Radiation Hardness

CMS HGCal Silicon Sensors

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16th Terascale Detector Workshop

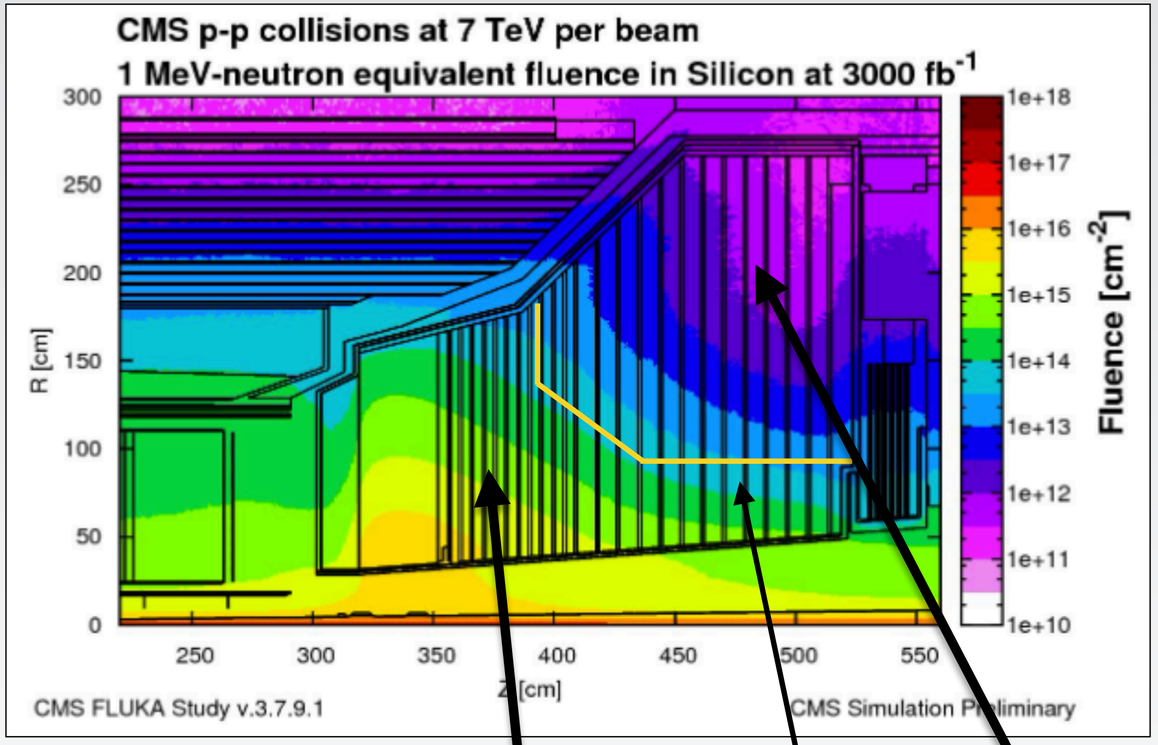
The HGCAL

Globally

- New endcap calorimeter for CMS (|η| = 1.5 - 3)
- 620 m^2 Si, 6M channels

Si sensors:

- High fluences up to 10^16 neq/cm2
- Two different sensor types, different optimal annealing scenarios
- Large area to cover with Si sensors: production line for 8” wafers being commissioned for HGCAL
- Radiation damage and annealing behaviour needs to be understood
- Crucial input for operation and warming up scenarios during technical stops



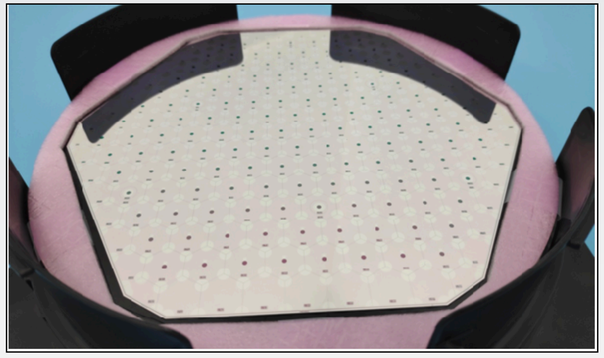
Silicon sensors (diodes)

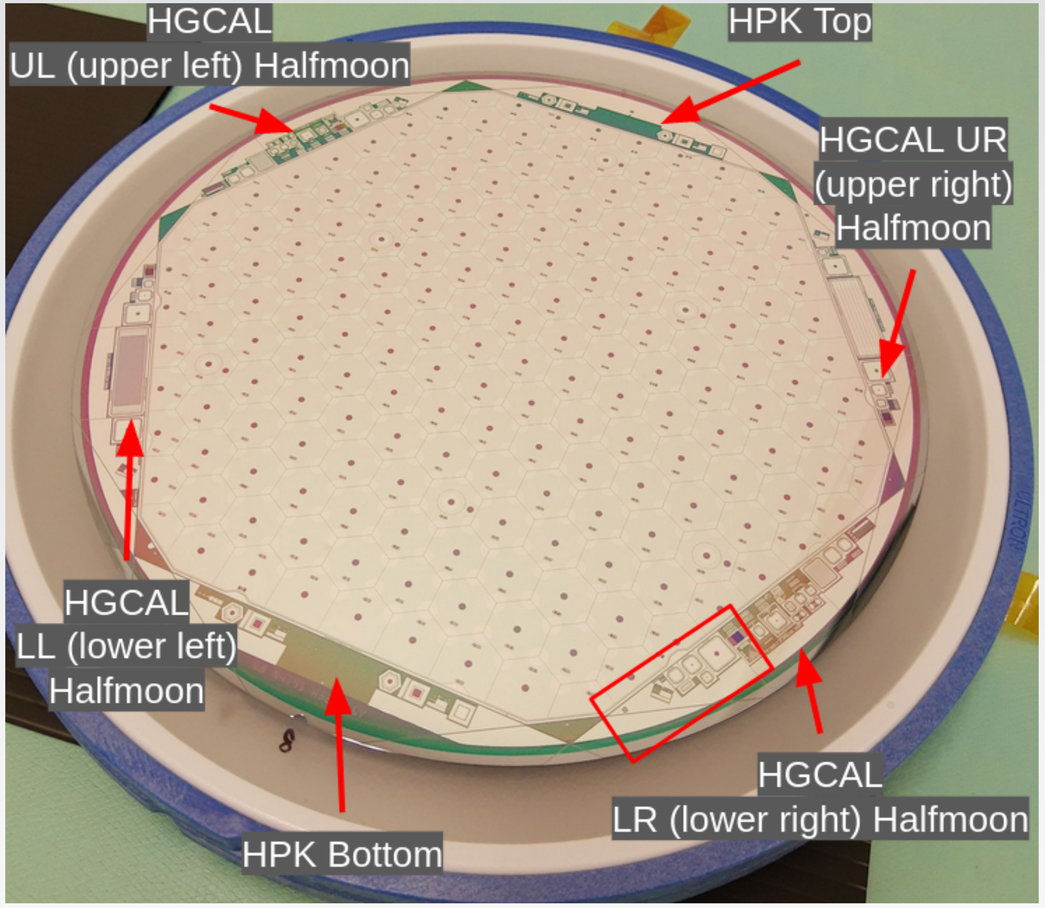
~ 5e13 n_{eq}/cm^2

Scintillator+ SiPMs

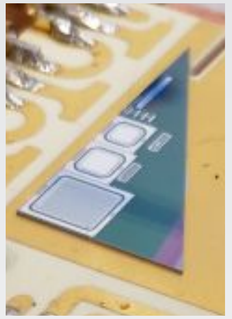
The Breadth of Studies

Full sensors





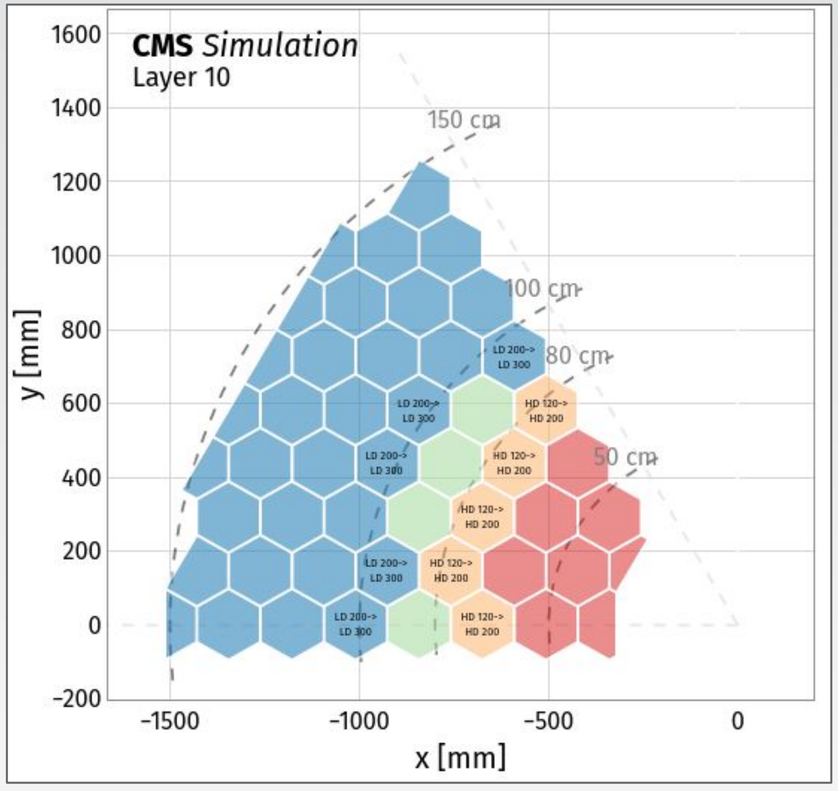
Surface

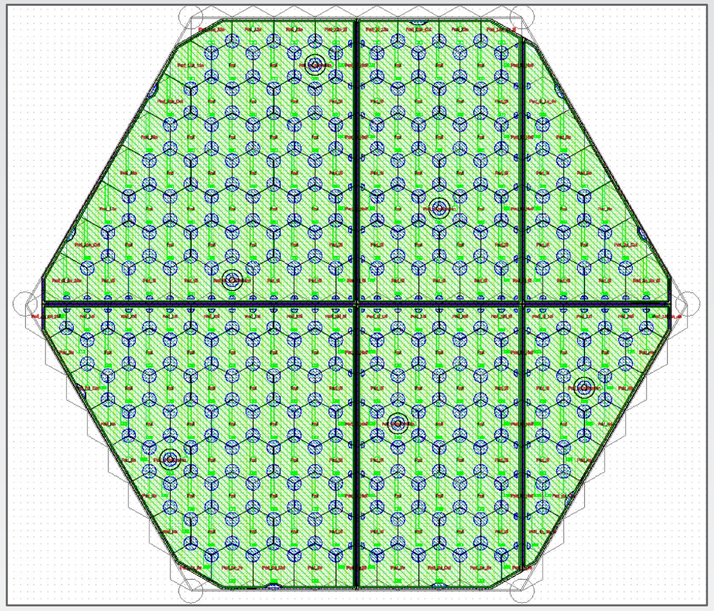


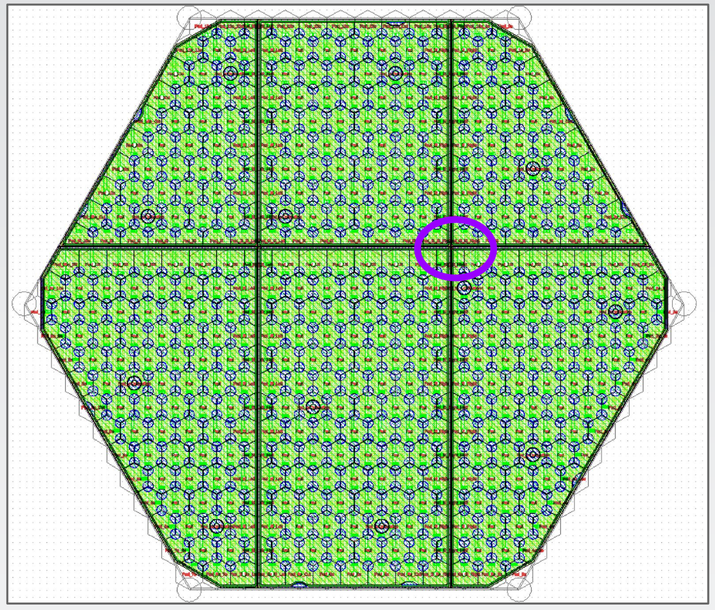
Bulk material

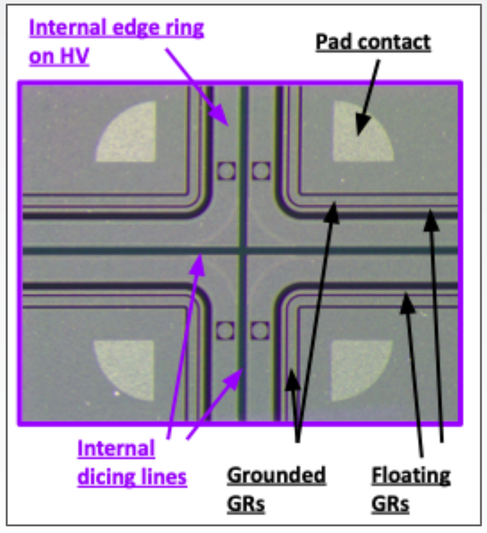
- In general three thicknesses and technologies
  - 300µm (FZ), up to 2 * 10^{15} n_{eq}/cm^2
  - 200µm (FZ), up to 5 * 10^{15} n_{eq}/cm^2 } Assuming 3 ab^{-1}
  - 120µm (EPI) , up to 10 * 10^{15} n_{eq}/cm^2

Full Sensor Studies





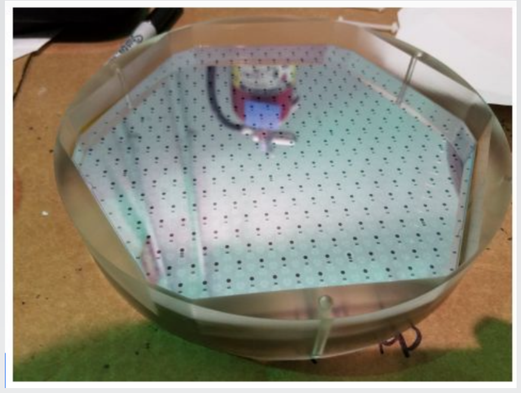


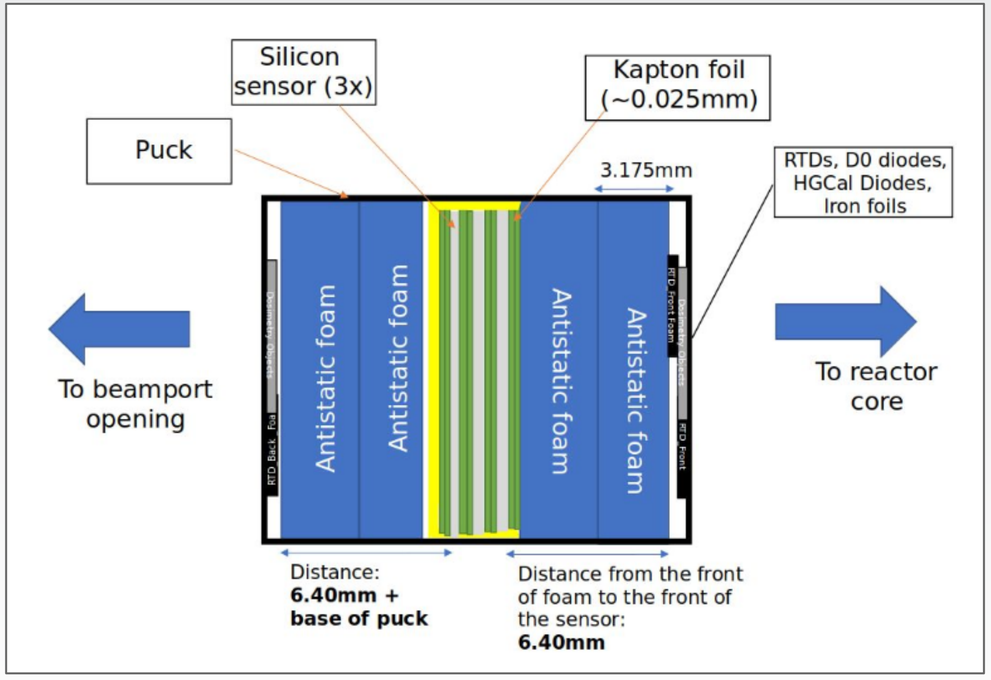


- Handling and ‘physical robustness’
- HV stability, radiation hardness
- Homogeneity of cell properties

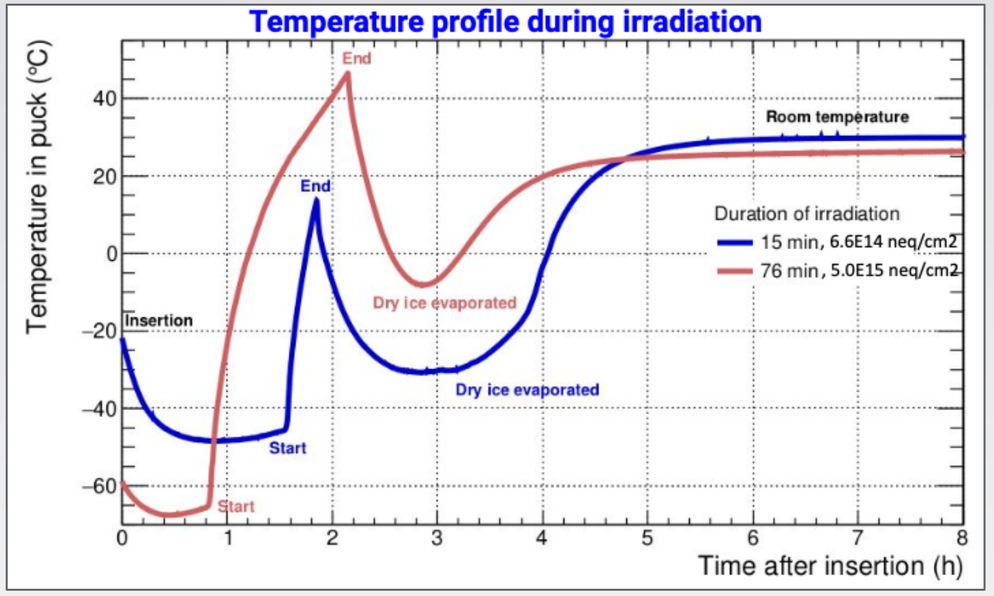
- Impact of geometry: partials, edges, supply lines, …

Irradiation of large wafers at RINSC





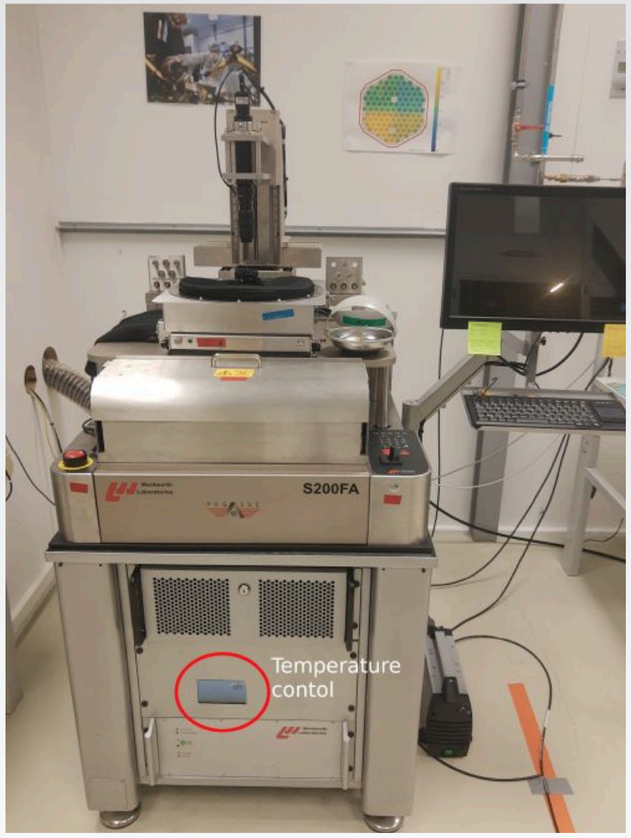
In a cylinder with dry ice

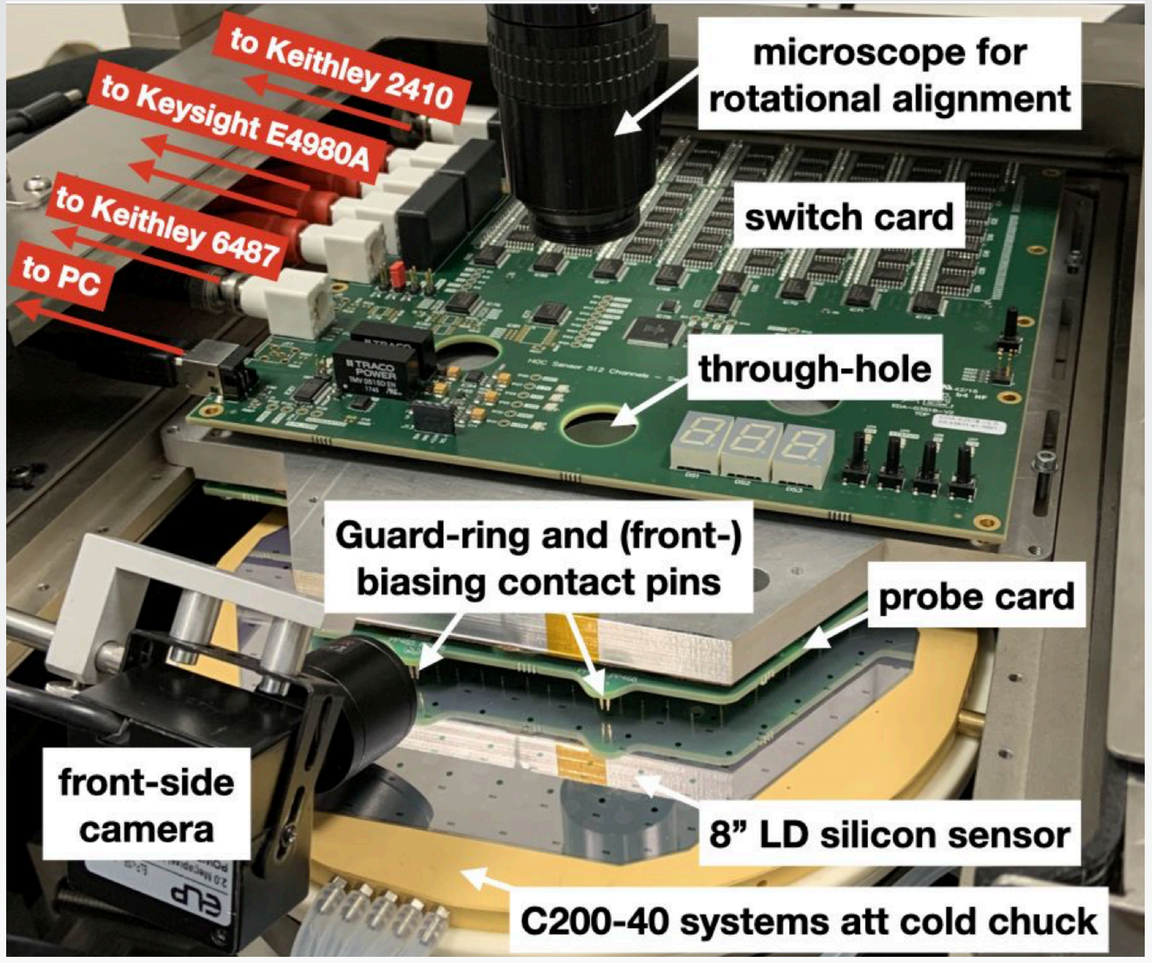


- Fluences up to 1 (1.6) n_{eq}/cm^2 expected for 3 (4.5) ab^{-1} of data

- Long exposure in the reactor
- Substantial annealing during irradiation
- Constant temperature monitoring required
- Recently achieved to stay within beneficial annealing regime
  - Optimised puck material
  - Split irradiation rounds

The Probe Station



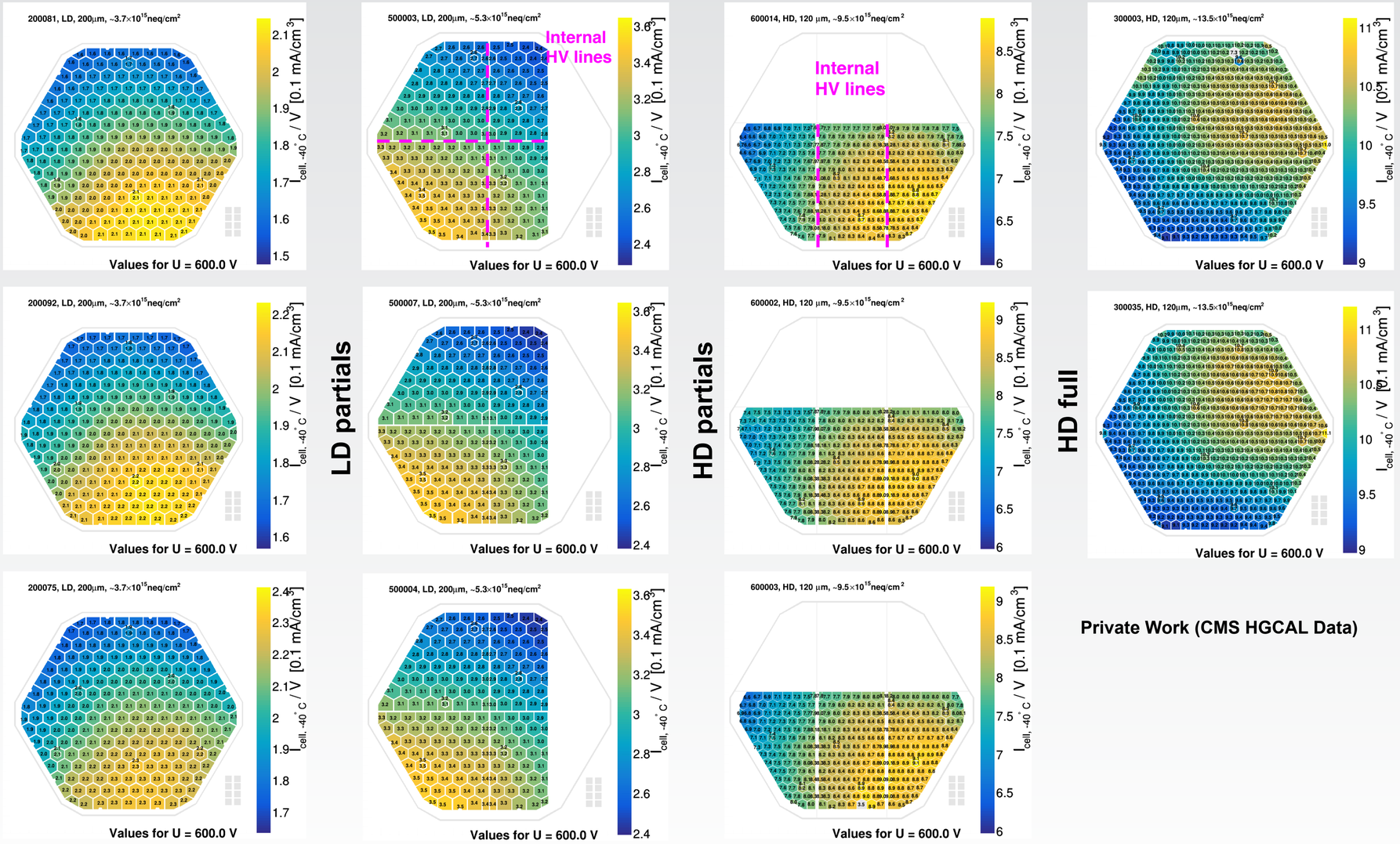


- Temperature controlled chuck ranging from -40˚C to typical annealing temperatures
- Open source design of probe card

E. Brondolin, et al,
arXiv:1903.10262, NIM A

Full and Partial Sensor Leakage Current

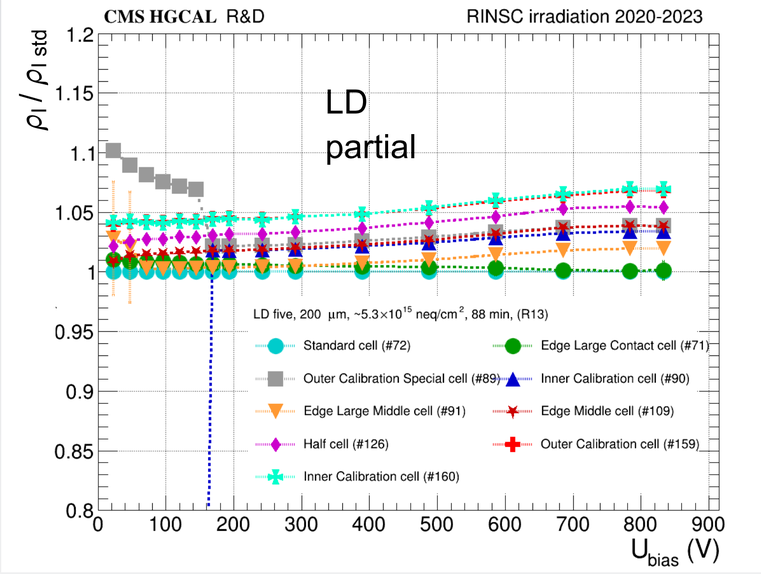
~3.7·10¹⁵ n_{eq}/cm²	~5.3·10¹⁵ n_{eq}/cm²	~9.5·10¹⁵ n_{eq}/cm²	~1.4·10¹⁶ n_{eq}/cm²
LD full	LD partials	HD partials	HD full

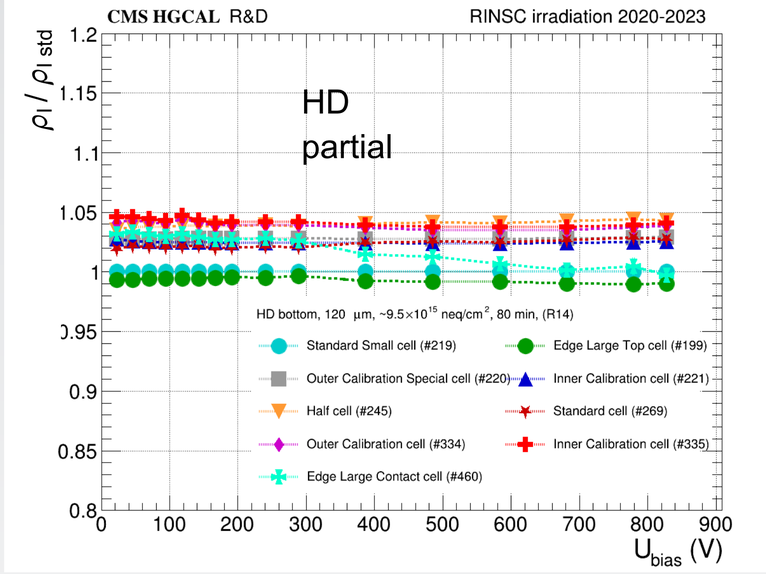


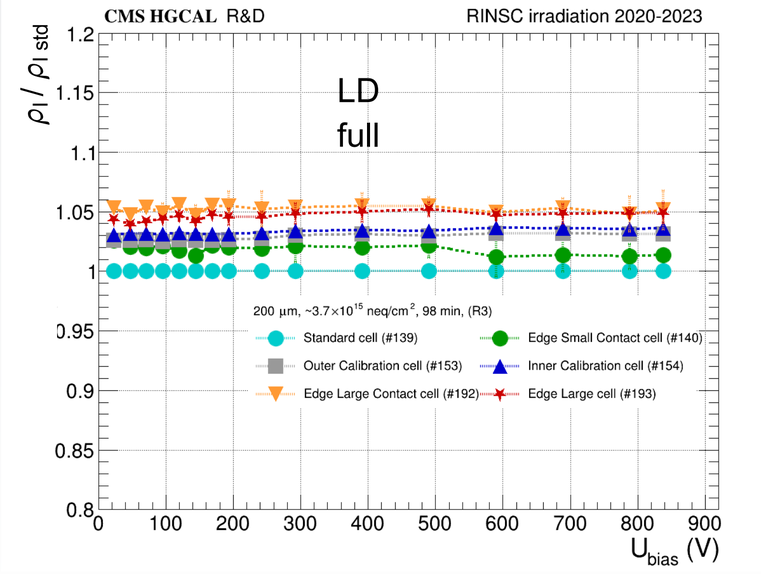
Private Work (CMS HGCAL Data)

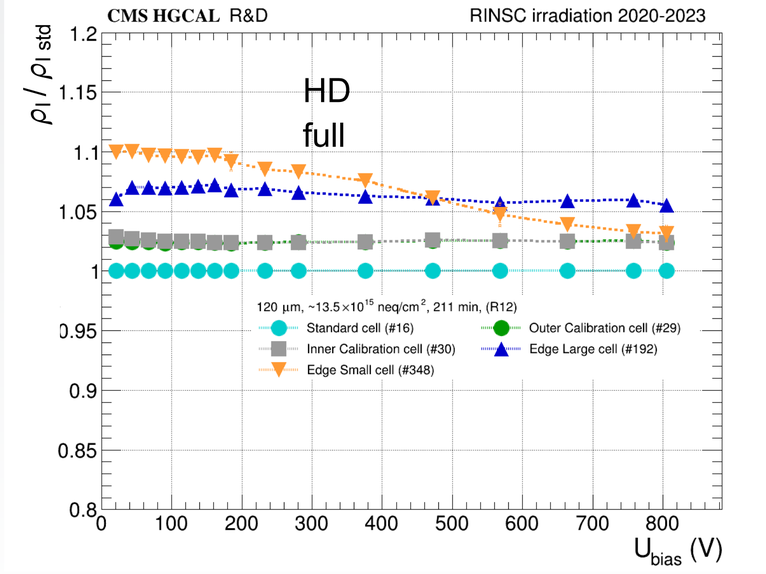
- Volume-normalised current increases with fluence
- Global pattern similar for all sensors in an irradiation batch
  - Fluence or annealing time profiles
- Locally, all cells, including those in proximity to dicing and internal supply lines, show very consistent leakage current behaviour

Quantitative Overview







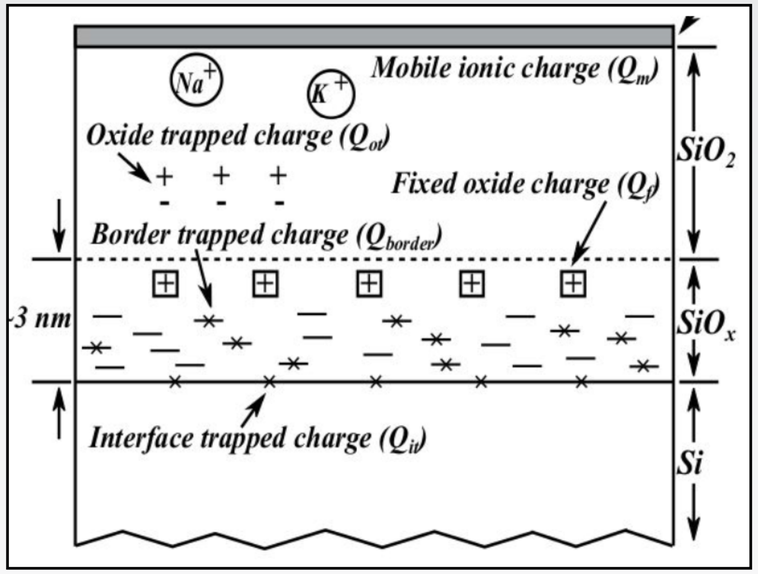


- Select cells on isofluence lines
- Normalise each cell current to the cell volume: ρ_I
- Normalise to the standard cell ρ
- Agree within 10% for different cell layouts and positions
- Mostly constant with bias voltage (same scaling)
- Even for large wafers, and partial wafers, the electrical characteristics are mostly homogenous

CMS HGCAL Collaboration,
arXiv:2209.10159, JINST
O. Kaluzinska,
https://indico.cern.ch/event/1334364/contributions/5672066/

Surface Damage

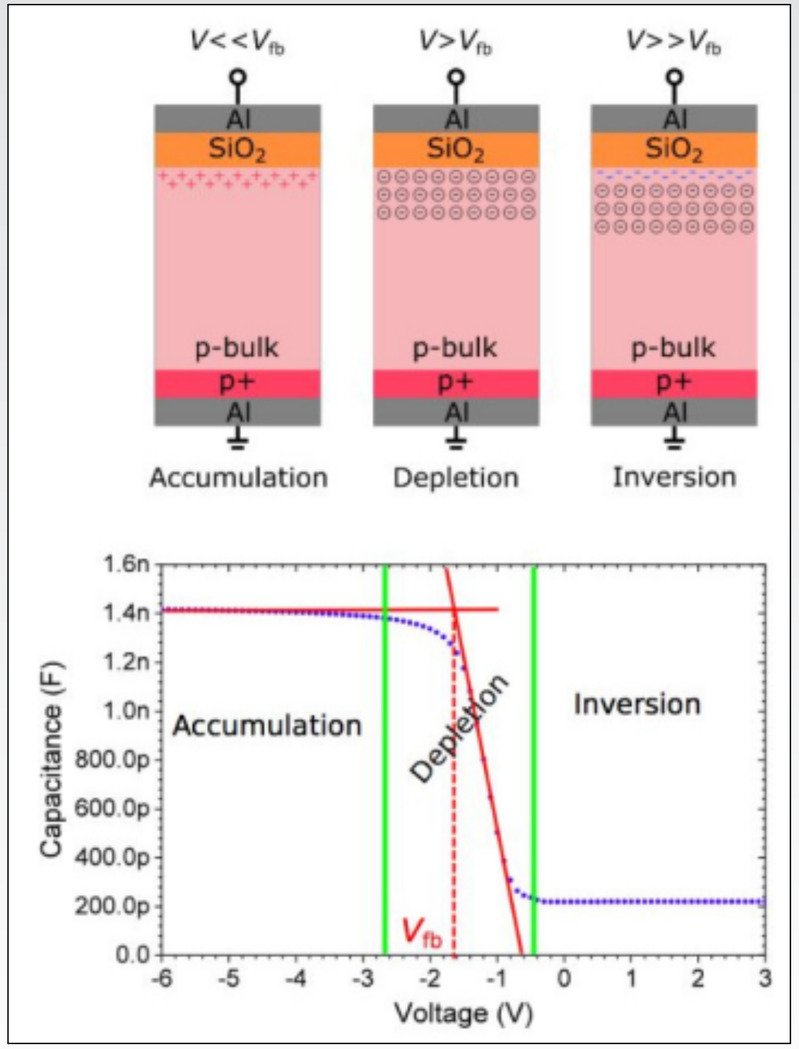
- EM radiation (X-ray) creates electron-hole pairs in the SiO_2 layer
- Holes can be trapped
- Creates charge build-up at the interface
  - Can deteriorate inter-pad isolation
- $N \propto -V_{FB}$



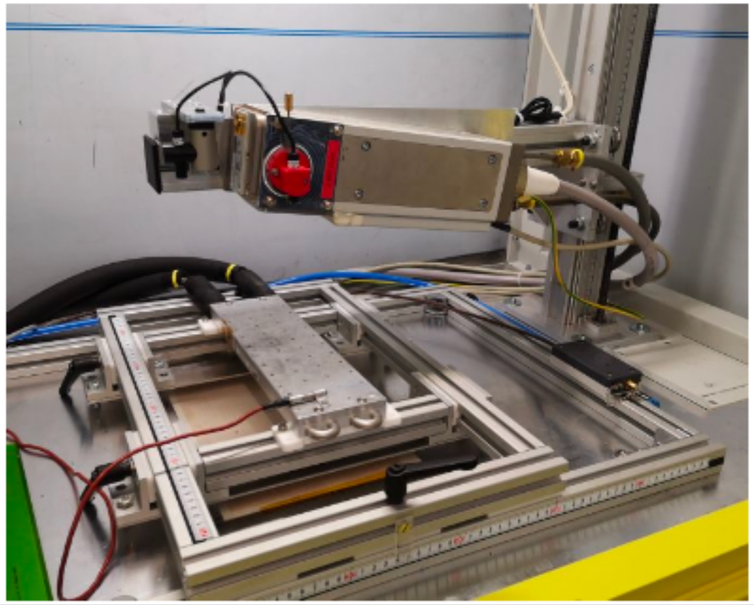
[PhD thesis of Ioannis Kopsalis]

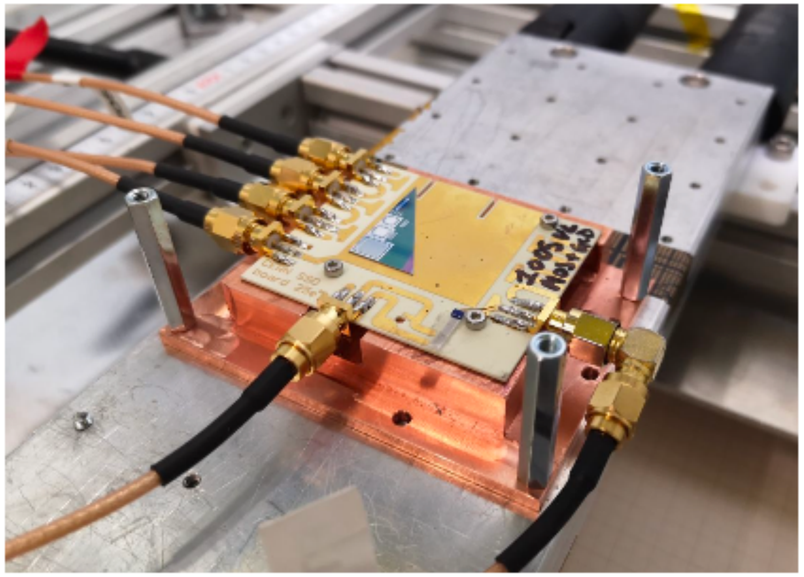
- Anneals relatively fast
- Challenging to measure in a reproducible way

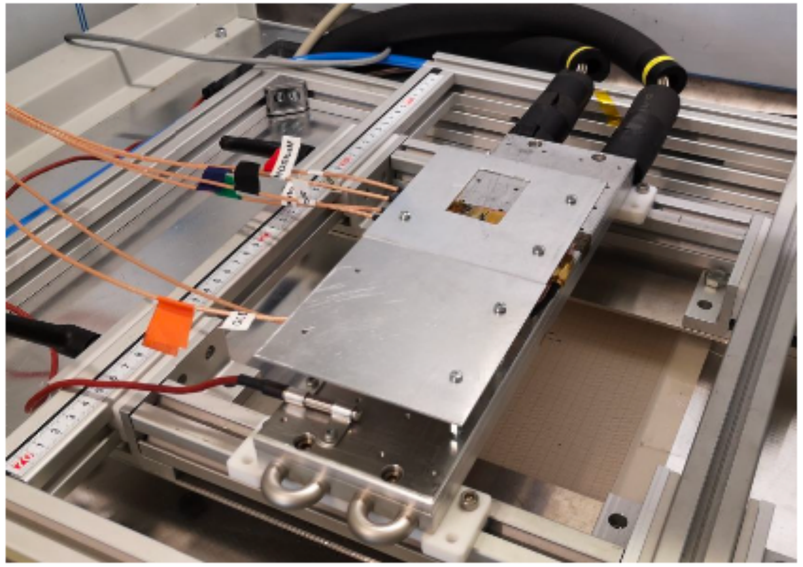
[Illustration V. Hinger]



X-ray Irradiation of Test Structure



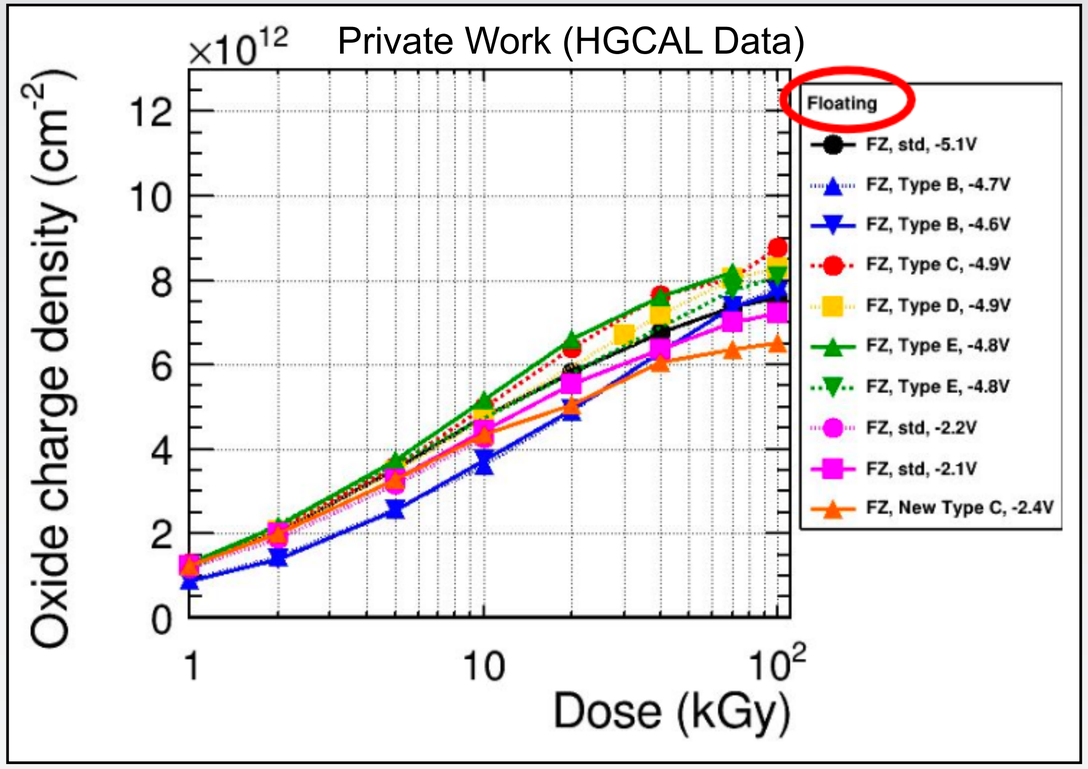


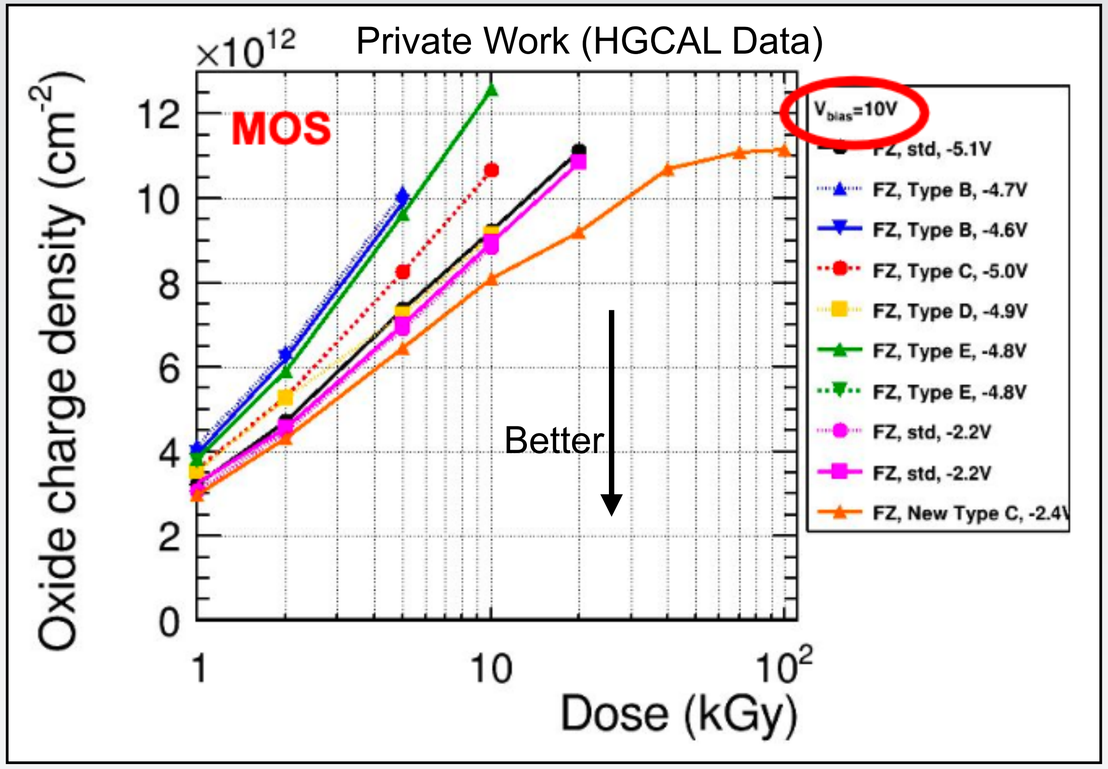


- Sample cooled during irradiation and measurement
- Integrated setup avoids moving the sample between irradiation and measurement steps
- Fully automated measurement software enables reproducible and long term measurements

- Allows systematically studying of different oxide variants provided by the manufacturer

Oxide Quality

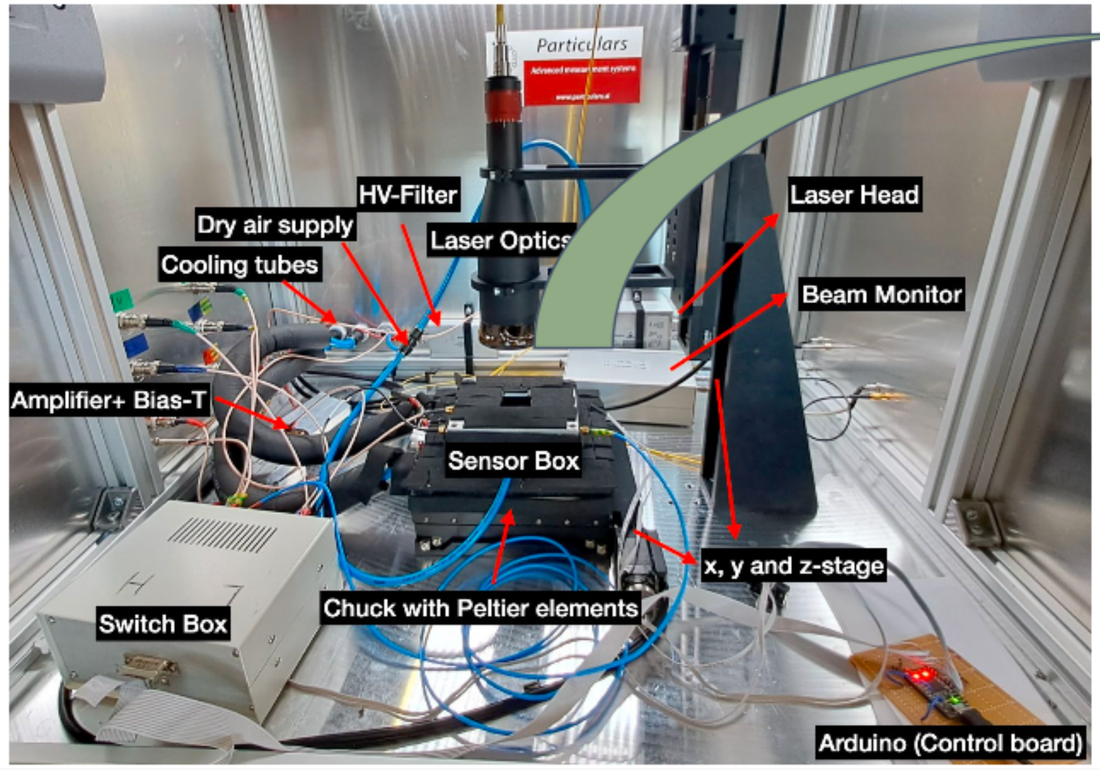


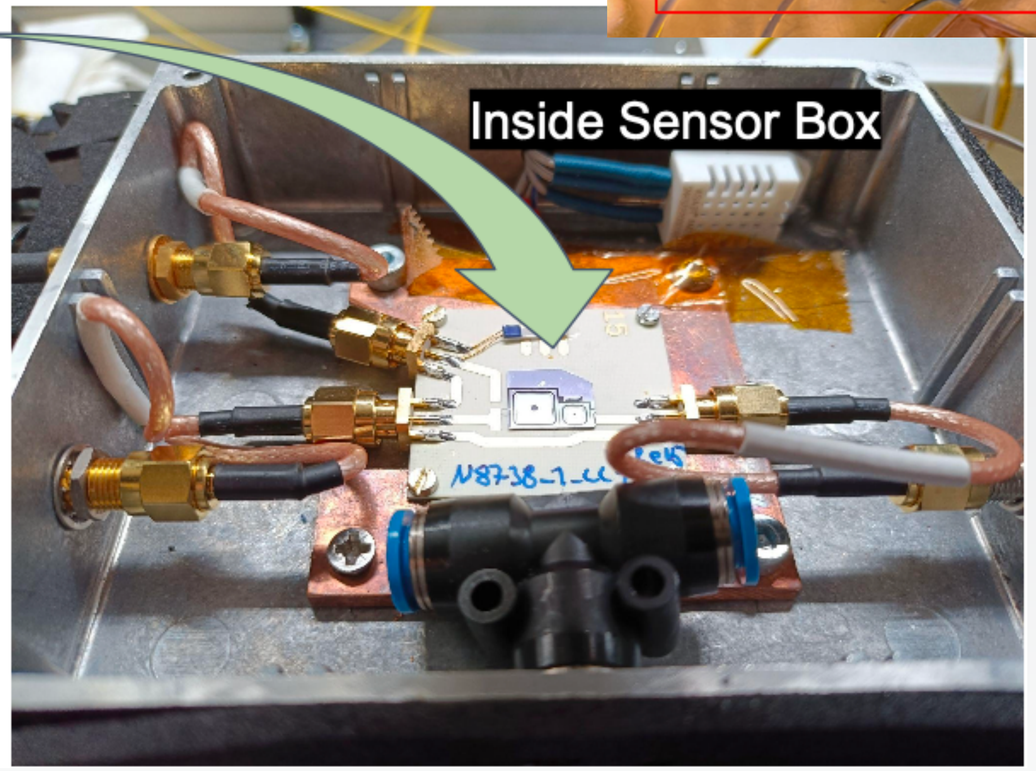


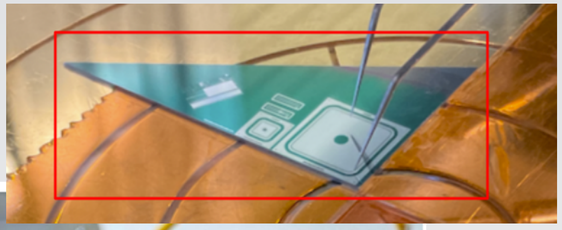
- Long continuous measurement campaigns possible (10^2 kGy correspond to a week)
- Detailed study of oxide quality using a floating and biased MOS (to emulate an electric field) …and other properties
- “New Type C” chosen for production

M. Defranchis,
https://indico.cern.ch/event/1096847/contributions/4743792/
paper in preparation

Characterising the Bulk Material

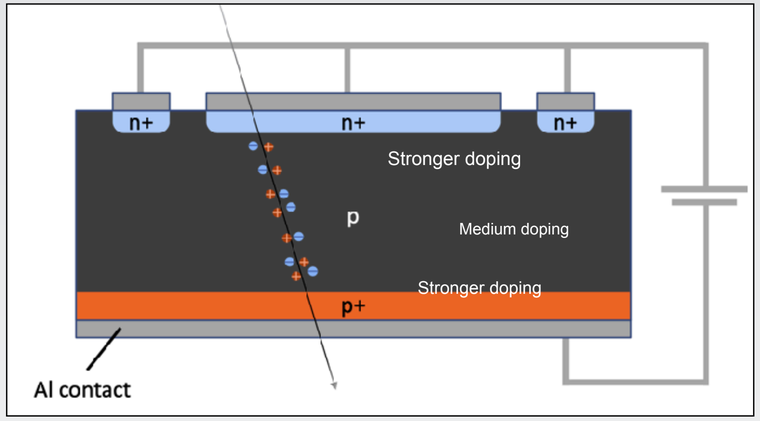


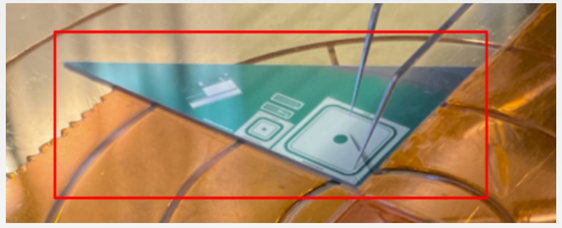


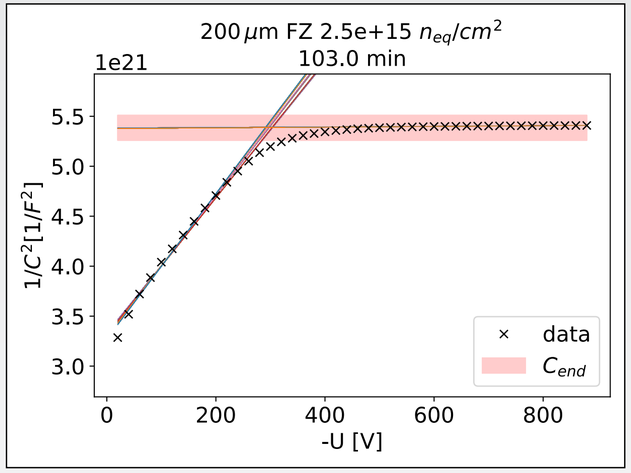


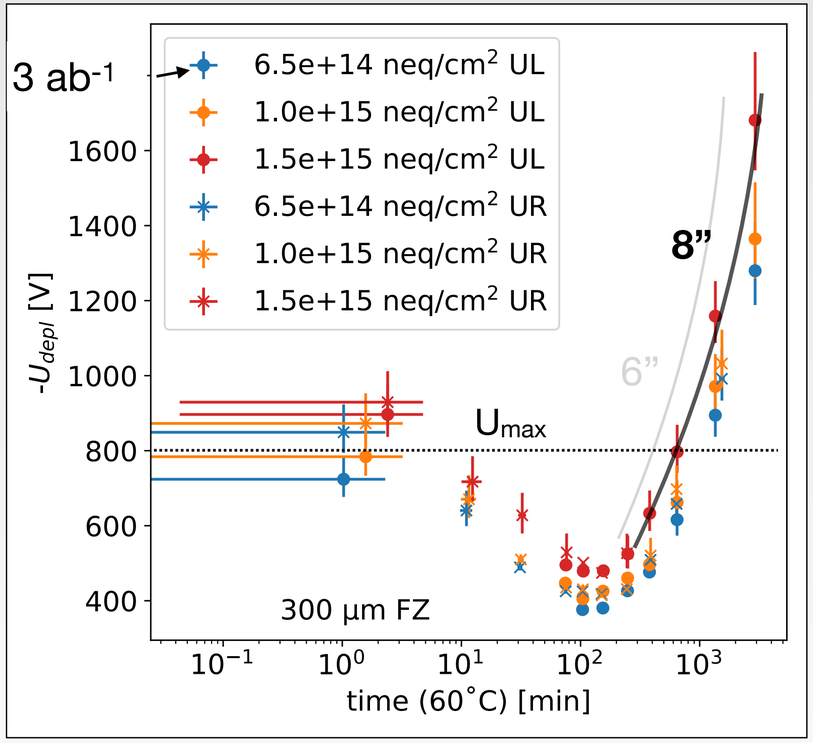
- Combined setup to measure charge collection, leakage current, and capacitance
- Enables precise and long-term annealing studies
- Irradiation of samples: JSI (well controlled environment)

Electrical Characteristics





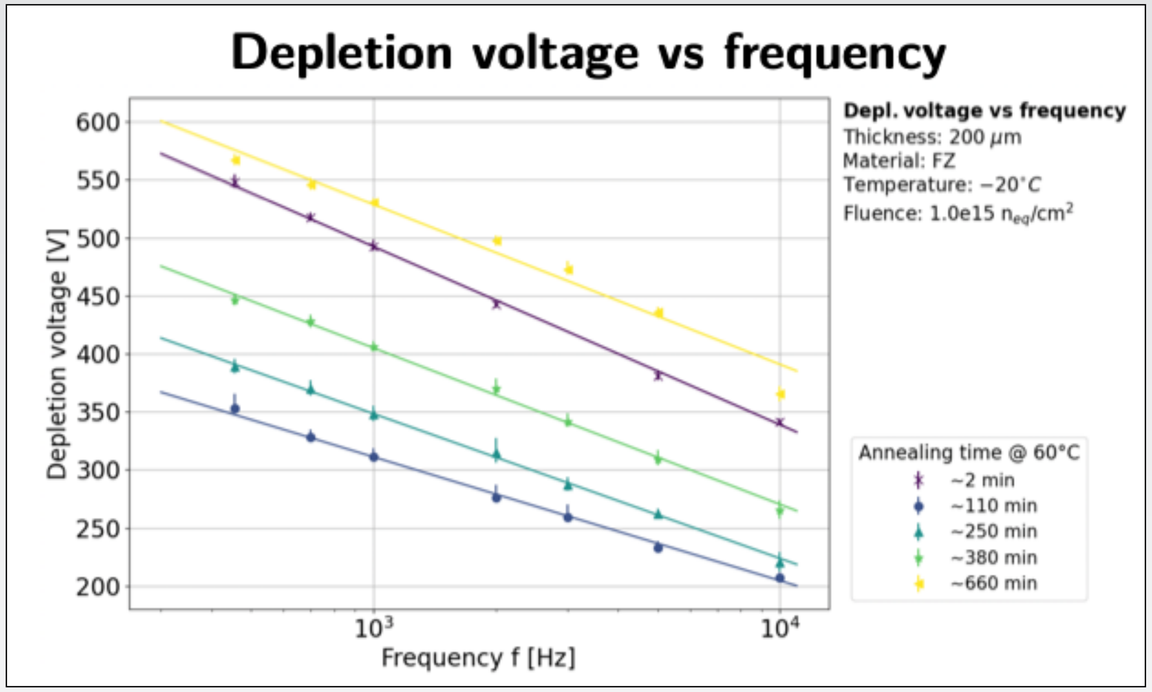


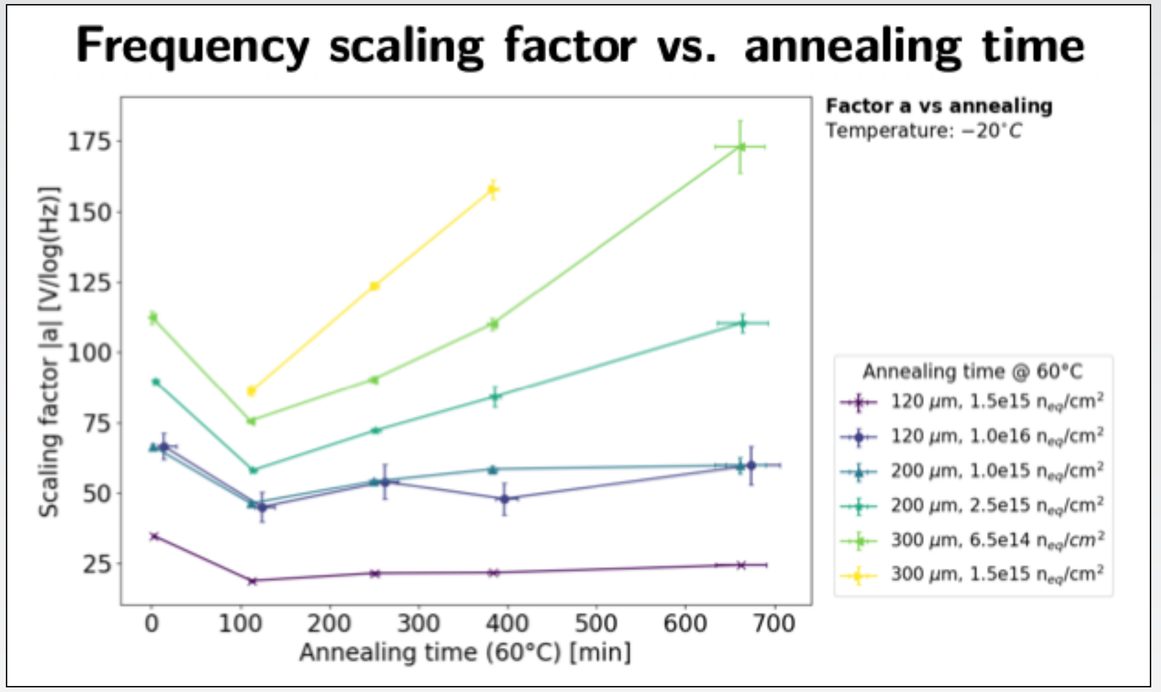


- The electrical capacitance can provide a handle to extract the depletion voltage
- Beneficial annealing dominates until approx. 100 minutes @ 60˚C

J.K. et al, arXiv:2211.04849, JINST

Frequency Dependence



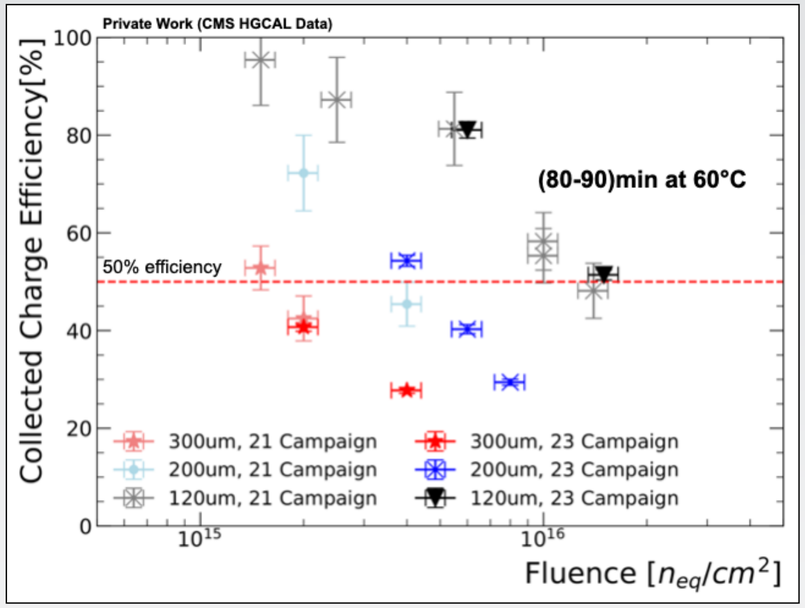


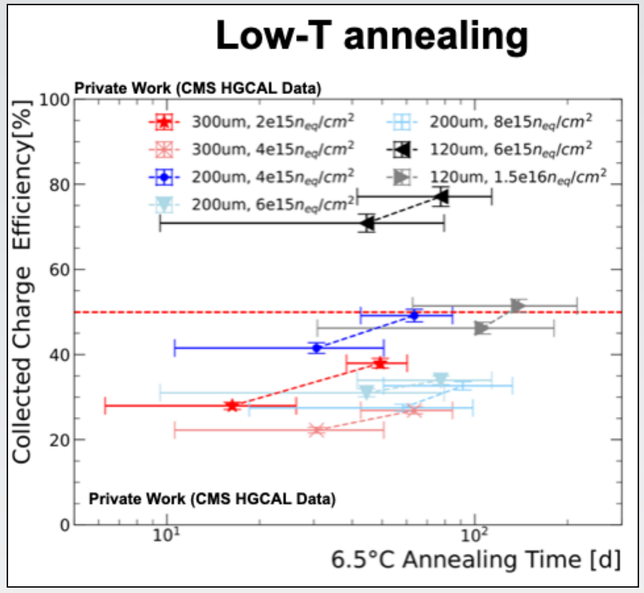
- Depletion voltage extracted from capacitance measurements depends on measurement frequency
- Higher fluencies and thicker sensors increase frequency dependence: there is no “good” frequency
- Frequency dependence also depends on annealing

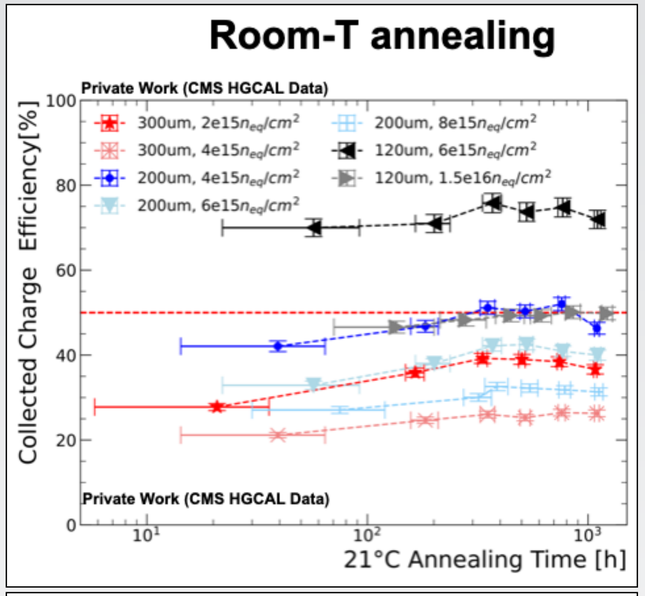
- Investigate collected charge instead

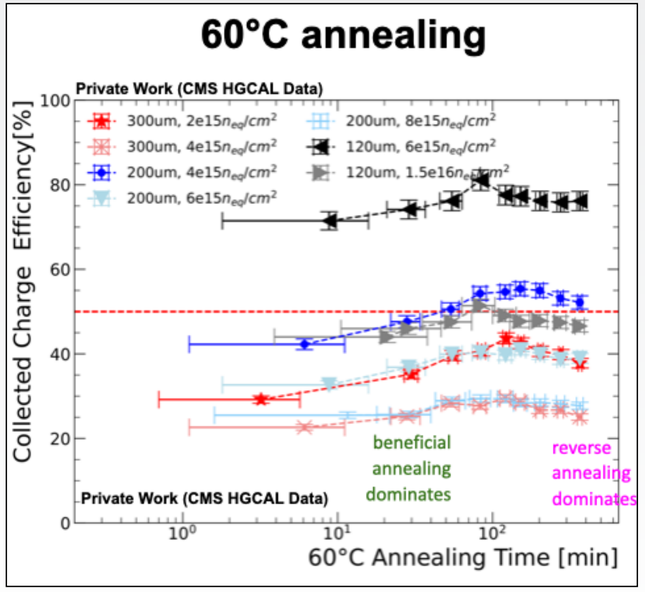
J.K. et al,
arXiv:2211.04849, JINST
L. Diehl,
https://indico.cern.ch/event/1270076/contributions/5450197/

Charge Collection Efficiency Annealing









- Thinner sensors are less affected by radiation (expected)
- Beneficial annealing visible at all temperatures
- Optimum similar for all sensors at 60˚C
- Goal: extract scaling behaviour as a function of temperature for extrapolation to HGCAL running conditions

O. Kaluzinska,
https://indico.cern.ch/event/1334364/contributions/5672066/
L. Diehl,
https://indico.cern.ch/event/1270076/contributions/5450197/

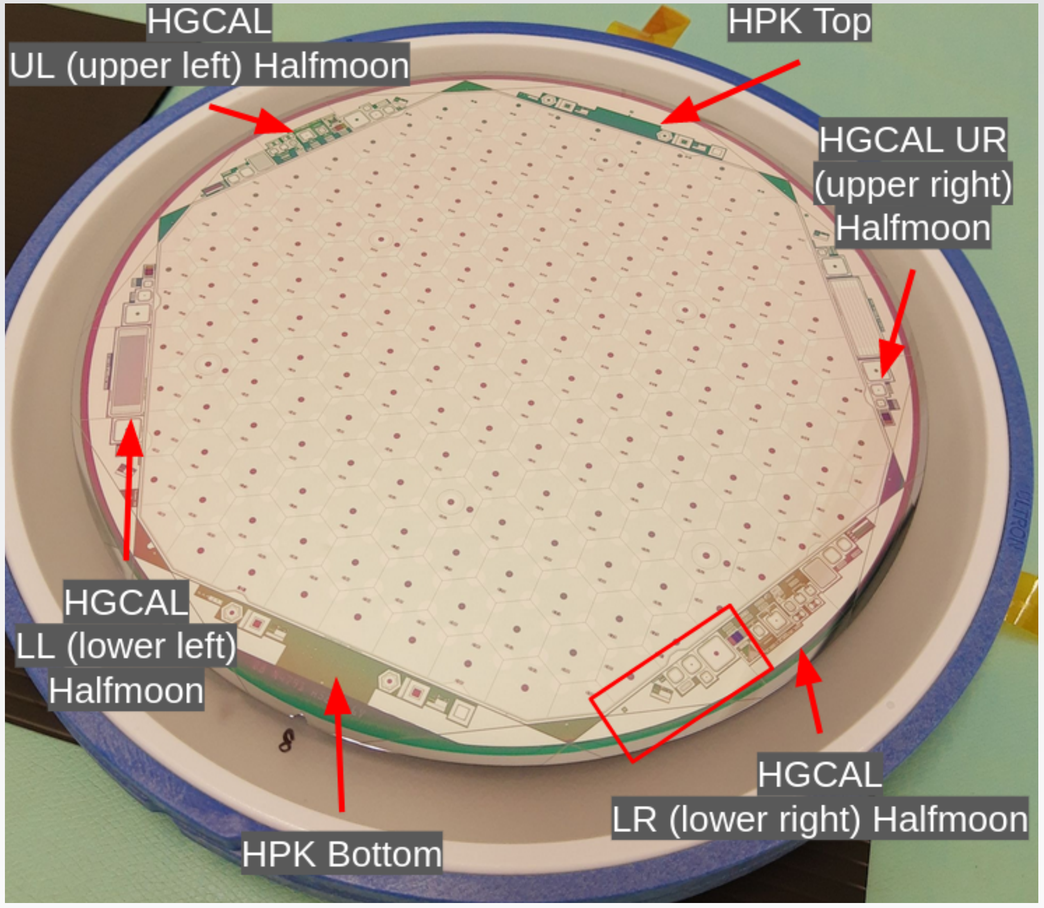
Summary

- A broad program of measurements to study the radiation hardness of the HGCAL silicon
  - Full sensors
  - Surface effects
  - Bulk properties

- First measurements with full and partial sensors up to 1.4 10^{16} n_{eq}/cm^2

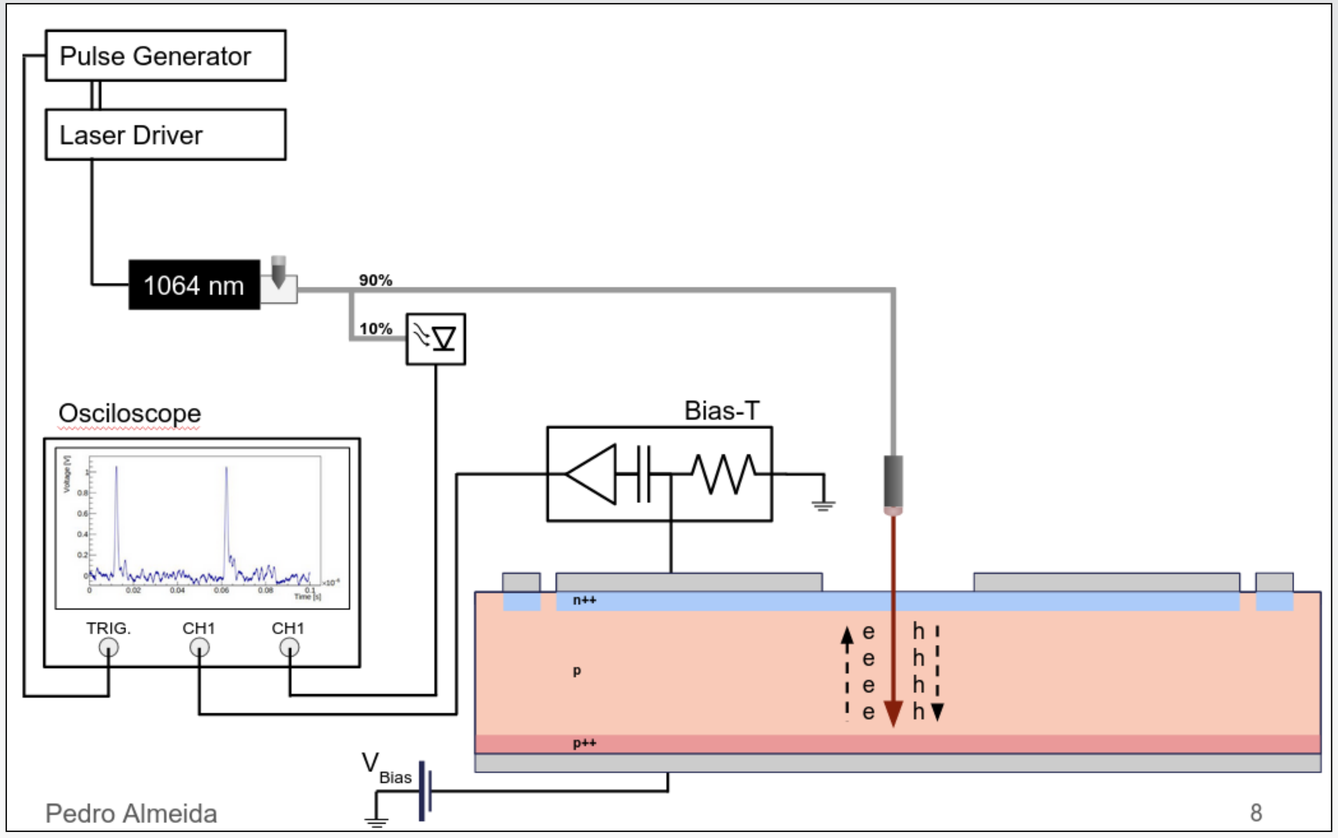
- Qualified surface damage in a reproducible manner

- Comprehensive studies of the bulk material in terms of electrical characteristics and charge collection also extending to different annealing temperatures



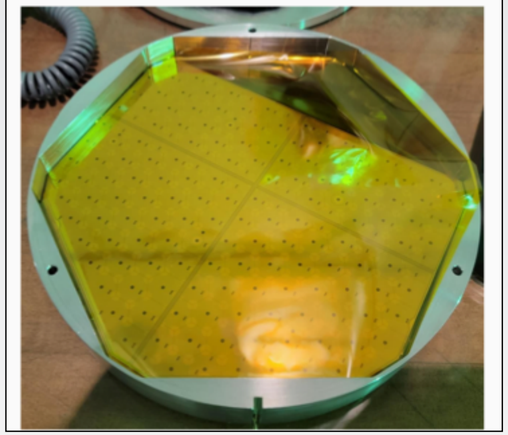
BACKUP

CCE measurement

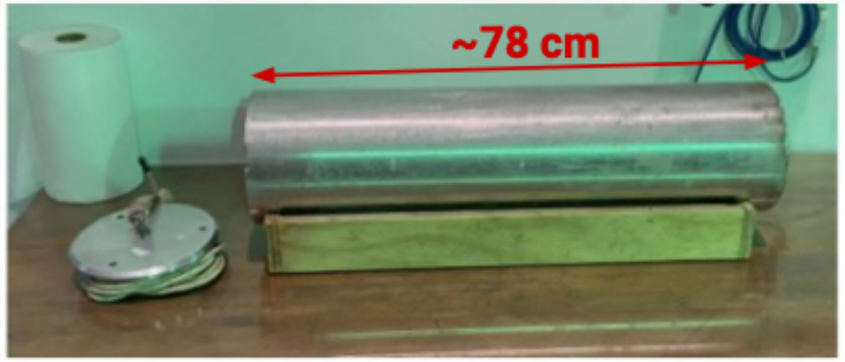


Full Sensor Irradiation Cooling

Sensor in a "hockey puck"

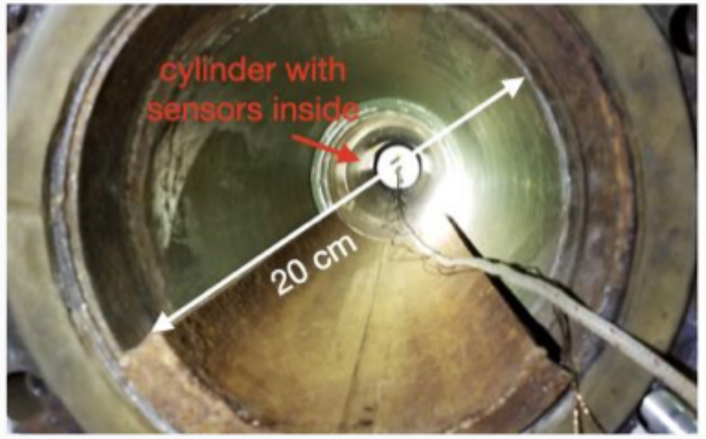


Cylinder



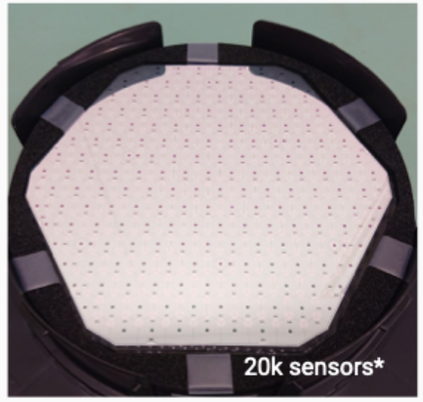
Dry ice for cooling of the cylinder

Cylinder in reactor beam port radial to reactor core

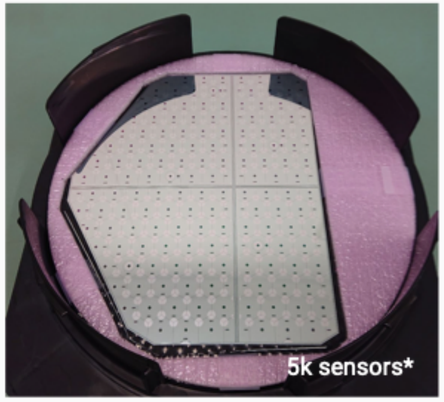


Wafer Types

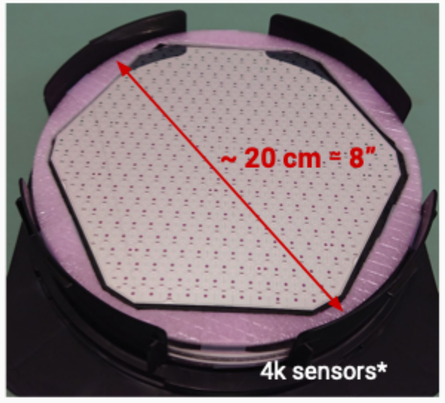
Low-Density sensor
~ 200 cells of 1.1 cm^2 size
300 µm & 200 µm active thickness



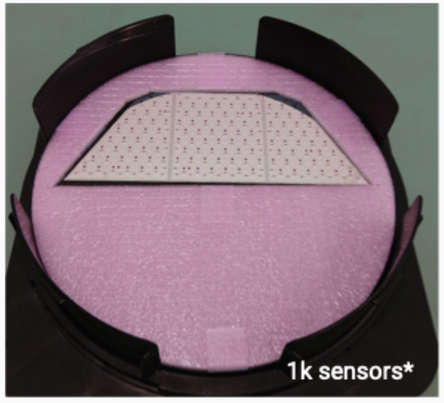
Low-Density "Partial sensor" example from "Multi-Geometry" sensor



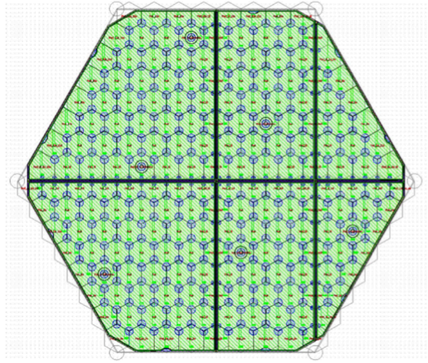
High-Density sensor
~ 450 cells of 0.5 cm^2 size
120 µm active thickness



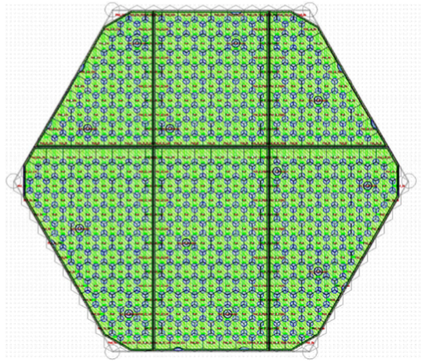
High-Density "Partial sensor" example from "Multi-Geometry" sensor



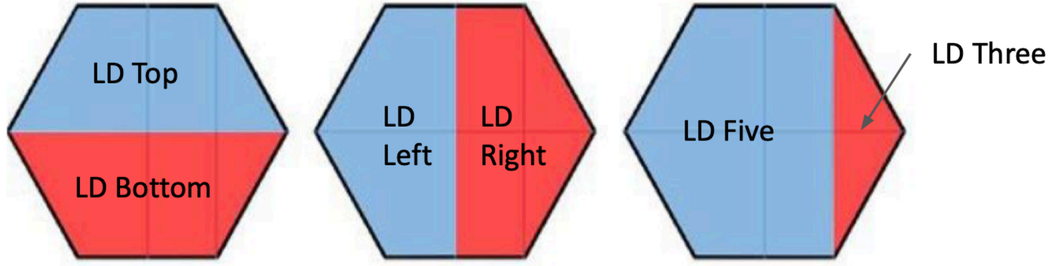
LD design



HD design



LD partial sensor cut types



HD partial sensor cut types