Characterization of Planar Pixel Sensors for the High-Luminosity Upgrade of the CMS Detector

Marco Meschini, on Behalf of Aliakbar Ebrahimi
Both of them on behalf of the CMS Tracker Group

10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging
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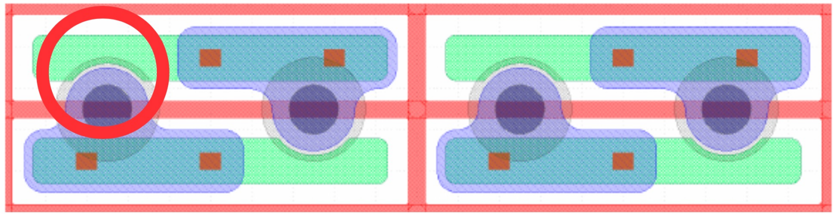
Santa Fe Plaza last night 11 PM

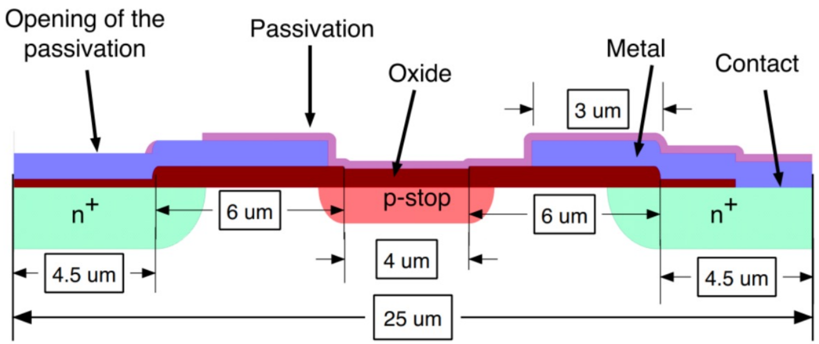
The Planar Sensors – Baseline Design

- Hybrid pixel detectors
- Produced by HPK, FBK and LFoundry
- n-in-p planar sensors for all but first barrel layer
- Advantages compared to current n-in-n sensors
  - Single-sided processing
  - Fewer number of production steps
  - Lower production cost
- 150 μm active thickness
  - Higher radiation hardness
  - Lower bias voltage for high efficiency
- 25 x 100 μm^2 pixel pitch
- Parylene coating applied on final modules for spark protection
- No n^+ implant under metal pads of adjacent pixel
  - Reduced crosstalk

“Bitten” n^+ implant



HPK & FBK 6” wafers

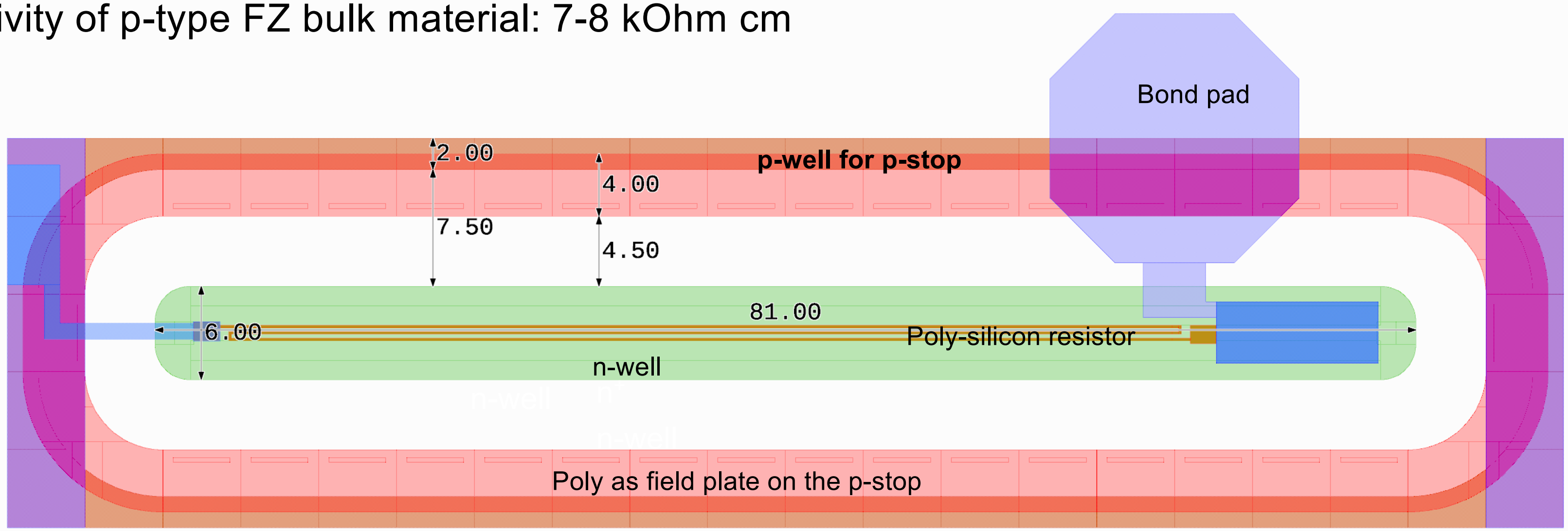


HPK baseline design with p-stop isolation

FBK baseline design has p-spray isolation

LFoundry Technology and Design

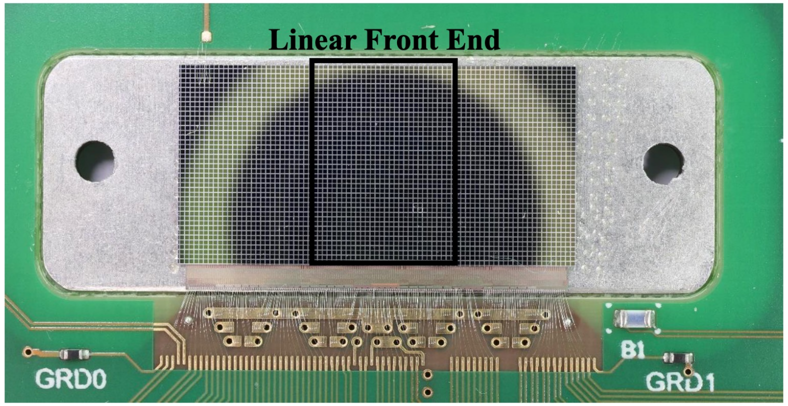
- Production of passive sensors on 150 nm CMOS LFoundry process
  - 8” wafers
  - 6 metal layers possible, 4 layers effectively used
  - n-well together with n^+ used in the pixel body implantation 6 μm x 81 μm
  - p-well with p^+ used for the p-stop
  - Low resistivity poly-silicon used for field-plates on top of p-stop
  - High resistive poly-silicon layer for bias resistors (square of 0.15 μm side): total resistance ~ 2.7 MOhm
  - Resistivity of p-type FZ bulk material: 7-8 kOhm cm

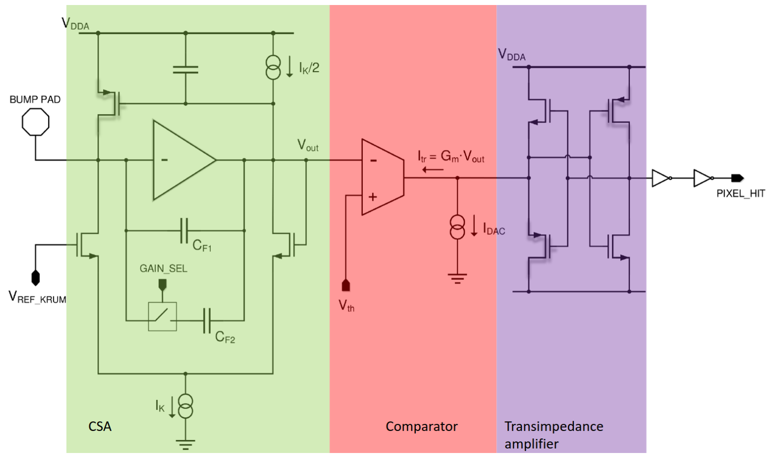


Readout Chip - RD53A

- 400 x 192 pixels
- 50 µm x 50 µm pixel pitch
- TSMC 65 nm CMOS technology
- Serial powering
- Three different analog front-ends
- Linear front-end chosen by CMS
  - 136 columns
  - Adjustable online threshold
  - 4-bit time-over-threshold

RD53A specs rated for 5MGy



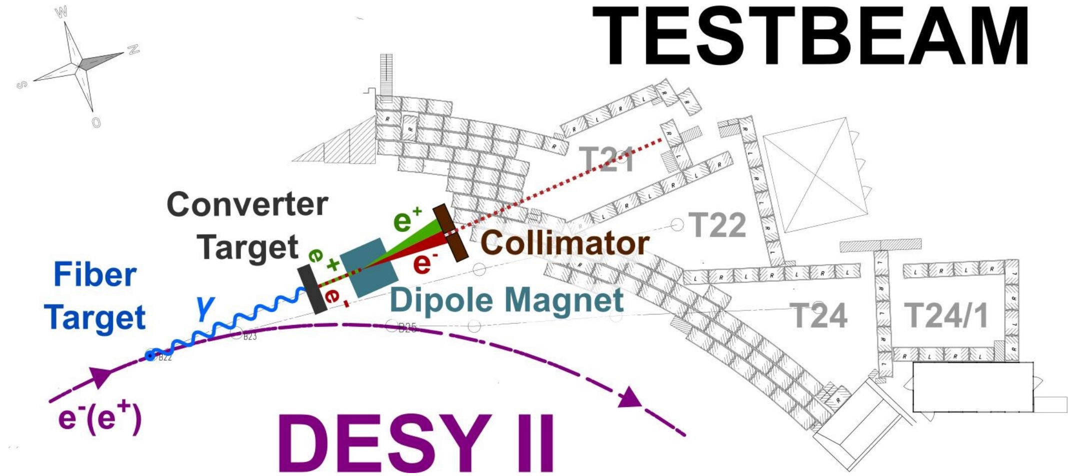


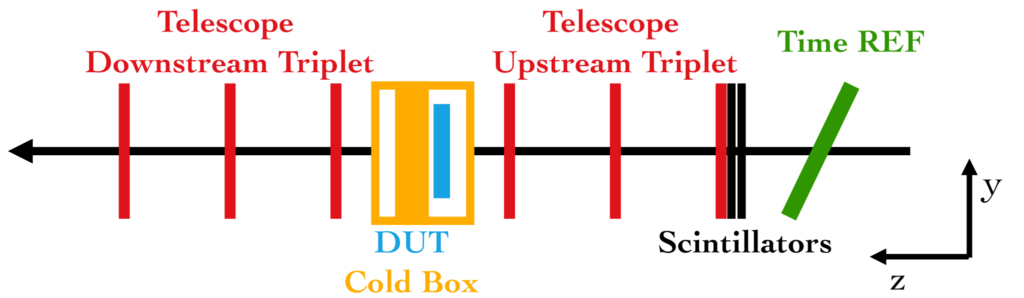
Schematic of the Linear analog front end flavor

All Modules Bump Bonded at IZM

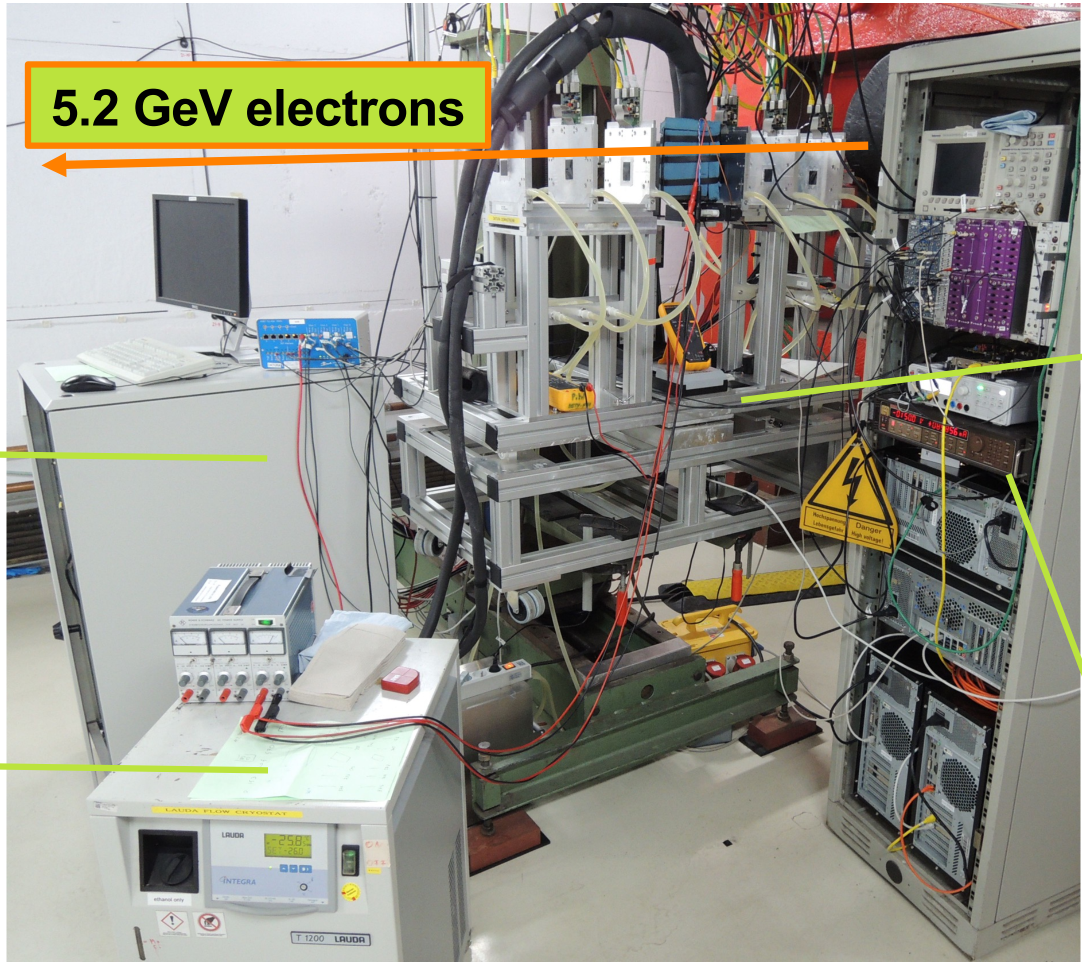
Beam Test Setup at DESY

- Data taken at DESY test-beam 21
- 5.2 or 5.6 GeV electrons
- Scintillator triggers
- EUDET DATURA telescope for tracking
  - 6 MIMOSA-26 planes
  - 115 μs integration time
- CMS phase-1 module as timing reference
- Device Under Test (DUT) cooled down to -24 deg C (or lower)





Beam Test Setup at DESY



DESY TEST BEAM.
TB 21

DATURA Telescope

Telescope DAQ

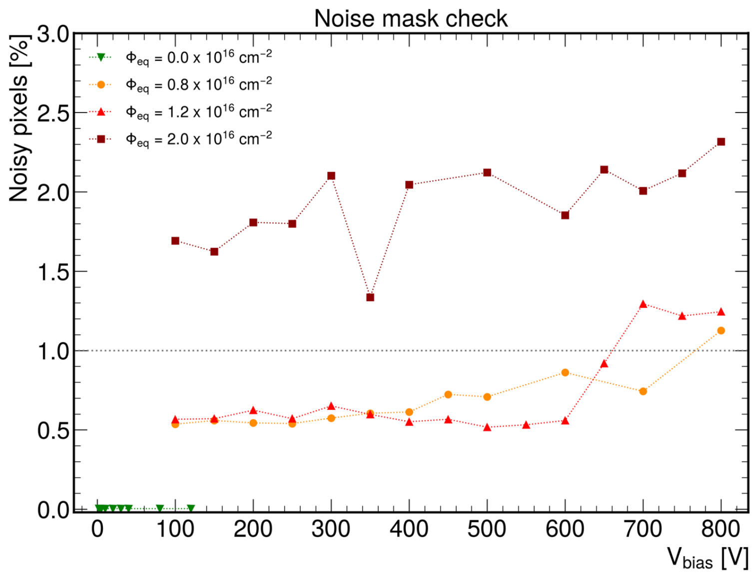
Cooling system

RD53A DAQ, power and trigger systems

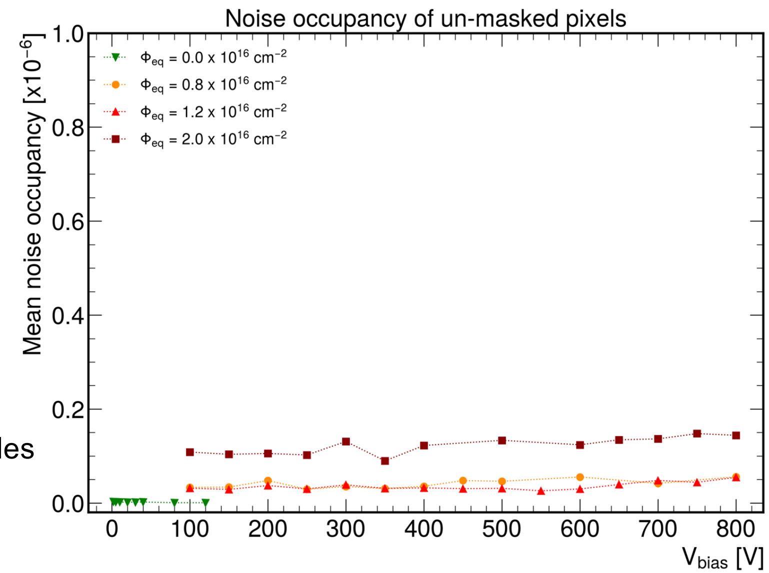
Noise Studies

- Requirements for the final module
  - Total number of masked pixels < 1%
  - Average noise occupancy of un-masked pixels < 10^{-6}
- Low noise level already achieved with RD53A modules

Modules irradiated at KIT 23MeV p beam
Very high TID: 15 MGy @ 1.0 x 10^{16} n_{eq} cm^{-2}



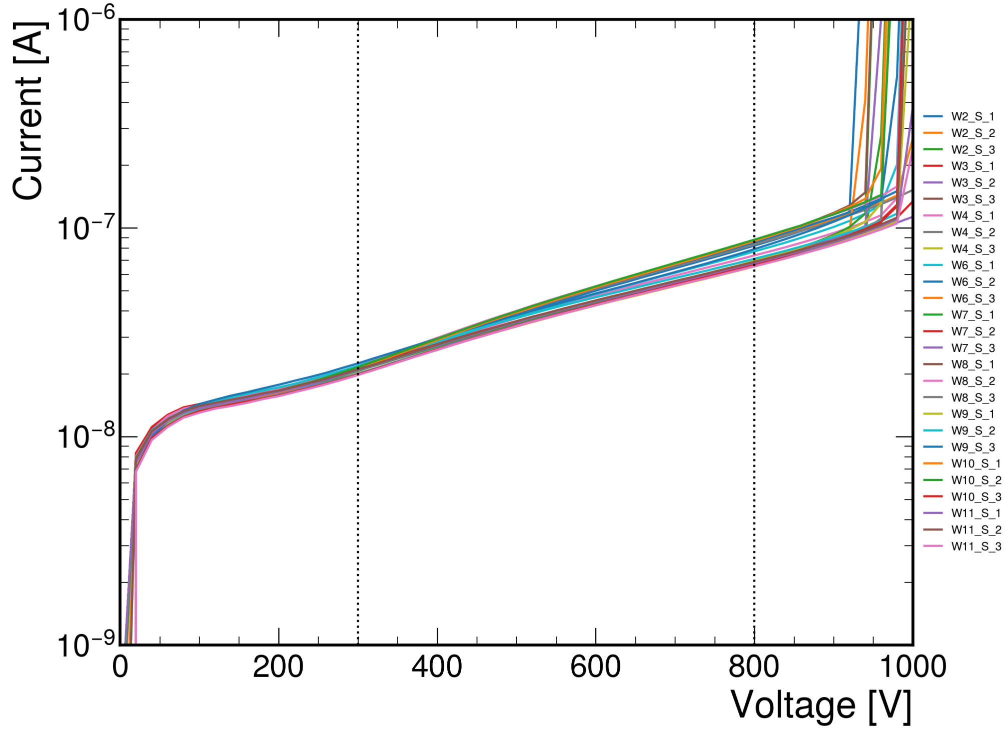
HPK single chip modules



Hit Efficiency and I-V Requirements

$$\epsilon_{hit} = \frac{N_{DUT}}{N_{tracks}}$$

- Non-irradiated:
  - $\varepsilon_{hit} > 99\%$
  - at vertical incidence, $V_{bias} = V_{dep.} + 50$ V, +20 °C
- Irradiated up to $\Phi_{eq} = 0.5 \times 10^{16}$ cm^{-2}:
  - $\varepsilon_{hit} > 99\%$
  - at vertical incidence, $V_{bias} < 800$ V, -20 °C
- Irradiated up to $\Phi_{eq} = 1.0 \times 10^{16}$ cm^{-2}:
  - $\varepsilon_{hit} > 98\%$
  - at vertical incidence, $V_{bias} < 800$ V, -20 °C

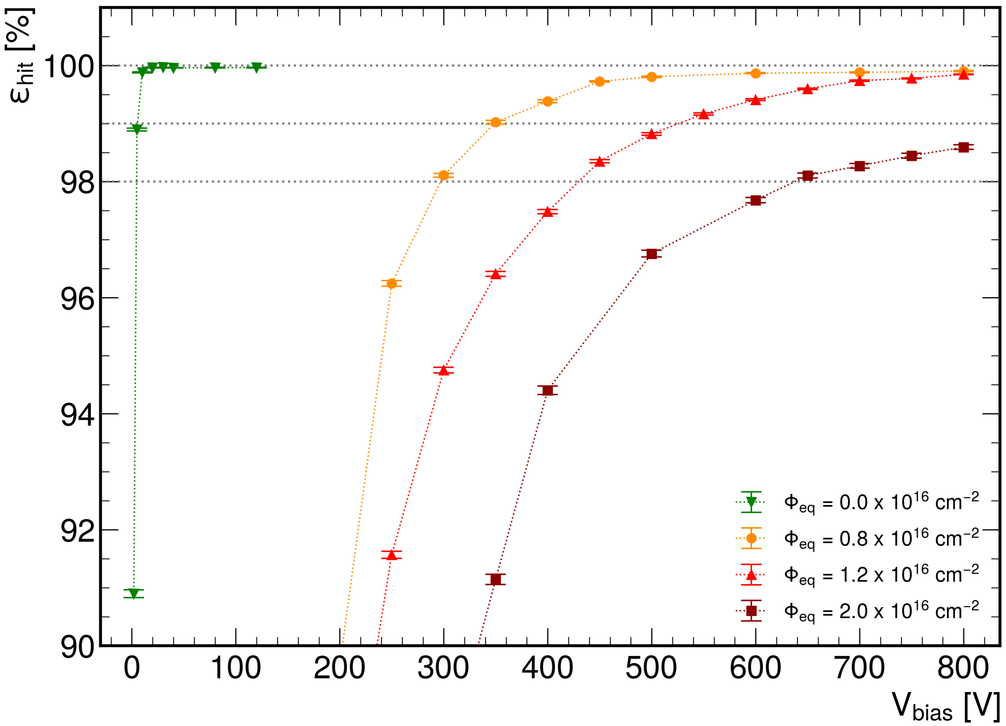


Leakage Current of HPK 25 µm x 100 µm RD53A sensors

Non irradiated sensor Leakage current final requirement:
$I_{Bias} < 0.75$ µA/cm^2 at V_{fd} +50V

Hit Efficiency – HPK Sensors

- Non-irradiated
  - Online threshold ~1300 e, +25 °C
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 5$ V ✓
- $\Phi_{eq} = 0.8 \times 10^{16}$ cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 350$ V ✓
- $\Phi_{eq} = 1.2 \times 10^{16}$ cm^{-2}
  - $\varepsilon_{hit} > 98\%$ at $V_{bias} > 450$ V ✓
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 550$ V ✓
- $\Phi_{eq} = 2.0 \times 10^{16}$ cm^{-2}
  - $\varepsilon_{hit} > 98\%$ at $V_{bias} > 650$ V ✓



Hit Efficiency vs. Angle of Incidence

- Non-irradiated
  - Online threshold ~1300 e, +25 °C
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 5$ V ✓
- $\Phi_{eq} = 0.8 \times 10^{16}$ cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 350$ V ✓
- $\Phi_{eq} = 1.2 \times 10^{16}$ cm^{-2}
  - $\varepsilon_{hit} > 98\%$ at $V_{bias} > 450$ V ✓
  - $\varepsilon_{hit} > 99\%$ at $V_{bias} > 550$ V ✓
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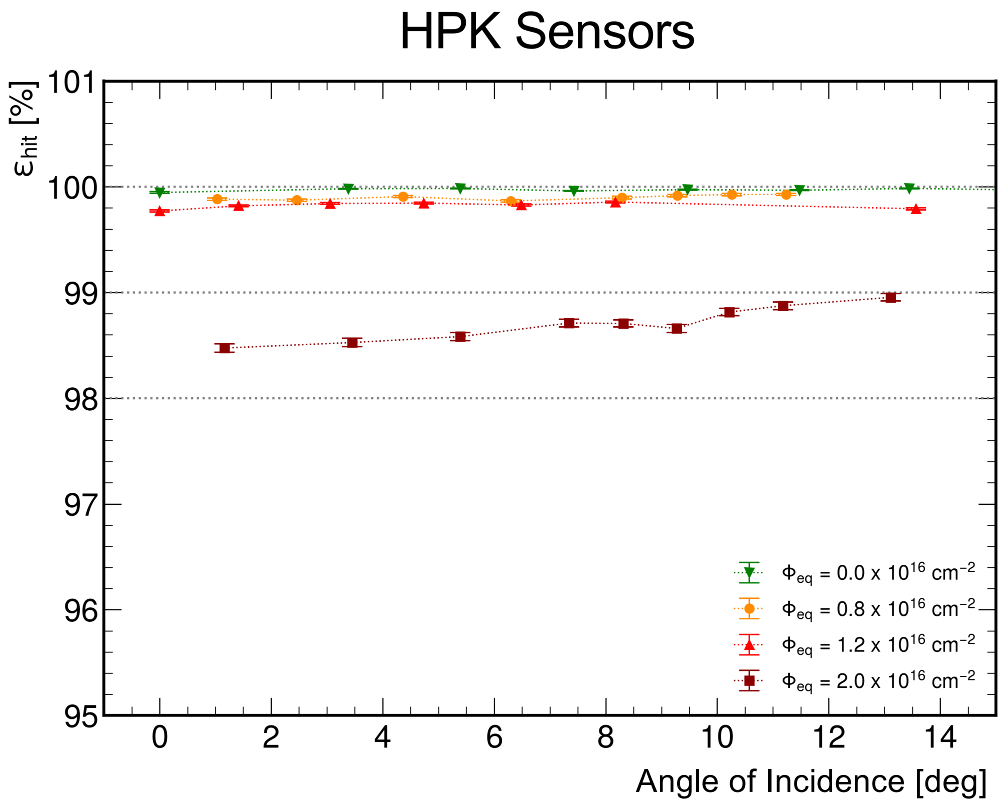
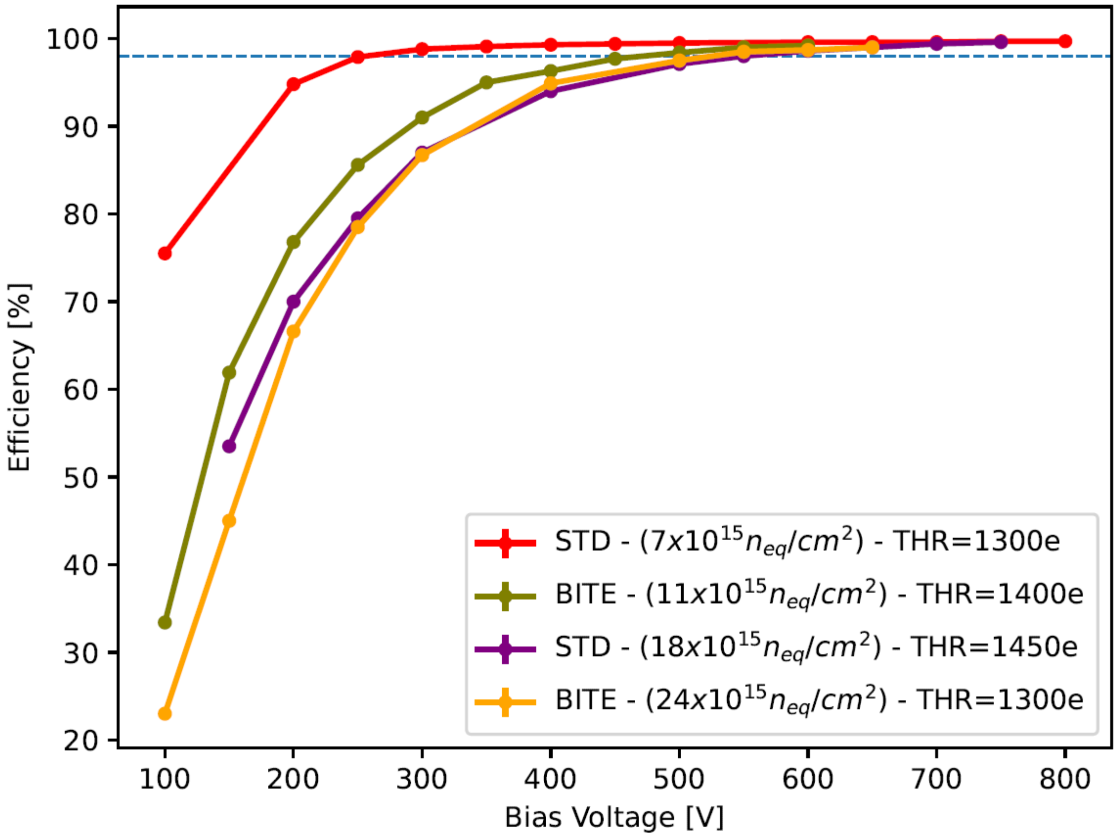


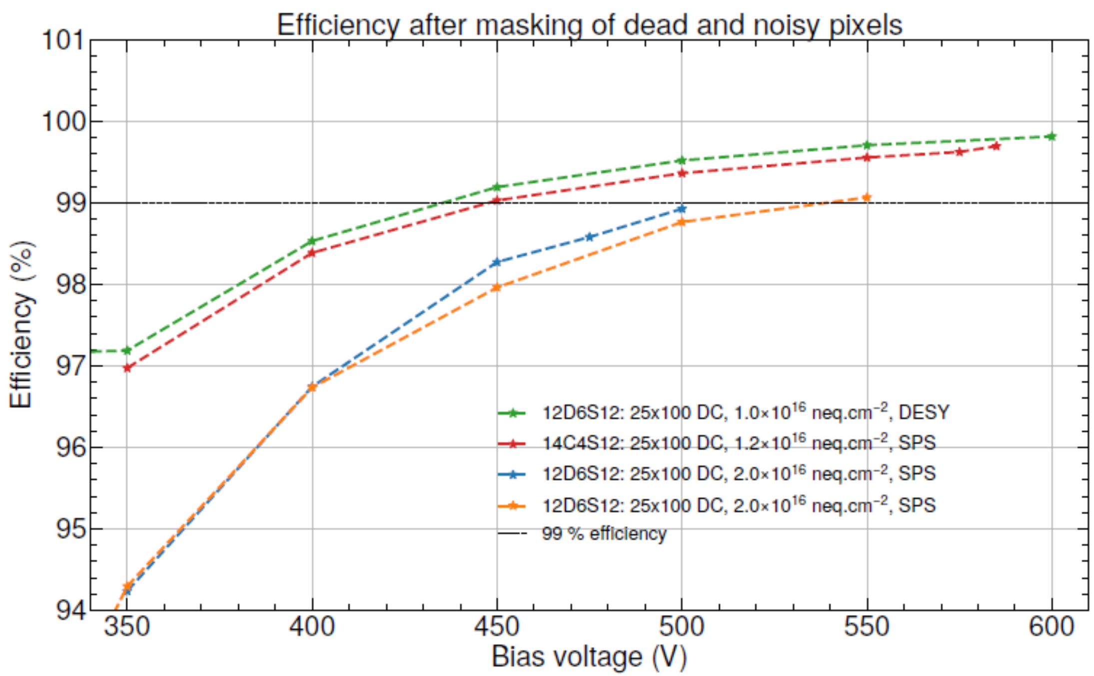
Hit Efficiency – FBK Sensors

- Φ_{eq} = **0.7 x 10^{16}** cm^{-2}
  - Online threshold ~1300 e, -25 °C
  - ε_{hit} > 99% at V_{bias} > 250 V ✓
- Φ_{eq} = **1.1 x 10^{16}** cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - ε_{hit} > 99% at V_{bias} > 450 V ✓
- Φ_{eq} = **1.8 x 10^{16}** cm^{-2}
  - Online threshold ~1450 e, -25 °C
  - ε_{hit} > 99% at V_{bias} > 550 V ✓
- Φ_{eq} = **2.4 x 10^{16}** cm^{-2}
  - ε_{hit} > 99% at V_{bias} > 550 V ✓



Hit Efficiency – LFoundry Sensors

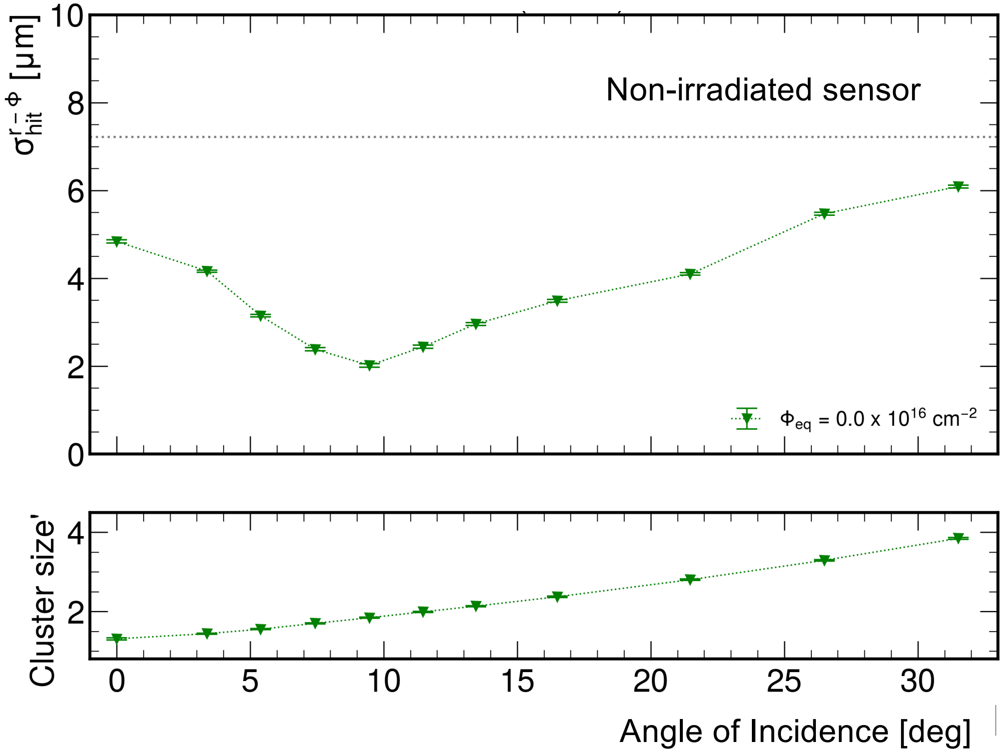
- Φ_{eq} = 1.0 x 10^{16} cm^{-2}
  - ε_{hit} > 99% at V_{bias} > 450 V ✓
- Φ_{eq} = 1.2 x 10^{16} cm^{-2}
  - ε_{hit} > 99% at V_{bias} > 450 V ✓
- Φ_{eq} = 2.0 x 10^{16} cm^{-2}
  - ε_{hit} > 99% at V_{bias} > 550 V ✓



Single Hit Spatial Resolution - HPK

- Non-irradiated at optimal angle:
  - Online threshold ~1300 e, +25 °C
  - **σ_{hit} ~ 2 μm** at V_{bias} = 120 V ✓
- $\Phi_{eq} = 0.8 \times 10^{16}$ cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 7.2 μm at V_{bias} = 600 V ✓
- $\Phi_{eq} = 1.2 \times 10^{16}$ cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 7.2 μm at V_{bias} = 800 V ✓
- $\Phi_{eq} = 2.0 \times 10^{16}$ cm^{-2}
  - σ_{hit} < 7.2 μm at V_{bias} = 800 V ✓

Rotation around the long pixel axis for charge sharing in the **25 μm** direction



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- $\Phi_{eq} = 1.2 \times 10^{16}$ cm^{-2}
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  - σ_{hit} < 7.2 µm at V_{bias} = 800 V ✓
- $\Phi_{eq} = 2.0 \times 10^{16}$ cm^{-2}
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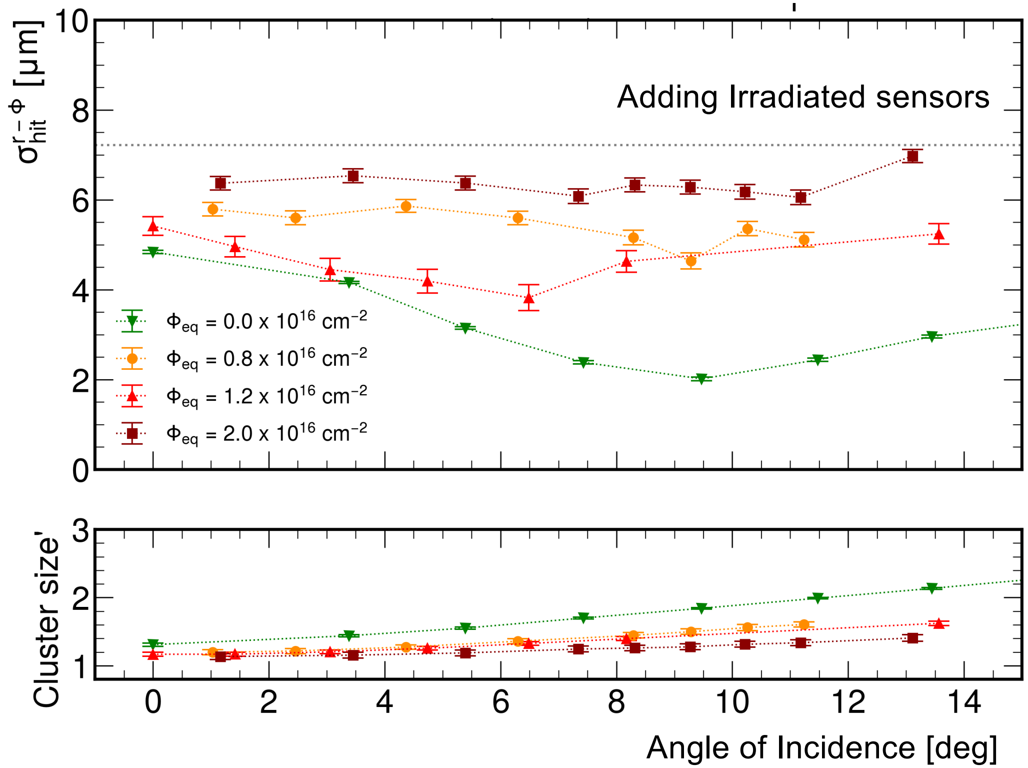
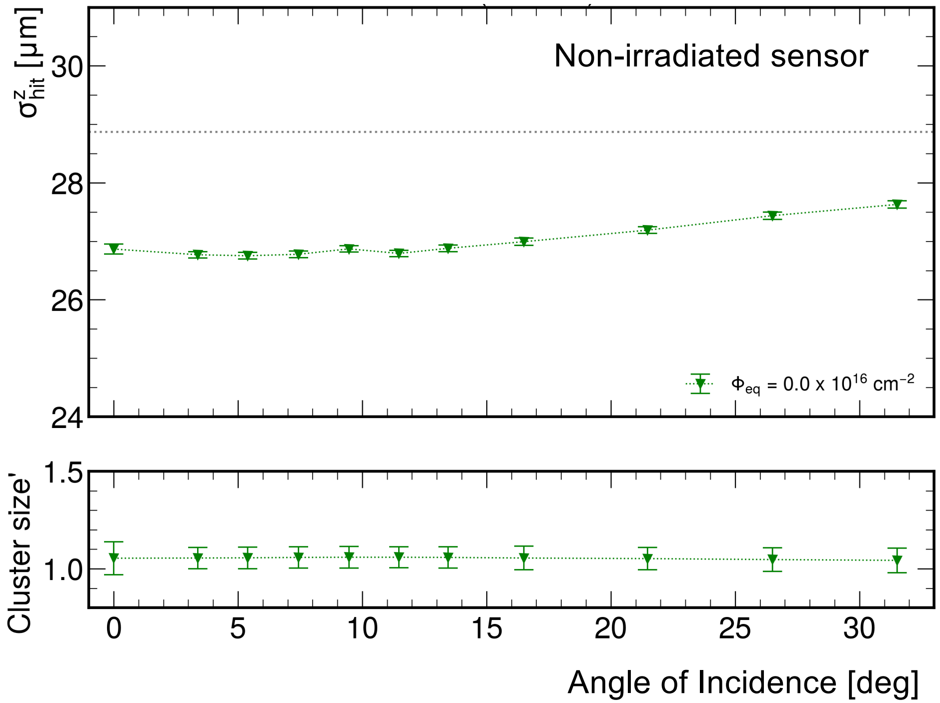
Rotation around the long pixel axis for charge sharing in the **25 µm** direction



Single Hit Spatial Resolution - HPK

- Non-irradiated at optimal angle:
  - Online threshold ~1300 e, +25 °C
  - σ_{hit} < 28,9 µm at V_{bias} = 120 V ✓
- Φ_{eq} = 0.8 x 10^{16} cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 28.9 µm at V_{bias} = 600 V ✓
- Φ_{eq} = 1.2 x 10^{16} cm^{-2}
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 28,9 µm at V_{bias} = 800 V ✓
- Φ_{eq} = 2.0 x 10^{16} cm^{-2}
  - σ_{hit} < 28,9 µm at V_{bias} = 800 V ✓

Rotation around the short pixel axis for charge sharing in the **100 µm** direction



Single Hit Spatial Resolution - HPK

- Non-irradiated at optimal angle:
  - Online threshold ~1300 e, +25 °C
  - σ_{hit} < 28,9 µm at V_{bias} = 120 V ✓
- $\Phi_{eq} = 0.8 \times 10^{16}\ cm^{-2}$
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 28.9 µm at V_{bias} = 600 V ✓
- $\Phi_{eq} = 1.2 \times 10^{16}\ cm^{-2}$
  - Online threshold ~1400 e, -25 °C
  - σ_{hit} < 28,9 µm at V_{bias} = 800 V ✓
- $\Phi_{eq} = 2.0 \times 10^{16}\ cm^{-2}$
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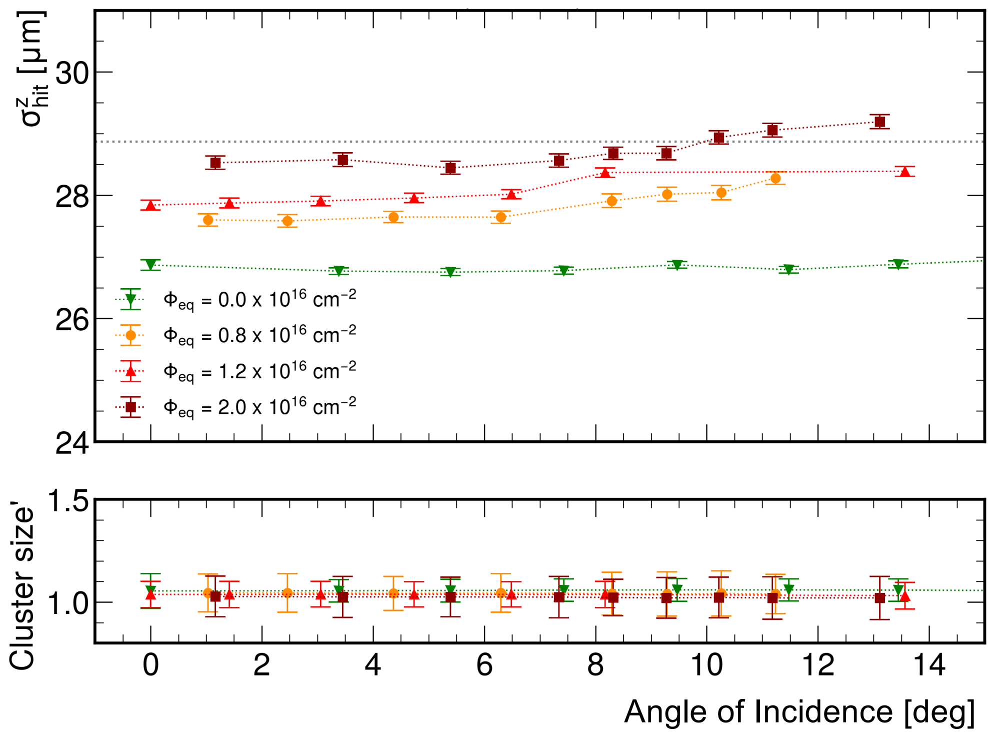
Rotation around the short pixel axis for charge sharing in the **100 µm** direction



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Conclusions and Outlook

- Planar Pixel Sensors produced by FBK, HPK and LFoundry have been characterized in a common effort by the CMS Tracker Collaboration
- Very good electrical behaviour before and after irradiation
- Hit efficiency of ~ 99% for modules irradiated up to 2.4 x 10^{16} n_{eq} cm^{-2}
- Hit resolution in r-φ (25 μm) and z (100 μm) better than binary resolution even after irradiation to the highest fluence
- **Sensors from all 3 vendors are qualified for the high-luminosity upgrade of the CMS pixel detector**
- Prototype S.C. Modules with CROC_v1 (CMS chip with final pixel matrix) are being tested as reported in Anna Macchiolo's talk
- First CROC quad full modules of 15.5cm^2 area are being assembled