Silicon Sensor Characterization and Radiation Hardness Studies

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on behalf of the CMS Collaboration

CALICE Collaboration Meeting
September 27, 2023

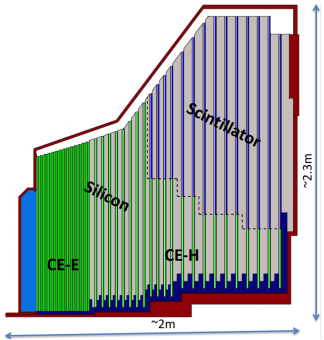
Outline

- Reminder of HGCAL
- Silicon Sensor Characterization: ARRAY-System
- HGCAL Silicon Sensor Status: Production
- Bulk Radiation Hardness Studies: Full Silicon Sensors and Test Structures

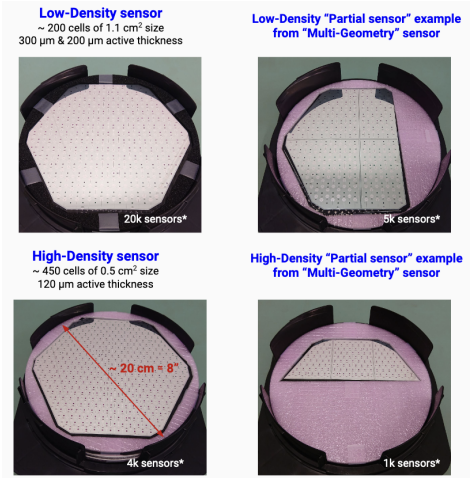
Reminder of HGCAL

- High Granularity Calorimeter (HGCAL) will replace the current CMS Endcap Calorimeter for the HL-LHC
- Silicon sensors will be used for the electromagnetic section and high radiation regions of the hadronic section
- ~620 m^2 silicon sensors produced on 8-inch wafers
- Three different thicknesses: 300 μm, 200 μm (Float zone) and 120 μm (Epitaxial)
- Fluences of up to 1e16 n_{eq}/cm^2

Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -35°C
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

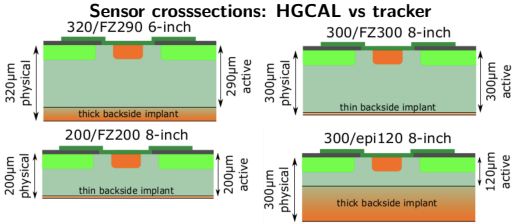


HGCAL: Silicon Sensors Reminder



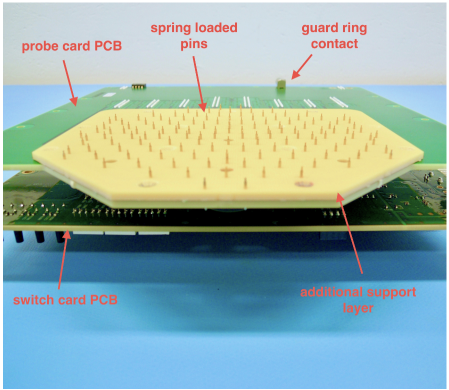
*needed in the final detector

- Silicon sensors produced by Hamamatsu (HPK)
- Hexagonal sensor geometry: Largest tile-able polygon
- Partial sensors to tile border regions
- Thickness and granularity adapted to expected fluence



ARRAY System: Motivation

- System needed for electrical sensor characterisation in prototyping phase and for quality control in mass production (IV, CV, V_{BD}, V_{FD}, C_{FD})
- Measurements with accuracy of O(100pA) and few pF for unirradiated samples, cell currents up to 10µA for irradiated sensors



- Need to bias all pads during testing
  → **Probe-card** based system
- System to switch between pads
  → **Switching matrix**
- Probe cards adaptable to sensor geometry
  → not limited to HGCAL
- Probe card in production for CALICE SiW-ECAL sensor layout

▸ ARRAY System Publication

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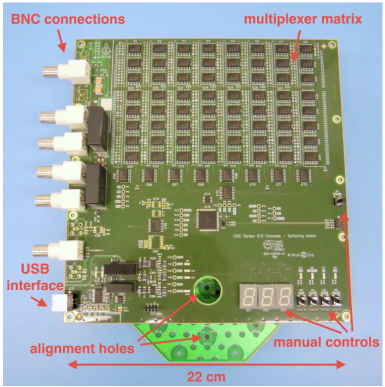

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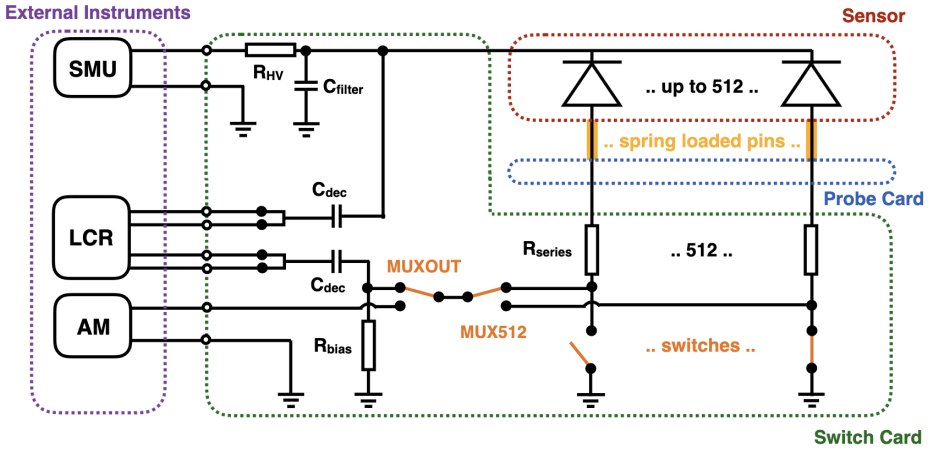
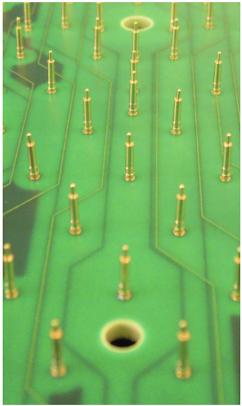
▸ ARRAY System Publication

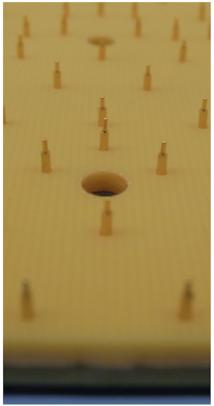
ARRAY System: Schematics

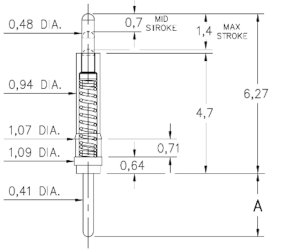
- Mother-daughter card system of switch card and probe card
  - Switch card: Large array of multiplexers that controls measurement
  - Probe card: Passive device, connects sensor using spring loaded pins



ARRAY System: Position Accuracy







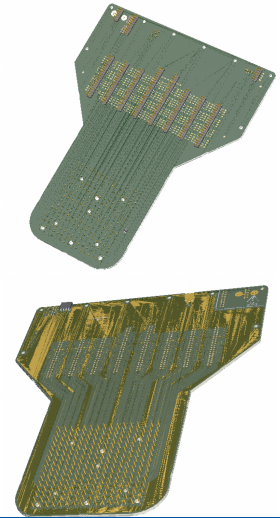
Unit=mm, A=3.81

- Spring loaded, gold plated pins with 1.4mm travel, 240µm radius at tip

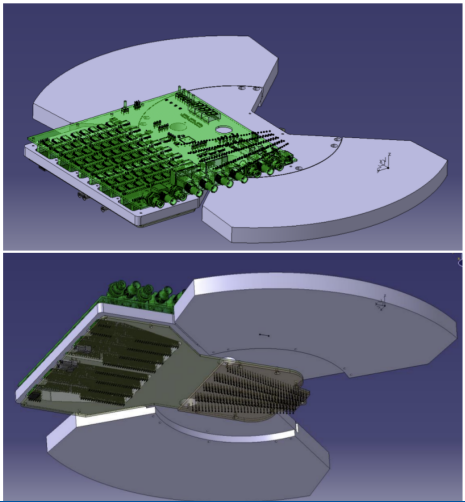
- Through-hole pins soldered into PCB by hand
- Yellow stiffener acts as jig keeping pins straight during assembly
- Precision good enough for contact pads of 1 mm

ARRAY System: ECAL Probe Card

New CALICE SiW-ECAL 6-inch 256-cell probe card

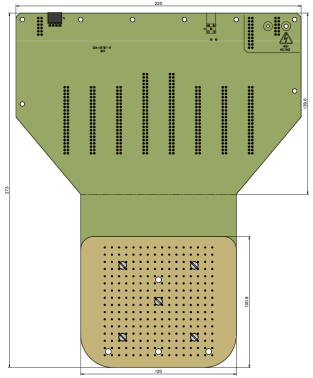


Lumical 6-inch 256-cell probe card inside PM5 probe station platen at Tel Aviv Univeristy



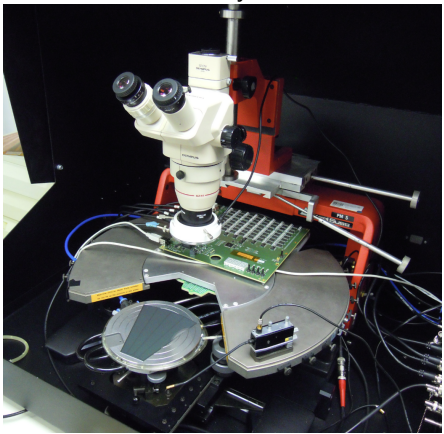
ARRAY System: ECAL Probe Card

CALICE SiW-ECAL probe card



- Probe card design finished summer 23
- Currently in production at CERN

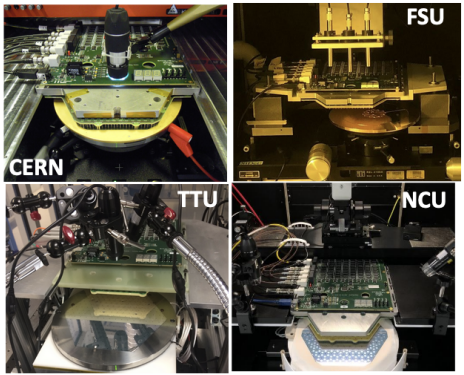
Tel Aviv University Probe Station



- Probe cards will be tested and used at Tel Aviv university and Valencia university

HGCAL Silicon Sensors: Status

- Production started for the full low density sensors
- Production Readiness Readiness review for full high-density and partial sensors next month
- Sensors measured at five sensor quality control sites (CERN, FSU, NCU, TTU, IHEP)
- Electrical characterization performed for 5% of all sensors in Production



Acceptance criteria

IV acceptance criteria

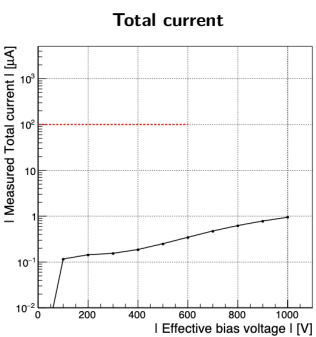
- Total current (over all cells and guard ring) at 600V below 100μA
- Total current not increasing by x2.5 from 600V to 800V
- Not more than 8 pads, or two neighbouring pads, with:
  - Pad current at 600V above 100nA or
    Pad current increasing by x2.5 from 600V to 800V if I600 > 10nA or
    Pad current above 25nA if I600V < 10nA

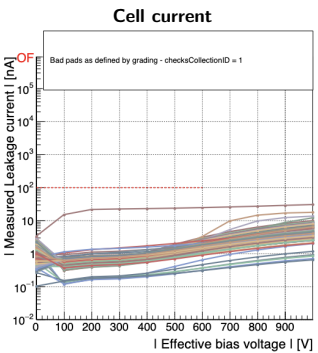
CV acceptance criteria

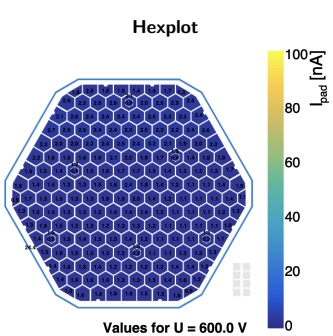
- Depletion voltage below a thickness-dependent limit (120μm: 70V, 200μm: 160V, 300μm: 370V)
- Depletion voltage spread within 10%
- Thickness variation below 10μm

HGCAL: Example IV Grading

- 300µm LD sensor from Pre-Series Shipments
- Passes all IV grading criteria for total current and per-pad current







Production: Status

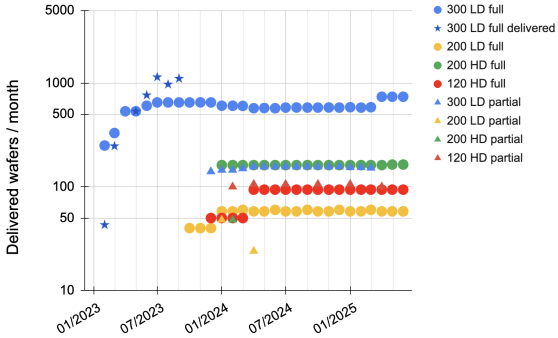
- Delivered Production Sensors: 300µm LD full sensors
- Status: Delivered by August 23, Tested before Sep 4 2023
- CMS-tested: No hard failures (= high absolute current, high # of bad cells)
- 4 HPK failed sensors 3 @ FSU, 1 @ TTU

		HGCAL SQC-sites				
	HPK	CERN	FSU	NCU	TTU	CMS Total
Delivered	-	333	615	73	566	**1587**
Next deliveries	-	~650	25	1142	948	**~2765**
Tested sensors	824	24	46	0*	33(3)	**103**
Tested batches	15	1	18	-	10	**29/67**
Failed sensors	4	0	0	-	1	**1/103**
I_{tot}(800 V) > 2.5*I_{tot}(600 V)	4	-	-	-	1	**1/103**
Yield [%]	99.5	100	100	-	97.0	**99.0**

Parenthesis: Accepted after remeasurement
* NCU probe station commission in progress

Quality Control: Progress and Plans

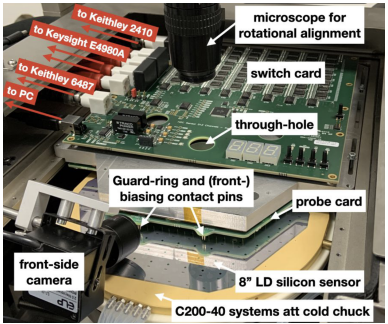
- Start with 300µm sensors, as highest number of sensors is needed
- HPK delivery started slow, but they catched up with large deliveries now
- 1 more month to QC the pre-production

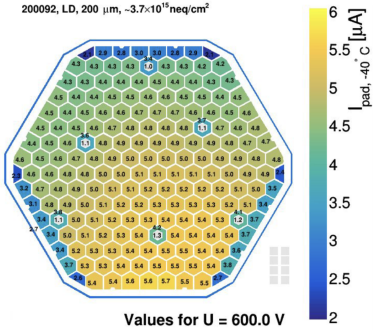


- Remaining 95% (24726 sensors) sampled with 5% rate - 1236 tested sensors, 2/day at 3 sites = 206 days = 42 weeks
- 11 FTE months required for 21 remaining months of deliveries

Radiation Hardness Studies: Full Sensors

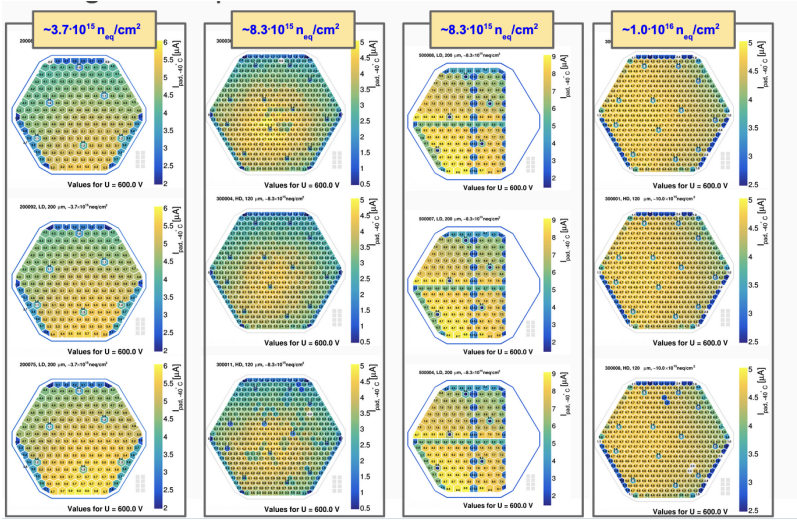
- Sensors irradiated at Rhode Island Nuclear Science Centre (RINSC), US
- Temperature-controlled chuck, enables measurements at -40°C as well as annealing at elevated temperatures
- Measurement of IV and CV of each individual cell along with total current measurements
- Example: IV measurement of a Low Density 200µm sensor irradiated to 3.7e15 n_{eq}/cm^2





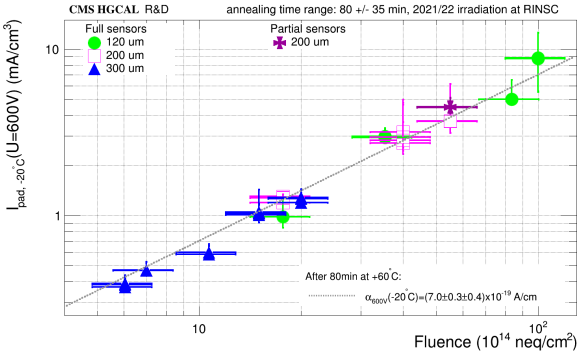
▸ Qualification of RINSC for HGCAL

Radiation Hardness Studies: Full Sensor Leakage Current



- Observed $(18 \pm 6)\%$ variation in per-cell leakage current across main sensor
- Consistent profiles between sensors irradiated together in same irradiation round
- Hypothesis: Fluence profile within the beam port

Radiation Hardness Studies: Full Sensor Damage Rate



- Use 3 neighboring full cells in the current (fluence) maximum within a sensor to estimated current related damage rate
- Compatible results using the total current

$$\frac{I}{V} = \alpha \cdot \Phi$$

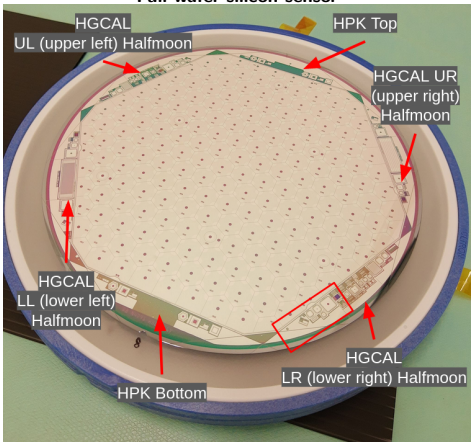
Extracted damage rate:

$$\alpha_{600\mathrm{V}}(20^\circ C) = (7.0 \pm 0.3(\mathrm{fluence, annealing}) \pm 0.4(\mathrm{chuck\ temperature\ variation}))\mathrm{A/cm}^2$$

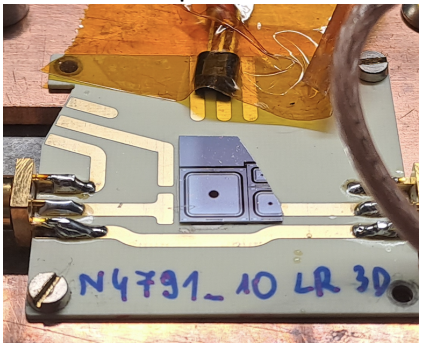
Silicon Test Structures: Diode Measurements

- Hexagonal sensor from circular wafer
- Remaining space used for small sized test structures, e.g. diodes
- Diodes are glued and wirebonded to a PCB for characterization, connectable via SMA

Full wafer silicon sensor

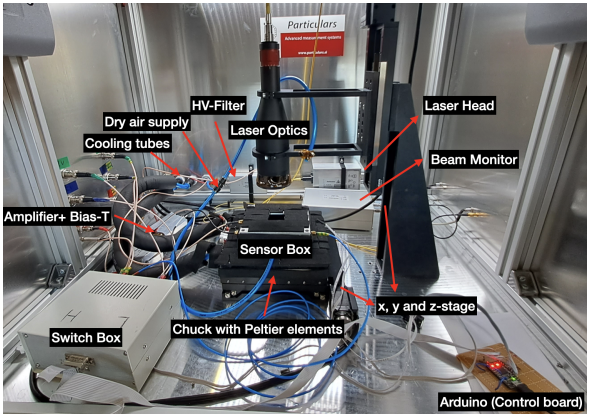


Sample on PCB

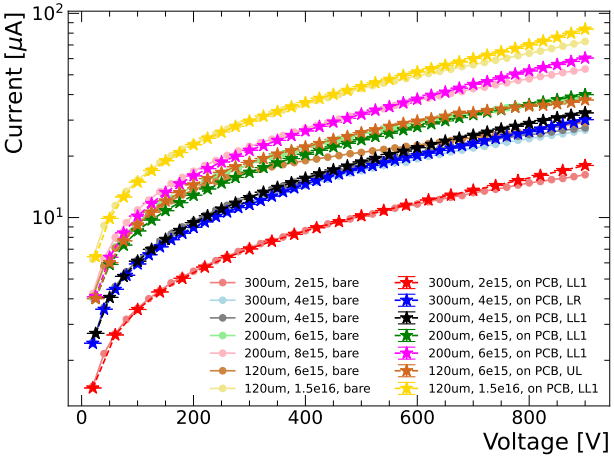


Radiation Hardness Studies: Measurement Setup

- New characterization setup built and commissioned
- Temperature: -20°C, PCB placed on a cooled copper holder inside an enclosed box
- IV, CV and Transient Current Technique (TCT) measurements (1064nm laser)
- Laser calibrated to 40MIP equivalent using unirradiated 300µm sample

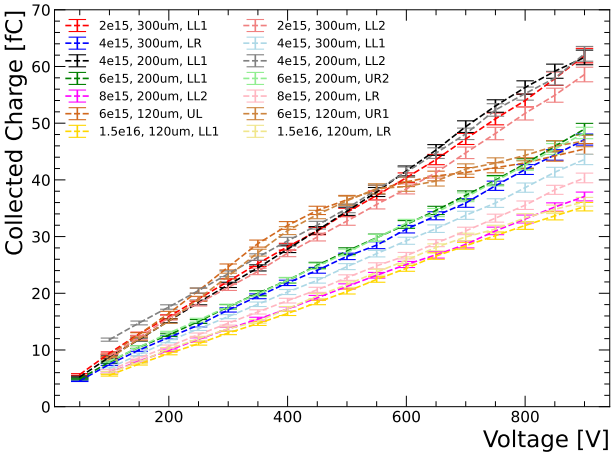


Radiation Hardness Studies: Diodes Leakage Current



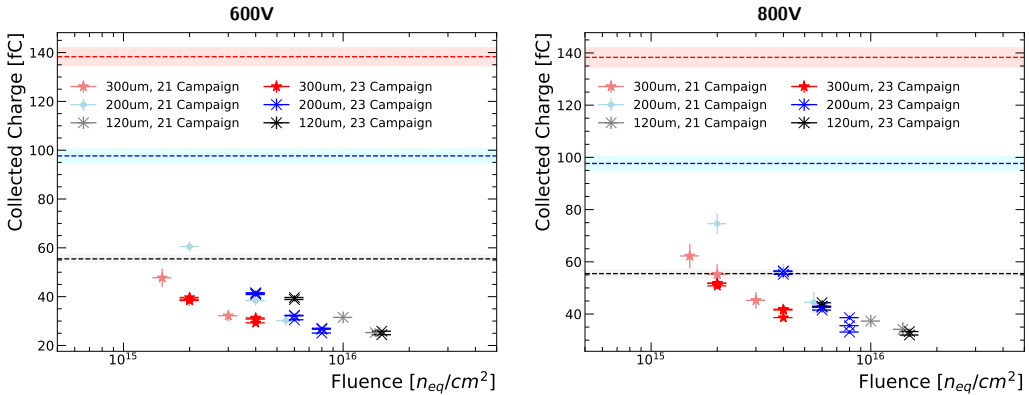
- Increase of leakage current with fluence
- Strong temperature dependence of current: IV measurements were used to tune and qualify the true temperature of the sensors in the new setup by comparison with bare measurements in an established setup

Radiation Hardness Studies: Collected Charge



- 2 samples per fluence: Consistent results
- Constant increase of charge with voltage: Saturation only for 120µm sensor irradiated to 6e15
- Sensors will be used for annealing study: Room temperature and 60°C annealing

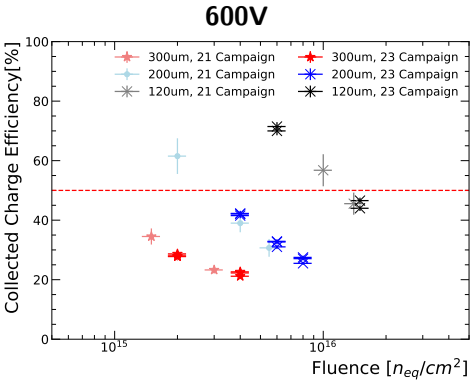
Radiation Hardness Studies: Collected Charge



Dotted lines: Collected charge measured in unirradiated sensors of the three thicknesses

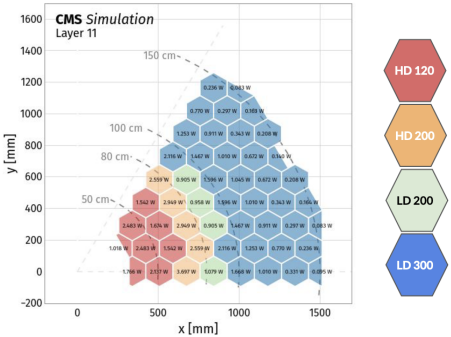
- Decrease of charge with fluence, consistent results from two irradiation campaigns
- Thinner sensors have better radiation hardness

Radiation Hardness Studies: Charge Collection Efficiency



- Layout optimization ongoing: More 200µm and 300µm sensors?
- Possibility of High Density 200µm sensors

- Before beneficial annealing: 50% efficiency at 600V still up to 3e15 n_{eq}/cm^2 for 200µm and up to 1.2e16n_{eq}/cm^2 for 120µm



Conclusions

- HGCAL entered the production phase for LD sensors (upcoming PRR for HD and partial sensors) and will perform quality assurance at five different institutes
- Adaptable switch- and probe card system allows for electrical characterization of individual cells for various sensor types
- New probe card soon to be delivered for CALICE SiW-ECAL
- Radiation hardness studies suggest that silicon sensors in HGCAL will survive and perform well until the end of HL-LHC
- New irradiated test structure results help to evaluate the optimization of the layout and positioning of the different thicknesses in the final detector