TREDI 2017

The CT-PPS tracking system with 3D pixel detectors

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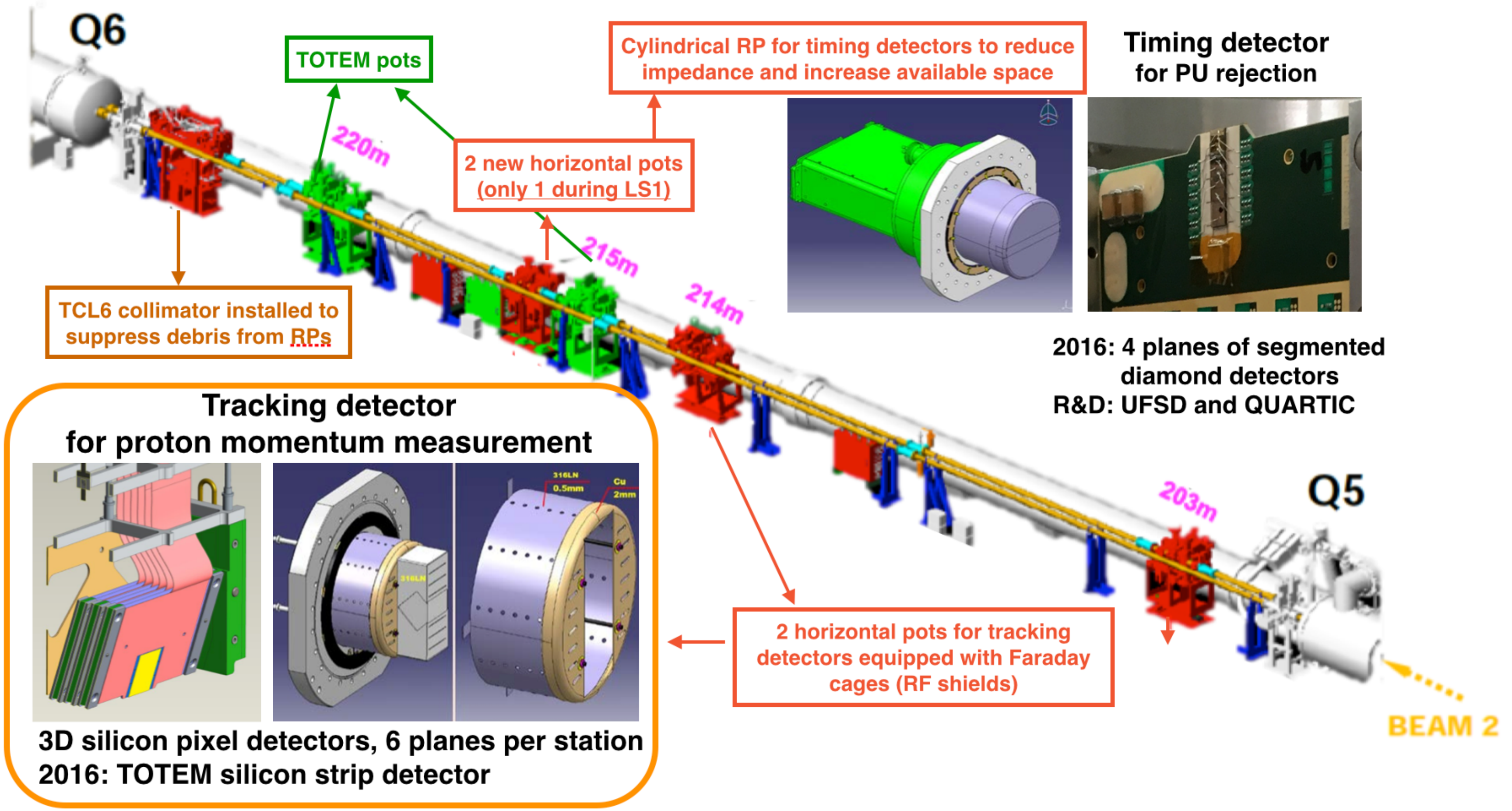
On behalf of the CMS and TOTEM Collaborations

CMS-TOTEM
Precision Proton Spectrometer

- The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS) allows measurement of **protons in the very forward regions** on both sides of CMS in **standard LHC running conditions**, taking advantage of the machine magnets to bend protons
- **Tracking and timing detectors** are placed in Roman pots between 205 and 220 m from the CMS/TOTEM IP, two stations for each detector on both sides

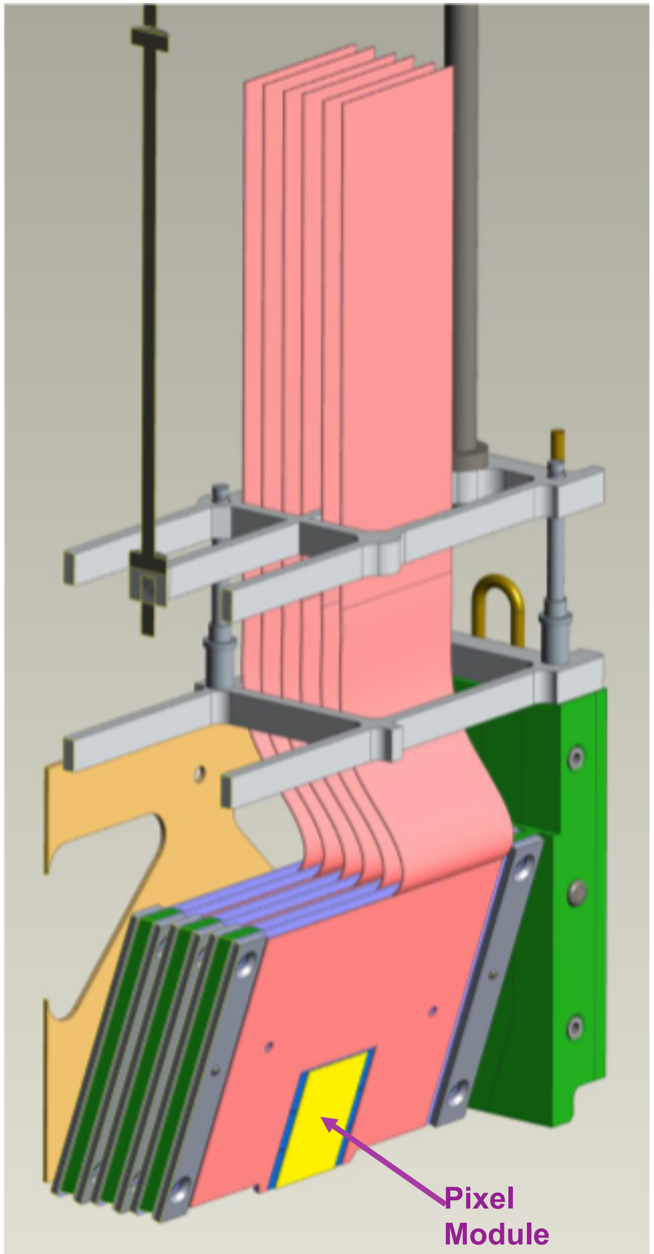


Tracking system

- **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**.

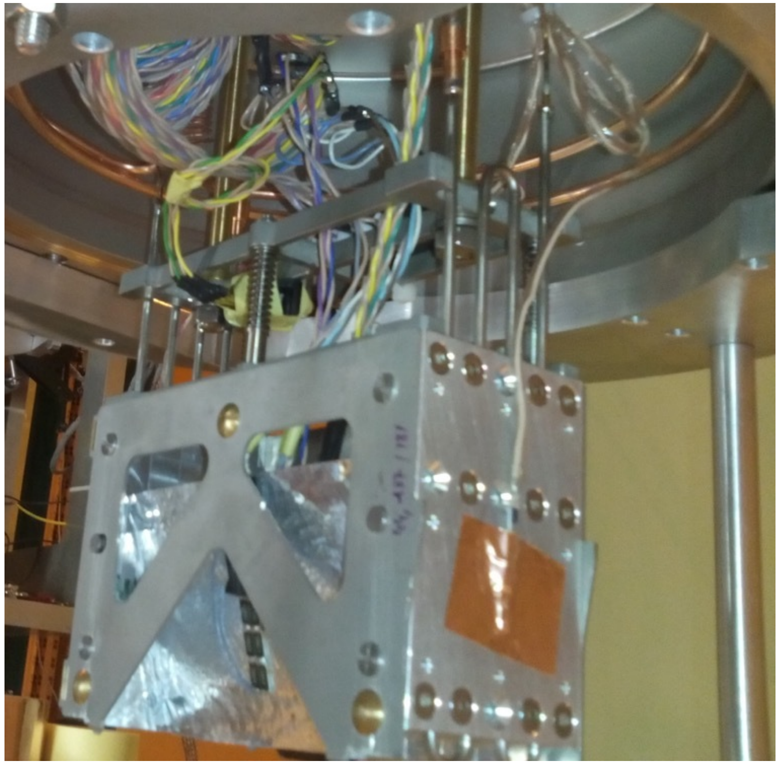
- **Baseline design**:
  - **3D sensor** technology chosen for its intrinsic high **radiation hardness** and the possibility to implement **slim edges**.
  - **Two stations per side, each with 6 detector planes tilted by 18.4°** to increase the cluster size and **improve resolution**.
  - **Readout chip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

Tracking detector - Mechanics

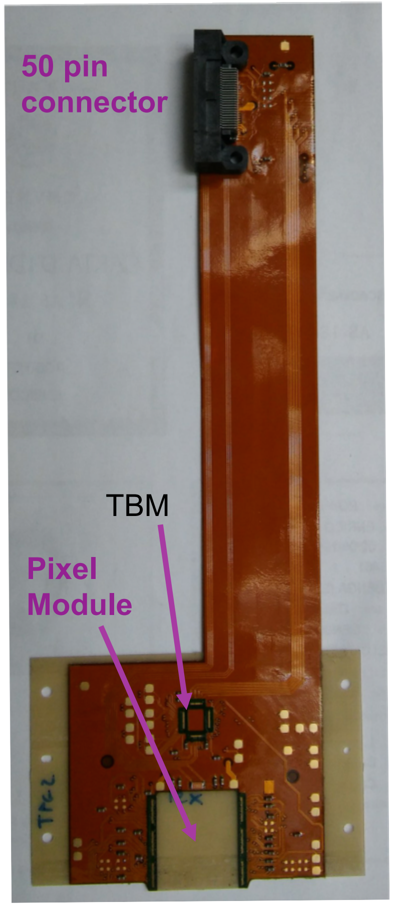


- 6 detector planes per pot.
- Al support structures produced in Genova.
- Detector heat dissipation provided by a TPG layer encapsulated in a thin aluminium layer connected to a cooling system identical to the TOTEM one.
- **Cooling tests showed heat dissipation according to requirements**.

Cooling test setup

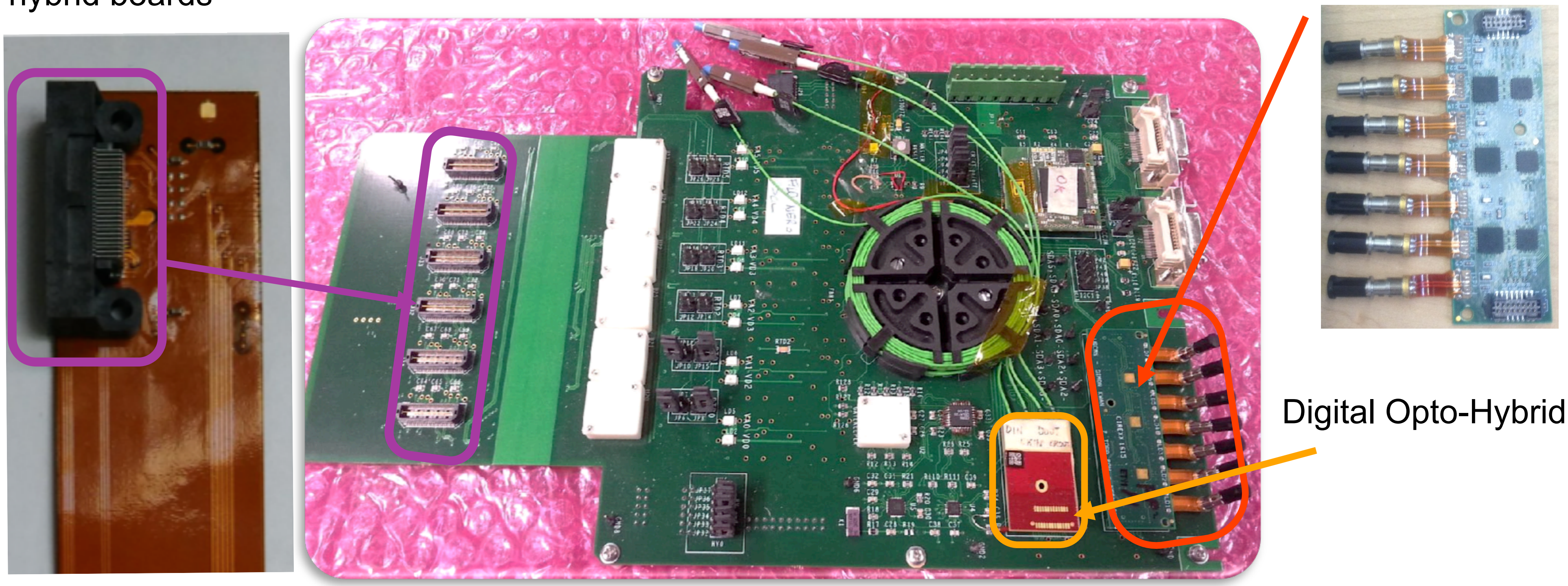


Flex hybrid



Tracking detector - Electronics

- **RPix Port Card is custom designed for CT-PPS to interface the tracking station to the readout electronics**.
- Concept: TOTEM board (to fit the RP space constraints) with components as in FPIX readout.
- **Port Card produced and under final test during this week.**



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)

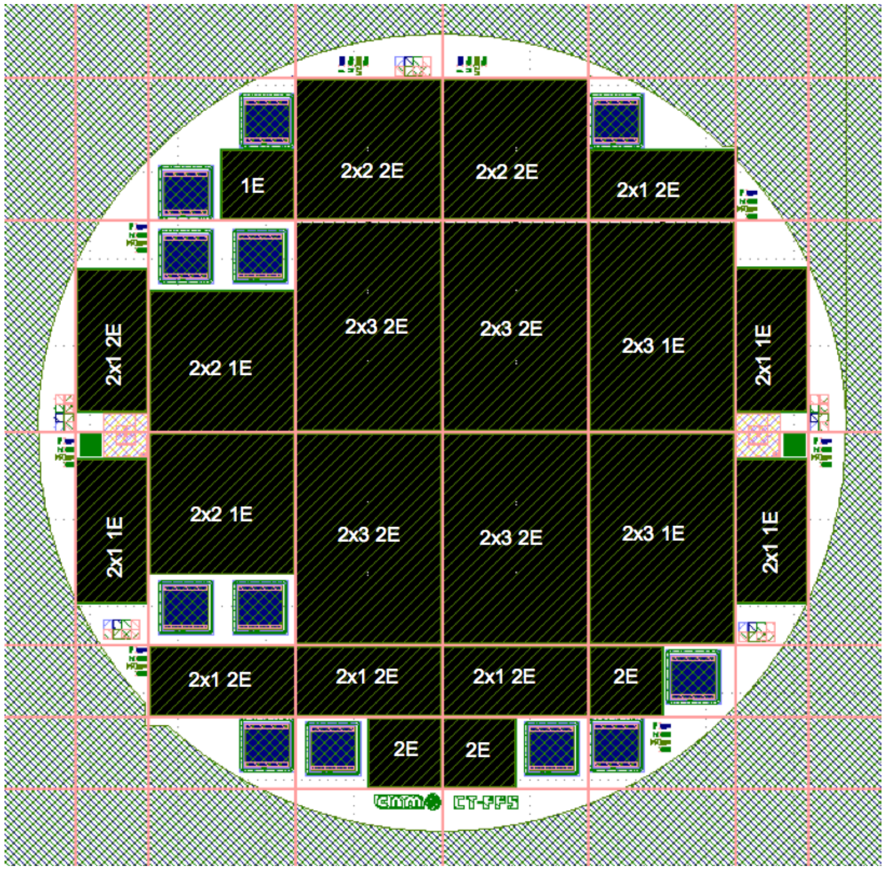
1E and 2x2 sensors also considered for module production.

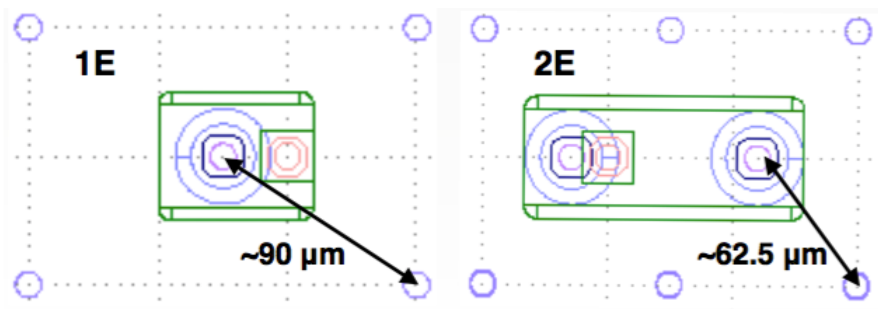
First batch of 3D sensors completed in December 2015.
In general good quality sensors but low yield, in particular of class A ones.

Second batch completed in May 2016.
A problem, probably with the p-stop implantation done by an external firm, caused values of breakdown voltage too low for using the sensors. In order to recover the production, a low-dose neutron irradiation (~5×10^{13} n_{eq}/cm^2) + annealing has been tried with promising results.

Third batch almost completed (March)

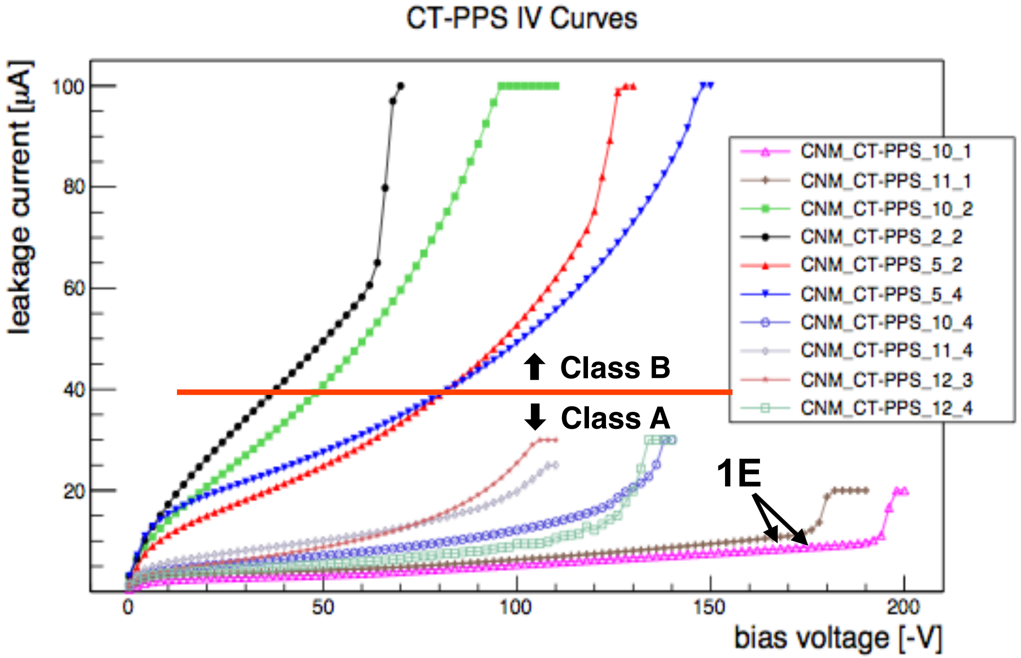
36 wafers produced at CNM





Module production and tests

- 3D sensor **IV curves** measured at CNM on wafer **using a temporary metal deposition**. Classification and selection of sensors based on these results.
- **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-planes package.
- **Test at SPS H8 beam-line for final validation** inside a Roman Pot with cooling and secondary vacuum.

Module testing

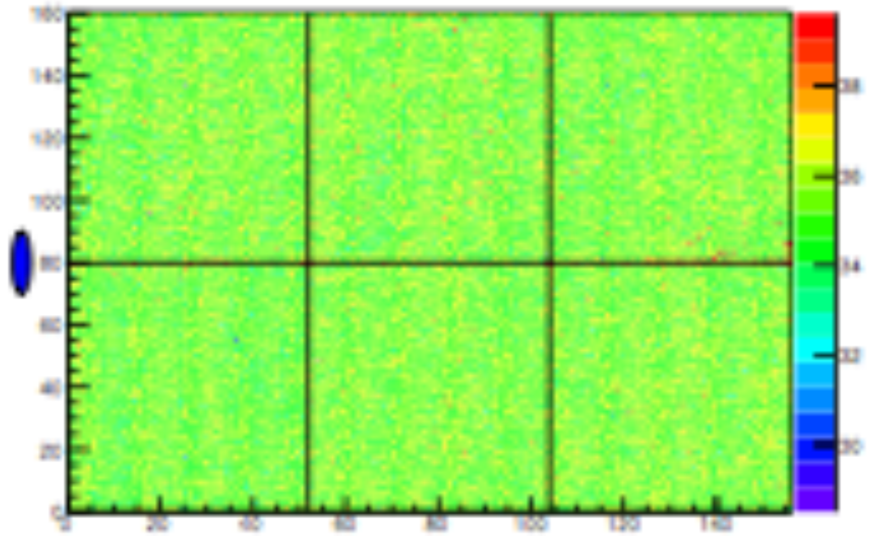
Detectors characterised and optimised in Torino and Genova laboratory:

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

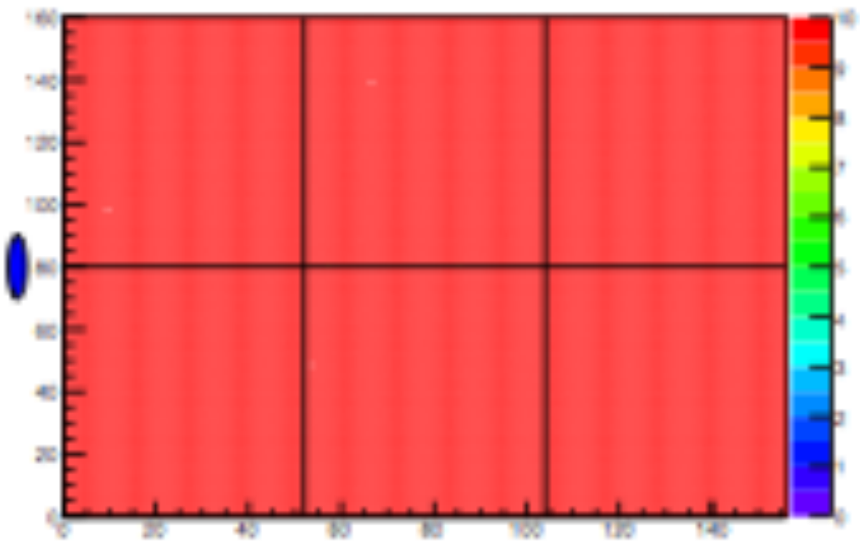
No damage due to flip-chip observed, based on sensor IV curve comparison and ROC performance before and after bump-bonding

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

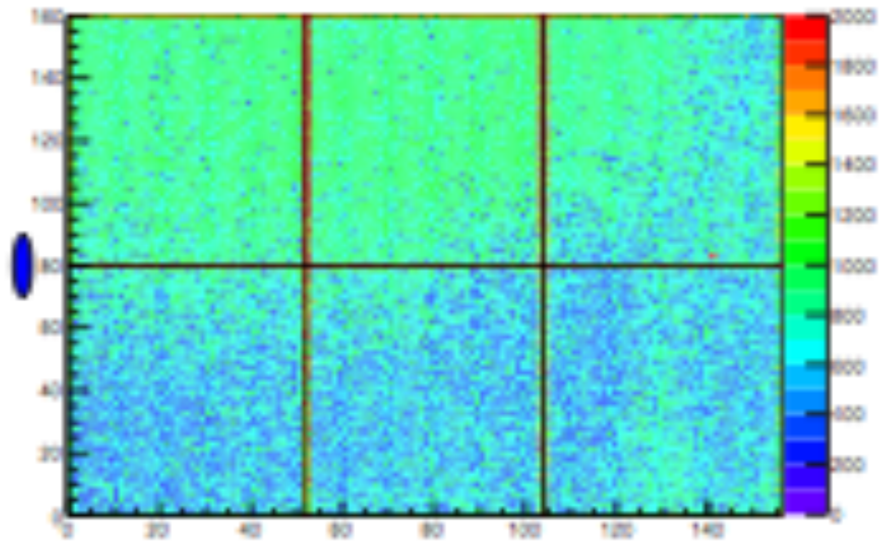
Module Trimmed Threshold Map



Module Pixel Alive



Module X-ray Map



Final modules

Summary of sensors used for the module production (from first batch)

24 modules are needed for the tracking stations

Pixel configuration	Class A	Class B	**Class A + B**	**2E + 1E**
3x2 2E	3	10	13	22
3x2 1E	7	2	9	
2x2 2E	4	9	13	24
2x2 1E	6	5	11	
1E (2E): one (two) readout electrode(s) per pixel			**Total**	46

Status of final modules available for assembling:

3x2 modules:
Tested 22/22
Good modules 18/22 (10 2E)

2x2 modules:
Tested 22/24
Good modules 17/22 (8 2E)

Most of the rejected modules broken during handling or wire-bonding at the beginning of the testing campaign.

Beam test - Efficiency

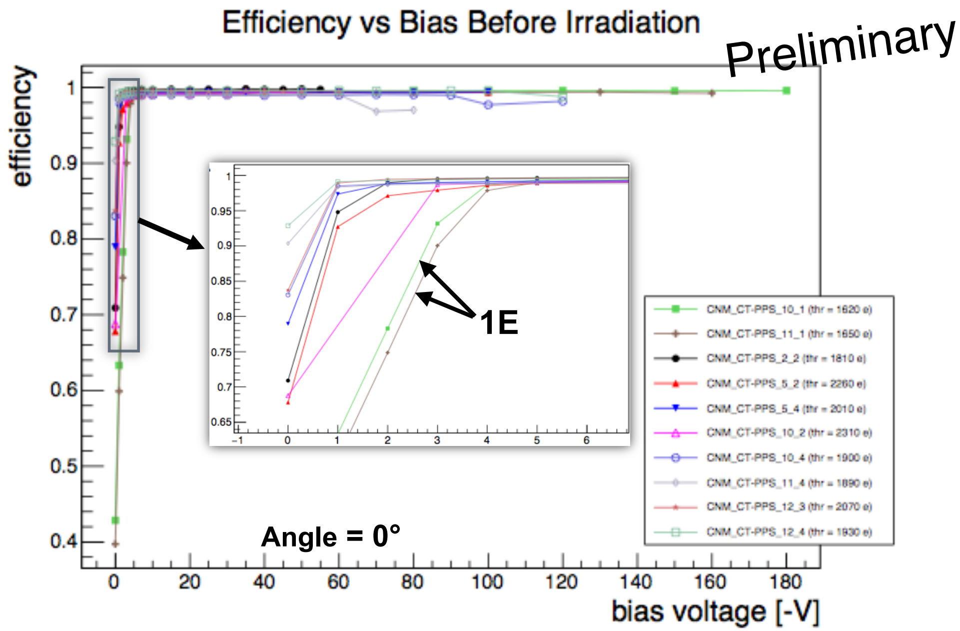
10 single-ROC sensors (**2 1E and 8 2E**) bump-bonded in March at IZM to the CMS Phase I ROC have been **tested at FNAL with 120 GeV protons.**
Sensors selected both of class A and B.

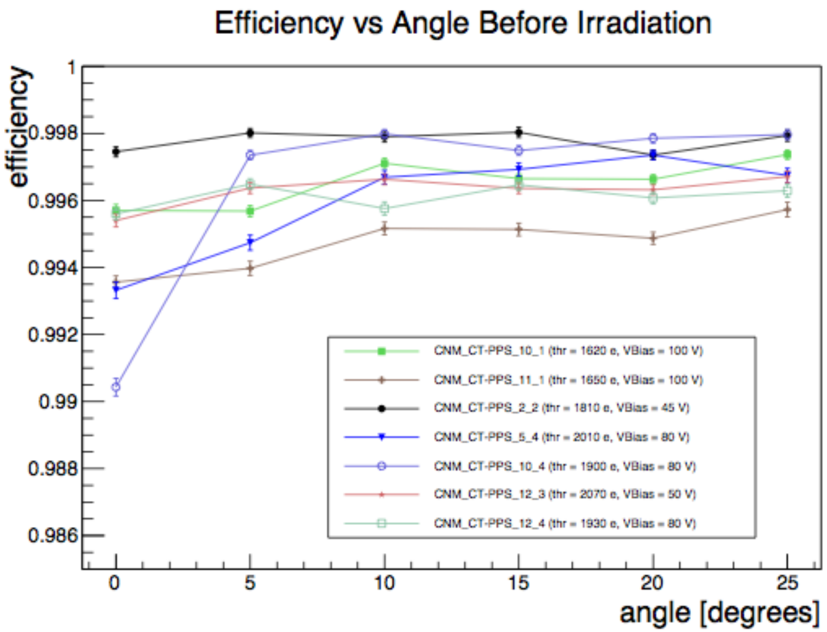
A telescope with 8 planes of CMS silicon pixel detectors allows to reconstruct tracks with a **resolution of 8 μm** in both x and y coordinates.

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.

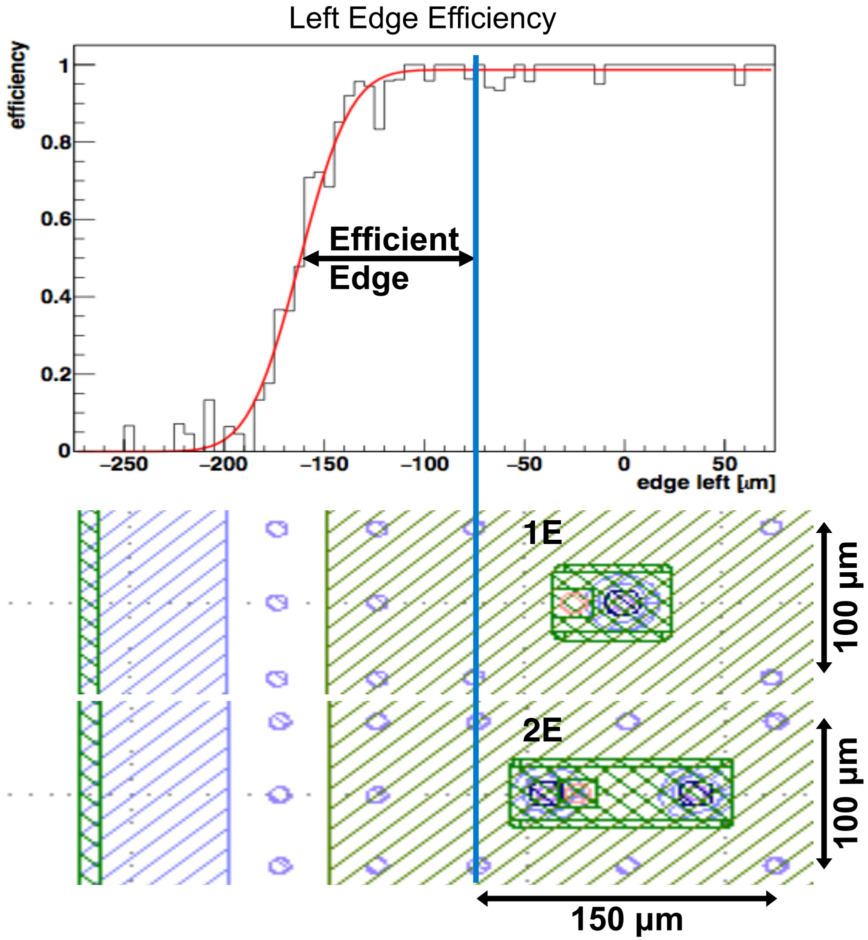
Efficiency greater than 99.4% at 20°.
(CT-PPS tracking detector angle = 18.4°)



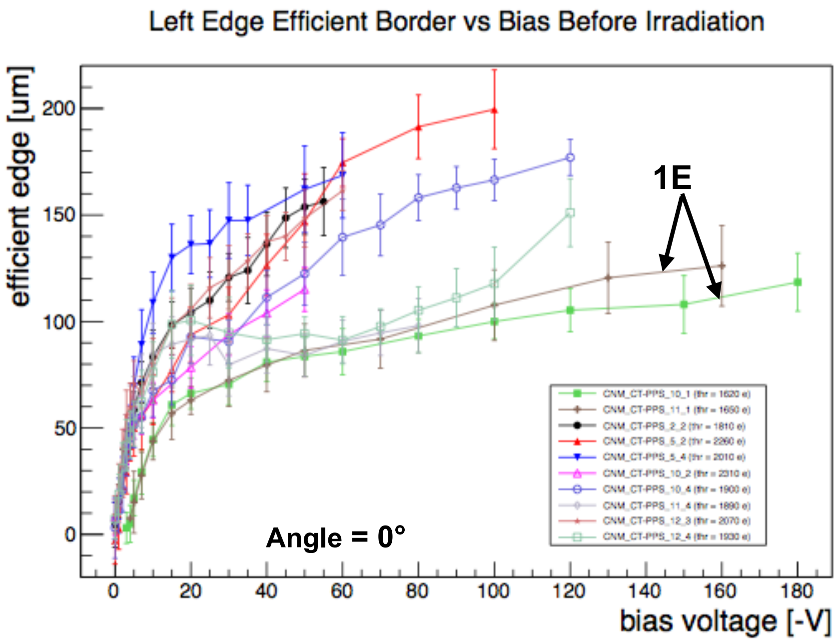


Beam test - Edge efficiency vs bias

Preliminary



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



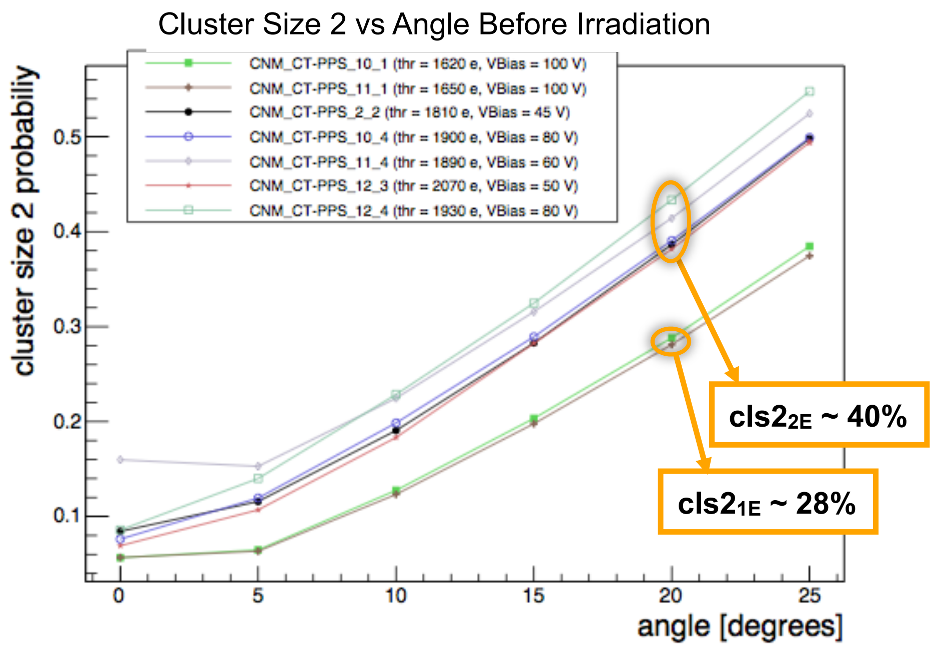
At a bias voltage of 40 V up to 150 μm can be gained at the edge of the sensor with the 2E layout.

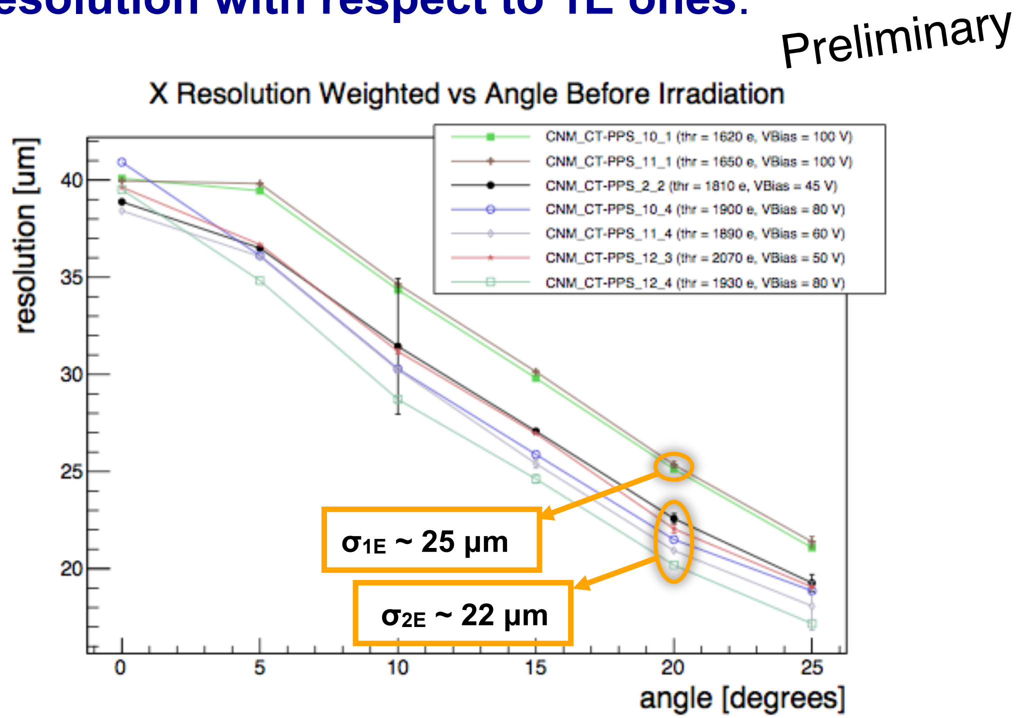
2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n^+-electrode closer to the sensor edge.

Beam test - Resolution vs angle

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**.





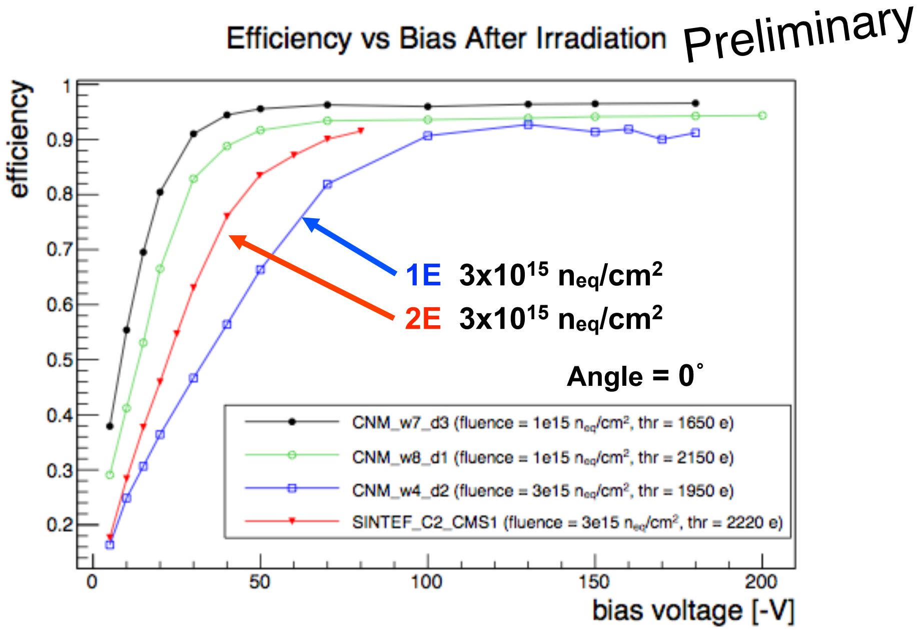
Considering a resolution per single plane between 20 and 25 μm, **the target resolution of ~10 μm can be achieved**.

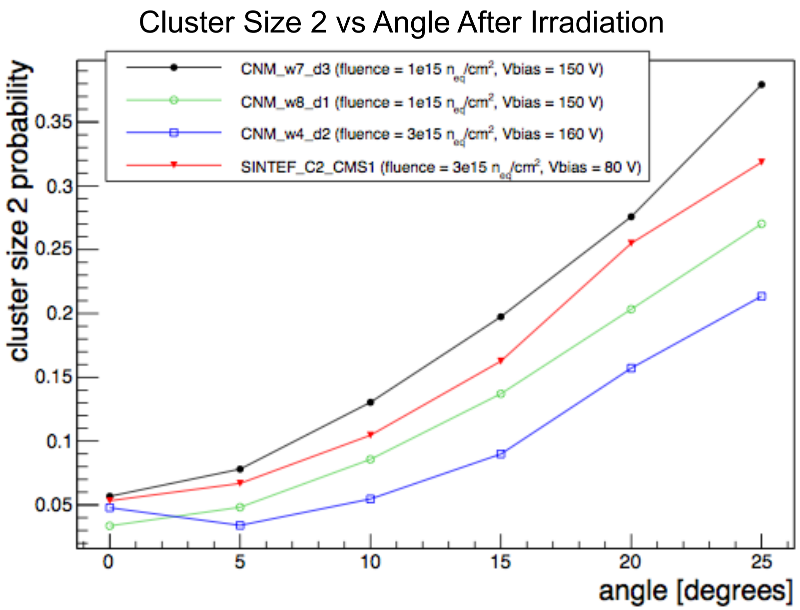
Performance after irradiation

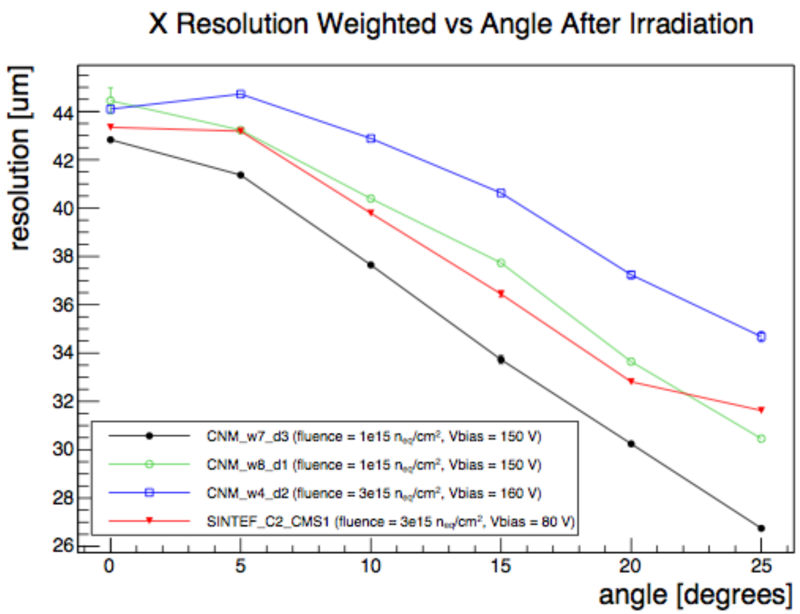
It is foreseen that **the detector will be irradiated during its life up to 5×10^{15} p/cm^2** which corresponds to ~1×10^{15} n_{eq}/cm^2.

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

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







Test at SPS H8

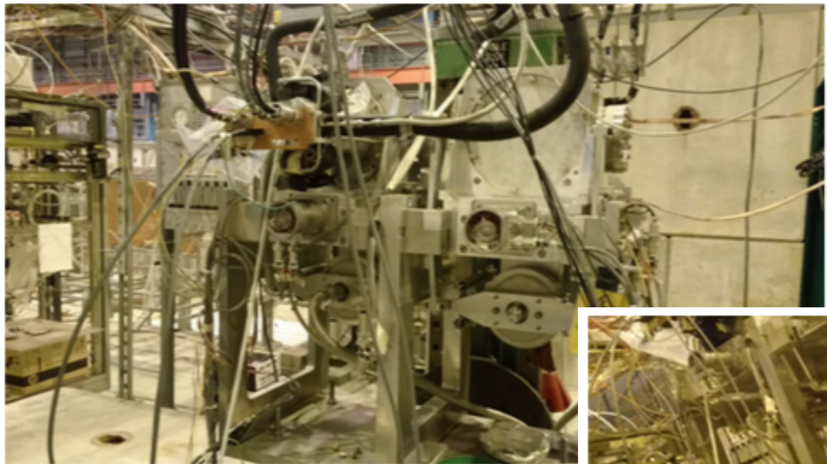
Test set-up at H8 very similar to real system in tunnel:

- same LV and HV system
- same slow control
- same DAQ

Vacuum and cooling system working properly with:

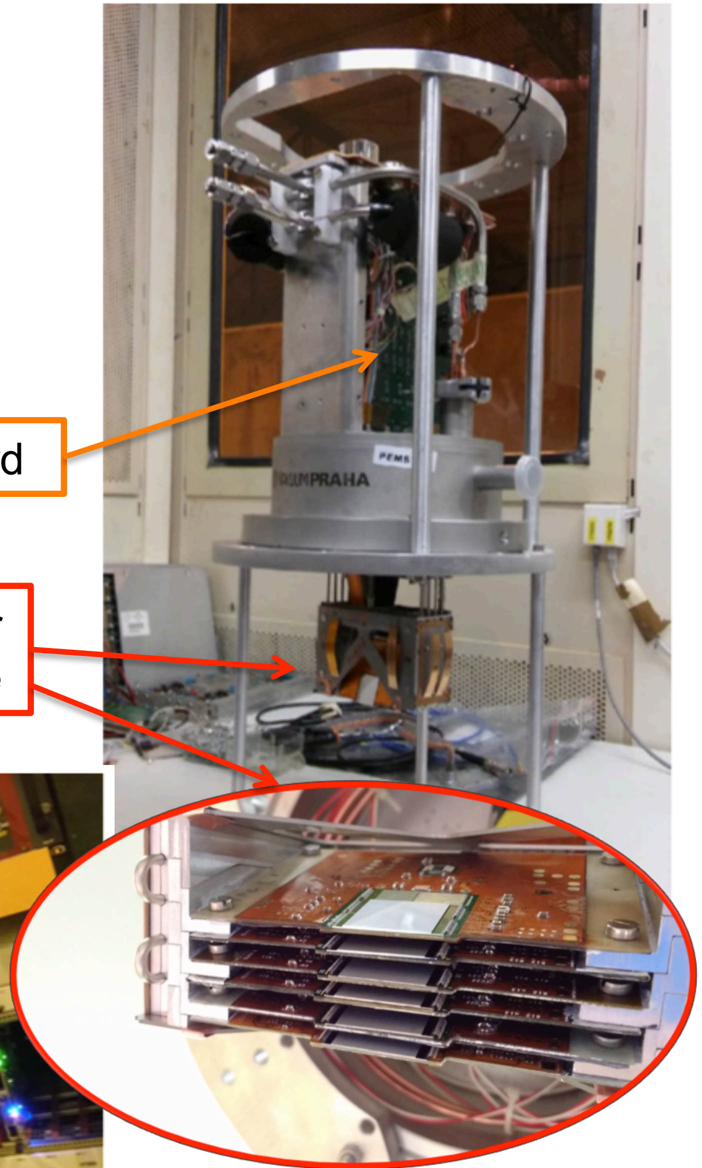
- p ≈ 0.04 mbar
- T ≈ - 25 C

Vacuum and cooling system



DAQ system (μTCA)

To be inserted in Roman Pot



Port Card

Detector package

Summary

- **During this end-of-the-year LHC shutdown 3D pixel detectors will be installed in the CT-PPS tracking Roman Pots.**
- **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** but also the 1E configuration ensures high efficiency.
- **Genova and Torino laboratories have qualified the final modules** with very good production yield.
- **Tracker mechanics and cooling successfully tested**.
- **RPix Port Card produced and under final test**.
- **Final pot assembling under test now at SPS H8.**
- **Installation in LHC tunnel foreseen in March.**

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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- Irradiation at the CERN IRRAD Proton Facility: F. Ravotti, A. Junkes

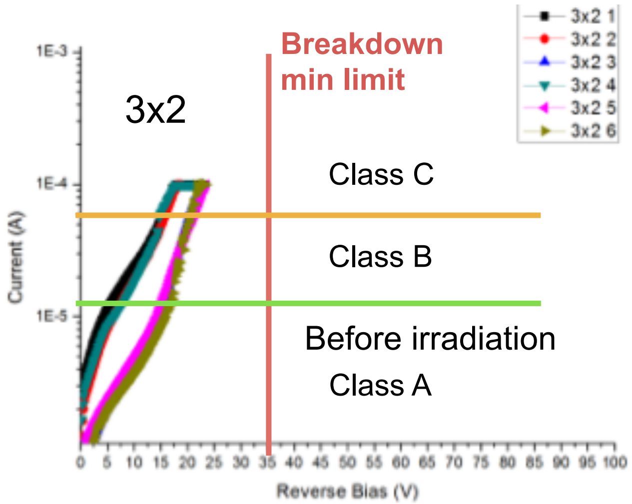
Thank you for your attention

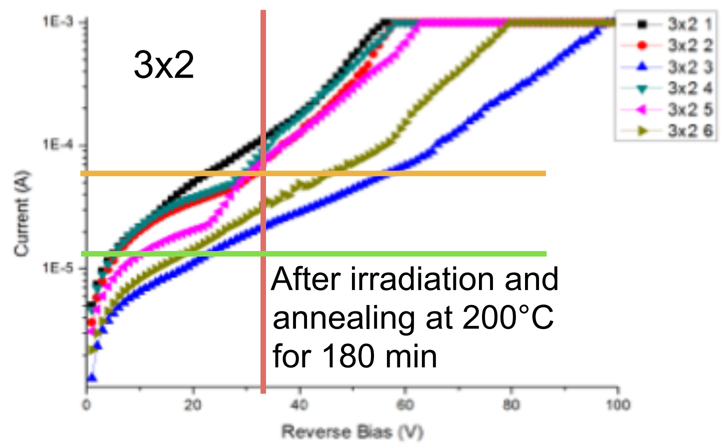
Backup

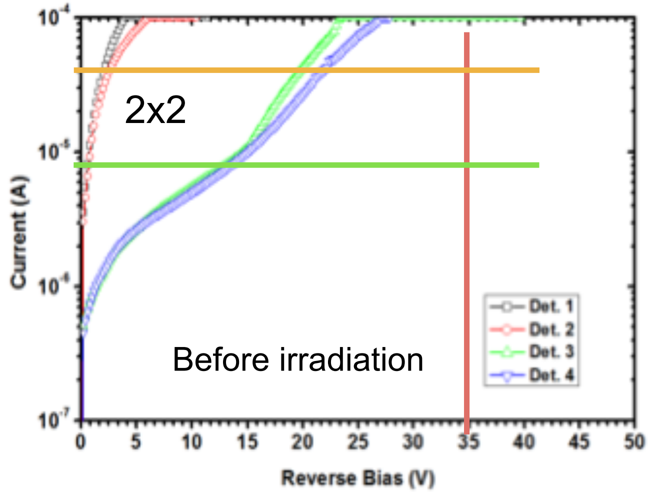
CNM second batch study

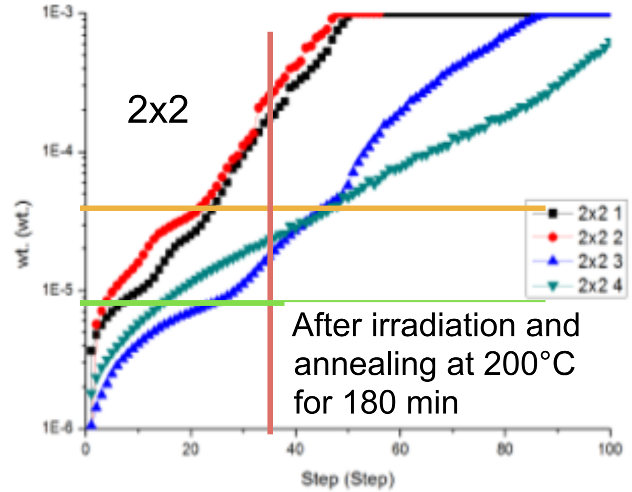
The second batch of 3D sensors had breakdown voltages below the required 25 V. The issue was ascribed to the p-stop implantation done by an external factory.

Low neutron dose irradiation (5-10 x 10^{14} n_{eq}/cm^2) + annealing should help based on other CNM 3D sensor studies. Test on sensors from wafer 11 showed promising results.









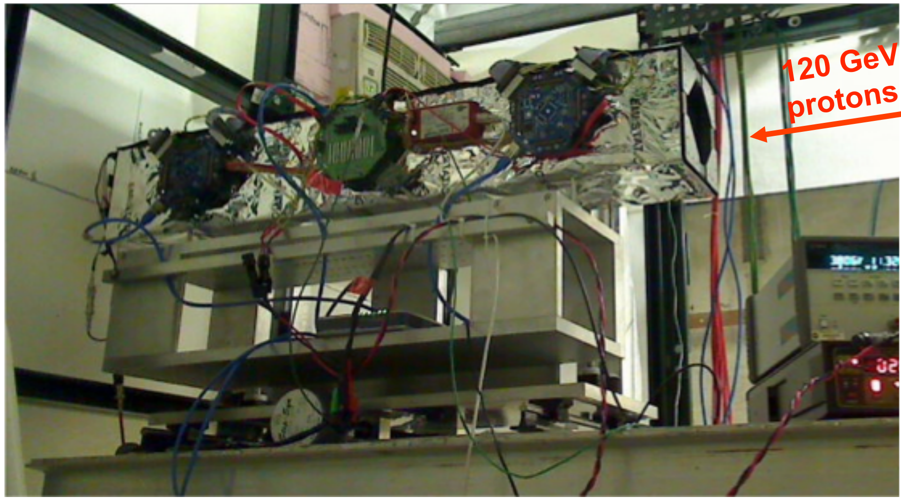
Specification to qualify the sensors

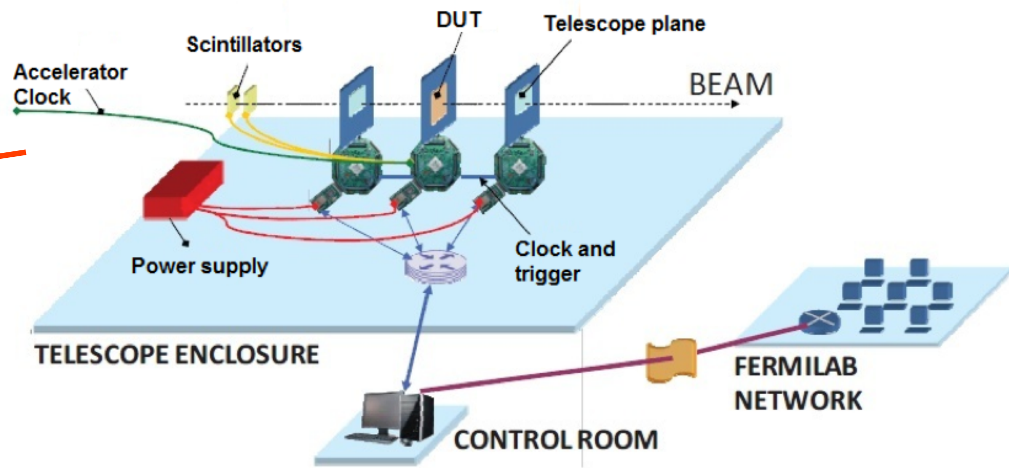
Define: Vop = Vdepl +10V
where Vdepl and Vop are respectively the full depletion and operation voltages.

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

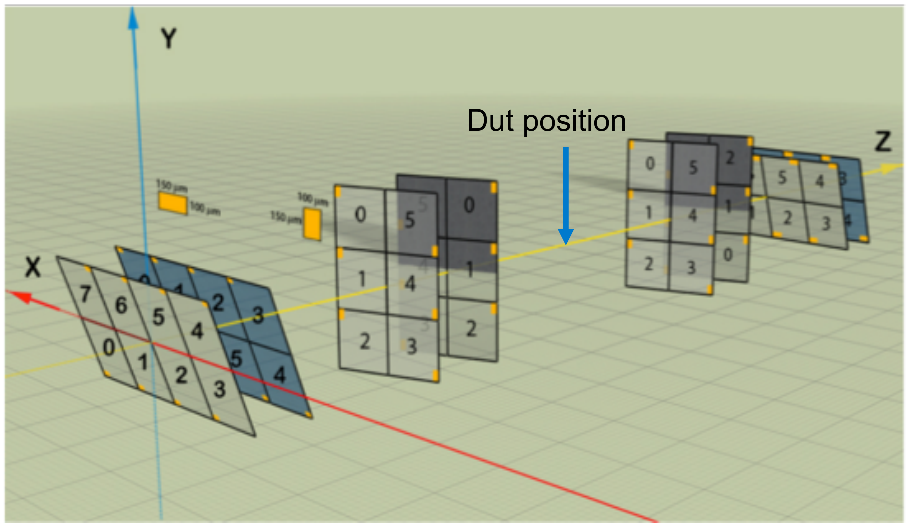
- **Vdepl < 20 V → OK**
- Breakdown voltage: **Vbd > 35 V**
- **[I(25V)/I(20V)] < 2**
- Current at operation voltage:
  - **Class A** I (Voperation) < 2uA per tile → very good
  - **Class B** 2uA < I (Voperation) < 10uA per tile → good enough
  - **Class C** I (Voperation) > 10uA per tile
- Wafer bow < 200um → OK

Testbeam at FNAL (T992 collaboration)



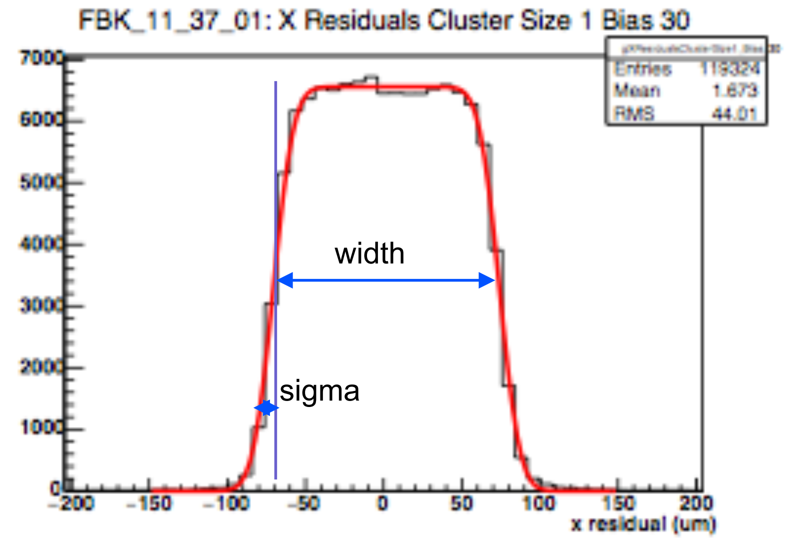


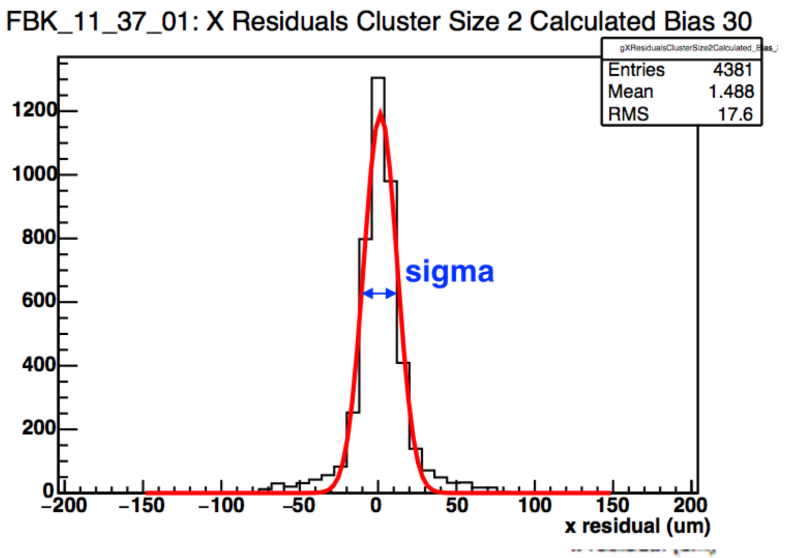
- **8 telescope planes** of CMS pixel modules (pixel size 100x150 μm^2), 4 upstream and 4 downstream with respect to the DUTs
- Telescope planes rotated of 25° with respect to 100 μm pixel pitch direction for improving **resolution to 8 μm**
- Rotation and cooling systems for the DUTs provided by Purdue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



Residuals plots

Preliminary





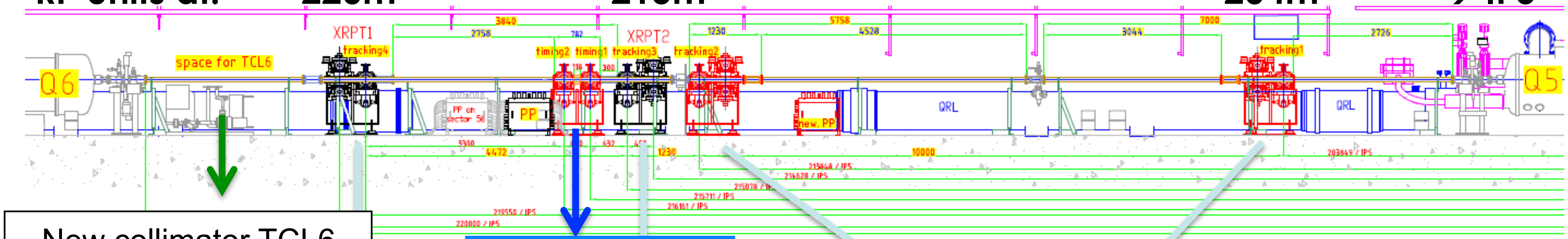
- Residuals cluster size 1 are fitted with a square function convoluted with a gaussian.
- Residuals cluster size 2 "Calculated" are evaluated by the charge asymmetry and fitted with a gaussian.

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

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

CT-PPS in the LHC beam line

RP units at: 220m ~ 215m 204m → IP5



New collimator TCL6 to protect magnet Q6

2 new horizontal cylindrical RPs

2 vertical + 1 horizontal RPs per station (relocated from 147m)

2 vertical + 1 horizontal RPs per station

Extreme flexibility in using Roman Pot units according to the running scenario

In particular, in the exploratory phase of 2015-2016:

- pursue the TOTEM / TOTEM+CMS physics programme at high-β^* low/medium luminosity
- prove the RP insertions and data taking at high luminosity and pileup

Relevant pots/detectors for low-β^* high luminosity runs:

2 new horizontal cylindrical RPs equipped with timing detectors

+

2 horizontal rectangular RPs equipped with tracking detectors

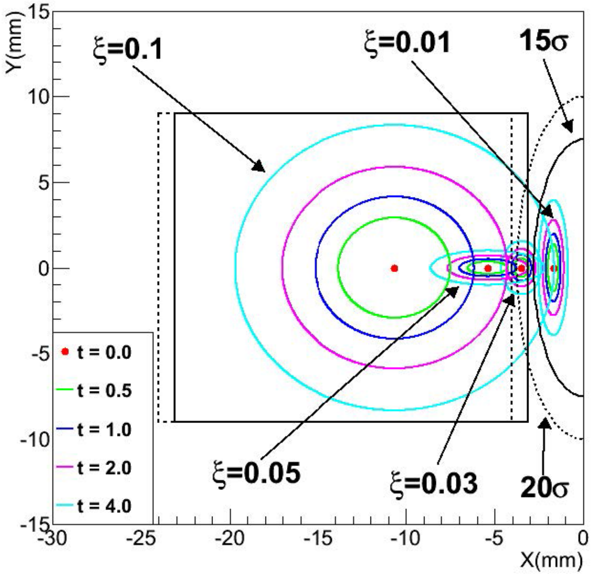
Experimental challenges

- Ability to **operate the detectors close to the beam (15σ)** to maximize acceptance for low momentum-loss protons

Need to **limit the additional RF impedence introduced by beam pockets**:
➢ new RPs with improved RF shielding
➢ R&D on Movable Beam Pipe as future beam pocket option

Need to **sustain very high radiation levels**. For 100 fb^{-1}:
• proton flux up to $5 \cdot 10^{15}$ cm^{-2} in the **tracker detectors**
• 10^{12} n_{eq}/cm^2 and 100 Gy in **photosensors** and **readout electronics**
➢ upgrade Si-strips to 3D Si pixel detectors
➢ R&D on solid state timing detectors (diamond, LGAD, 3D)

Position of scattered protons at 204m, for fixed (ξ,t)



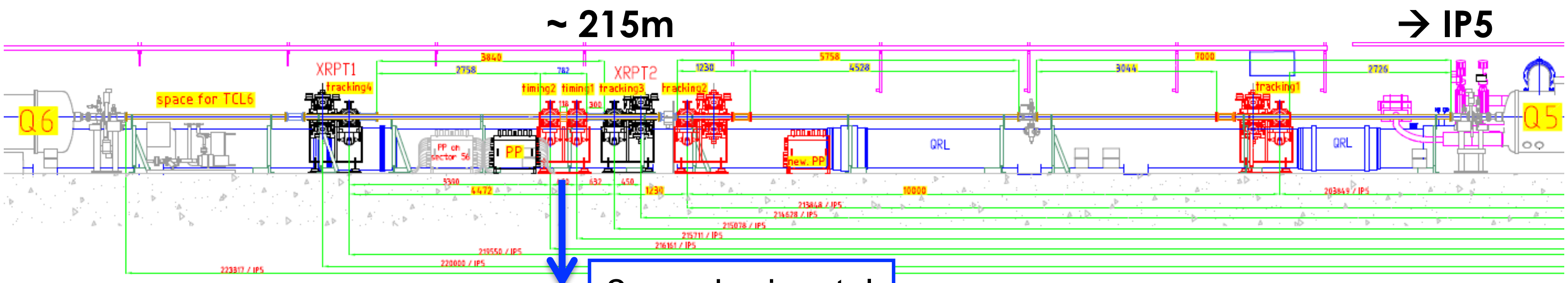
2% < ξ < 10%

- Ability to **reject the background** expected in the high pile-up (μ=50) environment of normal LHC running, mainly inelastic events overlapping with SD protons from the same bunch crossing

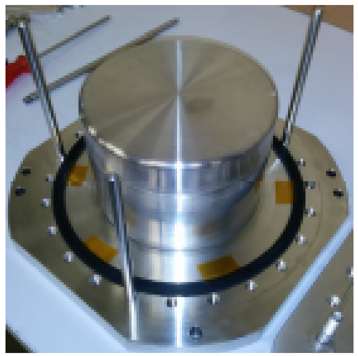
Use **proton timing** for primary vertex determination

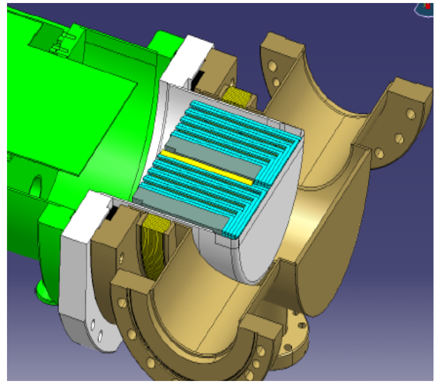
Exploit the **kinematical constraints** of CEP events

Timing detectors



2 new horizontal cylindrical RPs

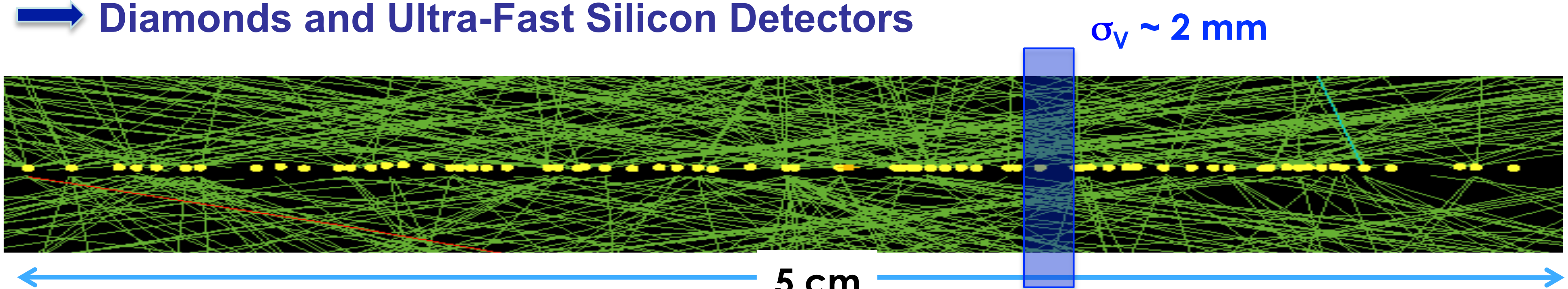




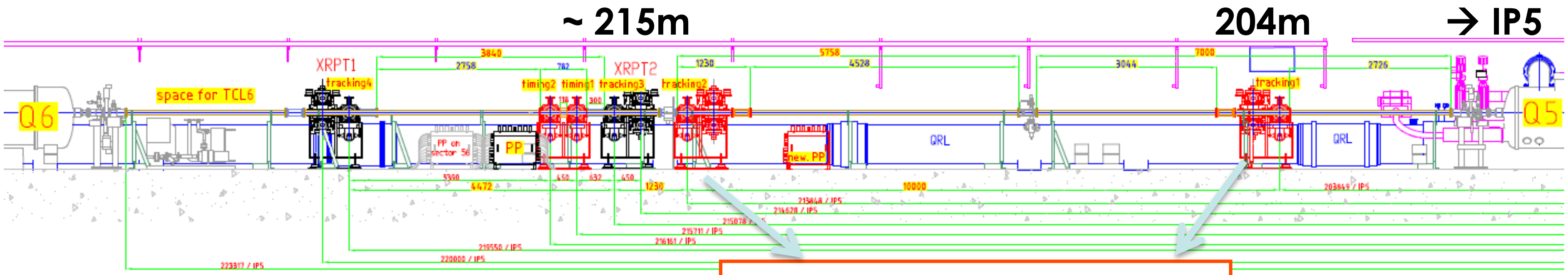
Proton timing measurement from both sides of CMS allows to determine the primary vertex, correlate it with that of the central detector and reject pile-up

- Time resolution ~10 ps → Vertex z-by-timing: ~2 mm
- Segmentation to cope with the high occupancy expected
- Edgeless (~ 200 μm)
- Radiation hard

➡ **Diamonds and Ultra-Fast Silicon Detectors**



Tracking detectors



2 horizontal rectangular RPs
~10 meters apart

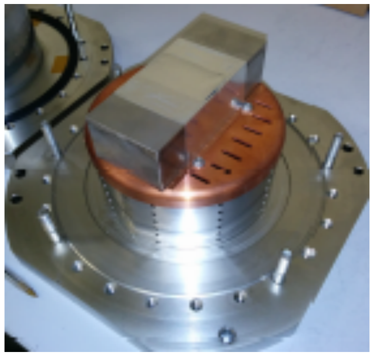
Position and angle, combined with the beam magnets, allow to determine the momentum of the scattered proton

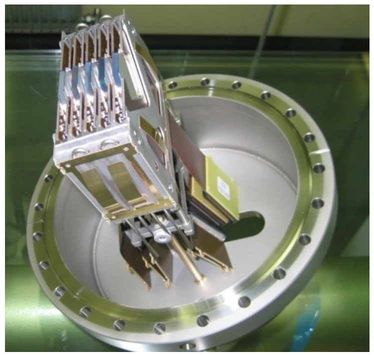
- Position resolution of ~10 µm
- Angular resolution of ~1-2 µrad
- Slim edges on side facing the beam
  → dead region ~100 µm
- Tolerance to inhomogeneous irradiation
  → $\sim 2 \cdot 10^{15}\ n_{eq}/cm^2$ close to the beam (for $100\ fb^{-1}$)

↓

3D silicon pixel detectors

- Detectors should fit into existing RPs

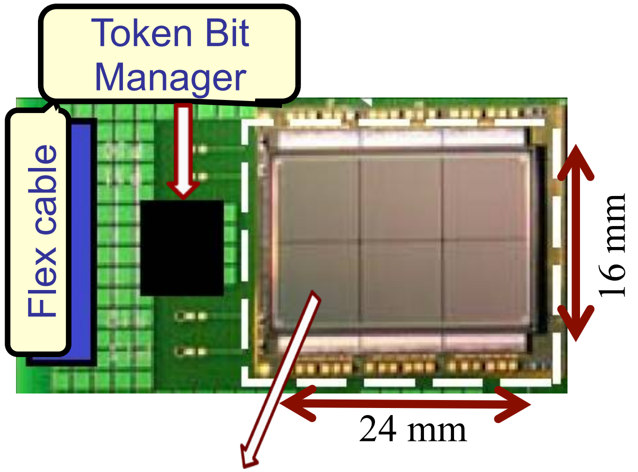




Tracking detectors

6 detector planes per station

For each plane:

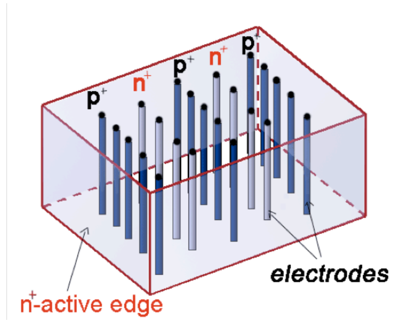


- 16 x 24 mm² **3D silicon pixel sensors**
- 150(x) x 100(y) μm² pixel pattern
  same as CMS pixel detectors
- **6 PSI46dig readout chips**
  (52x80 pixels each)

Same readout scheme as Phase-I upgrade of CMS Forward Pixel Tracker
→ Existing CMS DAQ components and software reused

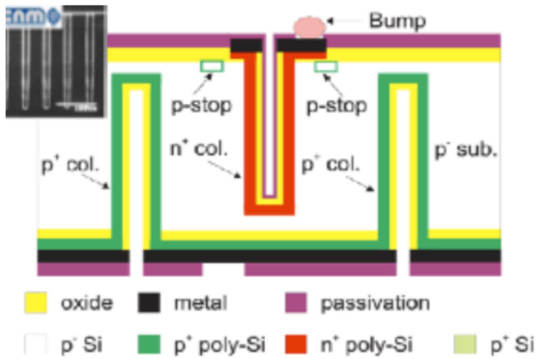
3D sensors consist of an array of columnar electrodes

- Mature technology after ATLAS IBL



Interesting features w.r.t. planar sensors:

- **Low depletion voltage** (~10 V)
- Fast charge collection time
- Reduced charged trapping probability and therefore **high radiation hardness**
- **Slim edges**, with dead area of ~100-200 μm or **Active edges**, with dead area reduced to a few μm
- Spatial resolution comparable with planar detectors



Chosen solution: CNM 3D with inter-electrode distance 62.5 μm (2E – 2 readout columns per pixel)

Tracker readout system

CT-PPS custom design

Already used for TOTEM Strips

From CMS Phase I pixel Upgrade