Radiation tolerance study using 8-inch full-wafer silicon sensors for CMS HGCAL

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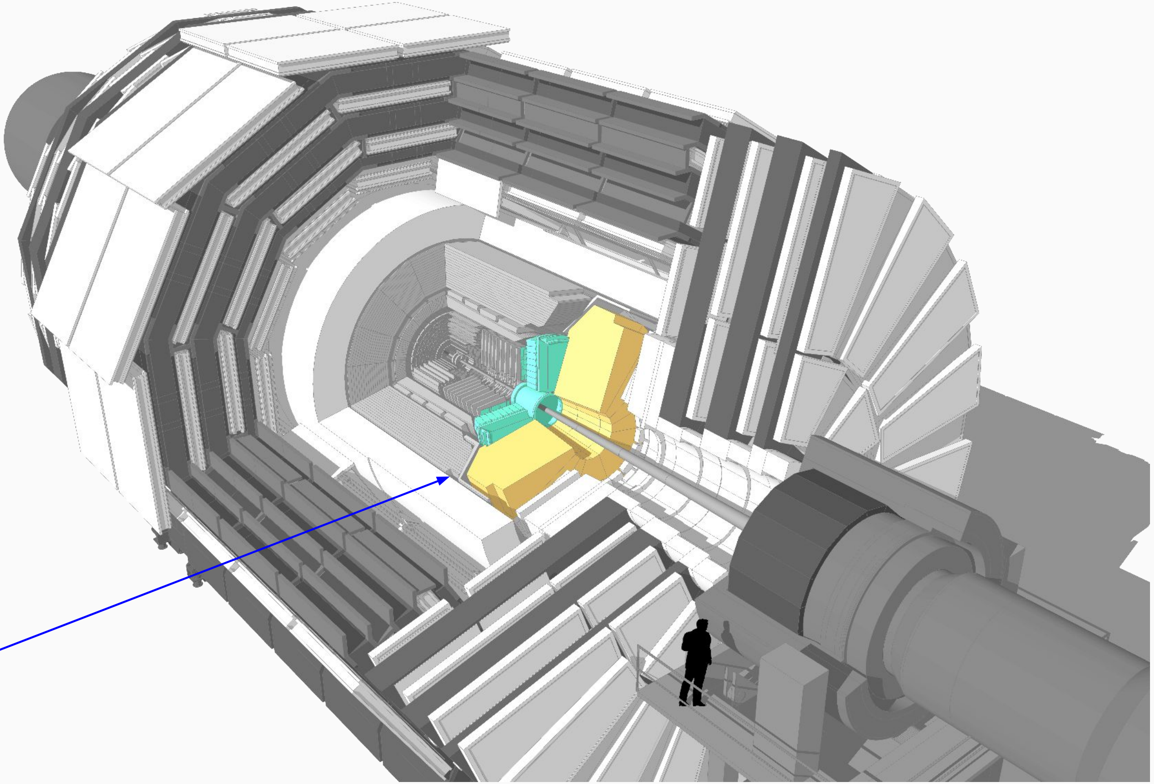
on behalf of the CMS collaboration

18th Trento Workshop on Advanced Silicon Radiation Detectors

Trento, Italy - February 28, 2023

CMS upgrade for HL-LHC



CMS experiment as of today

Tracker:
Radiation tolerant, high granularity, less material, tracks in hardware trigger (L1), coverage up to $|\eta| = 3.8$

Timing layer:
MIP timing to 30 - 60 ps, coverage up to $|\eta| = 3.0$

Calorimeter endcaps:
Coverage $1.5 < |\eta| < 3.0$, 620 m^2 of silicon sensors, radiation tolerant, high granularity, precise hit/cluster timing

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

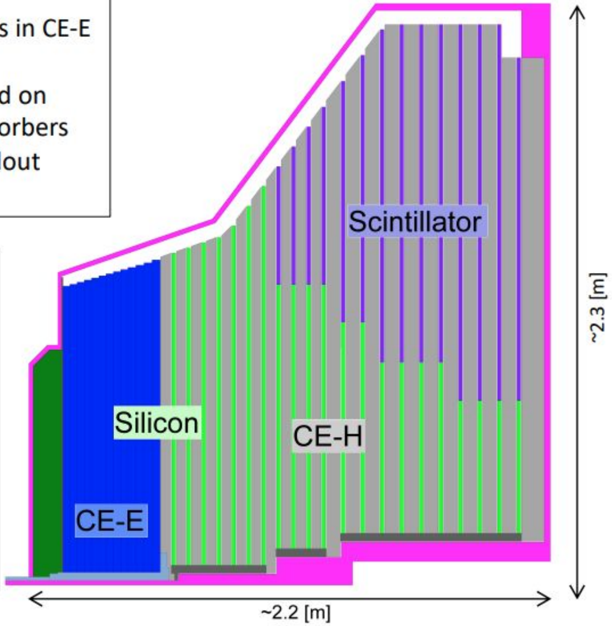
Muon system:
New electronics
GEM/RPC coverage in $1.5 < |\eta| < 2.4$, investigate Muon tagging at higher η

Calorimeter Endcap: a.k.a. HGCAL

Main parameters:

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap



Electromagnetic calorimeter (**CE-E**): Si, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Project scale and challenges:

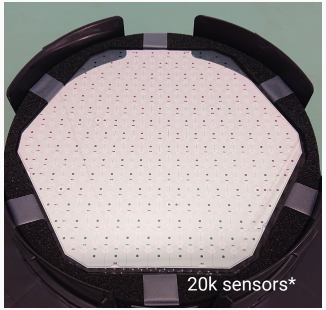
- By far largest approved project based on silicon sensors in HEP
  - → 3x area of ATLAS/CMS trackers
- First imaging calorimeter in collider experiment
  - → Pave the way for future collider detectors
- First application of 8" sensors in a detector
  - → Cost optimization
  - → Very large and fragile objects
  - → Develop novel production process together with industrial suppliers
  - → Radiation hardness qualification
  - → Needed novel irradiation facilities

620 m^2 of 8-inch silicon sensors

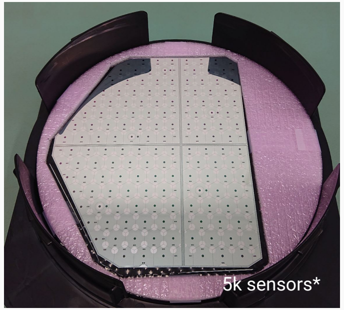
Low-Density sensor

~ 200 cells of 1.1 cm^2 size

300 µm & 200 µm active thickness



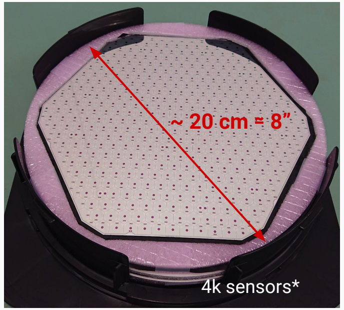
Low-Density "Partial sensor" example from "Multi-Geometry" sensor



High-Density sensor

~ 450 cells of 0.5 cm^2 size

120 µm active thickness



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

- Used for CE-E and high-radiation regions in CE-H
  - Thickness and granularity adapted to radiation field
- Hexagonal silicon sensor geometry
  - Largest regular tiling polygon
  - Maximise wafer usage
  - "Partial" sensors to tile border regions
- 8-inch wafers
  - Reduces number of modules w.r.t. 6-inch wafers
  - New production process and radiation-hardness qualification
- Planar, DC-coupled, p-type sensor cells
  - p-type more radiation tolerant than n-type sensors
- Sensor producer: Hamamatsu Photonics K. K. (HPK)

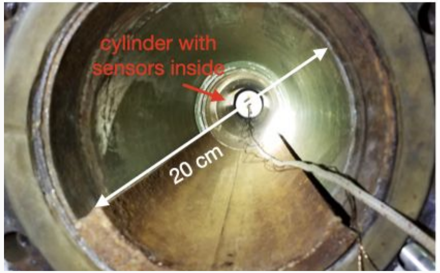
* needed in the final detector

RINSC large-area neutron irradiation facility

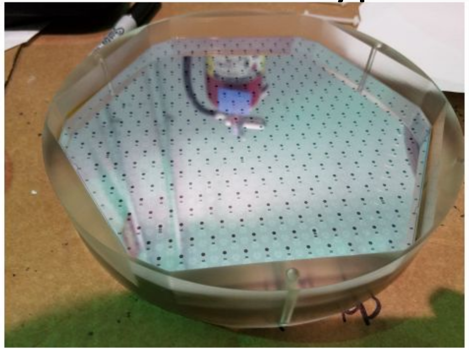
- Neutron irradiation facility Rhode Island Nuclear Science Centre (RINSC), US
  - First time qualification of RINSC for HGCAL
  - 2 MW, light-water cooled, pool-type reactor
  - Only irradiation facility able to host 8-inch wafers
- Neutron irradiation of HGCAL sensors in reactor beam port
  - Up to four HGCAL 8-inch sensors stacked in so-called “hockey puck“
  - Puck material: wood, aluminum, acrylic, PEEK (polymer used in engineering applications)
  - Puck inserted into aluminium cylinder
  - Cylinder inserted into beam port
- Description in Neutron Irradiation and Electrical Characterisation of the Silicon Sensors
  - Paper accepted for publication at JINST

RINSC reactor details

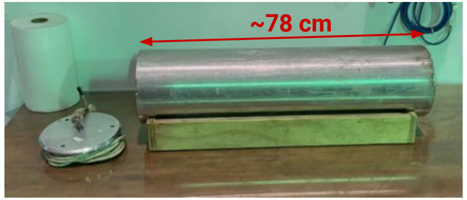
Cylinder in reactor beam port radial to reactor core



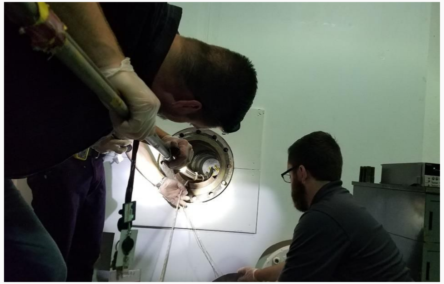
Sensor in a “hockey puck”



Cylinder



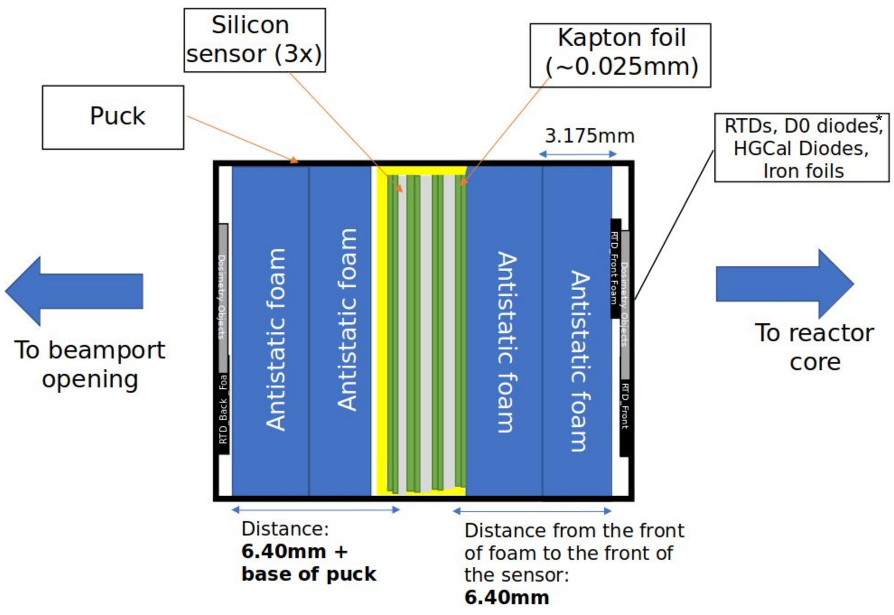
Dry ice for cooling of the cylinder



RINSC irradiations for HGCAL since 2020

- Extensive experience irradiating HGCAL prototype variants with different thicknesses, granularities, p-stops, oxides and sensor geometries
- Target fluences in range 10^{14} to 1.4×10^{16} n_{eq}/cm^2
- Steering of fluence delivery
  - Assuming constant reactor power,
    fluence scales linearly with irradiation time
  - Fluence monitored using
    silicon diodes and iron foils, located in front and back of the hockey puck
- 25 irradiation rounds performed for HGCAL with 3 to 4 sensors per round each
- Radiation campaign still ongoing, currently focussing on high fluences

Puck layer structure

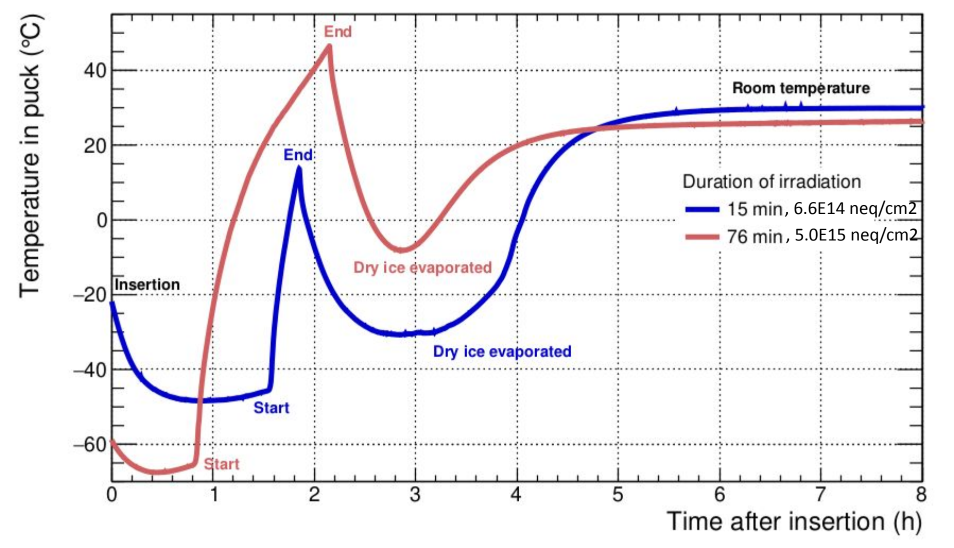


*silicon diodes, which were studied for usage in the D0 experiment

Neutron Irradiation and Electrical Characterisation of the First 8" Silicon Pad Sensor Prototypes for the CMS Calorimeter Endcap Upgrade

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

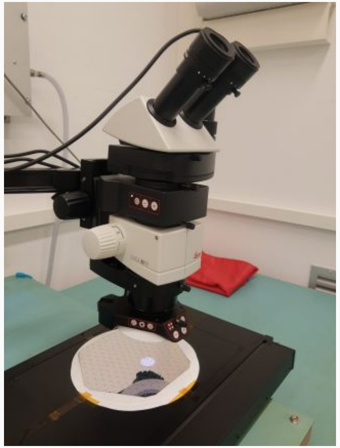


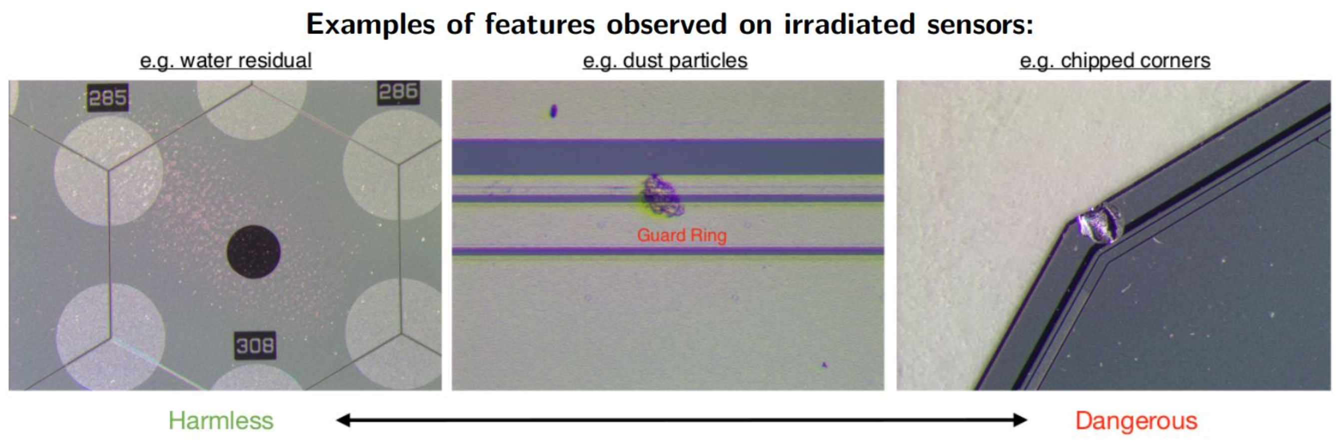
- Early high-fluence irradiation rounds brought sensors into regime where reverse annealing already dominated
- Counter measures implemented
  - Improved thermal conductivity of puck (optimised material, added ventilation holes)
  - Cooling of cylinder before irradiation
  - Splitting of high-fluence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

Neutron Irradiation and Electrical Characterisation of the First 8" Silicon Pad Sensor Prototypes for the CMS Calorimeter Endcap Upgrade

Visual inspection prior to post-irradiation IV+CV measurements

- Fully automated inspection of the whole sensor with the use of Machine Learning
- Identification of mechanical defects
- Removal of dust
- Focus on guard ring area where bias voltage and ground are close together





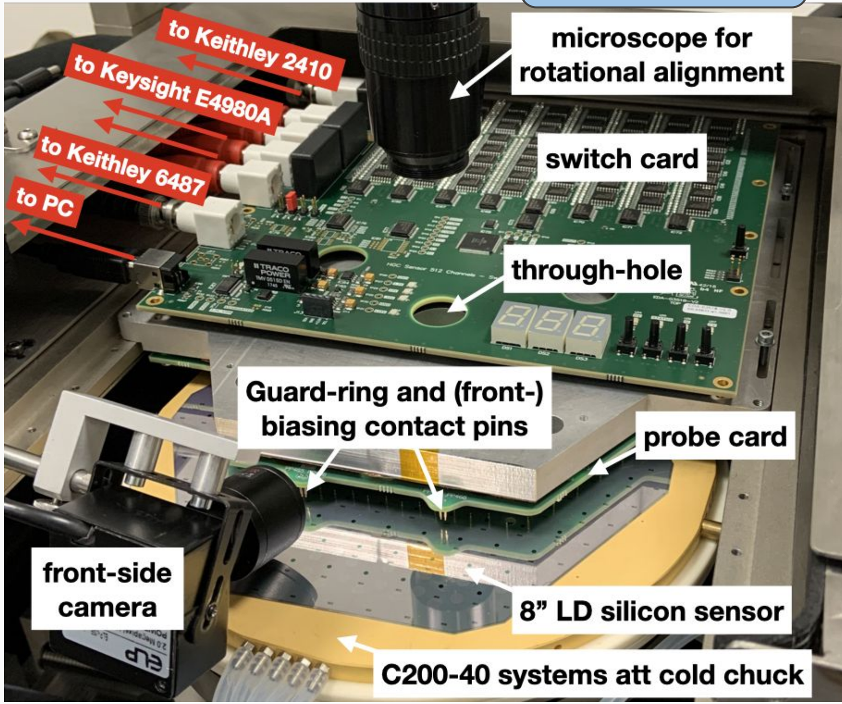
Anomaly detection for the quality control of silicon sensor wafers for the CMS HGCAL upgrade

Electrical characterization at CERN

ARRAY system

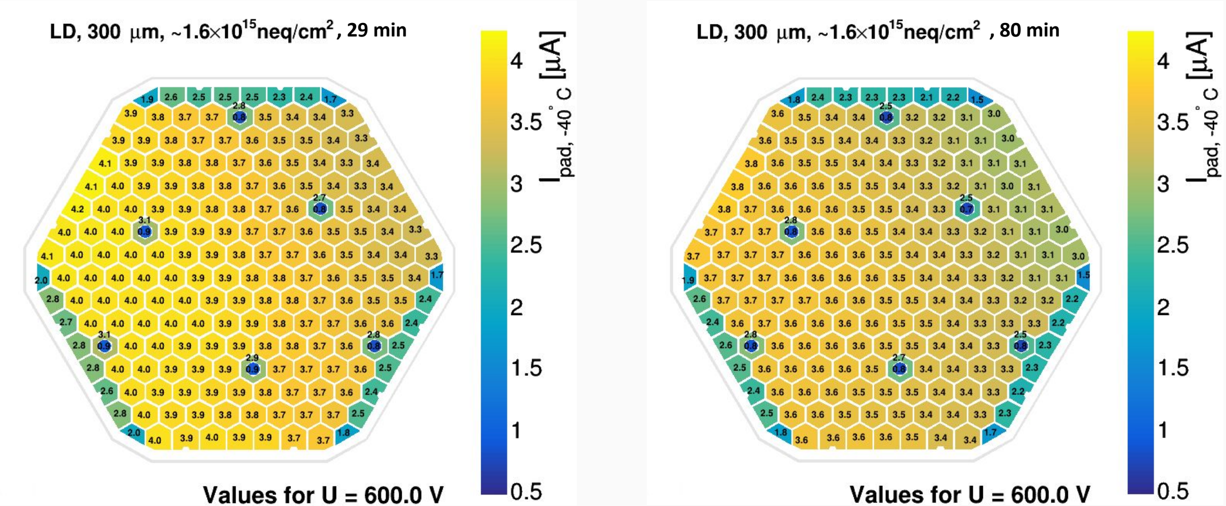
Annealing study

- Full sensor probe card and switch card system “ARRAY”
- Simultaneously contact and bias all pads in a sensor
- Perform per-cell IV and CV of all cells
- Temperature-controlled chuck, enables measurements at -40°C
    - ○ Temperature stable with time, less than 0.5°C inhomogeneity across the chuck at -40°C
- Heating of chuck to perform annealing studies
    - ○ Study IV and CV while warming samples up to total equivalent of ~80min@60°C



IV leakage current measurement

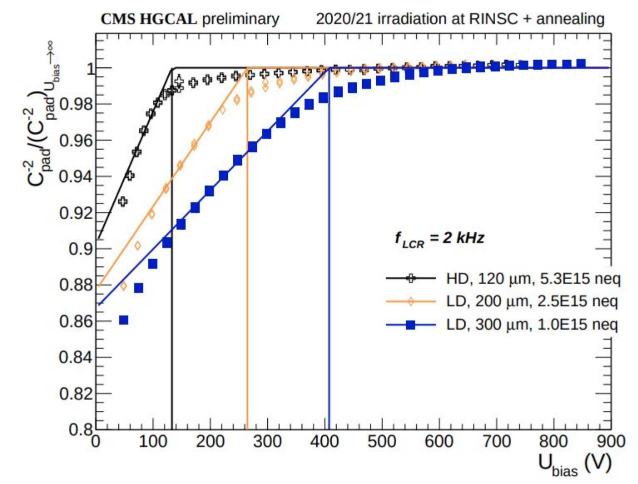
Per-cell leakage current before and after additional annealing

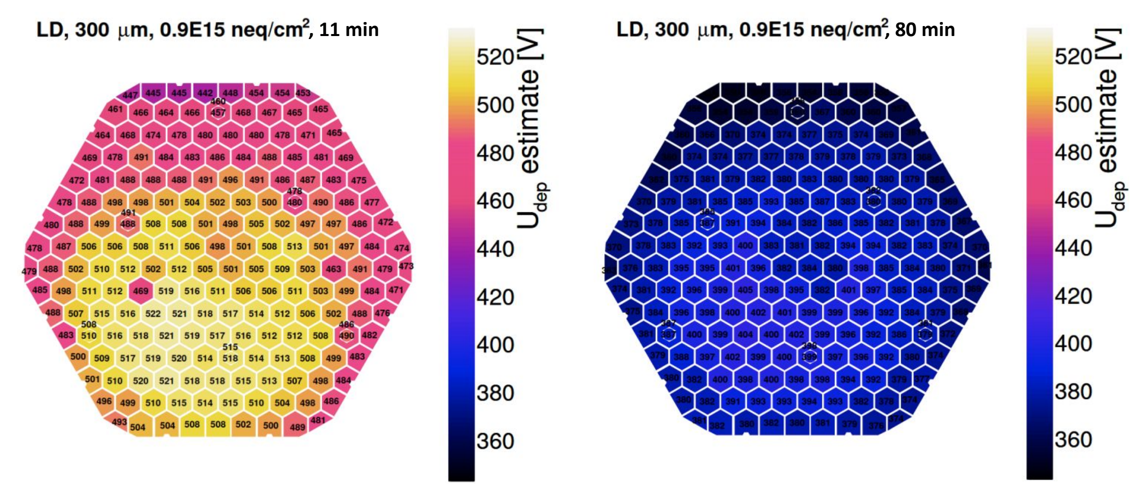


- I_{pad} reduces with additional annealing, as expected.
- (18±6)% variation in per-cell leakage current visible across sensors, consistent profiles between sensors irradiated together in same irradiation round.
  → Hypothesis: Fluence profile
- I_{pad} mostly scales with cell size and delivered fluence, as expected.

Depletion voltage vs. annealing time

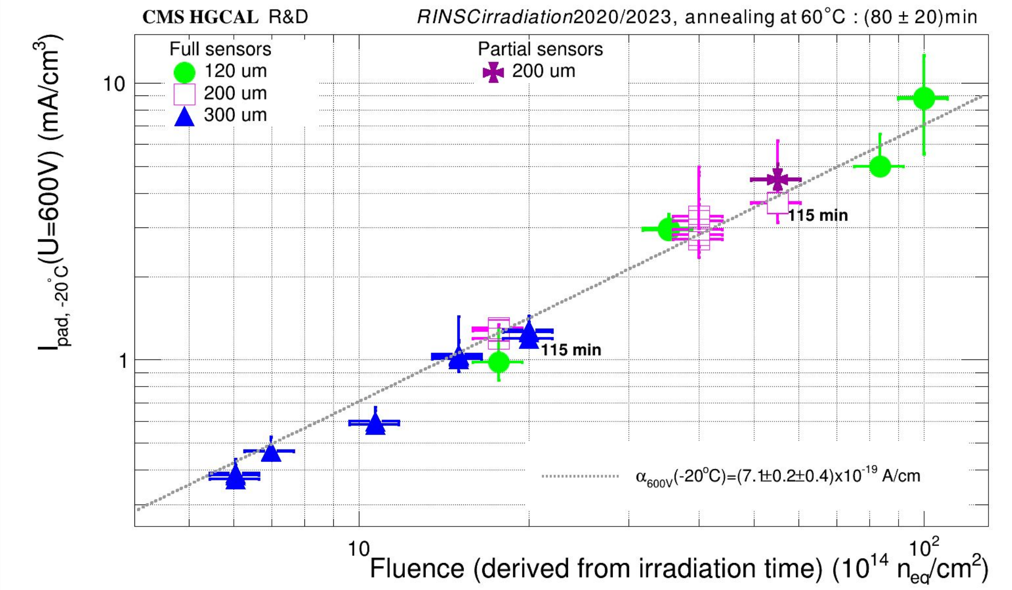
- Calculate in-reactor annealing time based on RINSC temperature readings
- Anneal in steps of time up to total equivalent of ~80min@60°C
- Perform IV+CV measurements between annealing steps
- Depletion voltage estimation based on squared-inverse of open-corrected serial capacitance
- Observation: Additional annealing up to 80min@60°C lowers the depletion voltage, as expected.
- Validation of good understanding of RINSC in-reactor annealing





Per-cell depletion voltage before and after additional annealing

Current related damage rate



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

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

Damage rates agree between [RINSC and established reference JSI]

- $\alpha_{-20^\circ C}$ = (6.9 ± 0.1(fluence, annealing) ± 0.4(chuck temperature variation))$\cdot 10^{-19}$ A/cm for full sensors (RINSC)
- $\alpha_{-20^\circ C}$ = (6.8 ± 0.1(uncorrelated)± 0.7(correlated))$\cdot 10^{-19}$ A/cm for diodes (JSI)

Summary

- CMS will replace its current endcap calorimeters with the HGCAL (High Granularity Calorimeter) for operations at the HL-LHC
- Silicon sensors made from 8-inch wafers will cover an area of over 620m^2
- 8-inch prototype silicon wafers were irradiated at a novel irradiation facility RINSC and they were electrically characterised for the first time
- In-reactor annealing at RINSC under control and monitored
- Fluence variation across 8-inch sensor in the order of (18±6)%
- Current related damage rate (after 80min@60°C annealing):
  - $\alpha_{-20°C} = (6.9 \pm 0.1(\text{fluence, annealing}) \pm 0.4(\text{chuck temperature variation}))\cdot 10^{-19}$ A/cm
  - Compatible with reference measurement using single diodes at JSI Ljubljana

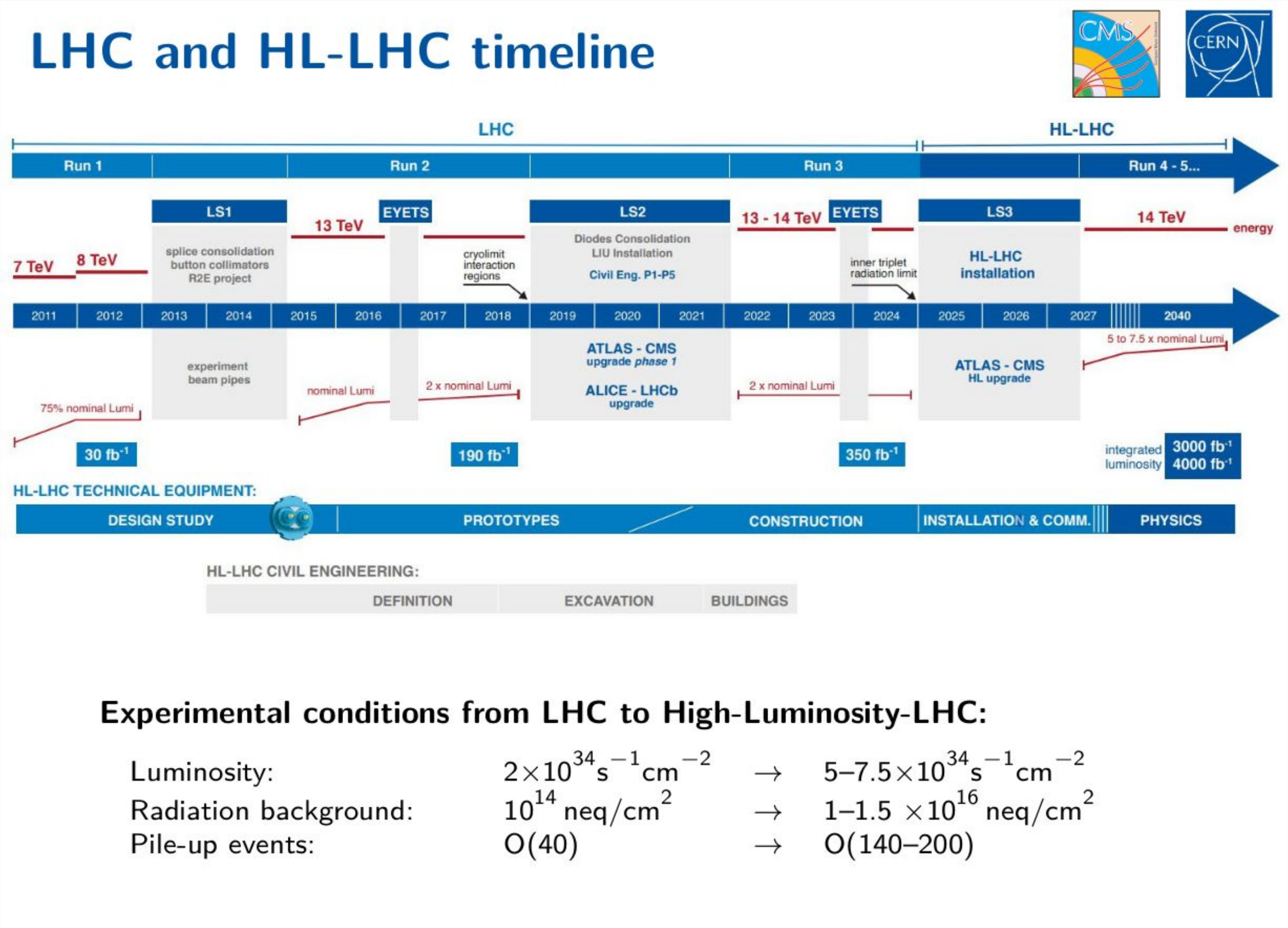
- Validation of both bulk radiation hardness of 8-inch prototype sensors and RINSC as irradiation facility

Acknowledgements

We thank the Brown University (Providence, Rhode Island, US) group, in particular Nick Hinton for irradiating the samples at RINSC and for providing detailed temperature and fluence measurements during irradiation.

We also thank the staff at the Rhode Island Nuclear Science Center for their support and guidance during these studies.

Backup

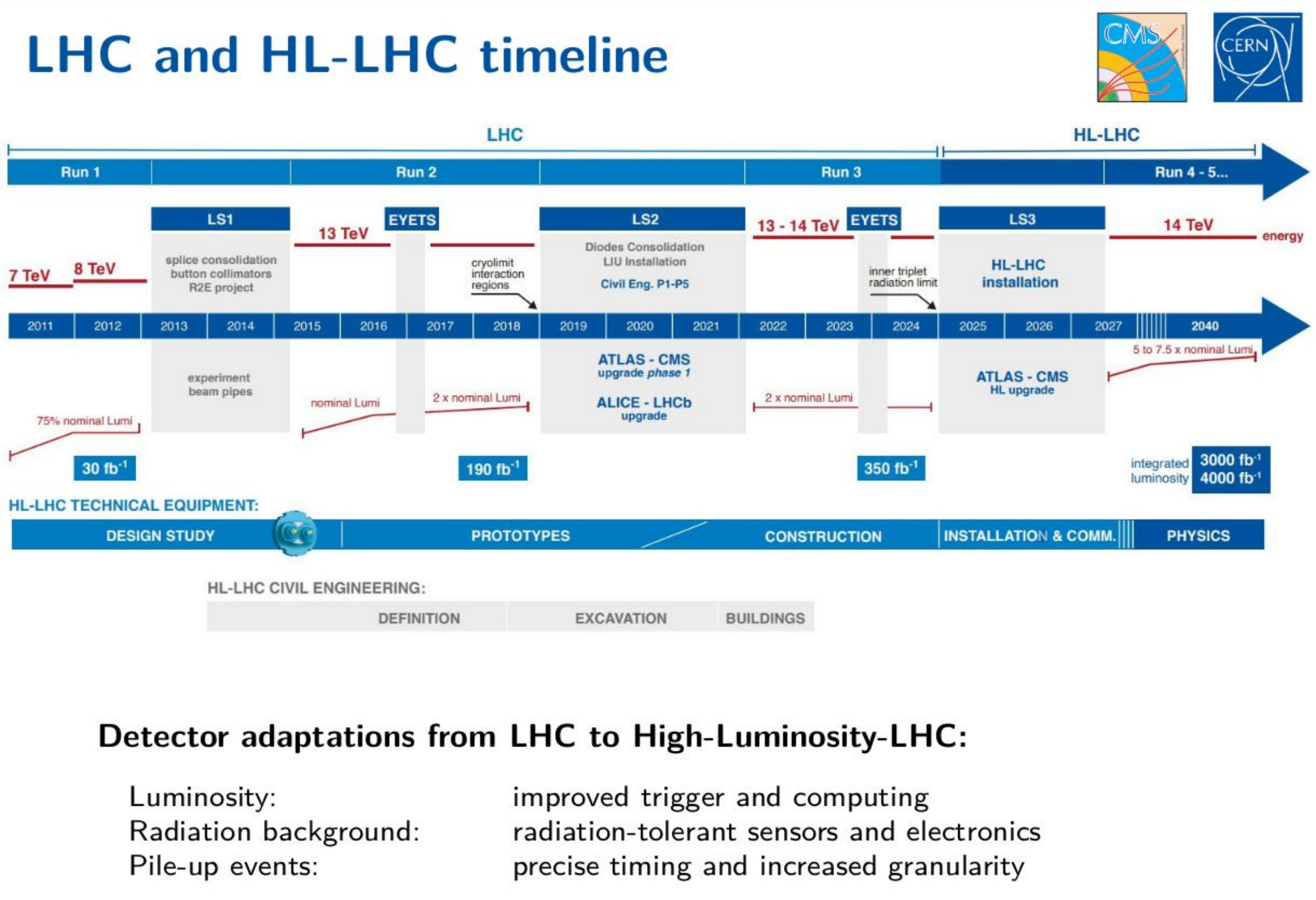


LHC and HL-LHC timeline

Experimental conditions from LHC to High-Luminosity-LHC:

Luminosity:	$2\times10^{34}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$	→	$5\text{–}7.5\times10^{34}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$
Radiation background:	10^{14} neq/cm^2	→	$1\text{–}1.5\times10^{16}$ neq/cm^2
Pile-up events:	O(40)	→	O(140–200)

HL-LHC Technical design report



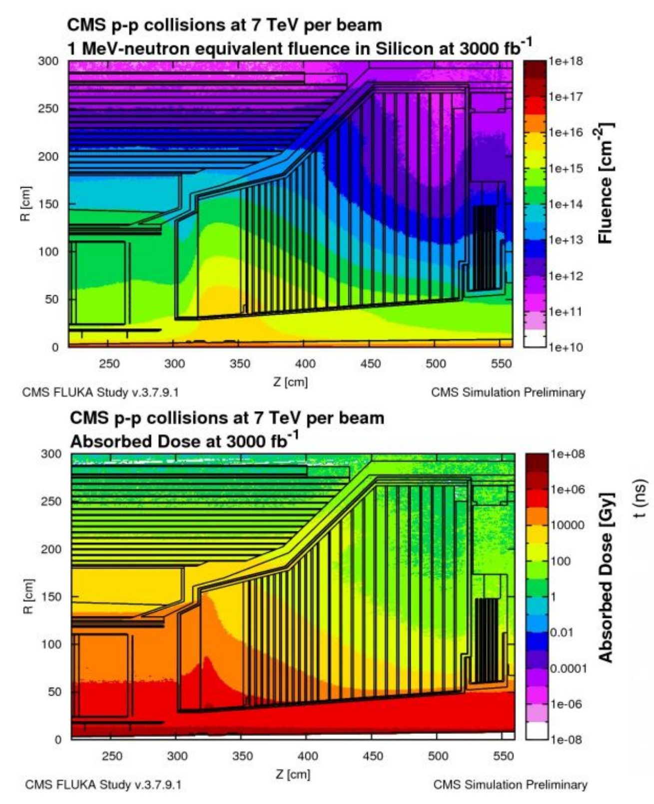
LHC and HL-LHC timeline

Detector adaptations from LHC to High-Luminosity-LHC:

Luminosity:	improved trigger and computing
Radiation background:	radiation-tolerant sensors and electronics
Pile-up events:	precise timing and increased granularity

HL-LHC Technical design report

Radiation levels expected for HL-LHC



CMS p-p collisions at 7 TeV per beam

1 MeV-neutron equivalent fluence in Silicon at 3000 fb^{-1}

CMS FLUKA Study v.3.7.9.1

CMS Simulation Preliminary

CMS p-p collisions at 7 TeV per beam

Absorbed Dose at 3000 fb^{-1}

CMS FLUKA Study v.3.7.9.1

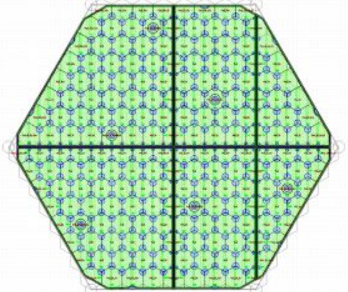
CMS Simulation Preliminary

- Radiation hardness
  - Fluences from 1 $\times 10^{12}$ neq/cm^2 to 1 $\times 10^{16}$ neq/cm^2
  - Dose from 10 Gy to 1 MGy

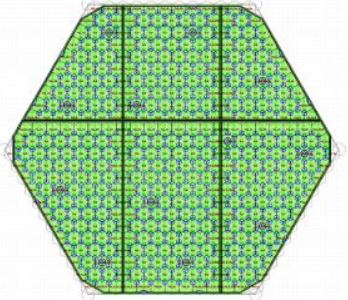
Upgrade of the CMS endcap calorimeter Technical design report

Partial sensors from Multi-Geometry wafers

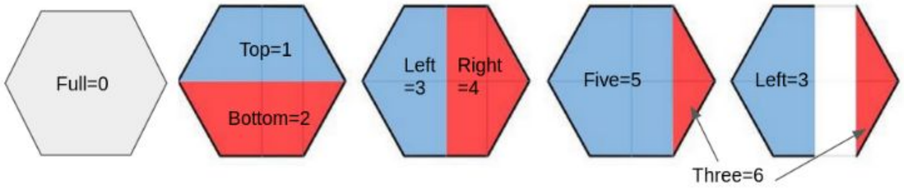
Low Density Multi-Geometry Wafer



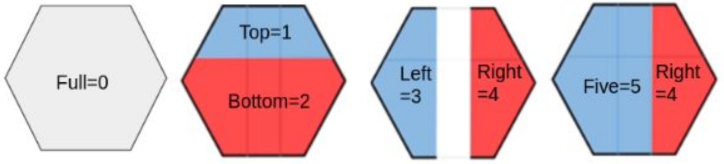
High Density Multi-Geometry Wafer



LD partial sensor layout names

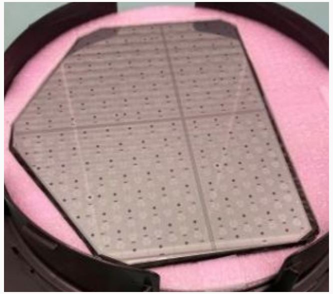


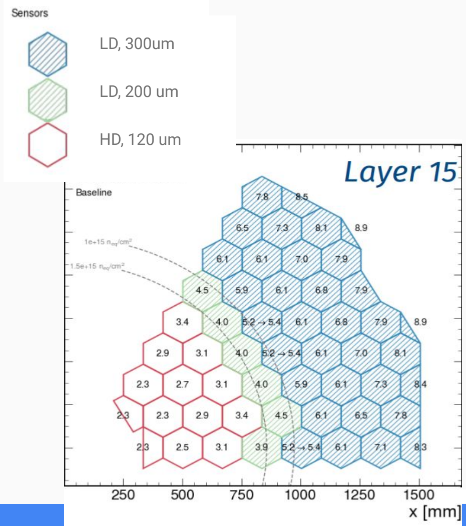
HD partial sensor layout names



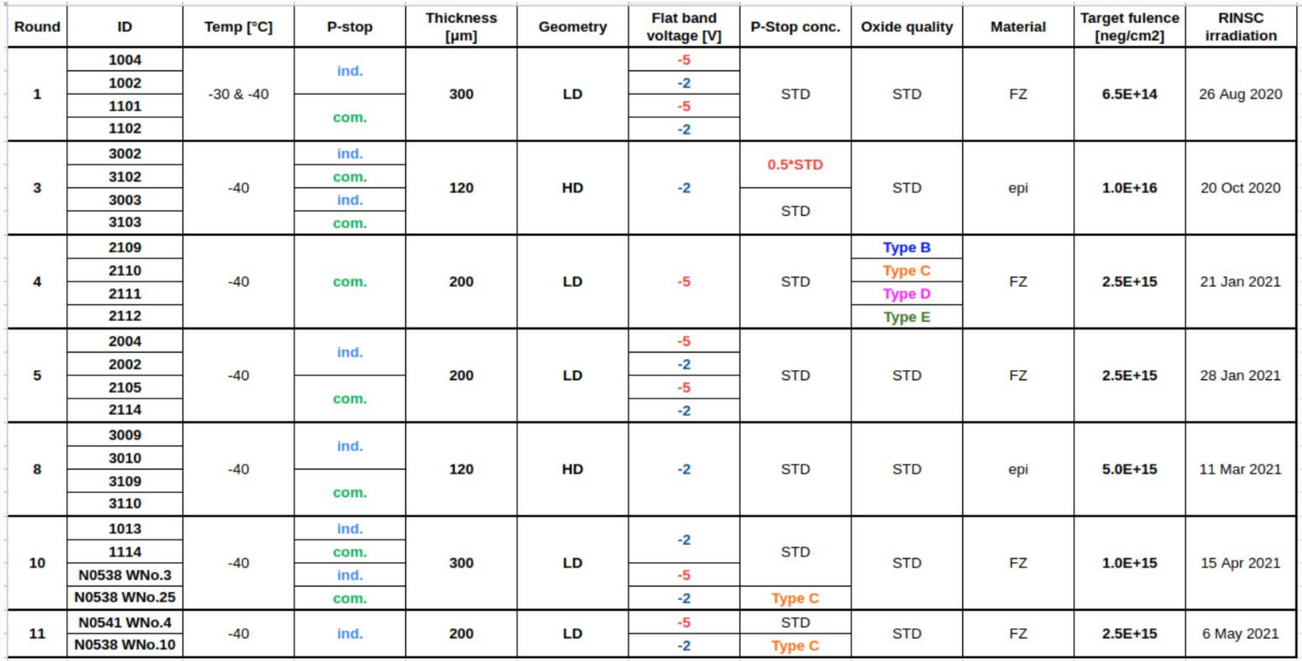
- Border regions of endcap will be tiled with partial sensors made from multi-geometry wafers
- Partial sensors allow increase in coverage of the detector
- Partials sensors increase complexity of the detector design significantly (increase in number of sensor variants, module PCBs, assembly tools, ...)

"LD five" partial sensor



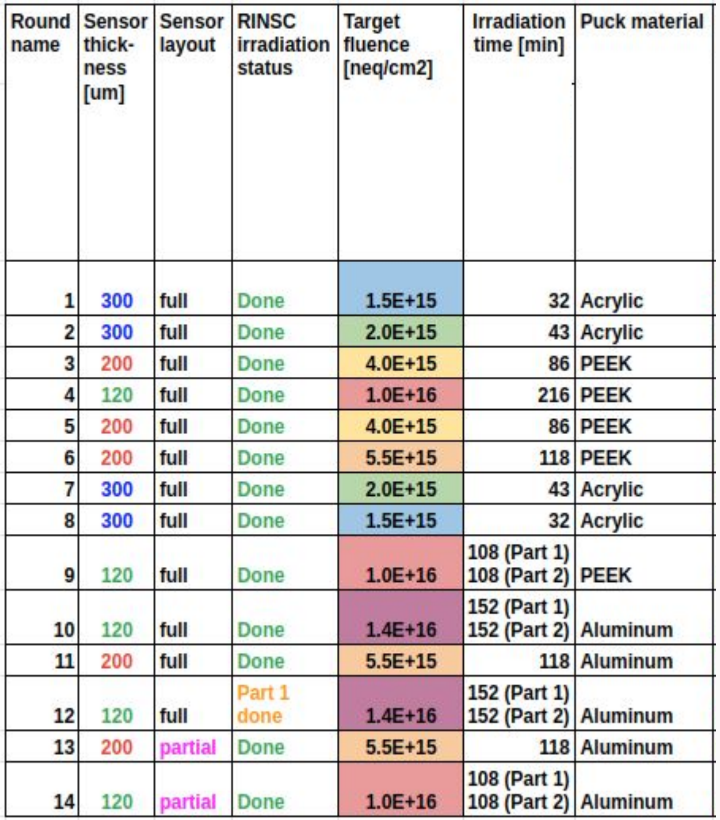


List of the sensors (version 1) characterised at CERN



Round	ID	Temp [°C]	P-stop	Thickness [µm]	Geometry	Flat band voltage [V]	P-Stop conc.	Oxide quality	Material	Target fulence [neg/cm2]	RINSC irradiation
1	1004	-30 & -40	ind.	300	LD	-5	STD	STD	FZ	6.5E+14	26 Aug 2020
	1002					-2					
	1101		com.			-5					
	1102					-2					
3	3002	-40	ind.	120	HD	-2	0.5*STD	STD	epi	1.0E+16	20 Oct 2020
	3102		com.								
	3003		ind.				STD				
	3103		com.								
4	2109	-40	com.	200	LD	-5	STD	Type B	FZ	2.5E+15	21 Jan 2021
	2110							Type C			
	2111							Type D			
	2112							Type E			
5	2004	-40	ind.	200	LD	-5	STD	STD	FZ	2.5E+15	28 Jan 2021
	2002					-2					
	2105		com.			-5					
	2114					-2					
8	3009	-40	ind.	120	HD	-2	STD	STD	epi	5.0E+15	11 Mar 2021
	3010										
	3109		com.								
	3110										
10	1013	-40	ind.	300	LD	-2	STD	STD	FZ	1.0E+15	15 Apr 2021
	1114		com.								
	N0538 WNo.3		ind.			-5					
	N0538 WNo.25		com.			-2	Type C				
11	N0541 WNo.4	-40	ind.	200	LD	-5	STD	STD	FZ	2.5E+15	6 May 2021
	N0538 WNo.10					-2	Type C				

List of the sensors (version 2) characterised at CERN



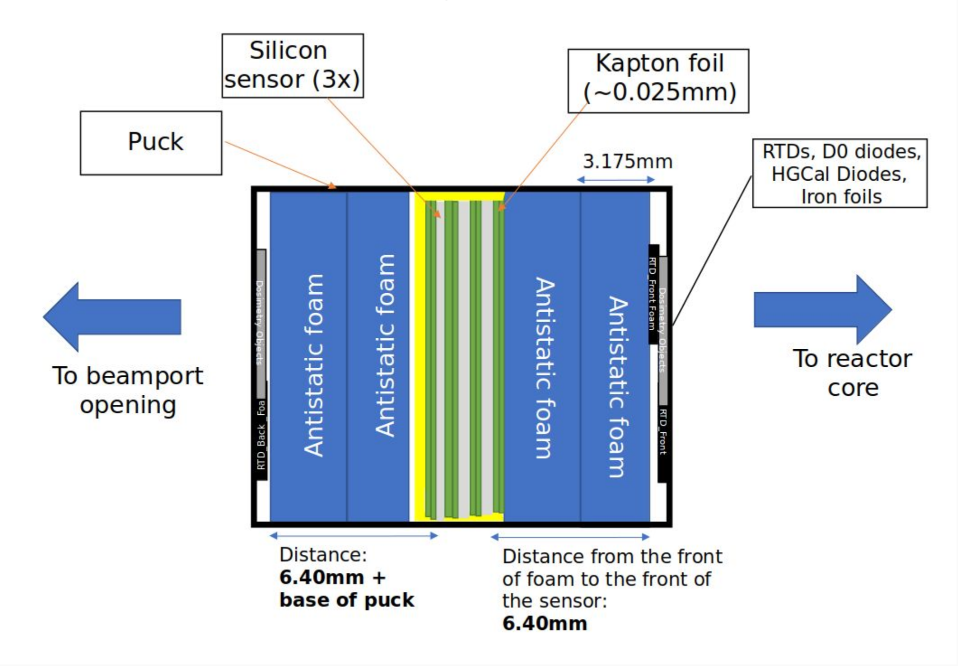
Round name	Sensor thick-ness [um]	Sensor layout	RINSC irradiation status	Target fluence [neq/cm2]	Irradiation time [min]	Puck material
1	300	full	Done	1.5E+15	32	Acrylic
2	300	full	Done	2.0E+15	43	Acrylic
3	200	full	Done	4.0E+15	86	PEEK
4	120	full	Done	1.0E+16	216	PEEK
5	200	full	Done	4.0E+15	86	PEEK
6	200	full	Done	5.5E+15	118	PEEK
7	300	full	Done	2.0E+15	43	Acrylic
8	300	full	Done	1.5E+15	32	Acrylic
9	120	full	Done	1.0E+16	108 (Part 1) 108 (Part 2)	PEEK
10	120	full	Done	1.4E+16	152 (Part 1) 152 (Part 2)	Aluminum
11	200	full	Done	5.5E+15	118	Aluminum
12	120	full	Part 1 done	1.4E+16	152 (Part 1) 152 (Part 2)	Aluminum
13	200	partial	Done	5.5E+15	118	Aluminum
14	120	partial	Done	1.0E+16	108 (Part 1) 108 (Part 2)	Aluminum

RINSC irradiations for HGCAL since 2020

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

- 25 irradiation rounds performed for HGCAL with 3 to 4 sensors per round each
- HGCAL prototype variants covered
    - 3 sensor thicknesses: 300µm, 200µm, 120µm
    - 2 sensor granularities: low and high granularity
    - 2 p-stop layout variants: individual and common
    - 2 p-stop concentration variants
    - 8 oxide variants
    - Full and partial sensors
- Radiation campaign still ongoing, currently focussing on high fluences

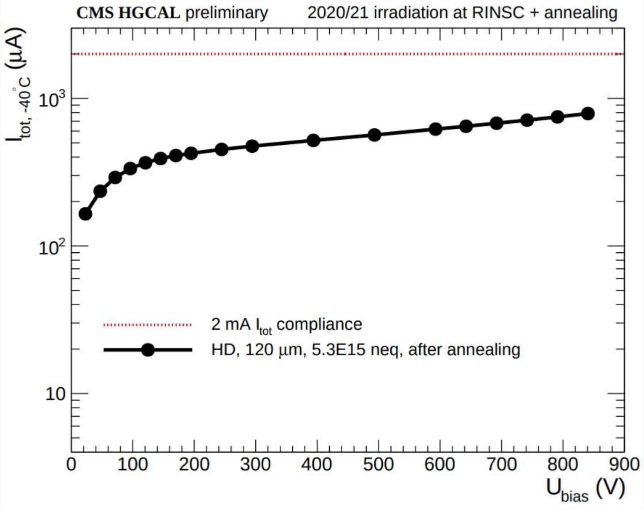
Puck layer structure



Neutron Irradiation and Electrical Characterisation of the First 8" Silicon Pad Sensor Prototypes for the CMS Calorimeter Endcap Upgrade

Total current measurement

- Measure total leakage current by increasing bias voltage in steps up to 850V
- The total leakage current I_{total} is restricted during the measurement to 2mA. This is a system-defined compliance limit to protect the ARRAY test system
- I_{total} is well below 2mA for most sensors

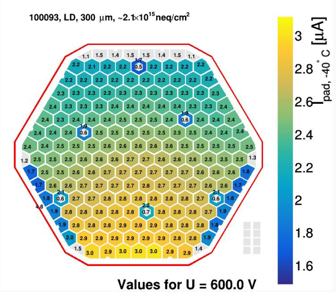


Compatible profiles for sensors of same round: Examples 1

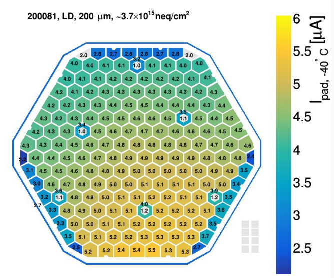
Round 1

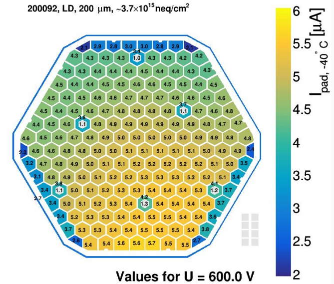
100082:
Chipped corner

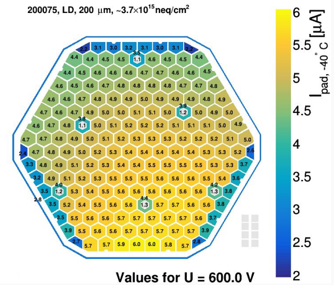
100076:
Chipped corner



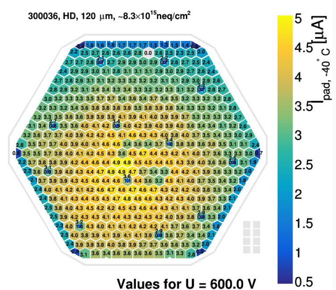
Round 3

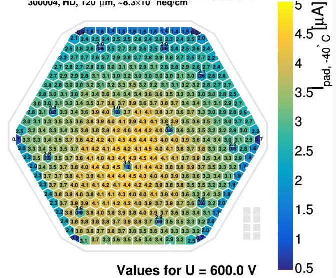


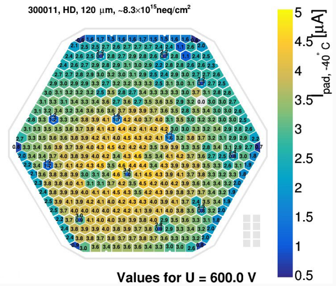




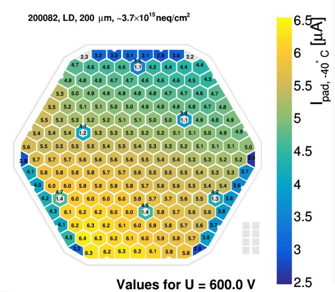
Round 4

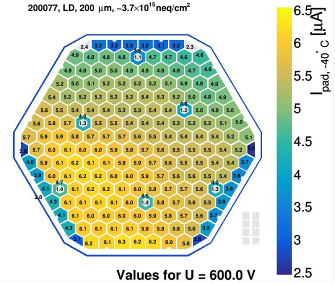


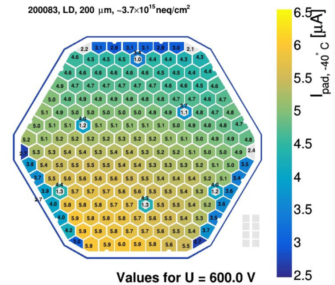




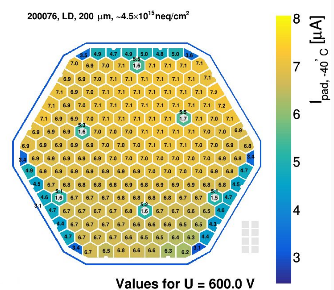
Round 5

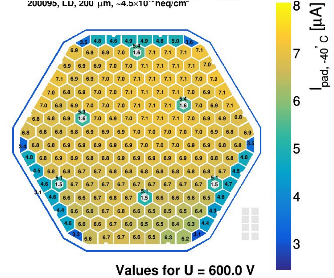






Round 6

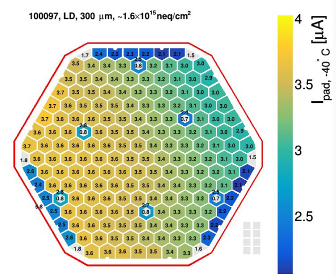


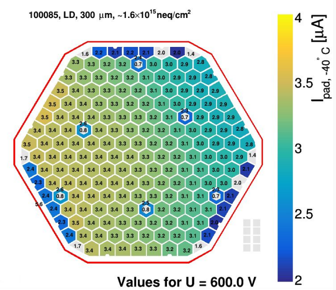


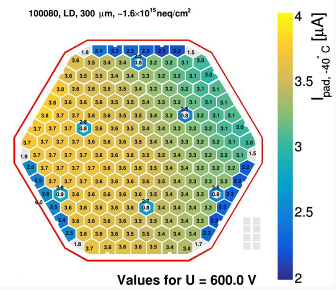
200093: not available

Compatible profiles for sensors of same round: Examples 2

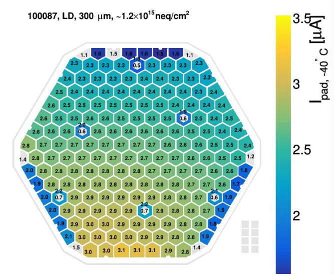
Round 7

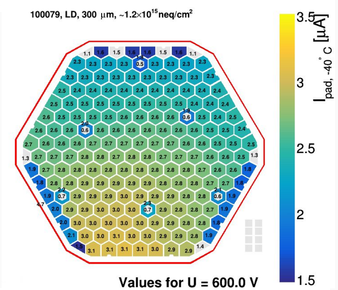


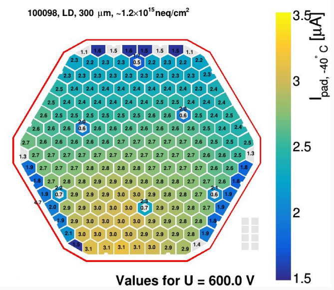




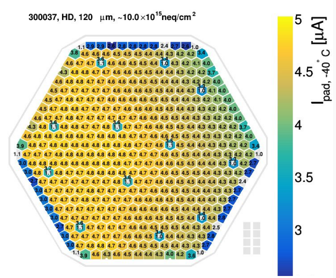
Round 8

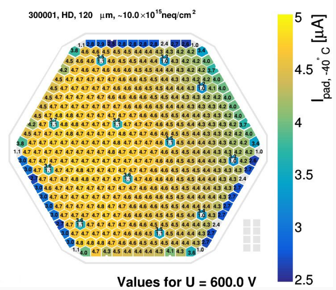


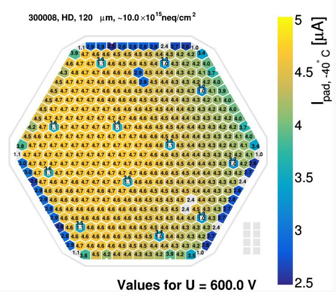




Round 9

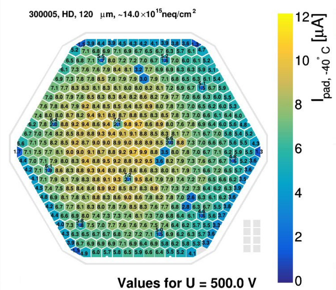


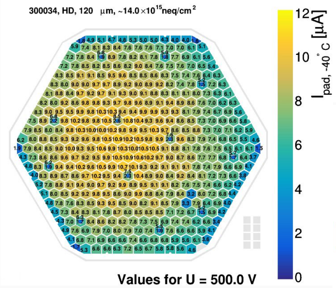




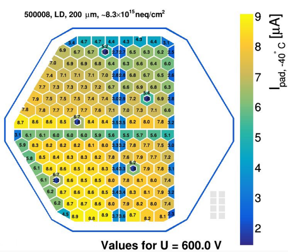
Round 10

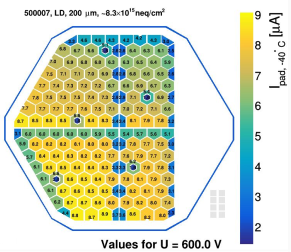
300009:
Chipped corner

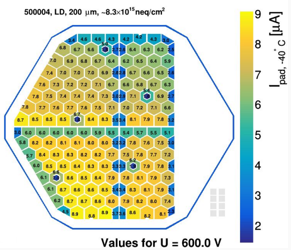


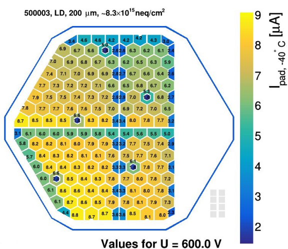


Round 13

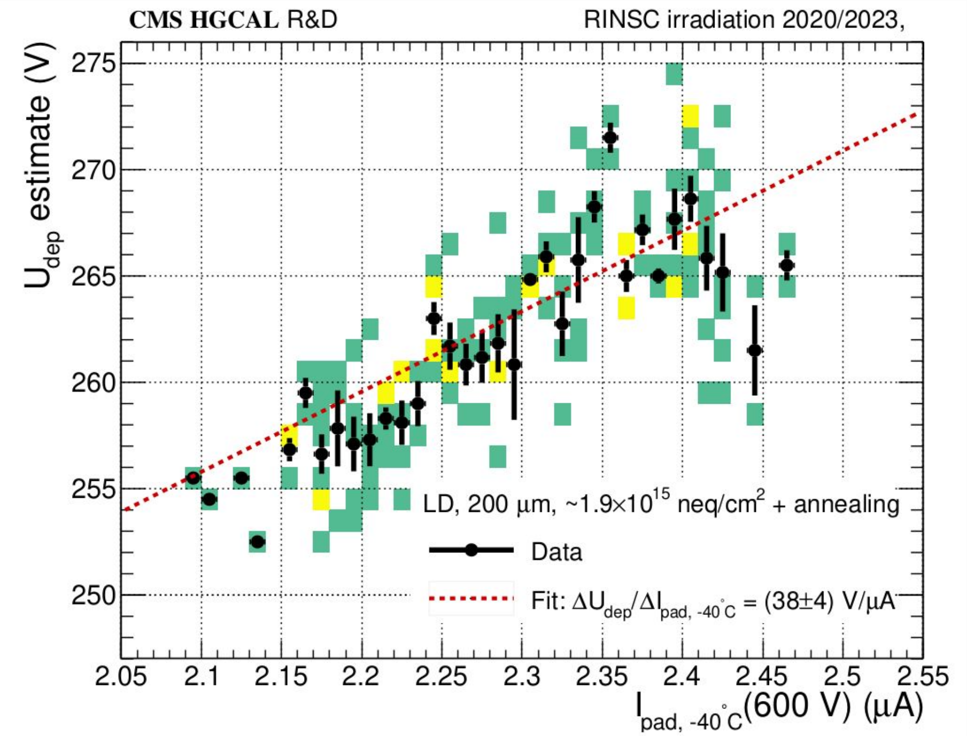








Correlation between fluence and U_{dep}



- Higher depletion voltage observed for higher leakage current
- Leakage current can be assumed to be a proxy for the delivered fluence