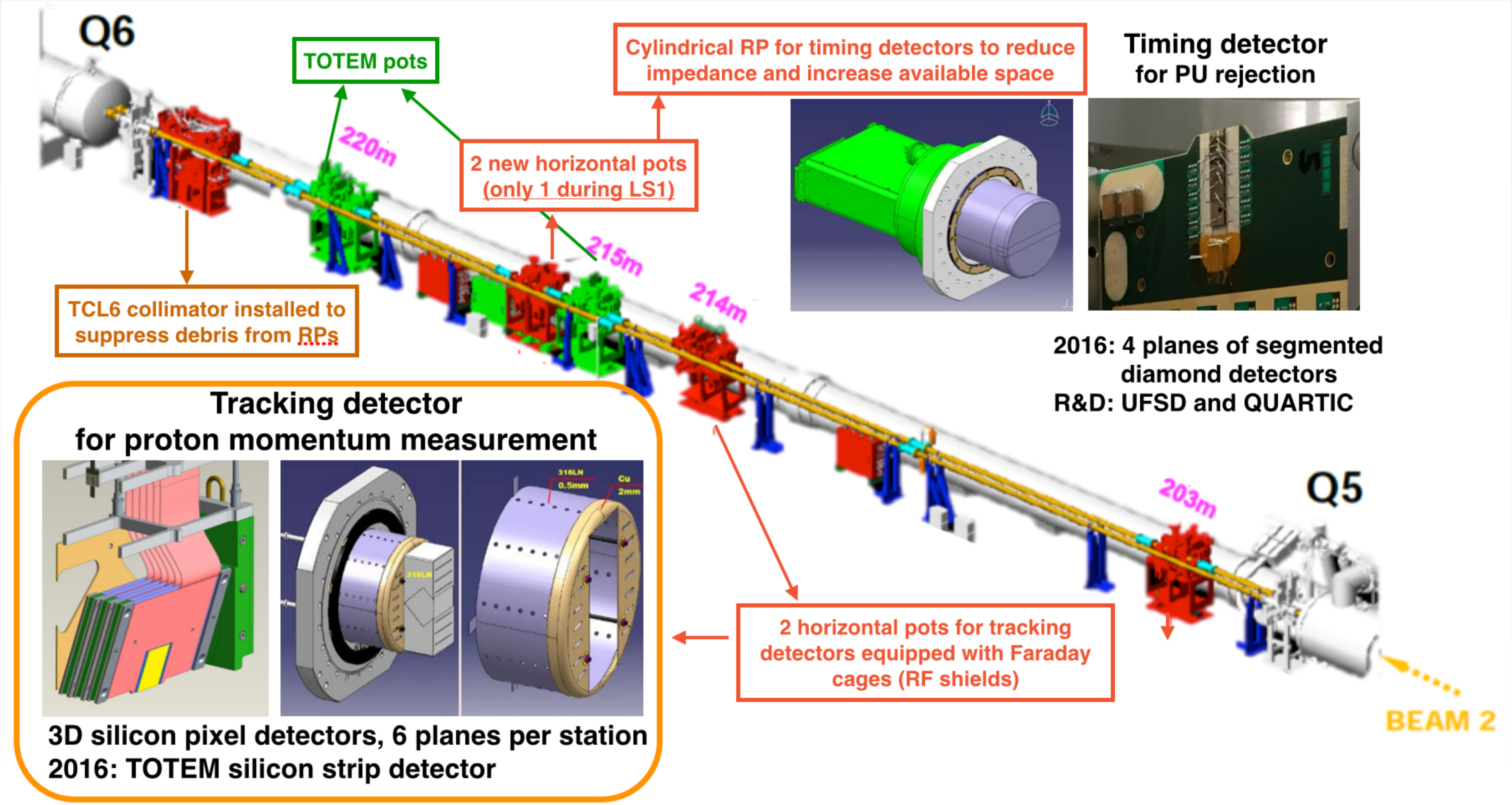
on behalf of the CMS and TOTEM Collaborations

8th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging

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

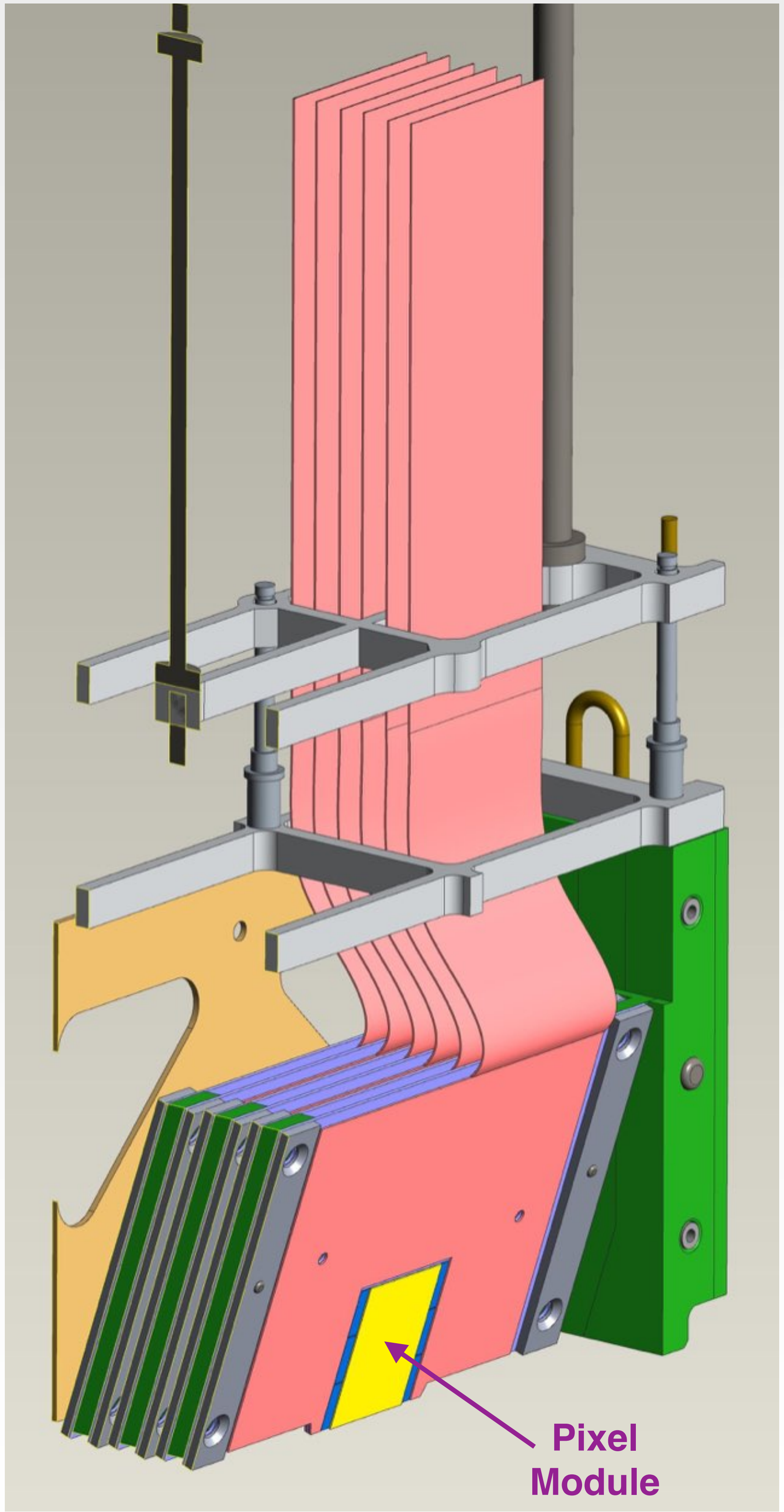


Tracking system

- **Requirements**:
  - **Sustain high radiation levels**: for 100 fb^{-1}, proton flux up to $5x10^{15}/cm^2$ in tracking detectors, $10^{12}\ n_{eq}/cm^2$ and 100 Gy in readout electronics.
  - **Small inefficient area at the edge of the sensor** toward the beam.
  - **Tracking resolution of ~10 μm**.

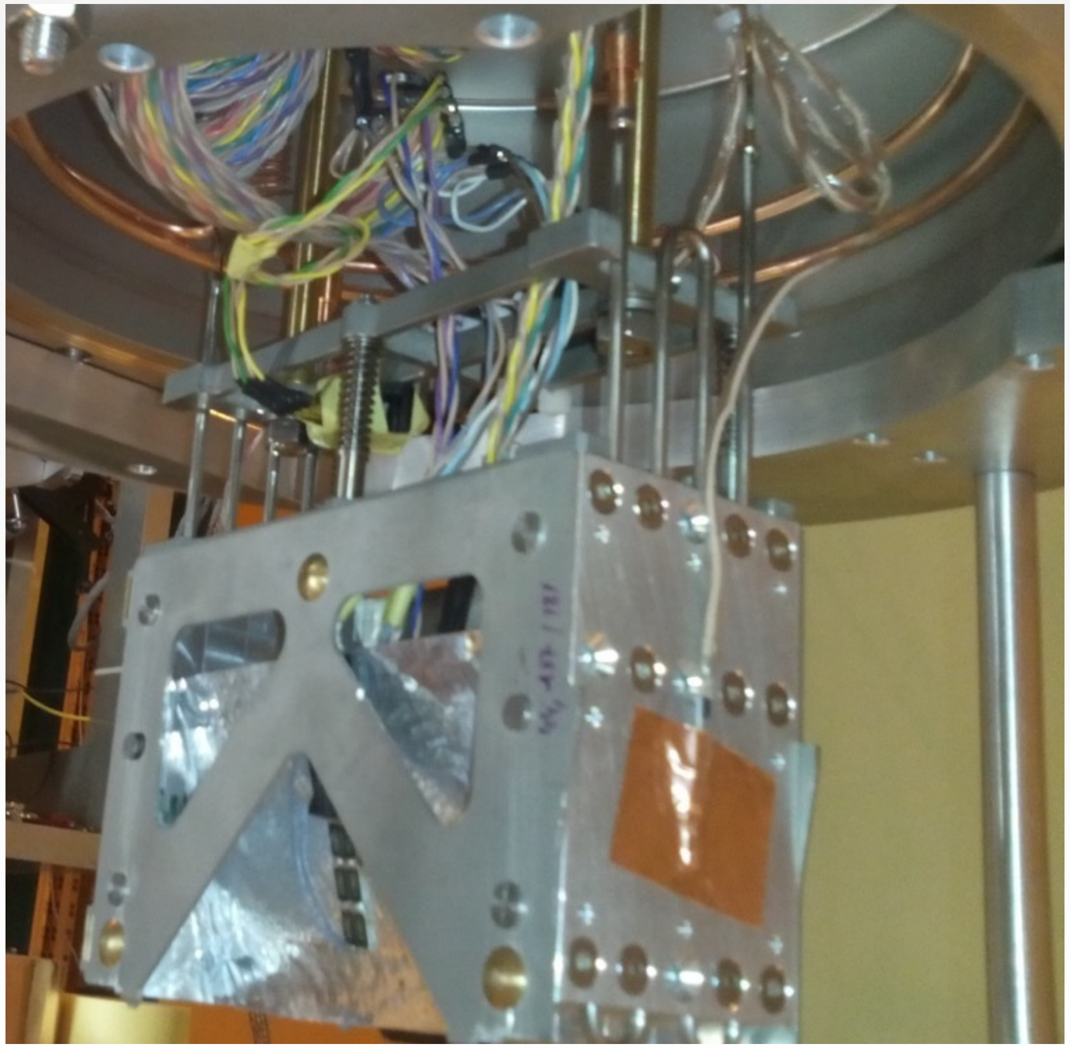
- **Baseline design**:
  - **3D sensor** technology chosen for its intrinsic high **radiation hardness** and the possibility to implement **slim edges**.
  - **Two stations per side, each with 6 detector planes tilted by 18.4°** to increase the cluster size and **improve resolution**.
  - **Readout chip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

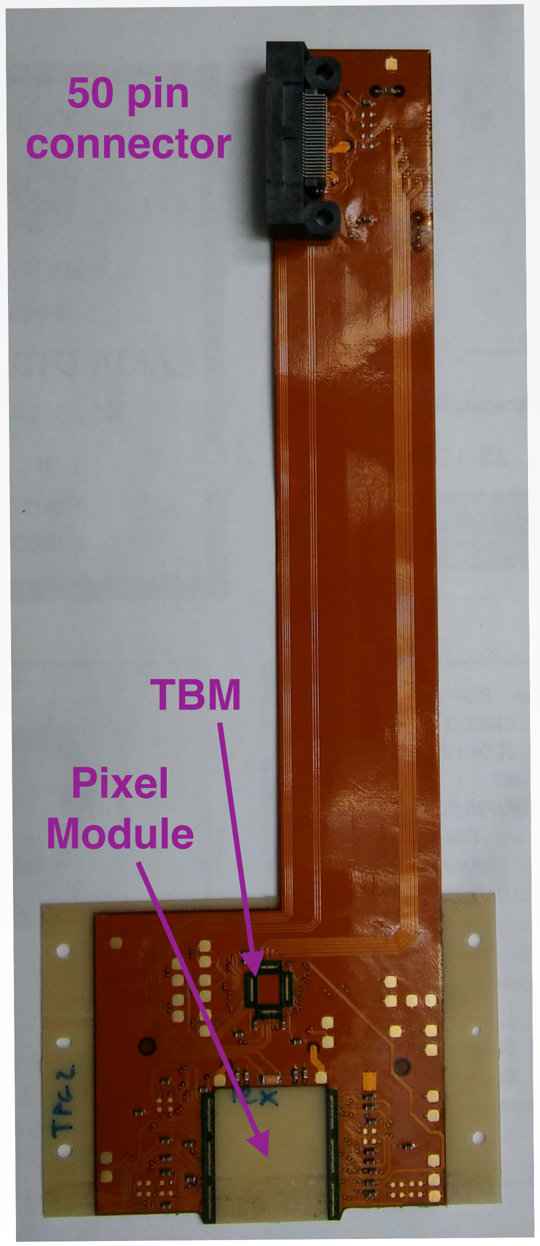
Tracking detector - Mechanics



- 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

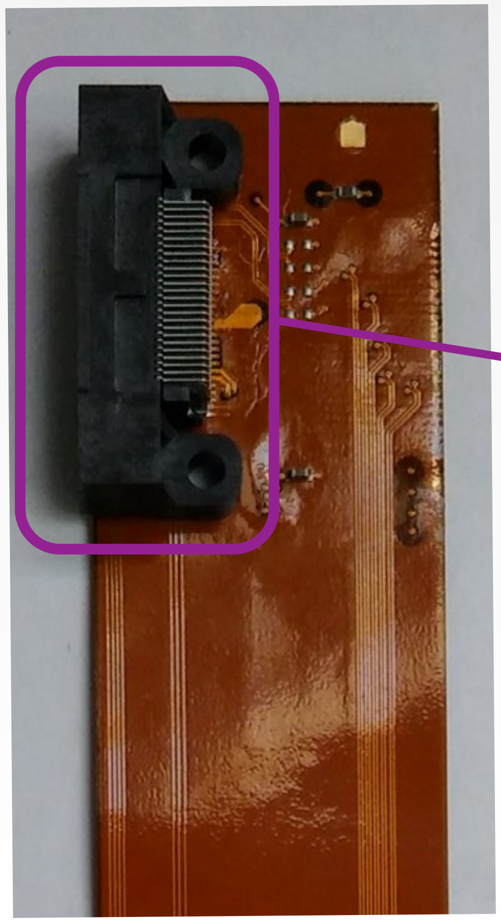




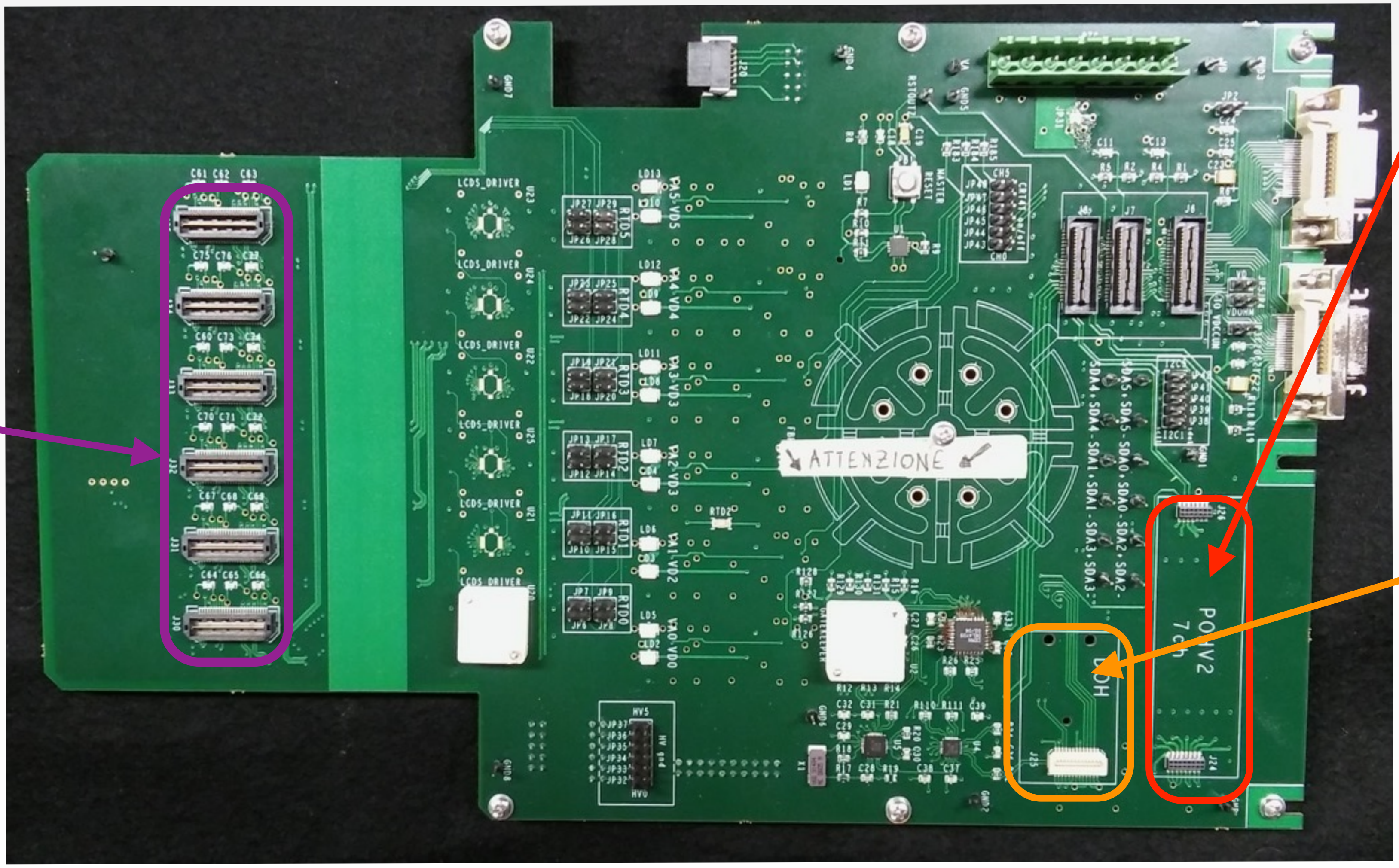
Tracking detector - Electronics

- **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 September.

Connectors for flex hybrid boards

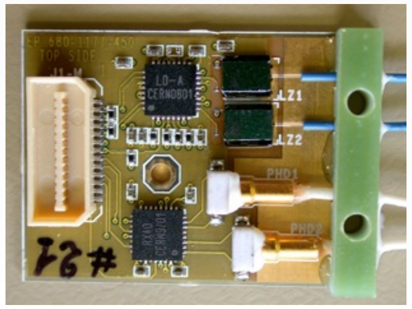


RPix Port Card



Pixel Opto-Hybrid

Digital Opto-Hybrid



3D sensors for CT-PPS

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

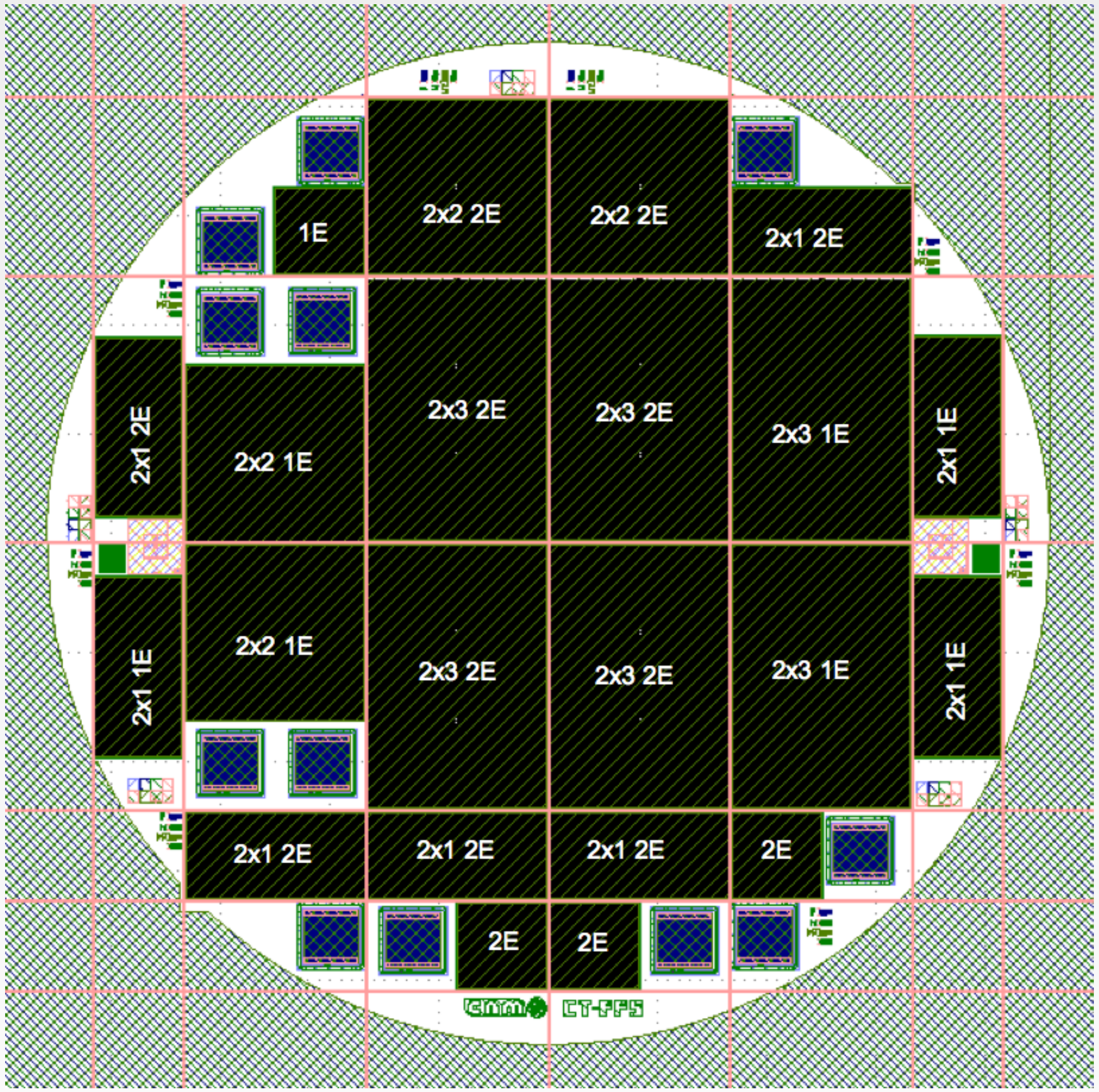
- **2E pixel** configuration (2 readout columns)
- 200 µm **slim edges**
- 2x3 sensors (6 ROCs each)

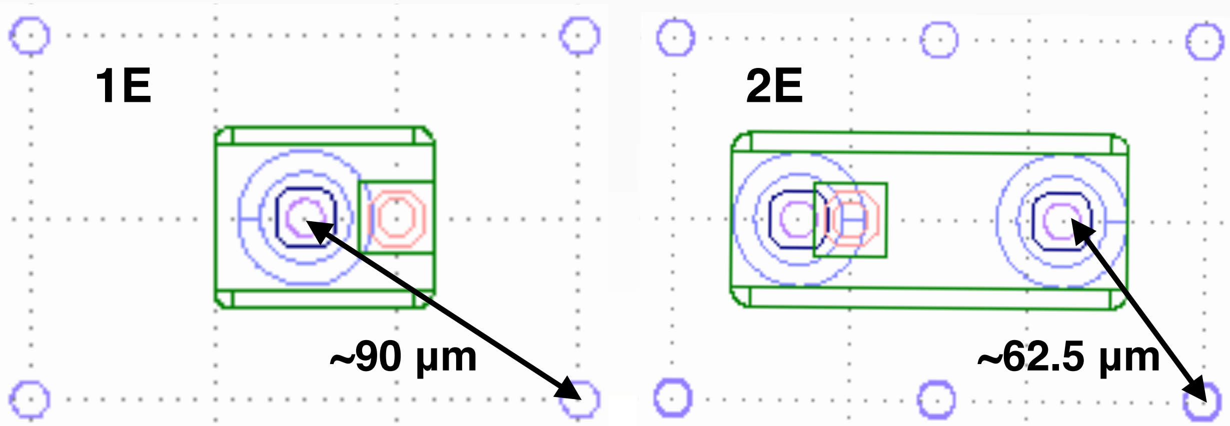
1E and 2x2 sensors as backup solution

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.

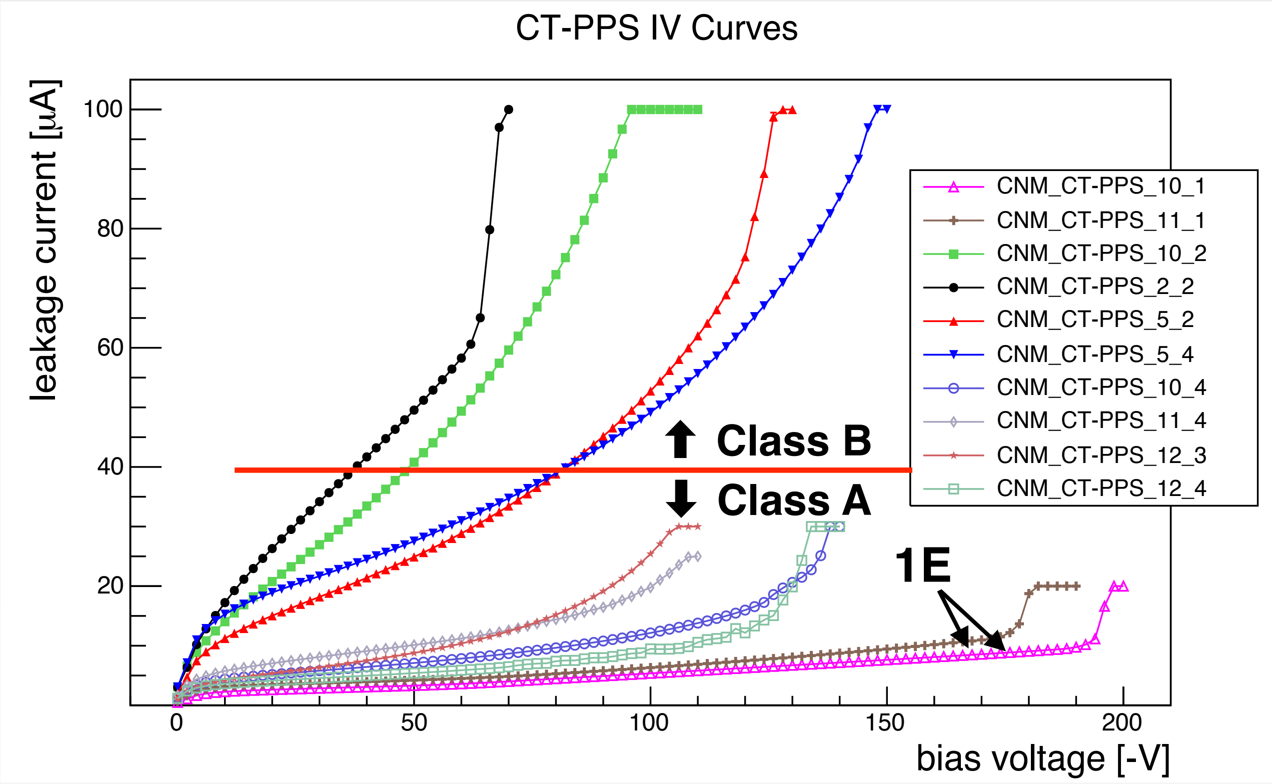
24 wafers produced at CNM





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.
- A total of 32 modules already available and under test, remaining modules in production
- Bump-bonding at IZM to the PSI46dig ReadOut Chip, same ROC as the CMS Phase I pixel detector upgrade.



- 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.

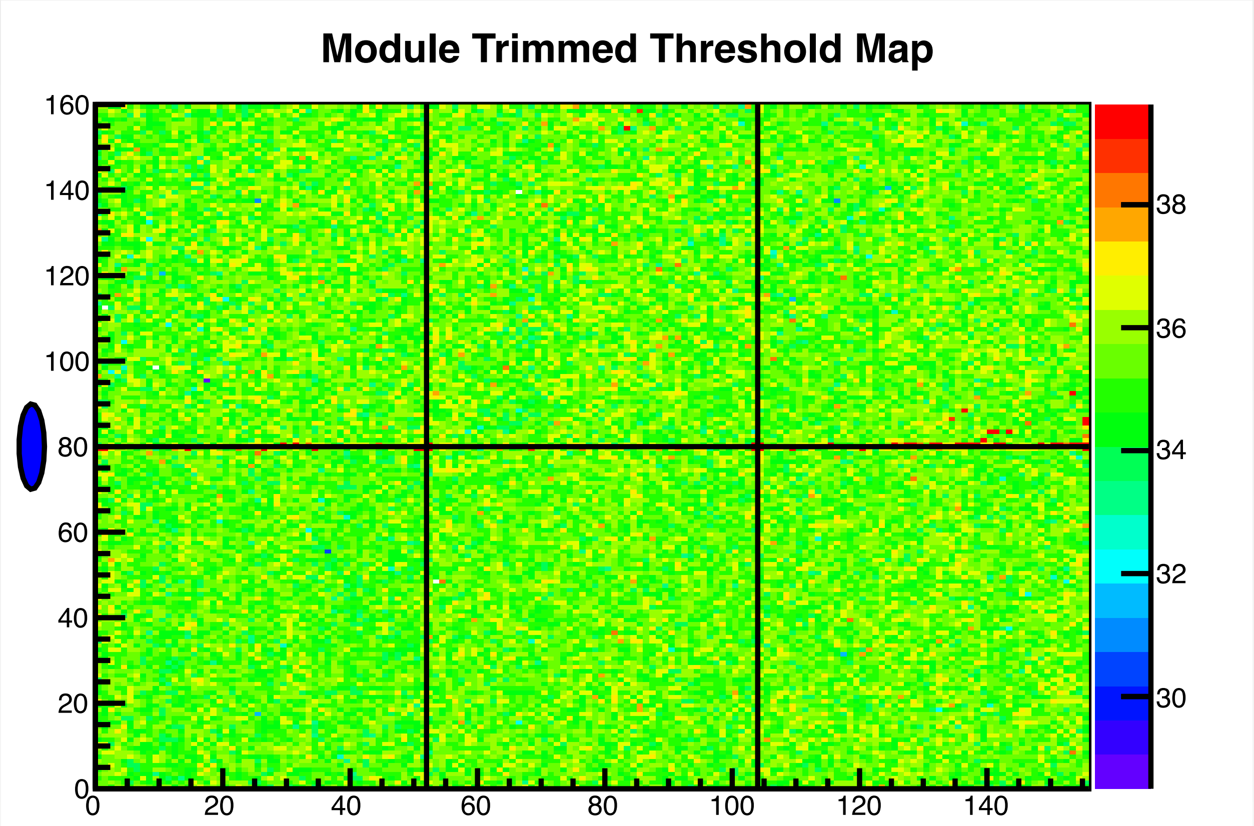
Module testing

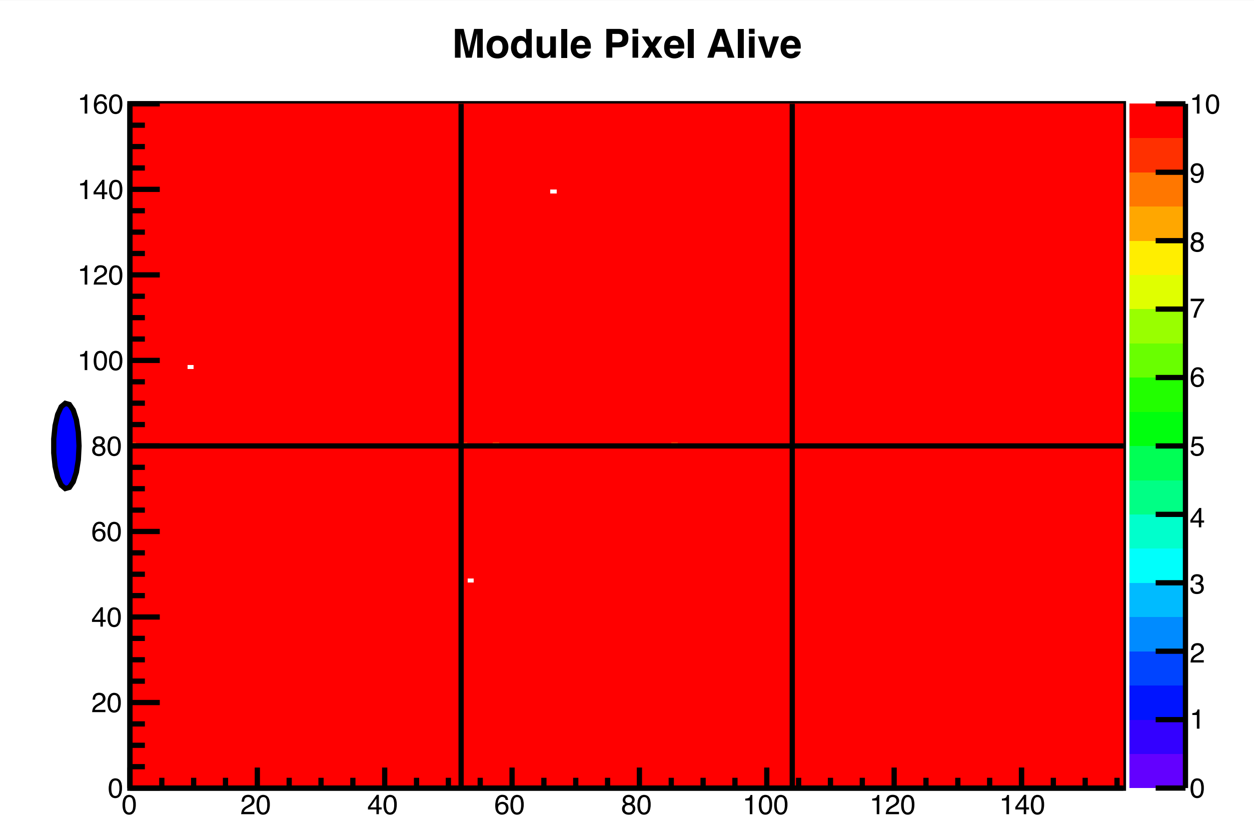
Detectors characterised and optimised in Torino and Genova laboratory:

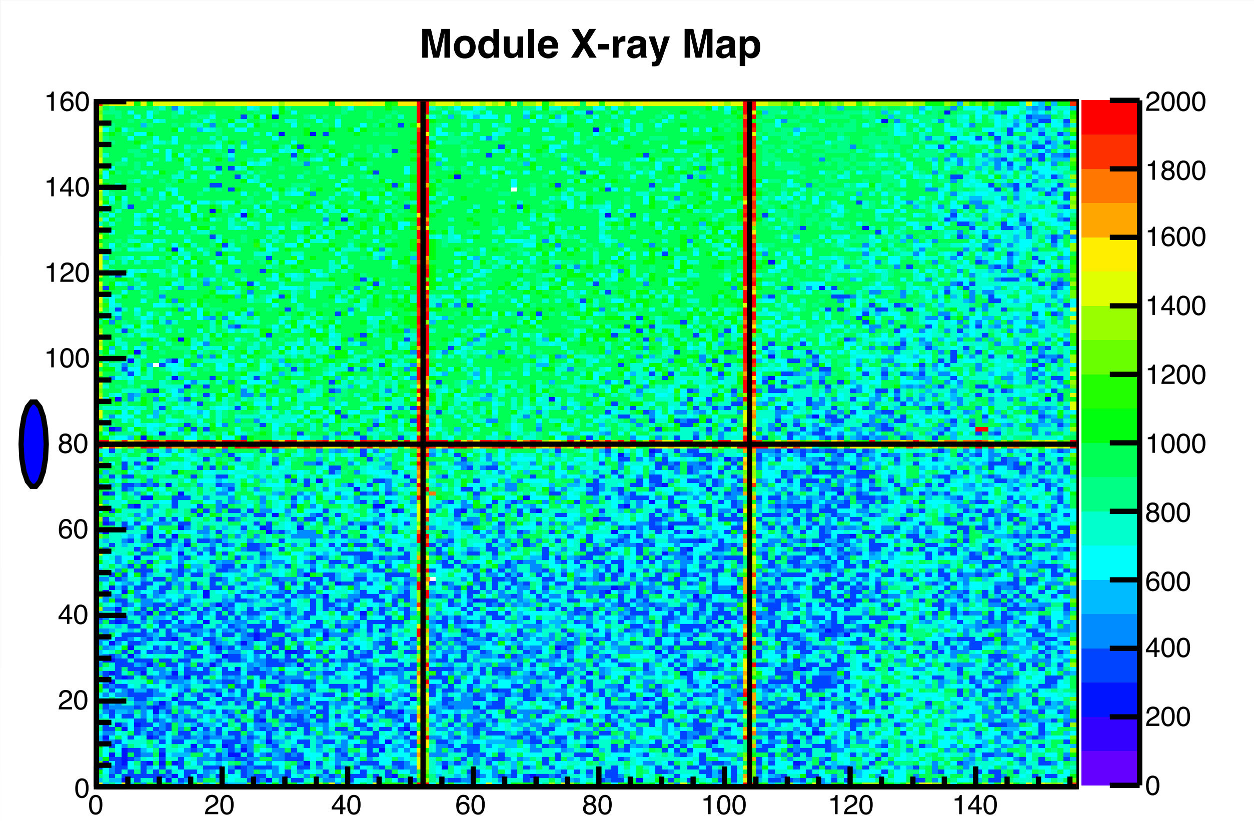
- IV curve
- ROC calibration and optimisation
- Threshold trimming to ~ 1800 e^-
- X-ray to check bump-bonding quality

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.







Beam test - Efficiency

Preliminary

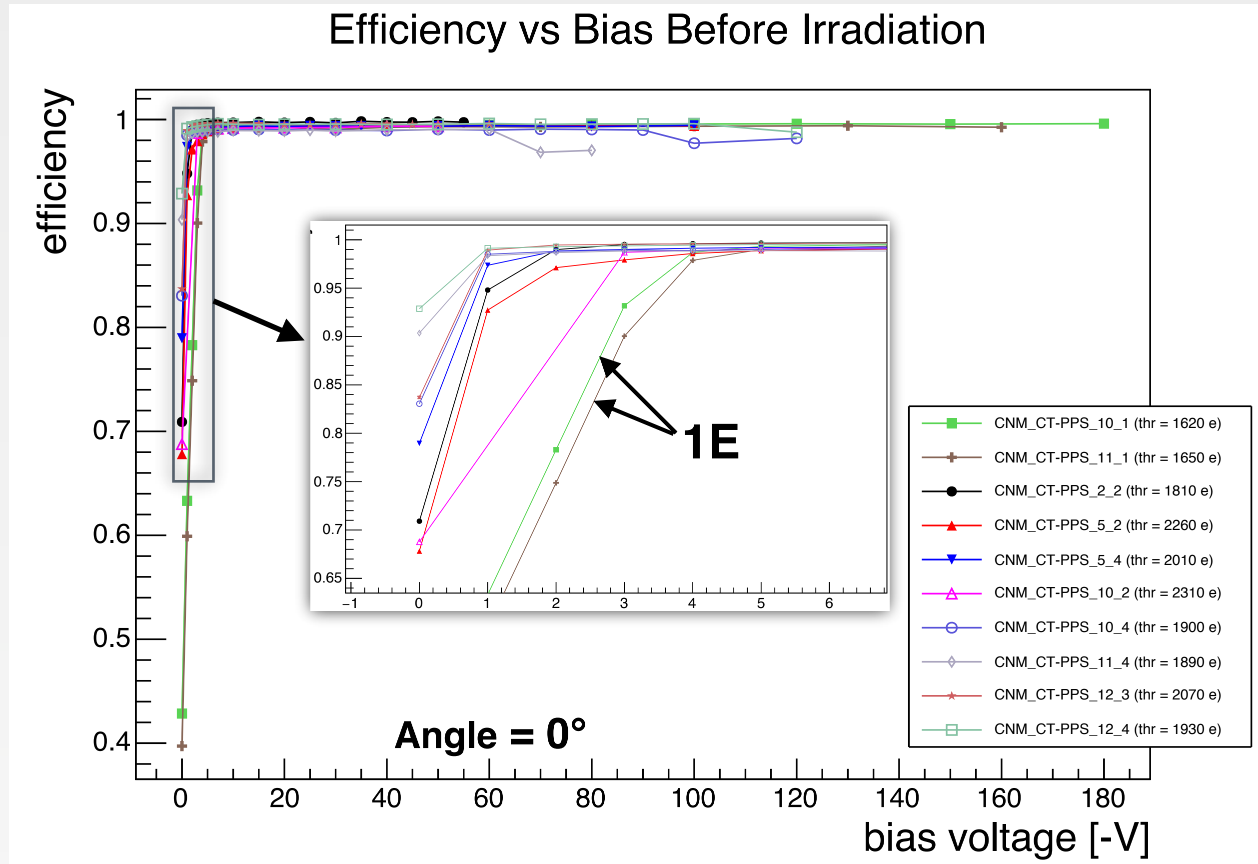
10 single-ROC sensors (**2 1E and 8 2E**) bump-bonded in March at IZM to the CMS Phase I ROC have been **tested at FNAL with 120 GeV protons.**
Sensors selected both of class A and B.

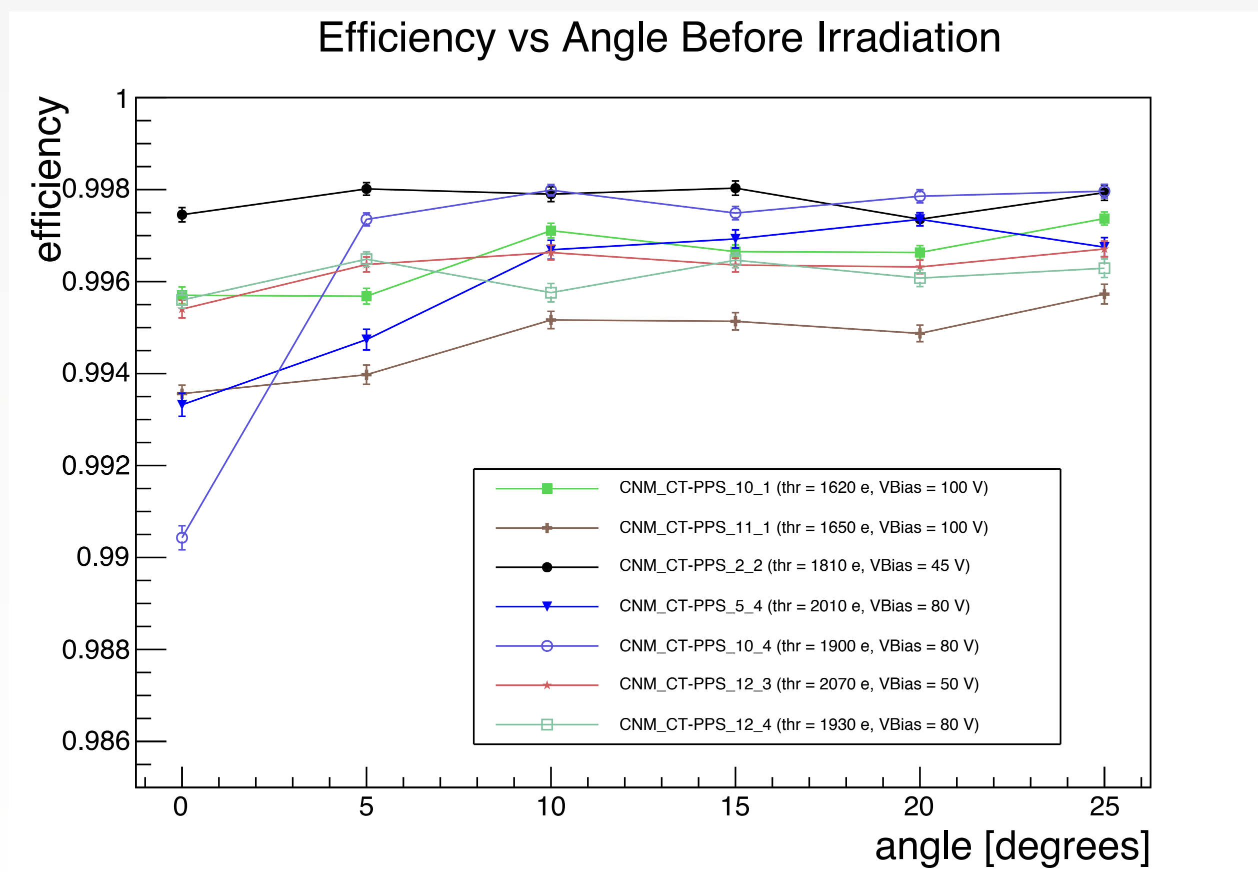
A telescope with 8 planes of CMS silicon pixel detectors allows to reconstruct tracks with a **resolution of 8 µm** in both x and y coordinates.

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.

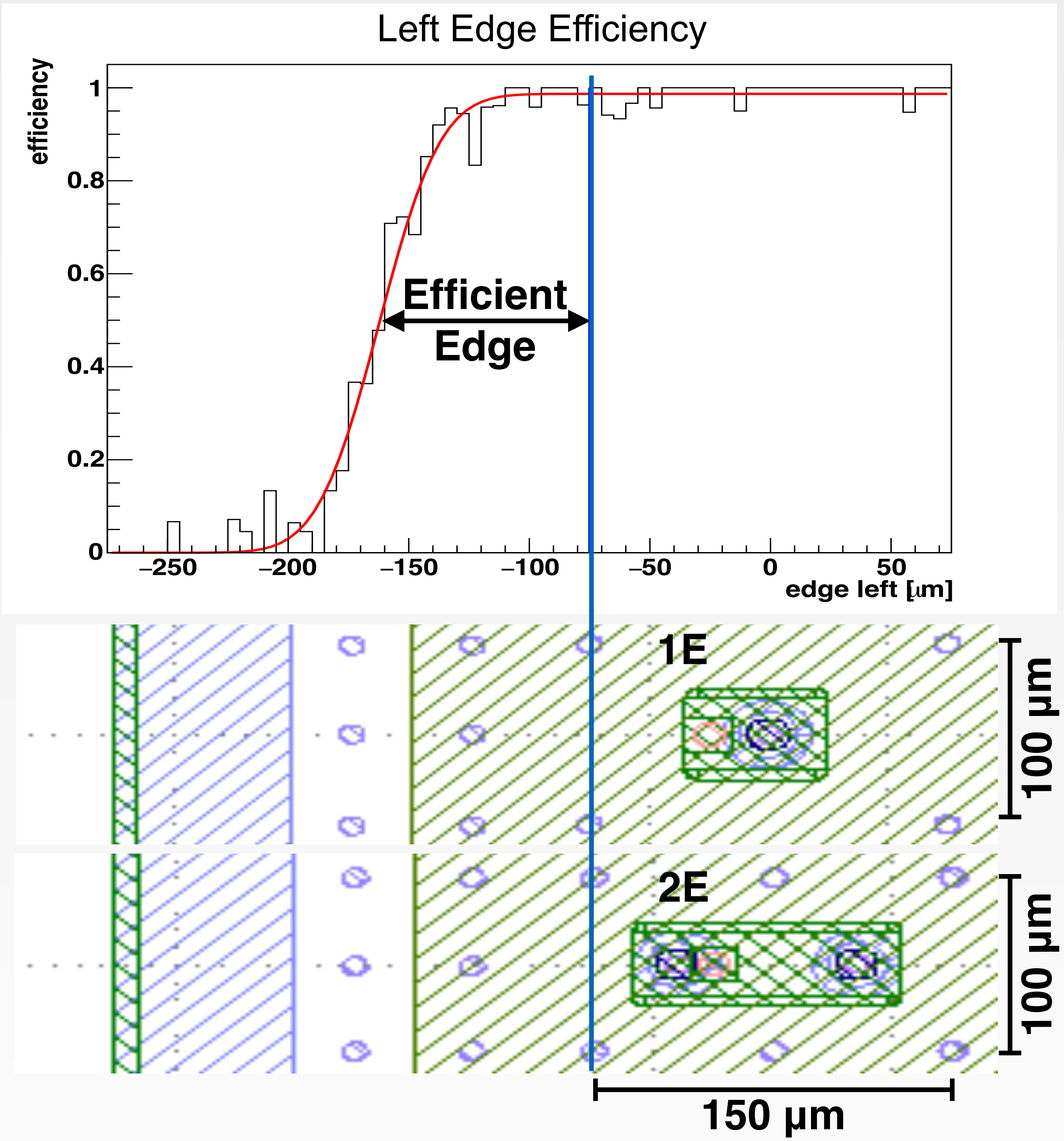
Efficiency greater than 99.4% at 20°.
(CT-PPS tracking detector angle = 18.4°)



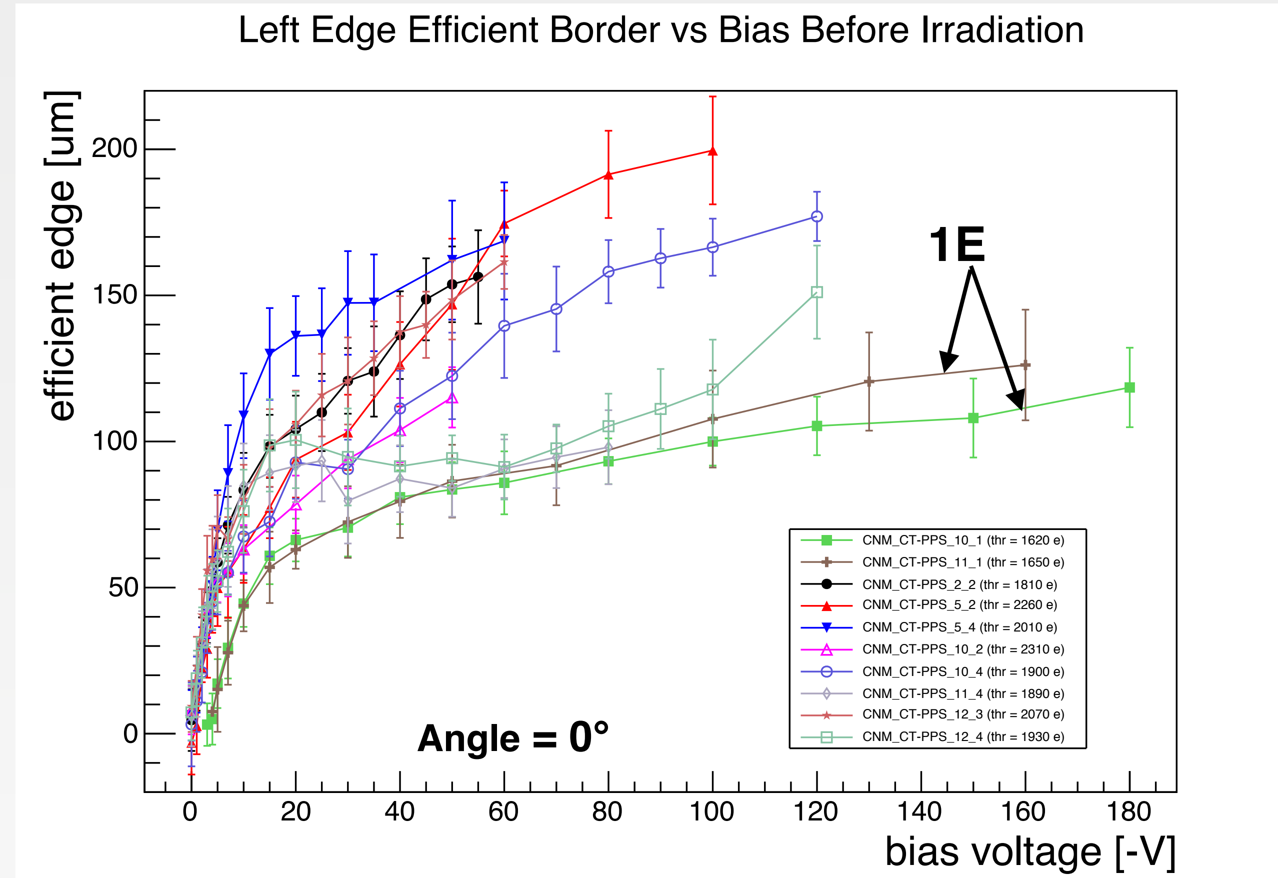


Beam test - Edge efficiency vs bias

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.

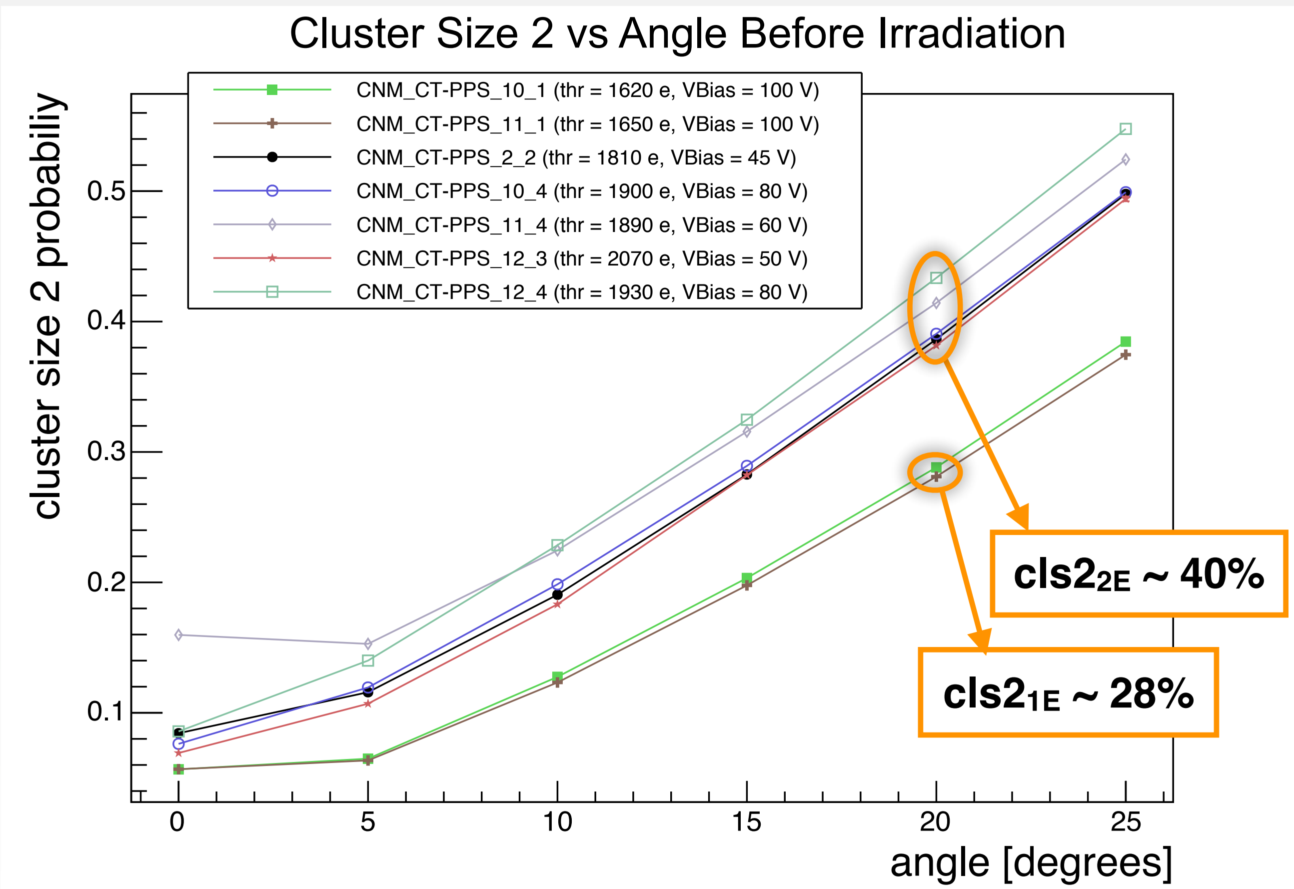
2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n+-electrode closer to the sensor edge.

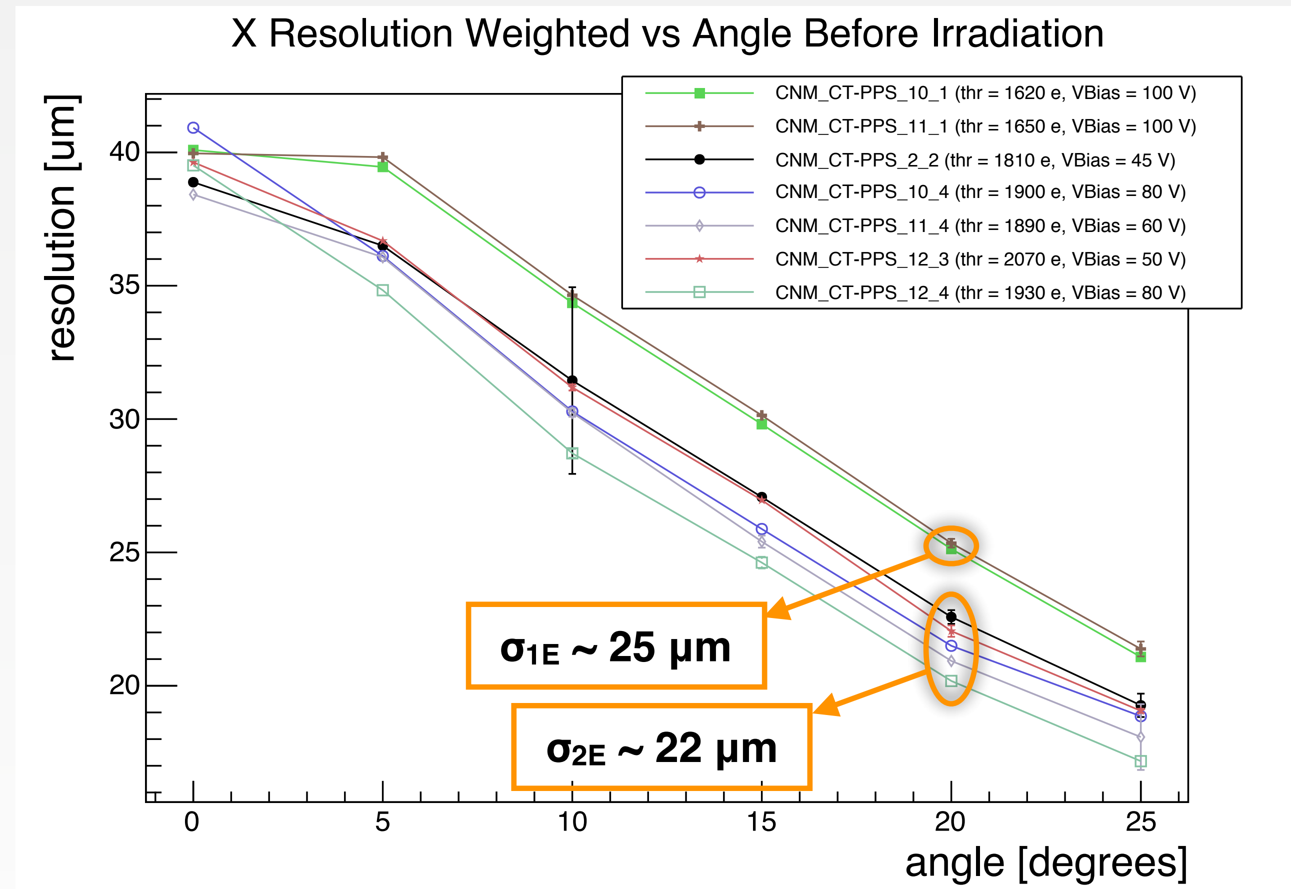
Beam test - Resolution vs angle

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**.





Considering a resolution per single plane between 20 and 25 μm, **the target resolution of ~10 μm can be achieved**.

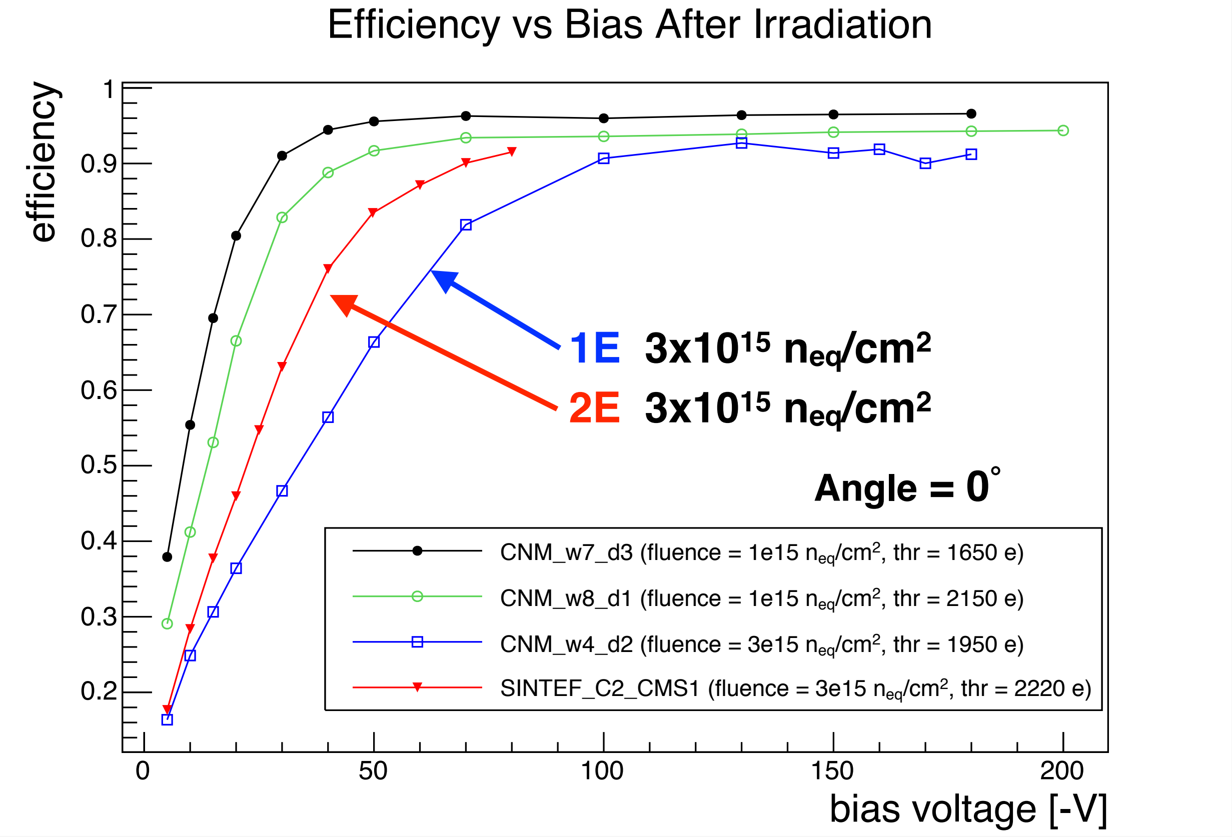
Performance after irradiation

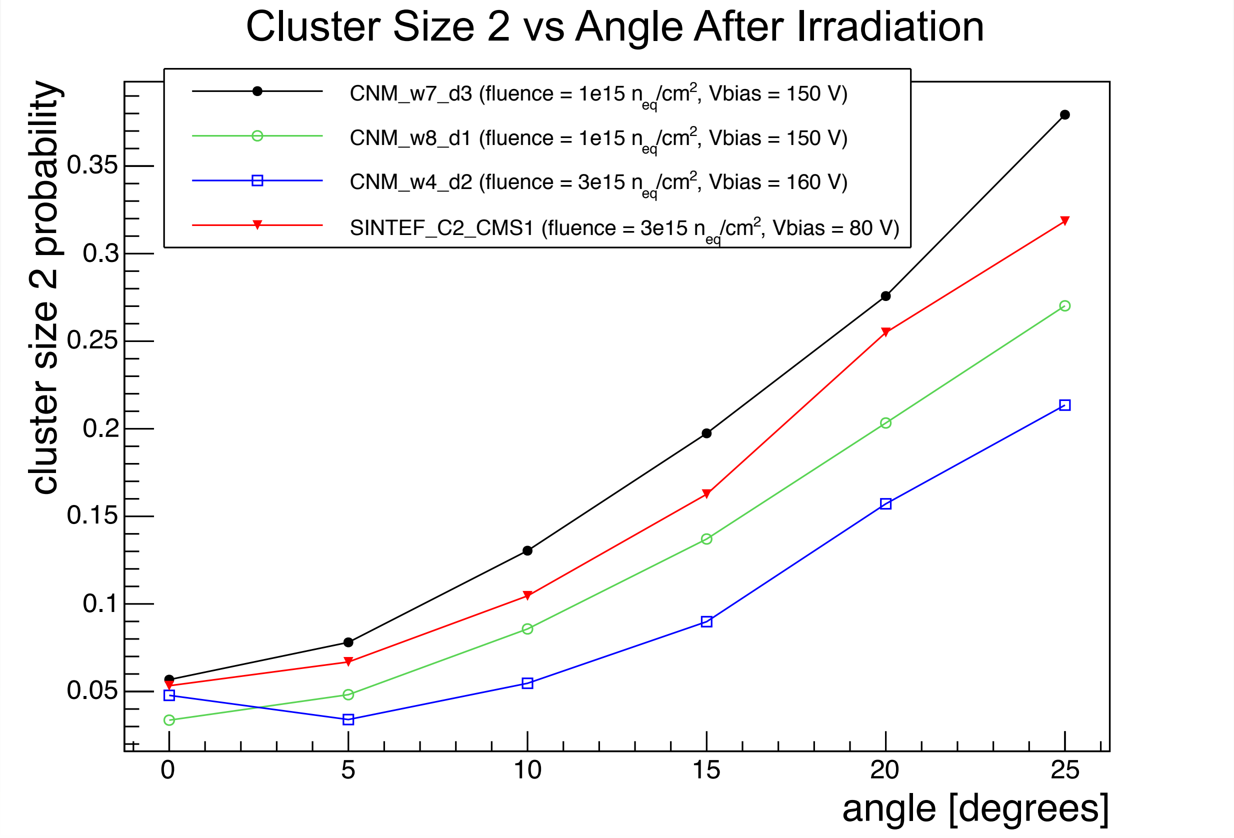
Preliminary

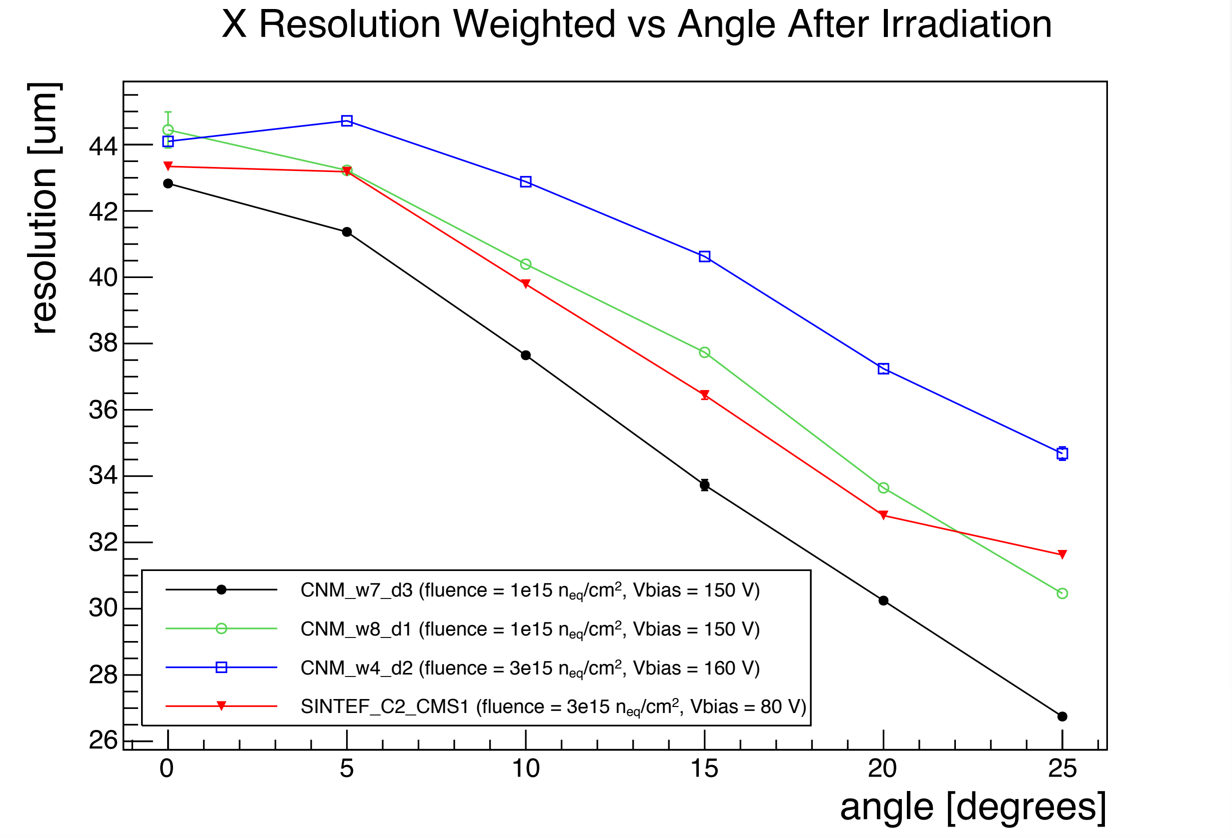
It is foreseen that **the detector will be irradiated during its life up to 5x10^{15} p/cm^2** which corresponds to ~1x10^{15} n$_{eq}$/cm^2.

3 1E CNM + 1 2E SINTEF sensors were irradiated at the CERN IRRAD Proton Facility with 24 GeV protons to fluences of 1x10^{15} and 3x10^{15} n$_{eq}$/cm^2 and tested in a beam at FNAL.

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







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 September.

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
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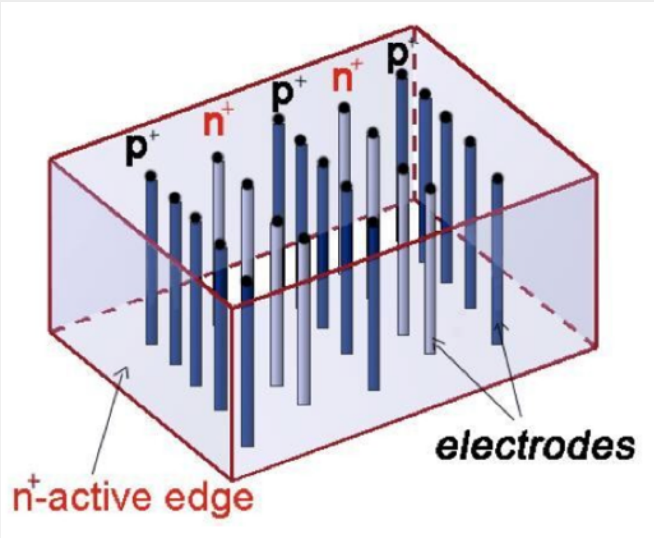
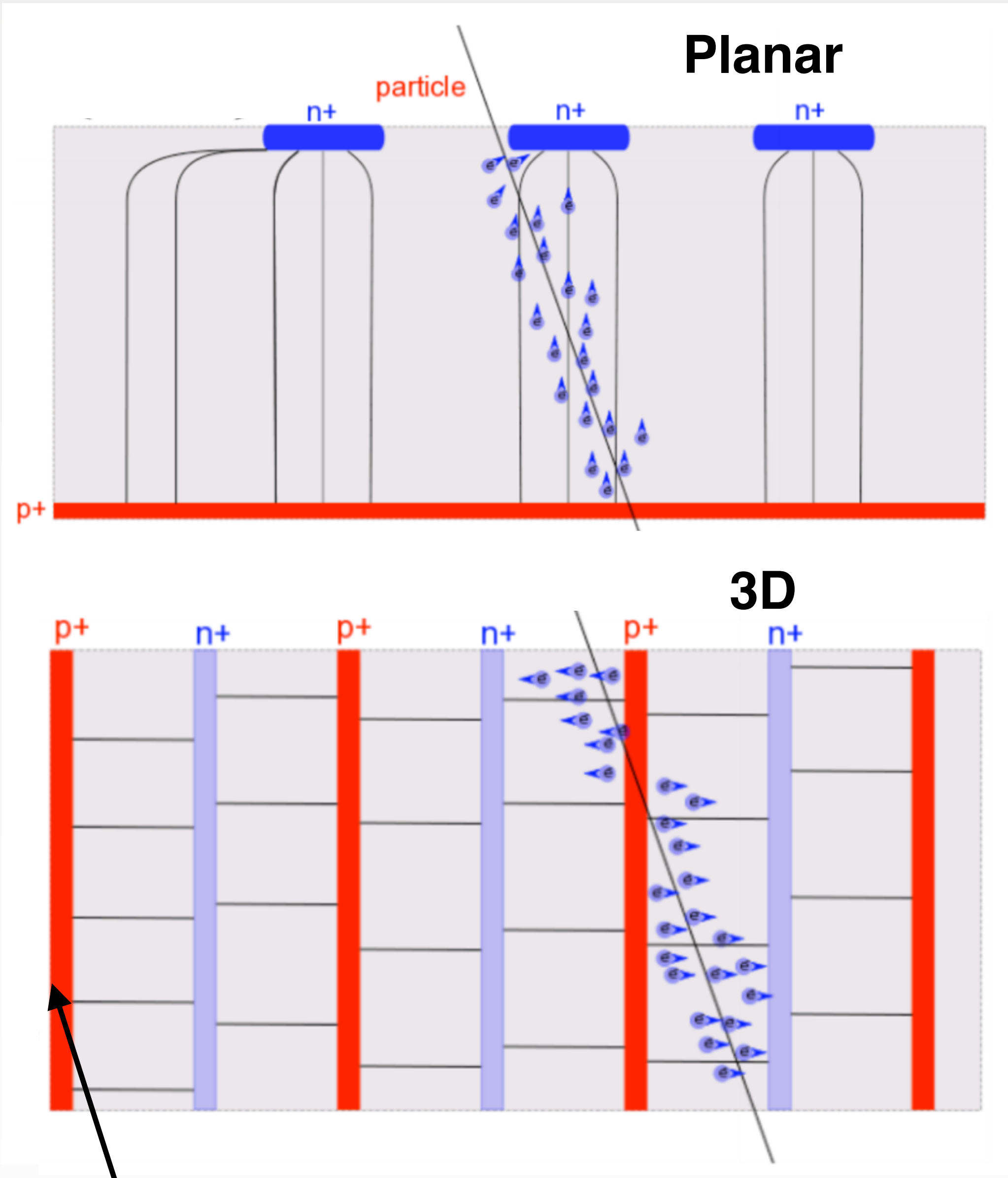
- SINTEF group: T.-E. Hansen, A. Kok, O. Koybasi, M. Povoli, A. Summanwar
- Irradiation at the CERN IRRAD Proton Facility: F. Ravotti, A. Junkes

Backup

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 ~ 5 μm and the distance between electrodes varies from 100 μm to 50 μm depending on the number of readout electrodes per pixel cell

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

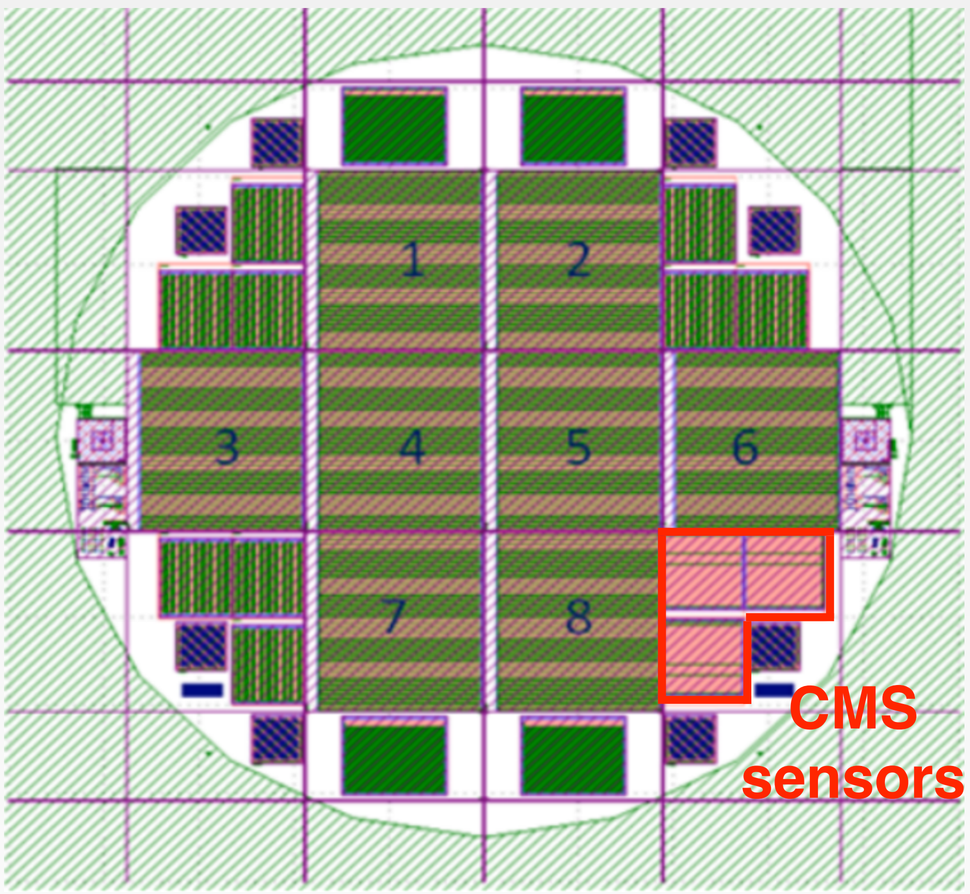
- Lower depletion voltage.
- Faster charge collection.
- Higher radiation hardness.

Disadvantages:

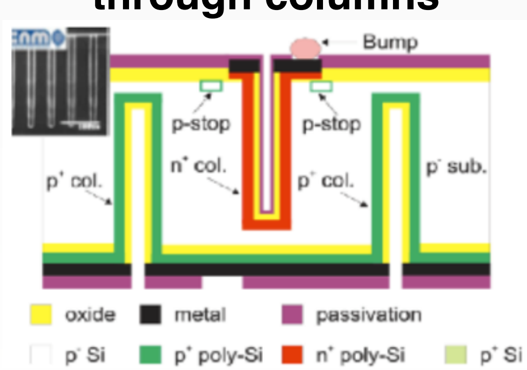
- Complex technology.
- Higher capacitance.

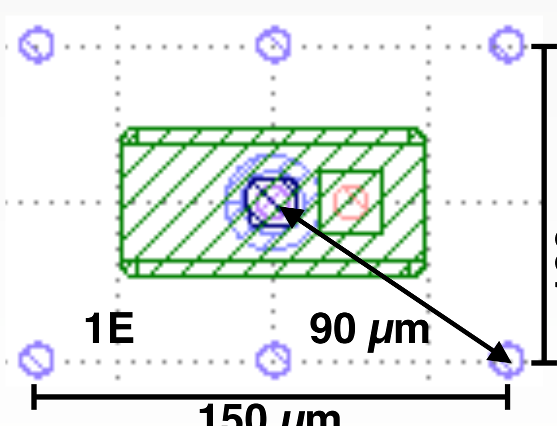
Tested CNM and SINTEF 3D sensors

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)

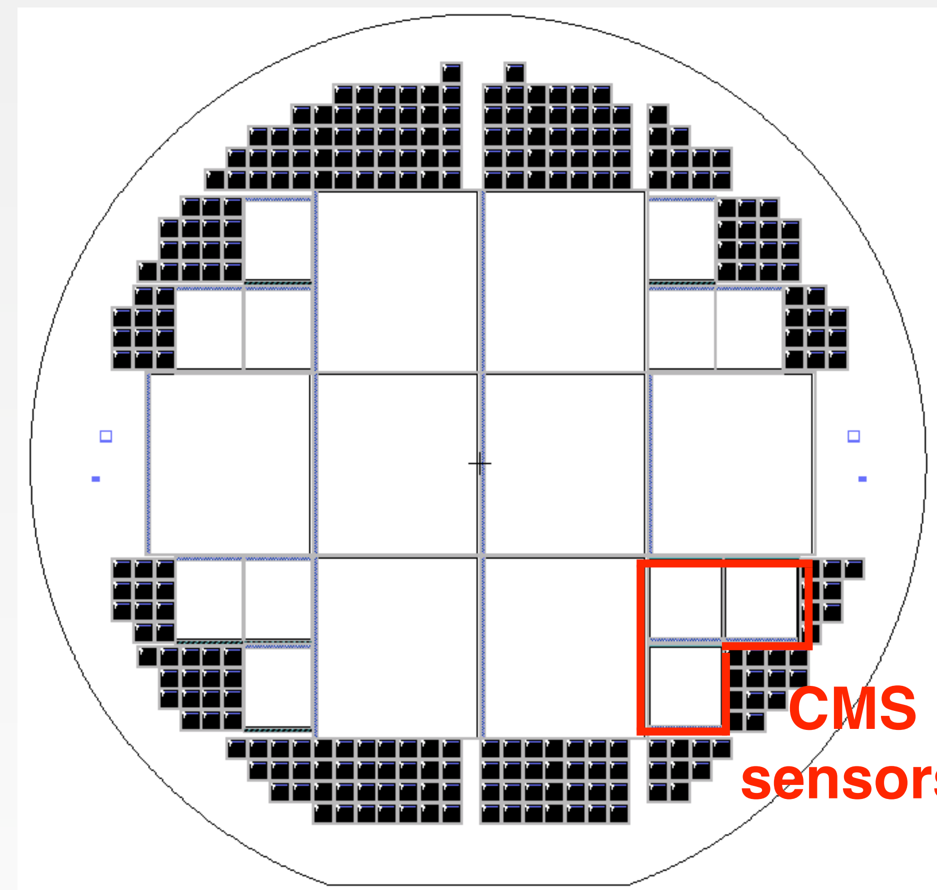


Double side not passing through columns

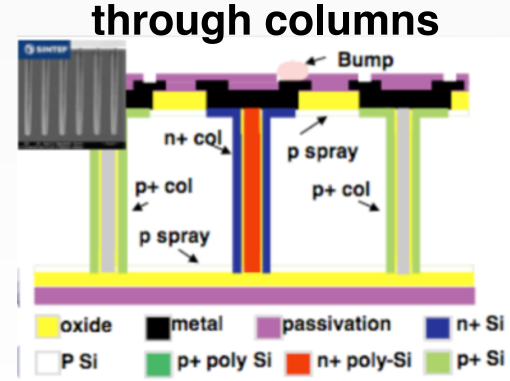


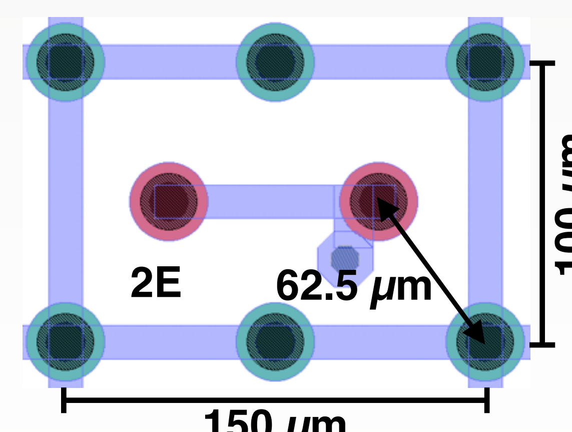


SINTEF Sensors
Wafer thickness = 200 µm
Support wafer not removed
Active edge 87 um larger than the last n+ column on 3 edges, much larger to host bias pad on left edge

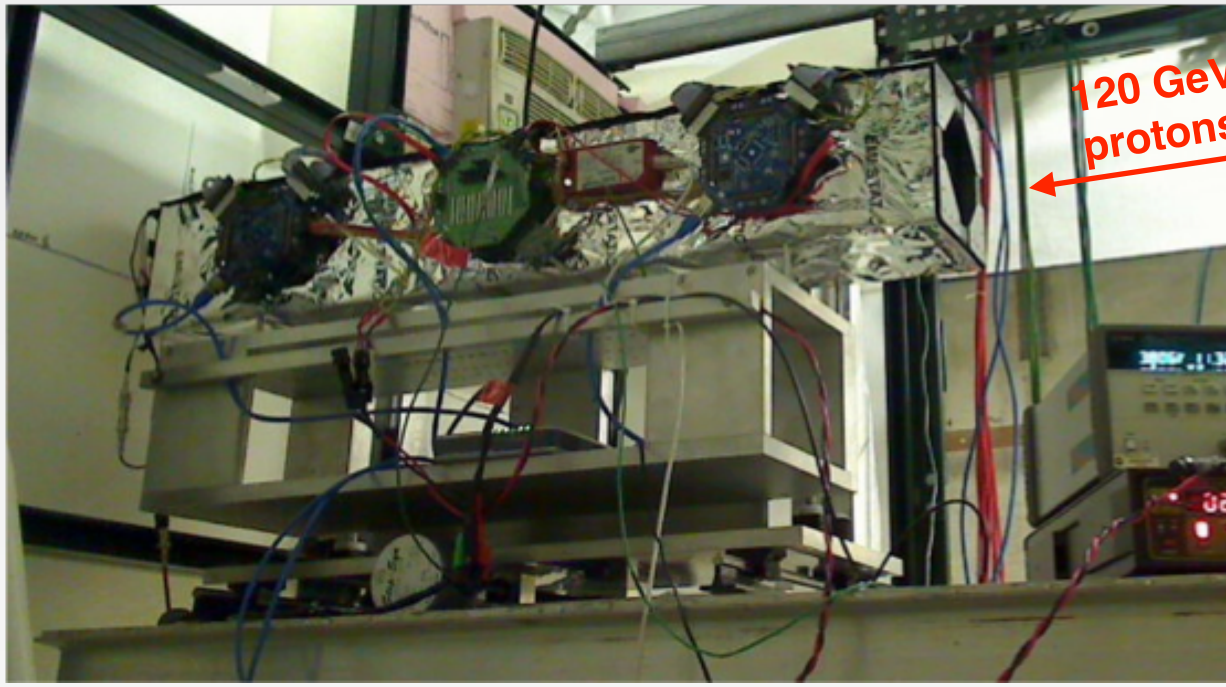


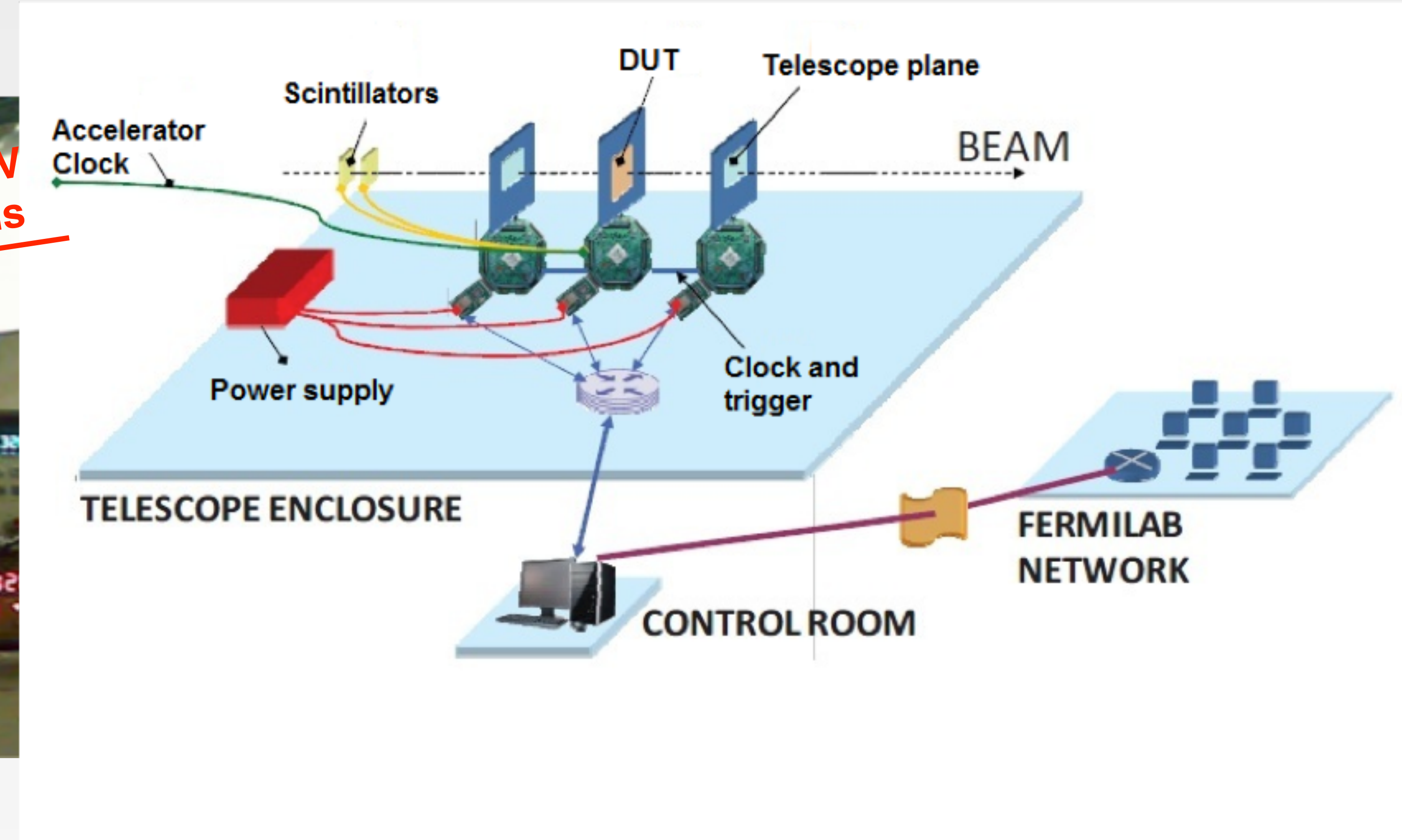
Single sided full passing through columns



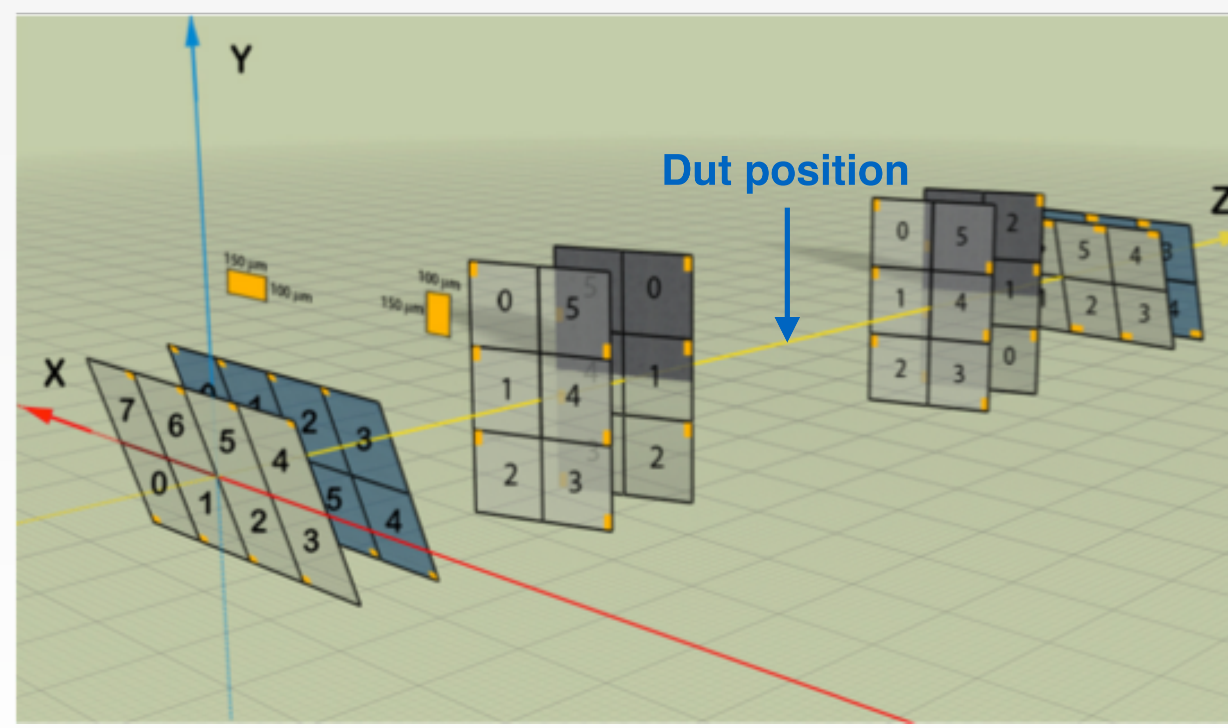


Testbeam at FNAL (T992 collaboration)



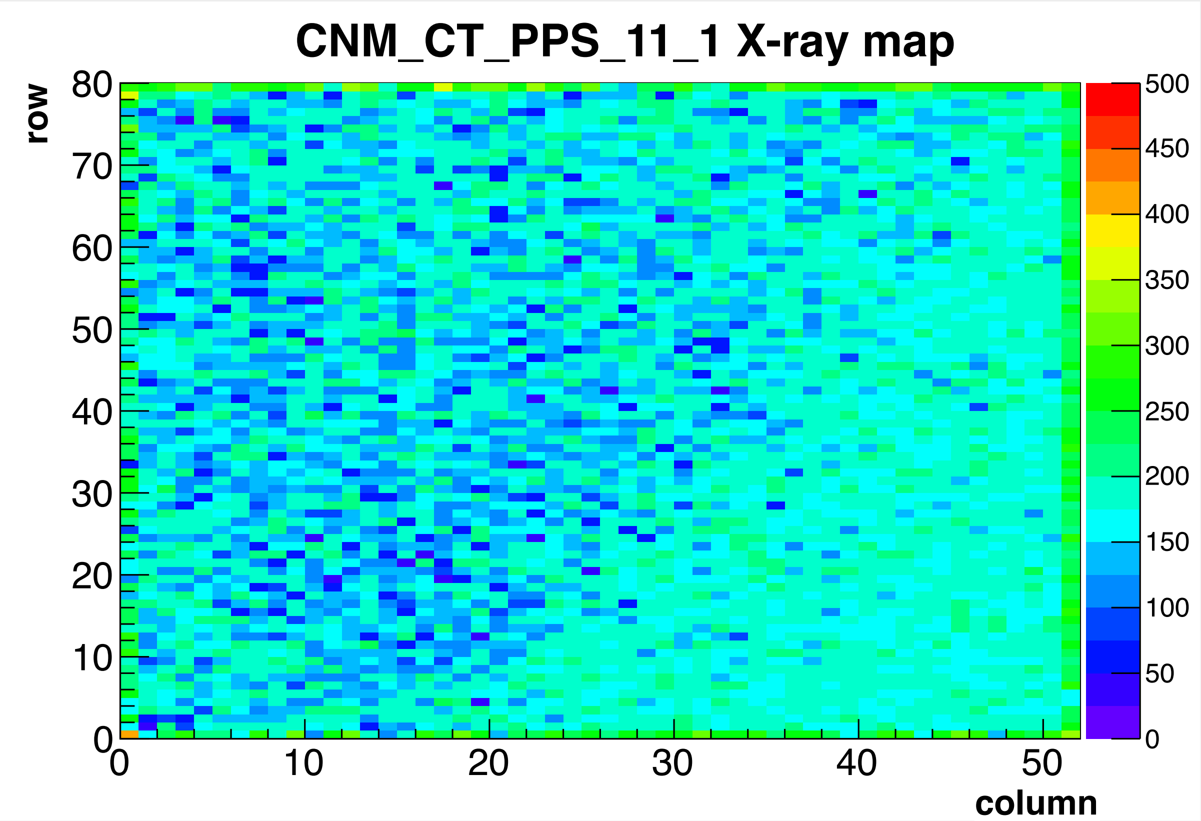


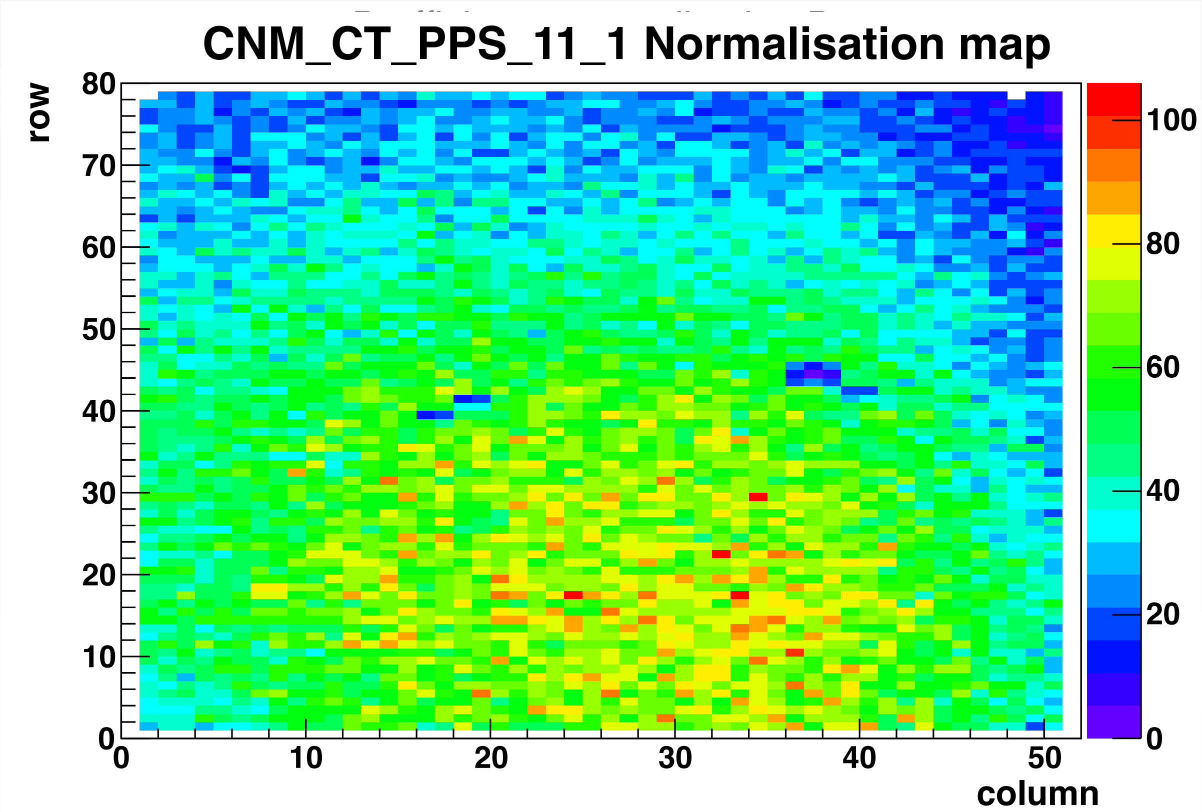
- **8 telescope planes** of CMS pixel modules (pixel size 100x150 μm^2), 4 upstream and 4 downstream with respect to the DUTs
- Telescope planes rotated of 25° with respect to 100 μm pixel pitch direction for improving **resolution to 8 μm**
- Rotation and cooling systems for the DUTs provided by Purdue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

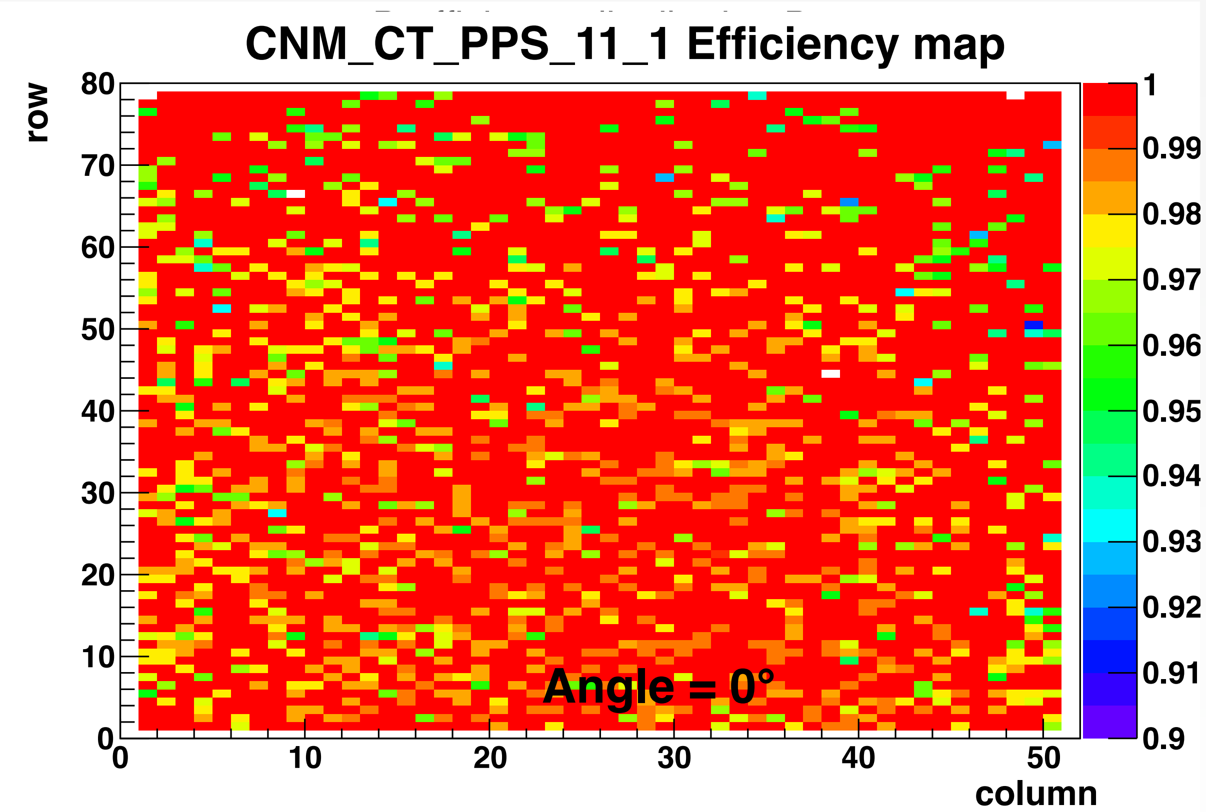


X-ray vs efficiency on single ROC

- 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**.

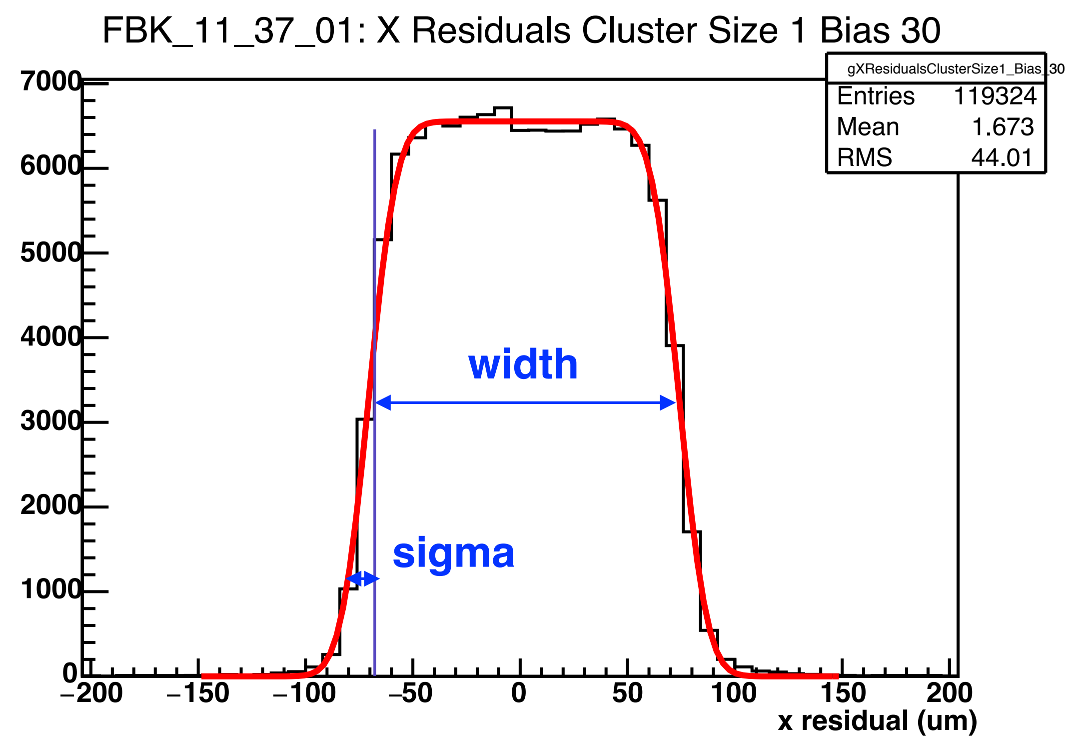


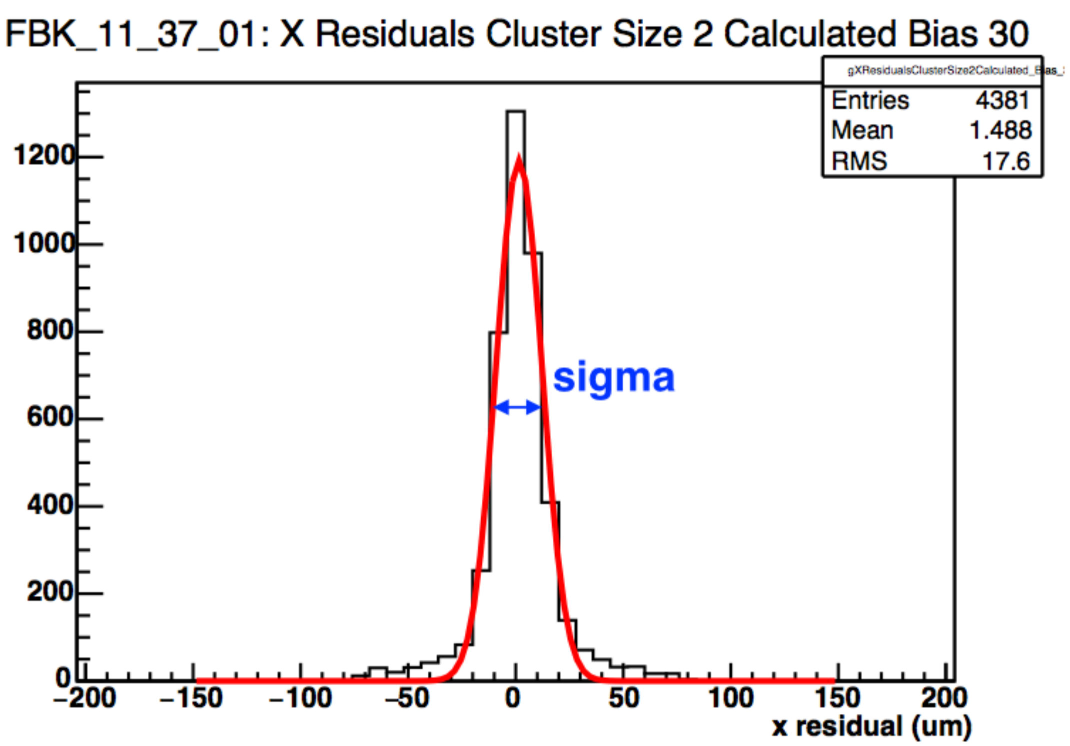




Residuals plots

Preliminary





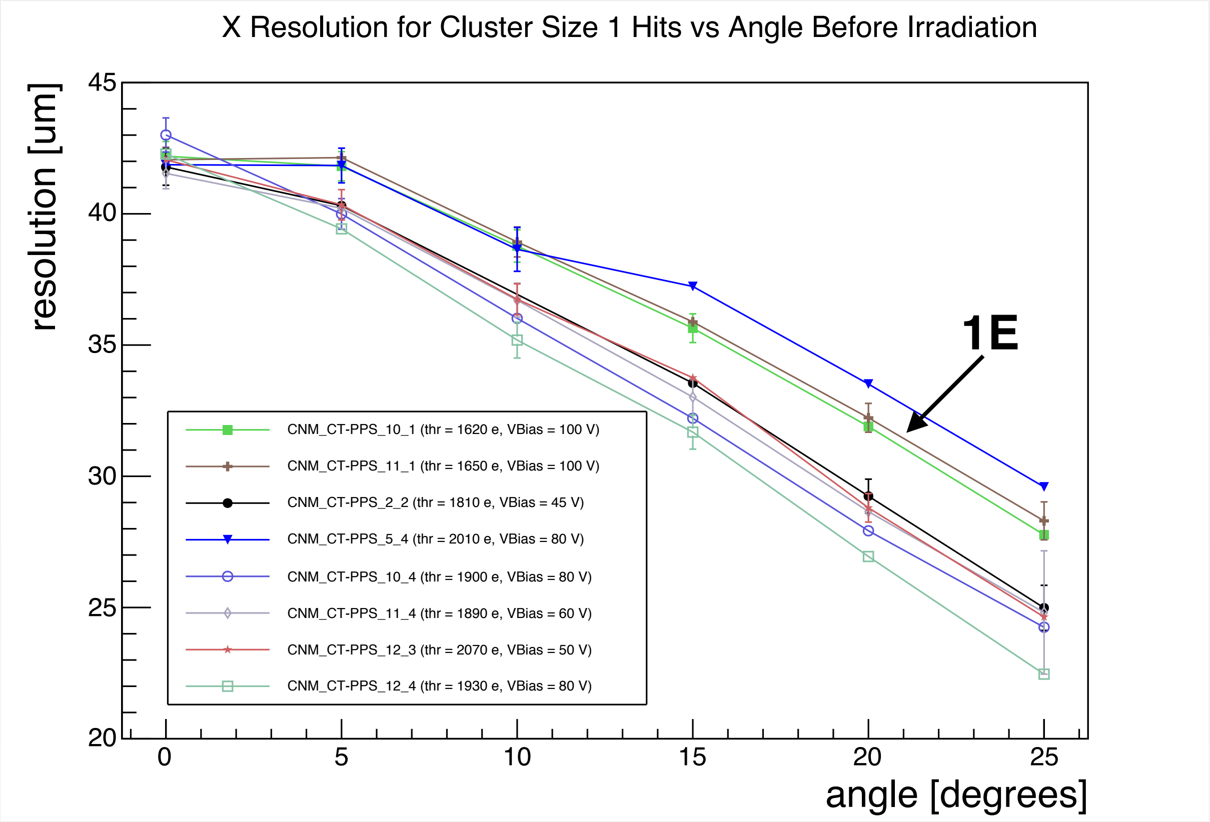
- Residuals cluster size 1 are fitted with a square function convoluted with a gaussian.
- Residuals cluster size 2 "Calculated" are evaluated by the charge asymmetry and fitted with a gaussian.

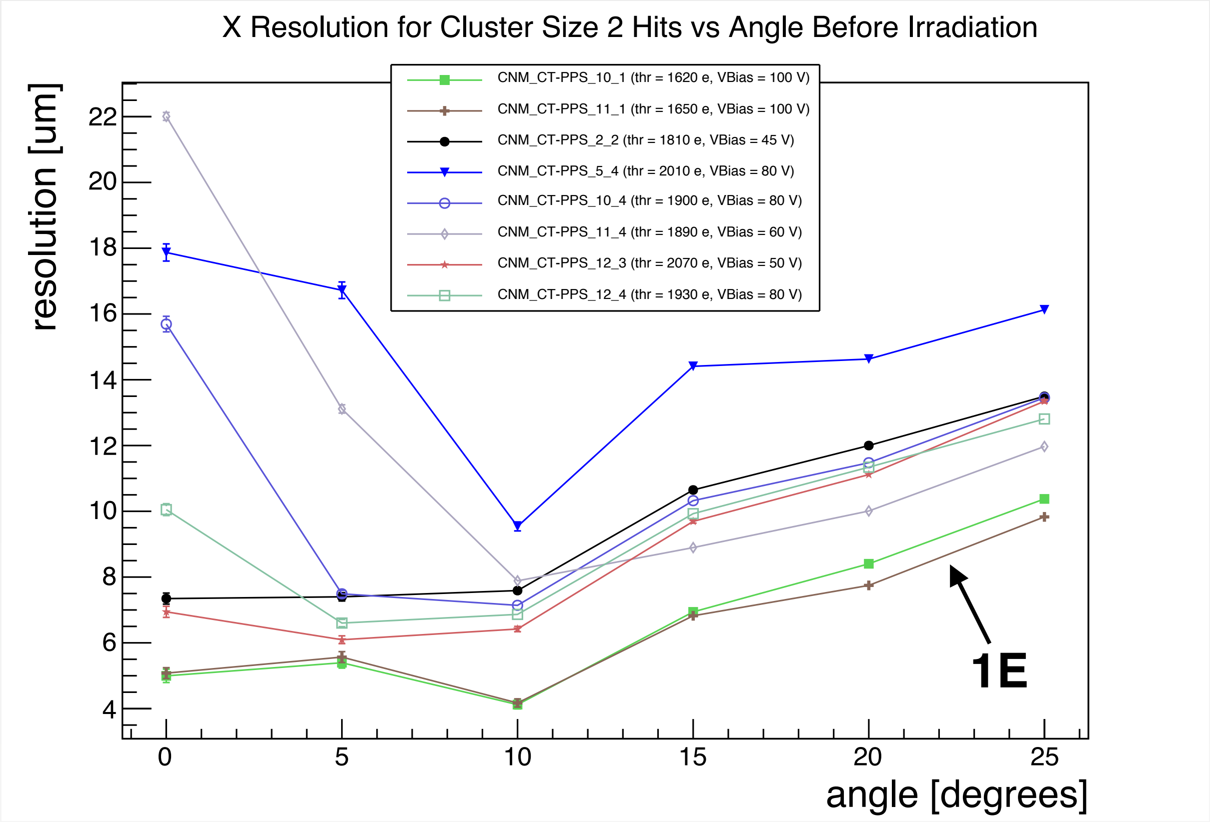
$$\sigma_{\mathrm{CS1}} = \sqrt{\left(\frac{width_{\mathrm{CS1}}}{\sqrt{12}}\right)^2 + sigma^2_{\mathrm{CS1}} - sigma^2_{\mathrm{telescope}}}$$

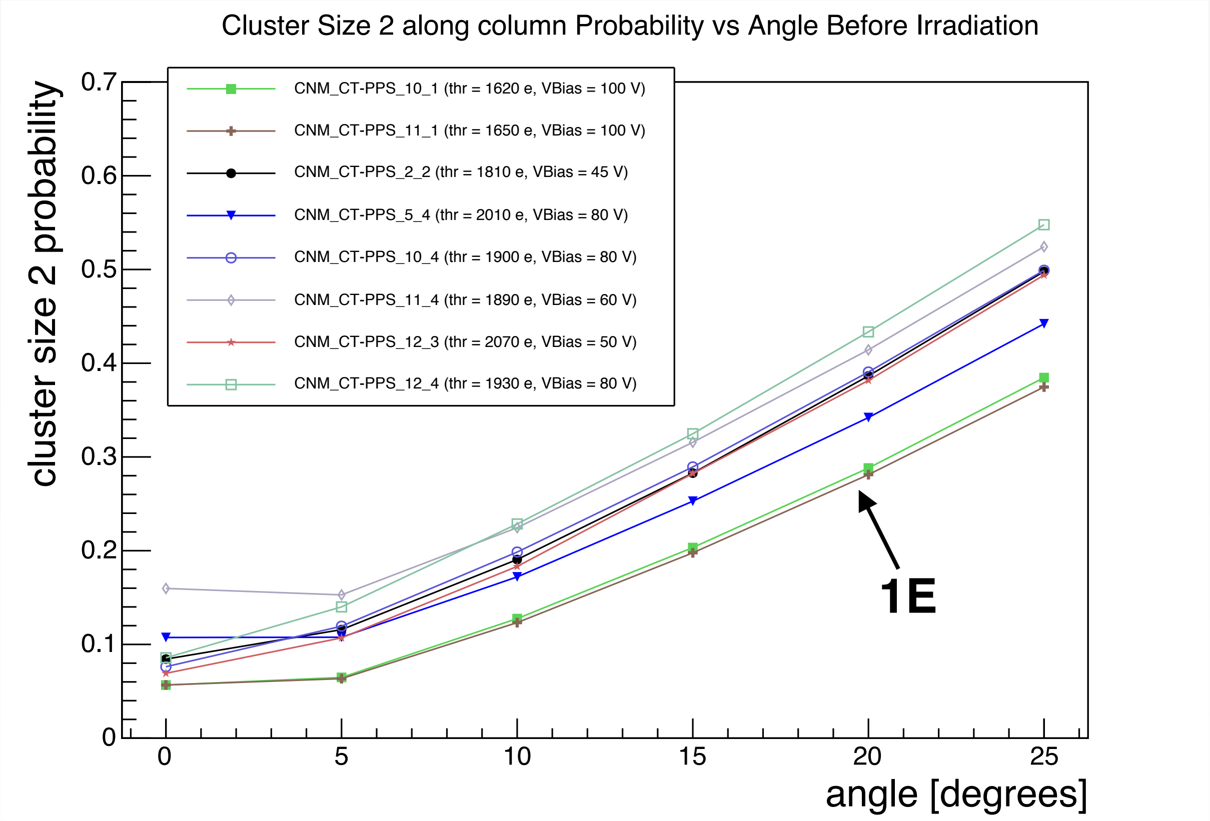
$$\sigma_{\mathrm{CS2}} = \sqrt{sigma^2_{\mathrm{CS2}} - sigma^2_{\mathrm{telescope}}}$$

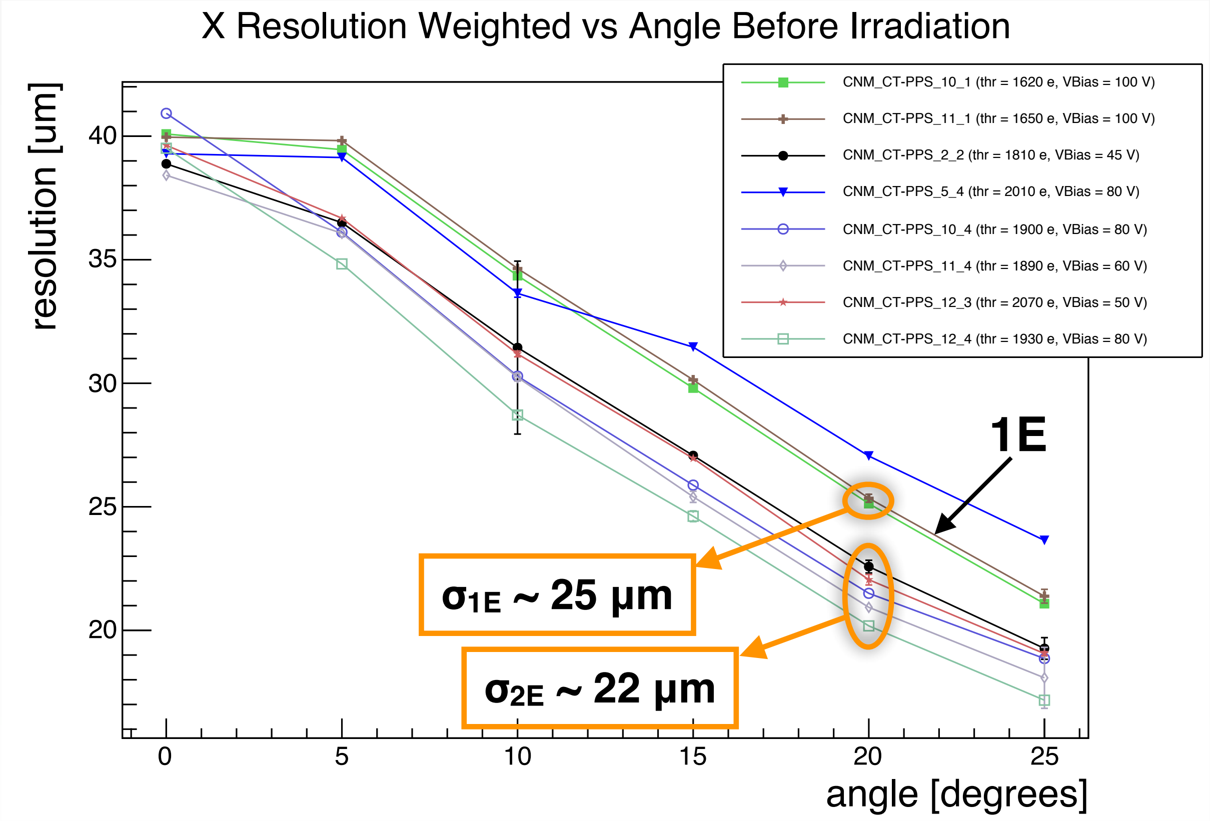
Resolution vs angle

Preliminary









Specification to qualify the devices

Define: Vop = Vdepl +10V where Vdepl and Vop are respectively the full depletion and operation voltages.

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

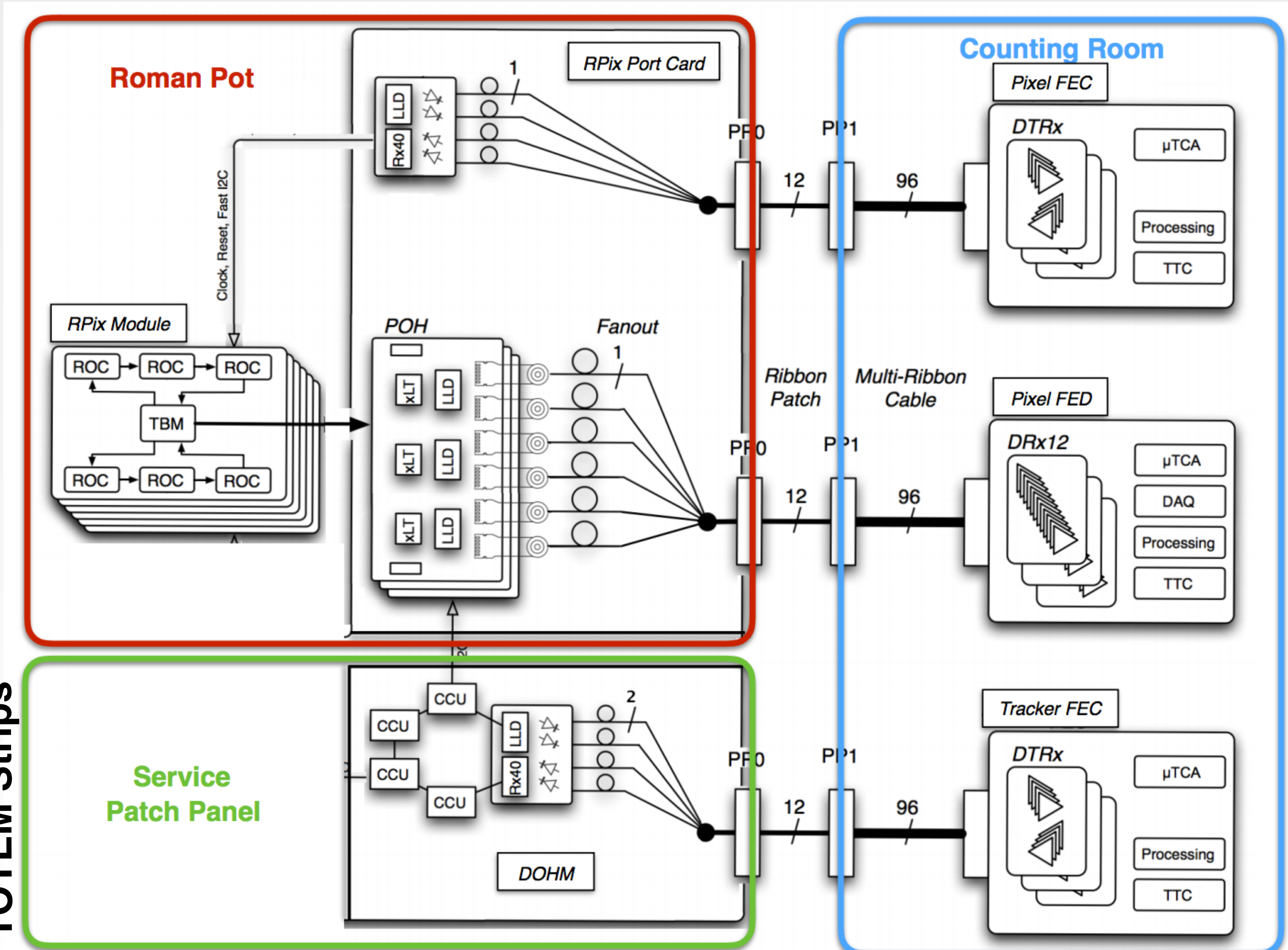
- **Vdepl < 20 V**
- Breakdown voltage: **Vbd > 35 V**
- **[I(25V)/I(20V)] < 2**
- Current at operation voltage:

  Class A I (Voperation) < 2uA per tile → very good

  Class B 2uA < I (Voperation) < 10uA per tile → good enough

  Class C I (Voperation) > 10uA per tile

Tracker readout system



CT-PPS custom design

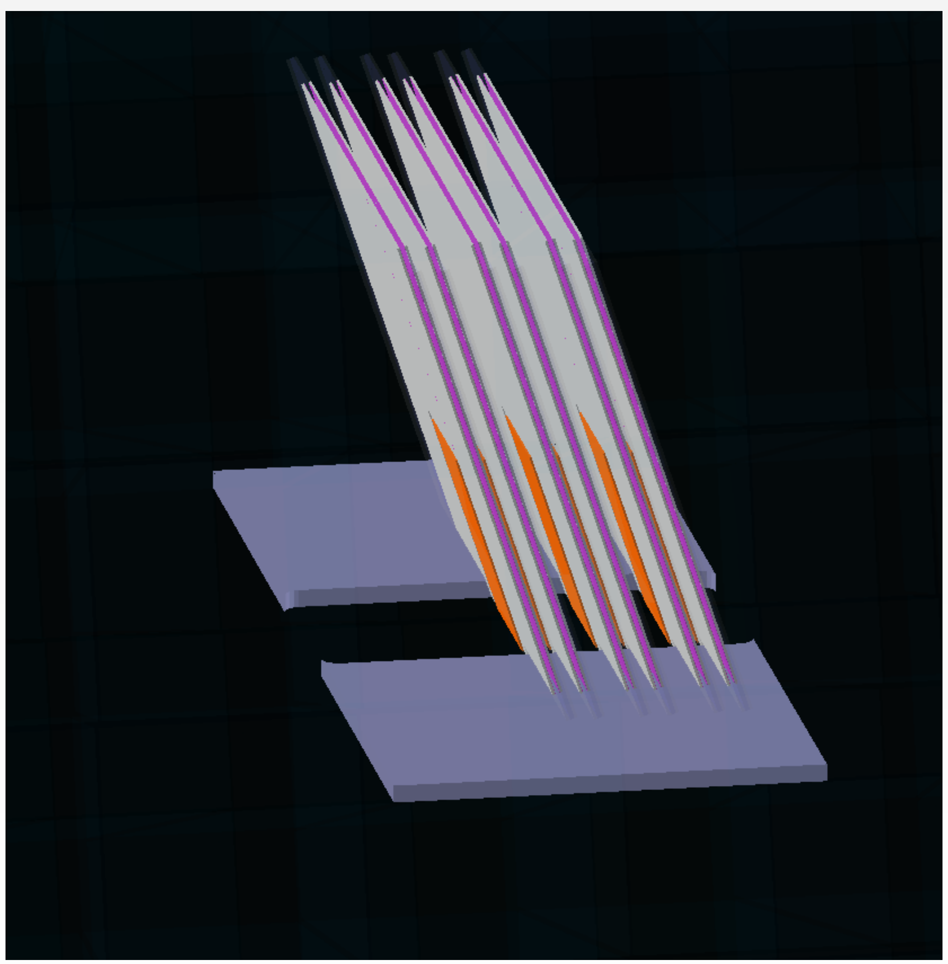
Already used for TOTEM Strips

From CMS Phase I pixel Upgrade

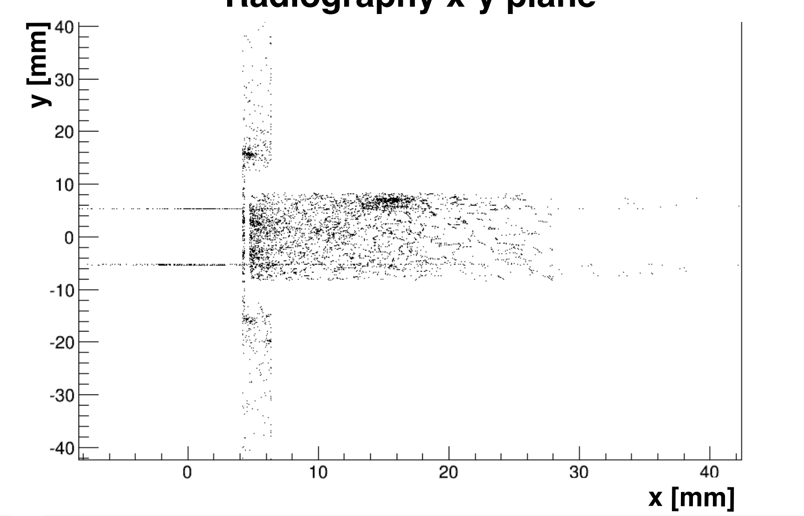
Tracker simulation

- **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.

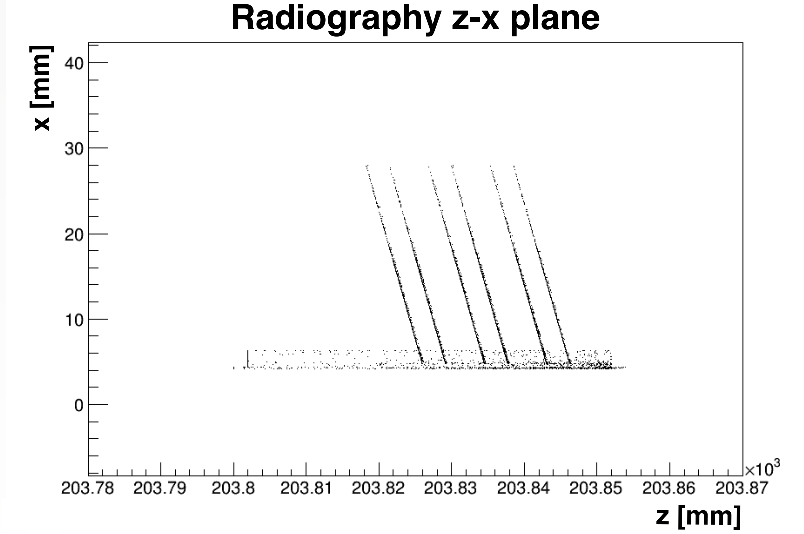
Fireworks



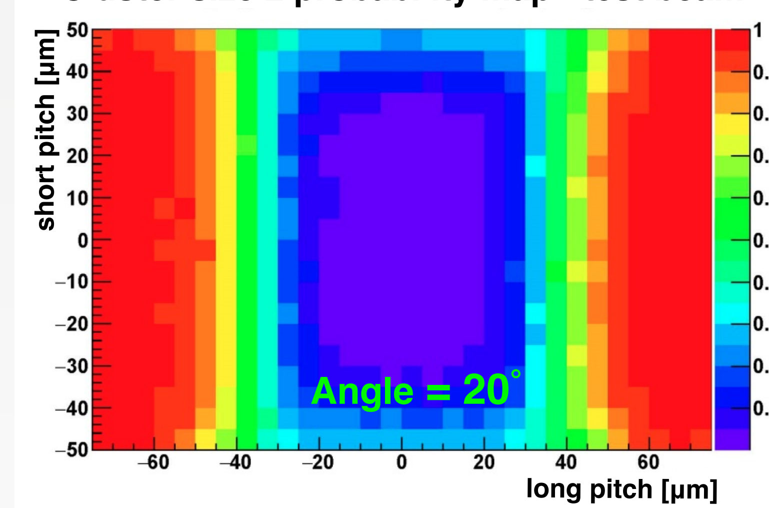
Radiography x-y plane



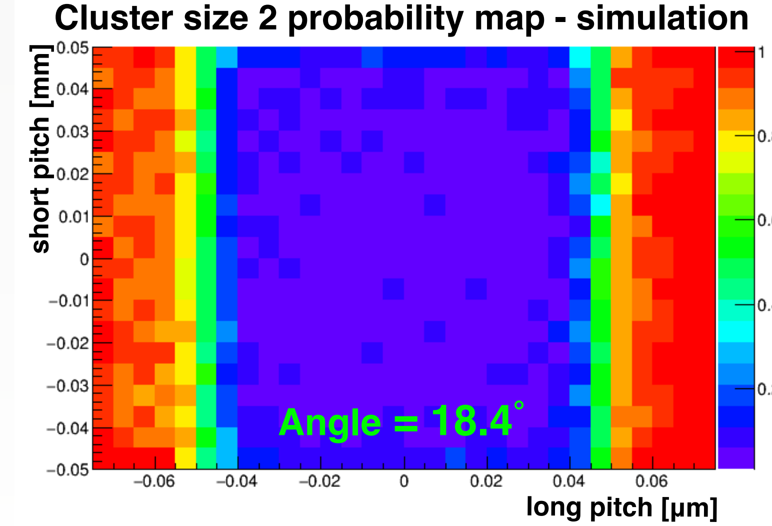
Radiography z-x plane



Cluster size 2 probability map - test beam

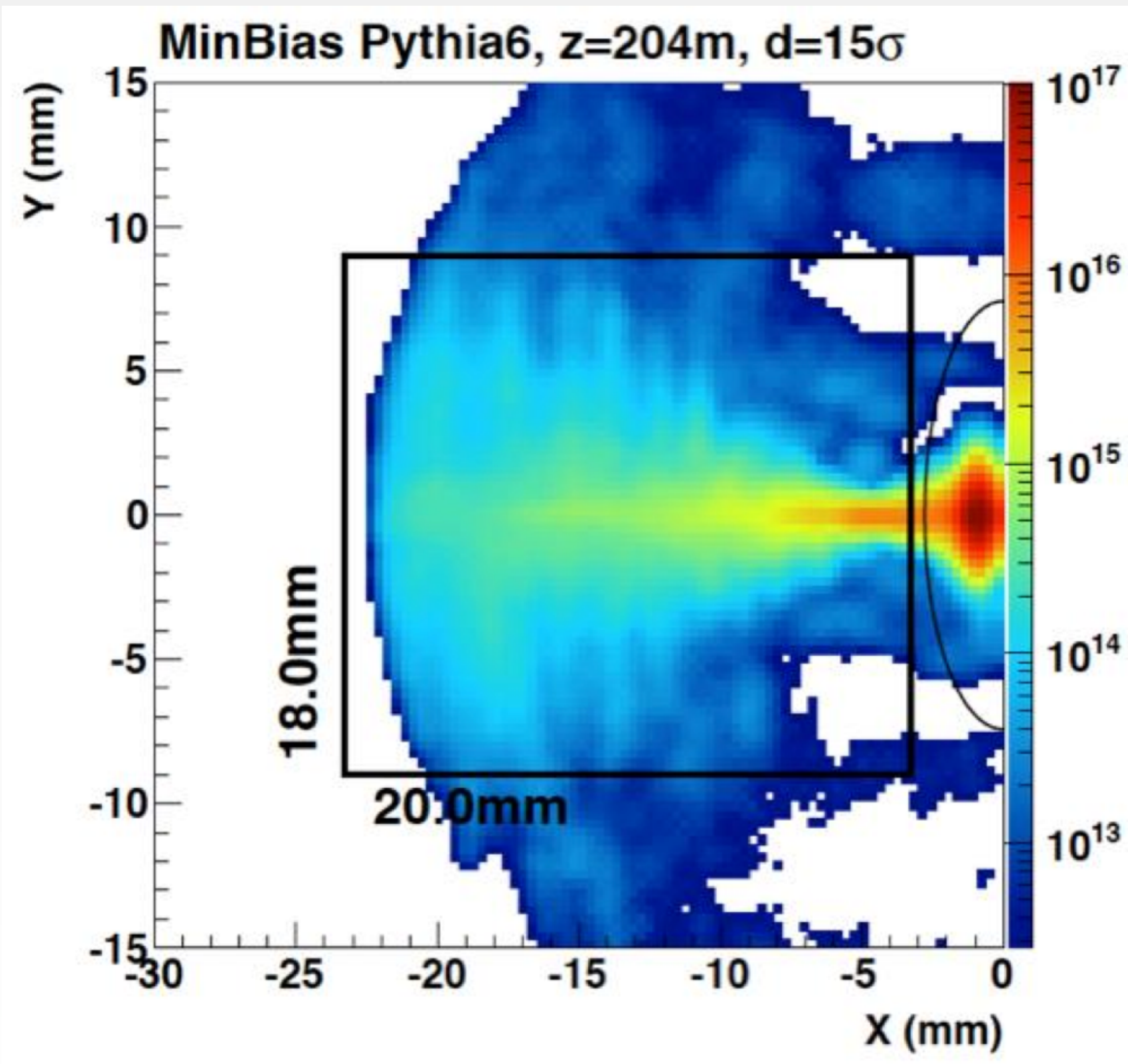


Cluster size 2 probability map - simulation



Radiation level

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



Per 100 fb^{-1}:

- Proton flux up to $5x10^{15}$ cm^{-2} in the pixel detectors
- 10^{12} neq/cm^2 and 100 Gy in photosensors and readout electronics