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

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The CMS Tracker Upgrade

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

Requirements

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

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

New pixel sensors and front-end electronics
New Inner Tracker layout
The Inner Tracker Layout

- “Simple” mechanical structure
- Simple installation and removal for potential replacement of parts
- 4.9 m² of pixel surface & $2 \times 10^9$ channels
- Inner layer at 30 mm from beam line

Tracker Forward PiXel (TFPX) (8 disks per side)

Tracker Barrel PiXel (TBPX) (4 layers)

Tracker Endcap PiXel (TEPX) (4 disks per side)

2736
$2 \times 2$ pixel modules

1156
$1 \times 2$ 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:
  - Pixel size reduced by a factor 6 from $100 \times 150$ $\mu$m$^2$
  - Two pixel cells under study → $25 \times 100$ $\mu$m$^2$ or $50 \times 50$ $\mu$m$^2$
  - Various pixel design configurations
    - Isolation → p-stop or p-spray
    - Sensor test bias scheme → punch trough or temporary metal

Phase 1

| 285 $\mu$m |

Phase 2

| 100 $\mu$m - 150 $\mu$m |
3D Pixel Sensors

- 3D pixel R&D (FBK & CNM)
- In 3D sensors the drift path is perpendicular to the active depth
  - Short drift distance $\rightarrow$ ~30 - 50 $\mu$m (3D) vs. 100 - 150 $\mu$m (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
RD53 ROC goals:
- Radiation hard (up to 5 MGy)
- Low thresholds and noise

65 nm technology & 50 × 50 μm² (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 μm² pitch without Punch-Through (PT) structure
  - One 50×50 μm² 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 μm² pitch
  - Irradiated @ CERN: (nominal) fluence of 1×10^{16} n_{eq} cm^{-2}
Planar Modules - Efficiency vs. Bias

- Efficiency increases with (effective) bias voltage $V_{bias}$
- Efficiency $> 99\%$ at $V_{bias} \sim 210\,\text{V}$
- Pixel thresholds ($V_{thr}$) tuned to $1400\,\text{e}^-$
- Leakage current $\sim 540\,\mu\text{A}$ at $V_{bias} \sim 295\,\text{V}$
  - Bad cooling contact on the module
- Efficiency starts saturating around $V_{bias} \sim 200\,\text{V}$
- Eff. max value: $97.6\%$ at $V_{bias} \sim 390\,\text{V}$
- Pixel thresholds tuned to $1200\,\text{e}^-$
- Leakage current $\sim 50\,\mu\text{A}$ at $V_{bias} \sim 390\,\text{V}$

Orthogonal Beam Incidence

Irradiated - $5 \times 10^{15} \, \text{n}_{\text{eq}} \, \text{cm}^{-2}$

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Planar no-PT Module - Cell Efficiency

- 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

- Plot scale starts at 0.9

Same efficiency colour scales!
Planar PT Module - Cell Efficiency #1

- 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)

Same efficiency colour scales!
Planar PT Module - Cell Efficiency #2

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

This module has been irradiated at CERN PS: the beam width was smaller than the chip, therefore the irradiation is not uniform.
CERN beam spot from irradiation is visible (and centered on Linear front-end)

\[ V_{\text{bias}} = 28 \text{ V} \]
Under-depleted

No efficiency drops visible (see next slide)

\[ V_{\text{bias}} = 146 \text{ V} \]
Fully-depleted
3D Module - Efficiency Map #2

- 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 $V_{bias}$

$V_{bias} = 146 \, V$

98.8% 99.0%
99.0% 98.8%
98.9% 98.9%

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Efficiency maps for 2×2 pixel grid

- Orthogonal beam incidence
- Efficiency gets more uniform with increasing bias voltage
  - At low $V_{\text{bias}}$, higher eff. near $n^+$ columns (electrodes)
  - Small eff. drop near $p^+$ columns at high $V_{\text{bias}}$

Efficiency colour scales are different!
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 $\sigma$ from the fit, the telescope resolution ($res_{tele}$) has been estimated with:
    \[
    \sigma^2_{no-rot} = res^2_{trivial} + res^2_{tele} \quad \text{where} \quad res_{trivial} = 50/\sqrt{12} \ \mu m
    \]
    \[
    \rightarrow \quad res_{tele} \approx 10 \ \mu m
    \]
  - 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 \mu m) at ~20° → cluster size ≥ 2 for geometry:
  \[
  \tan^{-1}(\text{pitch}/\text{active\_thickness}) = \tan^{-1}(50/130) \approx 21°
  \]
Outlook

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