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PERFORMANCE OF PLANAR PIXEL MODULES FOR THE PHASE-2 UPGRADE OF THE CMS INNER TRACKER

CMS Inner Tracker Upgrade for the High-Luminosity LHC

The Inner Tracker of the Compact Muon Solenoid (CMS) experiment will be entirely upgraded for the High-Luminosity Phase of the Large Hadron Collider (HL-LHC)[1].

Highlights

- Luminosity: **7.5 x 10^{34} cm^{-2} s^{-1}**
- Integrated luminosity: **3000 – 4000 fb^{-1}**
- Pile-up: <μ> = **200**
- ϕ_{max} planar modules $= 1 \times 10^{16}\ n_{eq} cm^{-2}$

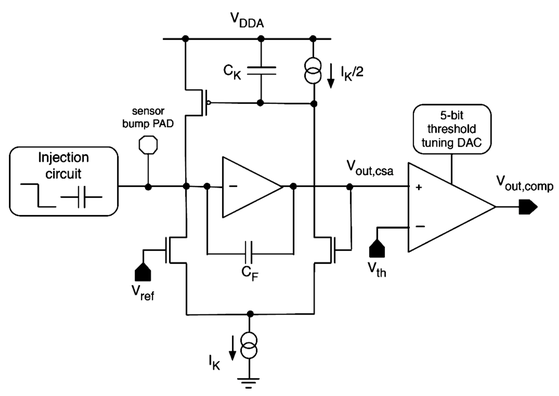
New pixel detectors for the CMS Inner Tracker

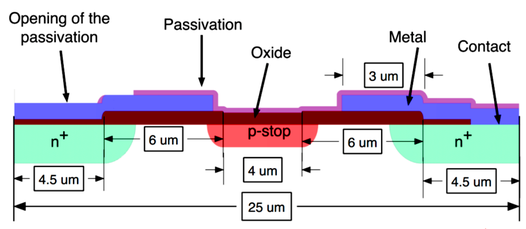
Pixel detectors of the Inner Tracker will feature a new **readout chip** (RD53C_CMS) and **sensor design**

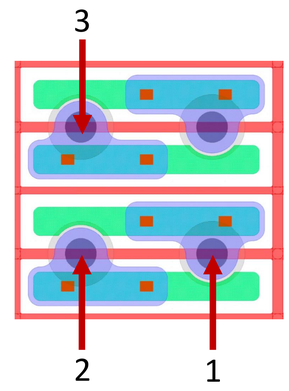
RD53B_CMS readout chips[2]

Implemented in **65 nm CMOS radiation-hard** technology:

- **432 x 336** pixels with **50 x 50 µm^2** pitch
- **Analog Front-End**:
  - **Single stage** with Krummenacher feedback
  - Low power **comparator**
  - 4 bit **counter** for charge digitization
  - 5 bit in-pixel DAC for **threshold tuning**







Planar sensors

- **n$^+$-in-p** Hamamatsu Photonics (HPK)
- Pitches of **25 x 100 µm^2** and active thickness of **150 µm**
- **Bitten** design: cutout in the neighboring pixel

Threshold studies

Pixels tuned to a **common threshold** to zero-suppress noise hits:

- Hit detection changes as function of **time** within the bunch crossing
- Feature of the **readout's architecture**
- Impact on the measured **crosstalk (XT)**

Crosstalk studies

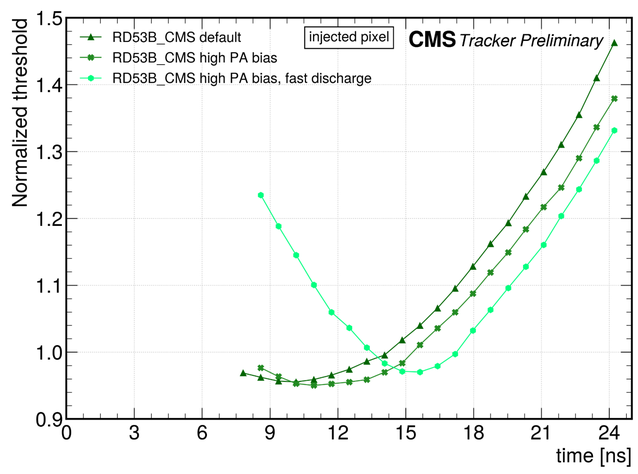
Must remain <10% for all geometrical configurations:

- Coupled pixels (1-2) with highest inter-pixel capacitance (14 fF)
- Uncoupled pixels (1-3) with second highest (6.5 fF)
- Avoid biasing of **reconstructed hit position**

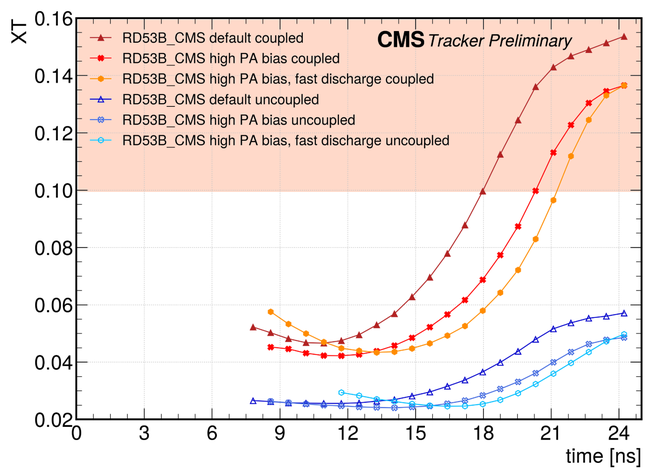
Phasing of clock in final experiment will target highest efficiency:

- Lowest threshold → minimum of threshold near crosstalk minimum

Effective threshold



Crosstalk



XT ~5% close to the threshold's minimum

Test beam measurements

Samples measured at DESY II Test Beam facility with **5.2 GeV e$^-$/e$^+$ beam**.

Modules **irradiated with 24 GeV/c protons** at Proton Irradiation Facility:

- **Non-uniform** fluence across **columns**
- Ranges from $\phi_{eq} = 0.5 \times 10^{16}\ cm^{-2}$ to $\phi_{eq} = 1.0 \times 10^{16}\ cm^{-2}$

Individual sections with different average fluences have been studied.

Observables

$$\varepsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}} \qquad \alpha = 1 - \frac{N^{pxl}_{masked}}{N^{pxl}_{total}} \qquad \sigma_{hit} = \sqrt{\sigma^2_{res} - \sigma^2_{tel}}$$

Main **module requirements**:

- Number of **masked pixels <1%** (noise occupancy threshold < 10^{-4})
- **Average noise occupancy** of unmasked pixels **<10^{-6}**
- At vertical incidence, for irradiated modules:

$$\phi_{ref} = 5 \times 10^{15}\ n_{eq} cm^{-2} \begin{cases} \Phi_{eq} < \Phi_{ref} & \varepsilon_{hit} \times \alpha > 99\% \quad V_{bias} \leq 600\ V \\ \Phi_{eq} > \Phi_{ref} & \varepsilon_{hit} \times \alpha > 98\% \quad V_{bias} \leq 800\ V \end{cases}$$

Studies on $\phi_{eq} = 1.0 \times 10^{16}\ cm^{-2}$ for different **thresholds**:

- Meet requirement for $\varepsilon_{hit} \times \alpha$
- Noisy pixels above requirement for threshold = 1000 e$^-$

Threshold $\geq$ 1200 e$^-$ to fulful $\varepsilon_{hit} \times \alpha$ and noise requirements

σ_{hit} better than binary limit before irradiation:

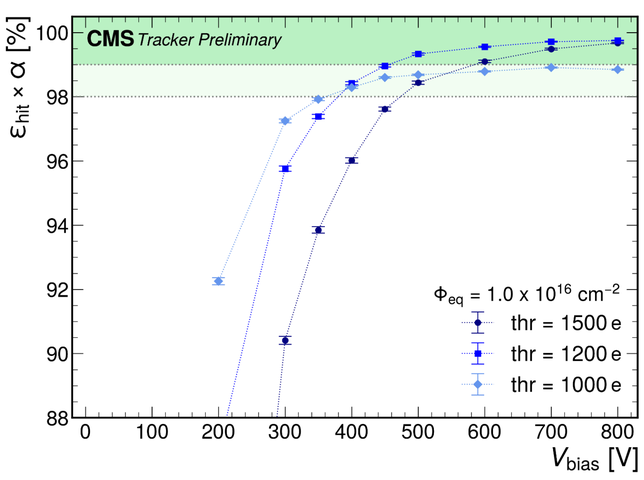
- Charge sharing

Aim after irradiation:

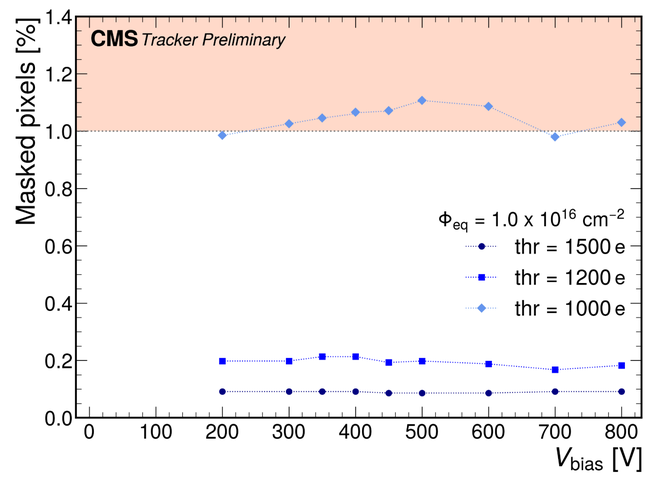
- $\sigma^{r-\phi}_{hit} <$ **7.2 µm** in r-ϕ (25 µm pixel pitch)
- $\sigma^{z}_{hit} <$ **28.9 µm** in z (100 µm pixel pitch) direction

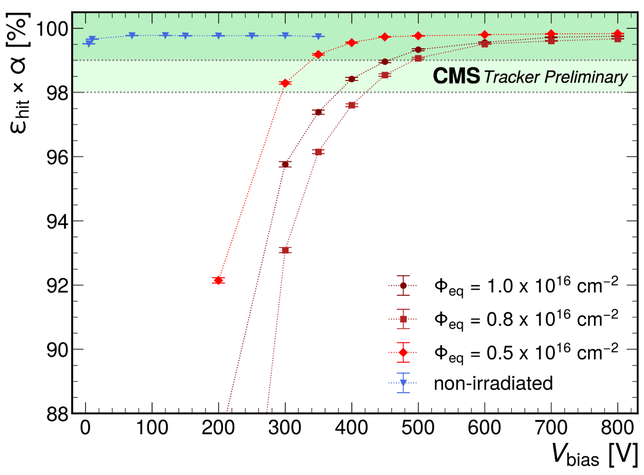
Planar sensors equipped with RD53B_CMS chips meet all requirements

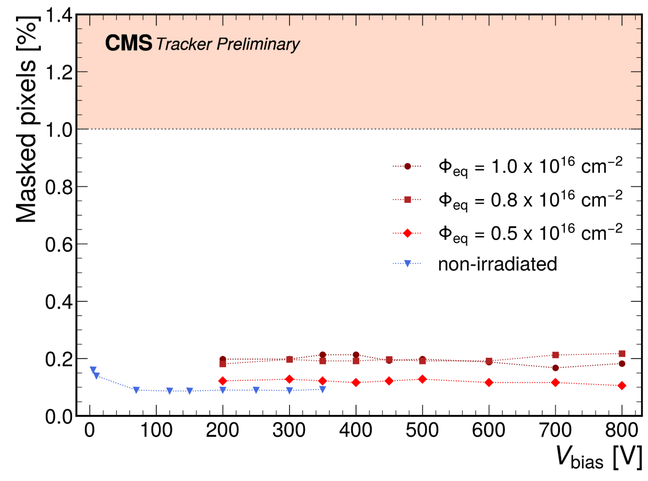
$\varepsilon_{hit} \times \alpha$



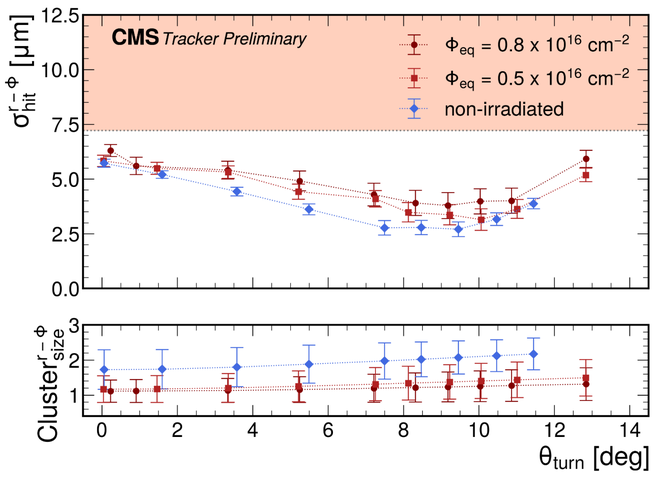
Masked pixels



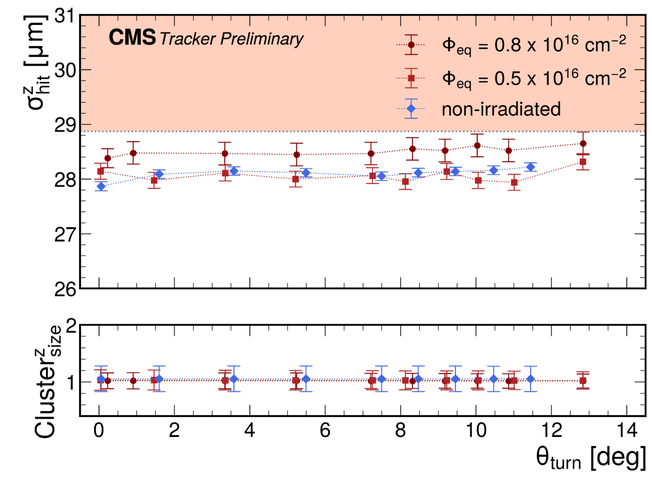




Resolution 25 µm



Resolution 100 µm



[1] The CMS Collaboration, ***The Phase 2 Upgrade of the CMS Tracker*** (2017) - CMS-TDR-014

[2] The RD53 Collaboration, ***RD53B Manual*** (2019) - CERN-RD53-PUB-19-002