SPONSORED BY THE
Federal Ministry of Education and Research
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

M. Antonello
On behalf of the Tracker Group of the CMS Collaboration

massimiliano.antonello@cern.ch

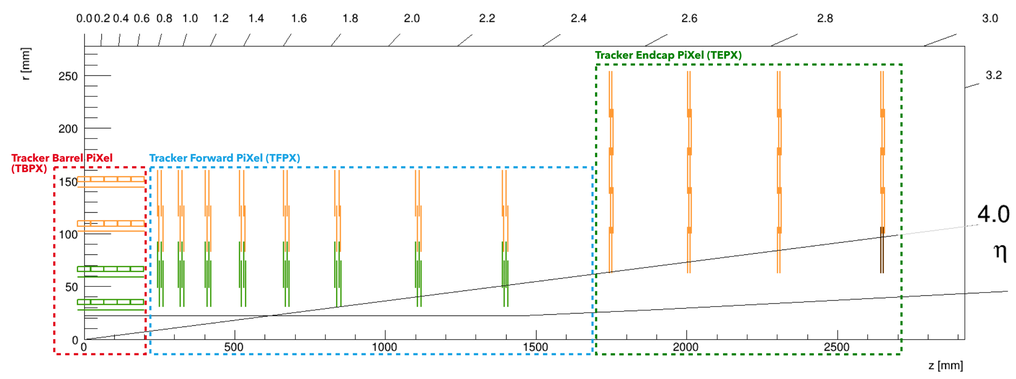
TEST BEAM RESULTS OF IRRADIATED MODULES FOR THE CMS PHASE 2 UPGRADE EQUIPPED WITH HPK PLANAR PIXEL SENSORS AND RD53B-CMS READOUT CHIPS

The new CMS Inner Tracker for the Phase 2 Upgrade

For the High-Luminosity phase of the Large Hadron Collider (HL-LHC) at CERN, the Inner Tracker (IT) system of the Compact Muon Solenoid (CMS) experiment will be entirely upgraded [1].

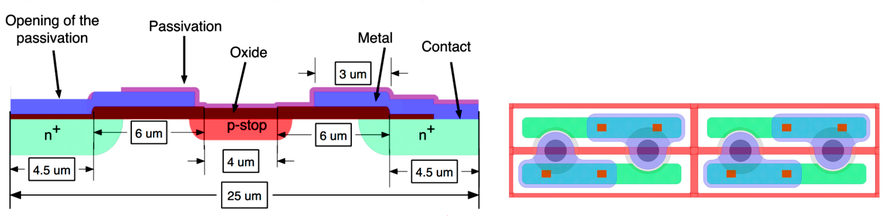
Key points:

- Luminosity of $7.5 \times 10^{34}\,cm^{-2}s^{-1}$, with an **integrated luminosity of 4000 fb^{-1}** (10 times higher than Phase 1)
- High radiation tolerance required:
  - **RD53B-CMS** validated up to **$\Phi_{eq} = 2.0 \times 10^{16}\,cm^{-2}$** (dose of ~10 MGy)
  - Planar sensors (3Ds for layer 1 of the barrel) with active thickness of **150 µm** (from 285 µm)
- Pile-up of **<µ> = 200** (5 times higher than Phase 1)
  - Pixel size reduced to **25x100 µm²** (from 100x150 µm²): occupancy < 10^{-4} and no cluster merging
- Only two types of **hybrid pixel modules**: system complexity reduced and flexible management of spares
  - **1156** 1x2 pixel modules (~1.8x4.4 cm²): two readout chips per module
  - **2736** 2x2 pixel modules (~3.7x4.4 cm²): four readout chips per module



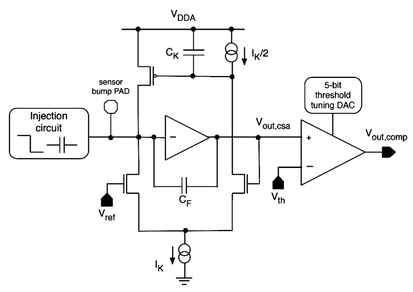
Planar sensors

- **n⁺-in-p** Hamamatsu Photonics (HPK) planar sensors
- Inter-chip regions with **big** pixels (for both 1x2 and 2x2 pixel modules)
- **No punch through bias dots**: single hit efficiency maximized
- **Parylene coating**: spark protection
- Special **"bitten"** design: no n⁺ implant under metal (reduced crosstalk)



RD53B-CMS readout chips

- Charge digitization through a **4-bit Time-over-Threshold (ToT)** counter at 40 MHz
- Adjustable **online threshold** below **1000 e⁻**
- **Full size chip**: 432x336 pixels (21.6x18.6 mm²)
- **50x50 µm²** pixel pitch
- Radiation hard design: **65 nm CMOS technology** (TSMC)
- Improved version of the RD53A **"linear"** front-end (FE) [2]
  - **Single stage** FE with Krummenacher feedback
  - Increased TDAC circuit **dynamic range** (with an extra 5th bit)
  - Improved **cluster charge estimation** (with dual slope ToT)



Test beam results

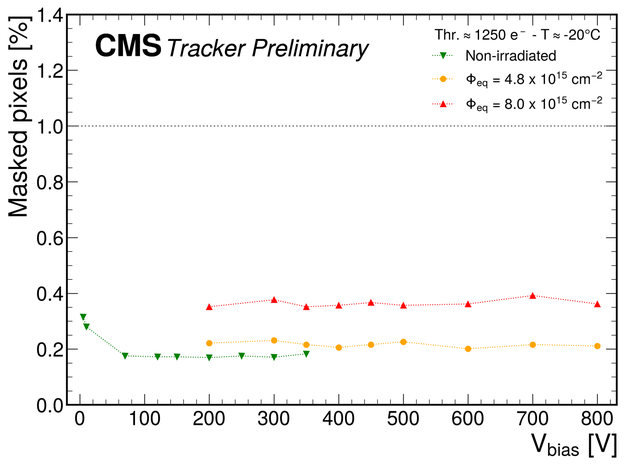
All the measurements for these studies were performed at the DESY II Test Beam facility with an **electron beam of 5.2 GeV**.
The modules were **irradiated with 24 GeV/c protons** at Proton Irradiation Facility (PS_IRRAD CERN).

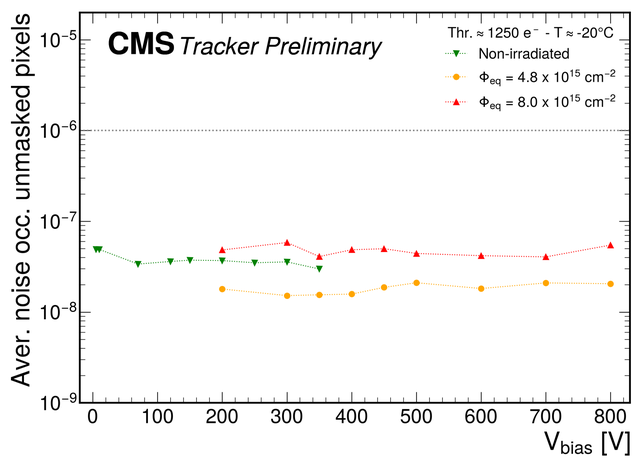
Single hit efficiency, acceptance and noise

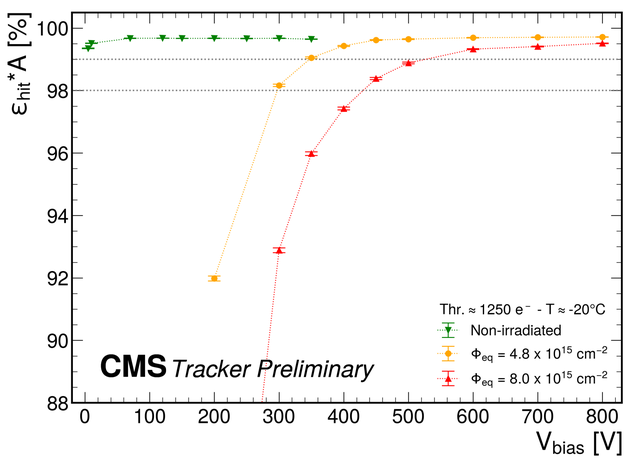
The number of layers of the IT has been optimized to ensure unaffected tracking performance even if data of one layer are missing. The main requirements for every module are:

- Total number of **masked pixels < 1%** (with an occupancy threshold to classify a pixel as noisy of 10^{-4})
- **Average noise occupancy** of the unmasked pixels **< 10^{-6}**
- At vertical incidence:
  - **ε_{hit}*A > 99% before** and after irradiation to **$\Phi_{eq} = 0.5 \times 10^{16}\,cm^{-2}$** ($V_{bias} \leq 600$ V and -20 °C)
  - **ε_{hit}*A > 98%** after irradiation to **$\Phi_{eq} = 1.0 \times 10^{16}\,cm^{-2}$** ($V_{bias} \leq 800$ V and -20 °C)

$$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}} \qquad A = 1 - \frac{N^{pxl}_{masked}}{N^{pxl}_{total}}$$





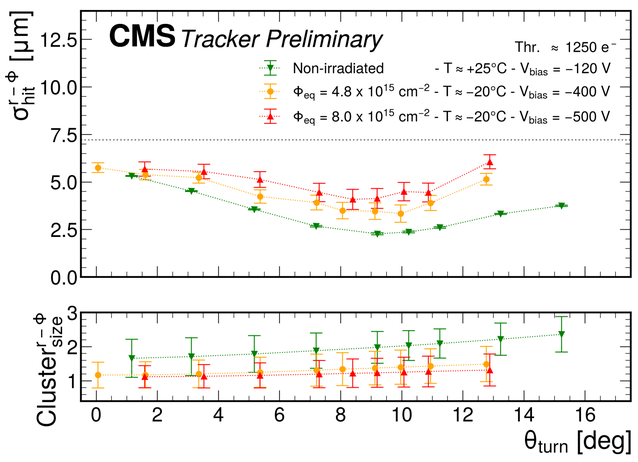


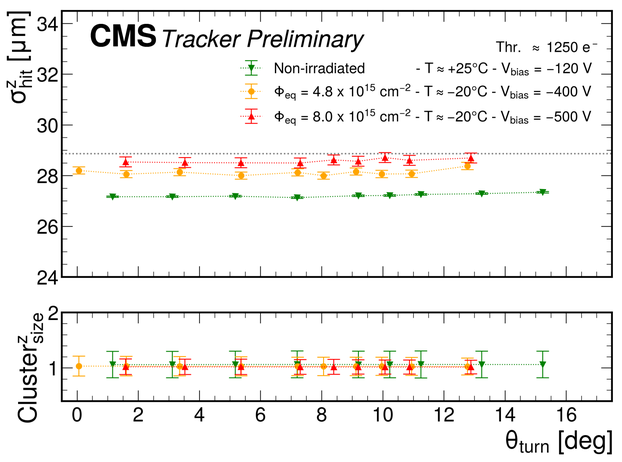
Single hit spatial resolution

Before irradiation, the single hit spatial resolution (σ_{hit}) is better than the binary limit owing to charge sharing and it degrades after irradiation. The aim is to reach a resolution below the binary limit for the full operation time and fluences, meaning $\sigma^{r-\phi}_{hit} \sim$ **7.2 µm** for the r-ϕ (25 µm pixel pitch) direction and $\sigma^{z}_{hit} \sim$ **28.9 µm** for the z (100 µm pixel pitch) direction.

$$\sigma_{hit} = \sqrt{\sigma^2_{res} - \sigma^2_{tpr}}$$

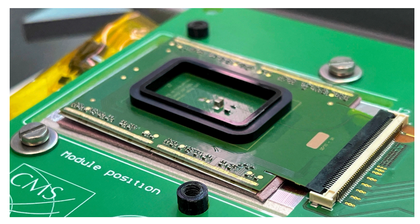
with: σ_{res} = truncated RMS from DUT residual distribution [3]
σ_{tpr} = truncated RMS from telescope track pointing resolution



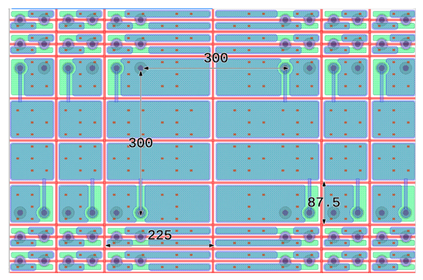


Validation of a full 2x2 module

- Non-irradiated and $\Phi_{eq} = 0.5 \times 10^{16}\,cm^{-2}$ modules tested: analysis ongoing



- Focus on the performances of the big pixels in the inter-chip regions



All the requirements of CMS are fulfilled by the modules equipped with planar HPK sensors and single RD53B-CMS readout chips.

[1] The CMS Collaboration, ***The Phase 2 Upgrade of the CMS Tracker*** (2017) - CMS-TDR-014
[2] The RD53 Collaboration, ***The RD53A Integrated Circuit*** (2017) - CERN-RD53-PUB-17-001
[3] M.Antonello, ***Results of planar pixel sensor qualification campaign for the CMS Phase 2 upgrade*** (2022) - CMS-CR-2022/259