Performances of Highly Irradiated 3D and Planar Pixel Sensors Interconnected to RD53A Readout Chip

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INFN Firenze

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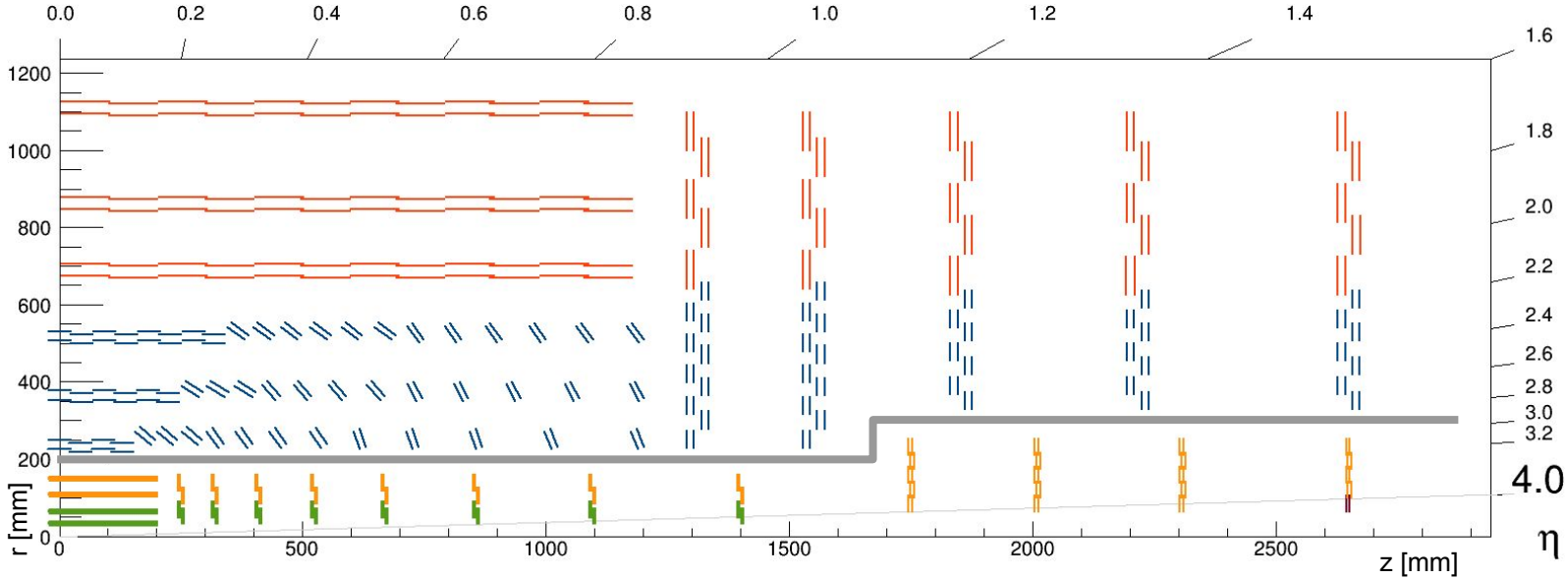
The CMS Tracker Upgrade

- Phase 2 of LHC will start in 2026 → Luminosity will reach **7.5×10^{34} cm^{-2} s^{-1}**
- The CMS Tracker will be completely replaced
- Composed by two sections → **Inner** (this talk) and **Outer** (see A. La Rosa talk)
- Unprecedented radiation levels → **2.3×10^{16} n_{eq} cm^{-2}** in the innermost layer (after 10 years of operations)



Outer Tracker
Strip and macro pixel detectors

Inner Tracker
Pixel detectors

The Inner Tracker Upgrade

Requirements

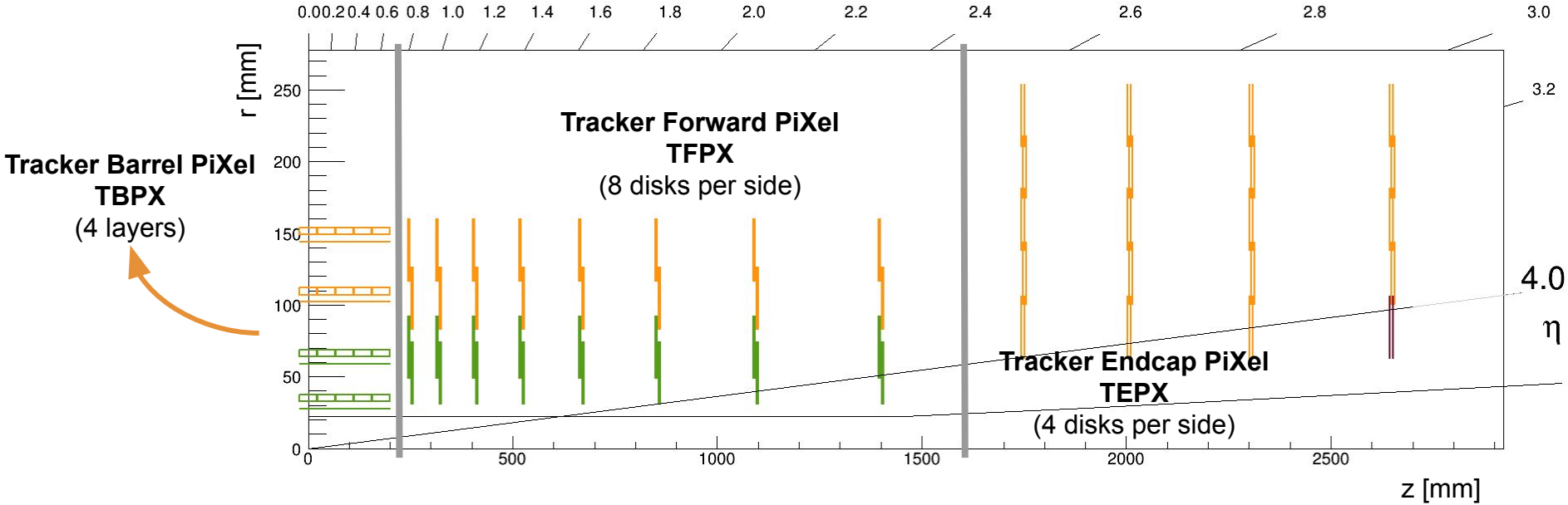
1. High granularity
2. Radiation resistance
3. Low material budget
4. Large acceptance

→ New pixel sensors and front-end electronics

→ New Inner Tracker layout

- Good two tracks separation → Needed in jet reconstruction
- Robust pattern recognition → Needed for high pileup conditions

The Inner Tracker Layout



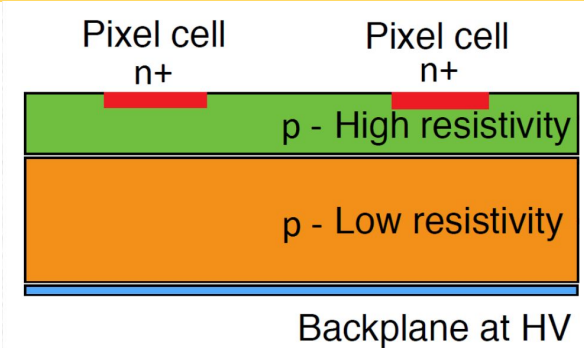
- "Simple" mechanical structure
- Simple installation and removal for potential replacement of parts
- 4.9 m^2 of pixel surface & 2×10^9 channels
- Inner layer at 30 mm from beam line

2736
2 × 2 pixel modules

1156
1 × 2 pixel modules

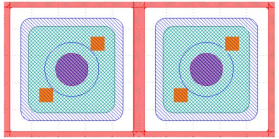
Planar Pixel Sensors

- Planar pixel *n-in-p* sensors R&D (HPK, FBK)
- Good charge collection efficiency on irradiated sensors
- Low active thickness:

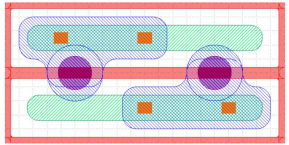


Phase 1	→	Phase 2
285 μm		100 μm - 150 μm

- Pixel size reduced by a factor 6 from 100 × 150 μm^2
- Two pixel cells under study → 25 × 100 μm^2 or 50 × 50 μm^2
- Various pixel design configurations
  - Isolation → p-stop or p-spray
  - Sensor test bias scheme → punch trough or temporary metal

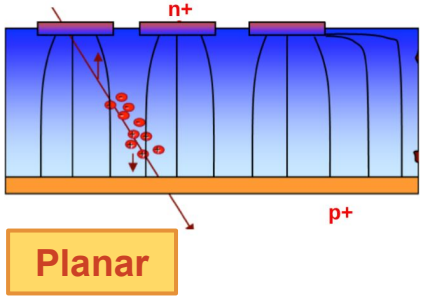


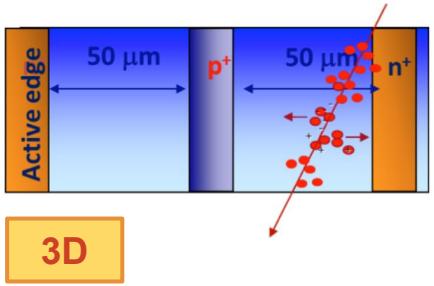
50 × 50 μm^2

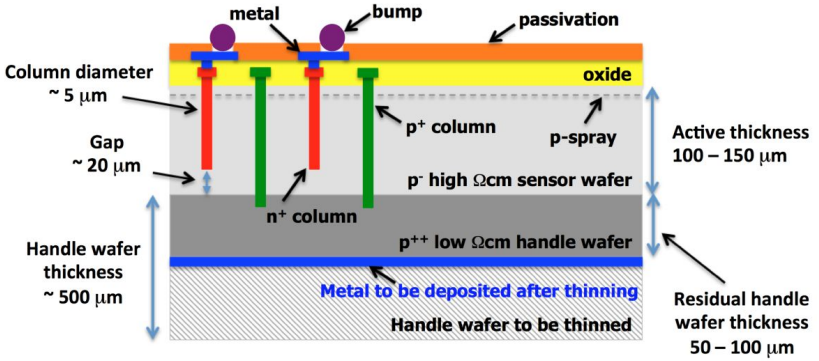


25 × 100 μm^2

3D Pixel Sensors







- 3D pixel R&D (FBK & CNM)
- In 3D sensors the drift path is perpendicular to the active depth
  - Short drift distance → ~30 - 50 µm (3D) vs.100 - 150 µm (Planar)
- Many advantages with respect to planar sensors
  - Smaller bias voltage needed to deplete the sensor
  - Less trapping in irradiated sensors, due to shorter drift distance
  - Same charge produced
- Promising candidates for the high radiation environment of the inner layers and rings

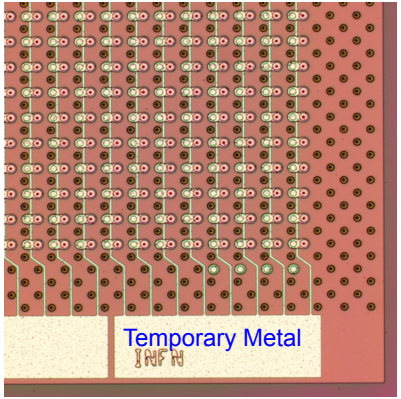
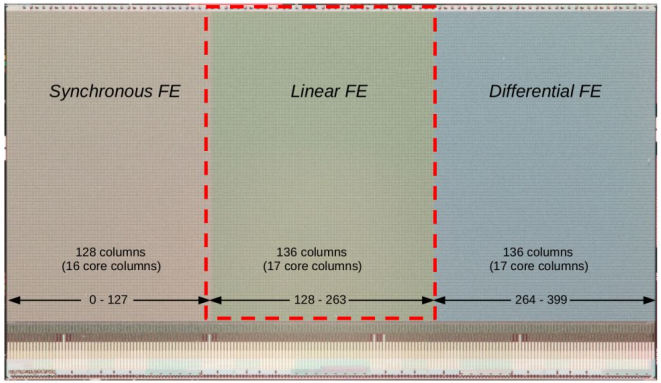


Photo from wafer

RD53 Readout Chip

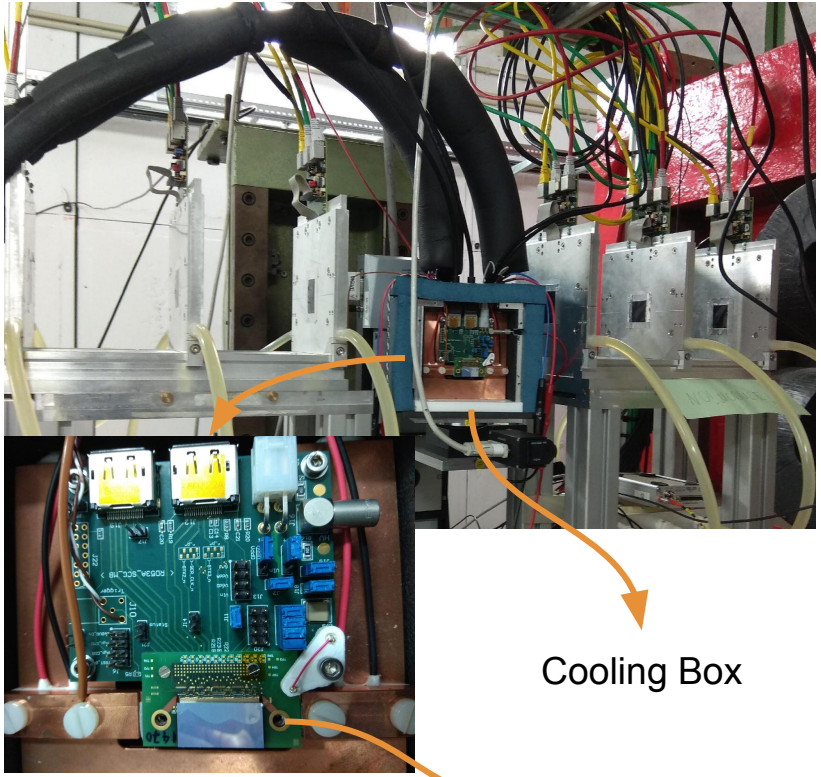
Only Linear front-end results will be shown!



- RD53 ROC goals:
  - Radiation hard (up to 5 MGy)
  - Low thresholds and noise
- 65 nm technology & 50 × 50 μm^2 (single) cell size
- RD53A prototype (~½ size of the final chip) used for R&D
- Three analog front-ends (Synchronous, Linear, Differential)
- Compatible for the capacitance of both planar and 3D sensors (about 50 fF per channel)
- CMS chose the Linear front-end for the final experiment

DESY Test Beam Setup

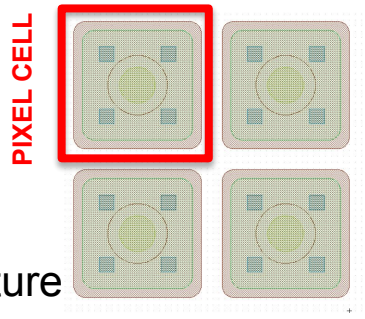
- Two Test Beams @ DESY in 2019
  - 5.2 GeV electrons beam
- Mimosa Telescope
  - 3 planes before the Device Under Test (DUT)
  - 3 planes after the DUT
  - Spatial resolution ~10 μm due to the Cooling Box needed for an irradiated DUT
  - All tested DUTs were kept at -27 °C



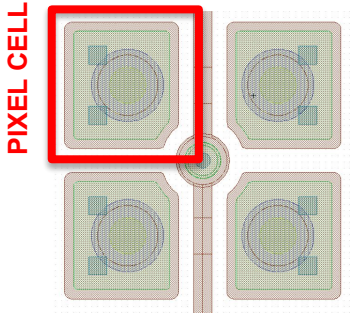
Tested Modules

- Two FBK Planar sensors - 100 μm active thickness
  - One 50×50 μm^2 pitch without Punch-Through (PT) structure
  - One 50×50 μm^2 pitch with PT
  - Both were irradiated @ KIT: fluence of 5×10^{15} $n_{eq}cm^{-2}$

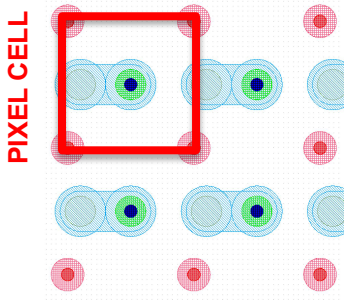
- One FBK 3D sensor - 130 μm active thickness
  - 50×50 μm^2 pitch
  - Irradiated @ CERN: (nominal) fluence of 1×10^{16} $n_{eq}cm^{-2}$



Planar - no-PT

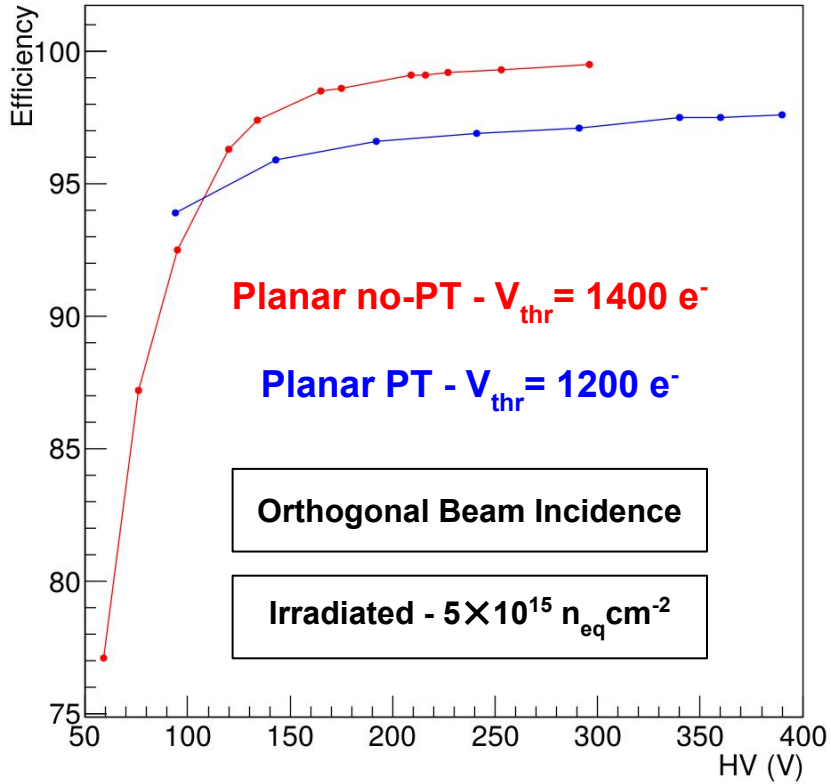


Planar - PT



3D

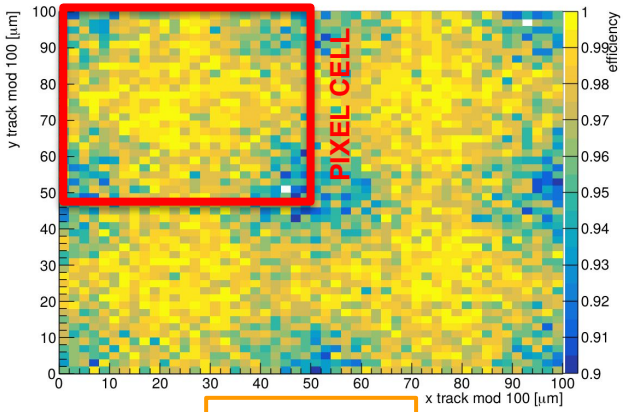
Planar Modules - Efficiency vs. Bias



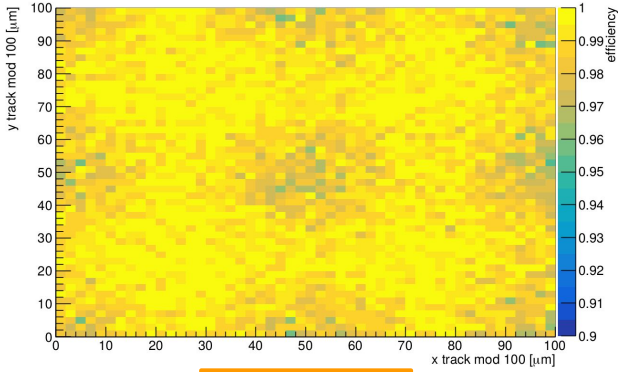
- Efficiency increases with (effective) bias voltage V_{bias}
- Efficiency > 99% at V_{bias}~210 V
- Pixel thresholds (V_{thr}) tuned to 1400 e^-
- Leakage current ~540 μA at V_{bias}~295 V
  - Bad cooling contact on the module

- Efficiency starts saturating around V_{bias}~200 V
- Eff. max value: 97.6% at V_{bias}~390 V
- Pixel thresholds tuned to 1200 e^-
- Leakage current ~50 μA at V_{bias}~390 V

Planar no-PT Module - Cell Efficiency

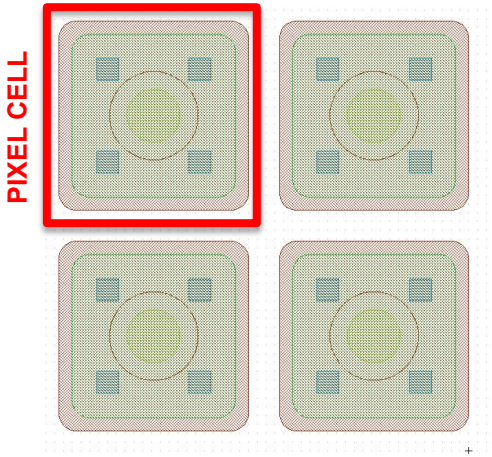


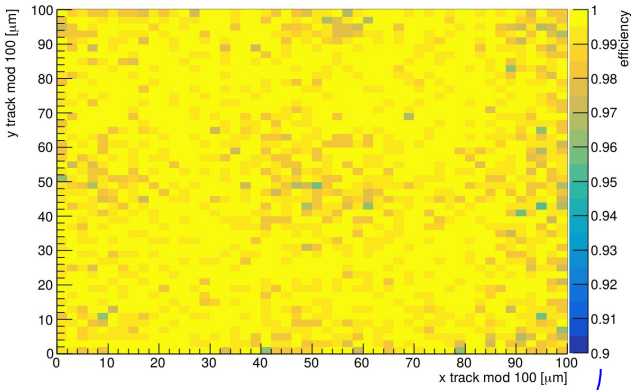
V_{bias} = 134 V



V_{bias} = 215 V

Same efficiency colour scales!



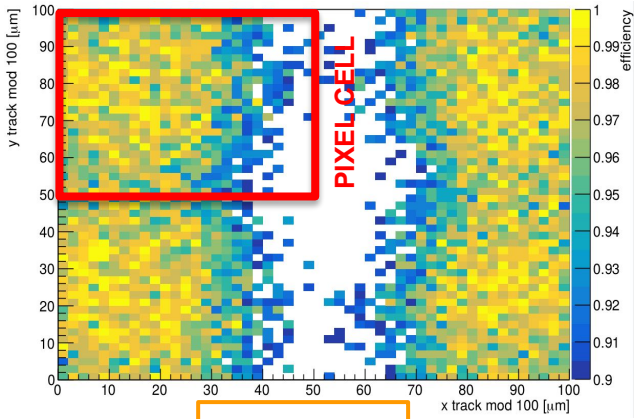


V_{bias} = 295 V

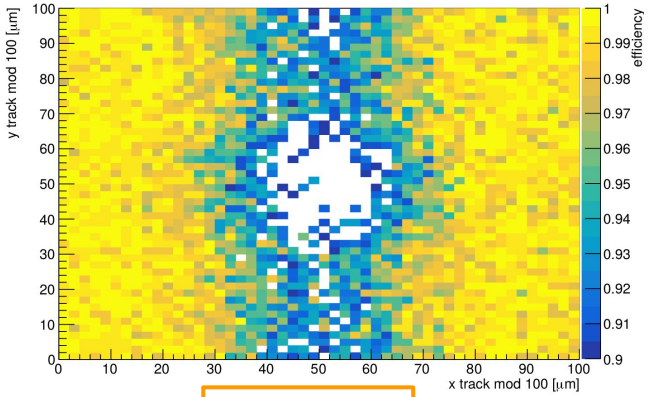
Plot scale starts at 0.9

- Efficiency maps for 2×2 pixel grid
  - Orthogonal beam incidence
- Efficiency gets more uniform with increasing bias voltage
- Small efficiency drops at the intersection of four pixels
  - This effect reduces with increasing bias voltage...
  - ...or small rotations

Planar PT Module - Cell Efficiency #1

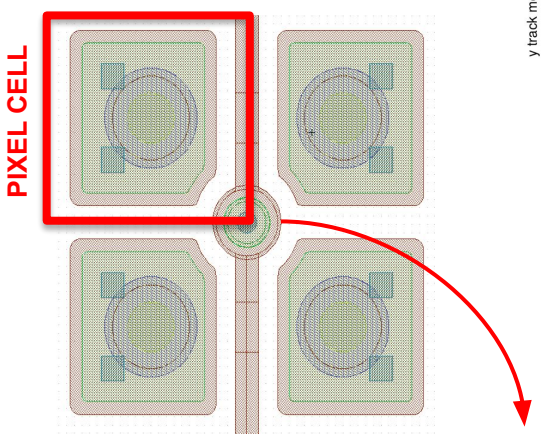


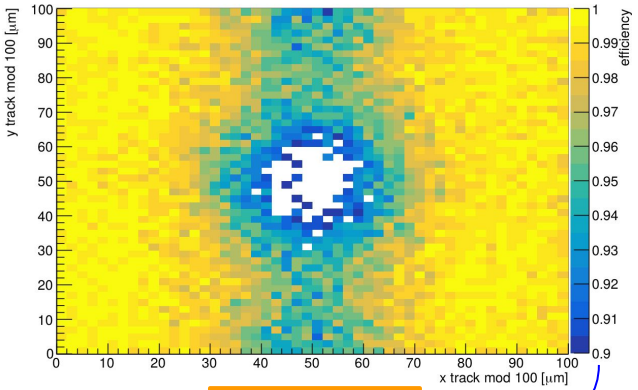
V_{bias} = 94 V



V_{bias} = 192 V

Same efficiency colour scales!



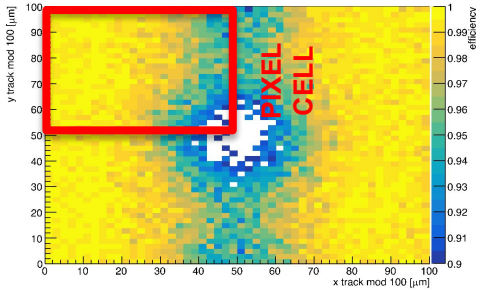


V_{bias} = 390 V

Plot scale starts at 0.9

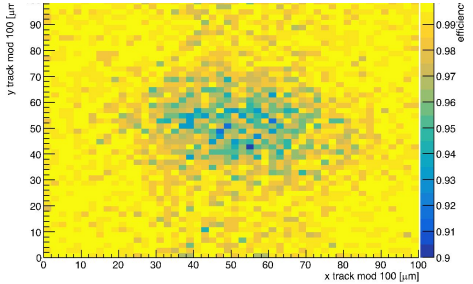
- Efficiency maps for 2×2 pixel grid
  - Orthogonal beam incidence
- Extended efficiency drop in the bias dot region (~80-85%)
  - Efficiency slowly recovers with increasing bias voltage
  - Rotations are also effective (see next slide)

Planar PT Module - Cell Efficiency #2

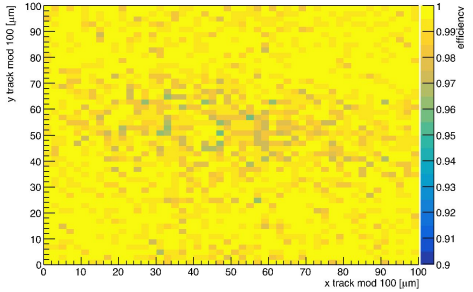


V_{bias} = 390 V

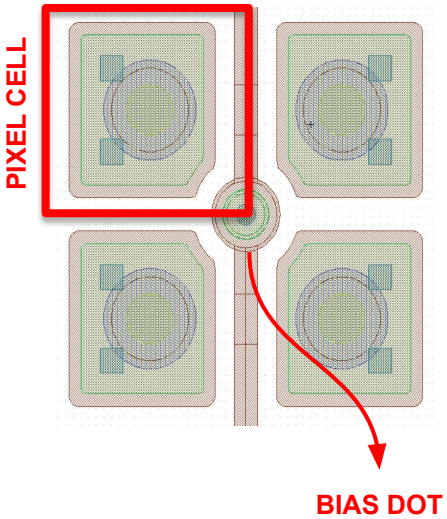
Rotation = 0˚

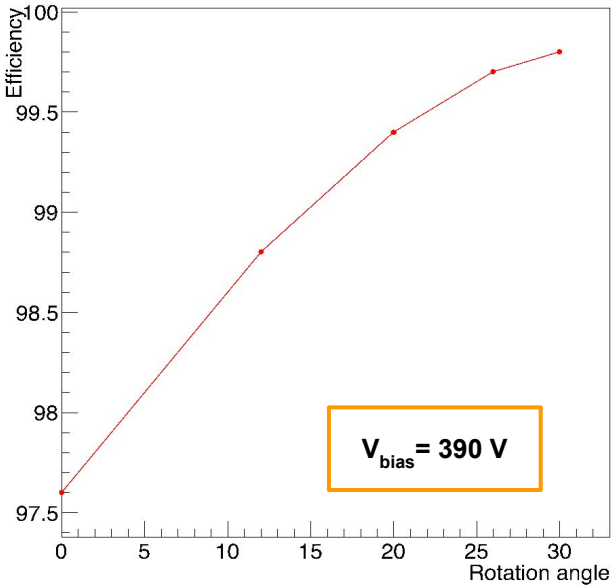


Rotation = 12°



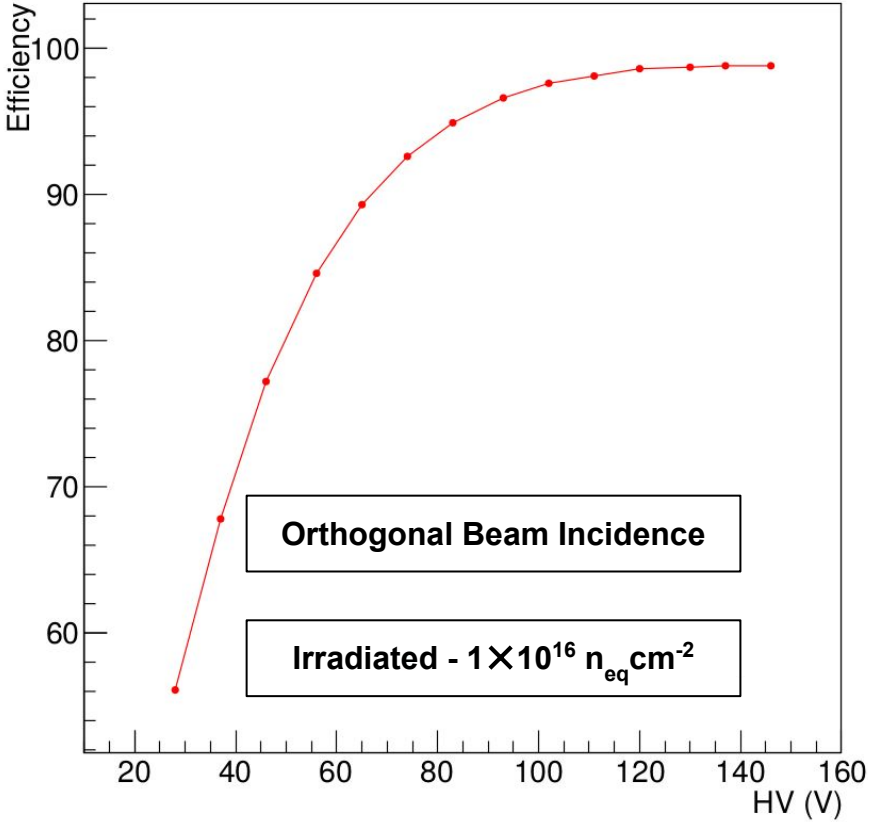
Rotation = 20˚





- Efficiency quickly increases by rotating the module
- The efficiency in the bias dot region is > 90% at 12°
  - At 20° the efficiency is almost uniform
- Global efficiency is > 99% at 15° rotation

3D Module - Efficiency vs. Bias

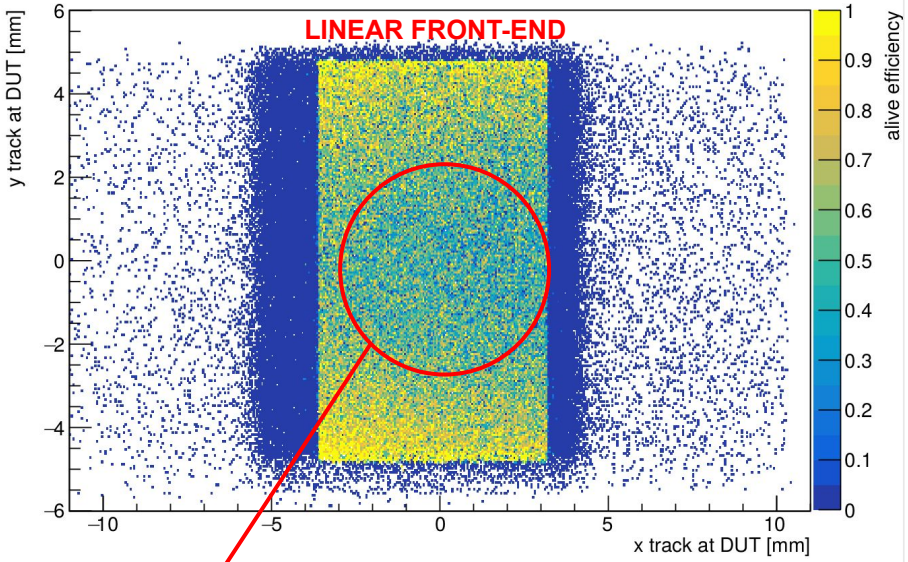


- Efficiency increases with effective bias voltage V_{bias}
  - Eff. saturates at V_{bias}~110 V
  - Eff. max value: 98.8% at V_{bias}= 146 V
- Efficiency > 99% with rotations > 6°
- Pixel thresholds tuned to ~1150 e^-
- Leakage current ~100 μA @ V_{bias}~110 V

This module has been irradiated at CERN PS: the beam width was smaller than the chip, therefore the irradiation is not uniform

3D Module - Efficiency Map #1

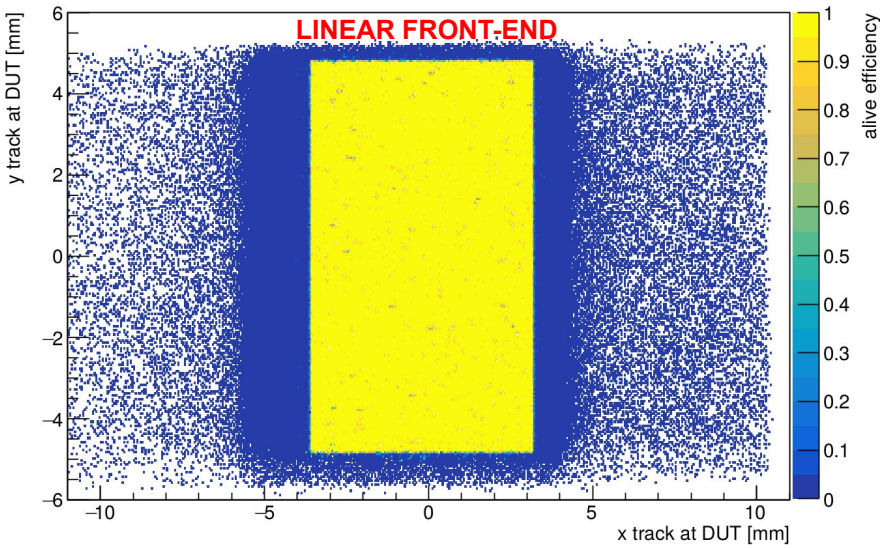
CERN beam spot from irradiation is visible (and centered on Linear front-end)



V_{bias} = 28 V

Under-depleted

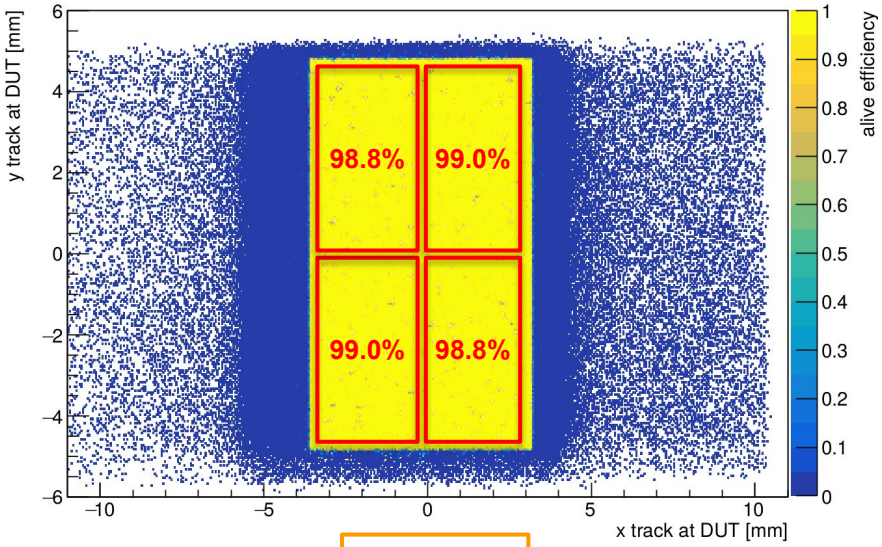
No efficiency drops visible (see next slide)



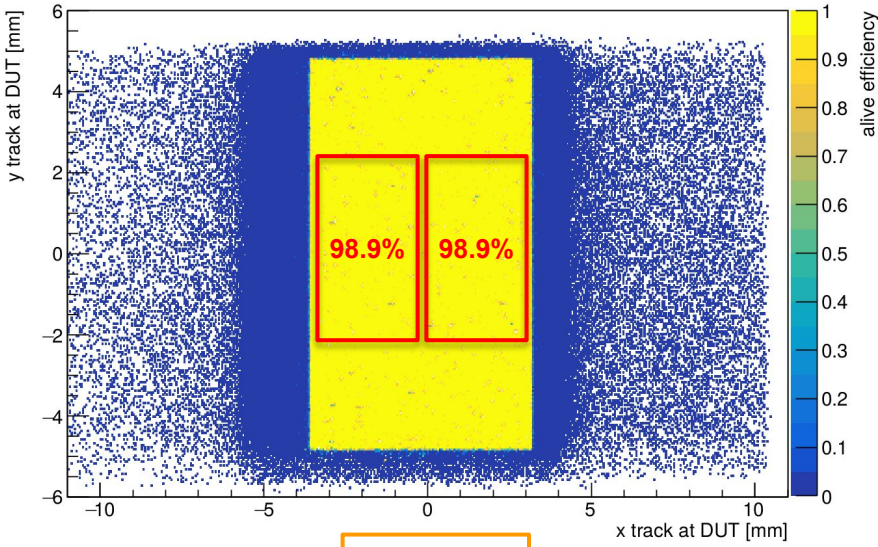
V_{bias} = 146 V

Fully-depleted

3D Module - Efficiency Map #2



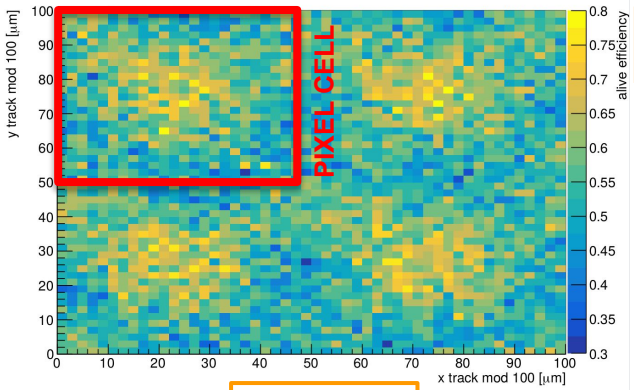
V_{bias}= 146 V



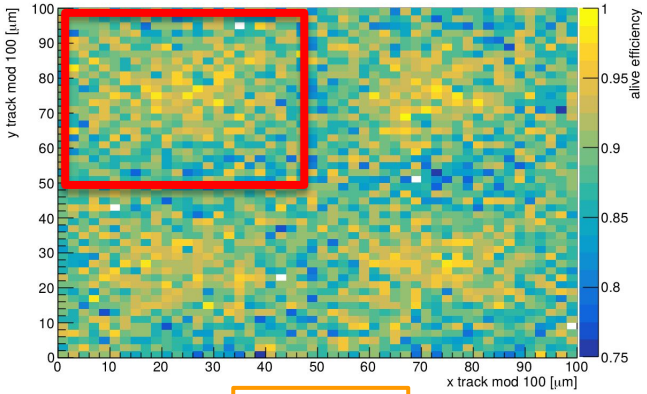
V_{bias}= 146 V

- Efficiency evaluated on smaller zones (red boxes)
- No significant drops in efficiency have been observed in the irradiation spot
- Efficiency is uniform across the sensor, at least at high V_{bias}

3D Module - Cell Efficiency

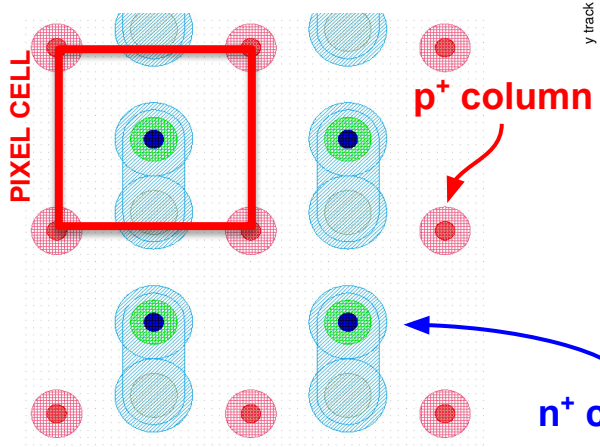


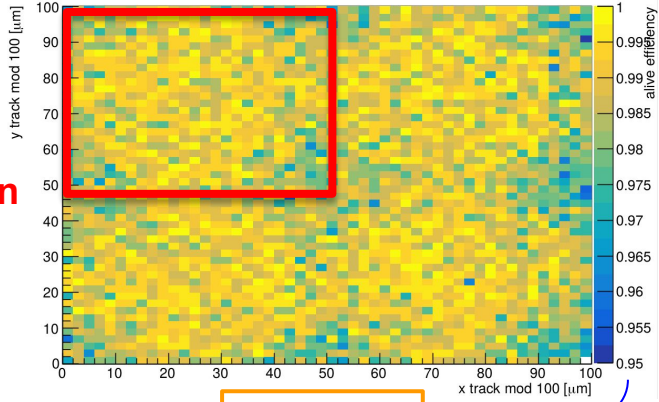
V_{bias} = 28 V



V_{bias} = 65 V

Efficiency colour scales are different!





V_{bias} = 146 V

Plot scale starts at 0.95

- Efficiency maps for 2×2 pixel grid
  - Orthogonal beam incidence
- Efficiency gets more uniform with increasing bias voltage
  - At low V_{bias} higher eff. near n^+ columns (electrodes)
  - Small eff. drop near p^+ columns at high V_{bias}

3D Module - Resolution vs. Rotation

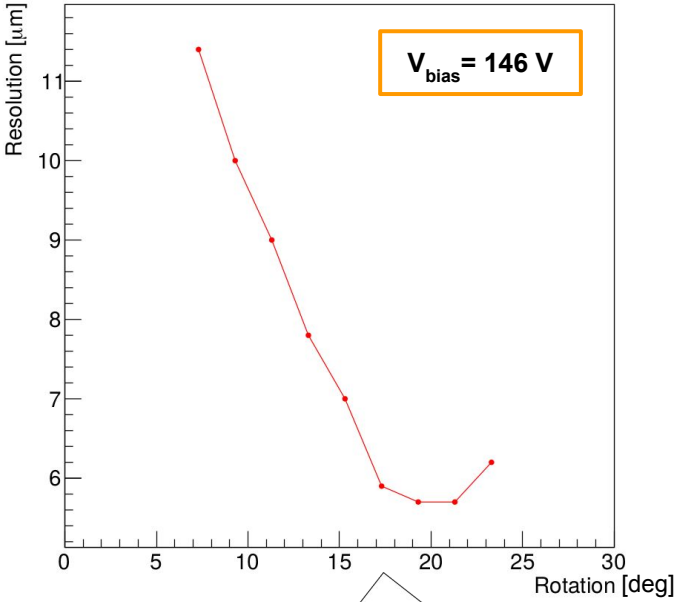
- To estimate the resolution (vs. rotation) of the 3D module:
  - Fit of the residuals (using student's t-distribution) on the rotated (rot) and unrotated (no-rot) coordinates
  - Using the σ from the fit, the telescope resolution (res_{tele}) has been estimated with:

$$\sigma^2_{no\text{-}rot} = res^2_{trivial} + res^2_{tele} \quad \text{where} \quad res_{trivial} = 50/\sqrt{12}\ \mu m$$

$$\rightarrow \quad res_{tele} \simeq 10\ \mu m$$

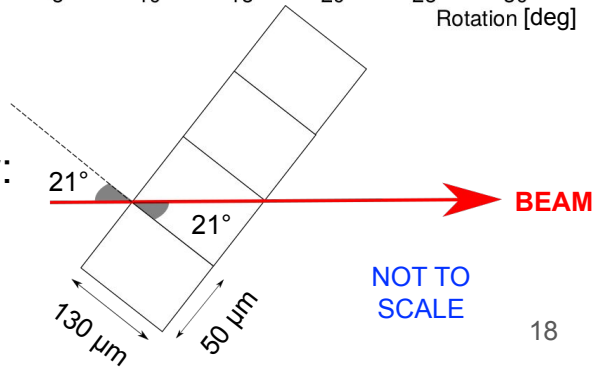
  - The resolution of the rotated coordinate (res_{rot}) has been estimated with:

$$res^2_{rot} = \sigma^2_{rot} - res^2_{tele}$$



- Best resolution (~5.7 μm) at ~20° → cluster size ≥ 2 for geometry:

$$\tan^{-1}(\ pitch/active\_thickness\ ) = \tan^{-1}(\ 50/130\ ) \simeq 21°$$



Outlook

- The CMS Inner Tracker Upgrade is extremely challenging
- Good results with irradiated (5×10^{15} $n_{eq}cm^{-2}$) FBK planar modules
  - Both are fully efficient at ~200 V
  - PT - related efficiency loss is mitigated by rotation
- The irradiated (1×10^{16} $n_{eq}cm^{-2}$) FBK 3D module is also very good
  - Fully efficient at ~100 V
- 25×100 μm^2 or 50×50 μm^2 and 3D/planar options are still open
- Sensors + ROC assemblies are compliant with half layer 1 and layer 2 radiation levels

Many Thanks to...

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