Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

Beam Test Studies with the latest Silicon Sensor Module Prototypes for the CMS Phase-2 Outer Tracker

23nd iWoRiD, June 2022 - **Florian Wittig**, Tobias Barvich, Bernd Berger, Alexander Dierlamm, Umut Elicabuk, Ulrich Husemann, Markus Klute, Gani Kösker, Roland Koppenhöfer, Stefan Maier, Thomas Müller, Andreas Nürnberg, Marius Neufeld, Hans Jürgen Simonis, Pia Steck, Lea Stockmeier

LHC and High Luminosity LHC

- LHC delivers proton-proton collisions with a bunch crossing frequency of 40 MHz at $\sqrt{s}$ =14 TeV
- **High Luminosity LHC (HL-LHC)**
  - begin of operation 2029
  - instantaneous luminosity $\mathcal{L}$ increased by factor 5 to 7
  - aiming for an integrated luminosity $\mathcal{L}_{int}$ of 3000 fb^{-1} to 4000 fb^{-1}

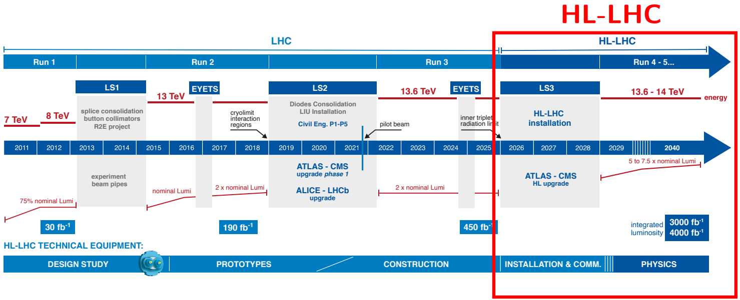
$\Longrightarrow$ higher statistic for precision measurements of key physics processes (e.g. Higgs coupling)

Instantaneous Luminosity $\mathcal{L}$:

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = \mathcal{L} \cdot \sigma_i$$

Integrated Luminosity $\mathcal{L}_{int}$:

$$N_i = \sigma_i \cdot \int_0^T \mathcal{L}(t)dt = \sigma_i \cdot \mathcal{L}_{int}$$



CMS Phase-2 Tracker

- upgrade of CMS experiment needed to fully exploit physics potential of the HL-LHC era
- CMS silicon tracker will be completely replaced

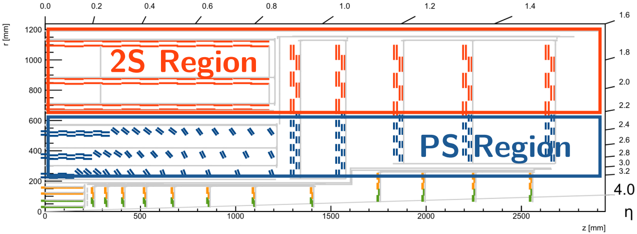
Requirements on the new CMS Tracker:

- improved radiation hardness
- higher granularity
- reduced material budget
- contribution to L1 trigger (Outer Tracker)

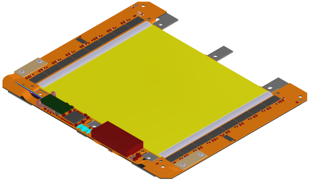
CMS Phase-2 Outer Tracker:

- ≈ 13.000 double sided modules
- PS modules: pixel and strip sensor
- 2S modules: two strip sensors

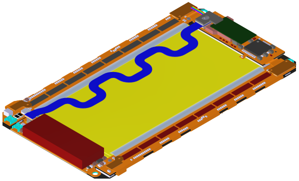
- KIT pledged to build about 2000 2S modules



2S Module

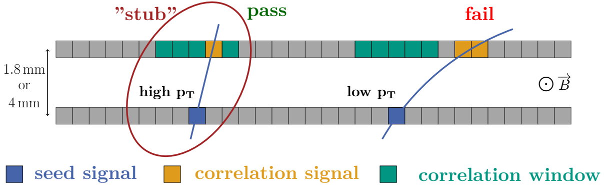


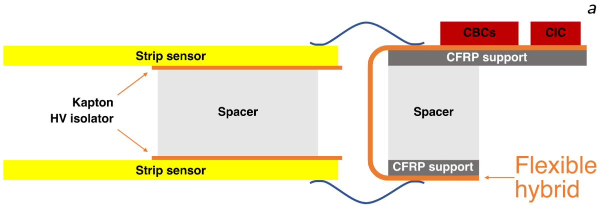
PS Module



Outer Tracker p_T-Module Concept

- Outer Tracker provides hit information at 40 MHz to the first CMS trigger stage
- limited bandwidth requires data reduction
  - reject hits from particles with $p_T \leq 2$ GeV
  - particles are bent by magnetic field
    - high $p_T \longrightarrow$ small curvature
  - correlate hits in two sensor layers on module level
    - precise sensor alignment in module required
    - programmable correlation window
- positive L1 trigger decision: all hits are read out



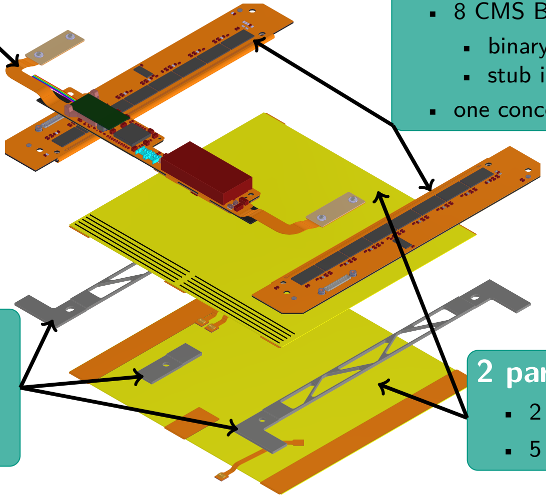


[a] taken from: https://cds.cern.ch/record/2272264, The Phase-2 Upgrade of the CMS Tracker, CERN, CMS Collaboration

CMS Phase-2 Outer Tracker 2S Module

Service Hybrid
- data transmission
- powering

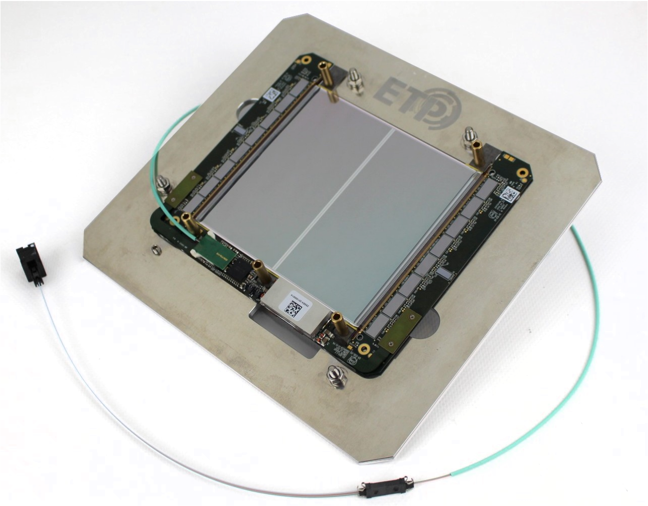
2 Front-End Hybrids
- 8 CMS Binary Chips each
  - binary readout of sensor signals
  - stub identification
- one concentrator chip each



Al-CF Spacer
- spacing between sensors
- mechanical fixation
- main cooling path

2 parallel silicon strip sensors
- 2×1016 strips each
- 5 cm length and 90 µm ptich

CMS Phase-2 Outer Tracker 2S Module



Investigated 2S Modules

- 2S module with non-irradiated components
- 2S module with irradiated sensors and hybrids (23 MeV protons)
  - study module performance towards the end of CMS runtime
  - top sensor: $\Phi_{top} = 5.2 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$
  - bottom sensor: $\Phi_{bot} = 3.7 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$
  - sensor annealing: 140 d at room temperature
  - front-end hybrids: $\Phi = 1.0 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ (150 kGy)
- requirements on the module performance
  - efficient hit and stub detection ($>$ 99 %) at low noise during the entire CMS runtime

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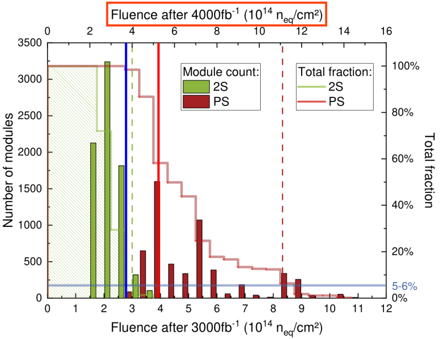
- requirements on the module performance
  - efficient hit and stub detection (> 99 %) at low noise during the entire CMS runtime

$\Longrightarrow$ **sensor fluences close to/above the highest fluence expected for the ultimate CMS runtime scenario**



2S modules

nominal scenario (3000 fb^{-1}):

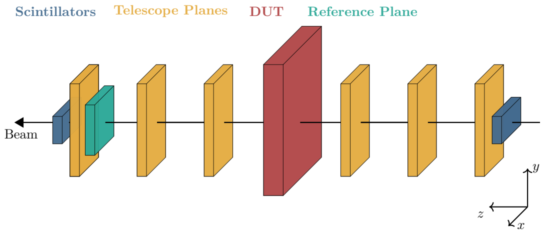
$< 5\,\%$ modules $\Phi > 3 \times 10^{14}\ n_{eq}/cm^2$

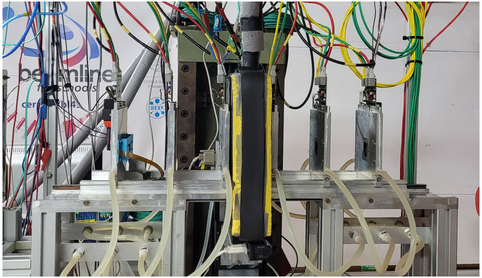
ultimate scenario (4000 fb^{-1}):

$< 5\,\%$ modules $\Phi > 4 \times 10^{14}\ n_{eq}/cm^2$

Beam Tests Setup

- efficiency studies with 2S modules at the test beam facility DESY
- setup integrated in DATURA beam telescope
  - track resolution of down to 3 µm
- Device Under Test (DUT) mounted on movement/rotation stage





Beam Tests Analysis

- EUTelescope framework used for track reconstruction
- tracks matched with DUT hits by using the following cuts:
  - **cluster efficiency:**

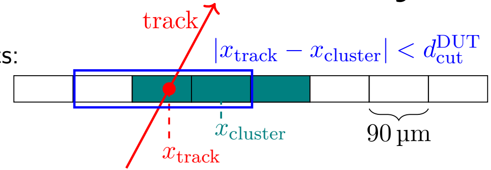
    $$|x_{\text{track}} - x_{\text{cluster}}| < 200\,\mu\text{m}$$

  - **stub efficiency:**

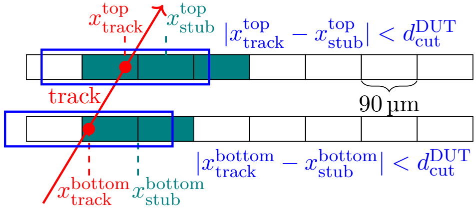
    $$|x^{\text{top}}_{\text{track}} - x^{\text{top}}_{\text{stub}}| < 200\,\mu\text{m} \textbf{ and}$$
    $$|x^{\text{bottom}}_{\text{track}} - x^{\text{bottom}}_{\text{stub}}| < 200\,\mu\text{m}$$

- $\text{effciency} = \frac{n_{\text{tracks\_matched}}}{n_{\text{tracks\_reconstructed}}}$

cluster efficiency:

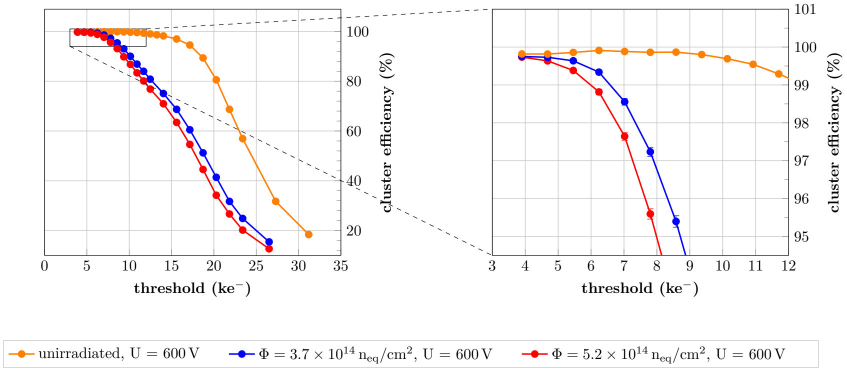


stub efficiency:



Threshold Scan

- efficiency decreasing with fluence (unirradiated, $\Phi = 3.7 \times 10^{14}\ n_{eq}/cm^2$, $\Phi = 5.2 \times 10^{14}\ n_{eq}/cm^2$)
- efficiency above 99.5% for thresholds up to 5000 e^- (irradiated sensors)



Threshold Scan

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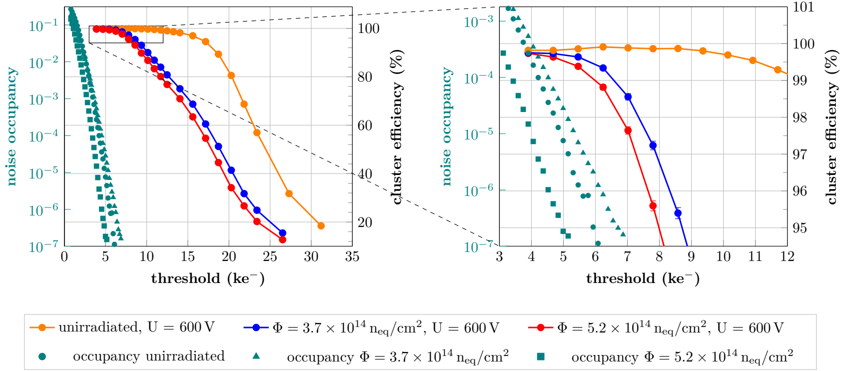
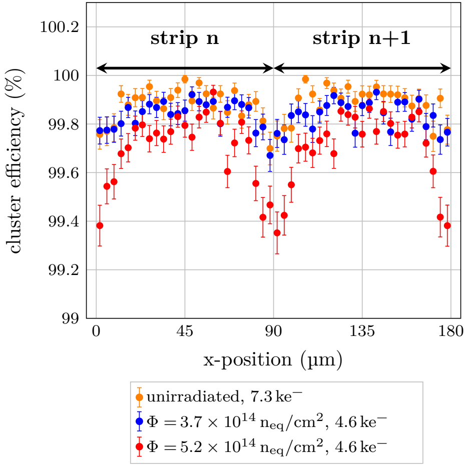
- efficiency above 99.5% for thresholds up to 5000 e^- (irradiated sensors)
- high noise occupancy observed with the latest 2S module prototypes (irrradiation independent)
  - Outer Tracker group is intensively working on mitigation



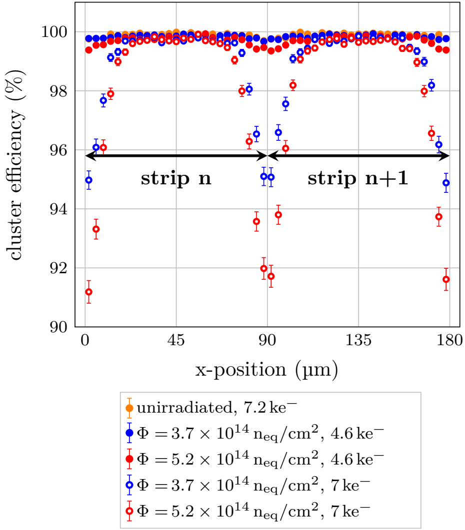
Interstrip Efficiency

- track down inefficient sensor regions by investigating the position-dependent efficiency
  - all illuminated strips superimposed within one plot → high statistics
- charge signal decreases after irradiation
  - interstrip region becomes inefficient first due to charge sharing



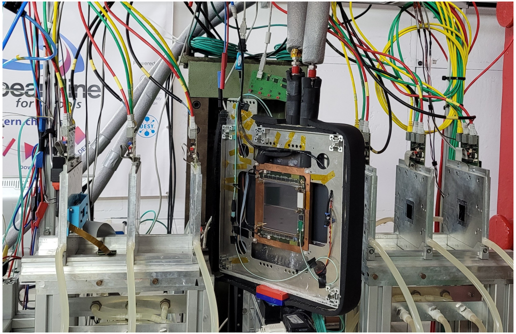
Interstrip Efficiency

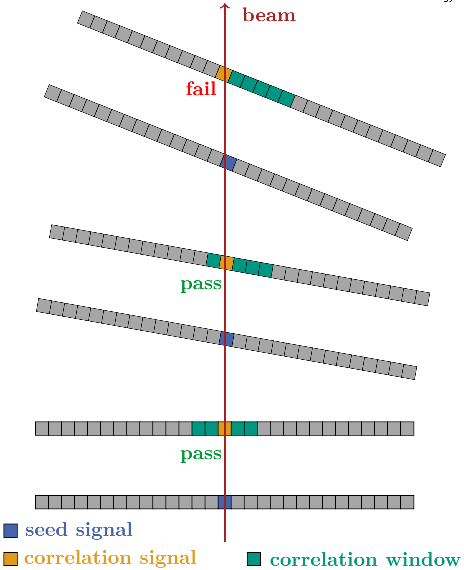
- track down inefficient sensor regions by investigating the position-dependent efficiency
  - all illuminated strips superimposed within one plot → high statistics
- charge signal decreases after irradiation
  - interstrip region becomes inefficient first due to charge sharing
- smaller operation window after irradiation
  - efficiency in interstip region shows pronounced drop with increasing threshold



Angular Scans - Unirradiated Module

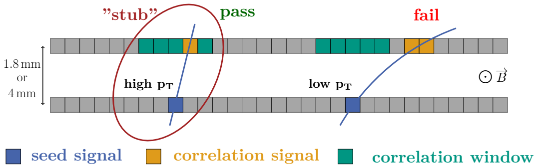
- stub mechanism tested by rotating module with respect to the beam
  - stub efficiency measured for different rotation angles

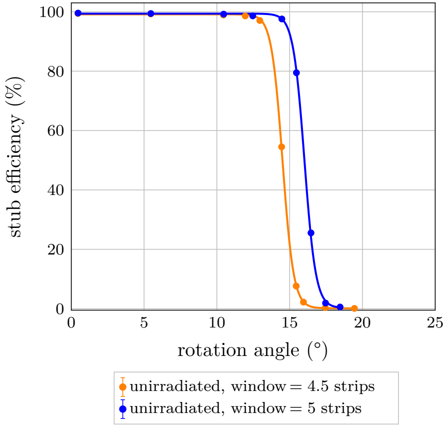




Angular Scans - Unirradiated Module

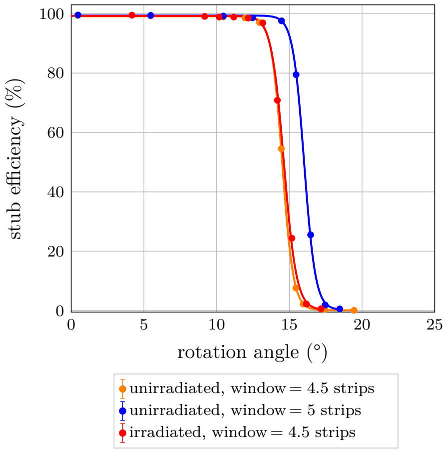
- stub mechanism tested by rotating the module with respect to the beam
  - stub efficiency measured for different rotation angles
  - sigmoid fit: $f(x) = \frac{a}{1+e^{-b(x-c)}} + d$
  - inflection point c used as reference
  - changing window size ↔ shifting inflection point
    - $c = (14.513 \pm 0.017 \pm 0.005)^\circ$, $c = (16.019 \pm 0.014 \pm 0.004)^\circ$





Angular Scans - Irradiated vs Unirradiated

- stub mechanism tested by rotating the module with respect to the beam
  - stub efficiency measured for different rotation angles
  - sigmoid fit: $f(x) = \frac{a}{1+e^{-b(x-c)}} + d$
  - inflection point c used as reference
  - changing window size ↔ shifting inflection point
    - $c = (14.513 \pm 0.017 \pm 0.005)^\circ$,
      $c = (16.019 \pm 0.014 \pm 0.004)^\circ$
  - inflection point measured with irradiated module consistent with unirradiated one
    - $c = (14.513 \pm 0.017 \pm 0.005)^\circ$,
      $c = (14.628 \pm 0.013 \pm 0.007)^\circ$
  - independently assembled modules deliver compatible results!



DUT Resolution

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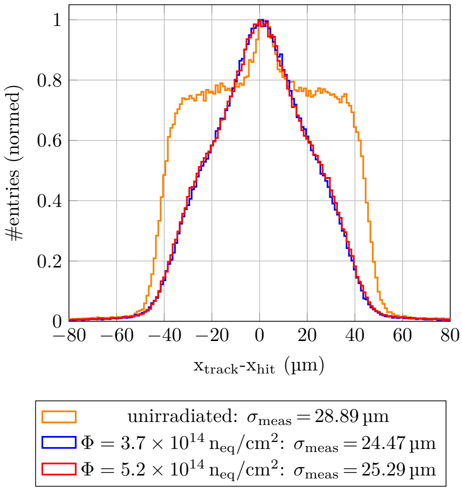
- binary readout: resolution given by $\sigma = \frac{pitch}{\sqrt{12}}$
  - binary resolution 2S sensor: $\sigma_{\mathrm{DUT}} = 26\,\mu\mathrm{m}$
- measured resolution combination of telescope and DUT resolution: $\sigma_{\mathrm{meas}} = \sqrt{\sigma_{\mathrm{DUT}}^2 + \sigma_{\mathrm{tel}}^2}$
- increased charge sharing after irradiation
  $\longrightarrow$ improved resolution
- calculated DUT resolution assuming $\sigma_{\mathrm{tel}} \approx 3\,\mu\mathrm{m}$[a]:
  - $\sigma_{\mathrm{DUT}} = (28.75 \pm 0.02)\,\mu\mathrm{m}$
  - $\sigma_{\mathrm{DUT}} = (24.20 \pm 0.02)\,\mu\mathrm{m}$
  - $\sigma_{\mathrm{DUT}} = (25.03 \pm 0.02)\,\mu\mathrm{m}$



[a] Simulation:S. Spannagel and H. Jansen, GBL Track Resolution Calculator v2.0, 2016. doi:10.5281/zenodo.48795

Summary

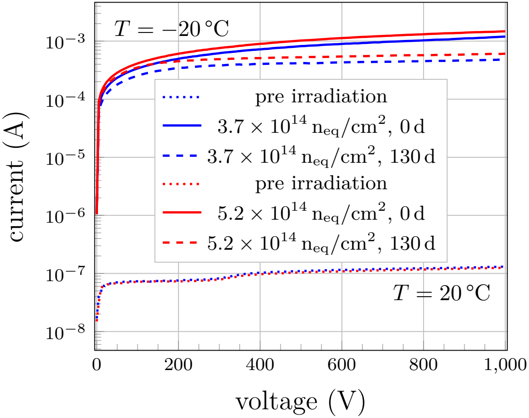
- HL-LHC phase: CMS Phase-2 Upgrade $\longrightarrow$ complete replacement of the CMS silicon tracker
- beam test studies with 2S module prototypes for the CMS Phase-2 Outer Tracker at DESY
  - different sensor fluences investigated ($3.7 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ and $5.2 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$)
    - sensor fluences close to/above the 2S fluences expected at the end of CMS runtime
  - front-end hybrids irradiated to $1.0 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ (150 kGy)
- cluster and stub efficiencies above 99% can be reached at reasonable thresholds
- stub logic works as expected, turn on angles in good agreement with expectation
- improved sensor resolution after irradiation due to charge sharing

$\Longrightarrow$ **2S module design meets the requirements, only small optimizations needed for production readiness**

Backup

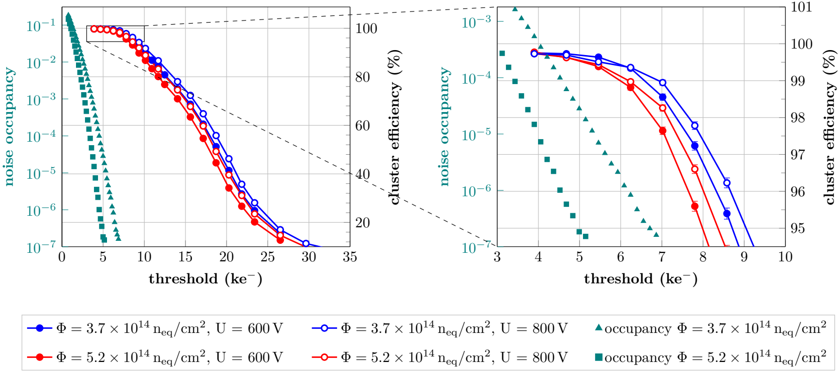
Sensor IV Measurements - Irradiated Module

- sensors tested with probe station pre (after) irradiation at 20 °C (–20 °C)
  - increased current after irradiation, higher fluence ↔ higher current
- leakage current decreased by annealing
  - $\Phi = 3.7 \times 10^{14}\, n_{eq}/cm^2$: 895 µA → 430 µA
  - $\Phi = 5.2 \times 10^{14}\, n_{eq}/cm^2$: 1113 µA → 544 µA
  - **sum:** 2008 µA (974 µA) before (after) annealing
- module current during beam test: 2045 µA
- sensor currents scaled to module current reveals $T_{sensor} = -13.5\,°C$
  - $I \sim T^2 e^{\frac{-1.2\,eV}{2kT}}$



Threshold Scan at 600 V and 800 V

- cluster efficiency decreasing with fluence ($\Phi = 3.7 \times 10^{14}\ n_{eq}/cm^2$, $\Phi = 5.2 \times 10^{14}\ n_{eq}/cm^2$)
- increasing efficiency at 800 V (high thresholds)
- efficiency above 99% for thresholds up to 6000 e^- at 800 V



Cluster Size

- position-dependent cluster size along x-axis
  - all illuminated strips superimposed within one plot $\longrightarrow$ high statistics
- increased cluster size at the interstrip region due to charge sharing
  - cluster size significantly enlarged after irradiation