EP-DT
Detector Technologies

Radiation tolerance and annealing studies using test-structure diodes from 8-inch silicon sensors for CMS HGCAL

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on behalf of the CMS Collaboration

1st DRD3 week on Solid State Detectors R&D
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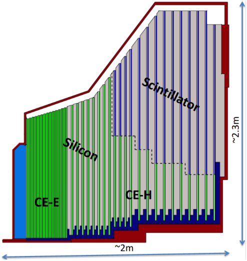
CERN

Short reminder of HGCAL

- CMS will replace Calorimeter Endcaps (CE) for HL-LHC operation
- CE to be implemented in HGCAL (High Granularity Calorimeter) concept
- Silicon sensors will be used for the electromagnetic section and high radiation regions of the hadronic section of the CE
- $\sim$620 m^2 silicon sensors produced on 8-inch wafers
- 3 different thicknesses: 300 µm, 200 µm (Float zone) and 120 µm (Epitaxial) - thinner sensors in high fluence regions
- Fluences of up to 1e16 n_{eq}/cm^2

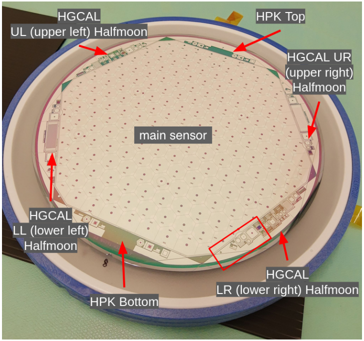
Key Parameters:
Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



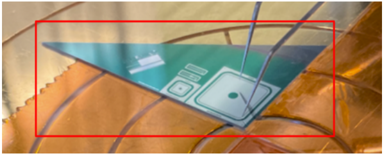
Silicon test structures: Diode measurements

- Hexagonal sensor from circular wafer
- Remaining space used for small sized test structures, e.g. diodes
- 8-inch wafers (20 cm), diodes with $0.5 \times 0.5\,\mathrm{cm}^2$ active area

Full wafer silicon sensor



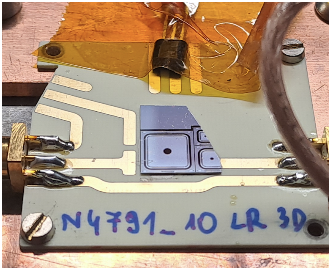
Test-structure diode contacted using two needles (pad and guardring)



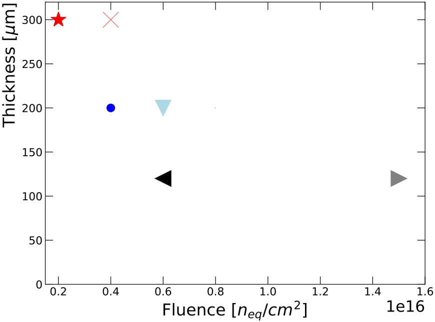
High fluence irradiation campaign overview

- Test structures: Single pad diodes
- Neutron irradiation at JSI (Jozef Stefan Institute), Ljubljana, Slovenia
- 3 batches with 7 sensors each
- 3 annealing temperatures: 6.5°C, 20°C and 60°C - all ongoing!
  - Extrapolate to lower temperatures, evaluate operating scenarios
- Leakage current and capacitance vs voltage (IV/CV) and charge collection (CC) measurement results

Test-structure diode on PCB



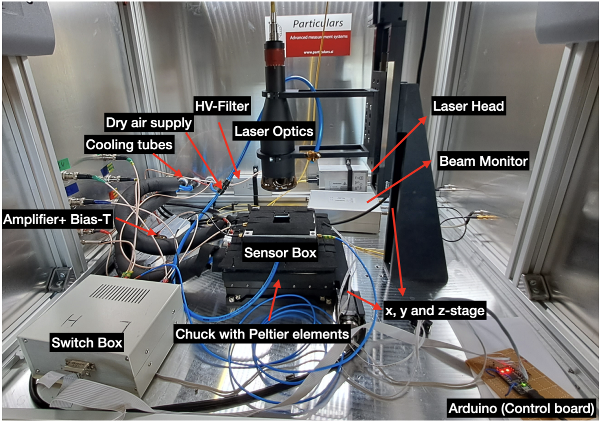
Sample overview per batch



Experimental setup

- Particulars TCT setup upgraded it to IV+CV+TCT setup
- Switchbox to change measurement type automatically
- Sensors are glued and wirebonded to a PCB, placed on a cooled copper holder, connected via SMA connectors

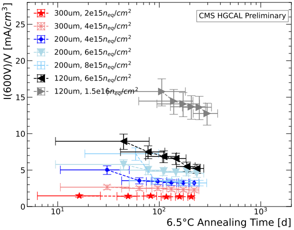
Particulars Setup



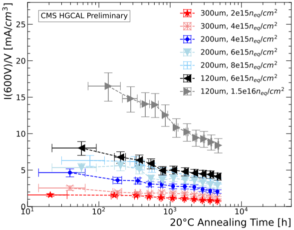
Leakage current

- Volume-normalised leakage current at 600V
- Expected decrease for both annealing temperatures
- Extraction of damage parameter α - expected decrease
  - To be used to extract leakage current annealing time constant and temperature scaling factors once campaign is completed

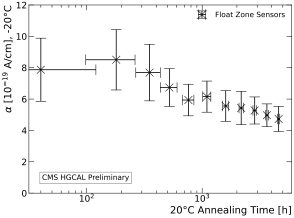
6.5°C annealing, I_{leak}



20°C annealing, I_{leak}



20°C annealing, α

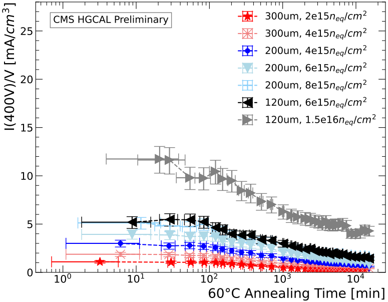


Damage parameter α: $\frac{I}{V} = \alpha \cdot \phi$

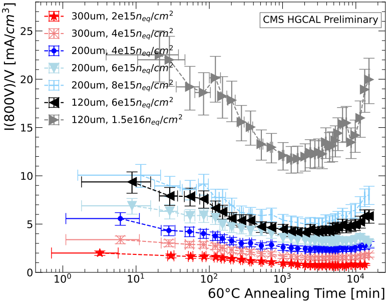
Leakage current

- 60°C annealing progressed furthest
- Expected continuous decrease at 400V
- Increase for high fluences at 800V after long annealing times
  - Hints towards high electric fields producing multiplication - to be confirmed in CC measurements

400V



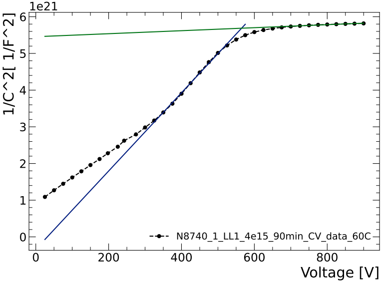
800V



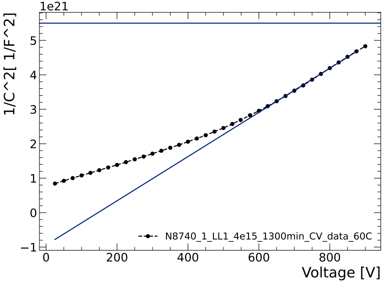
Saturation voltage from CV measurements

- Only extractable for some samples (thin sensors/lower fluences)
- Frequency and temperature dependence - "saturation" instead of "depletion" voltage
- Two methods of extraction: Direct (two fits) or end-capacitance assumption (EC) - constant capacitance beyond saturation independent of annealing time

Direct extraction
200 μm, 4e15 n_{eq}/cm^2, 120 min



End capacitance assumption
200 μm, 4e15 n_{eq}/cm^2, 1300 min

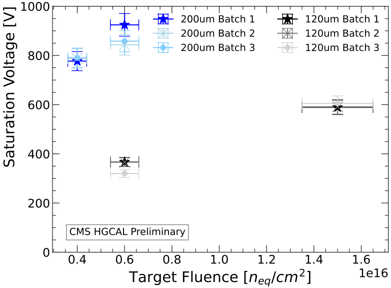


All measurements at $-20^\circ C$ and 2kHz frequency

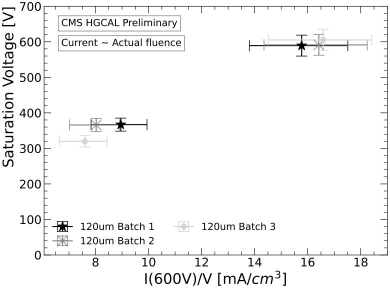
Saturation voltage vs fluence

- 10% variation in extracted Vdep at same fluence
  - In agreement with expected fluence variation (visible in leakage current variation)
- Only thin sensors can be used for this study - saturation not reached until 1000V for 300um samples

Saturation voltage vs fluence

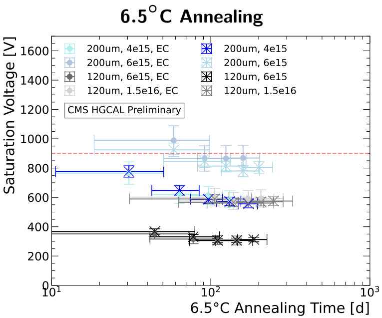


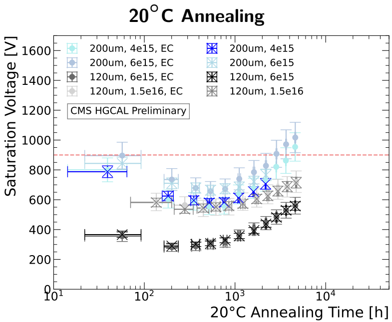
Saturation voltage vs current



Saturation voltage - Annealing

- Expected decrease during beneficial annealing for both temperatures
- Difference in time scale clearly visible (hours vs days), 20°C annealing further progressed
- Increase during reverse annealing already clearly visible for 20°C
- Minimum earlier for EPI sensors than for FZ sensors

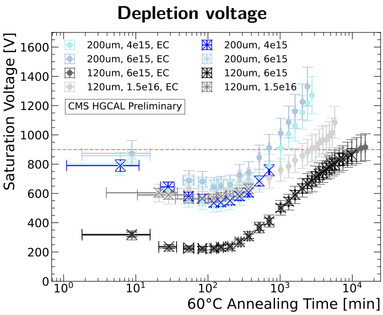


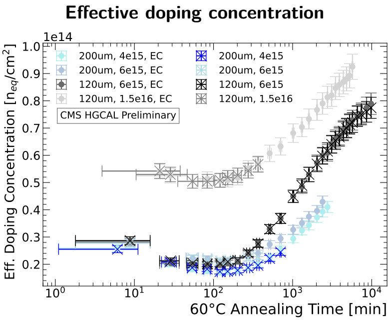


EC: Extracted with end capacitance assumption

Saturation voltage - Annealing

- 60°C annealing: First hints towards saturation for annealing times >10000min
- Directly correlates with the effective doping concentration
  - Difference in N_{eff} increase for 6e15 sensors - possibly due to different processing (FZ vs EPI)
- Ongoing works: Hamburg model fits to extract annealing time constants



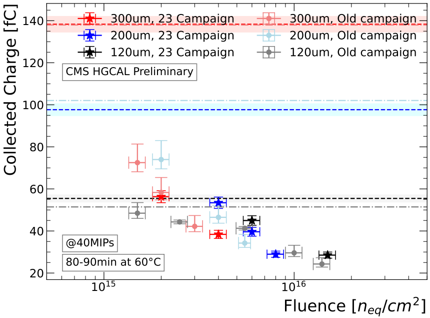


$$N_{eff} = 2 \cdot \epsilon_0 \cdot \epsilon \cdot V_{dep} / (q_0 \cdot d^2)$$

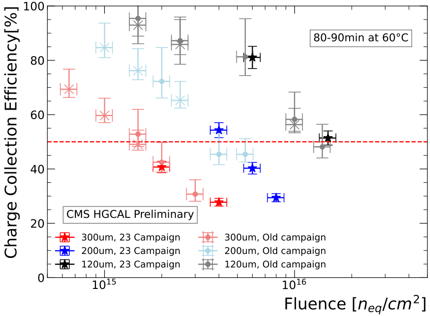
Charge collection vs fluence

- Comparison with previous studies (measured in different setup in 2021 and 2023)
- After 80-90 min annealing at 60°C
- Broad fluence range covered - this campaign focuses on high fluences
- Results from different campaigns are well in agreement

Charge collection: 600 V



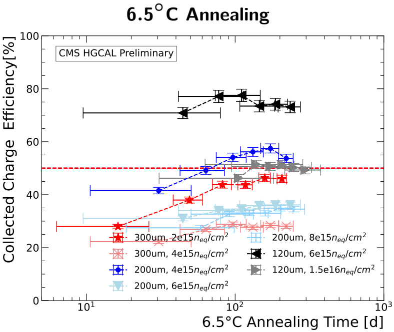
Charge collection efficiency: 600 V

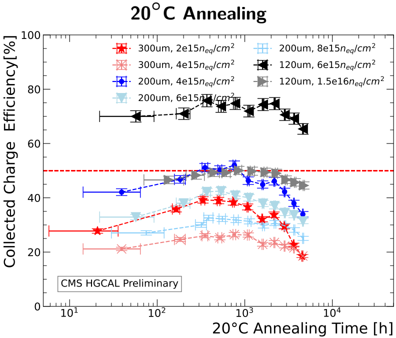


Dotted lines: Expected charge for unirradiated sensors/ 50% efficiency

Charge collection - Annealing

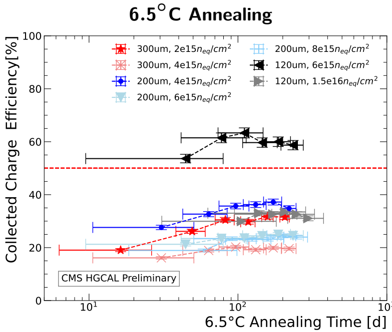
- 6.5 and 20°C annealing at 600V
- Expected increase of charge during beneficial annealing for both temperatures
- Maximum seems to be reached for low temperature, but more data is necessary to confirm
- Clear decrease started for room temperature annealing

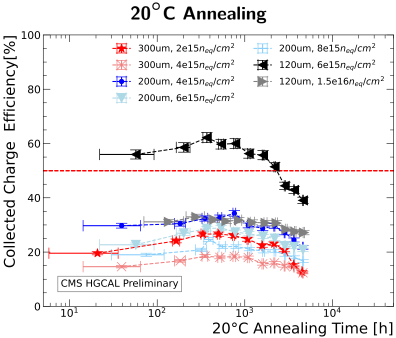




Charge collection - Annealing

- 6.5 and 20°C annealing at 400V
- For low temperature also at 400V hard to determine maximum
- Slightly clearer for room temperature: 200-400h for epi sensors, 400-600h for FZ sensors
- Calculated in-reactor annealing time for these lower temperatures gives a large uncertainty

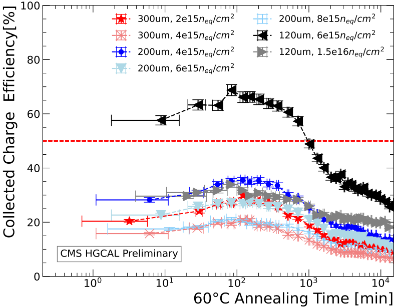




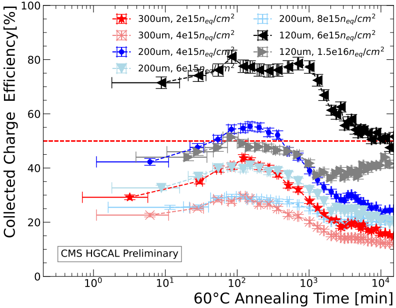
Charge collection - Annealing

- 60°C annealing
- Expected increase of charge during beneficial annealing and expected decrease afterwards during reverse annealing
- The maximum seems to be reached around 110-120 min for FZ, 90 min for EPI - in agreement with other studies on p-type sensors
- At 600 V, the dropoff is later for the 6e15 n_{eq}/cm^2 120 μm sensor, increase again after 1000min for the highest fluence

Efficiency at 400 V



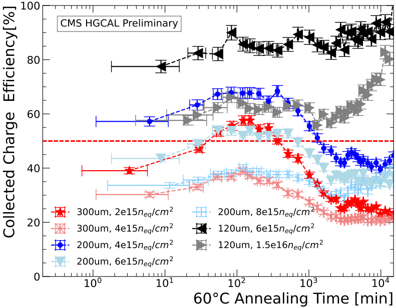
Efficiency at 600 V



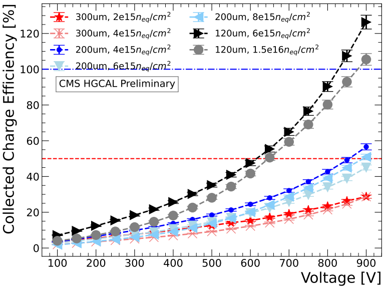
Charge collection - Annealing

- No decrease of charge at 800 V for the 120 µm sensors
  - Clear increase for highest fluence
- Saturation/ increase again for higher fluences of the thicker sensors
- Electric field effects: Onset of charge multiplication due to high electric fields
  - Correlates with the observed increase in leakage current
  - Efficiency above 100% for 120 µm sensors at 900V after 13200min

Charge collection efficiency: 800 V



Efficiency after 13200min annealing

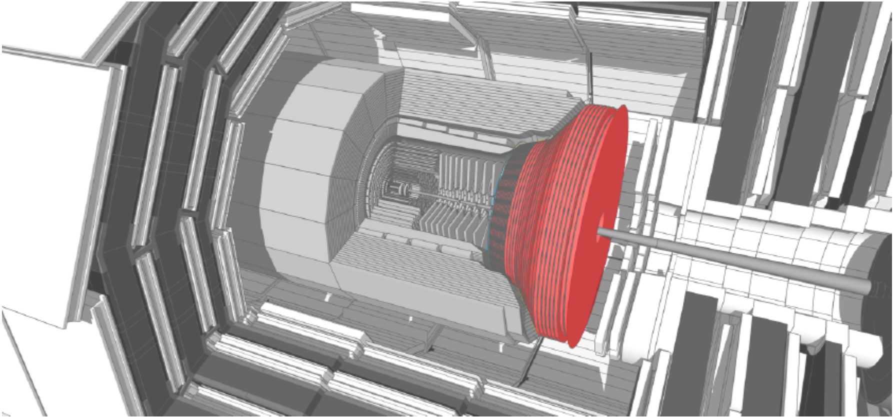


Dotted lines: Expected charge for 50% (red) and 100% (blue) efficiency

Conclusions

- Ongoing broad annealing study covering a fluence range of 2e15 n_{eq}/cm^2 to 1.5e16 n_{eq}/cm^2 at 3 annealing temperatures: 6.5°C, 20°C and 60°C
- IV, CV and Charge Collection measurements done for each step
- Observed expected behaviour during beneficial and reverse annealing - reverse annealing not clearly reached yet for lowest temperature
- Observation of *charge multiplication* for higher fluences at high voltages after annealing times >1000min (60°C annealing)
- Further results, including the extraction of annealing time constants and scaling factors are expected within the upcoming months
- Time parameters (e.g. time of N_{eff} minimum) so far in line with observed values from other studies with p-type sensors, but deviate from n-type studies

Thank you for the attention



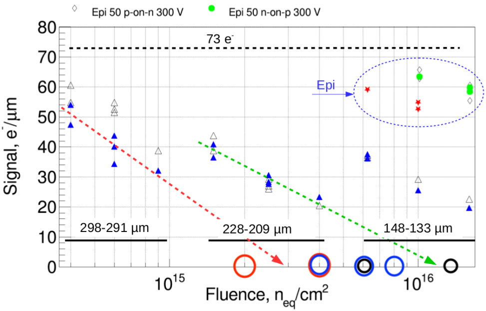
Backup

Irradiation campaign goals

Up to which fluence can we use which thickness

→ Does the charge collection follow the expected linear trend?

→ How does the leakage current and noise evolve with fluence?



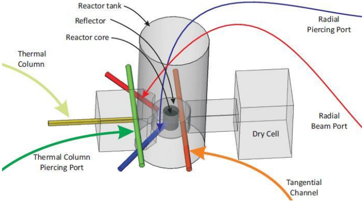
New campaign: O 300 µm, O 200 µm, O 120 µm
E. Curras Rivera, PhD Thesis 2017, HGCAL TDR

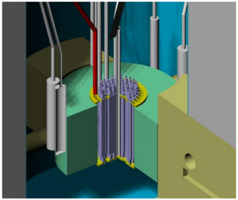
Which operation scenarios of HGCAL are feasible?

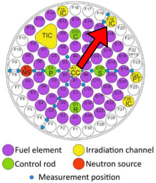
- Scintillators+SiPMs vs silicon sensors: temperature scenario needs to be good for both technologies
- Extraction of annealing time parameters at different temperatures
- Scaling factors between different annealing temperatures

Irradiation at JSI Ljubljana

- Well established irradiation site used by RD50 community
- Same irradiation channel used for all test structure irradiations
- Estimation of fluence precision: within $\pm 10\%$



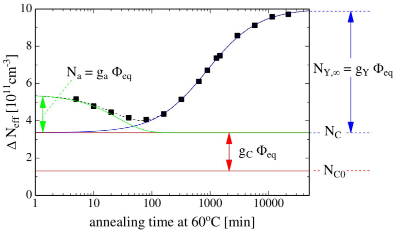




Hamburg model

Change of effective doping concentration with respect to before annealing:

$$\Delta N_{eff} = N_{eff,0} - N_{eff}(t)$$



Long term reverse annealing
$N_Y(t) = g_Y \Phi_{eq}(1 - \exp(-t/\tau_Y))$
Build-up of acceptors during long-term annealing - first order process

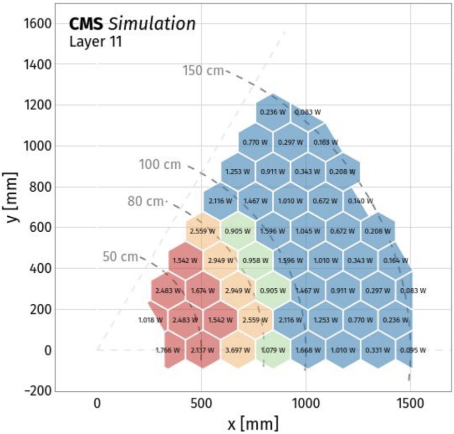
$$N_{eff}(t) = N_A(t) + N_C + N_Y(t)$$

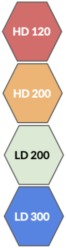
Short term annealing
$N_A(t) = g_a \Phi_{eq} \exp(-t/\tau_a)$
First order decay of acceptors introduced (proportional to Φ) during irradiation

Stable damage
$N_C = N_{C0}(1 - \exp(-c\Phi_{eq})) + g_c\Phi_{eq}$
Introduction of stable acceptors and incomplete "donor removal"

M.Moll, Bethe Forum on Detector Physics 2014

Introduction to HGCAL



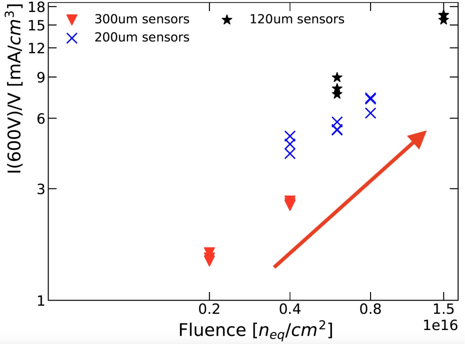


- 2 granularities: High and Low Density
- Hexagonal sensors: Optimal wafer usage and tiling

Leakage current vs fluence

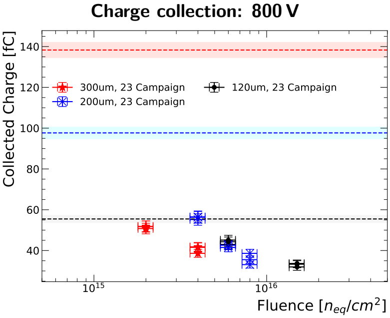
- Initial = first post irradiation measurement = no additional annealing
- Expected increase with fluence
- Observe 10% leakage current difference in samples of same irradiation round, potentially linked to fluence inhomogenities along irradiation tube. Observed for the first time
- Offsets for different thicknesses - observed before (difference in electric field at same voltage)

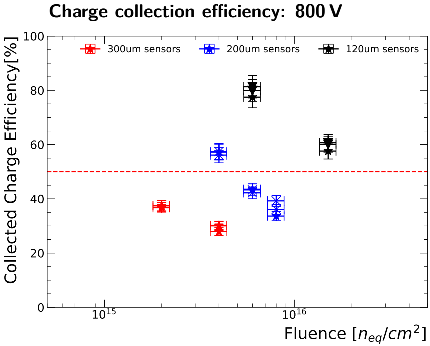
Volume-normalised leakage current at 600 V



Initial results: Charge collection

- Higher charge at 800V than at 600V (Slide 9) as expected
- 120um sensors stay above 50% efficiency up to 1.5e16 n_{eq}/cm^2
- Slightly larger spread between sensors

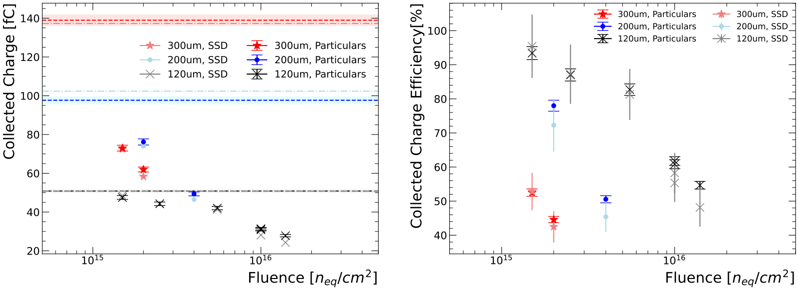




Dotted lines: Expected charge for unirradiated sensors/ 50% efficiency

Charge comparison/Setup validation

Comparison of measurements at 600V after 80min annealing in two different setups

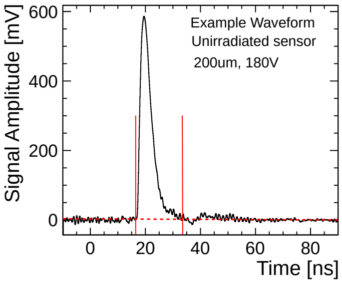


- Dotted lines represent unirradiated sensor measurements
- Results agree well within uncertainties between SSD and Particulars setups
- Measurement series used to validate a new Particulars-Setup as new standard IV/CV/TCT setup for upcoming campaigns

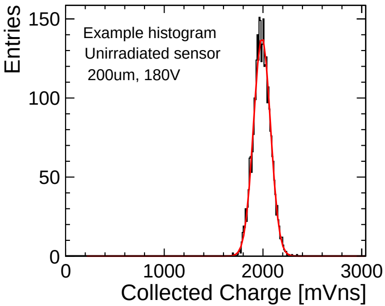
Charge collection measurements

- Transient Current Technique (TCT): Infrared laser @1kHz from the top
- Laser calibrated to 40 MIP (Minimal Ionizing Particle) equivalent using unirradiated 300µm sample
- 300 events per voltage, each event average of 50 waveforms
- Integration over pulse → histogram → mean of Gauss-fit = Collected charge

Recorded waveform (averaged)

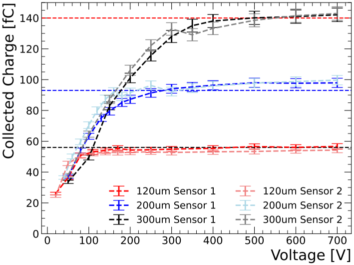


Charge collection histogram



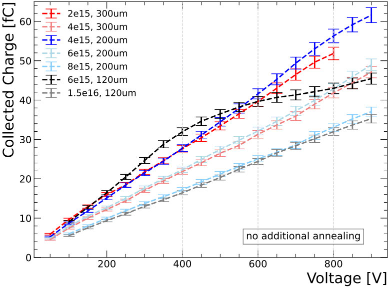
Charge collection measurements

Non-irradiated sensors



Used for crosschecks and reference measurements

Irradiated sensors



Further analysis focuses on charge collection and efficiency at specific voltages (400 V, 600 V, 800 V)

Dotted lines: Expected charge for different thicknesses

Ongoing works

- Fits to access leakage current annealing time constant once enough data is recorded - *fluence variation might pose an issue for the fits*
- Fits to extract beneficial and reverse annealing time constants (CV) - need for more data during reverse annealing for both parameters - *limited data sets for saturation voltages might pose an issue for the fits*
- Extraction of scaling factors between annealing temperatures for both beneficial and reverse annealing*
- Comparison of the maximum charge increase during beneficial annealing for different temperatures*
- Comparison of the extracted minimum from CV measurements and maximum in charge collection at different temperatures*
- Comparison of proton and neutron irradiation damage: Proton irradiation campaign planned

**once enough data is recorded for lower temperatures*