Radiation tolerance of 8-inch silicon sensors for CMS HGCAL

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43rd RD50 Workshop on Radiation Hard Semiconductor Devices
CERN, Geneva, Switzerland
November 29, 2023

Outline

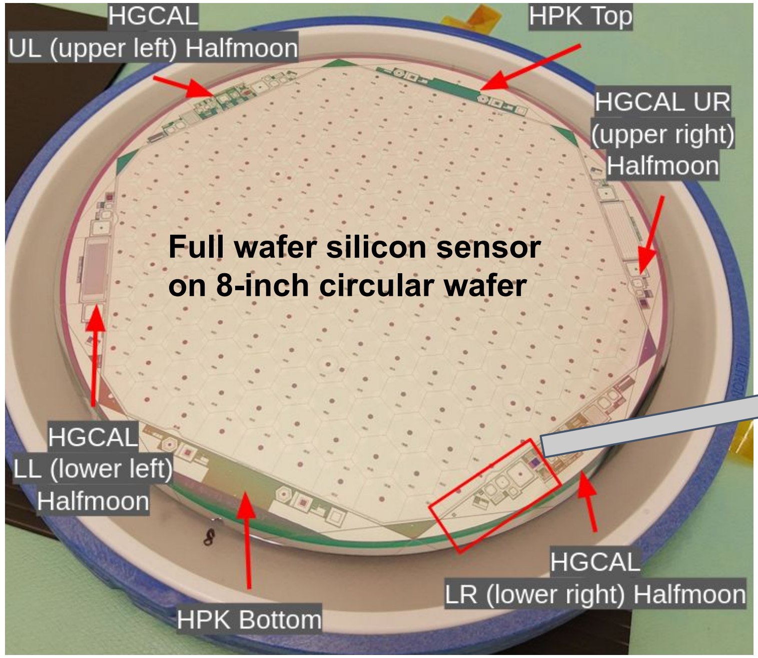
- Silicon sensors for High-Granularity Calorimeter (HGCAL)

- Neutron irradiation facilities

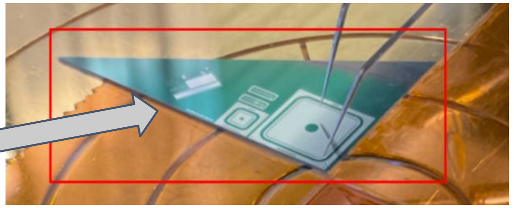
- Updates since last RD50 workshop
  1. First full sensor irradiation at RINSC up to $1.4\cdot10^{16}$ n_{eq}/cm^2 (~4.5 ab^{-1} expectation)
  2. Per-cell leakage current comparison between HGCAL sensor layouts (“full” vs. “partial”)
  3. Depletion voltage extracted from CV and Charge Collection data
  4. Annealing campaigns at different temperatures

Silicon sensors for CMS HGCAL

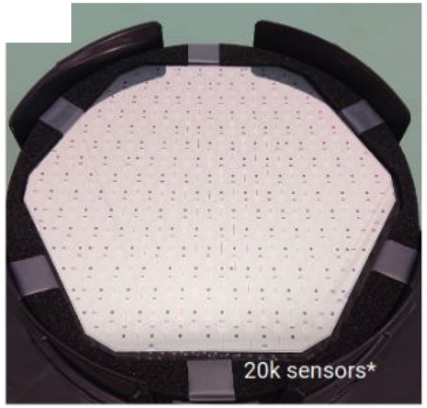
- Introduction to HGCAL at previous RD50 Workshop
- Silicon sensors:
  - 8-inch wafers, p type, planar, DC coupled, 120/200/300 µm
  - hexagonal **full sensors**
  - **partial sensors** cut from multi-geometry wafers
  - **test structure diodes** from the remaining space of circular wafer



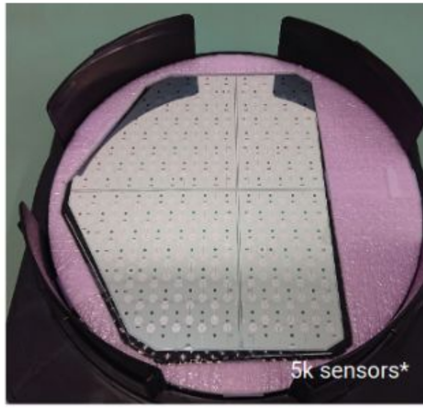
Test-structure diode contacted with two needles (pad and guardring)



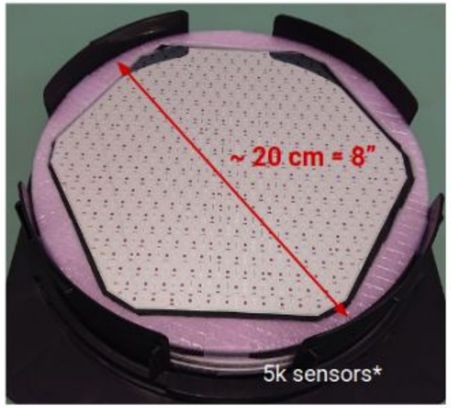
Low-Density sensor
~ 200 cells of ~1.1 cm² size
300 µm & 200 µm active thickness



Low-Density "Partial sensor" example from "Multi-Geometry" sensor



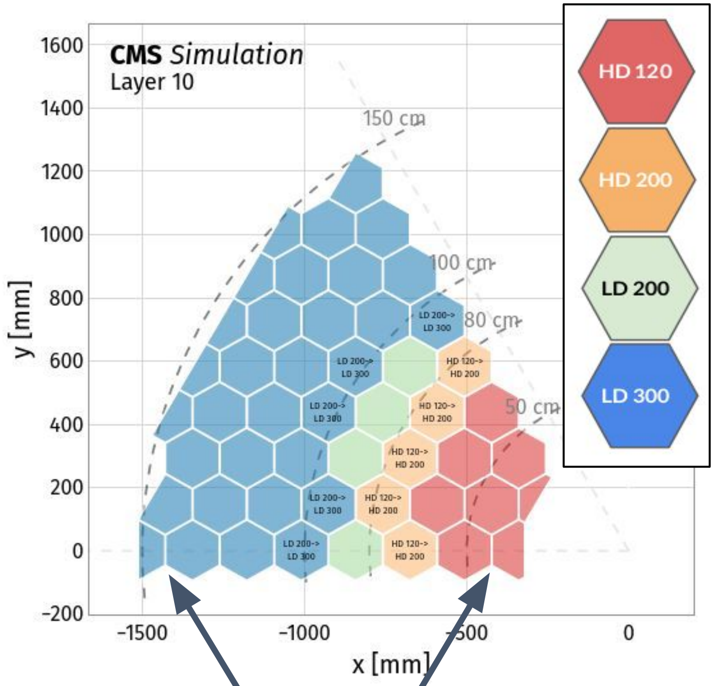
High-Density sensor
~ 450 cells of ~0.5 cm² size
120 µm & 200 µm active thickness

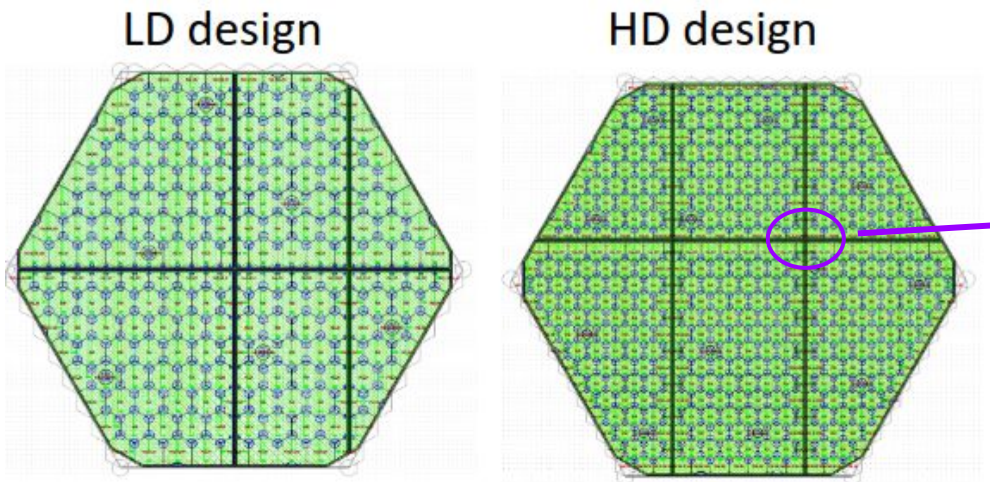


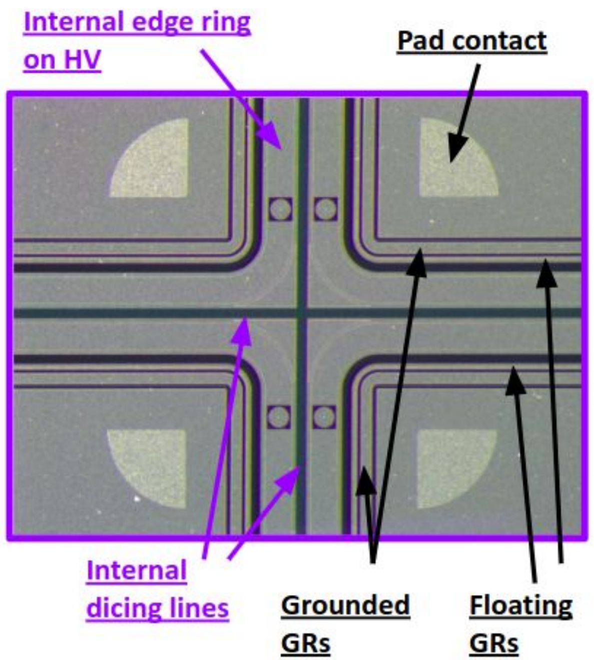
High-Density "Partial sensor" example from "Multi-Geometry" sensor

* needed in the final detector

Design features of multi-geometry wafers







- Partial sensors to tile border region of HGCAL layers
- One sensor mask for multiple partial sensor variants (“top”, “bottom”, “left”, “right”, “five”)
- **Internal dicing lines** on the High Voltage potential in the active sensor area

- First irradiation and electrical characterization of partial sensors
- Monitor in particular properties of cells close to the dicing lines

HGCAL device irradiation done at two institutes

JSI

Jožef Stefan Institute, Ljubljana, Slovenia

- Well established neutron irradiation facility
- Small sized HGCAL test structures irradiated in tubes in reactor core
- Temperatures up to 45-55°C
  - In-reactor annealing times between 3 min and 20 min at 60°C equivalent for covered fluence range

RINSC

Rhode Island Nuclear Science Centre, US

- Relatively new neutron irradiation facility
- HGCAL 8” sensors irradiated in radial beam port
- Initial high fluence radiation rounds with >100°C
  - Learned to maintain moderate temperatures during irradiation by using dry ice, using heat conducting sensor holders, splitting long irradiation rounds in 2
  - Now staying well in beneficial annealing
- 26 irradiation rounds performed for HGCAL so far with 3-4 sensors per round

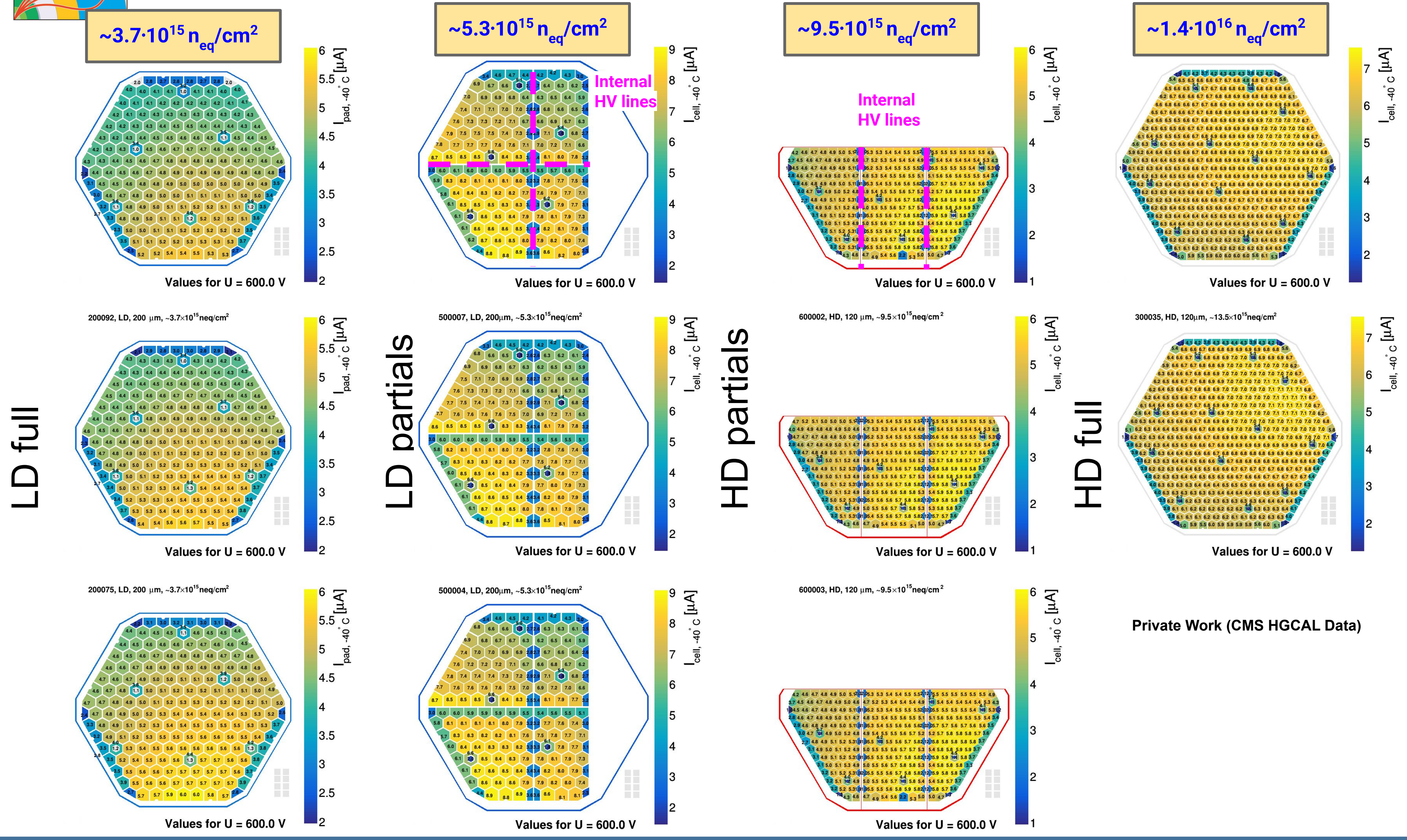
[Isothermal annealing of radiation defects in bulk material of diodes from 8" silicon wafers]

Sensor thicknesses and fluence limits @ $3ab^{-1}$:

- 300 μm (FZ) → up to $2 \cdot 10^{15}\ n_{eq}/cm^2$
- 200 μm (FZ) → up to $5 \cdot 10^{15}\ n_{eq}/cm^2$
- 120 μm (epi)→ up to $10 \cdot 10^{15}\ n_{eq}/cm^2$

[Neutron Irradiation and Electrical Characterisation of 8" Silicon Pad Sensors]

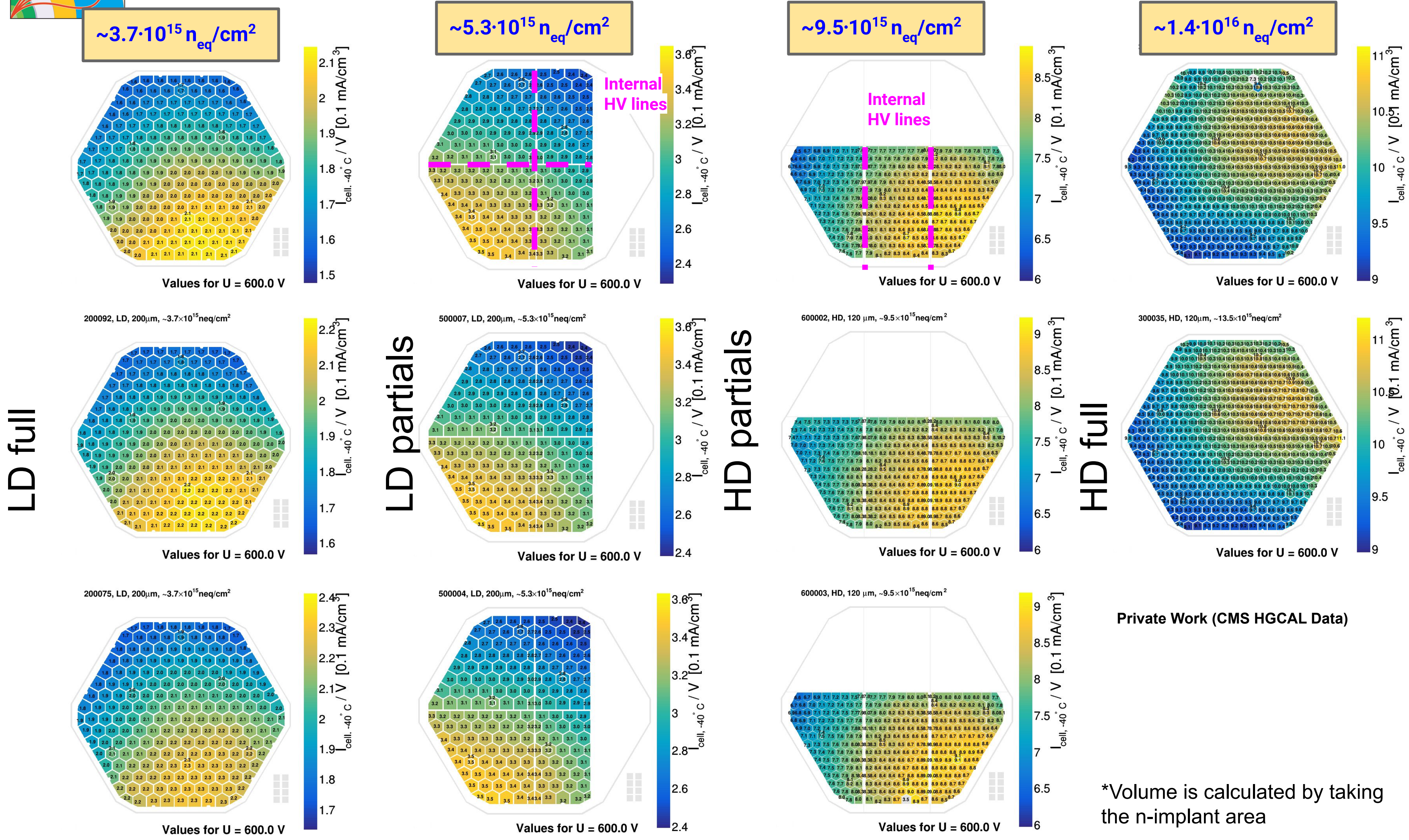
No outliers in cell leakage current after irradiation



- **First irradiation up to $1.4 \cdot 10^{16}\ n_{eq}/cm^2$**
- **First partial sensor irradiations**

- Cell currents increase with fluence
- Cell current variation within one sensor dominated by **cell volume**

Increase sensitivity when normalising to volume

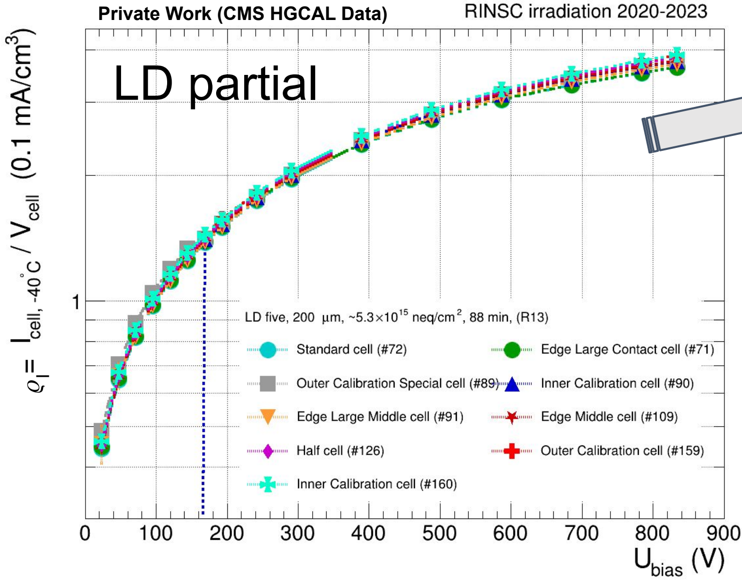


*Volume is calculated by taking the n-implant area

- Volume* normalised cell current exhibits gradients across sensor
- Similar gradient between sensors of same irradiation round
- Gradient potentially linked to **fluence profile** and/or **annealing time profile**
- **All cells, including cells next to internal and external dicing lines, with same IV behaviour as standard cells**

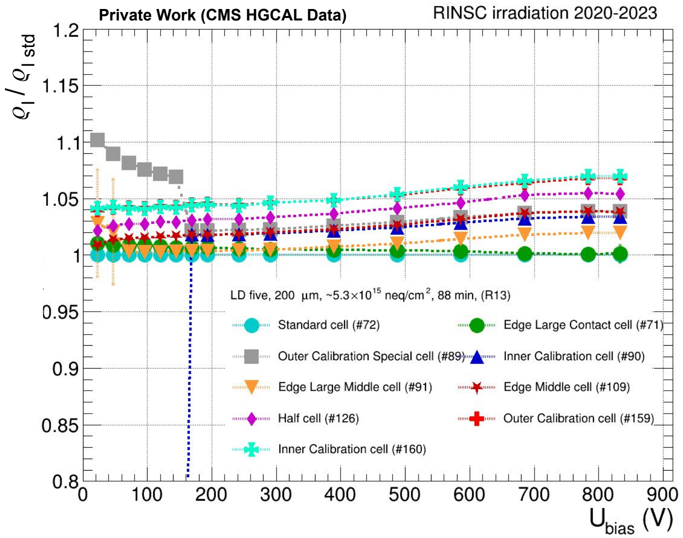
Compatible behaviour of all cell types and locations

Compare volume normalised IV curves for cells approximately along “iso-fluence” lines

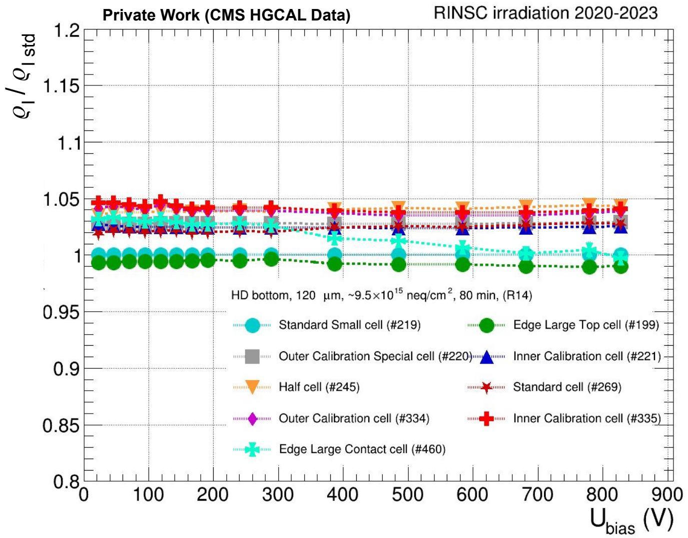


- Current densities
  - Agree within 10% for different cell layouts
  - Mostly constant with bias voltages

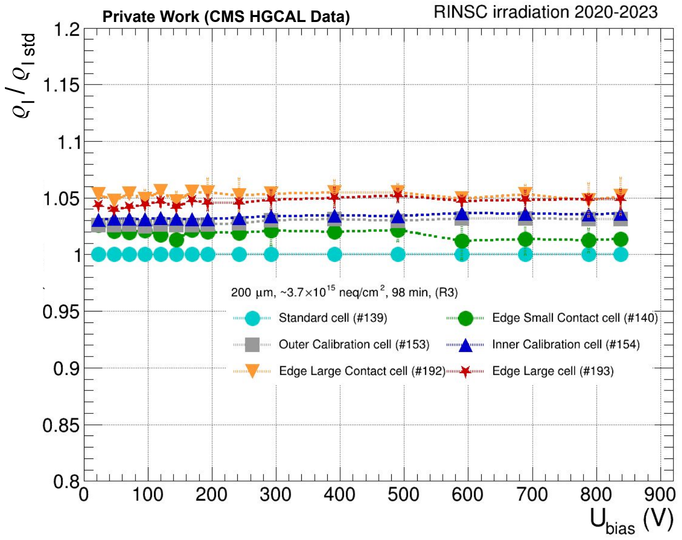
LD partial



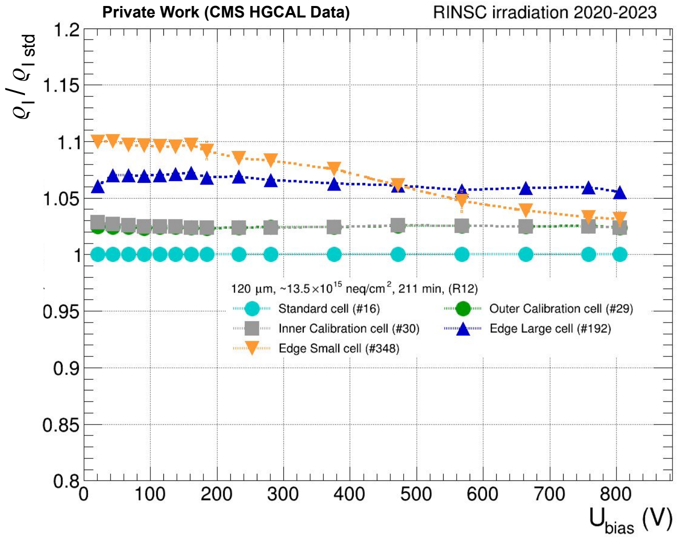
HD partial



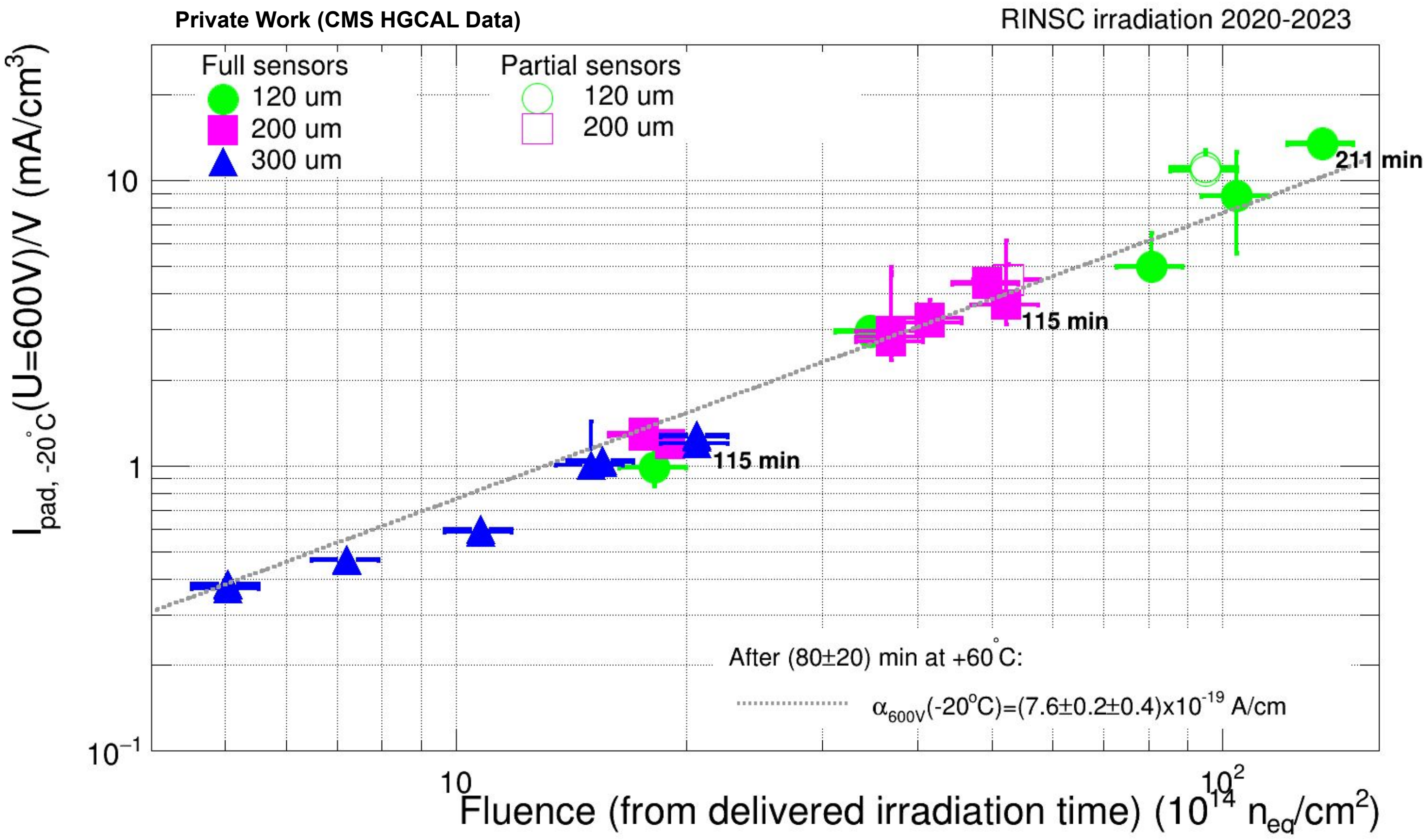
LD full



HD full



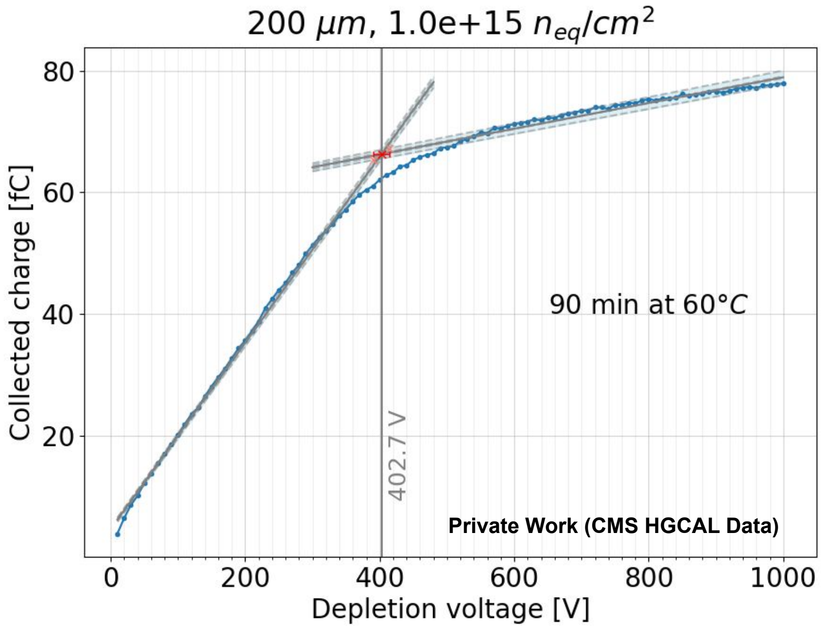
Partial sensors follow the same trend as full sensors

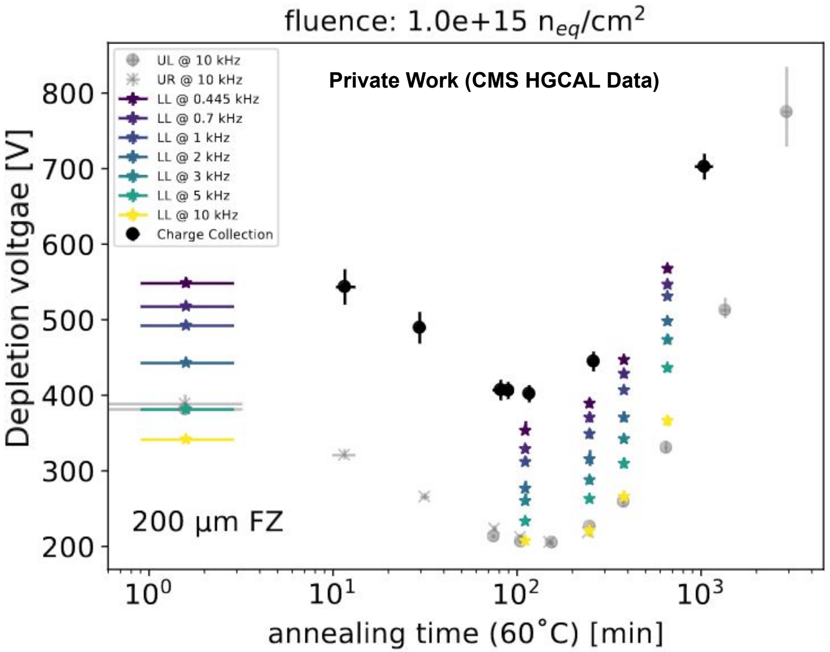


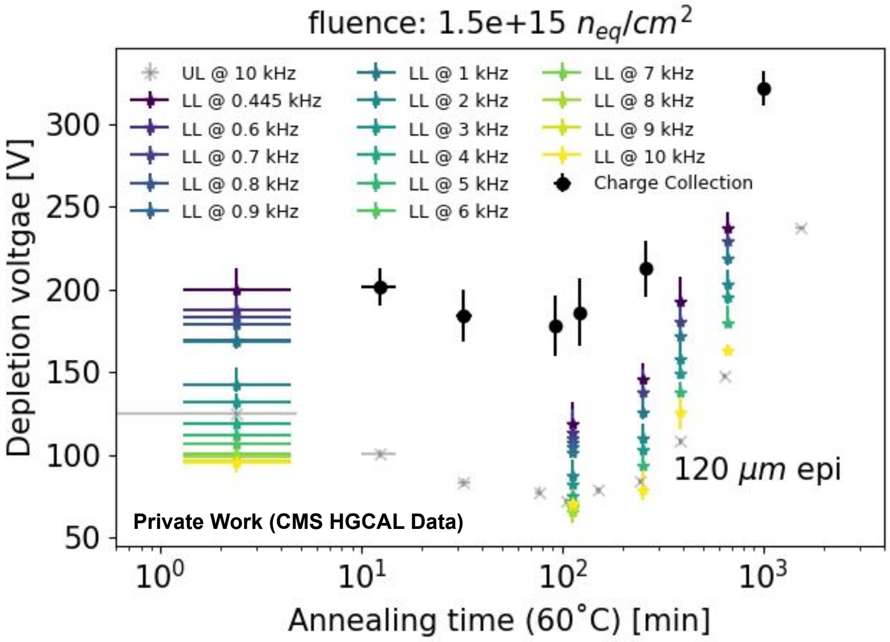
- Pad current from 3 full cells in the fluence maximum
- Partial sensors with internal HV lines follow **same trend** as full sensors in terms of **current related damage rate**
- Compatible results for single diode from JSI Ljubljana irradiation

[Isothermal annealing of radiation defects in bulk material of diodes from 8" silicon wafers]

Depletion voltage is dependent on frequency and method







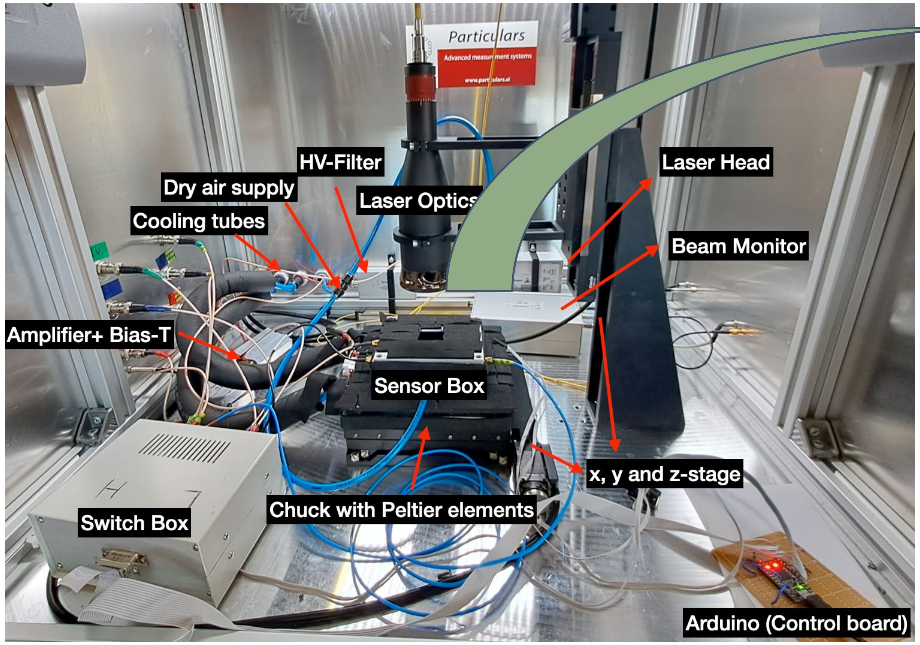
- CV extracted depletion voltage **is frequency dependent** - [RD50 Workshop]
  - The **lower** the frequency, the **higher** the depletion voltage value (445 Hz - 10 kHz studied)
- New:
  - Extract the depletion voltage **also** from **charge collection** - gives even higher values
  - **U_{dep} from CC and CV follow similar trend, e.g. exhibit same time of minimum**
  - **Limits fluence range to measure (maximum bias voltage used 1000V)**

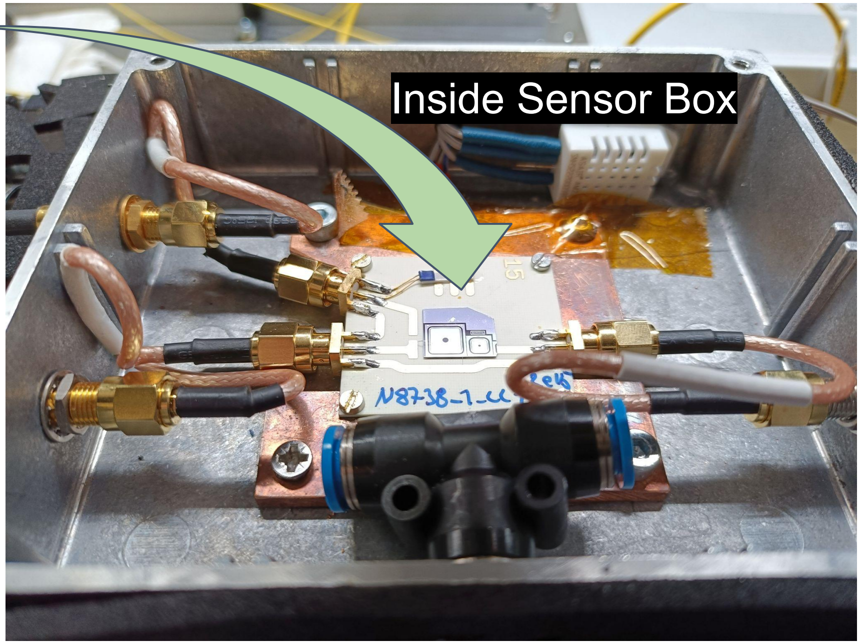
New TCT-IV-CV campaign for 3 annealing temperatures

- Reminder: **new setup** at CERN for TCT + IV/CV measurements provided by **Particulars**
- Setup **validated** as presented at previous [RD50 Workshop]
- **First results** of the ongoing campaign: **annealing at different temperatures**: 6.5°C (LT - low temperature), 21°C (RT - room temperature), 60°C
- 7 irradiated sensors for each campaign
- Fluences equivalent to ~3-4ab^{-1} expectation per thickness

Update on setup development:

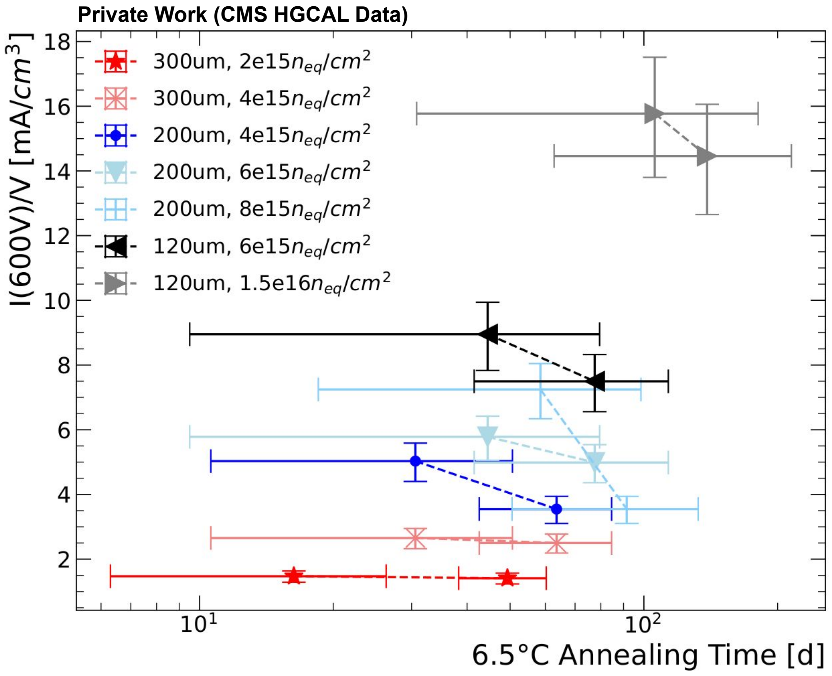
- able to measure IV, CV and TCT
- different softwares for:
  - IV, CV, temperature control (developed by CMS HGCAL Si Sensors group)
  - TCT (provided by Particulars)
- automatic switching between the measurements with the use of switch box
- efforts towards the full automation of the setup and humidity control is ongoing



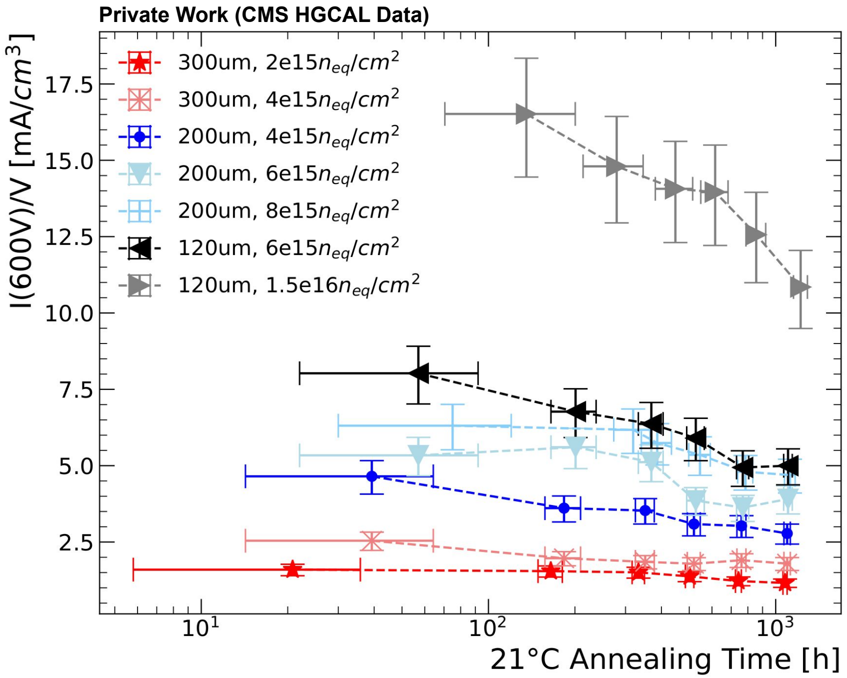


Leakage current decreases with annealing time

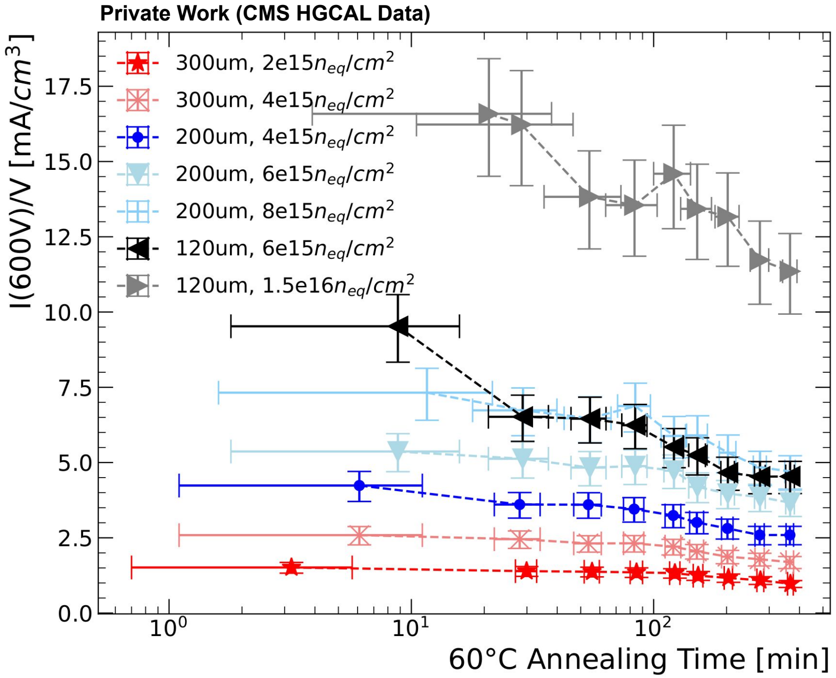
Low-T annealing



Room-T annealing



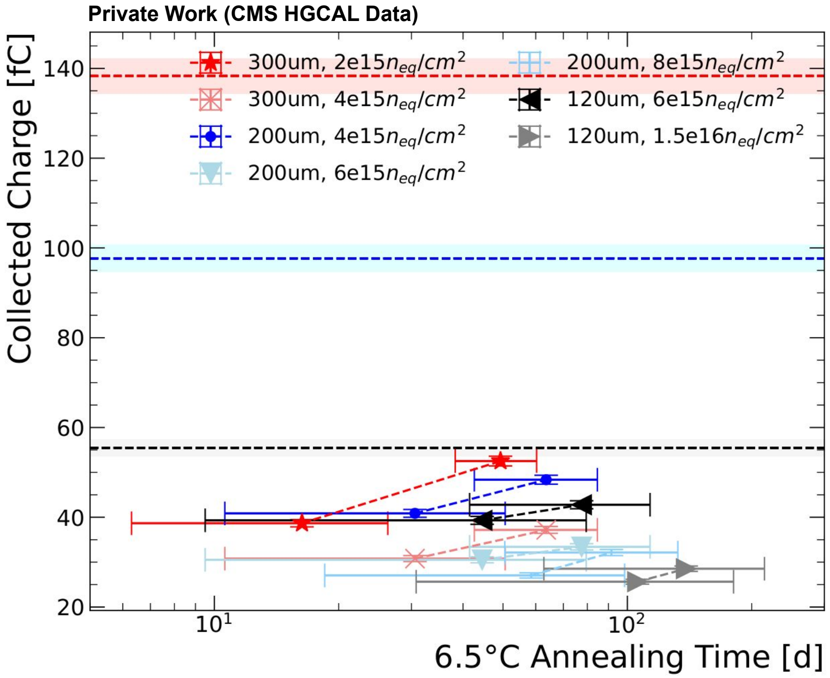
60°C annealing



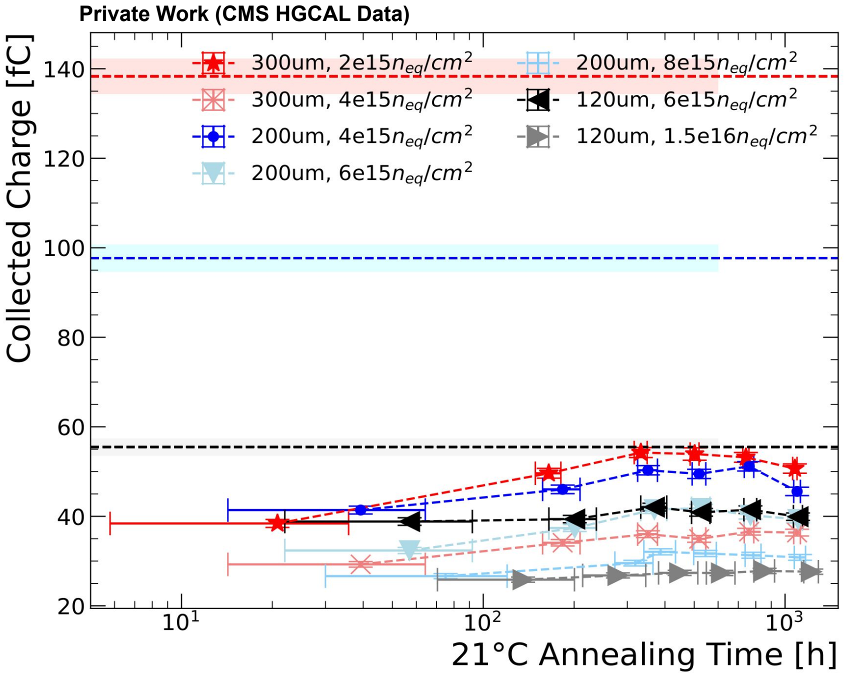
- Current at 600 V normalized to diode’s volume
- **Decrease with ongoing annealing visible for all temperatures**
- Some fluctuations visible - potentially some measurement temperature corrections necessary
- All three campaigns still ongoing

Collected charge changes over annealing time

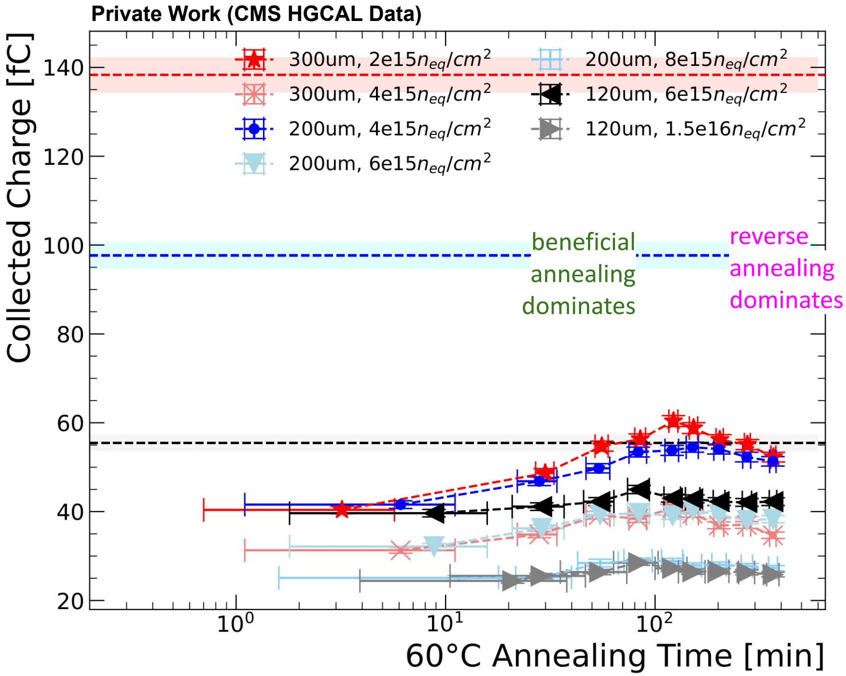
Low-T annealing



Room-T annealing



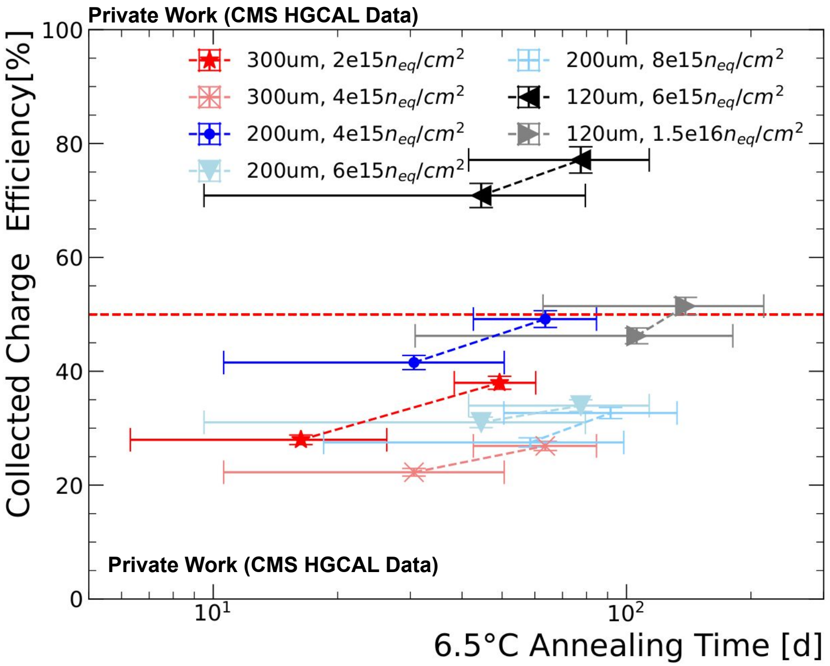
60°C annealing



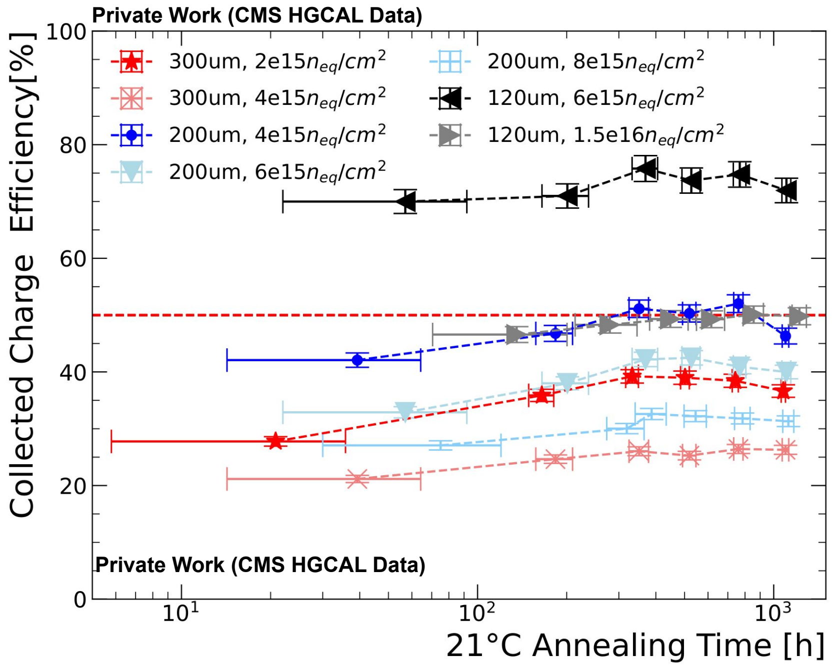
- An **increase of collected charge** for first steps of annealing visible
- Seems to have stronger effect on the thicker sensors
- **Beneficial annealing** until 90-110 min for 60°C and 16-17 days (~400 h) for RT (to be confirmed with further annealing)
- LT samples likely still in beneficial annealing

Charge collection efficiency mostly below 50%

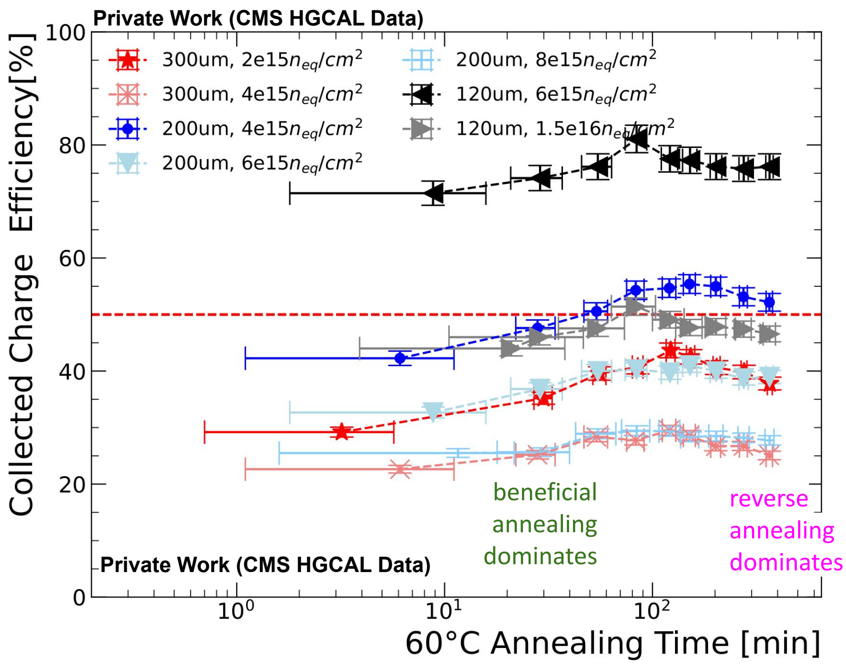
Low-T annealing



Room-T annealing

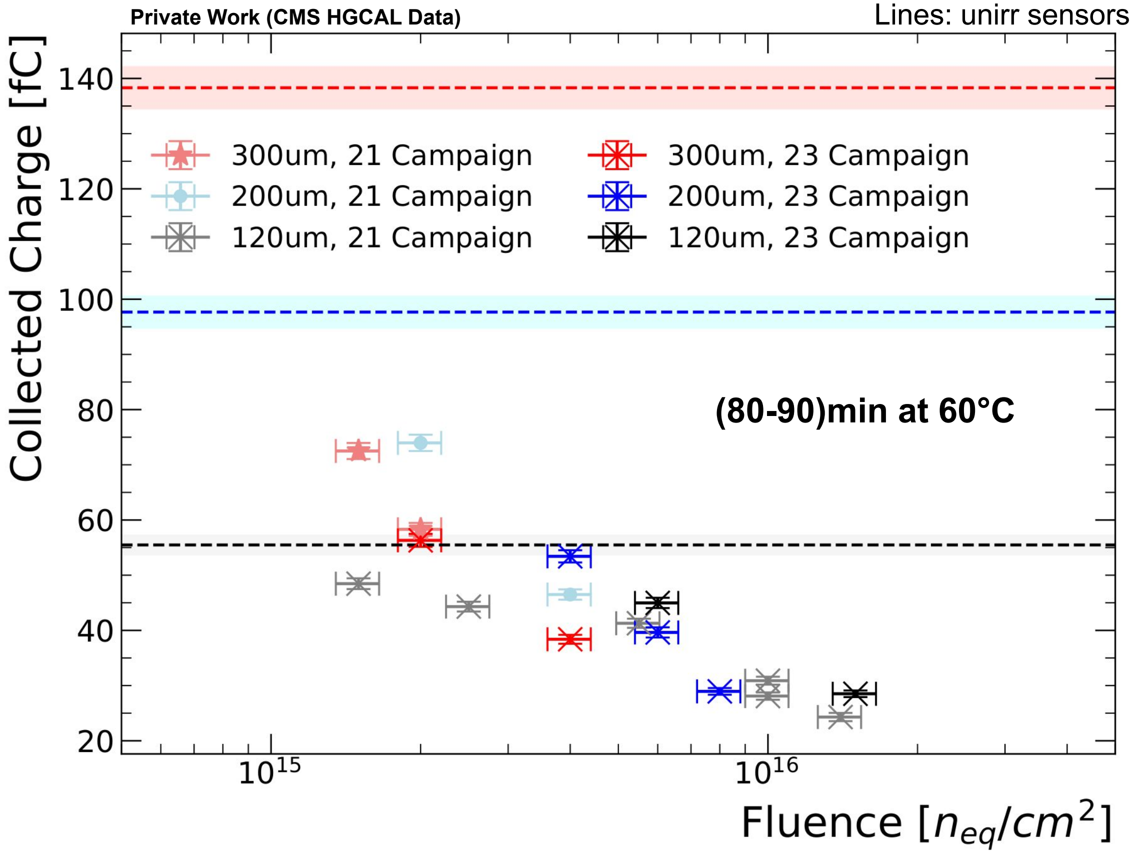


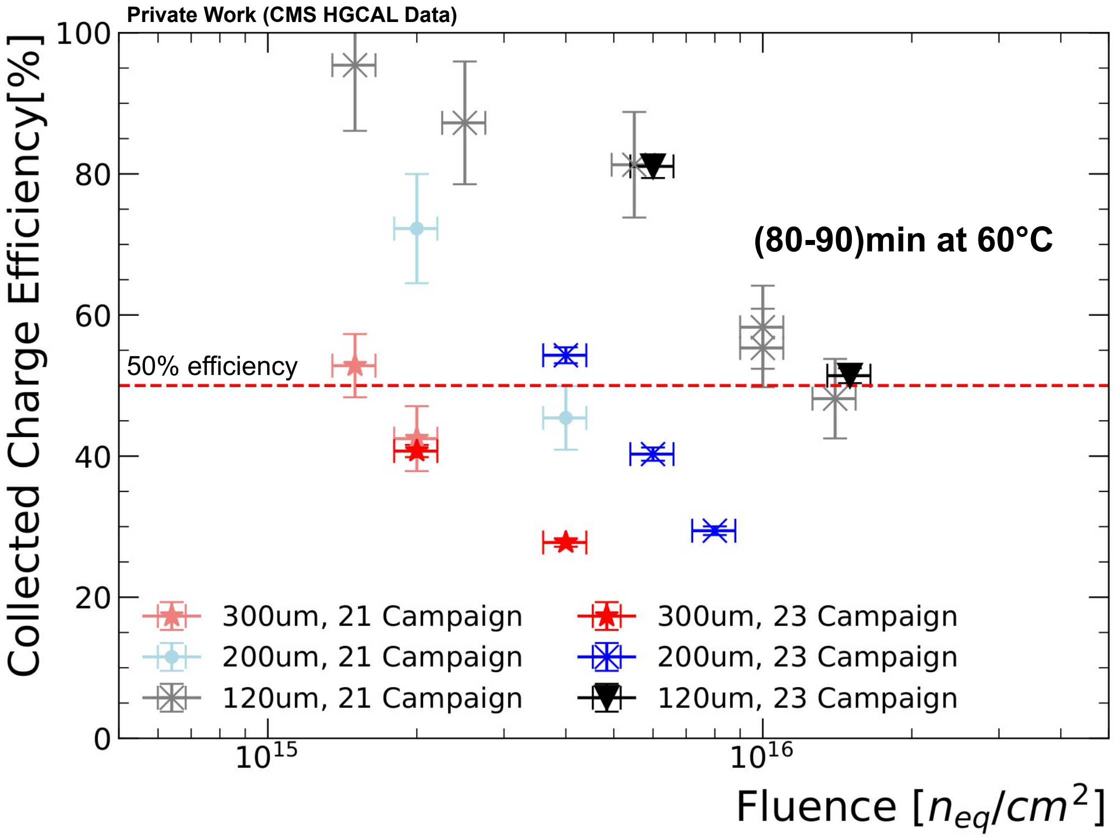
60°C annealing



- **Thinner** sensors have **higher** efficiency at same fluence - as expected
- Reached region dominated by reverse annealing in 60°C campaign
- Goal: Extract scaling factor between annealing temperatures. More measurements needed.

Increase fluence range covered with HGCAL sensors





- 2021 and 2023 campaigns performed in different setups (CERN SSD TCT+, Particulars)
- Plot data of 80-90 min annealing step at 60°C for both campaigns
- Data points at similar fluences agree within uncertainties

Take-home messages

- First measurements with full and partial sensors irradiated up to $1.4 \cdot 10^{16}$ n_{eq}/cm^2
  - Current increase with fluence following expectations
  - Current density of cells close to internal dicing lines compatible with standard cells

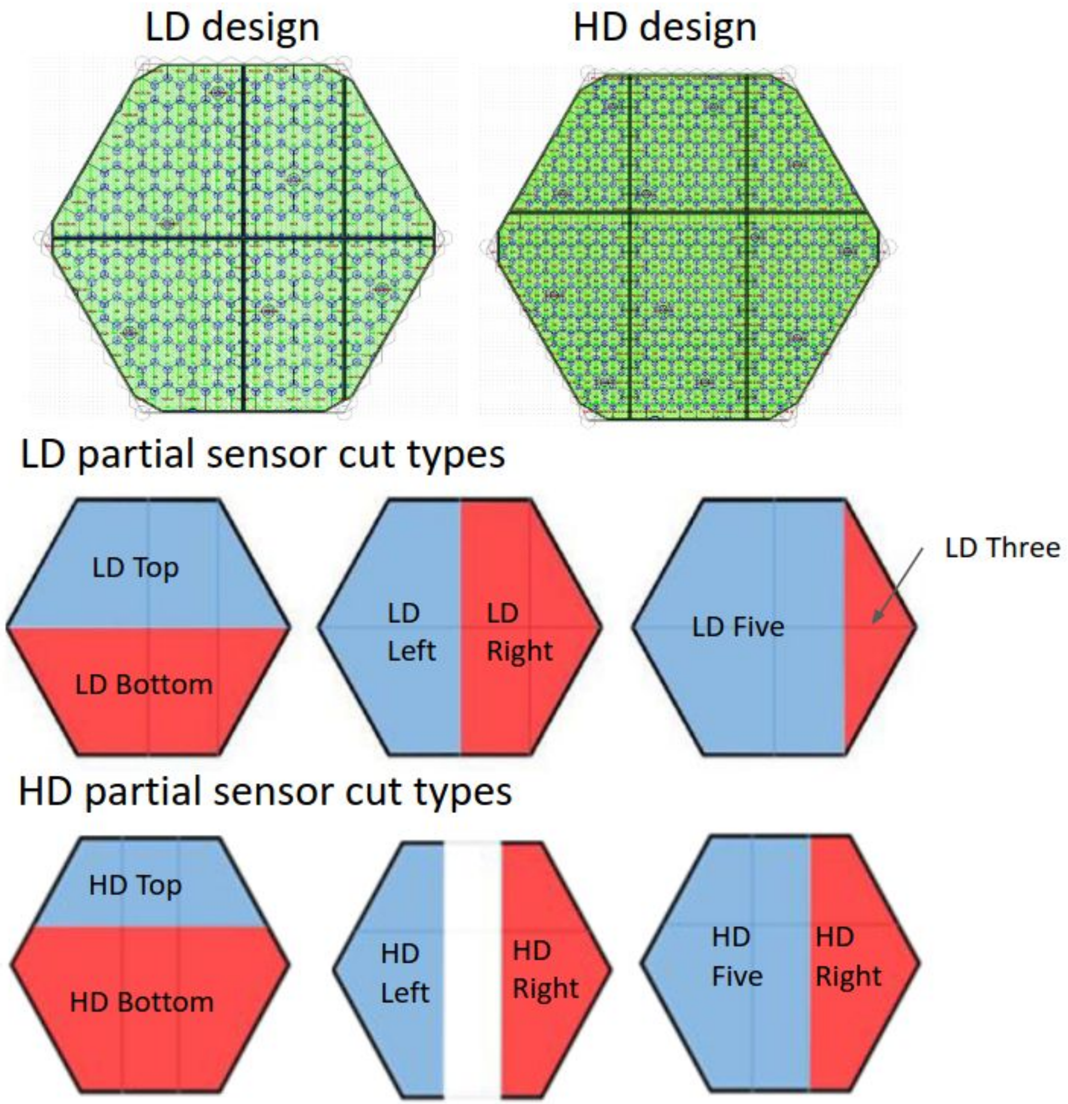
- Comparison of depletion voltage extracted from CV and CC shows similar trends
  - Circumvent frequency dependence in CV measurements by using CC data
  - High depletion voltage from CC limits fluence range that can be covered

- New TCT-IV-CV campaign with different annealing temperatures ongoing
  - Samples irradiated to fluences corresponding to end of live time of HGCAL
  - 60°C and RT annealing campaigns close to the end of beneficial annealing, first annealing steps for low-temperature annealing done
  - Similar levels and trends found in all 3 campaigns up to now
  - Results agree within uncertainties with earlier campaigns, performed in different setup
  - Goal: Estimate scaling factors between annealing temperatures for 8-inch p-type material

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA)

Backup

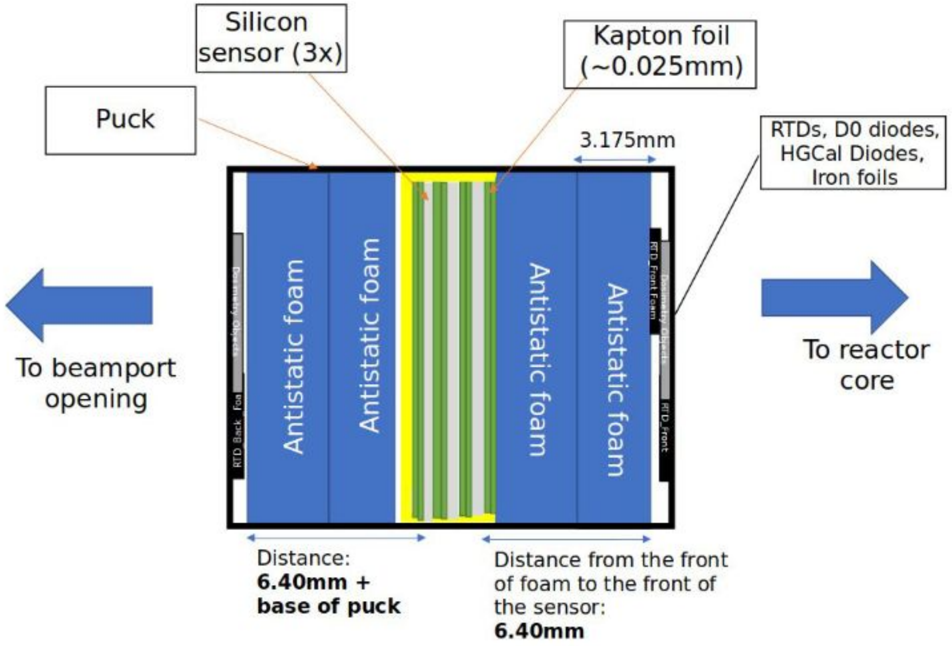
Partial Sensors from Multi-Geometry Wafers



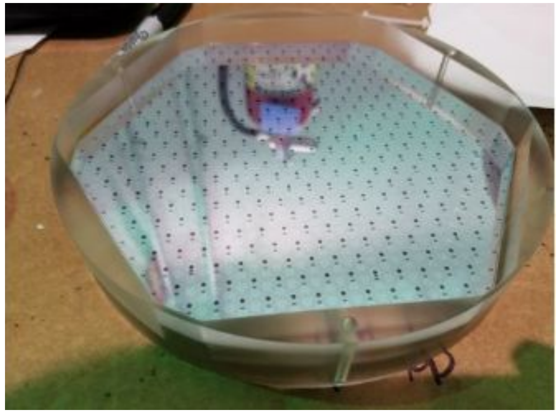
RINSC fluence steering and monitoring

- Target fluence from few 10^{14} to $1.4 \cdot 10^{16}$ n_{eq}/cm^2
- Steering of fluence delivery
  - Assuming constant reactor power, fluence scales linearly with irradiation time following 21.5 min = 10^{15} n_{eq}/cm^2
  - Run reactor with constant power within ± 3%
- Monitoring of fluence delivery
  - Delivered fluence monitored using silicon diodes (“D0” diodes of 200µm, “HGCAL” diodes of 120µm thickness) and iron foils, located in front and back of the hockey puck

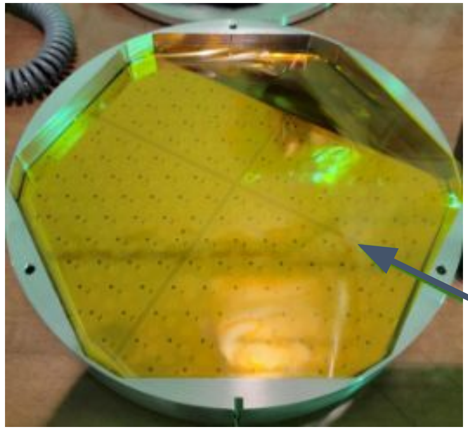
Puck layer structure



Acrylic “hockey puck”



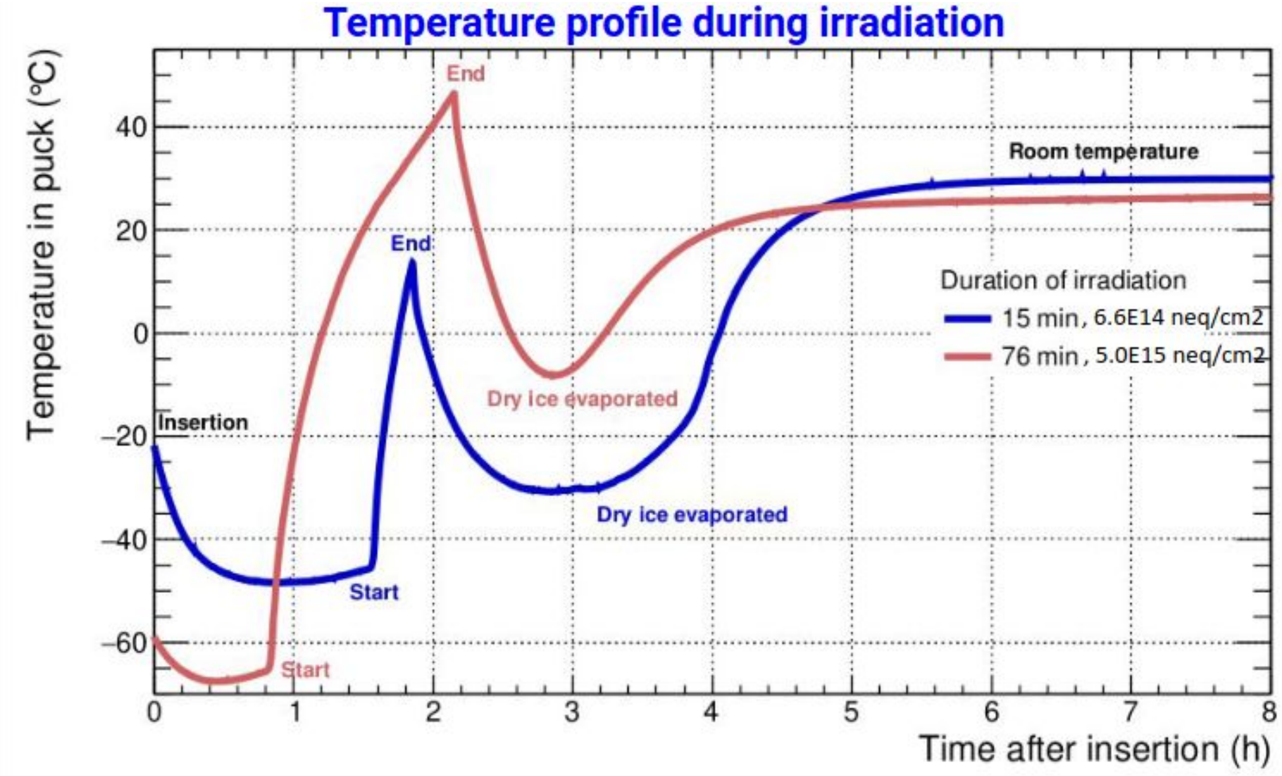
Aluminium “hockey puck”



Kapton foil to separate sensors

Temperature during RINSC irradiation

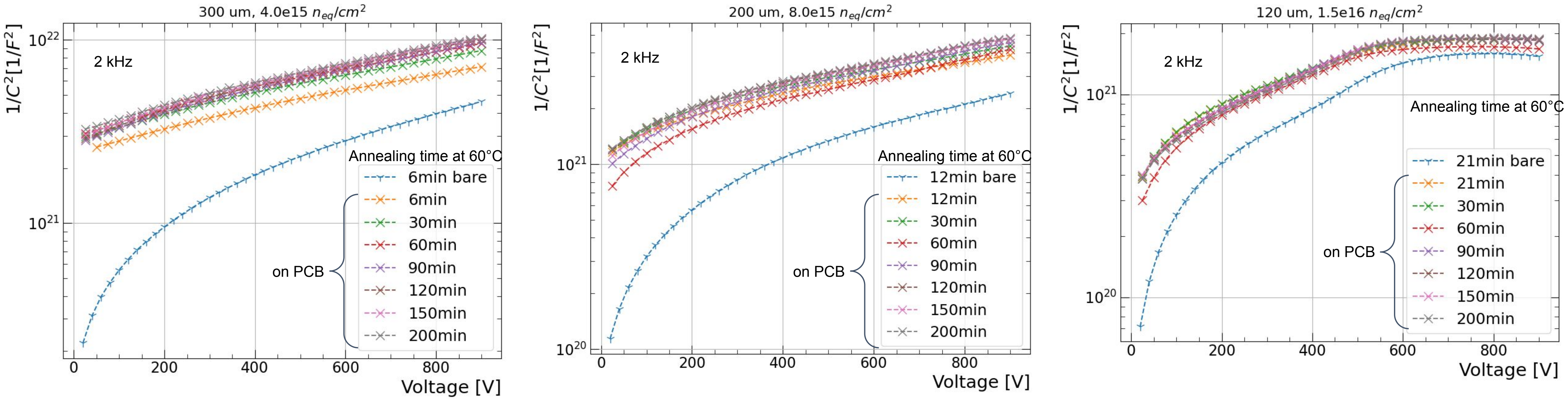
- Temperature in beam port increases strongly during irradiation
  - Sample cooling using dry ice to limit in-situ annealing
  - Temperature monitoring to understand annealing history of irradiated sensors



- Early high-fluence irradiation rounds brought sensors into regime where reverse annealing already dominated
- Counter measures implemented
  - Improved thermal conductivity of puck (optimised material, added ventilation holes)
  - Cooling of cylinder before irradiation
  - Splitting of high-fluence irradiations into 2 irradiation rounds

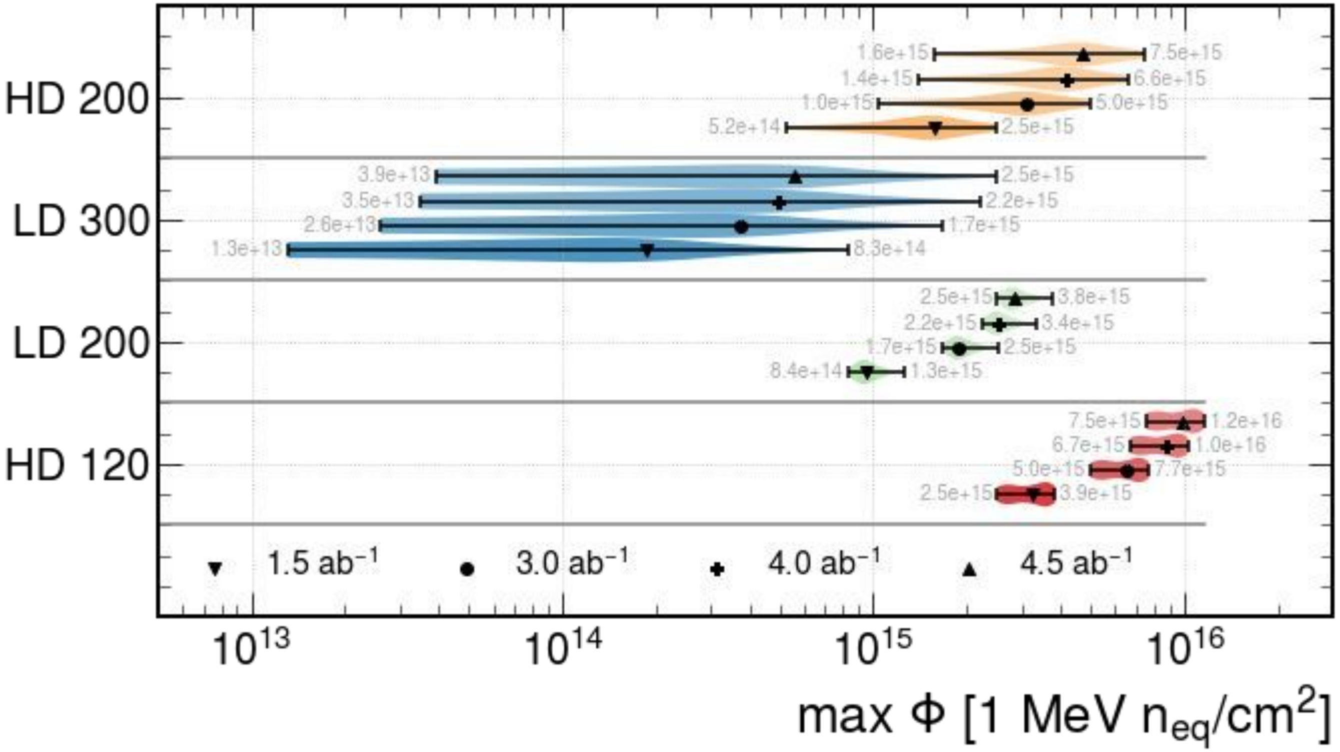
[Neutron Irradiation and Electrical Characterisation of 8" Silicon Pad Sensors]

Example capacitance-voltage results



- For most samples we do not see saturation of capacitance (visible for epi sensors)
- **Do not extract depletion voltage** from CV data as it is frequency dependent
- **Do not perform CV frequency scans** in the ongoing campaign
- Results 'on PCB' not compatible with bare sensors; under investigation

Fluence expectation



Upper limit for 3ab^{-1}

200um: ~5.E15

300um: ~2.E15

120um: ~1.E16