The CT-PPS tracking detector: hardware and operational experience

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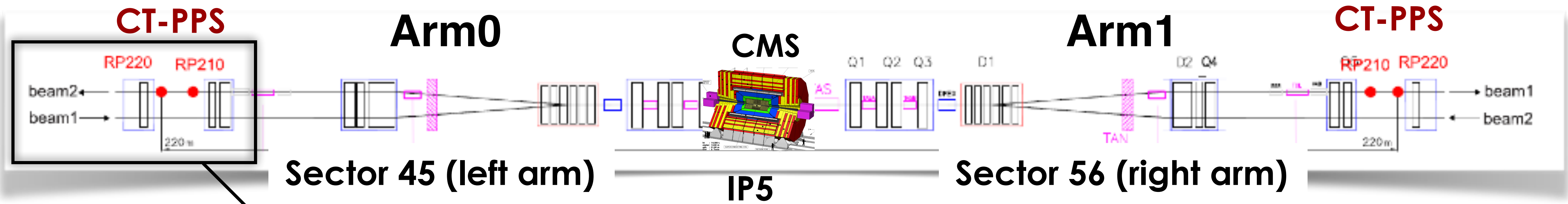
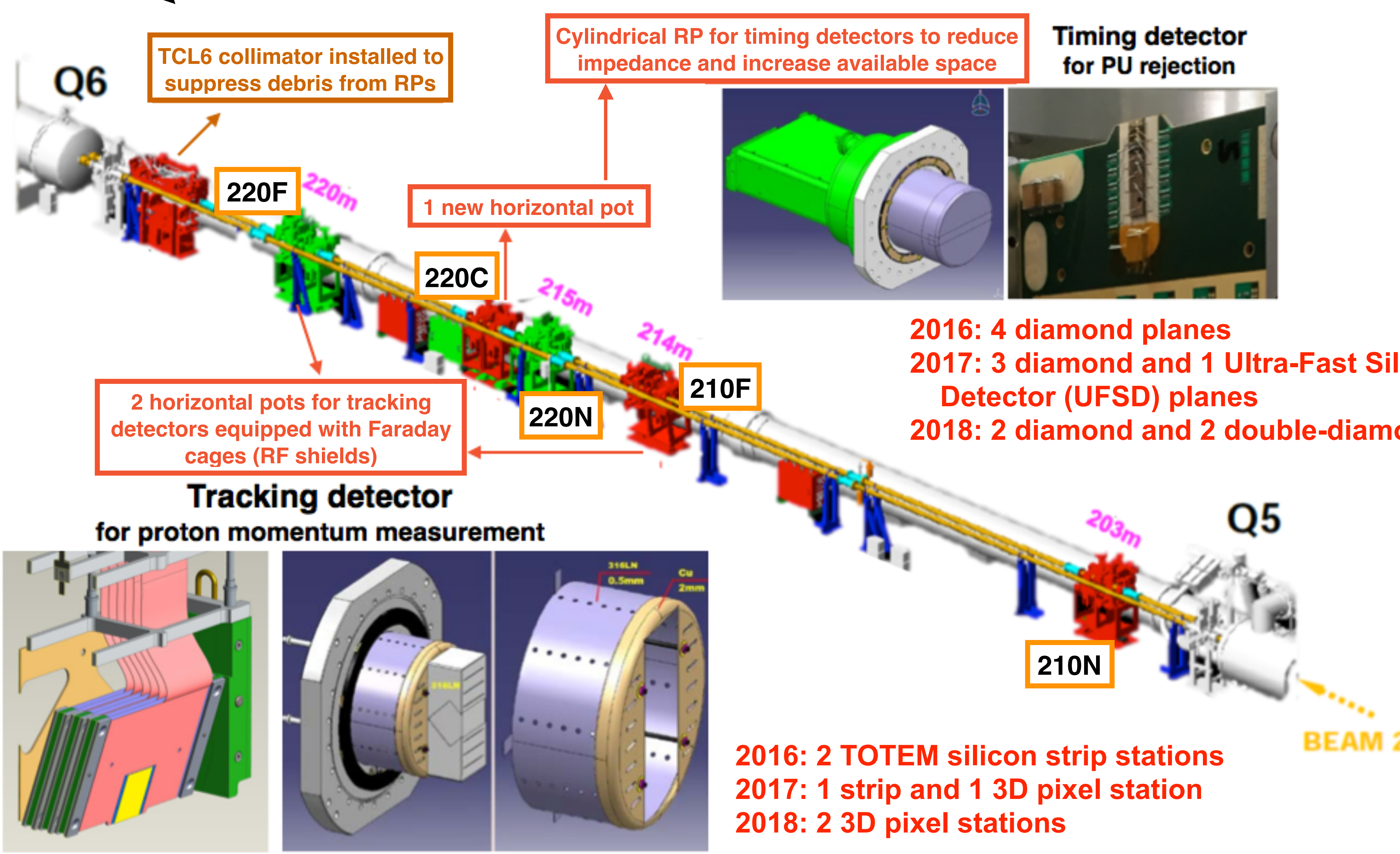
Detector setup



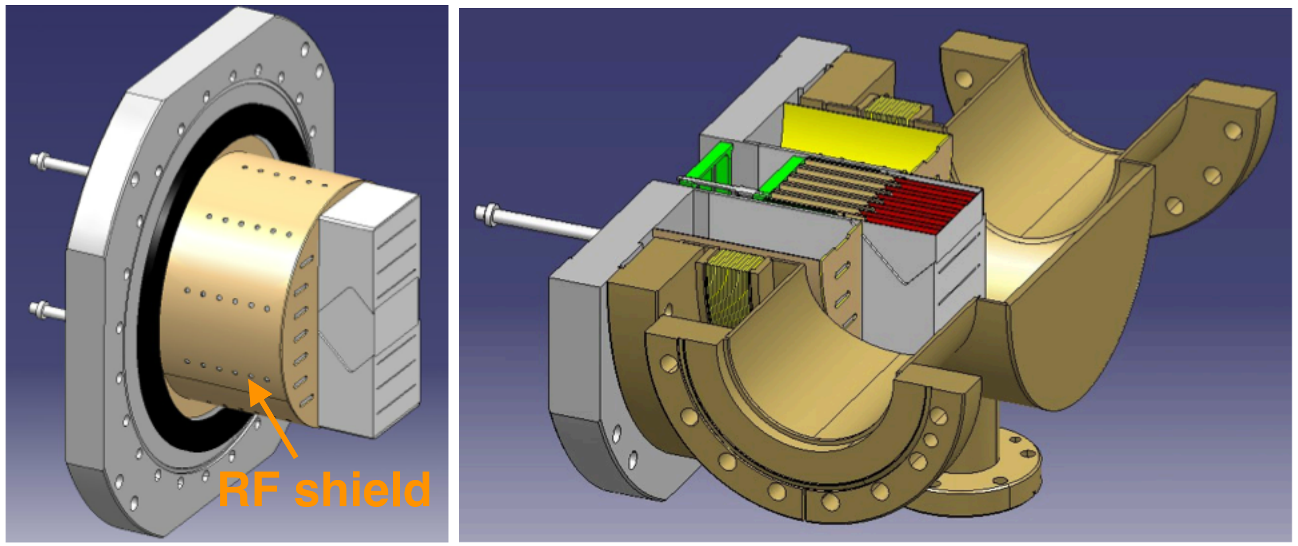


2016: 4 diamond planes
2017: 3 diamond and 1 Ultra-Fast Silicon Detector (UFSD) planes
2018: 2 diamond and 2 double-diamond planes

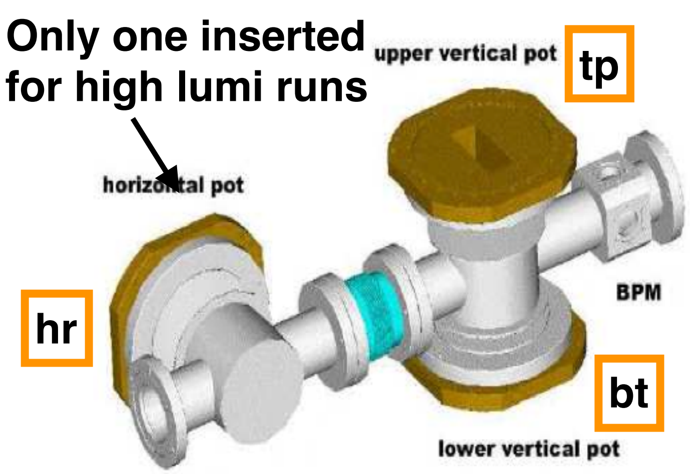
2016: 2 TOTEM silicon strip stations
2017: 1 strip and 1 3D pixel station
2018: 2 3D pixel stations

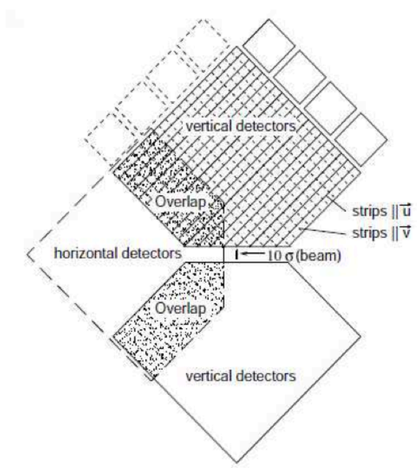
Roman pots (RP)

RP for tracking stations



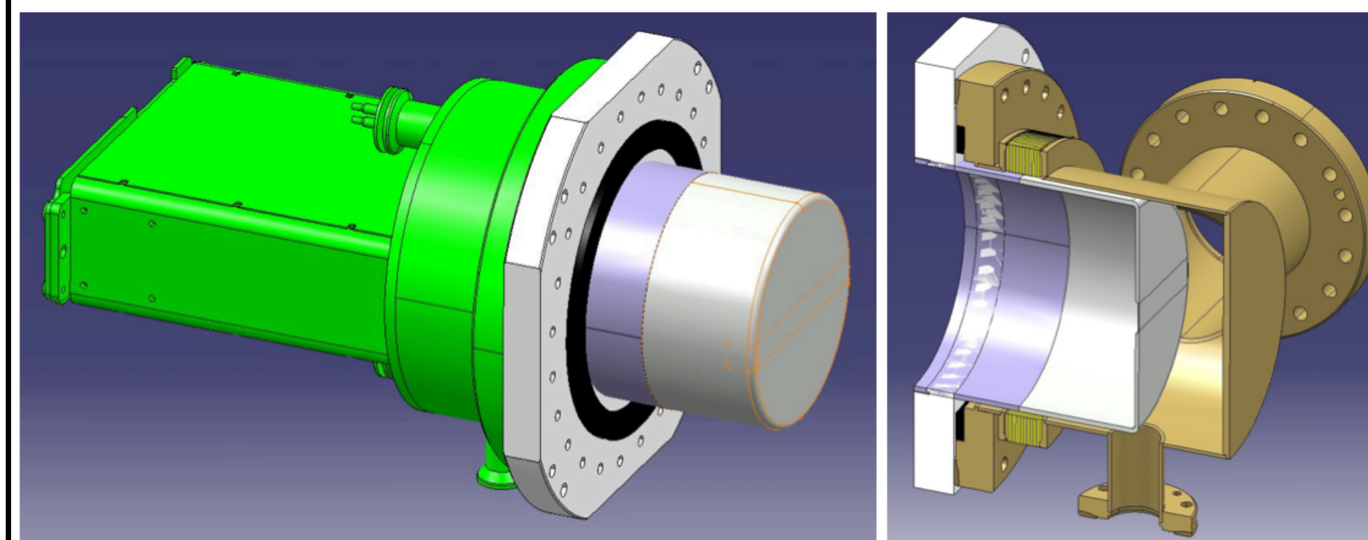
Each station includes 3 RPs (1 horizontal and 2 vertical for alignment runs only).





The tracking RPs are **equipped with a thin window 150 μm thick toward the beam**.

RP for timing stations



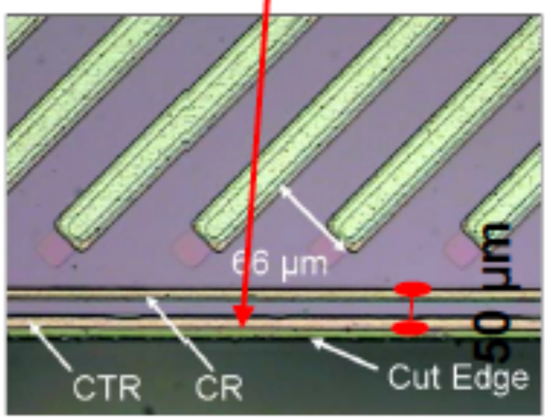
New cylindrical design to host larger detectors and reduce the impedance.

The timing RPs are **equipped with a 300 μm thick window towards the beam.**
The thickness is required to compensate the pressure gradient on the larger window.

No vertical stations needed, the alignment is done by propagating tracks from the tracking stations.

The CT-PPS RPs are inserted at ~15σ from the LHC beam in standard high lumi fills.

TOTEM strip detectors



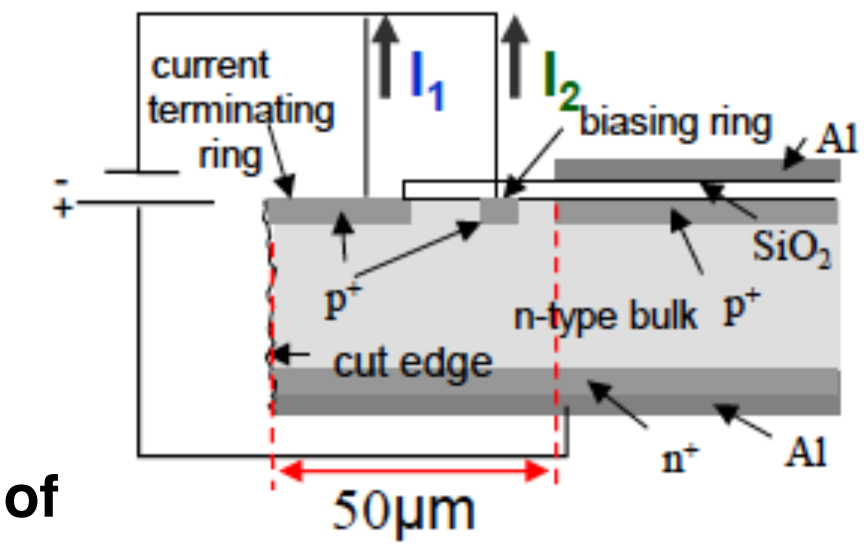
Micro-strip silicon detectors with edgeless technology:

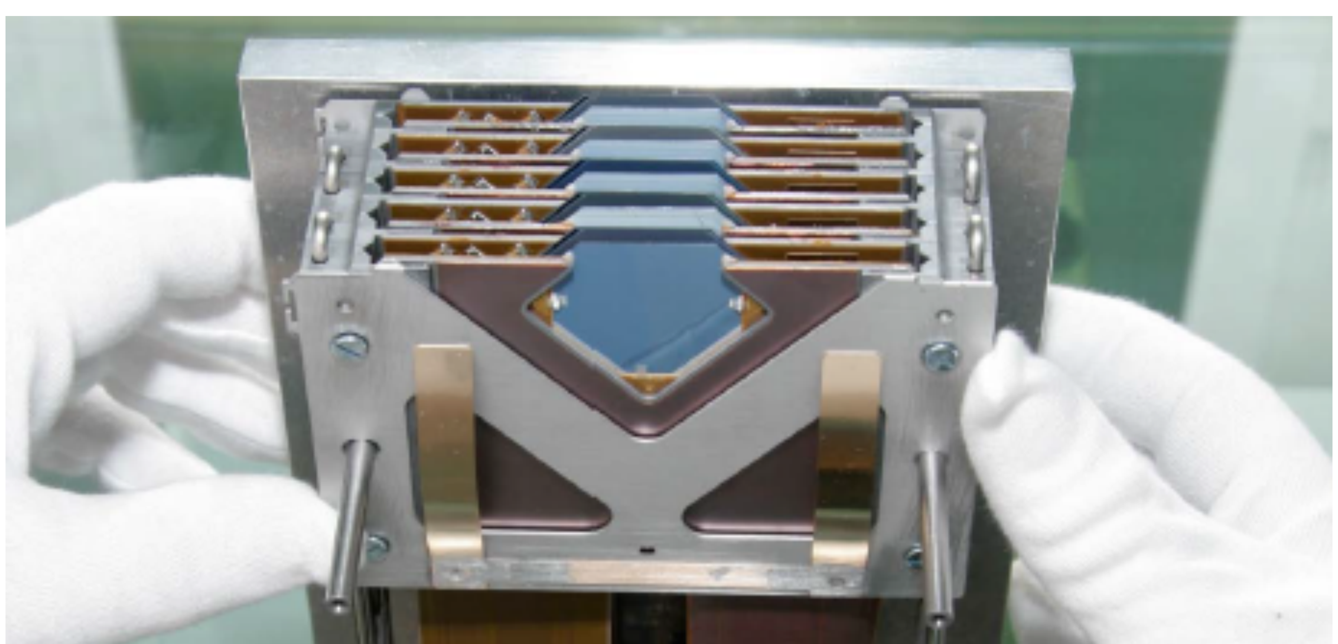
- 512 strips per plane, with ± 45° orientation
- Strip pitch = 66 µm
- Inactive edge = 50 µm
- Resolution ~20 µm
- **Lifetime up to an integrated flux of 5 x 10^{14} p/cm^2**
- Binary readout provided by 4 VFAT2 (128 channel each). VFAT2 has trigger capability, currently not integrated in the CMS L1 trigger system

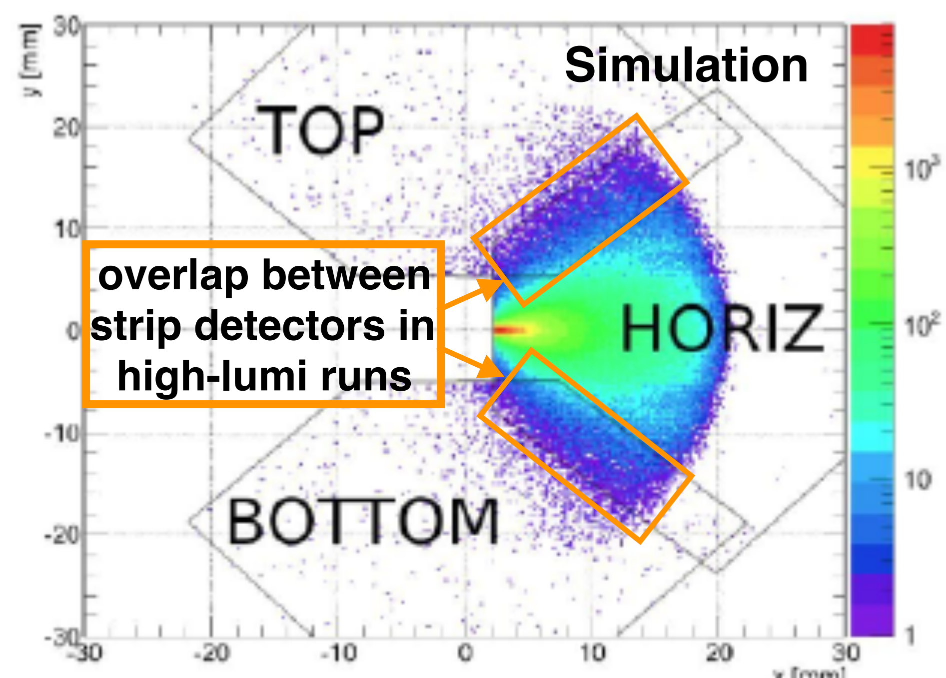
Each station is composed of 10 planes.

Hit/track reconstruction using consolidated TOTEM algorithms fully integrated in the CMS official software since 2016.

Planar technology + CTS (Current Terminating Structure)





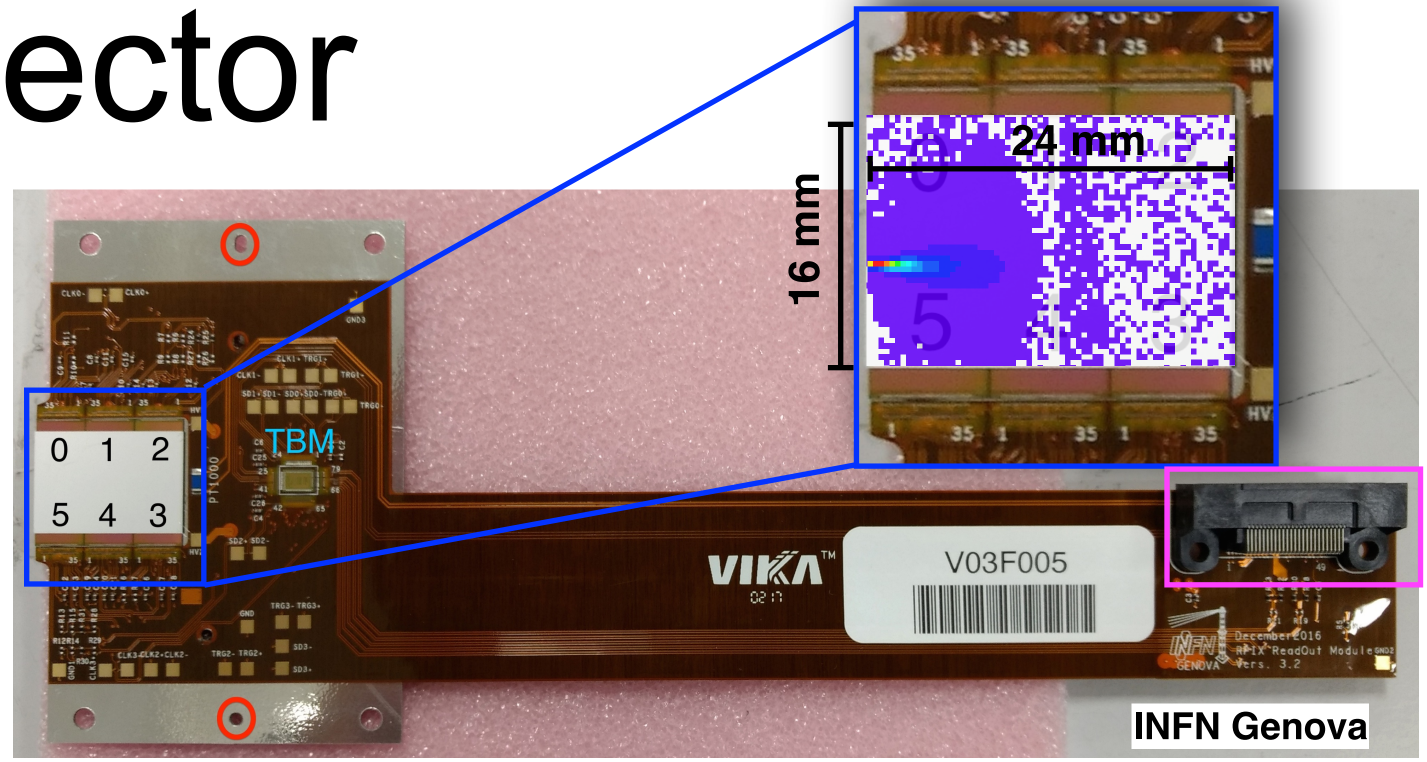


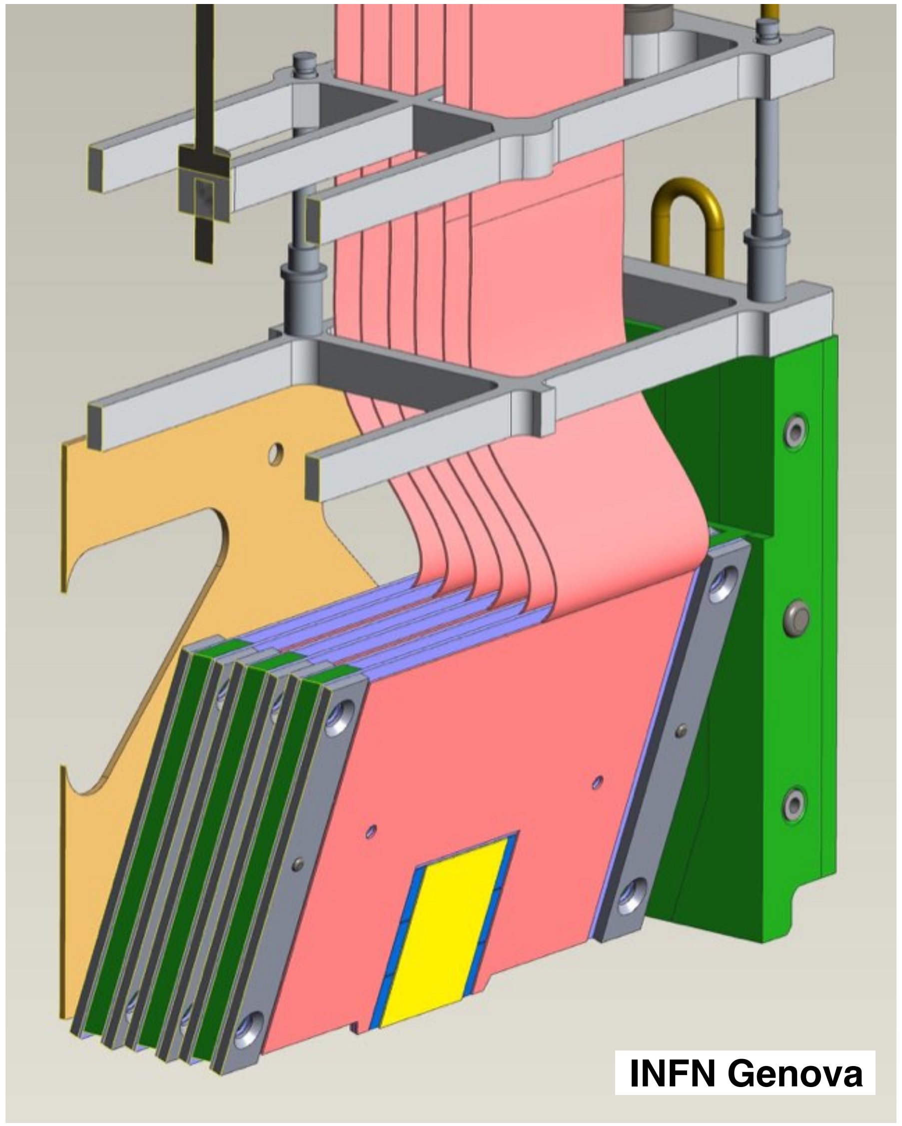
Tracking system with pixel 3D

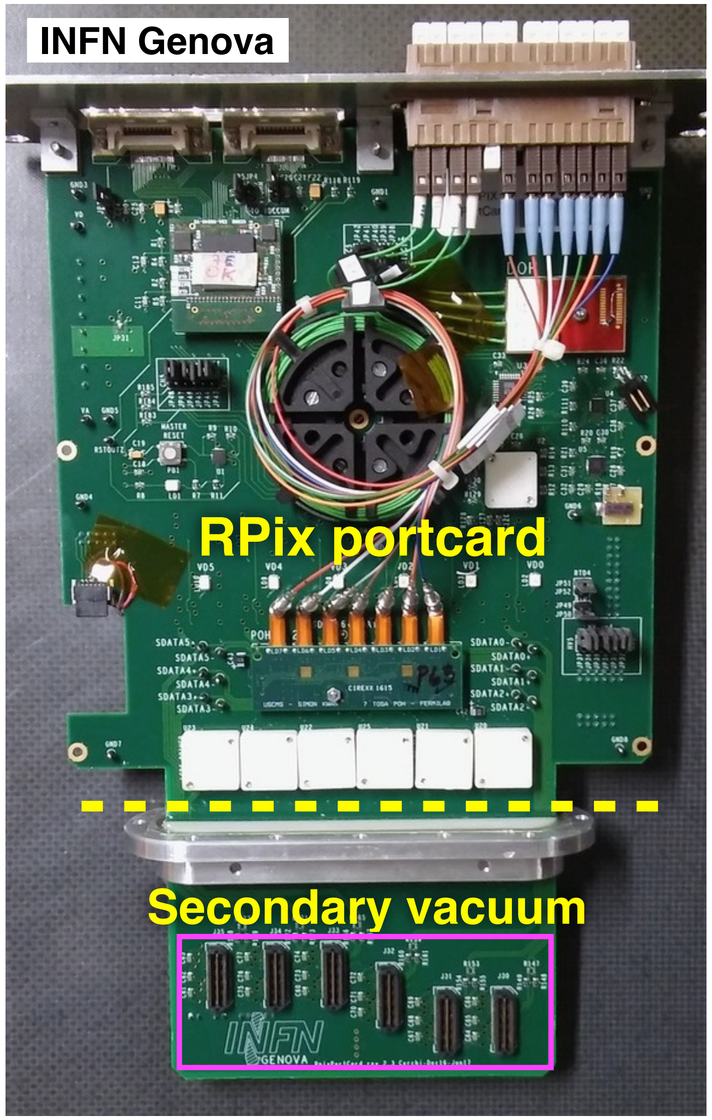
- **Requirements**:
  - **Sustain high radiation levels**: for 100 fb^{-1}, proton flux up to $5x10^{15}/cm^2$ in tracking detectors, corresponding to ~1-3 x 10^{15} n_{eq}/cm^2.
  - **Small inefficient area at the edge of the sensor** towards the beam.
  - **Tracking resolution of ~10 and 30 μm** along x and y directions, respectively.
- **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.
  - **Run at -20ºC and in vacuum** (pressure < 20 mbar) to avoid condensation and stress of the Roman pot thin window.

CT-PPS pixel detector

Each plane is equipped with a sensor bump-bonded to the psi46dig ReadOut Chip (ROC) developed for the CMS Phase I upgrade of the CMS pixel tracker.
The detector is precisely glued on a Thermal Pyrolithic Graphite (TPG) layer that **provides the thermal contact** with the sides of the package connected to the cooling pipes.







Modules are wire-bonded to the flex circuits which are connected to the RPix portcard.

The RPix portcard interfaces the front-end electronics with the detector planes.
Concept: TOTEM board (to fit the RP space constraints) with components from the CMS Phase I forward pixel readout.

Front-end boards are the same as those of the Phase I CMS pixel tracker.

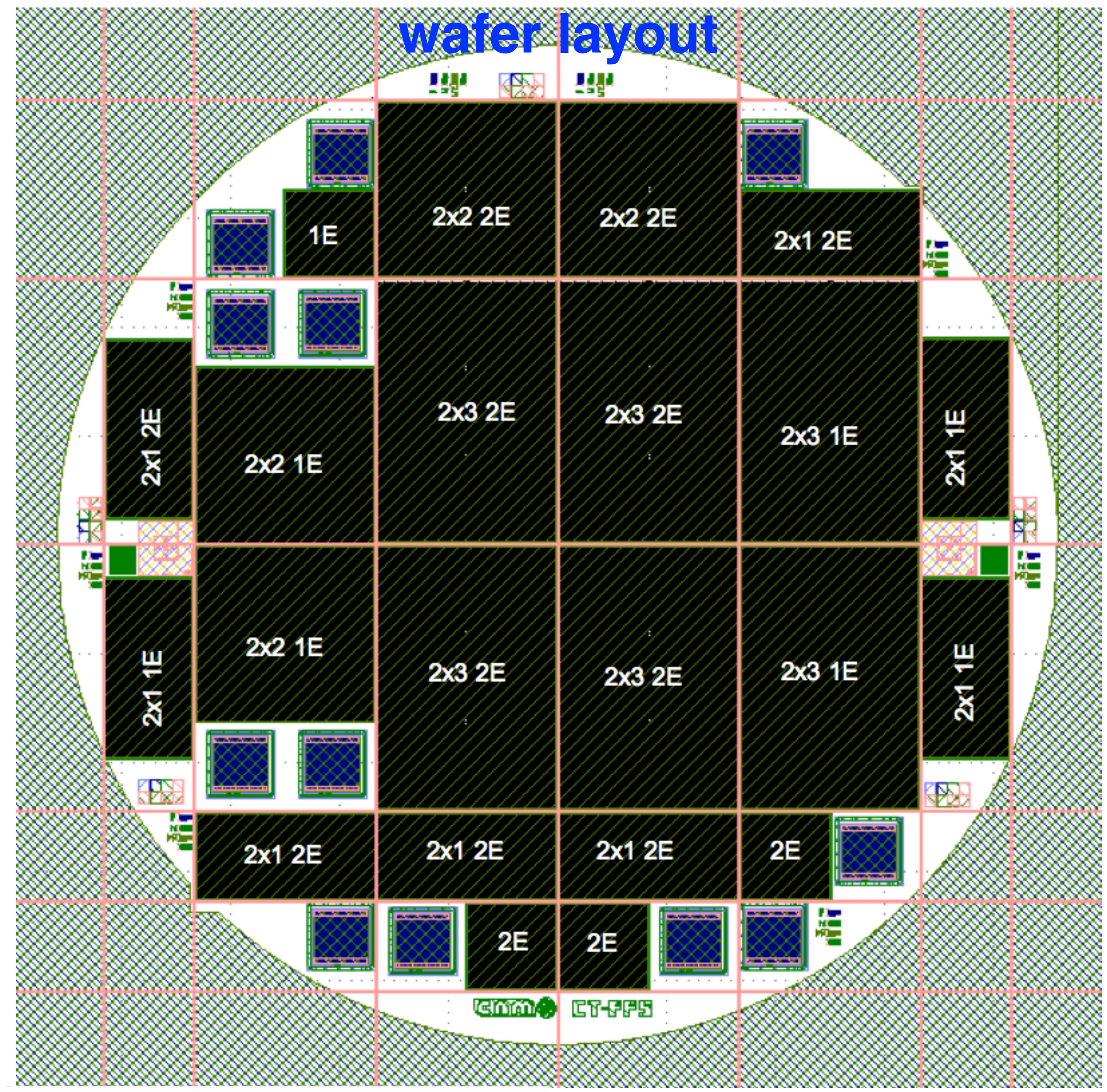
3D sensors for CT-PPS

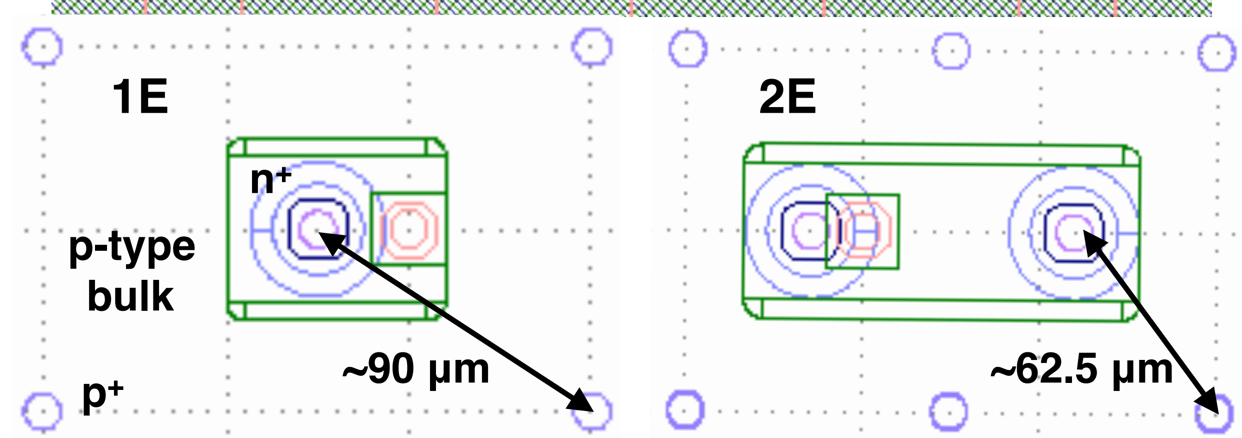
3D sensors produced in double-sided not-fully-passing-through technology by CNM
Baseline design:

- **2E pixel** configuration (2 readout columns)
- 200 μm **slim edges** with column fences
- 3x2 sensors (6 ROCs each)

1E and 2x2 sensors as backup solution

3 batches of 12 wafers each have been produced at CNM





Specifications to qualify the devices:

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

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	$I(V_{op}) < 2$uA per tile
Class B	$2uA < I(V_{op}) < 10$uA per tile
Class C	$I(V_{op}) > 10$uA per tile

CNM production results

Sensor IV curves have been measured on wafer before bump-bonding by means of a temporary metal deposition to short all the pixels.

First batch of 12 wafers completed in December 2015.
In general good quality sensors but low yield, in particular of the class A ones.

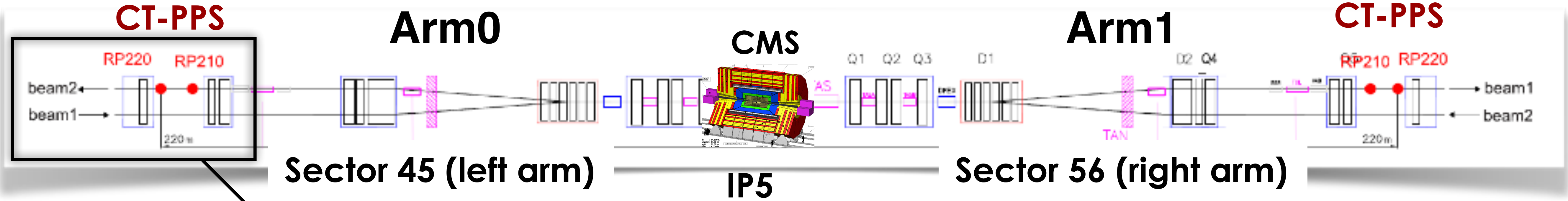
Pixel configuration	Class A	Class B	Class A + B	2E + 1E
3x2 2E	3	10	13	22
3x2 1E	7	2	9	
2x2 2E	4	9	13	24
2x2 1E	6	5	11	
			Total	46

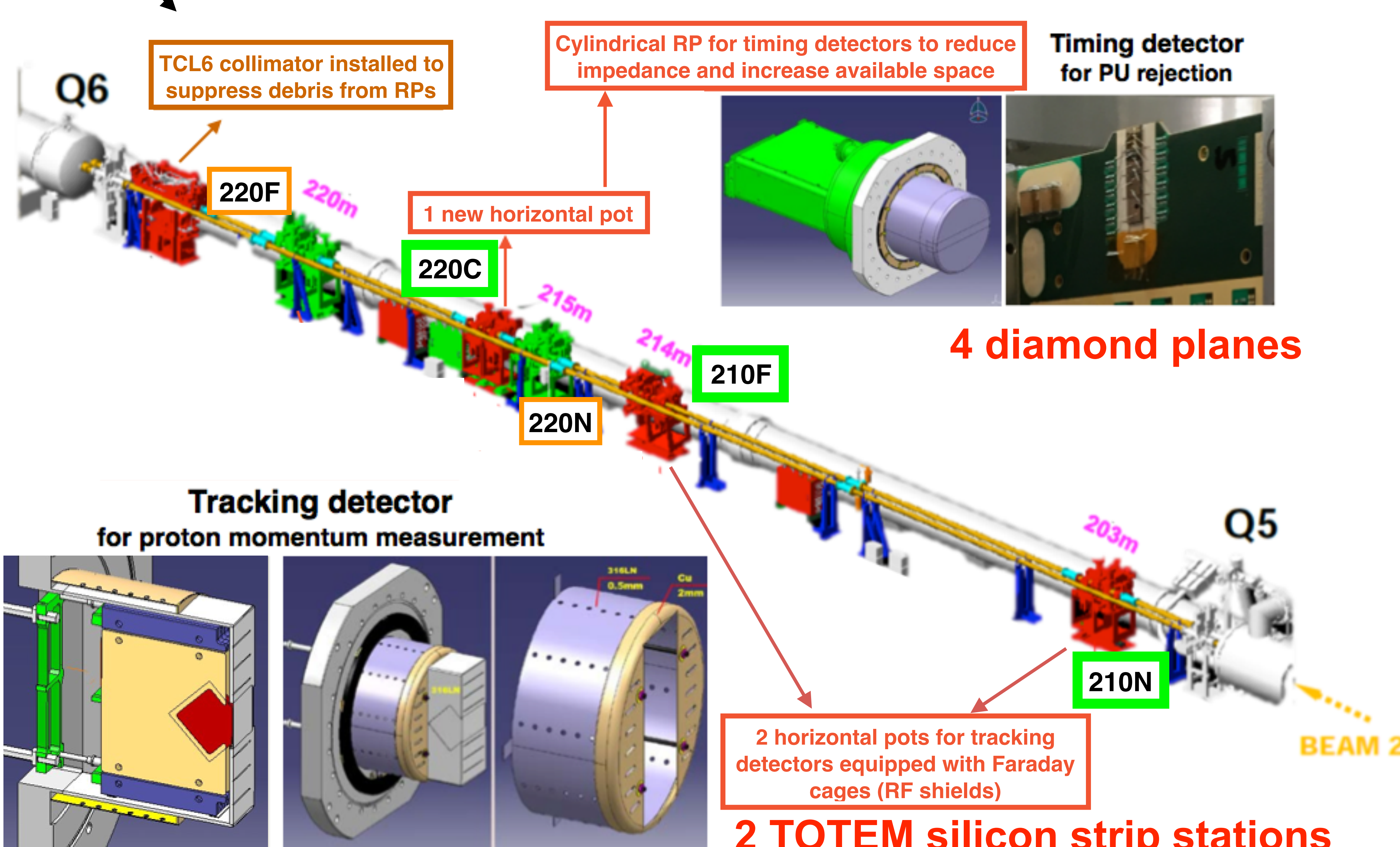
Second batch production completed in May 2016.
A problem, probably with the p-stop implantation, caused values of breakdown voltage too low to allow using the sensors.

Third batch production completed in June 2017.
Sensors showed a large leakage current that would classify all the modules as class C. After discussing with the psi46dig designers it has been decided to relax the current limit above the ROC specifications and accept sensors with a leakage current up to 400 μA per tile -> further ~50 modules available.

2016 accelerated program

2016 detector setup





Timing detector for PU rejection

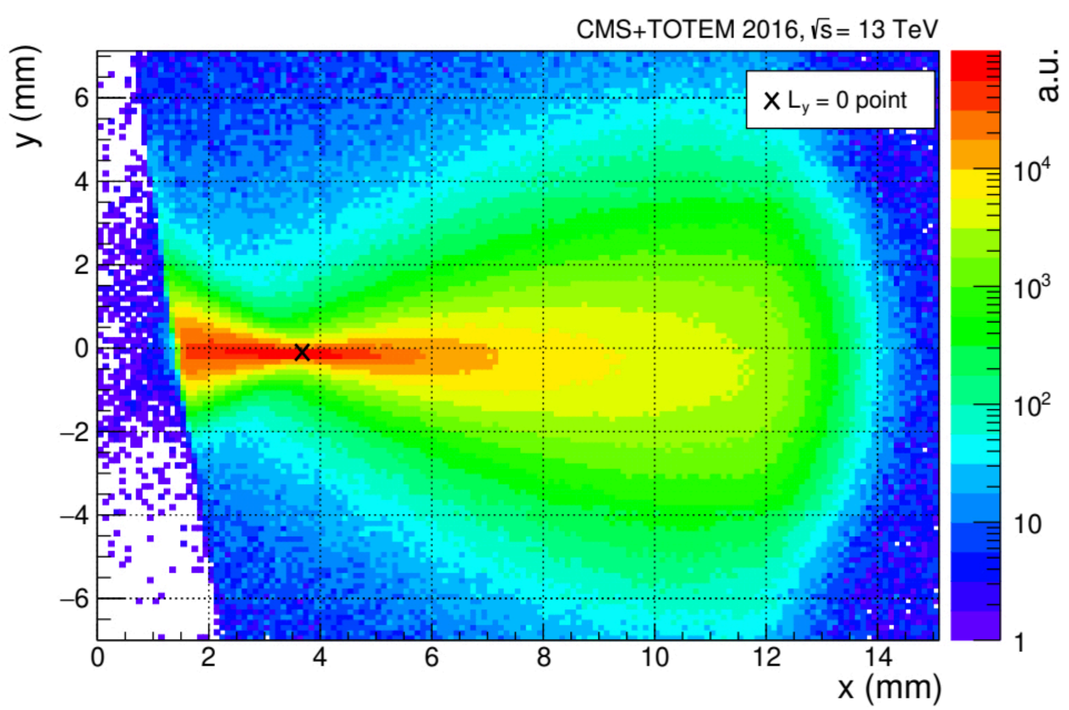
4 diamond planes

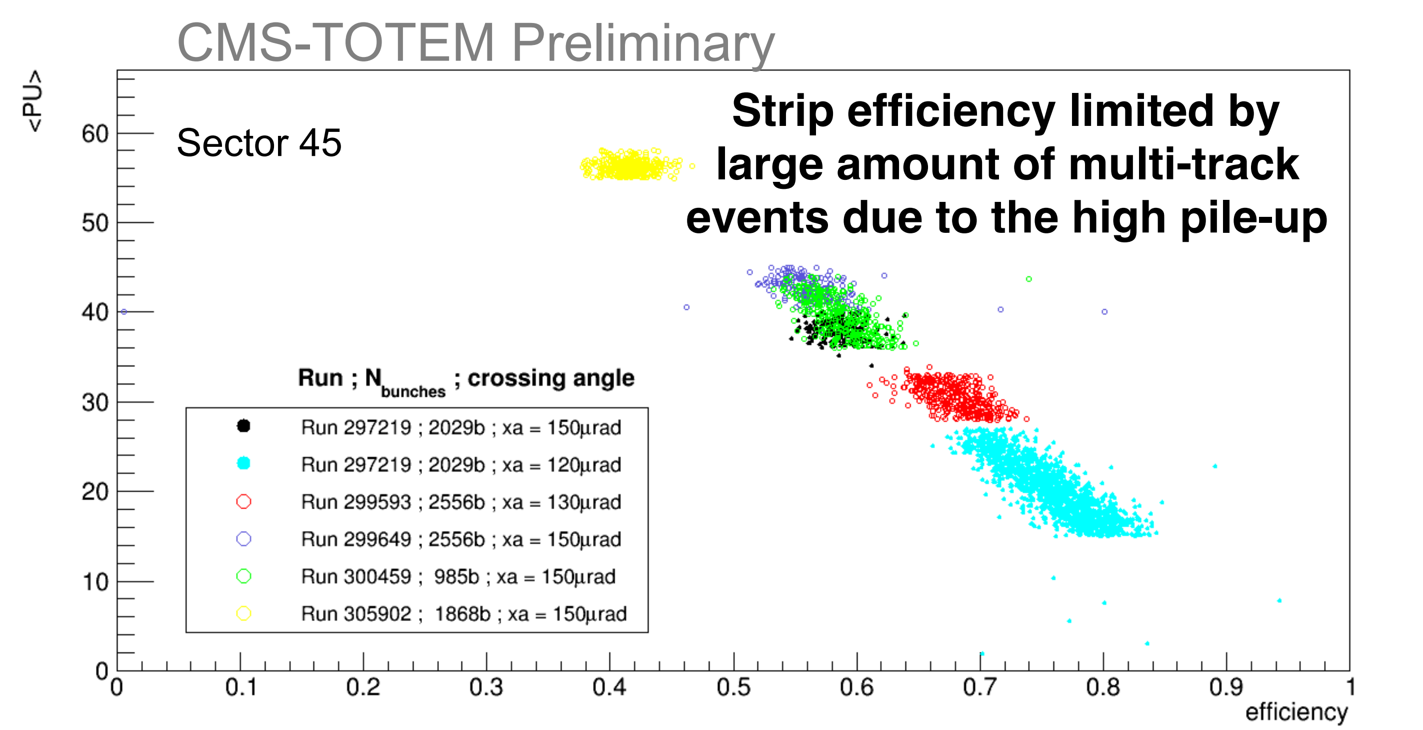
Tracking detector for proton momentum measurement

2 TOTEM silicon strip stations

2016 data taking

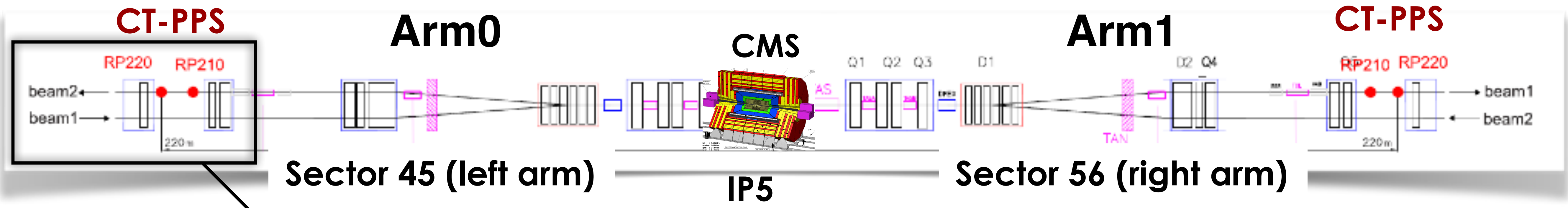
- In the 2015 data collected by CMS and ATLAS a mild enhancement was observed at ~750 GeV in the diphoton invariant mass spectrum.
- The possibility that the process could be produced with both protons intact in the final state made really interesting an early installation of the detector.
- In 2016 the pixel detector was not yet available and the TOTEM strip detectors were available.
- In 2016 an integrated luminosity of ~15 fb^{-1} was collected and a sample of 9.4 fb^{-1} was used to obtain the CT-PPS first physics results (arXiv:1803.04496)

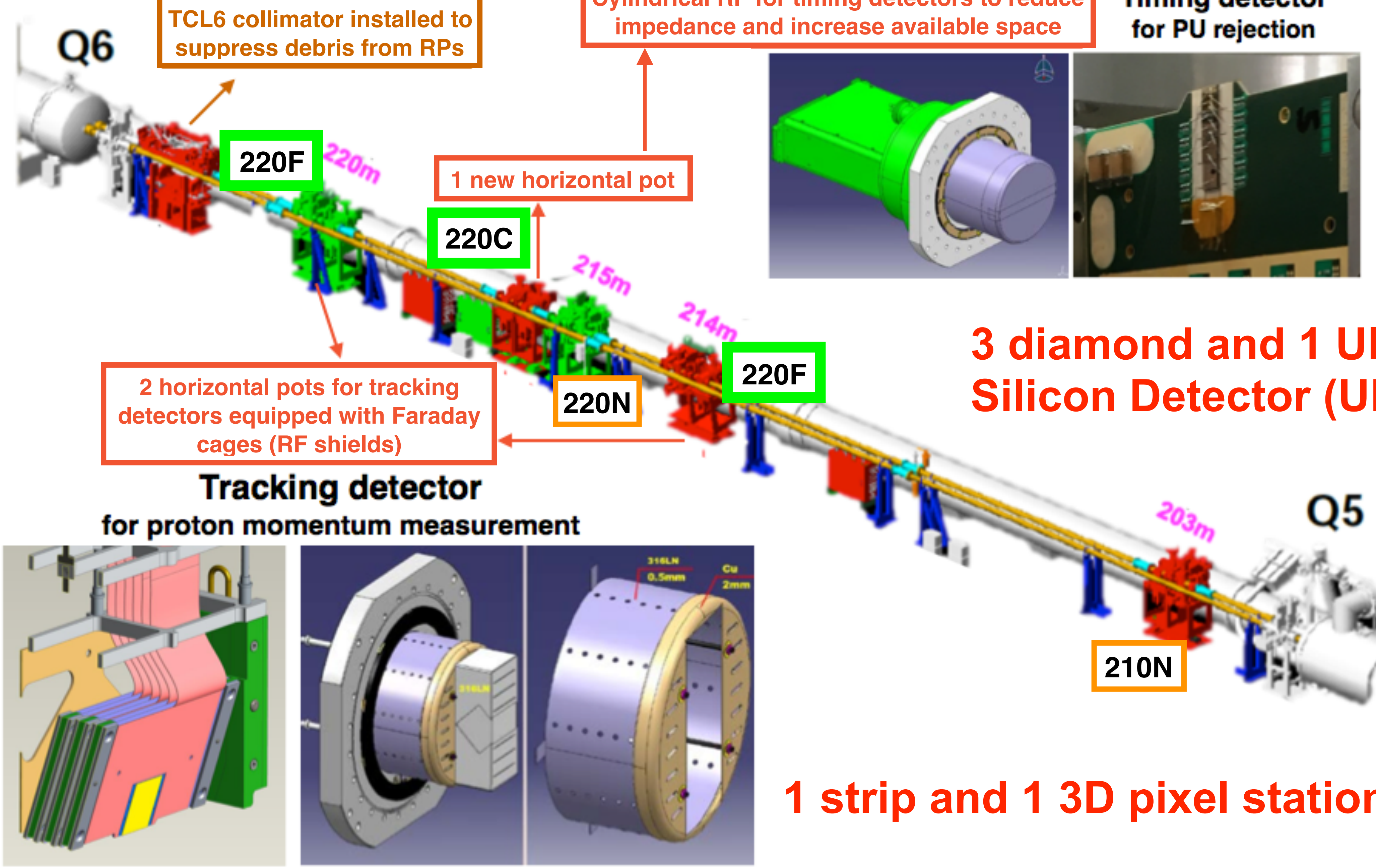




2017 data taking and operational experience

2017 detector setup





Cylindrical RP for timing detectors to reduce impedance and increase available space

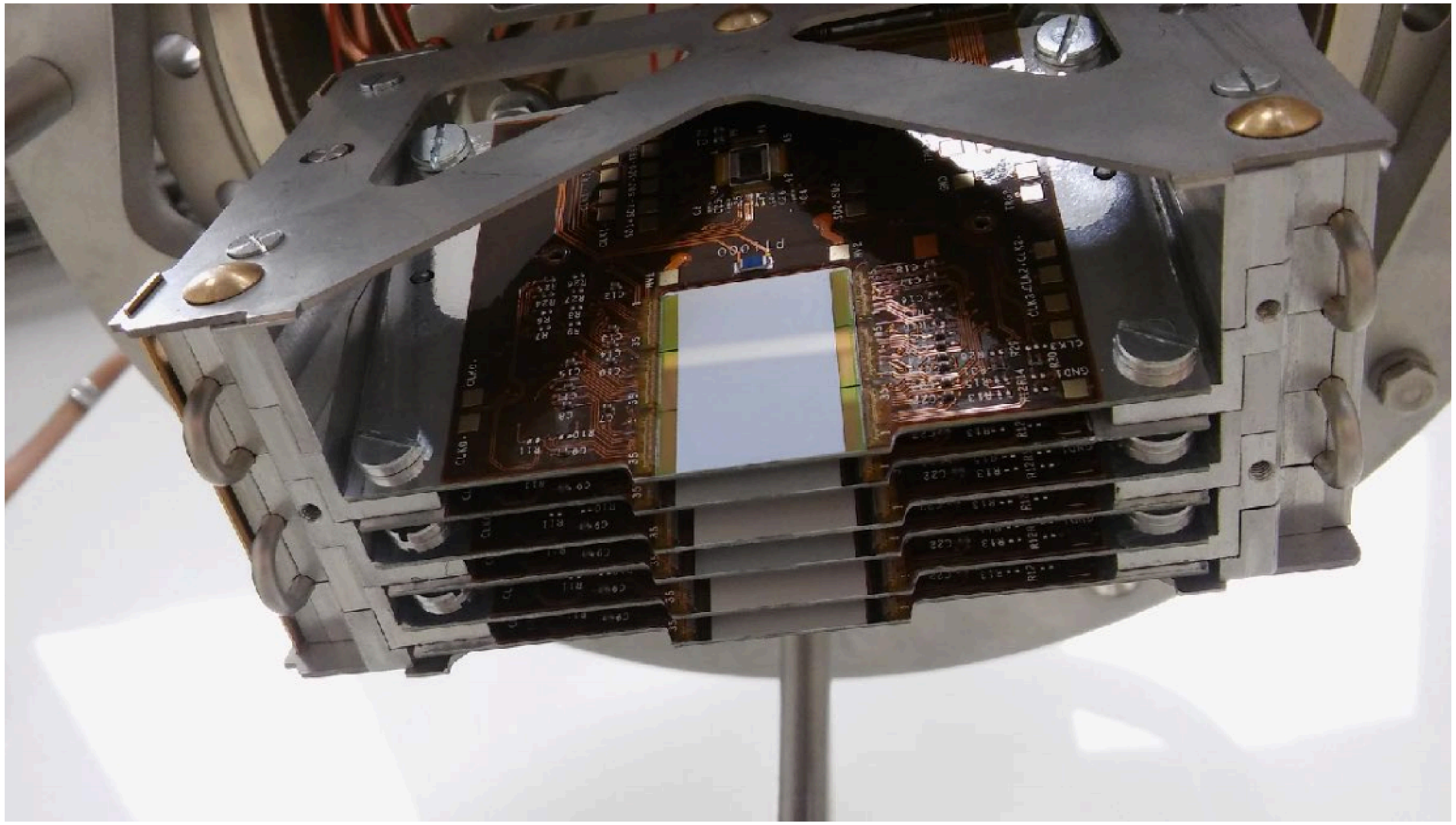
Timing detector for PU rejection

3 diamond and 1 Ultra-Fast Silicon Detector (UFSD) planes

Tracking detector for proton momentum measurement

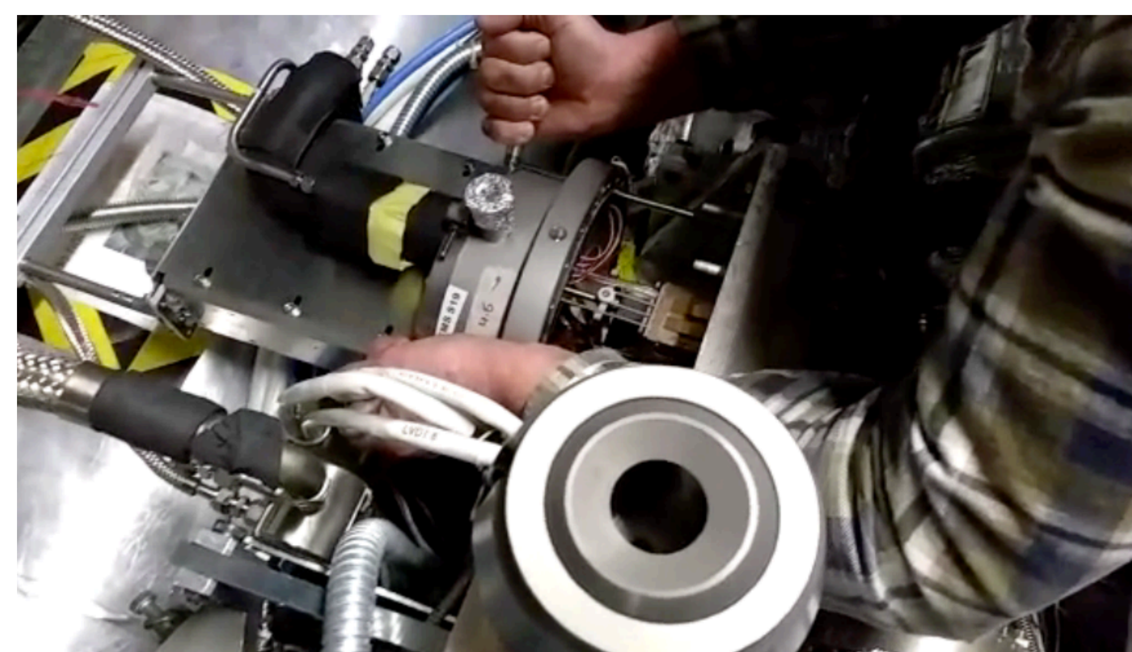
1 strip and 1 3D pixel station

Module assembly and installation



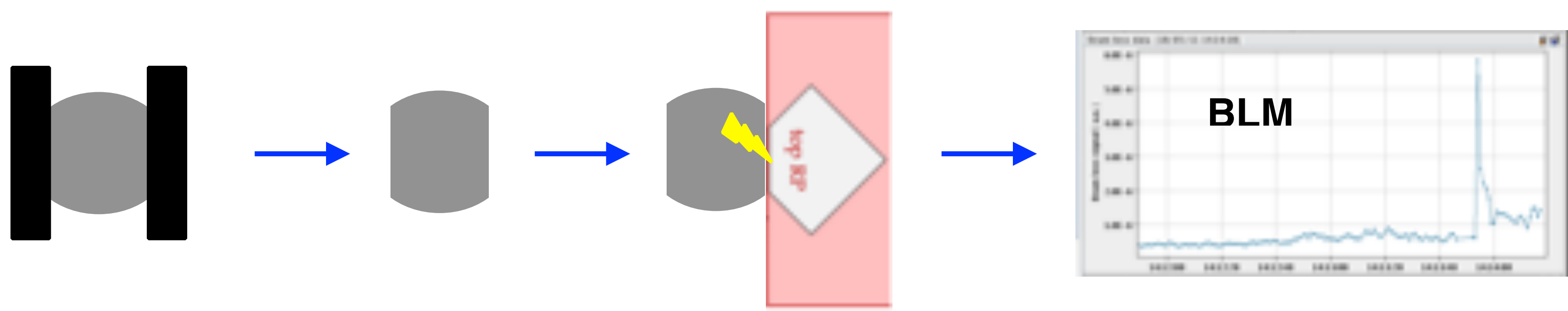
Two tracking stations were assembled and fully tested in lab and in the expected conditions of secondary vacuum and cooling. Each station has 5 3x2 + 1 2x2 modules.

The detectors were installed in the Roman pots along the LHC at the end of March 2017 and commissioned with the first protons.



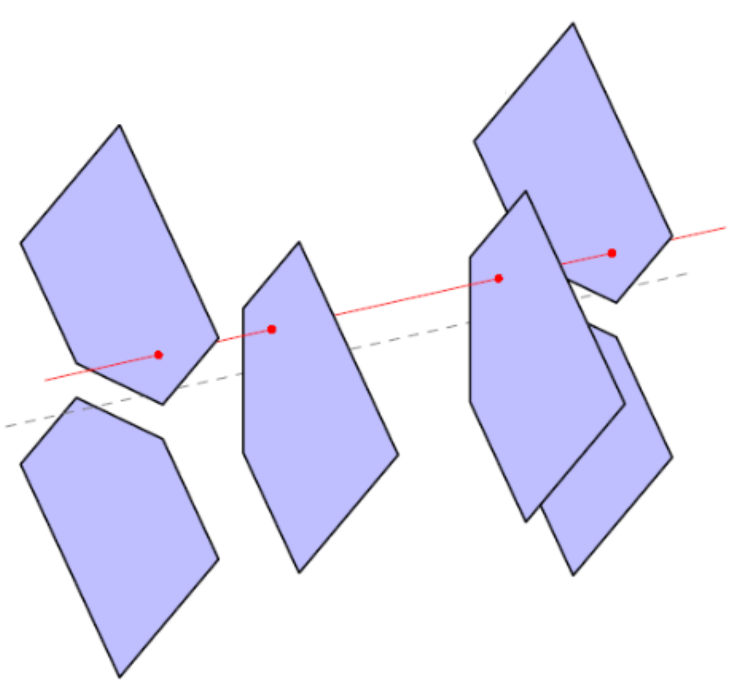
Alignment run procedure

- **Goal: RP alignment with respect to the collimators, relative alignment between the RPs, alignment with respect to the beam, optics determination**.
- Upstream collimators are closed to about 5 - 8.5 sigmas. The RPs (both horizontal and vertical) are slowly moved one by one towards the beam. A spike in the downstream BLMs indicates that the RP has reached the same position as the collimator in terms of beam sigmas.

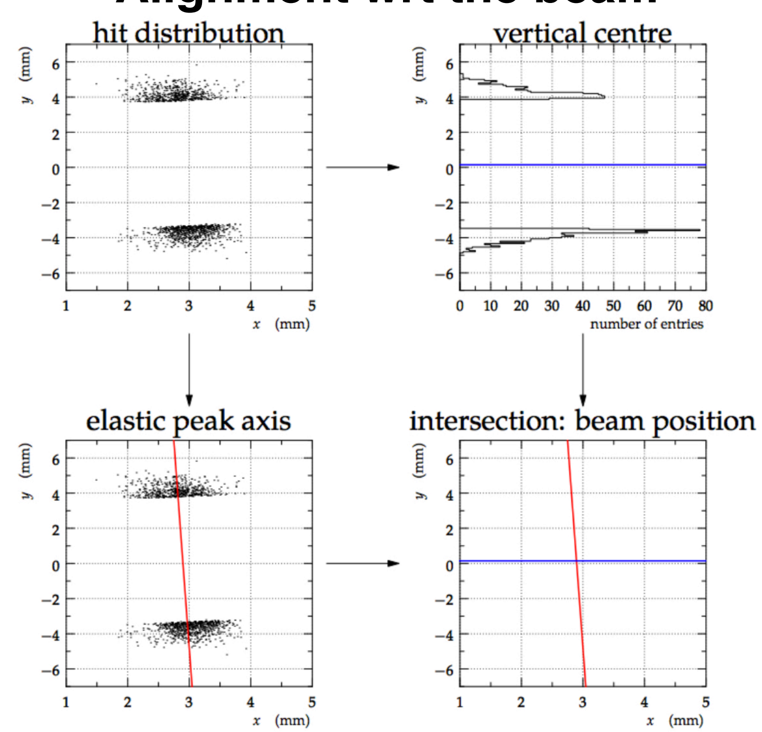


- Alignment with respect to the beam based on the elastic protons measured in the vertical RPs

RP relative alignment

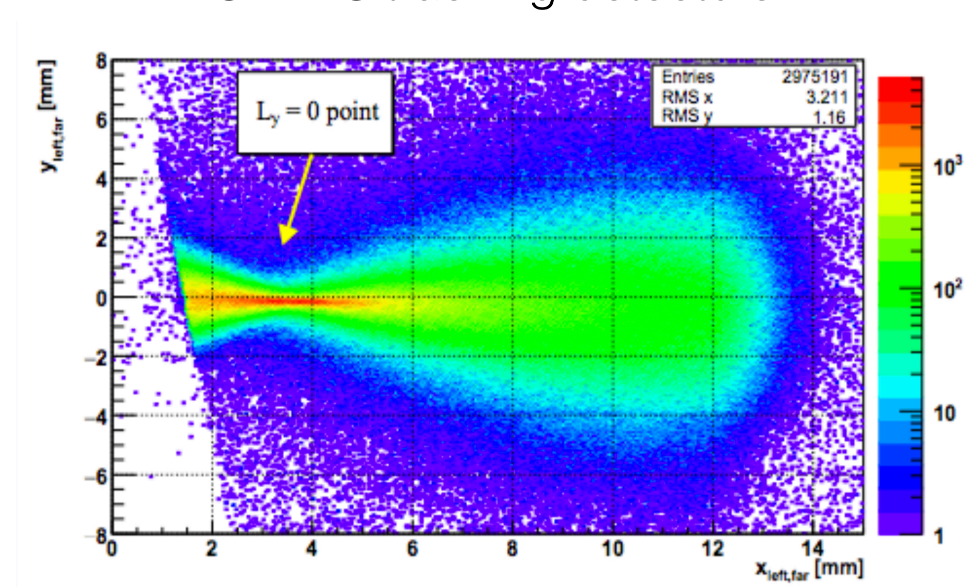


Alignment wrt the beam

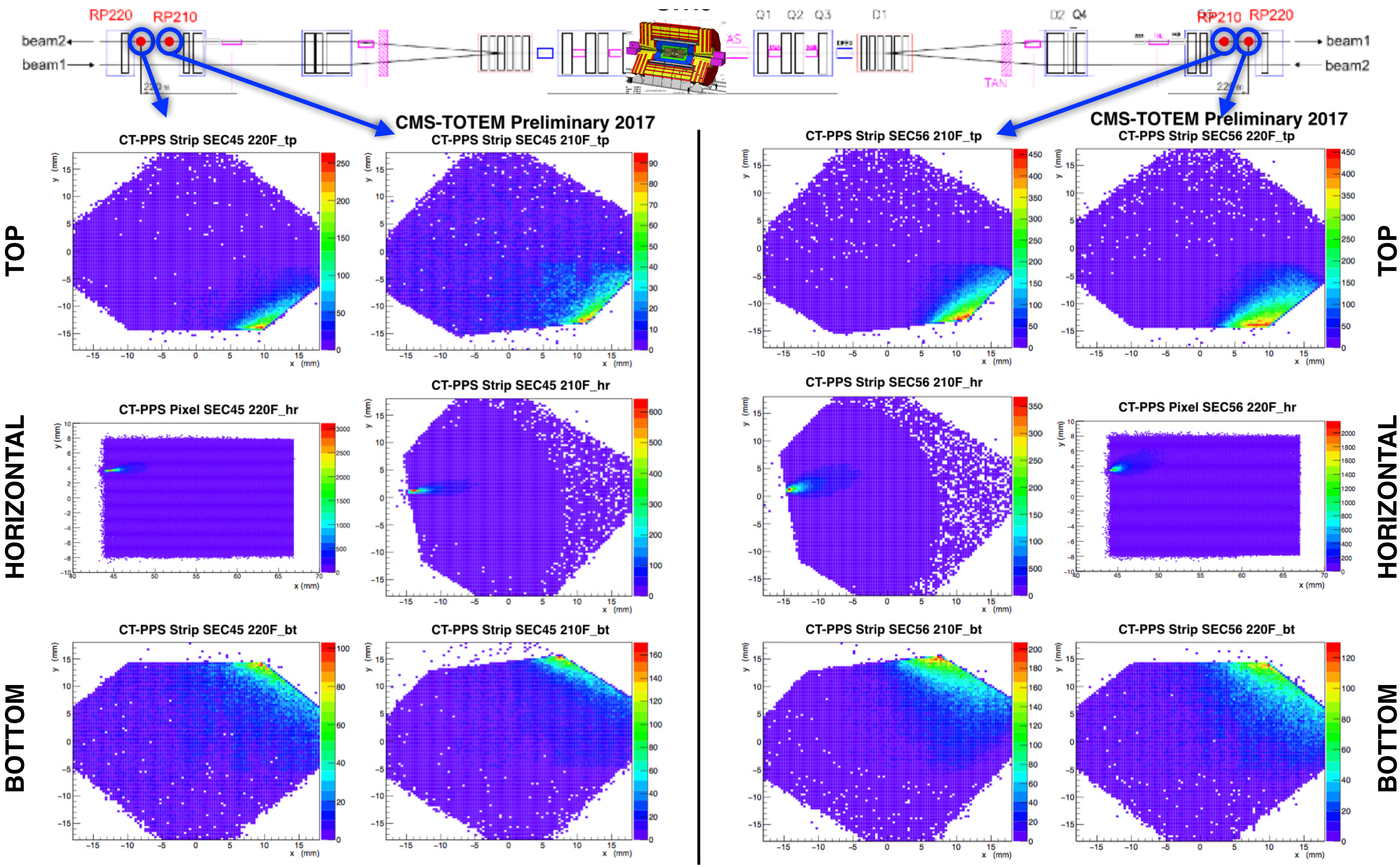


Optics tuning

Based on the hit profile on the CT-PPS tracking detectors

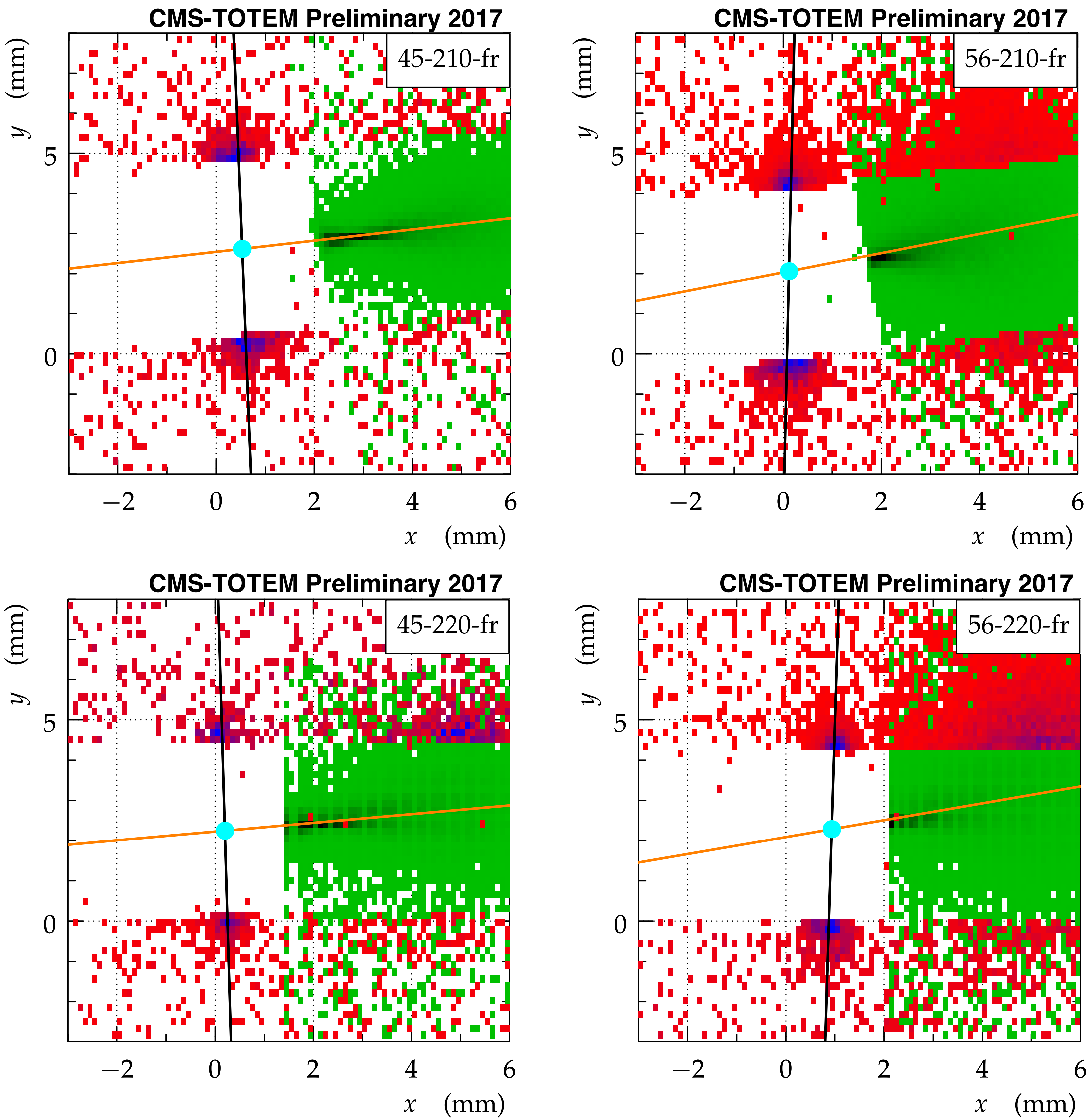


2017 Roman pot alignment run



Data collected during the alignment run at the end of May 2017
x-y coordinates relative to an arbitrary system of reference

RP relative and global alignment



Data of alignment runs are currently under study.

A first estimation of the Roman pot relative alignment and beam position is shown:

- black line: axis of elastic hits
- orange line: fit and extrapolation of hit profile in the horizontal RPs
- cyan point: intersection of black and orange line, estimate of beam position

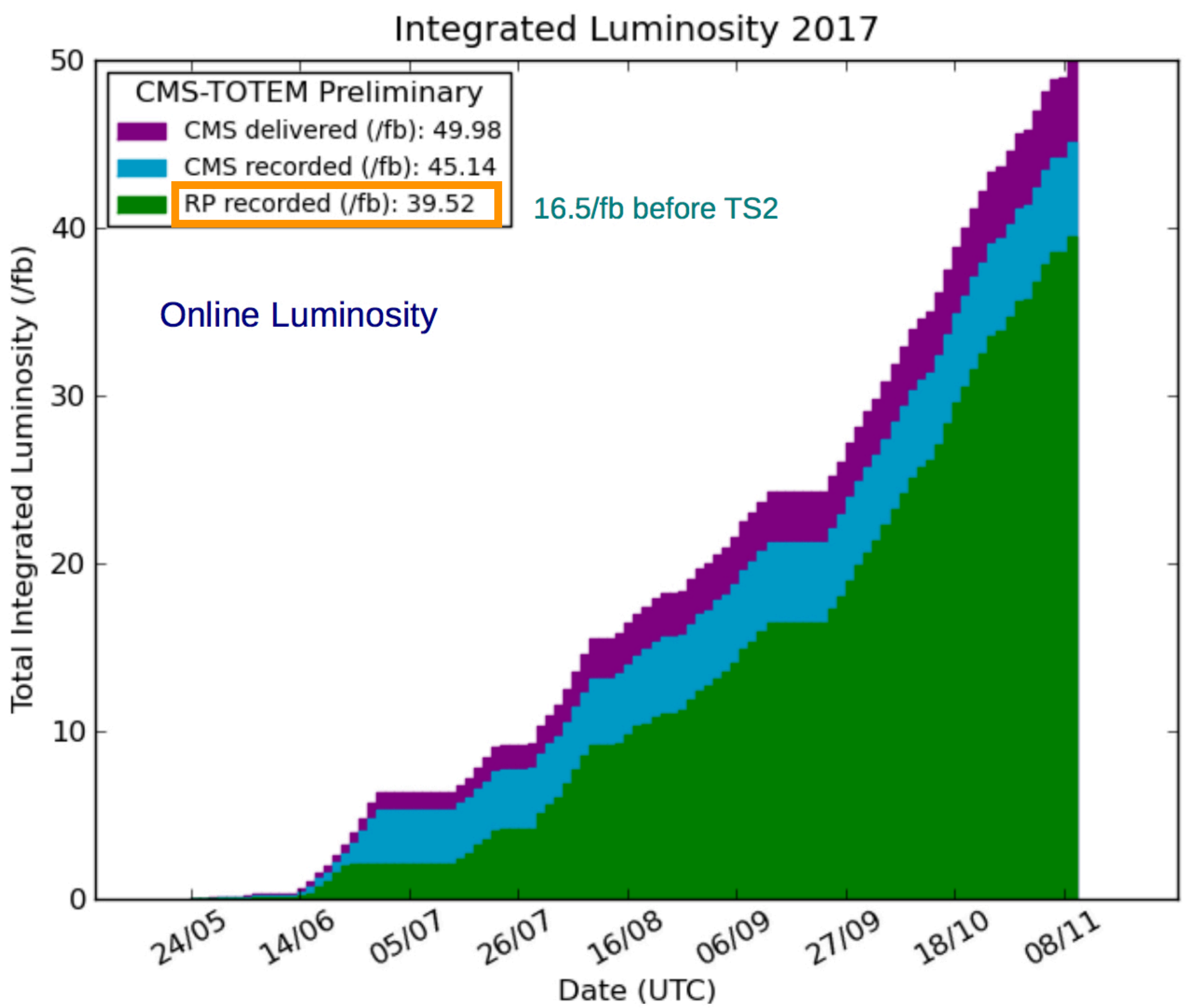
The fine determination of the optics parameters is ongoing.

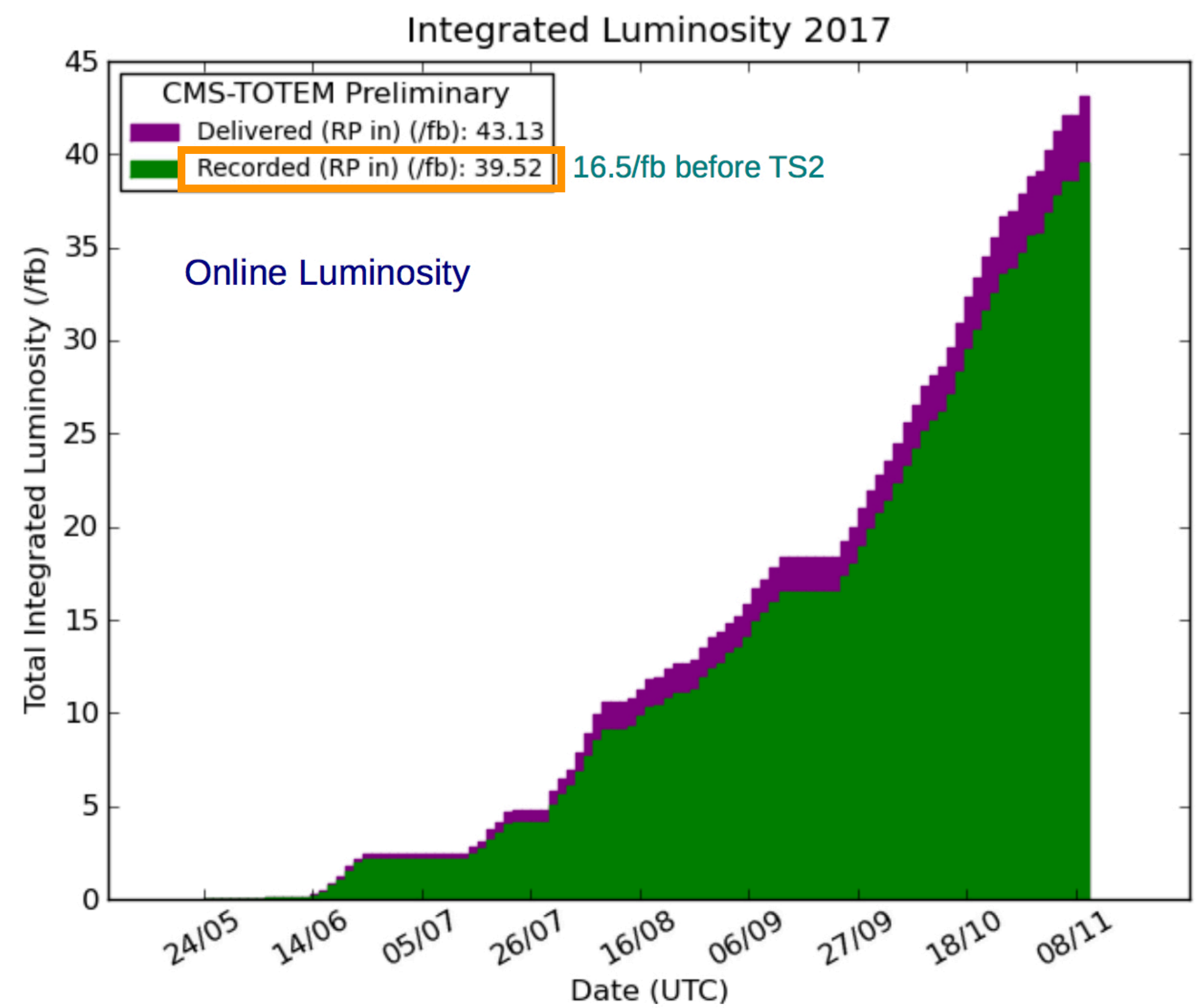
2017 data taking

- The Roman pots were inserted during the LHC intensity ramp-up up to the maximum 2017 luminosity with ~2556 bunches. They were certified for the 2017 data taking and they were **inserted in all high luminosity fills since the Technical Stop 1** (beginning of July 2017)

- **The CT-PPS detector was running stably** with very low impact on the CMS data taking.

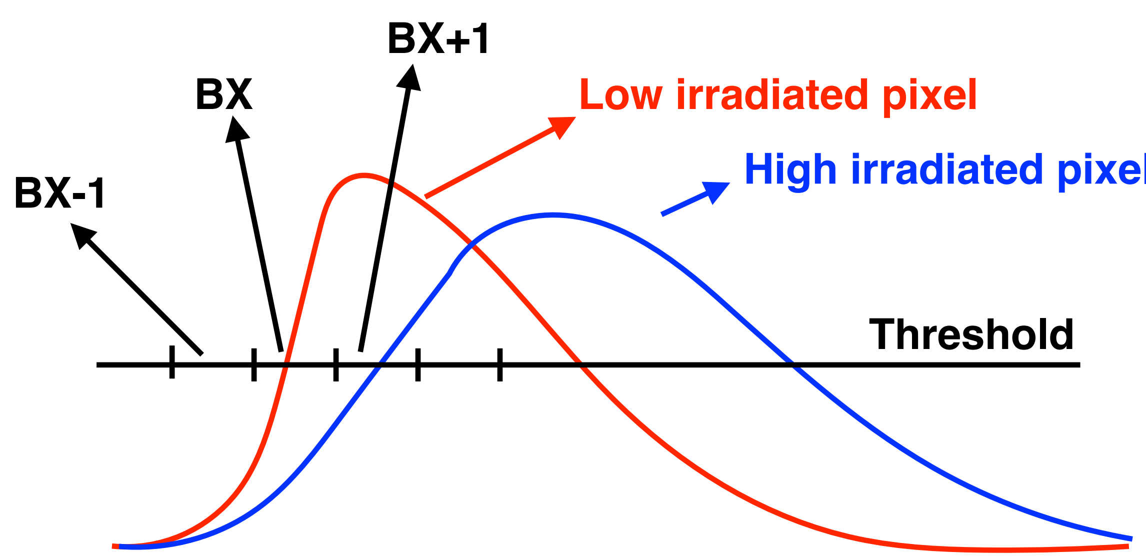
- **In the 2017 CT-PPS collected ~40 fb^{-1} of data**.





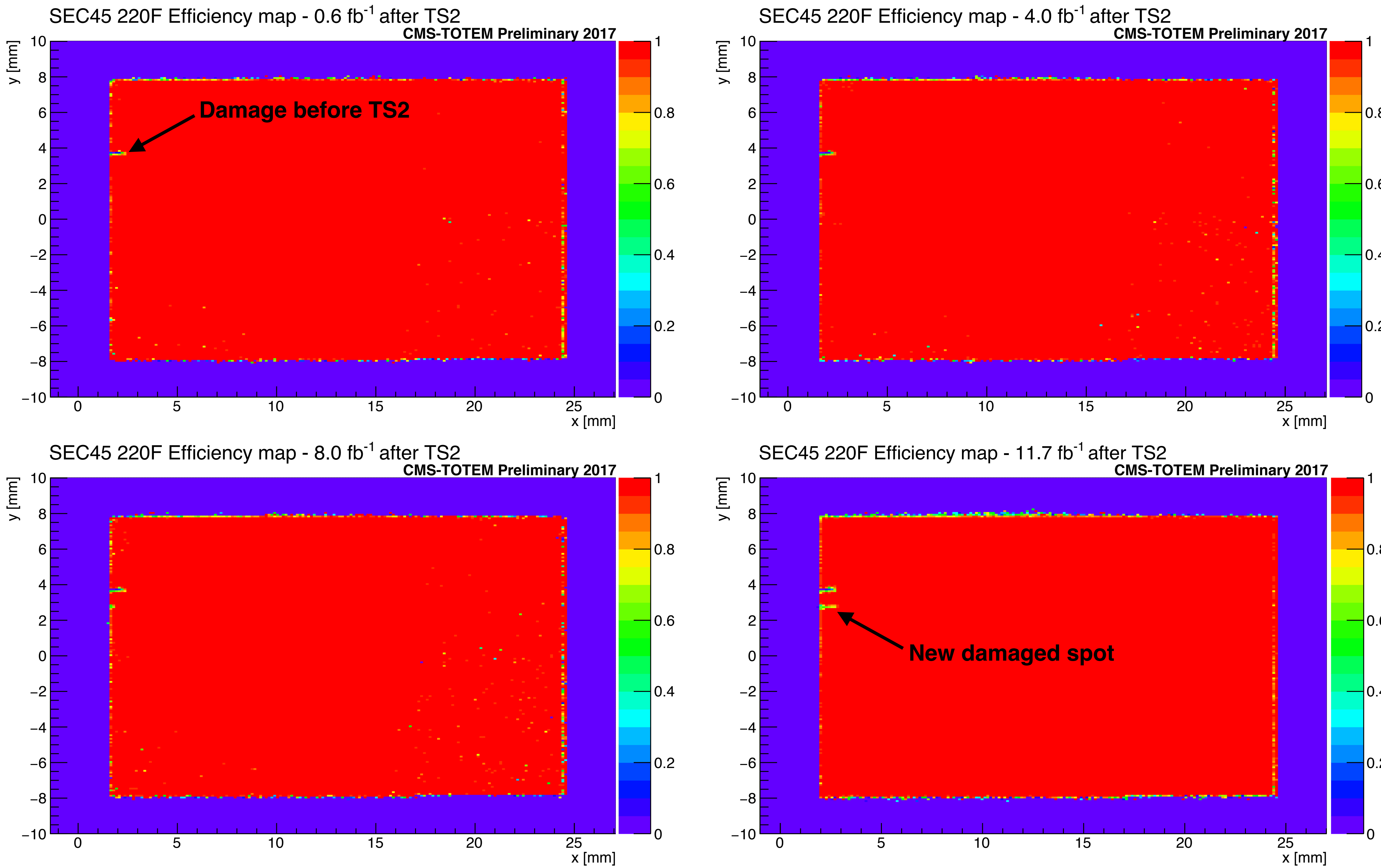
Readout chip radiation damage

- The ROC used in CT-PPS is the same as that in layers 2-3-4 of the CMS central pixel detector.
- The chip was not optimised for non-uniform irradiation.
- After several irradiation tests, it has been understood that a non-uniform irradiation causes a difference between the analog current supplied to the most and the least irradiated pixels.
- The net result is that the amplified signal is slowed down and is associated to the following 25 ns clock window (BX):



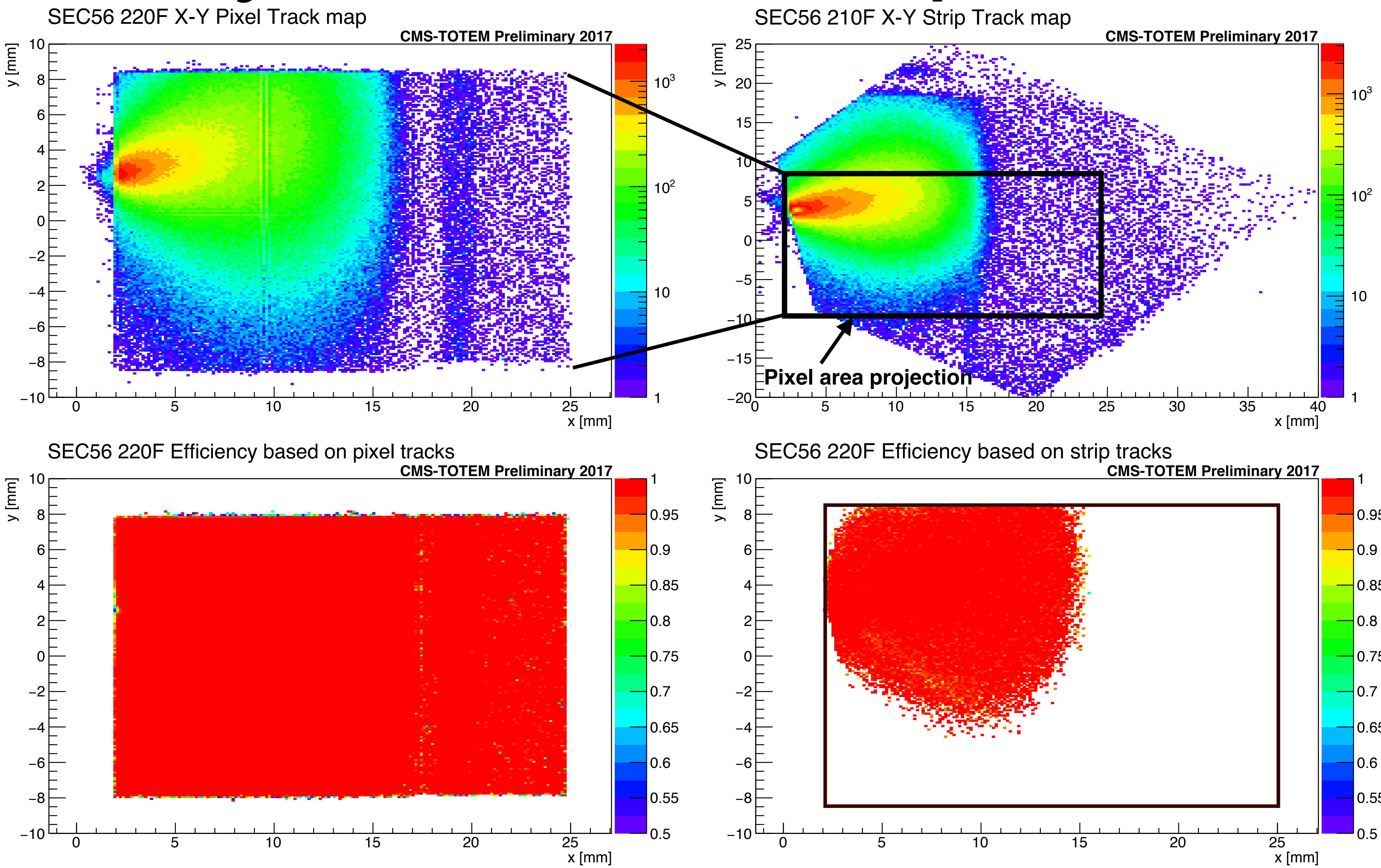
- The irradiation studies showed that the effect appears after an irradiation compatible with a collected integrated luminosity ~8 fb^{-1}. To mitigate the impact on the data quality, the tracking stations were lifted during the 2017 Technical Stop 2 (TS2) to shift the occupancy maximum away from the damaged region.

Efficiency vs Integrated luminosity



Efficiency based on tracks reconstructed within the same tracking station. The inefficient spot at ~4 mm is caused by the radiation damage before TS2. In TS2 the tracking stations were raised by ~1 mm. **A second spot appears as the integrated luminosity increases**, corresponding to the new occupancy maximum.

Efficiency based on strip tracks



The **pixel efficiency** calculated with the tracks reconstructed within the same pixel station is **validated with tracks reconstructed in the strip detectors**. To avoid showers produced by the cylindrical timing pot located between the strip and the pixel stations, the study was carried out for a fill with the timing pots out. The efficiency is calculated with the requirement of at least 15 entries per bin (~ 1 pixel cell) to avoid low-statistics fluctuations (hence the shape of the region in the bottom right plot).

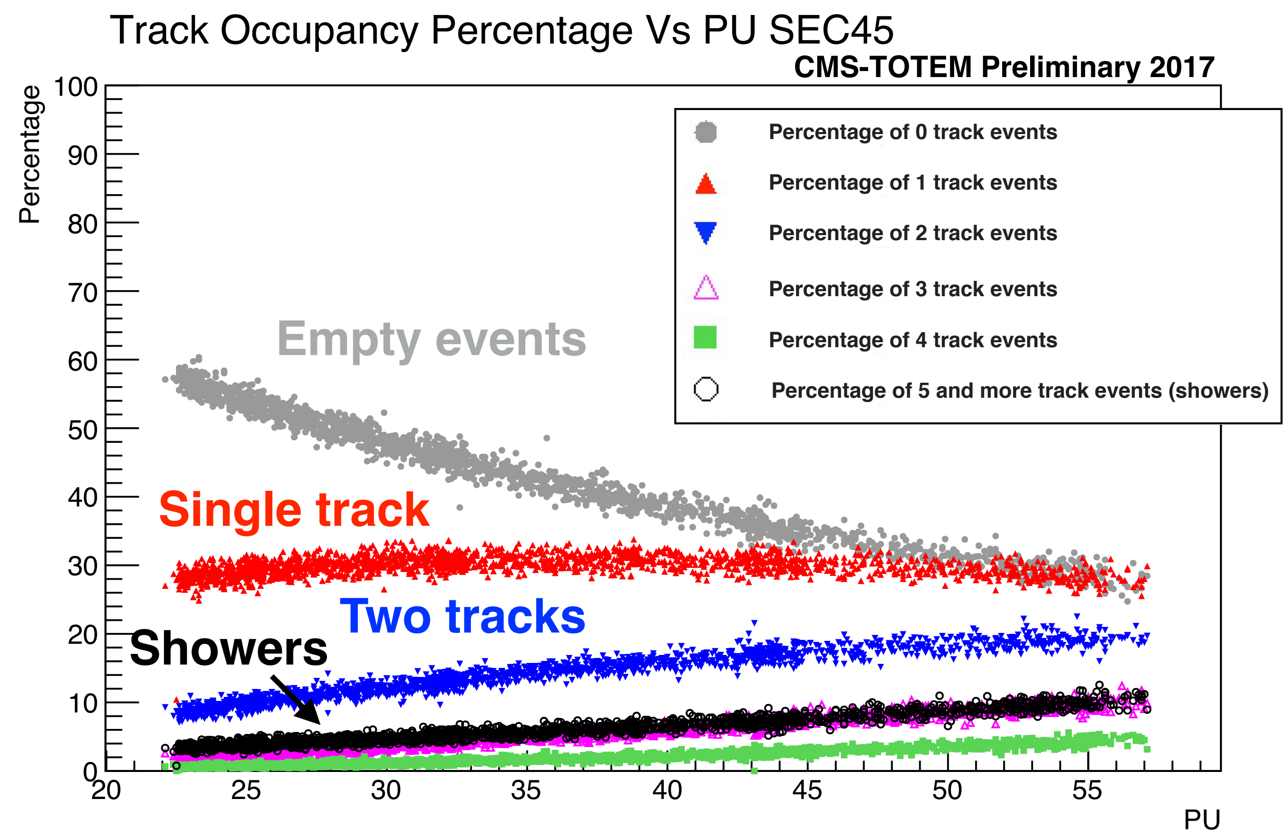
Track reconstruction

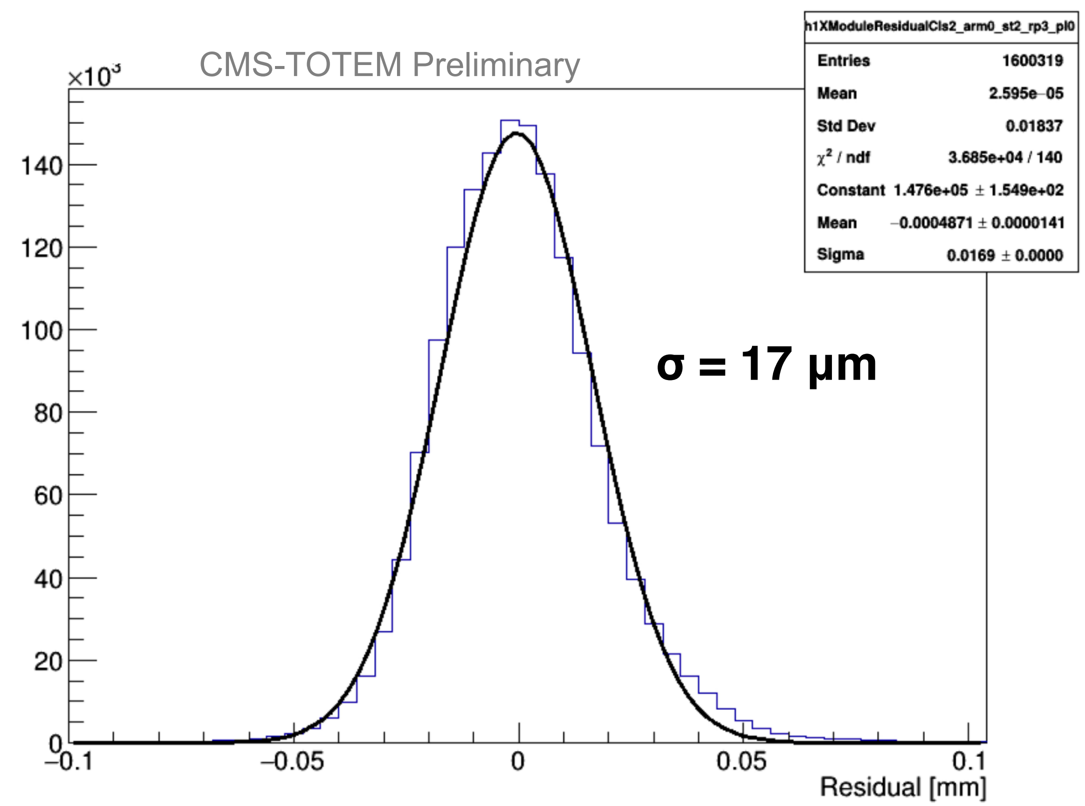
The number of tracks reconstructed by the pixel detector shows a clear correlation with the number of PU events

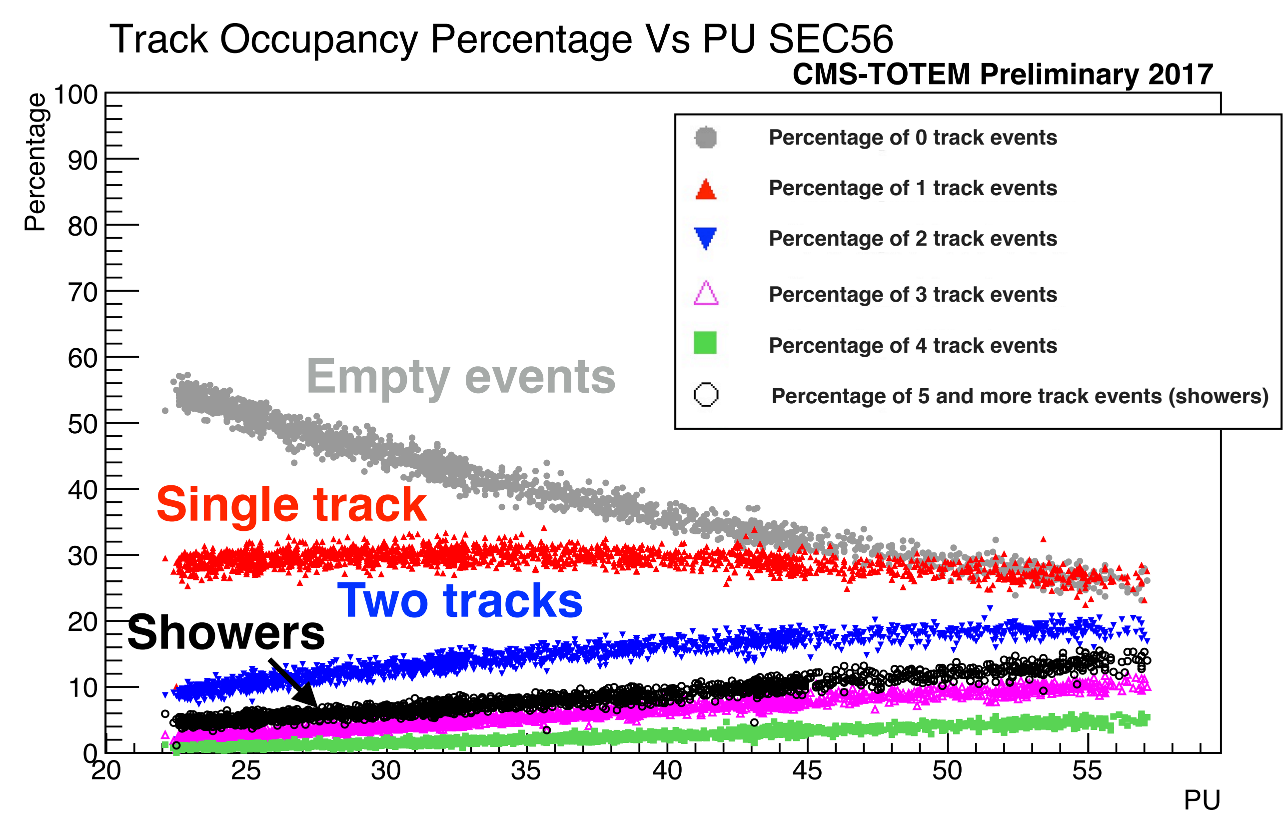
Percentage of showers/tracks ≥ 5 (**black points**) is directly proportional to PU and at the maximum luminosity reaches 10%.

Residuals are consistent with those obtained at the beam tests.

The pixel tracker works as expected.

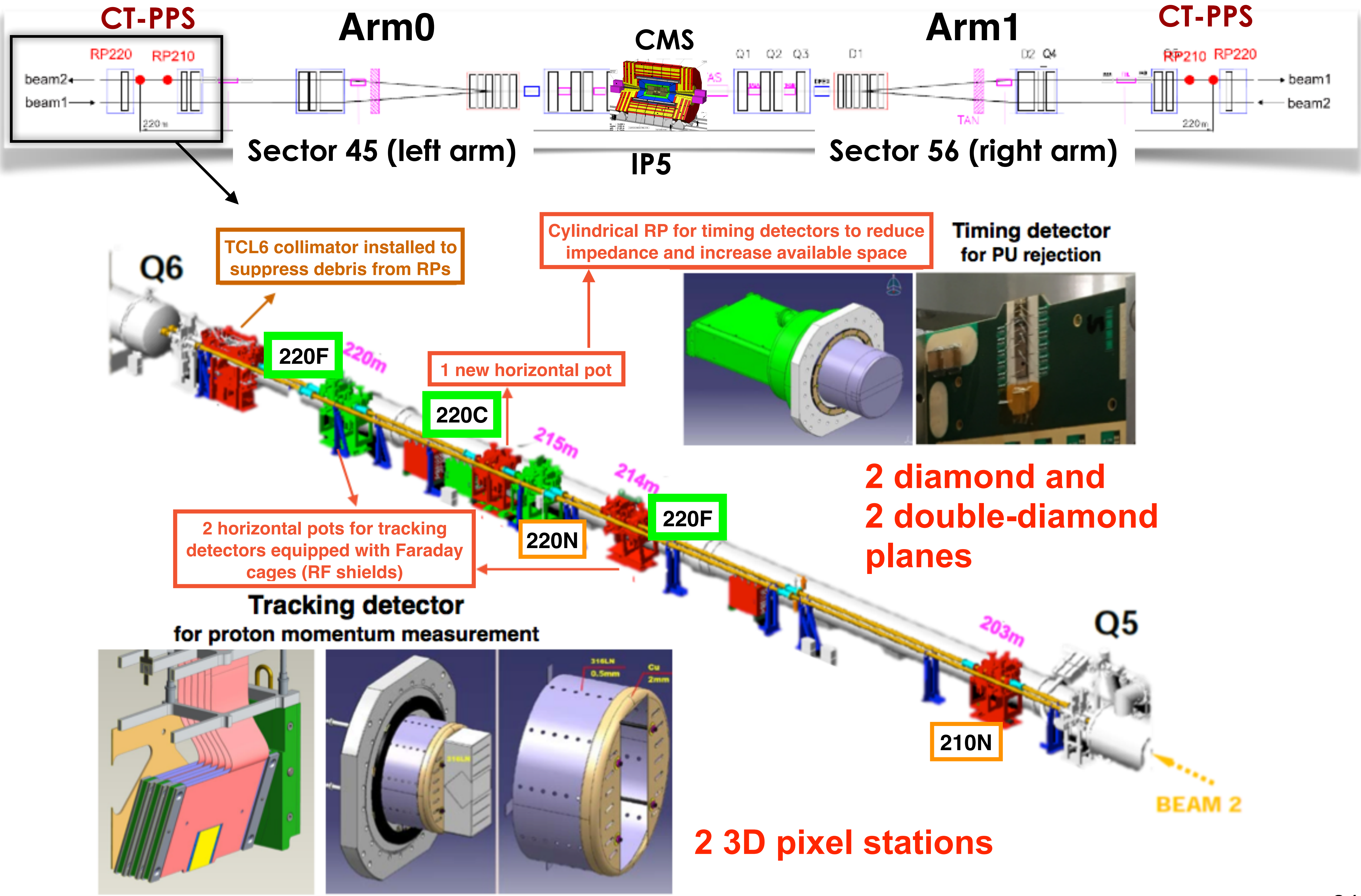






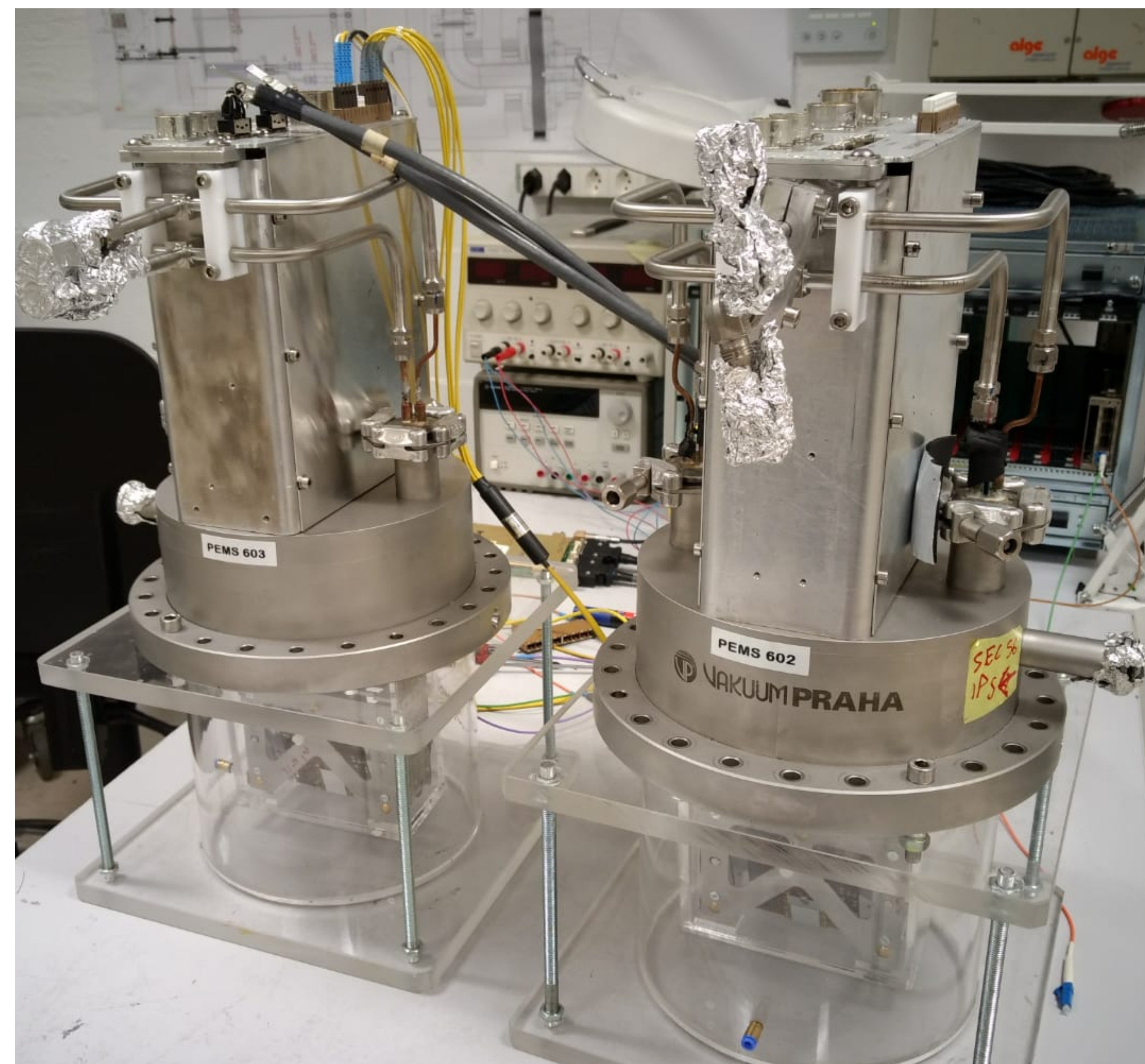
2018 data taking

2018 detector setup



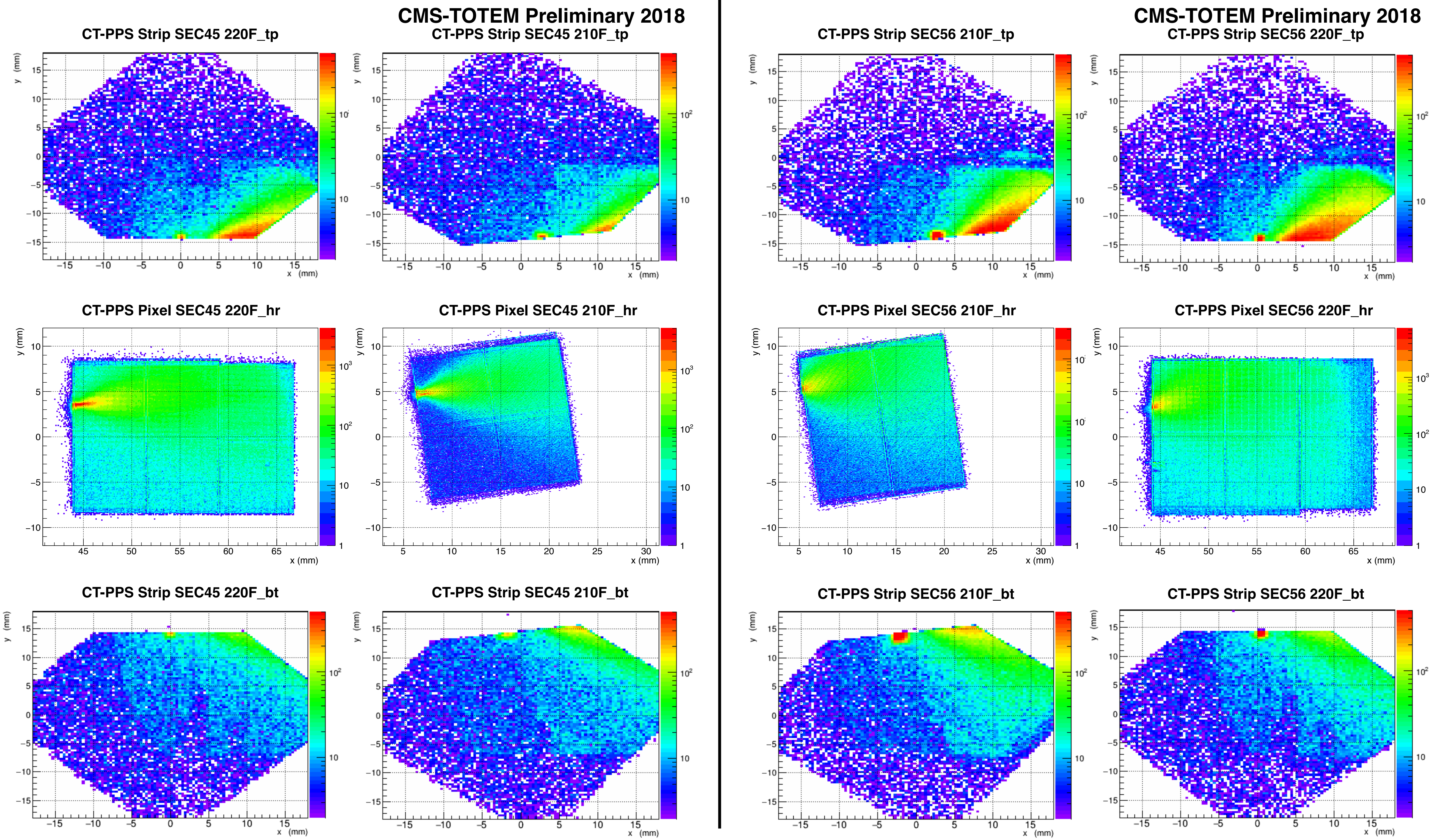
2018 tracking detectors

- Two further 3D pixel detector packages for the 210F tracking stations were assembled and tested in the same conditions expected in LHC.
- Due to the lack of high quality 3x2 modules, the new stations are mostly equipped with 2x2 detectors, which still guarantee a good acceptance.
- For the 220F stations the 2017 detectors were swapped between SEC45 and SEC56 so that the damaged areas are now localised away from the high intensity spot, ensuring high performance detector also for the 2018 data taking
- All the pixel stations have been installed in February 2018 during the year-end technical stop of LHC.



2018 Roman pot alignment run

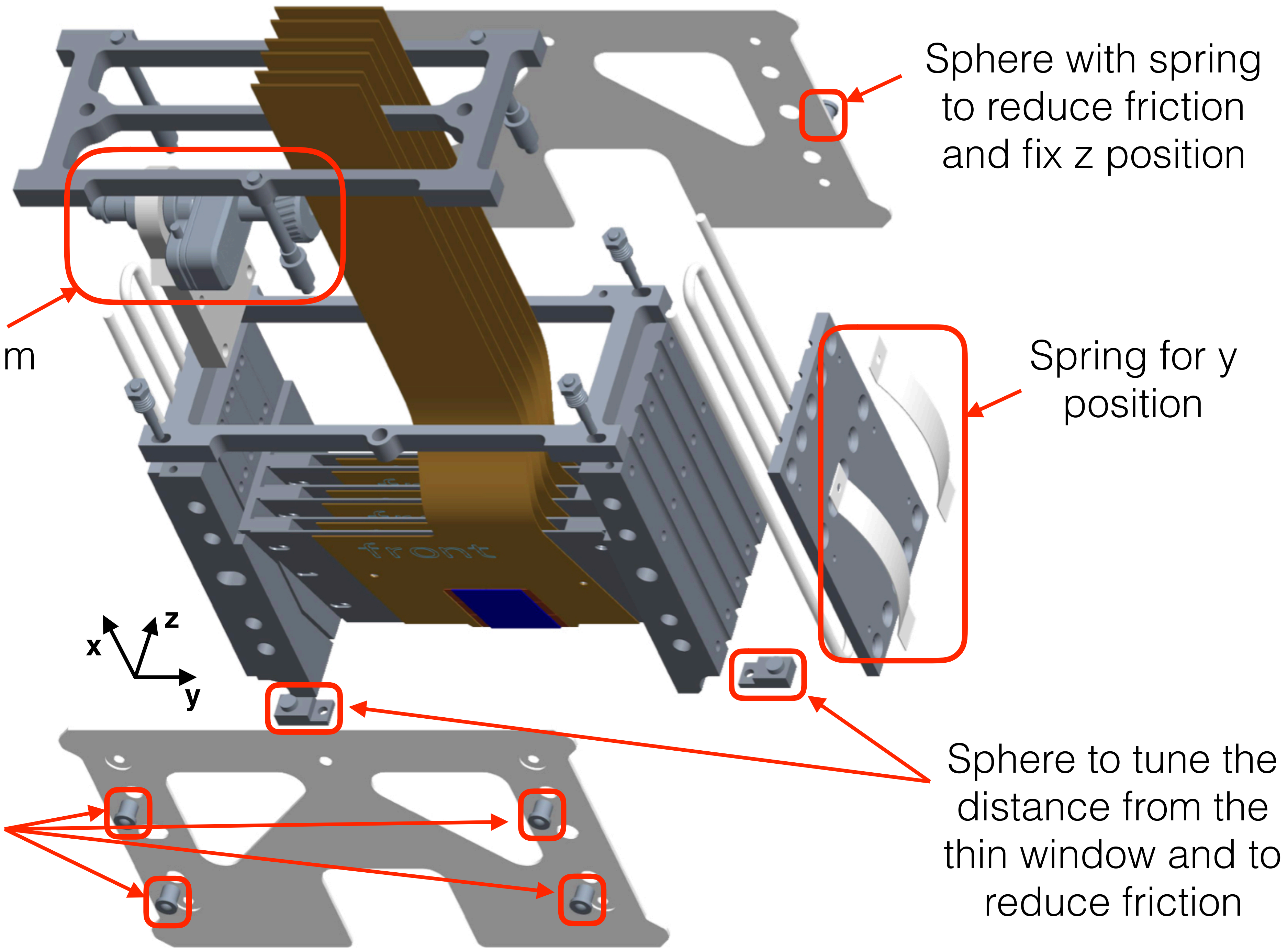
Sector 45 **Sector 56**



Data collected during the alignment run in April 2018
x-y coordinates relative to an arbitrary system of reference

Detectors with remote movement

To mitigate the radiation damage of the electronics, we are developing a new detector package that can be moved inside the RP in a quick tunnel access. Five position spaced by 500 μm will be available, so as to handle up to ~50 fb^{-1} with minimal efficiency loss. We plan to install the new packages as soon as they are ready and validated.



Summary and conclusions

- **2016 CT-PPS installation with an "accelerated program"**
  2 silicon strip stations per side
  - **~15 fb^{-1} collected**.
  - First physics results: arXiv:1803.04496
- **2017 CT-PPS tracking detector installation**
  1 silicon strip and 1 3D silicon pixel (**first usage in CMS**) tracking station per side
  - **~40 fb^{-1} collected**.
  - Detector alignment and optics determination is ongoing
  - Performance of the pixel detectors is that expected from beam tests and irradiation campaigns
- **2018 CT-PPS tracking detector installation completed in February**:
  2 3D silicon pixel tracking stations per side (final detector configuration)
  - **The CT-PPS tracking detector is running stably**.
  - For mitigating the effect of the ROC non-uniform irradiation damage on the data quality, detector packages with a remote movable system are under development and foreseen to be installed as soon as ready and validated

Backup

Physics motivations

QCD: LHC as gluon-gluon collider with tagged proton

- Exclusive two and three jet events
- Test of pQCD mechanism of exclusive production
- Gluon jet samples with small component of quark jets

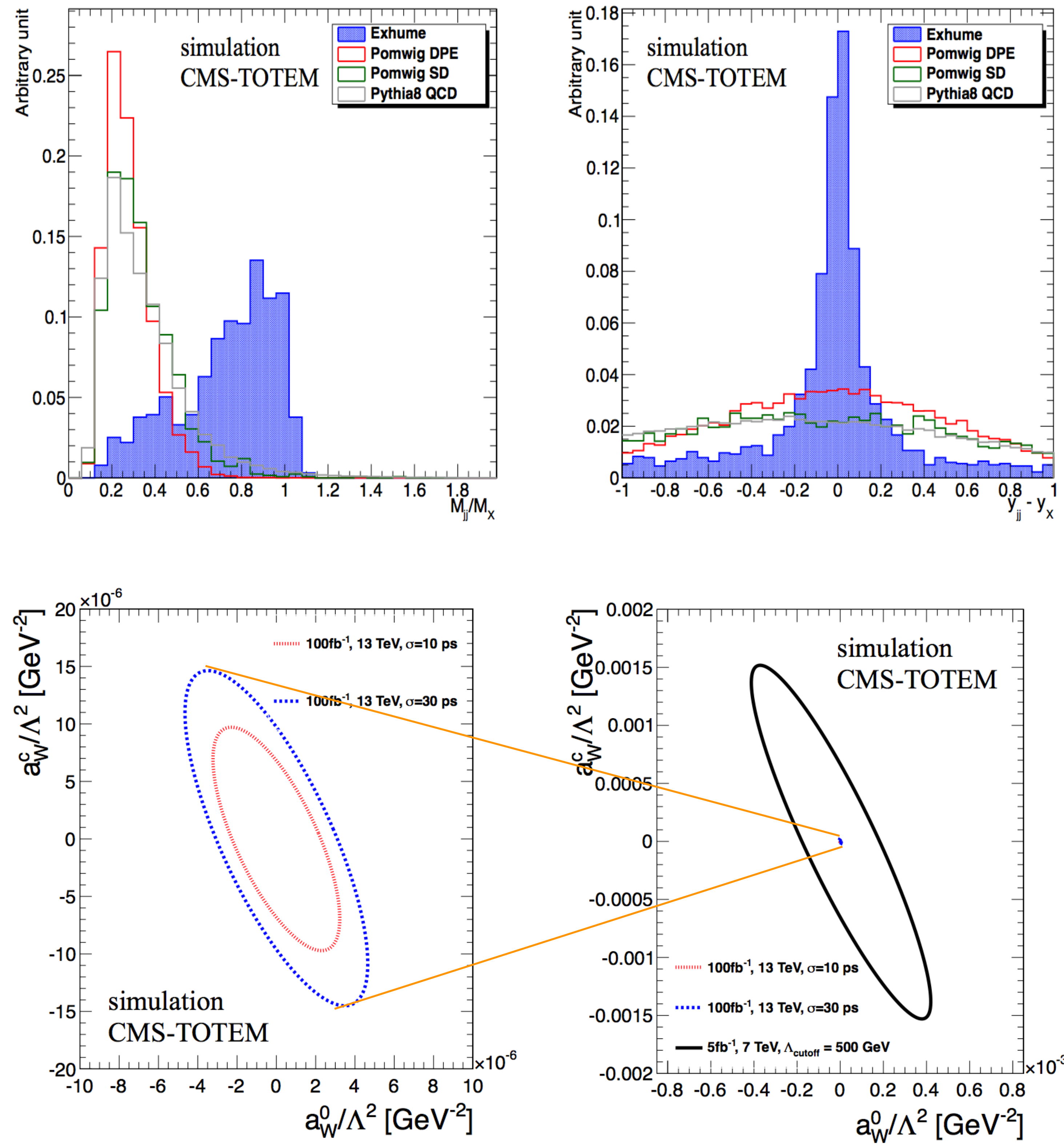
EWK: LHC used as photon-photon collider

- Measurement of $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for anomalous quartic gauge couplings (AQGCs) with high sensitivity

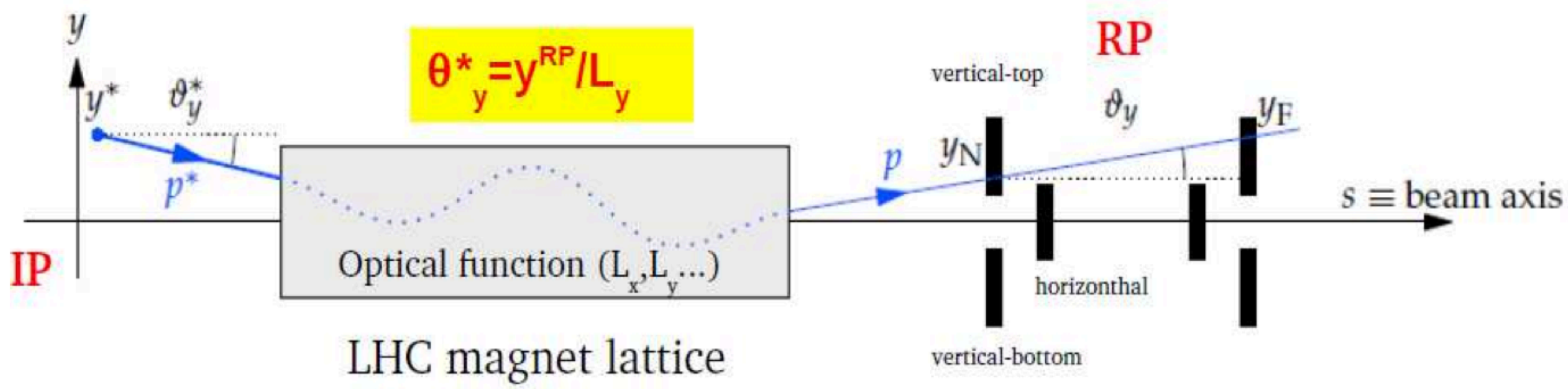
Beyond Standard Model:

- Clean events (no underlying event)
- Independent mass measurement by pp system
- JPC quantum numbers 0++, 2++

TDR studies

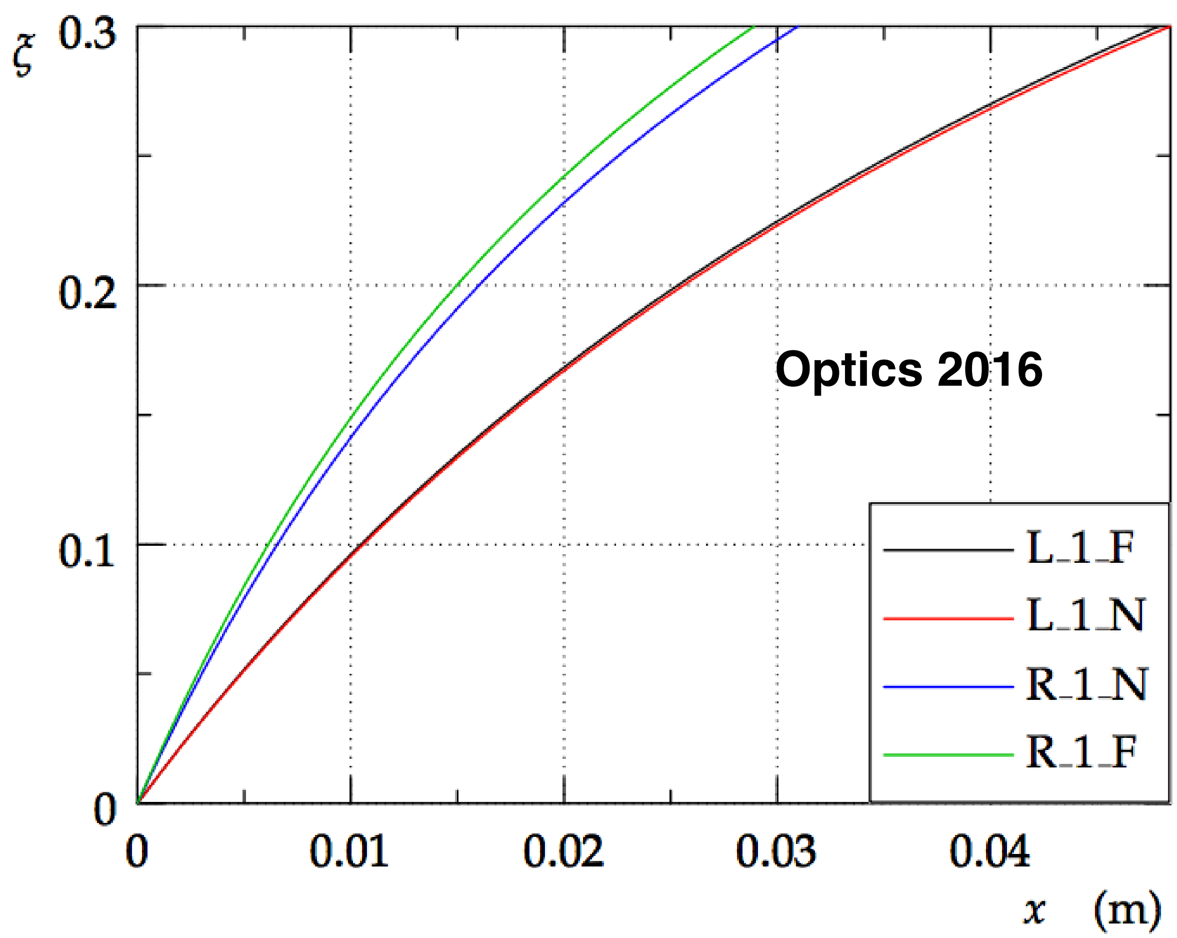


LHC beam optics



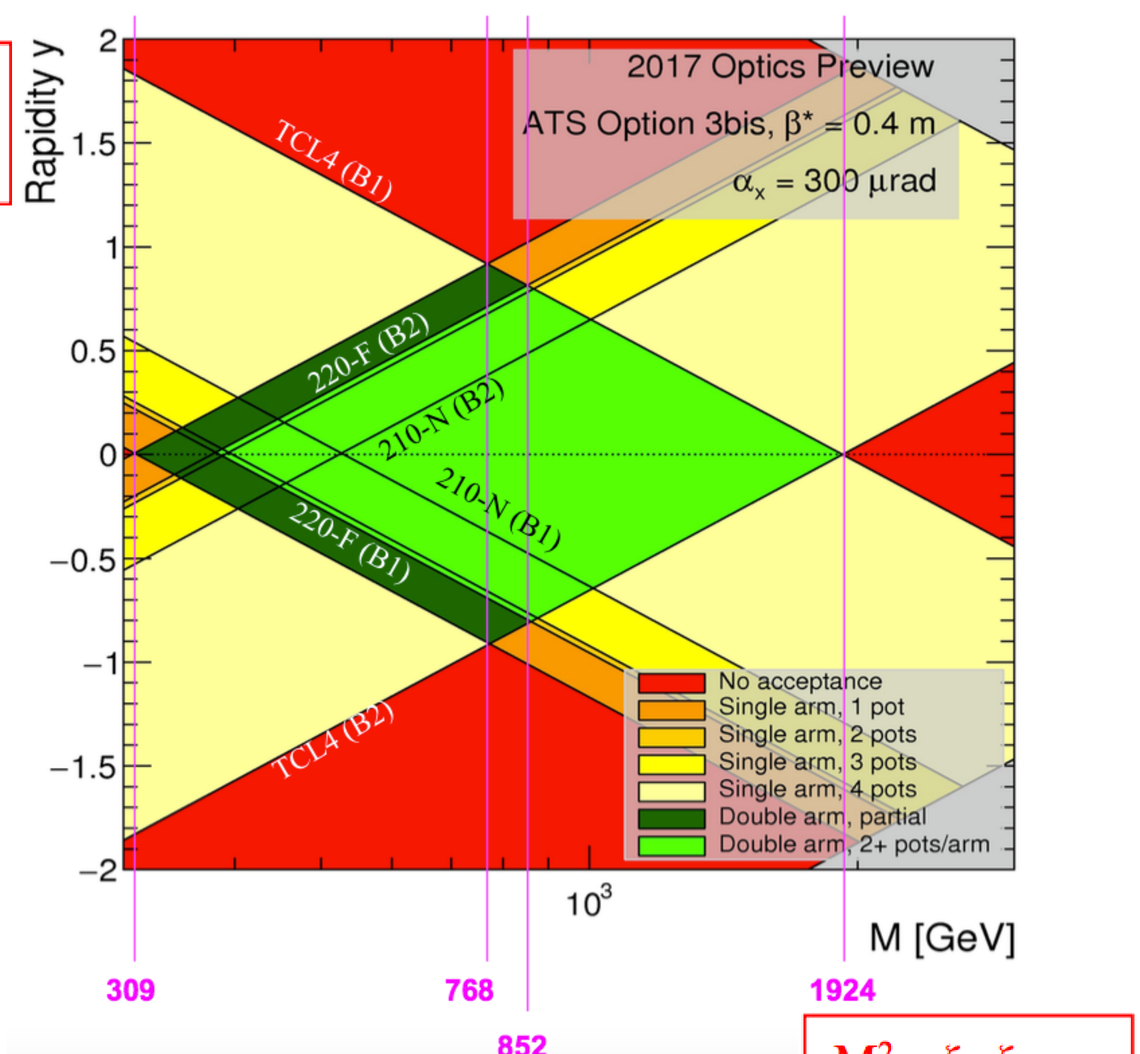
Proton kinematics at the detector is determined by optics and proton kinematics at IP.

ξ vs x at the RP



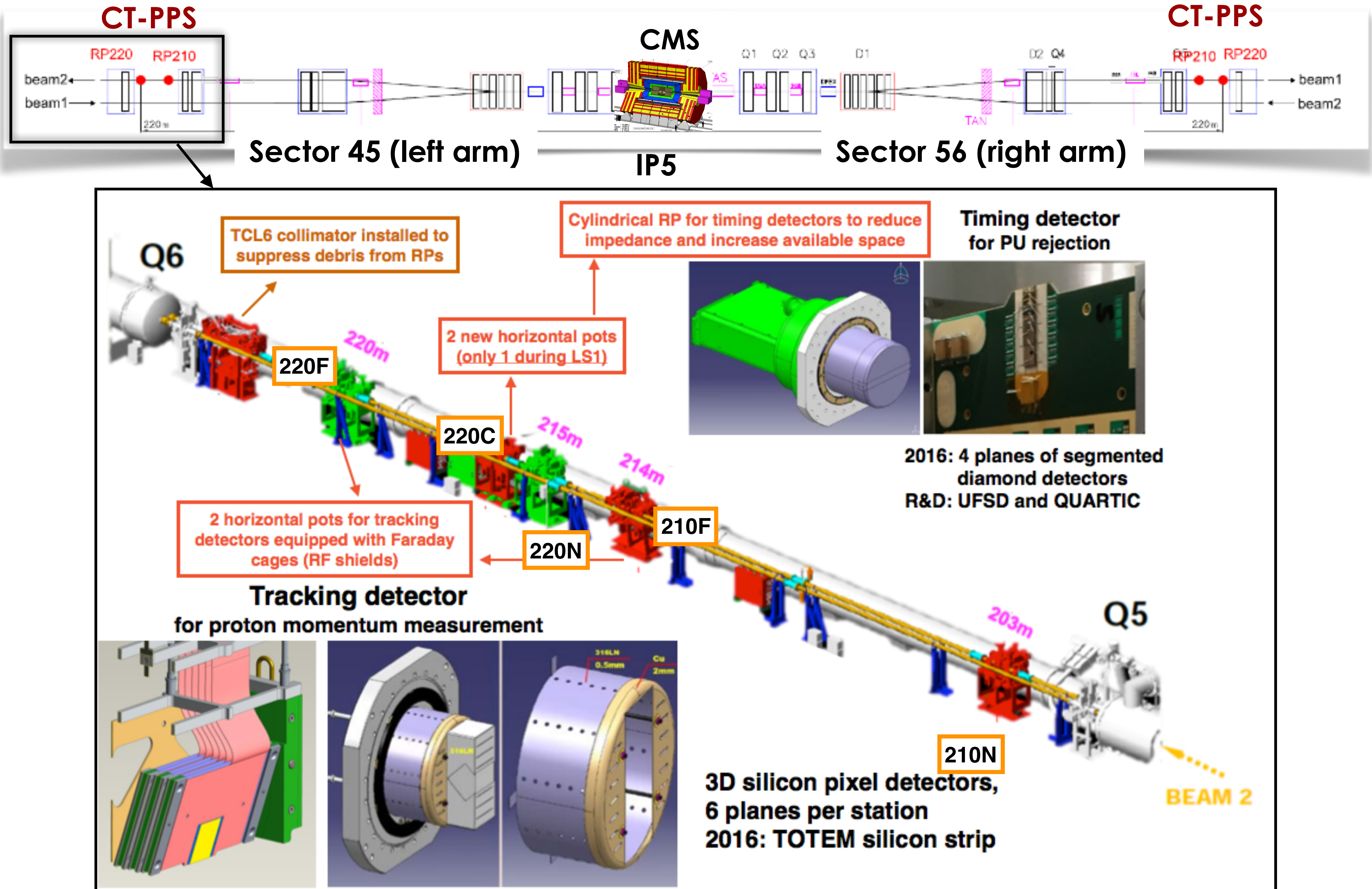
Mass and rapidity acceptance

$$y = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$$



$$M^2 = \xi_1 \xi_2 s$$

Detector setup in 2016



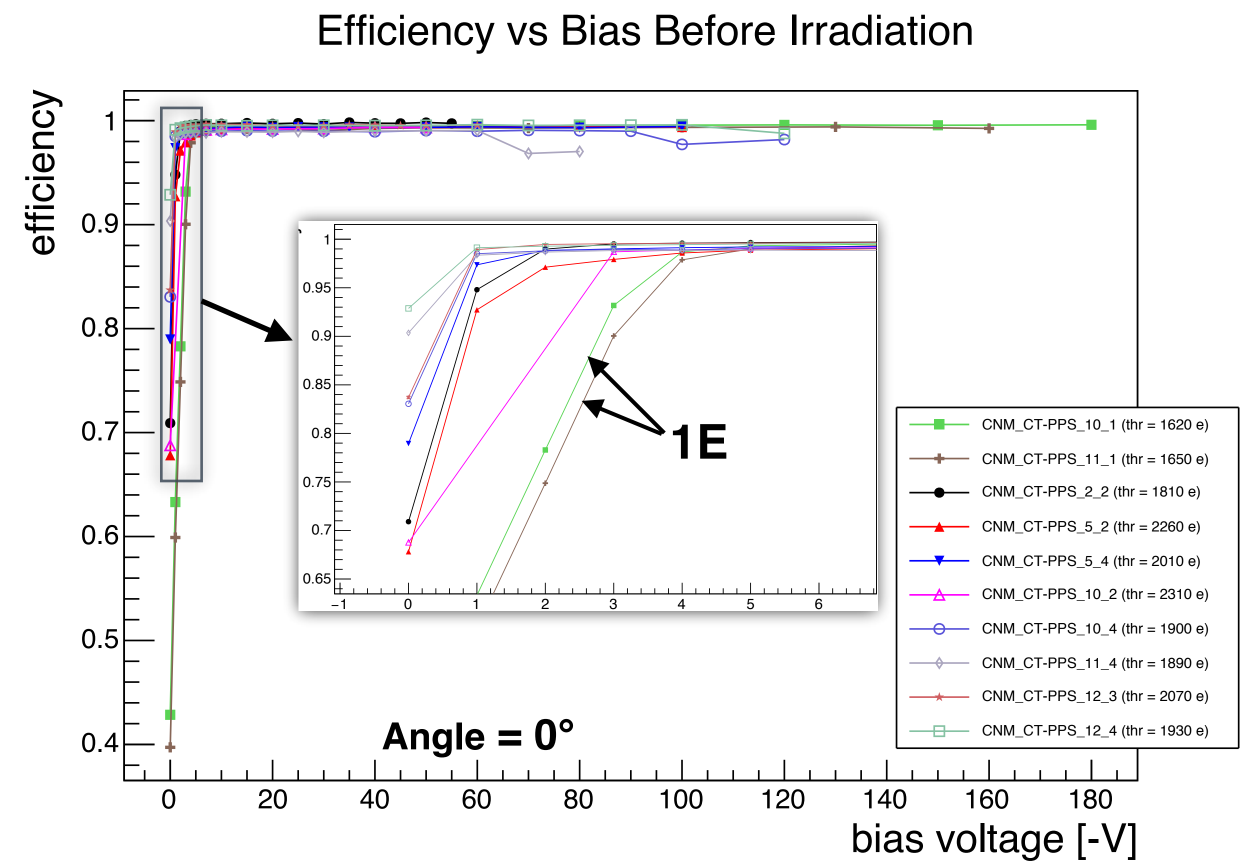
3D detectors - Efficiency

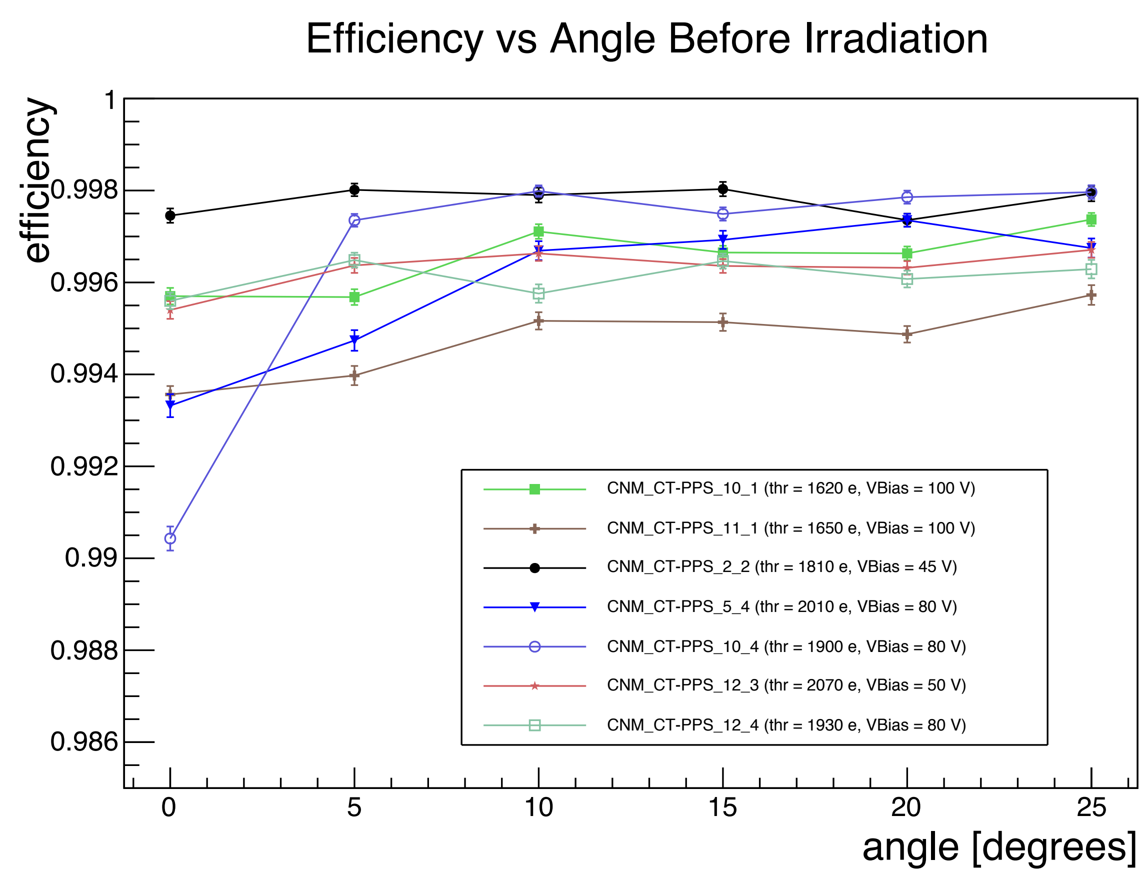
10 single-ROC sensors (**2 1E and 8 2E**) from the first production have been bump-bonded at IZM to the ROC and have been **tested at FNAL on beam.**
Sensors selected of both class A and B.

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.

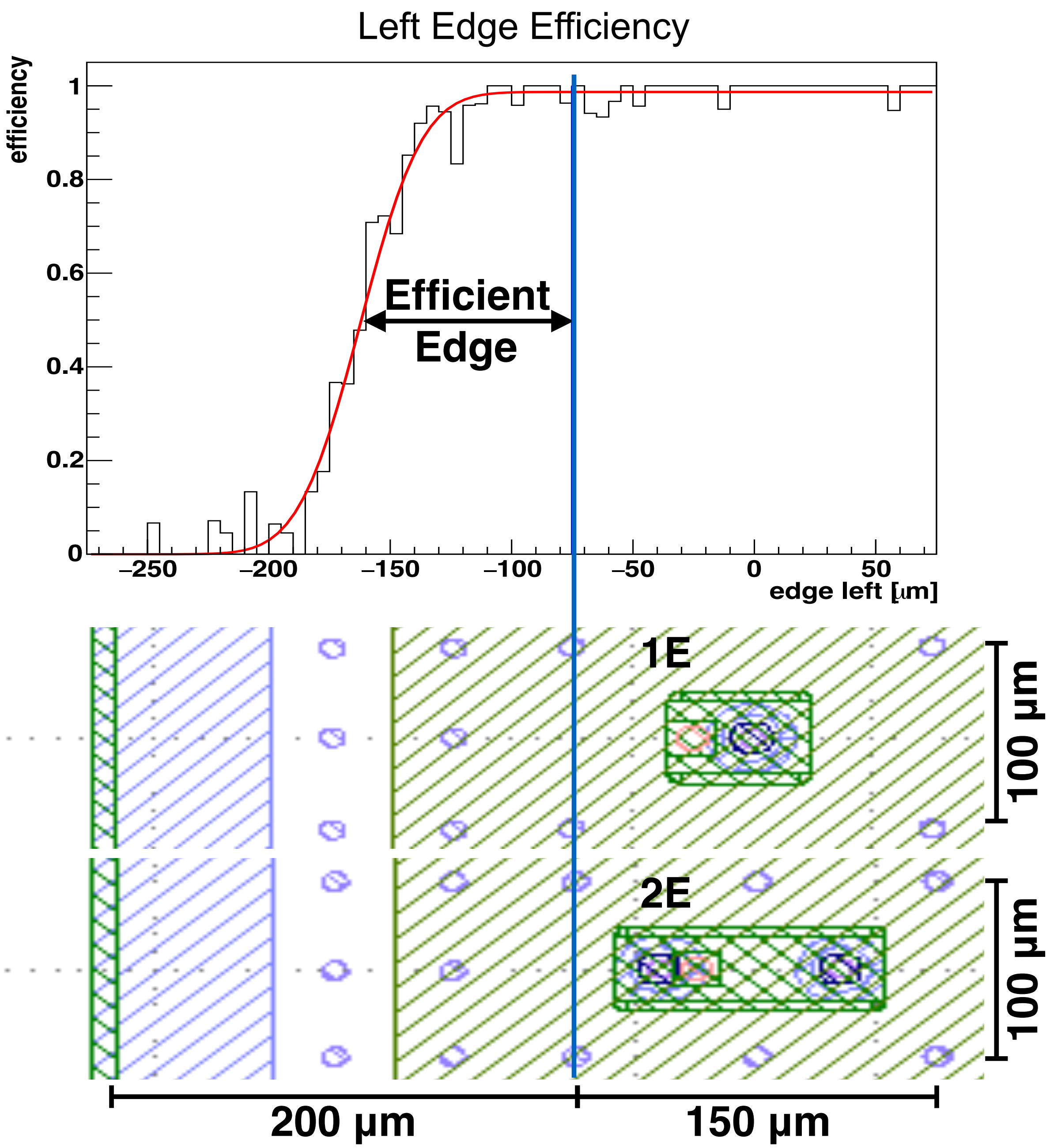
Thanks to the not-fully passing-through columns and the well optimised thresholds, high efficiency is obtained even without rotating the sensors.

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

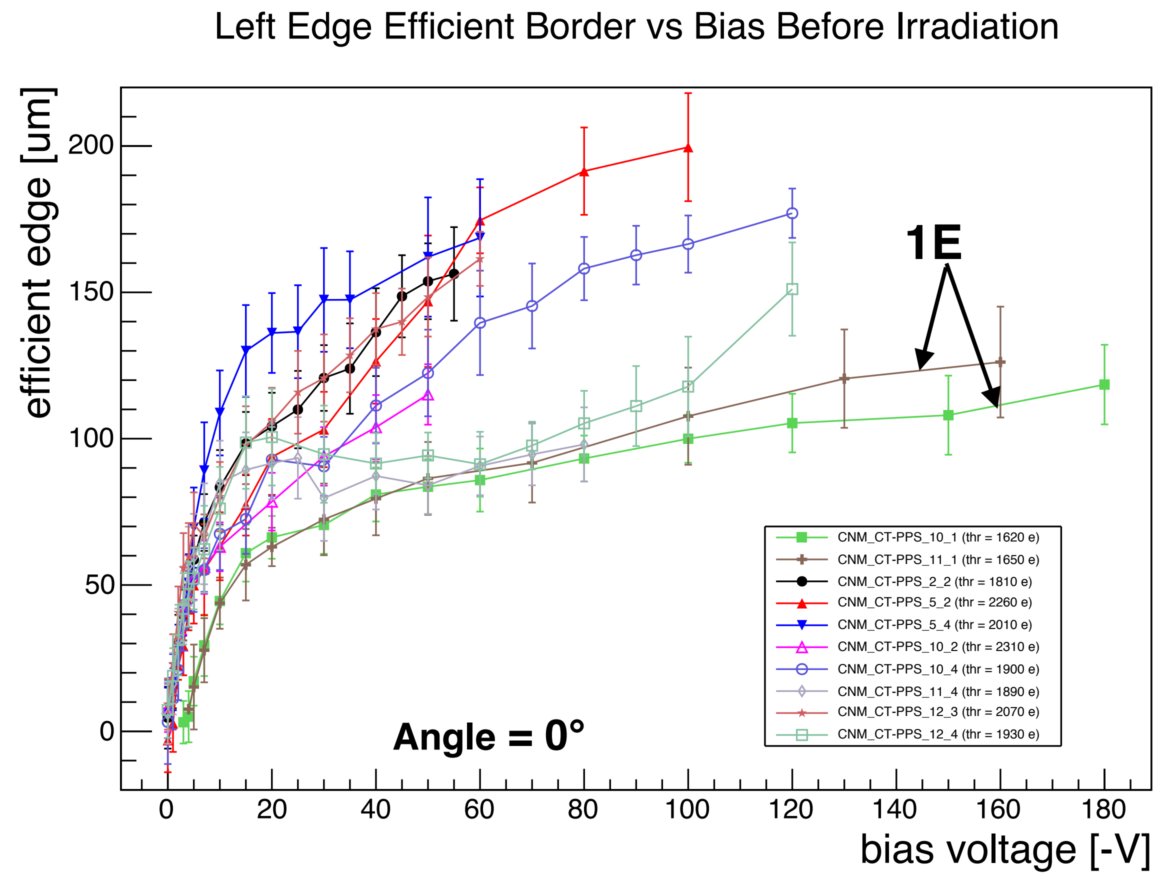




3D detectors - Edge efficiency vs bias



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



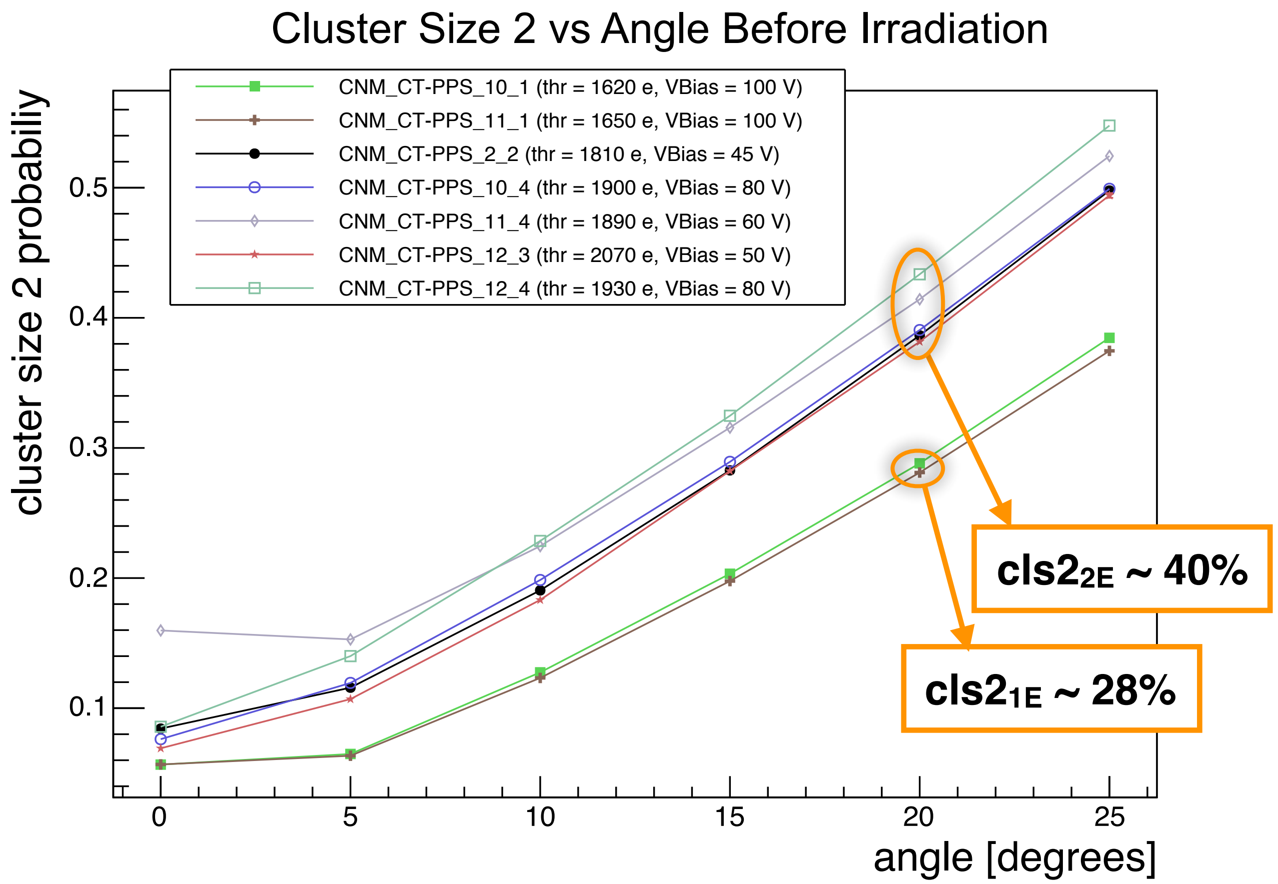
At a bias voltage of 40 V up to 150 μm can be gained at the edge of the sensor with the 2E layout.

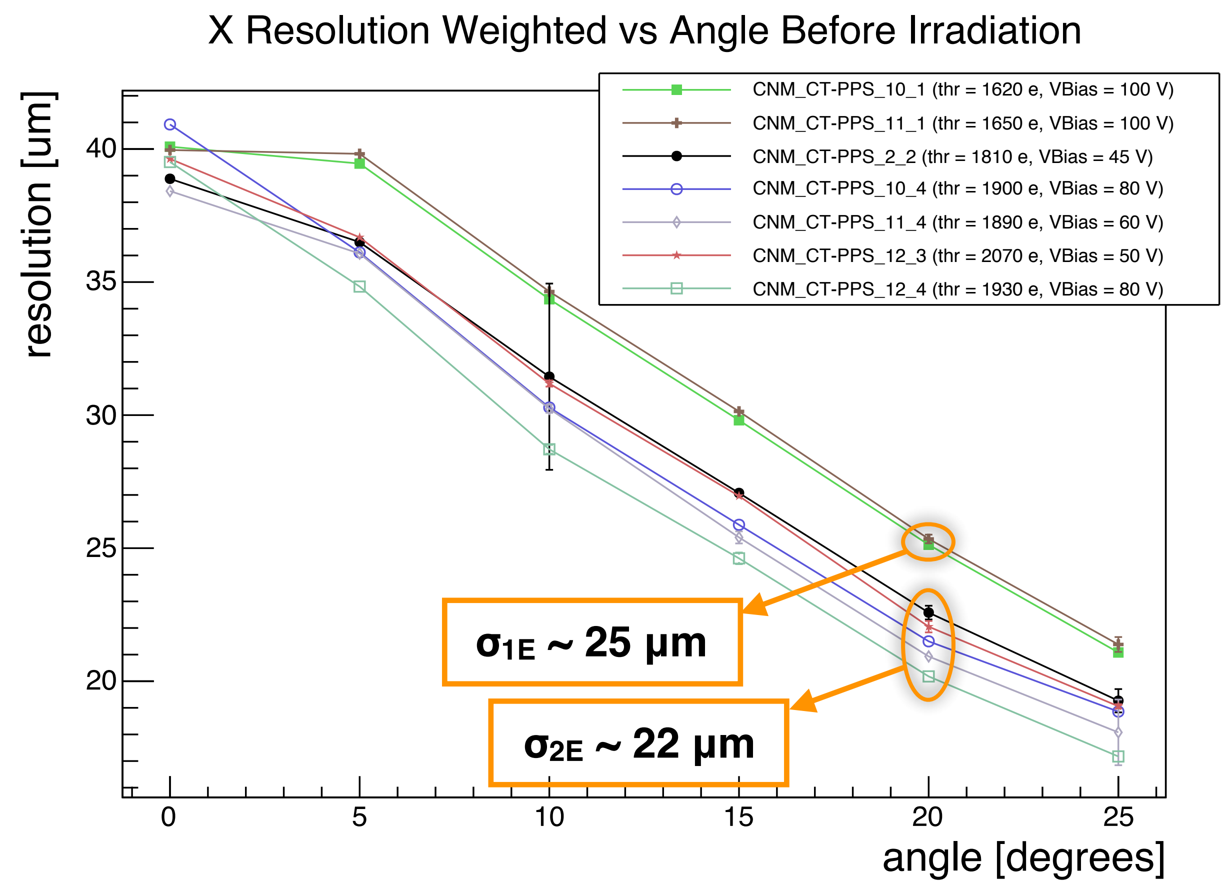
2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n^+-electrode closer to the sensor edge.

3D detectors - Resolution vs angle

Detector resolution is evaluated by fitting residuals separately for clusters of 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 22 and 25 μm, **the target resolution of ~10 μm can be achieved** considering the 6 planes per station.

CNM single-ROC sensors demonstrated to fulfill the CT-PPS requirements.

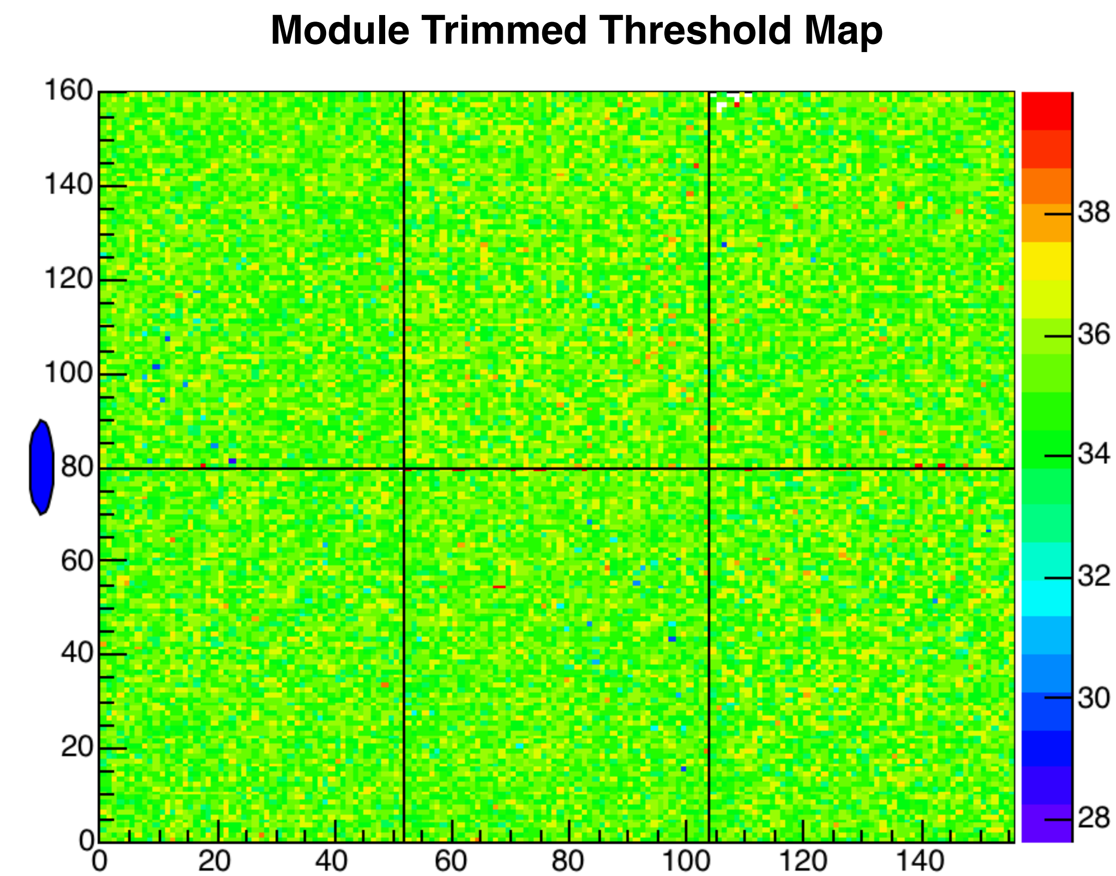
Module testing

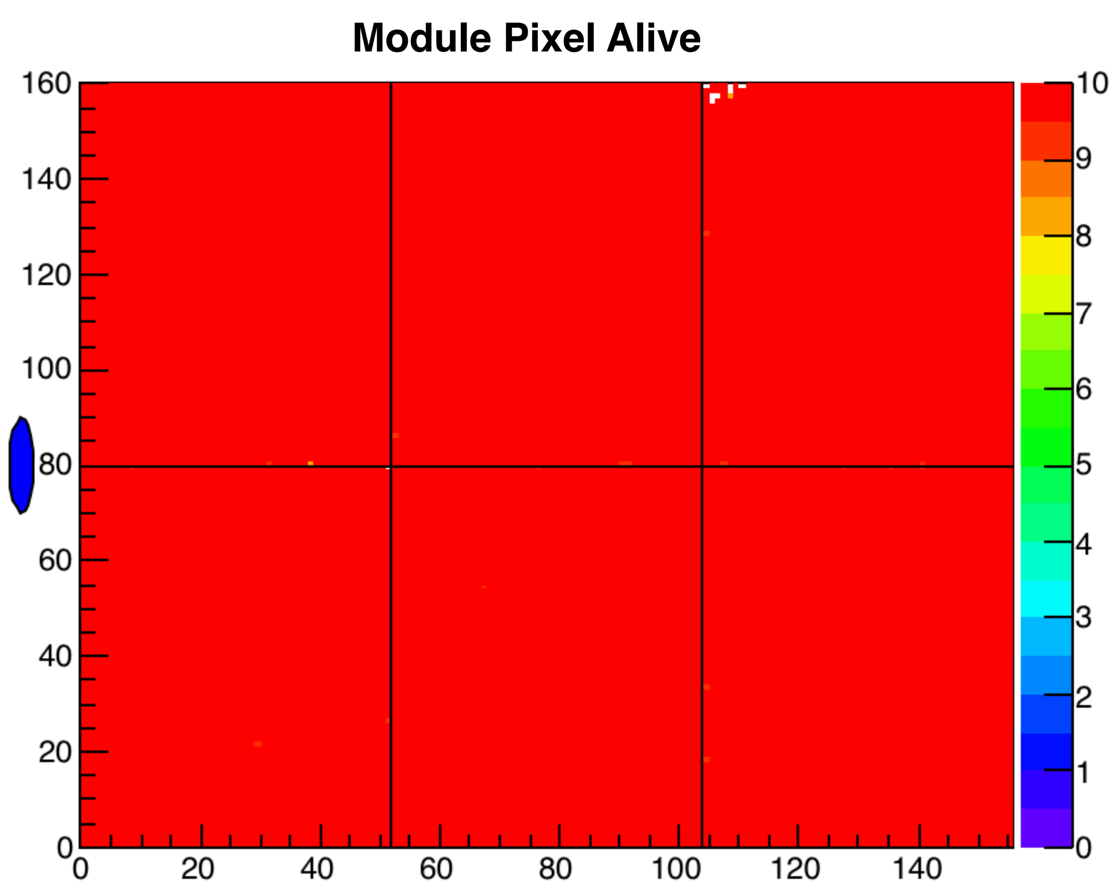
Detectors characterised and optimised in Torino and Genova by a temporary wire-bonding and gluing with gel-pak film on flex hybrid:

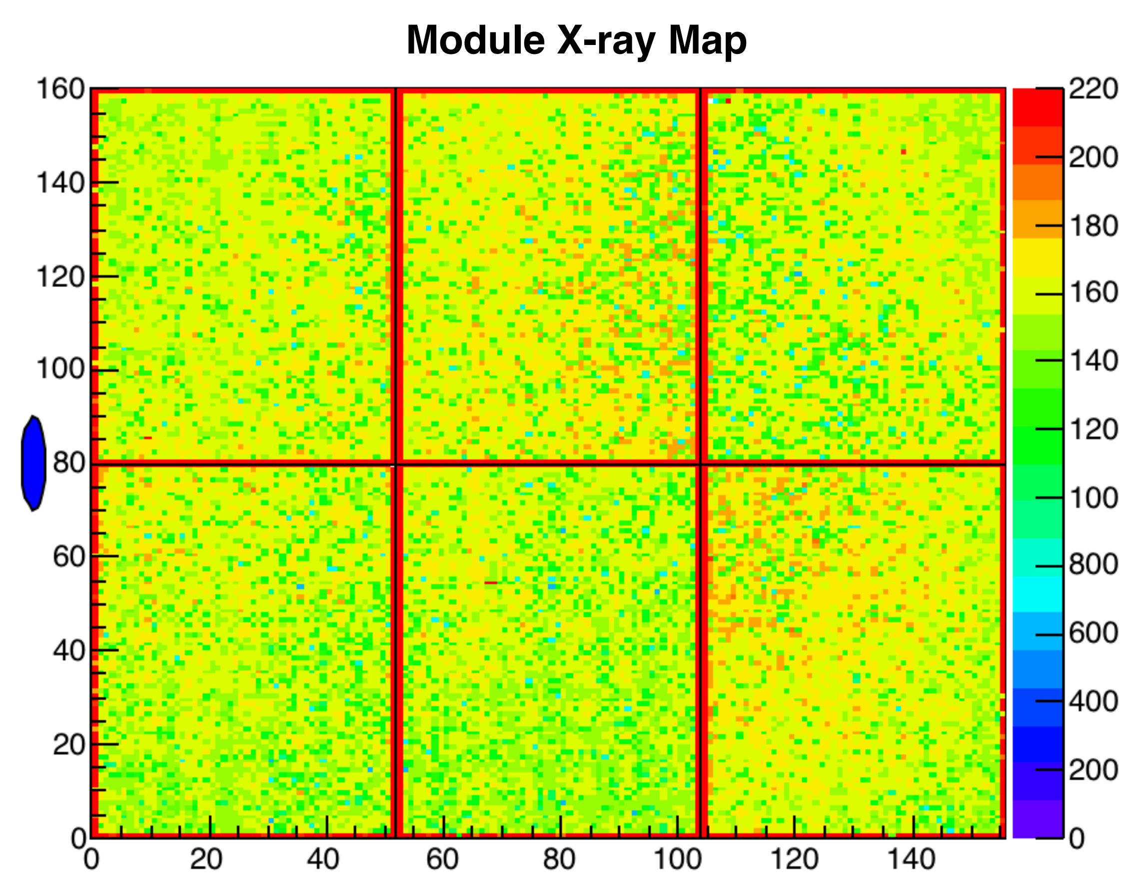
- IV curve
- ROC calibration and optimisation
- Threshold trimming to ~ 1800 e^-
- X-ray to check bump-bonding quality

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

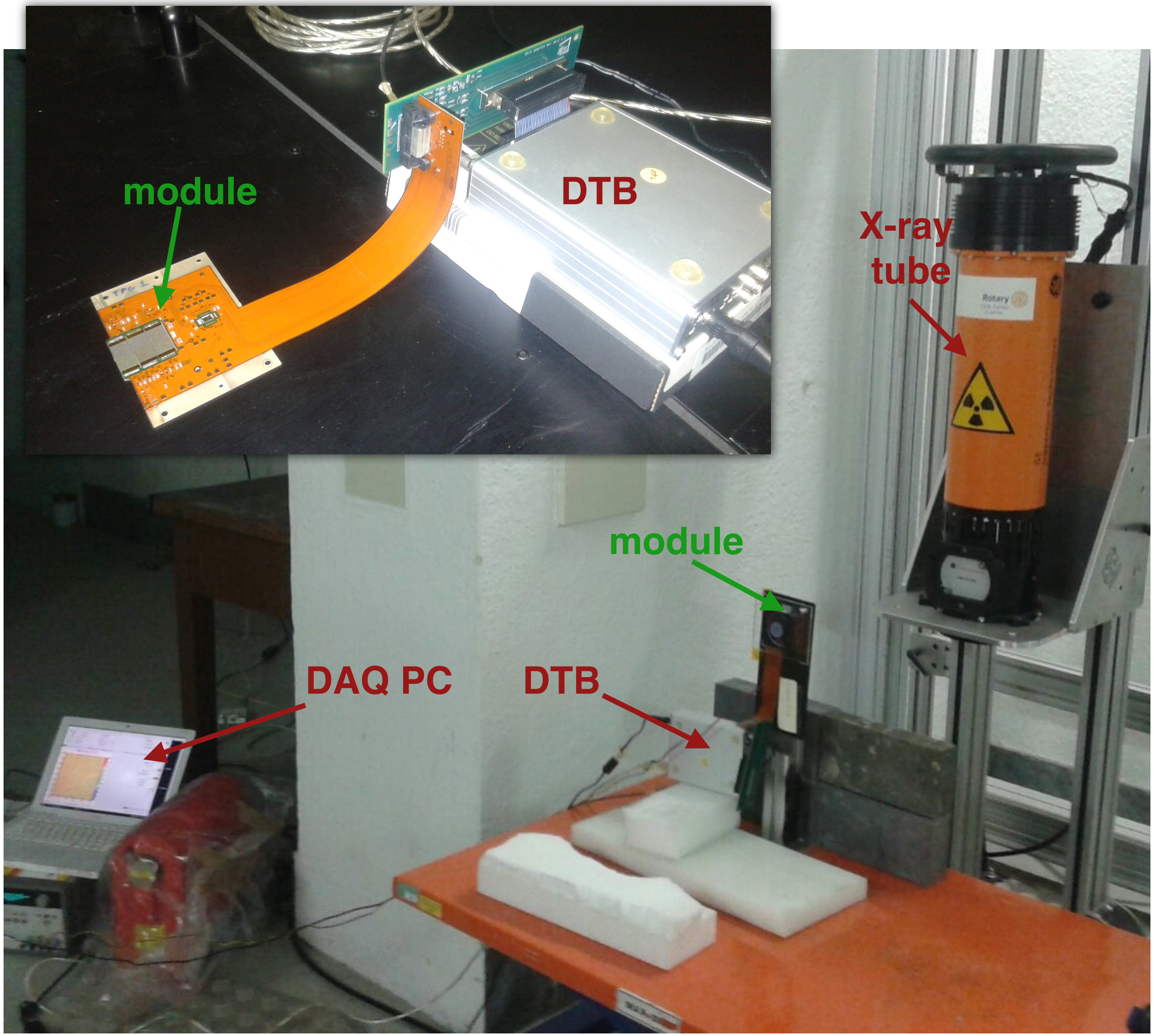
Good quality of bump-bonding

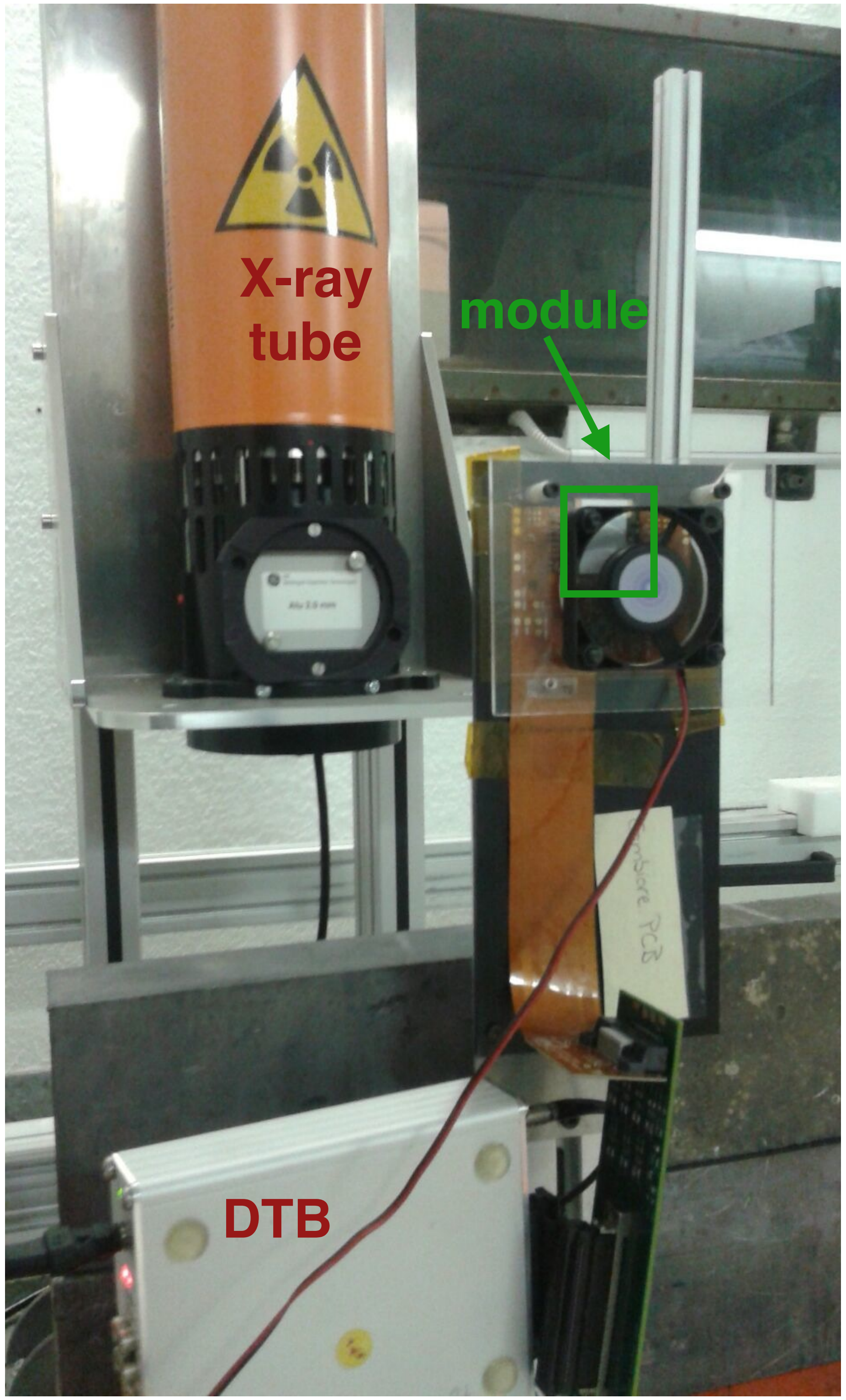






Torino X-ray setup





Status of module production - batch 1

3x2 module

Module	Layout	Class on wafer
3x2_b1w1d2	2E	B
3x2_b1w1d3	1E	B
3x2_b1w1d5	2E	B
3x2_b1w1d6	1E	B
3x2_b1w2d3	1E	A
3x2_b1w2d4	2E	B
3x2_b1w2d6	1E	A
3x2_b1w5d2	2E	B
3x2_b1w5d3	1E	A
3x2_b1w5d4	2E	B
3x2_b1w5d5	2E	B
3x2_b1w5d6	1E	A
3x2_b1w6d1	2E	B
3x2_b1w6d4	2E	B
3x2_b1w11d1	2E	B
3x2_b1w11d5	2E	B
3x2_b1w11d6	1E	A
3x2_b1w12d1	2E	A
3x2_b1w12d2	2E	A
3x2_b1w12d3	1E	A
3x2_b1w12d4	2E	A
3x2_b1w12d6	1E	A

2x2 module

Module	Layout	Class on wafer
2x2_b1w1d1	2E	B
2x2_b1w1d2	2E	B
2x2_b1w2d1	2E	B
2x2_b1w2d2	2E	A
2x2_b1w2d4	1E	A
2x2_b1w5d1	2E	B
2x2_b1w5d2	2E	A
2x2_b1w5d3	1E	A
2x2_b1w5d4	1E	A
2x2_b1w6d1	2E	B
2x2_b1w6d2	2E	B
2x2_b1w6d3	1E	B
2x2_b1w6d4	1E	B
2x2_b1w10d1	2E	A
2x2_b1w10d3	1E	B
2x2_b1w10d4	1E	A
2x2_b1w11d1	2E	B
2x2_b1w11d2	2E	B
2x2_b1w11d3	1E	A
2x2_b1w11d4	1E	A
2x2_b1w12d1	2E	B
2x2_b1w12d2	2E	A
2x2_b1w12d3	1E	B
2x2_b1w12d4	1E	B

Color code:
Green → Ok
Light green → few defects but still good
Light blue → timing issue, maybe usable but still under investigation
Orange → quite serious problems, better not to use it
Red → not usable

All red modules have been broken during handling or wire-bonding at the beginning of testing campaign.

Status of 3x2:
Tested 22/22
Good sensors 16/22 (7 2E)

Status of 2x2:
Tested 22/24
Good sensors 18/22 (10 2E)

For the 2017 data taking only 2 pixel stations (one per each side) have been installed.

Mainly green 3x2 modules have been selected for the final station assembly.

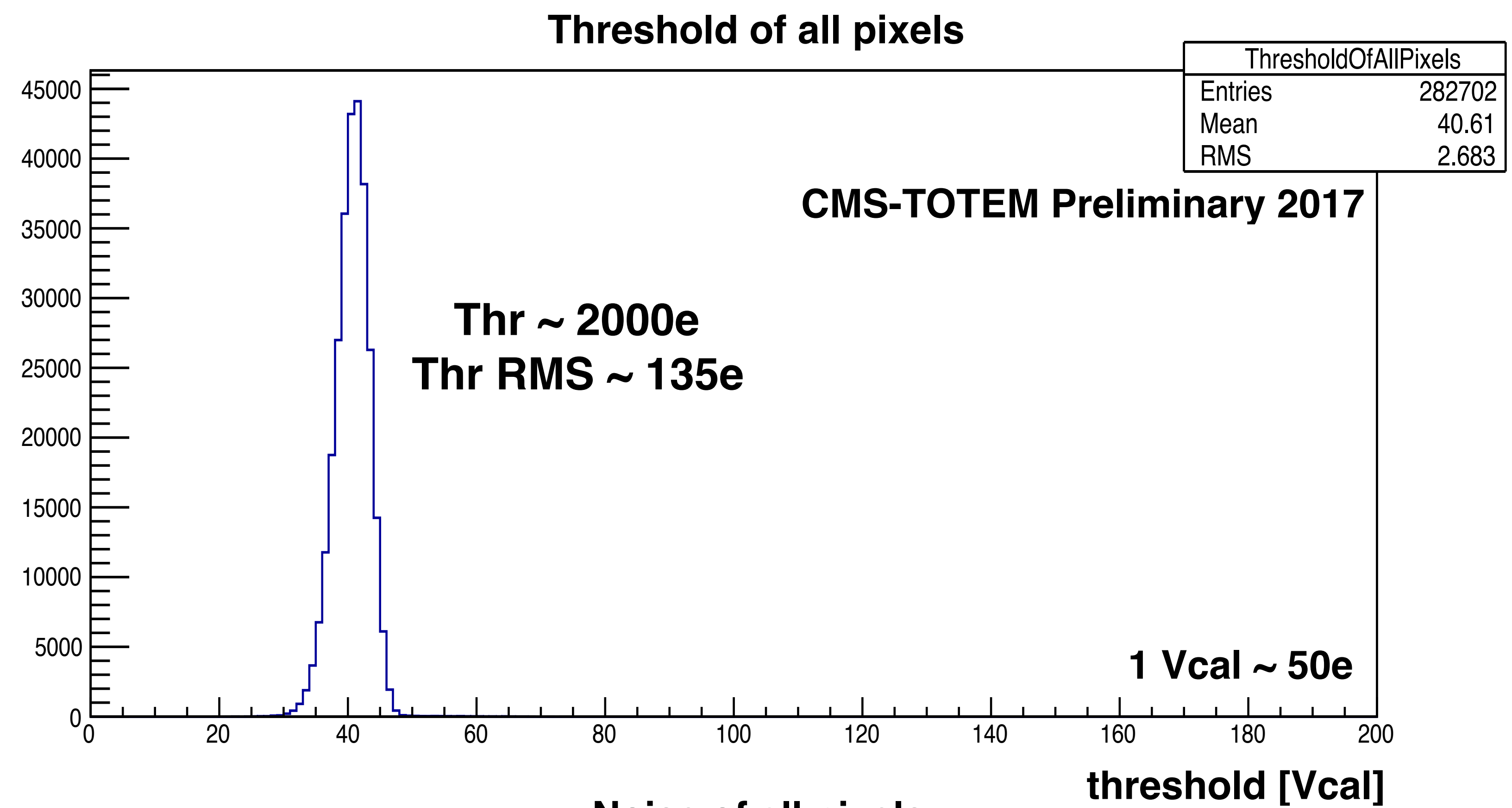
Pixel calibration - I

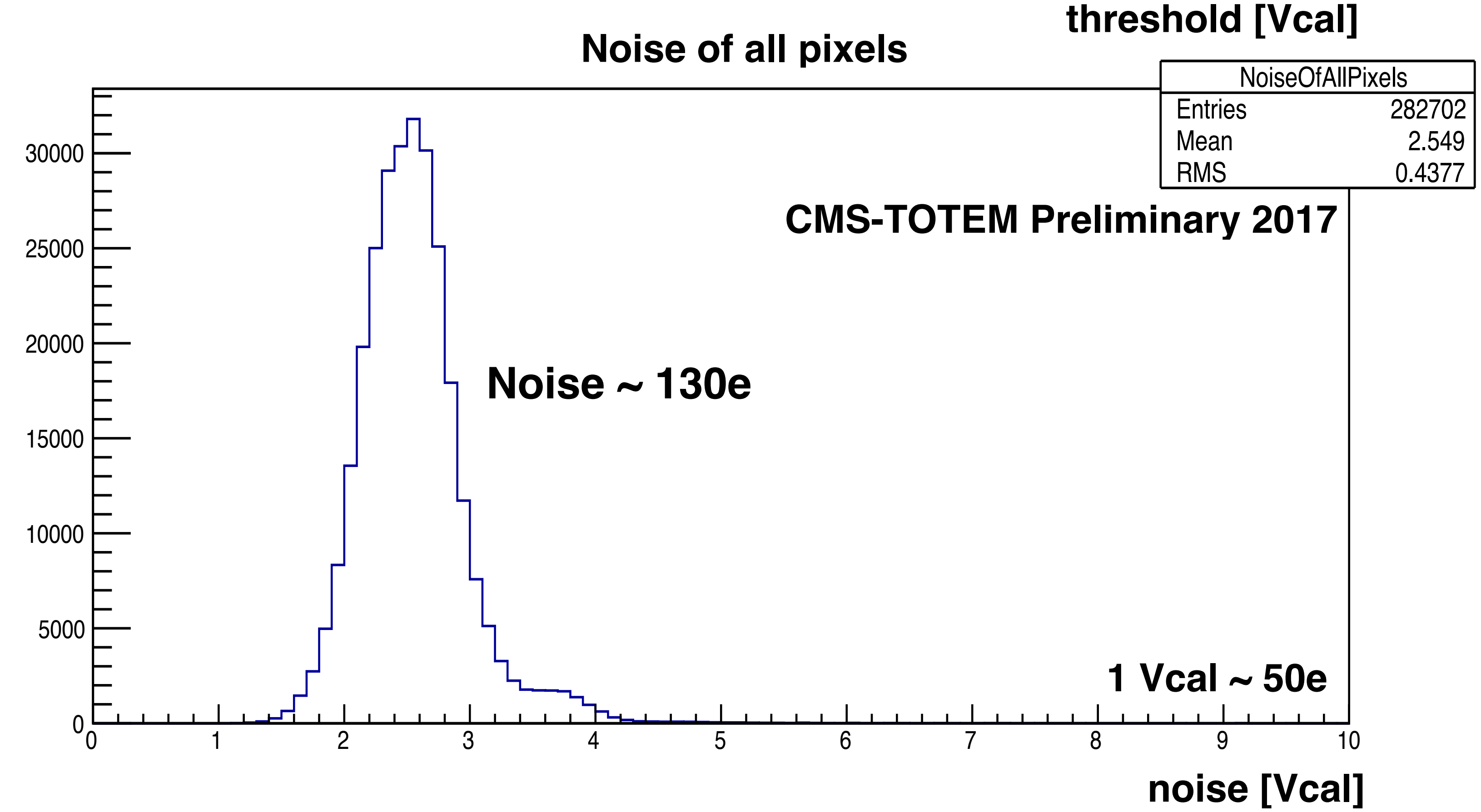
The pixel modules have been tested and optimised in the Torino and Genova laboratories during the module selection phase, with the same procedure used for the CMS Phase I ones.

The calibrations and tests are made by means of the internal calibration circuit present in the psi46dig ROC.

The obtained register values have been used as a starting point for the detector optimisation in the LHC tunnel.

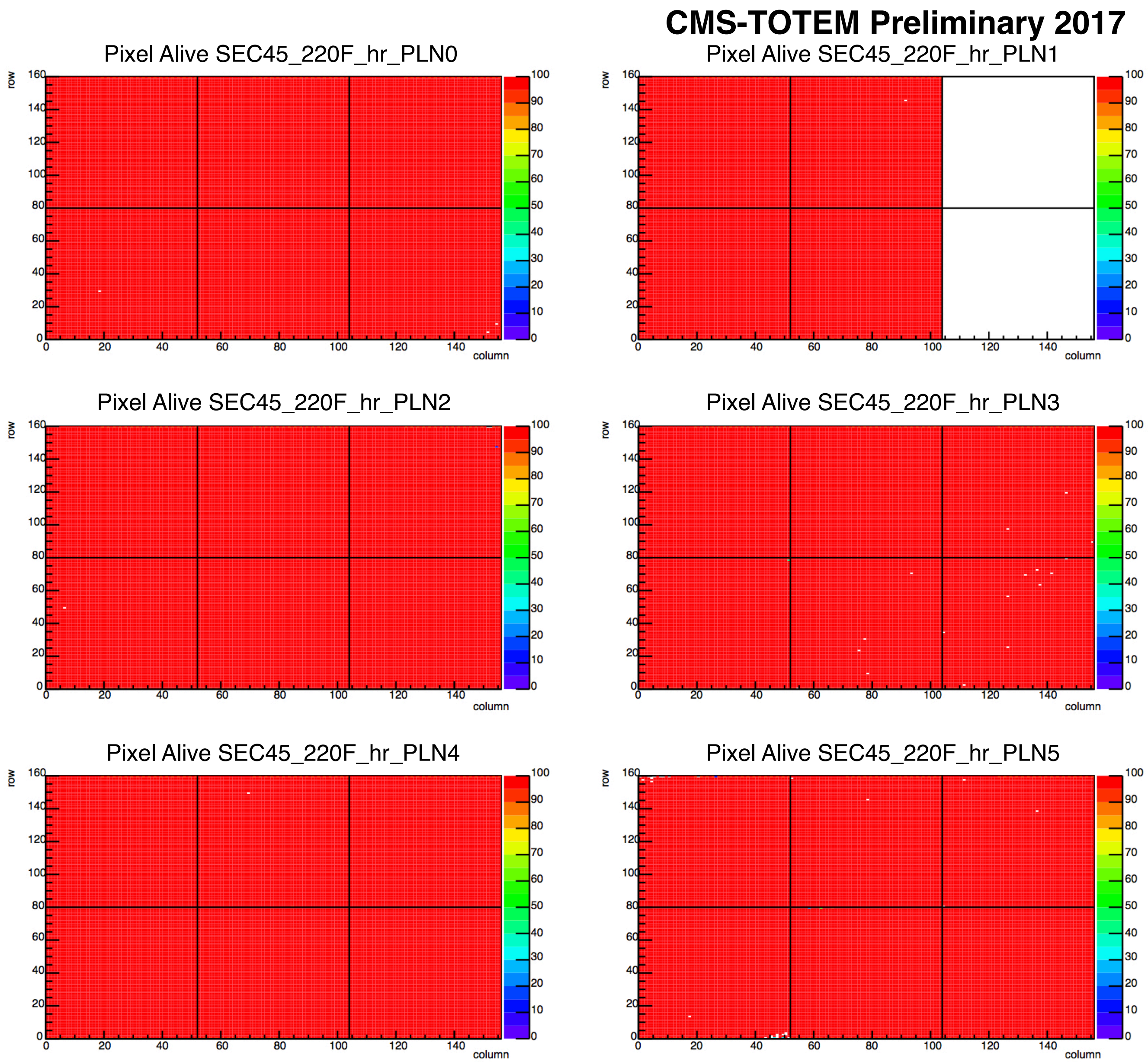
A calibration campaign has been carried out.



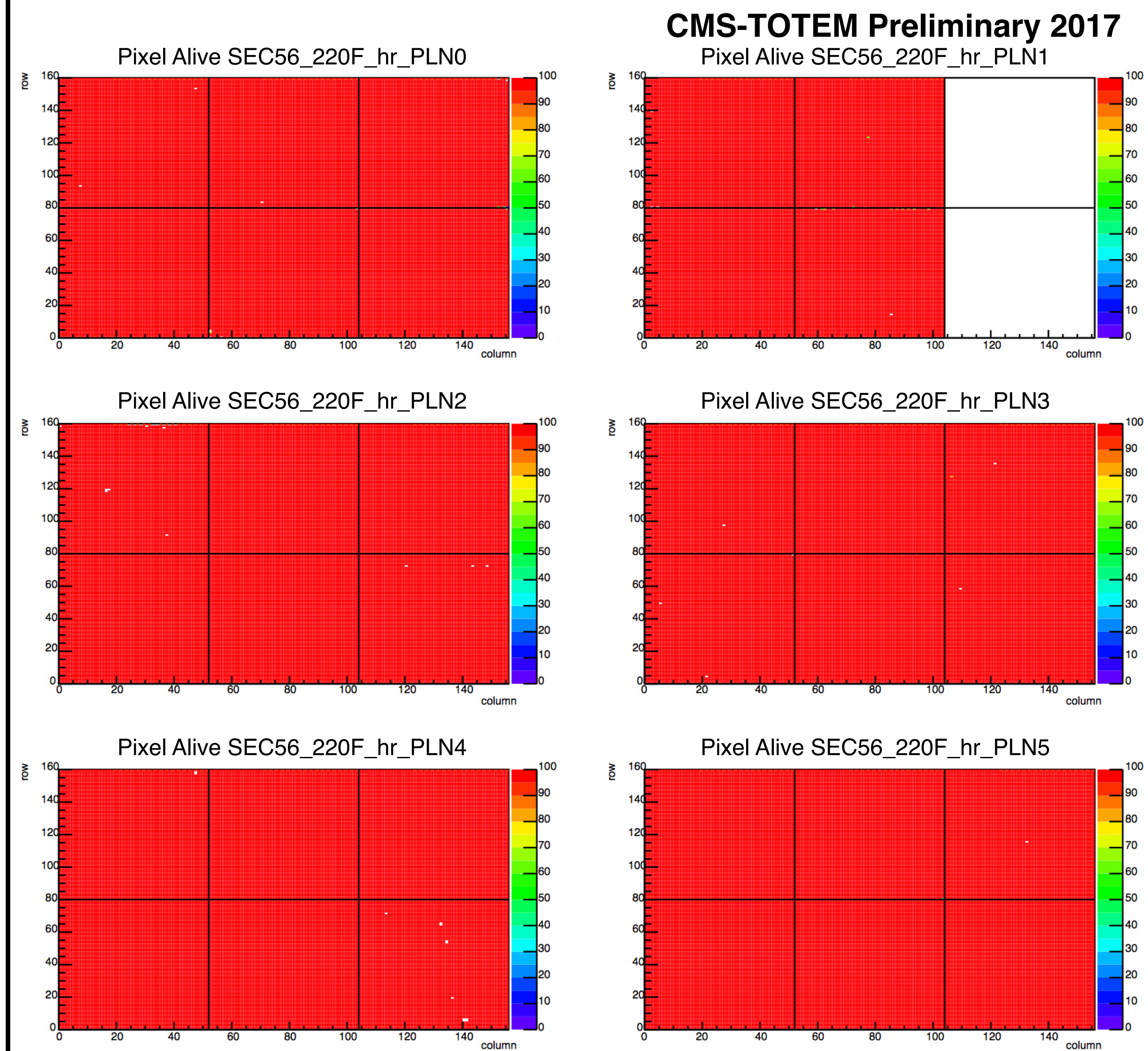


Pixel calibration - II

Module maps for sector 45
installed on LHC beam-pipe 2



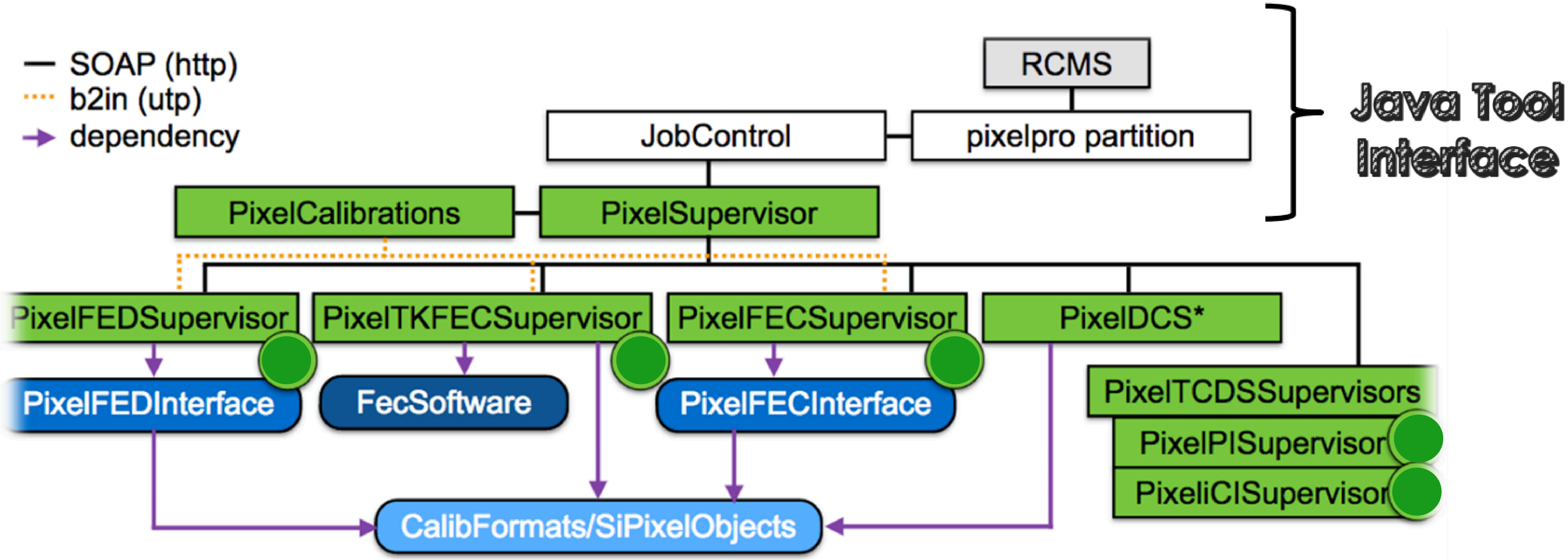
Module maps for sector 56
installed on LHC beam-pipe 1



Very low number of bad pixels (eff<90%) = 129 (<0.05% of all channels)

CT-PPS pixel tracker DAQ

- The DAQ and calibration software for the CT-PPS pixel detector is based on the CMS Phase I Pixel Online Software (POS).
- **The software has been adapted to the CT-PPS electronics.**



- **The software has been fully tested in laboratory** and all the standard calibration procedures have been verified.
- The tests done on the modules during their qualification provided the initial setting which have been further optimised with the DAQ software.
- The software demonstrated to be reliable.

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