Karlsruhe Institute of Technology

Beam Test of Silicon Sensor Modules with Irradiated Sensors for the CMS Experiment

T 60.7

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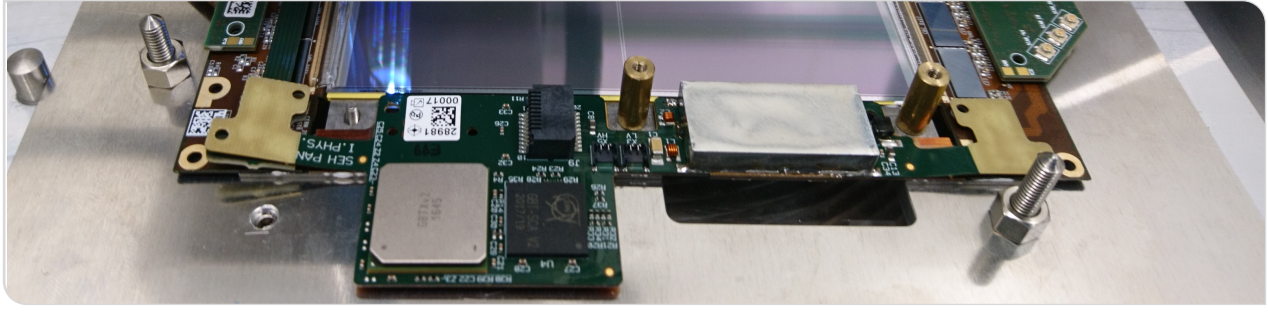
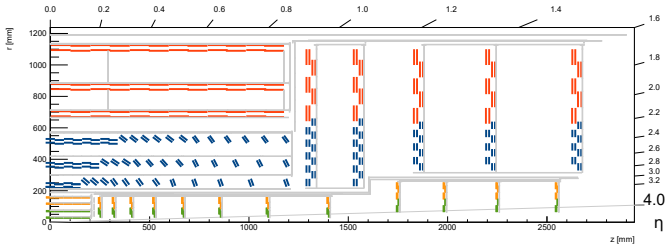


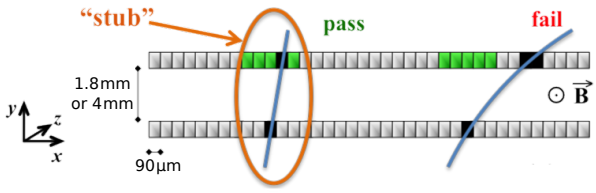
The Phase-2 Upgrade of the CMS Outer Tracker

Phase-2 Upgrade of the CMS Outer Tracker

- New silicon tracker in the CMS experiment for HL-LHC by 2027
- Requirements for the Outer Tracker upgrade:
  - Improved radiation tolerance up to $1 \times 10^{15}\, n_{eq} cm^{-2}$
  - Increased granularity
  - Improved two-track separation
  - Reduced material in tracking volume
  - Contribution to L1 trigger
- Silicon sensors in tracker modules will be operated at about $-20°C$



2S modules and PS modules in the Phase-2 Outer Tracker



2S Module for the CMS Outer Tracker

Service Hybrid

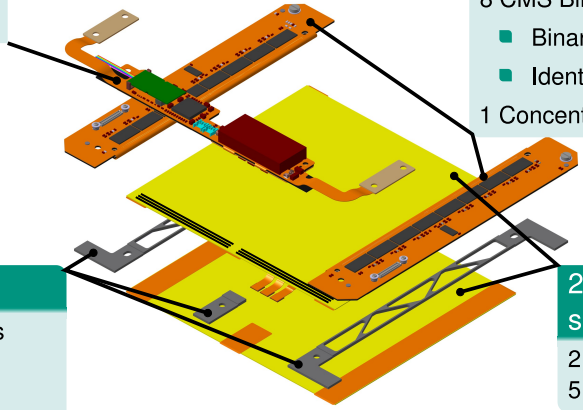
Powering
Data transmission

2 Front-end Hybrids

8 CMS Binary Chips[2] each

- Binary readout of sensor signals
- Identification of stubs

1 Concentrator Chip each



Al-CF[1] Spacer

Spacing between sensors
Main cooling path
Mechanical fixation

2 parallel silicon strip sensors

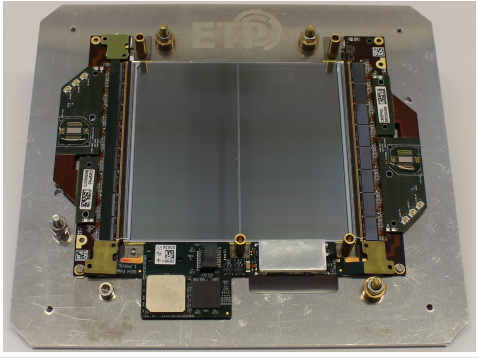
2×1016 strips each
5 cm length, 90 µm pitch

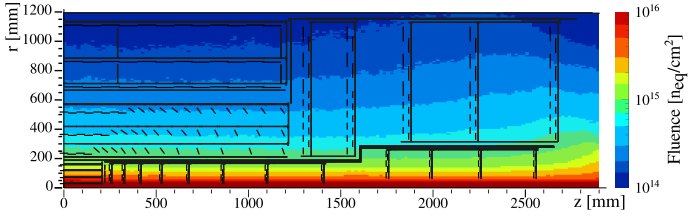
[1] Aluminum / carbon fiber composite

[2] Prydderch et al., *CBC3: a CMS microstrip readout ASIC with logic for track-trigger modules at HL-LHC*, CMS-CR-2017-383

2S Module Prototype with Irradiated Sensors

- Study performance of 2S modules after 10 years of operation in CMS
- Expected maximum 2S module fluence for 4000 fb^{-1}: approximately 5×10^{14} n_{eq}/cm^2
- Irradiated 2S sensors before module assembly with 23 MeV protons at KIT to 4.6×10^{14} n_{eq}/cm^2
- CMS tracker operated cold, but short phases of warming up needed and desired
  → Different equivalent annealing times for top and bottom sensor: 10 d@RT and 200 d@RT

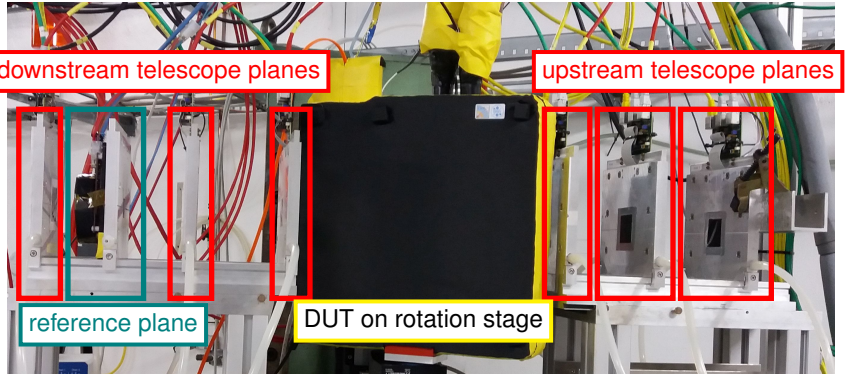


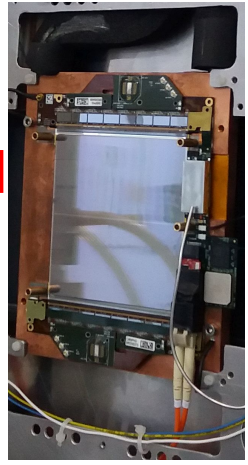


Beam Test of 2S Module with Irradiated Sensors

Experimental Setup

- One week of beam time at DESY Beam Test Facility (August 2020)
- 2S modules cooled down to $\approx -17^{\circ}\mathrm{C}$ sensor temperature





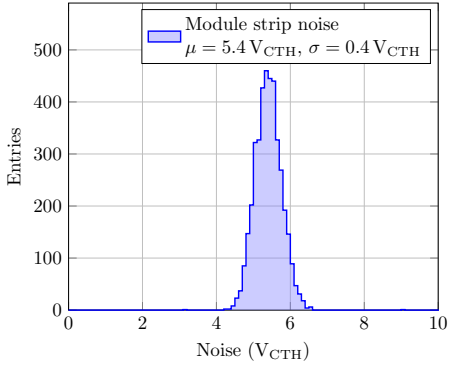
Measurement Program and Module Noise

Measurement Program:

- Threshold scans at different bias voltages
  → study hit and stub detection efficiency
- Angular scans at different bias voltages
  → study stub resolution by mimicking bent particle incidence
- Bias voltage scan

2S Module Noise:

- CMS Binary Chip strip noise at $\approx 850\,e^-$ at $T_{sensor} \approx -17°C$
- Noise comparable with results of unirradiated 2S modules at room temperature

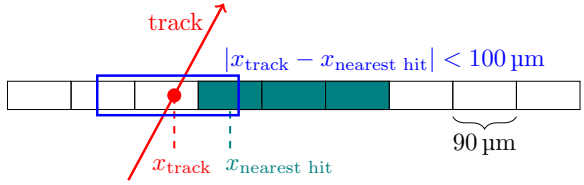


conversion factor: $1\,V_{CTH} = 156\,e^-$

Definition of Efficiencies

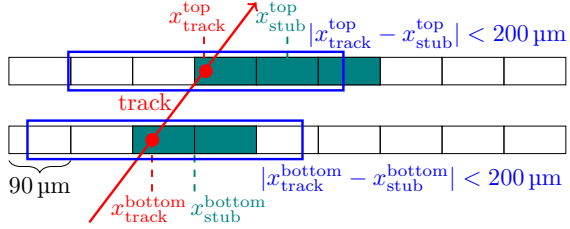
Hit Efficiency: "nearest hit"

- Evaluated for individual sensors
- Track to hit matching for
  $|x_{\text{track}} - x_{\text{nearest hit}}| < 100\,\mu\text{m}$



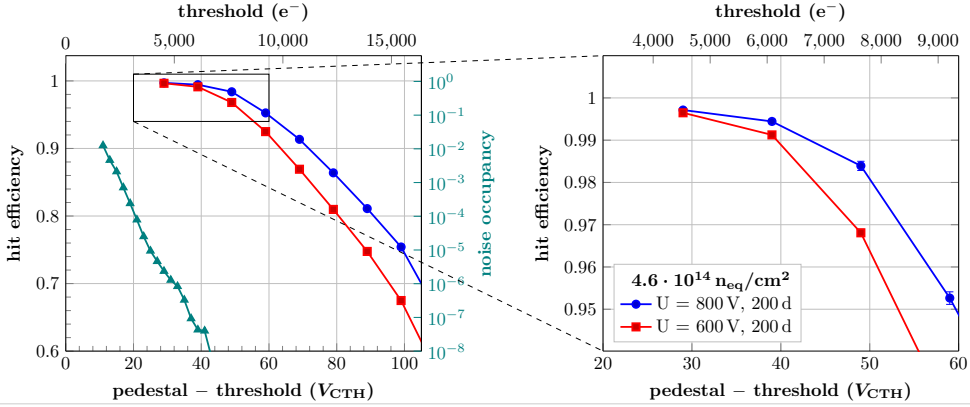
Stub Efficiency:

- Evaluated for combined sensors
- Track to stub matching for
  $|x^{\text{bottom}}_{\text{track}} - x^{\text{bottom}}_{\text{stub}}| < 200\,\mu\text{m}$
  and $|x^{\text{top}}_{\text{track}} - x^{\text{top}}_{\text{stub}}| < 200\,\mu\text{m}$



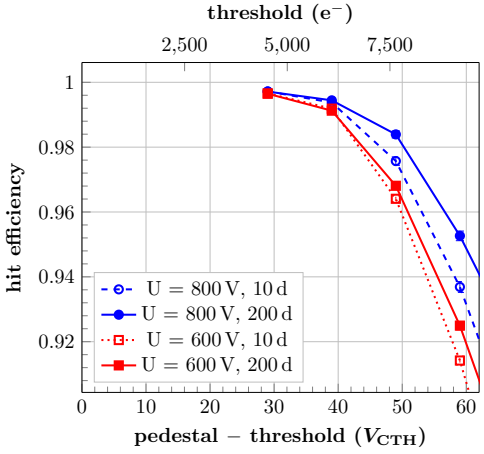
Threshold Scan at Different Bias Voltages

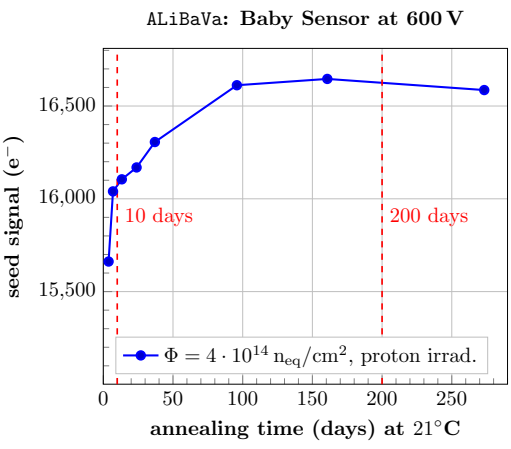
- Data for perpendicular beam incidence
- Up to threshold of 6000 e^- sensor efficient with more than 99% at 600 V
- Noise occupancy below 10^{-5} for all threshold scan data points
- Increasing voltage to 800 V yields small increase in efficiency



Threshold Scan at Different Annealing States

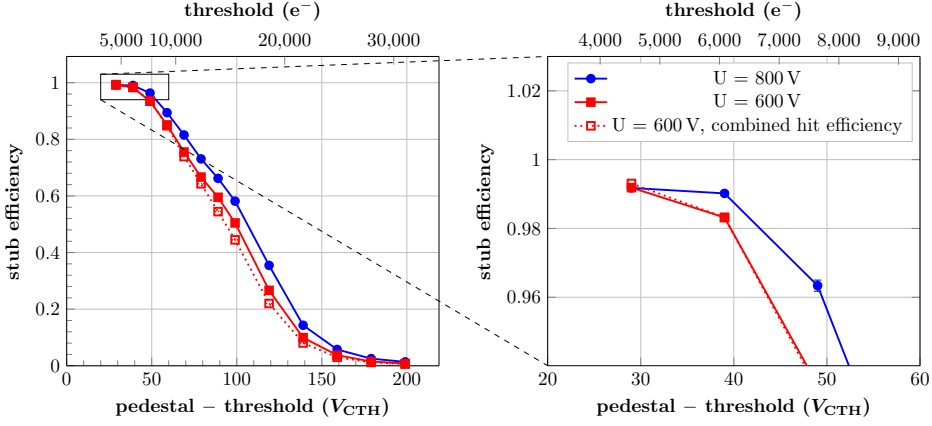
- Sensor with 200 d of annealing slightly more efficient
- Compatible with signal measurements of proton irradiated sensors using analogue readout (ALiBaVa)





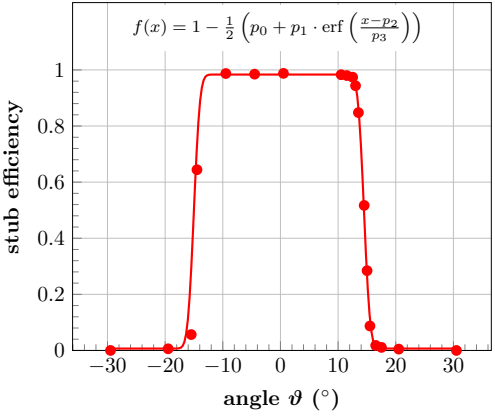
Module Stub Efficiency – Threshold Scan

- Data for perpendicular beam incidence
- Module stub efficiency of more than 98% at 600 V and nominal threshold
- Stub efficiency compatible with combined sensor hit efficiency



Module Stub Efficiency – Angular Scan

- Stub window set to ±4.5 strips, $U = 600\,\mathrm{V}$
- Geometrical expectation of module design with $d = 1.68\,\mathrm{mm}$ leads to $p_2 \approx 13.9°$
  → deviation explained by varying sensor distance along module side (s. next slide)

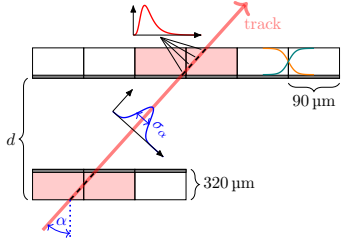


Data for $\vartheta \geq 0°$

fit $f(\vartheta)$ for $\vartheta \geq 0°$
$f(-\vartheta)$ for $\vartheta < 0°$

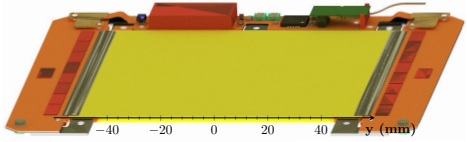
Fit results

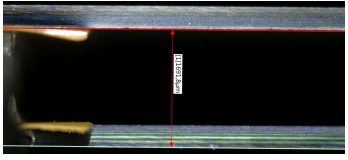
$p_0 = 1.0098$	± 0.0005
$p_1 = 0.9768$	± 0.0006
$p_2 = 14.496$	± 0.004
$p_3 = 1.176$	± 0.006
$\chi^2/\mathrm{ndf} =$	$568.6/8$

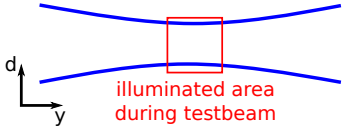


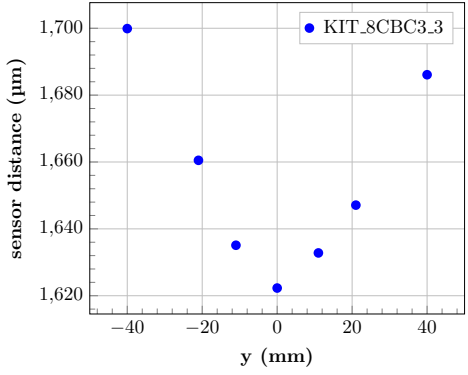
Measurement of 2S Module Sensor Distances

- Sensor distance measured using microscope along hybrid-free module side
- Measurement uncertainty approximately ±10 µm
- Sensor distance shows relative bow of ≈ 80 µm
- Area $-4\,\text{mm} \leq x \leq 6\,\text{mm}$ illuminated during angular scans
  $\Rightarrow d = 1.625\,\text{mm}$ leads to $p_2 \approx 14.49°$
  $\Rightarrow$ consistent with testbeam data









Summary and Outlook

- Successfully performed 2S module beam test with irradiated sensors up to $4.6 \cdot 10^{14} n_{eq}/cm^2$
- Modules show high efficiencies and low noise occupancy at nominal bias voltage (600 V)
  - Hit efficiency of more than 99% for noise occupancy less than 10^{-5}
  - Stub efficiency of more than 98%
- Efficiency comparison between different annealing states coincides with analogue signal measurements
- Angular scan proves stub logic functionality
- Measured stub efficiency turn-on angle corresponds to expectation taking into account measured module prototype sensor distance

Outlook:

- Finalise testbeam analysis
- CMS Detector Note and Publication together with results from unirradiated 2S module testbeams in preparation

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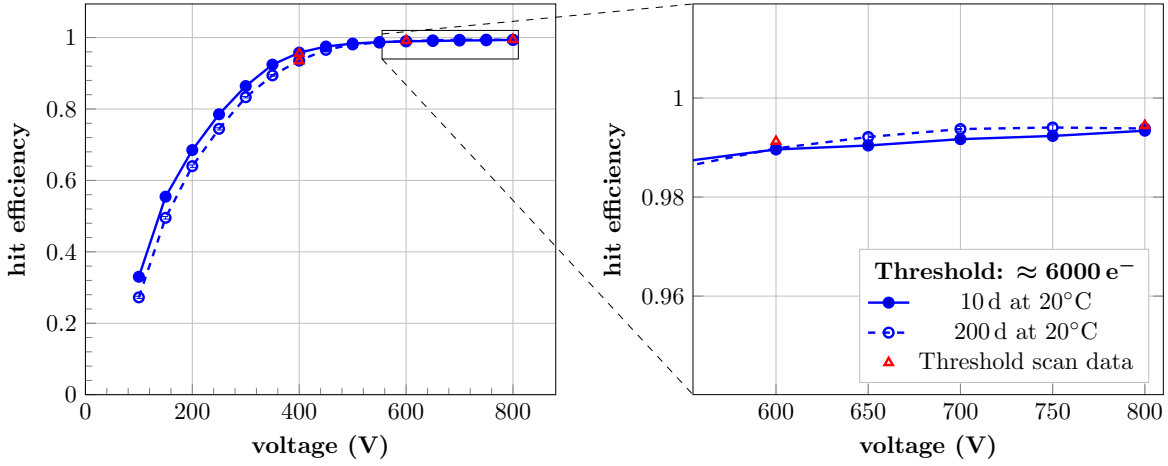
Backup

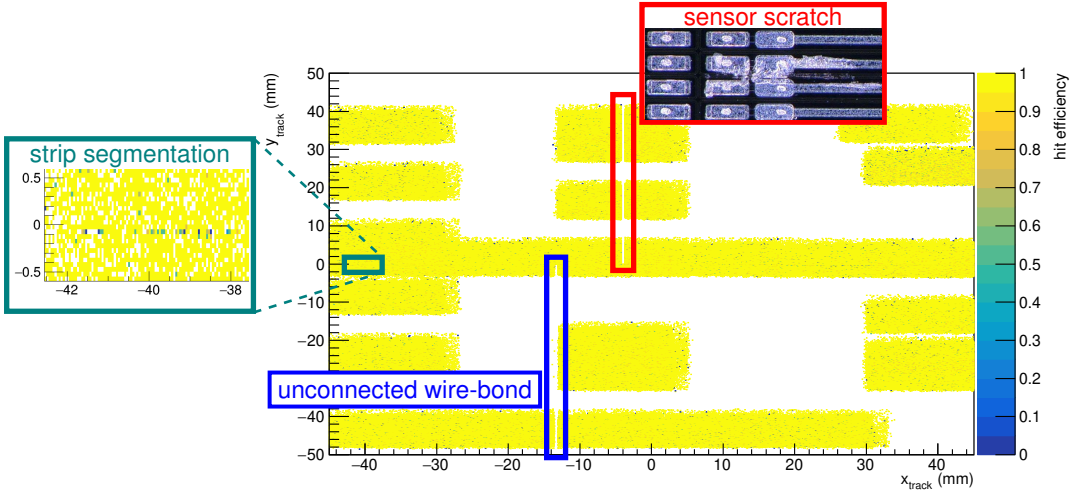
Bias Scan

- Depleted region and thus efficiency grows with bias voltage
- Data consistent with threshold scan results



Bottom Sensor Hit Efficiency

- Sensors efficient in illuminated areas, previously detected defects during functional testing are masked



Inpixel-Efficiencies