Lessons learned in RINSC neutron irradiation of 8-inch HGCAL silicon sensors

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on behalf of the CMS collaboration

1st DRD3 week on Solid State Detectors R&D

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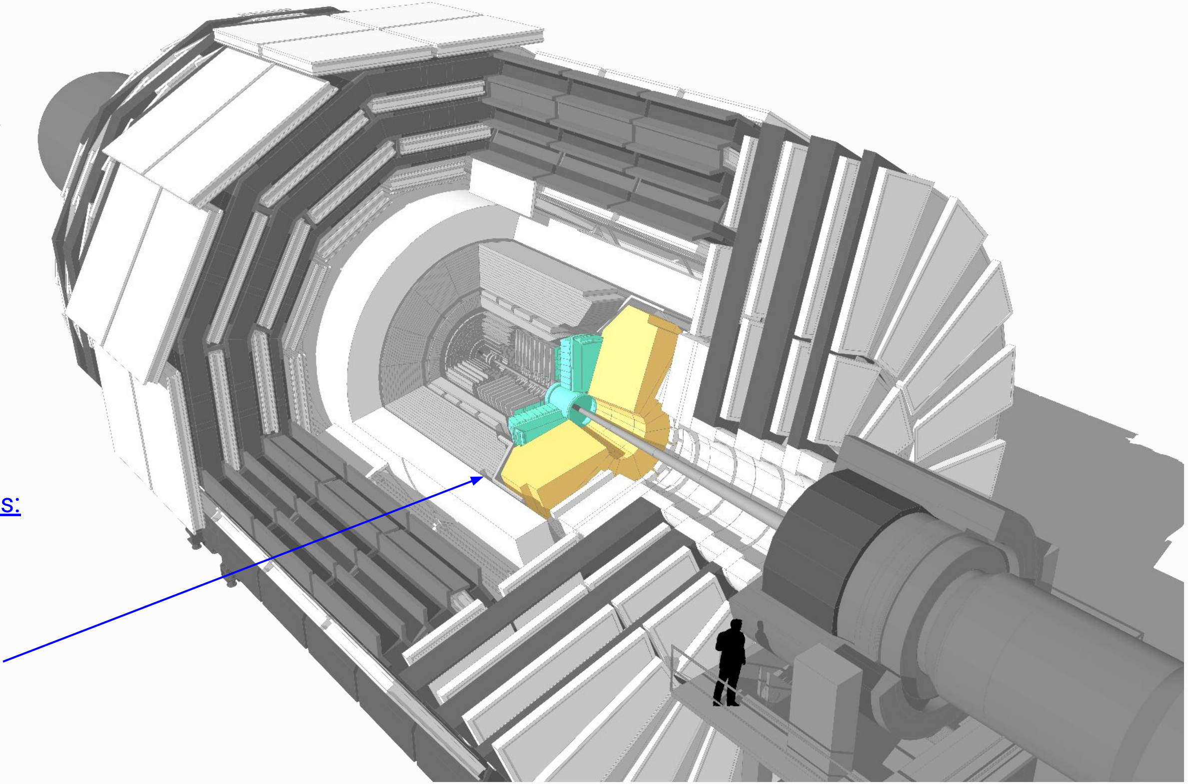
CMS upgrades for HL-LHC

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



CMS detector as of today

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

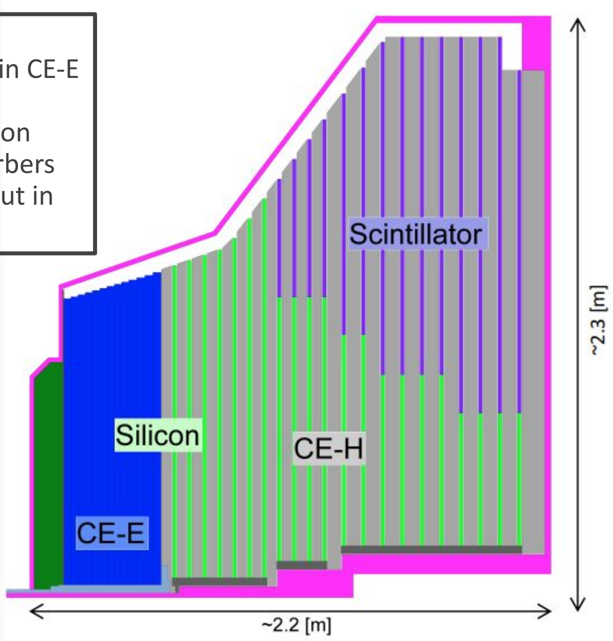
Muon system:
New electronics
GEM/RPC coverage in $1.5 < |\eta| < 2.4$, investigate Muon tagging at higher η

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 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -35°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



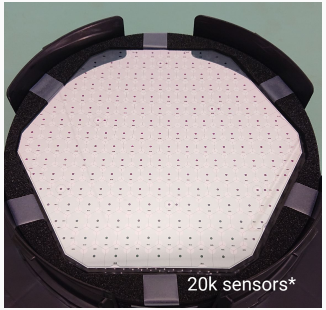
Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Project scale and challenges:

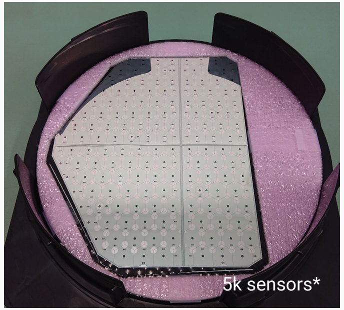
- By far largest approved project based on silicon sensors in HEP
  - → 3x area of ATLAS/CMS trackers
- First imaging calorimeter approved for installation in collider experiment
  - → Pave the way for future collider detectors
- First application of 8” sensors in a detector
  - → Cost optimization
  - → 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

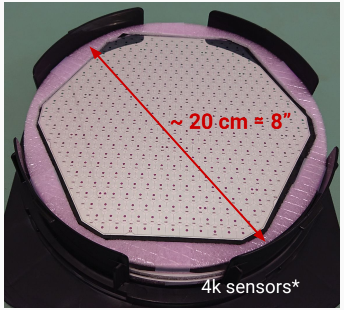
Low-Density sensor
~ 200 cells of 1.1 cm^2 size
300 μm & 200 μm active thickness



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

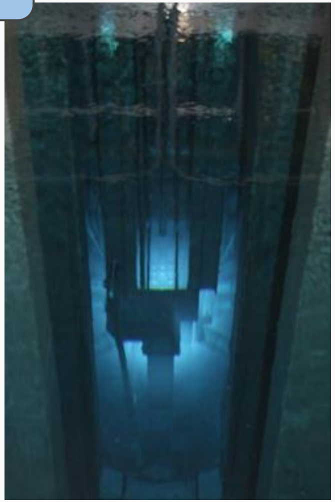
RINSC reactor details

- Neutron irradiation facility Rhode Island Nuclear Science Centre (RINSC), US
    - 2 MW, light-water cooled, pool-type reactor
    - Plate type fuel: U_3Si_2, cladded with aluminum, enriched to <20 % Uranium-235
    - Core of fuel assemblies moderated with combination of graphite and beryllium
    - Only irradiation facility able to host 8-inch wafers

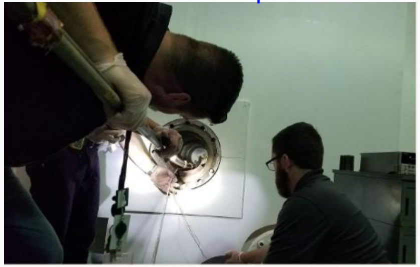
- Sample delivery methods available at RINSC
    - Pneumatic rabbit system
        - Deliver samples into reactor core for a precise time while reactor is running
        - Sample sizes up to 28 mm x 150 mm
    - Beam ports → Used for HGCAL
        - Accommodate samples up to 8” diameter
        - Access only when reactor is off, significant edge effects for small fluences
        - Samples only removed day-after irradiation

- Experience irradiating HGCAL prototype variants since 2020
    - 30 irradiation rounds with target fluences from $6.5 \cdot 10^{14}$ to $1.4 \cdot 10^{16}$ n_{eq}/cm^2

Reactor core



Radial beam port

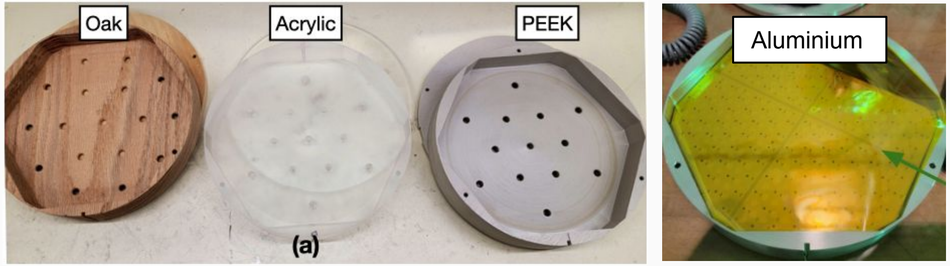


HGCAL sensor irradiation at RINSC

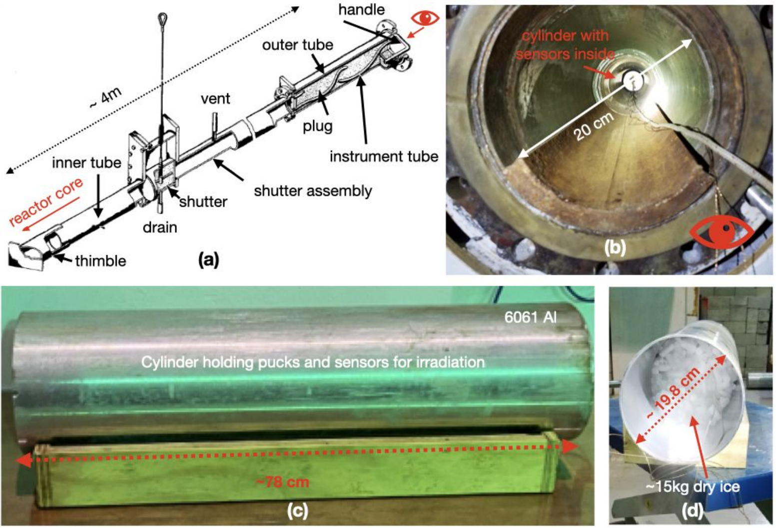
- Neutron irradiation of HGCAL 8-inch sensors at Rhode Island Nuclear Science Center (RINSC)
  - Sensors in container called “hockey puck”
  - Puck materials used so far:
    Wood (oak), Acrylic, PEEK, Aluminum
  - <=4 sensors stacked on top of each other
  - Puck inserted into aluminum cylinder filled with 15-18 kg dry ice for temperature control
  - Cylinder inserted into radial beam port

- Countermeasures to minimize in-reactor annealing due to high reactor temperatures
  - Ventilation holes in puck
  - Splitting of high-fluence irradiations into 2 irradiation rounds, each with new ice
  - Cooling of cylinder before filling dry ice
  - Use puck material with high thermal conductivity: Aluminum

Sensor holders: “hockey puck”



Cylinder containing puck and dry ice in beam port



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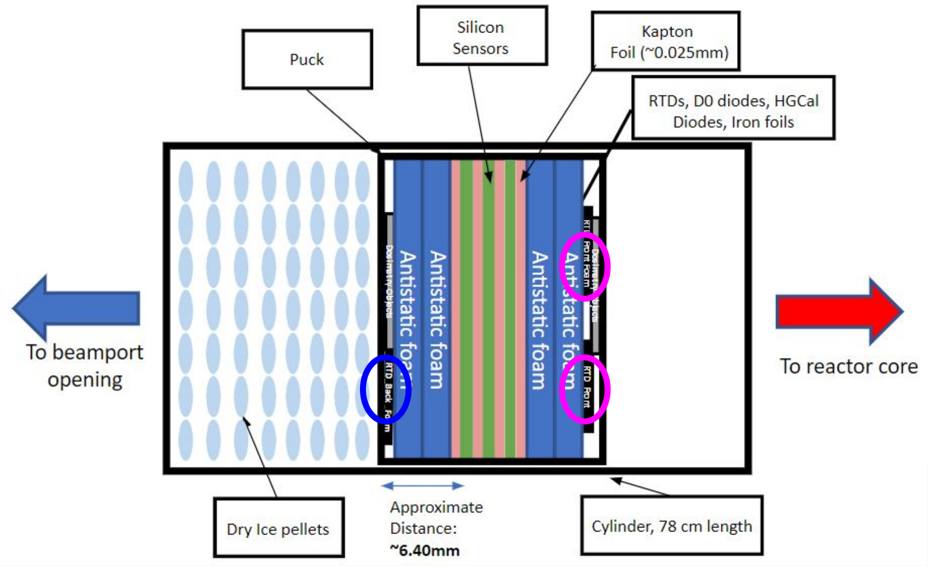
Temperature profiles experienced by HGCal sensors in RINSC irradiations

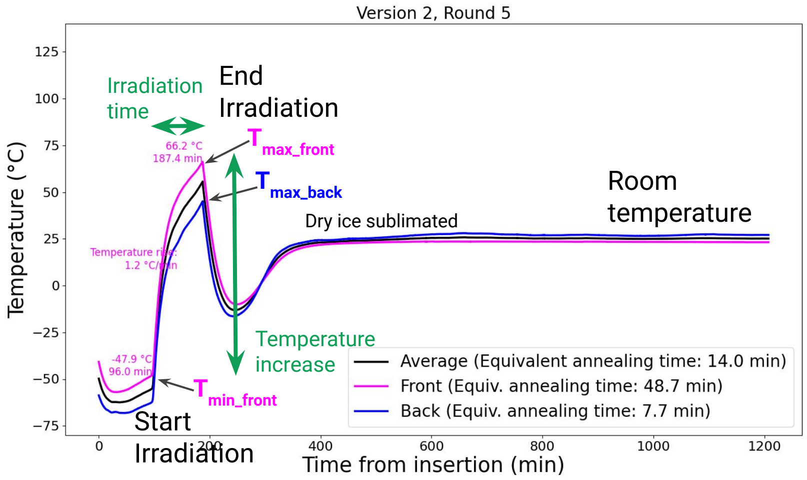
Temperature profiles in RINSC irradiations

- Temperature of silicon sensors monitored by **RTD**s in the front and back of the hockey puck



Back **Front**

Schematics not to scale,
zoomed into x-axis for better visibility

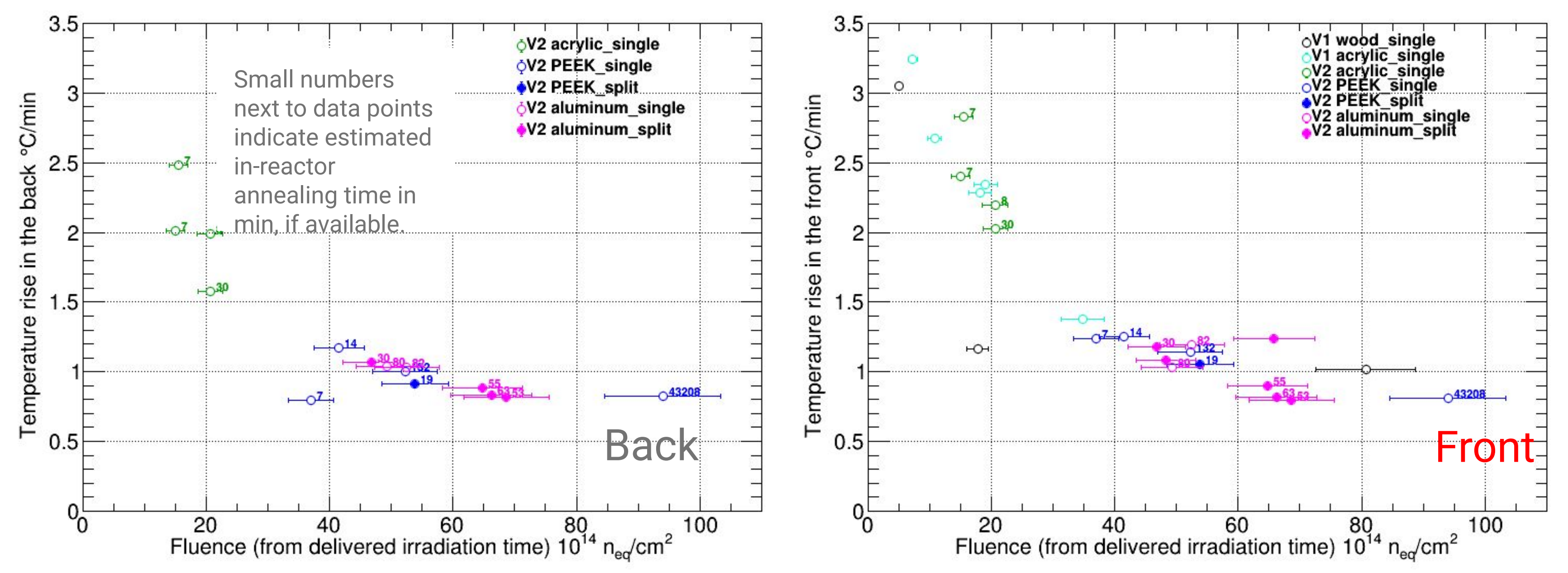


Observables used:

- Temperature rise during irradiation
- $T_{max,front}$ = Maximum temperature in the front of the puck (at the reactor side)
- $\Delta T_{max} = T_{max,front} - T_{max,back}$ = Temperature difference between the front and the back of the puck

$$\text{Temperature\_rise} = \frac{T_{max\_front} - T_{min\_front}}{\text{time}(T_{max\_front}) - \text{time}(T_{min\_front})}$$

Temperature increase rate vs. Fluence

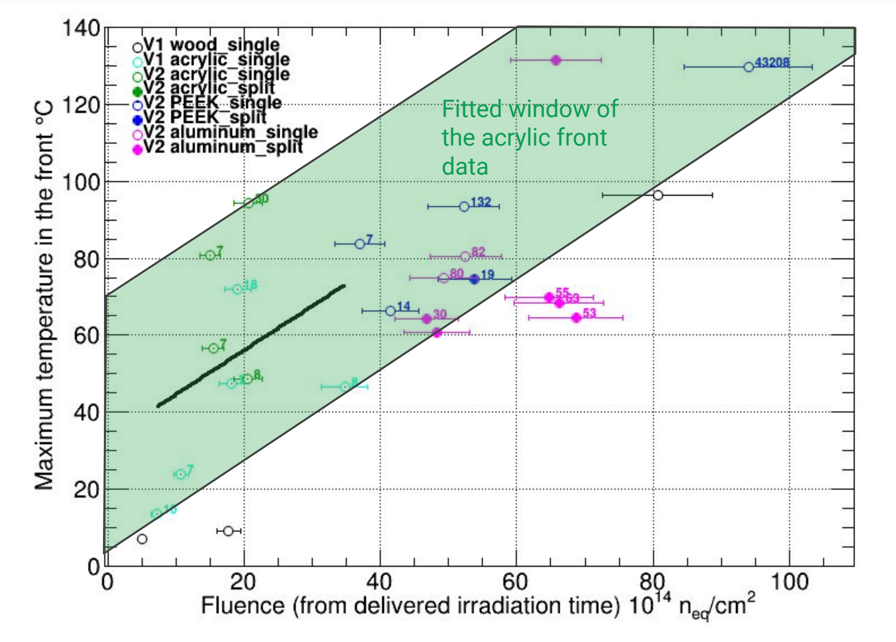


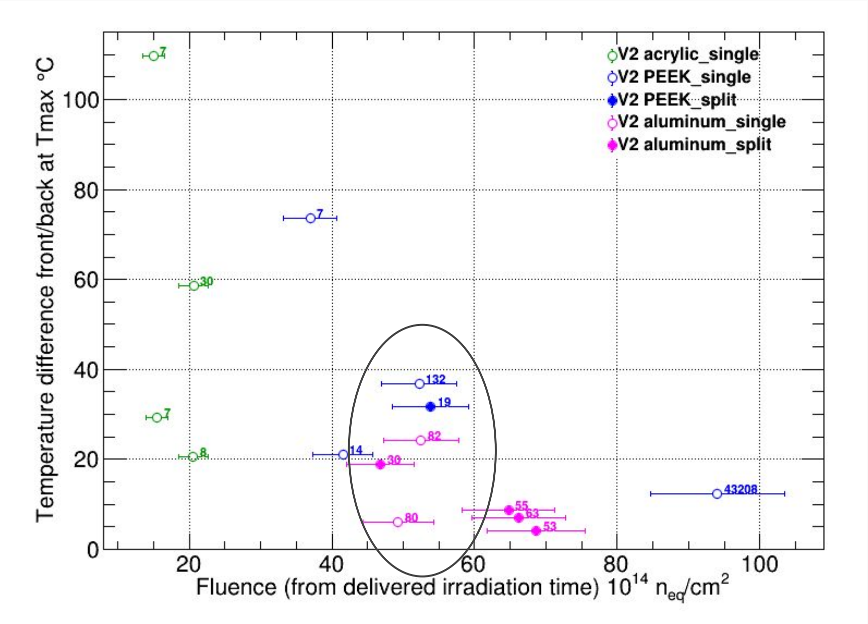
Small numbers next to data points indicate estimated in-reactor annealing time in min, if available.

Split rounds enter the plot twice for each part at approximately half the target fluence

- Temperature increase rate
  - Slightly higher in the front than in the back
  - Decreases with fluence for both front and the back
  - Difference between front and back highest for Acrylic, for which data is only available at low fluence. Could be due to material or due to low fluence.

T_{max_front} and ΔT_{max} (front-back) vs. Fluence



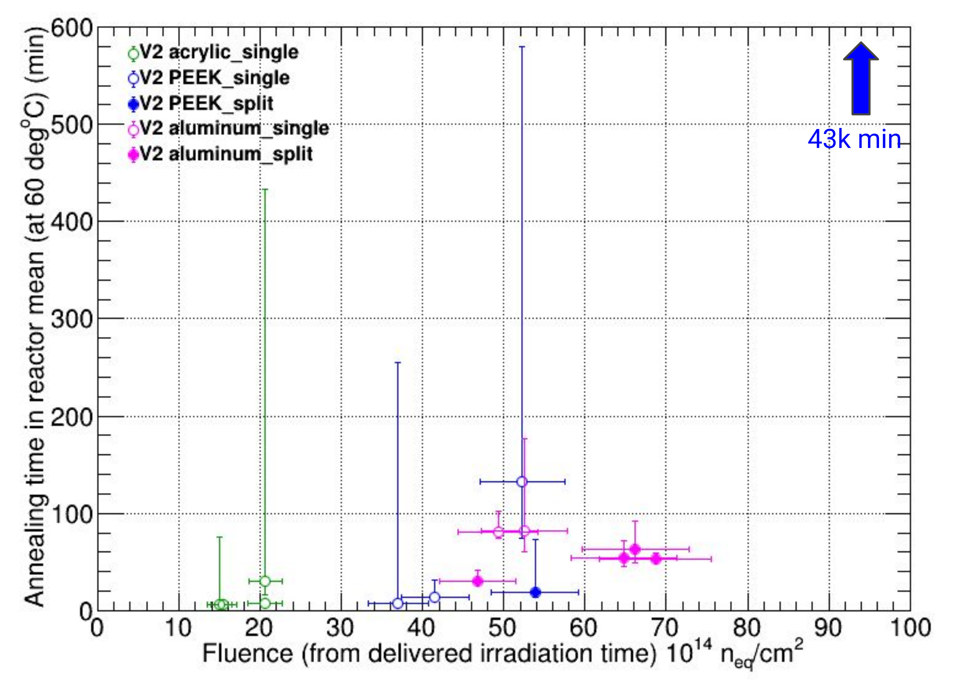


- Maximum temperature increases with duration of irradiation (= fluence), as expected
- Extrapolated values from low fluence acrylic points -> Some T_{max_front} in aluminum and wood pucks lower

- Temperature higher closer to reactor core (ΔT>0)
- Temperature difference decreases with fluence
- At same fluence, lower ΔT in aluminum than in PEEK
  - Could be linked to better thermal conductivity of aluminum

Split rounds enter the plot twice for each part at approximately half the target fluence

In-reactor annealing time vs. Fluence



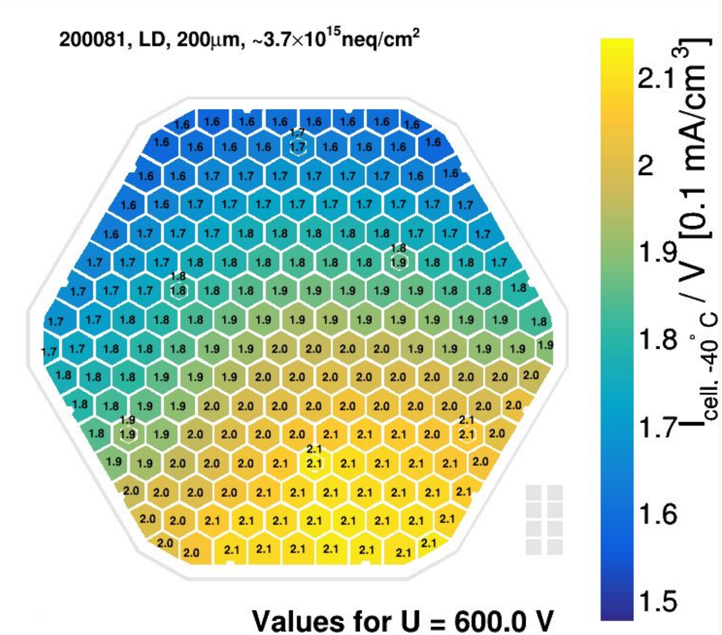
- Equivalent annealing time at 60°C calculated from full temperature profiles of irradiation and waiting time after irradiation (up to 1day)
  - Strongly impacted by short time at T_{max}
  - Influenced also by long time at room temperature (different between seasons)

- Annealing time at sensors with large uncertainties due to front back difference
- In-reactor annealing time rises with fluence, as expected
- No clear effect of puck material at similar fluence visible

Split rounds enter twice at approximately half the target fluence
Included only averaged results (where back and front temperature data are present)

Leakage currents profiles in HGCal sensors

Reminder: leakage current homogeneity



$$\mathrm{MAD} = \mathrm{median}(|X_i - \mathrm{median}(X)|)$$

$$\mathrm{RMAD} = \frac{\mathrm{MAD}}{\mathrm{median}(X)}$$

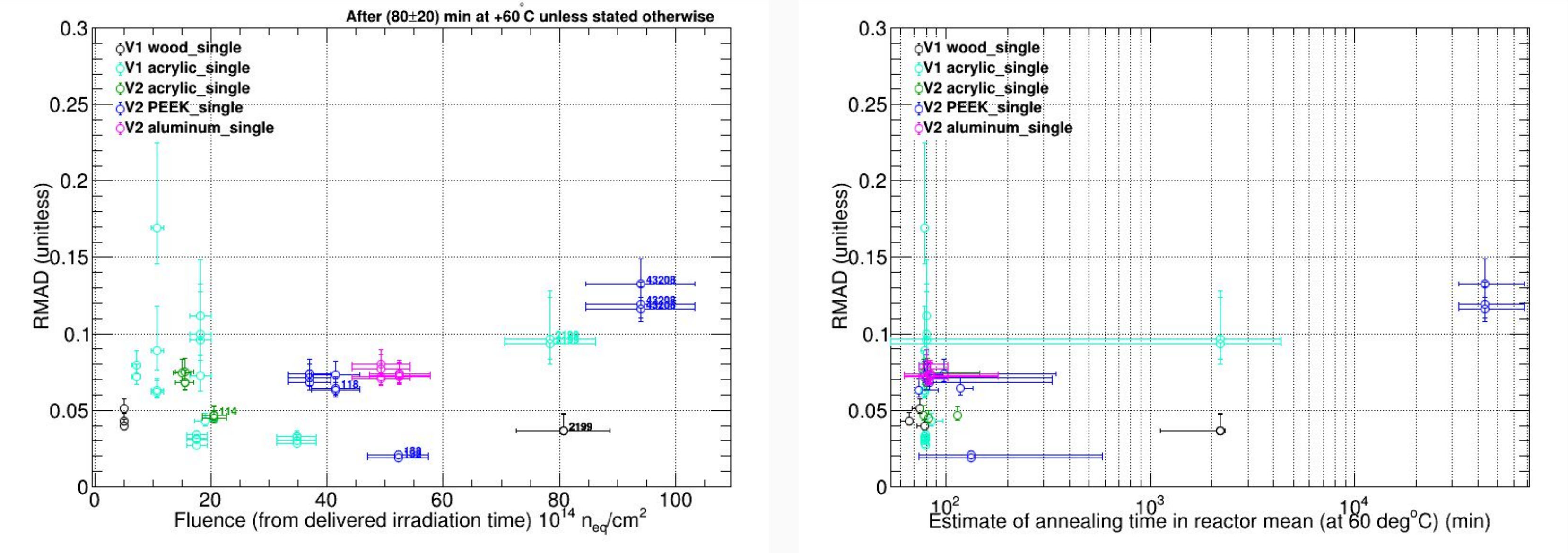
- Observe gradient in volume normalised leakage current in sensors that were irradiated at RINSC
- Similar gradient between sensors of same irradiation round
- Hypotheses under study:
  1. Fluence inhomogeneity from reactor
  2. Annealing time inhomogeneity across wafer
     - Inhomogeneous cooling could appear due to dry ice being used up during irradiation
     - Leftover ice could pool at the bottom of the cylinder leading to top of wafers exposed to higher temperatures

- Quantify gradient by Relative Median Absolute Deviation (RMAD) is Median Absolute Deviation (MAD) divided by the median.

- Note: Also study for same data sets: Relative current median = I_cell_median / fluence => equal to alpha of one data point

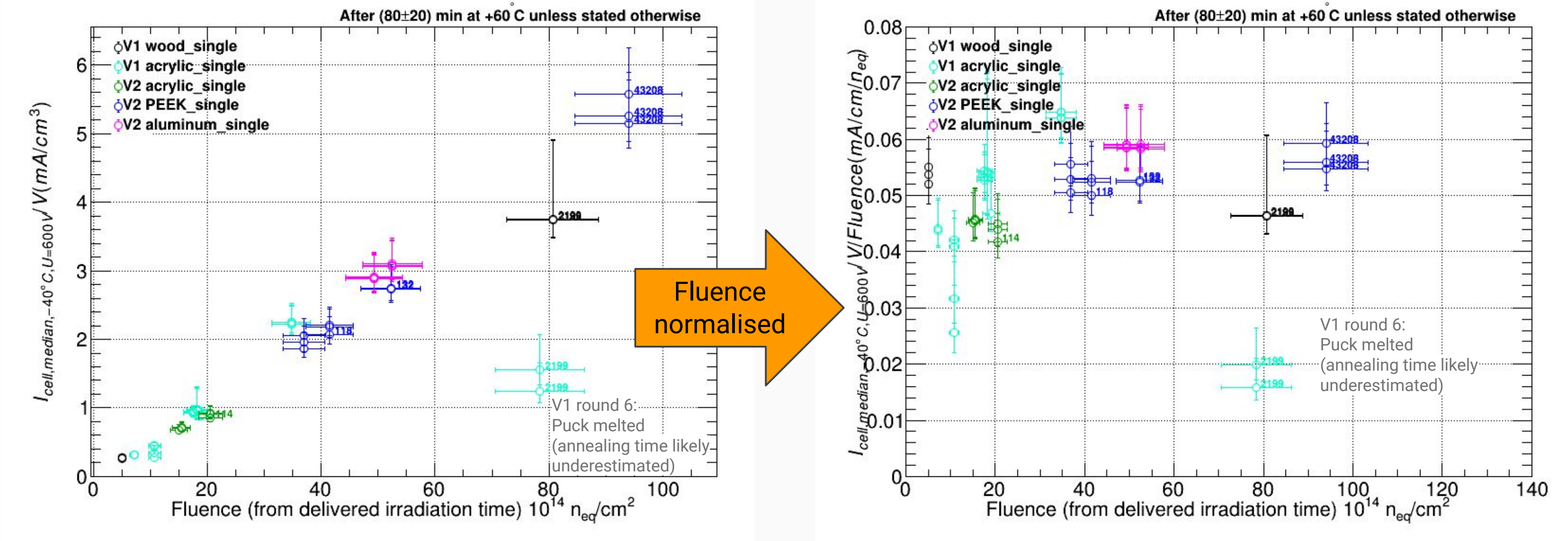
*Volume is calculated by taking the n-implant area

Gradient for puck materials (single rounds)



- RMAD similar for different fluences and annealing times
- No clear difference between puck materials

Relative current median: single rounds

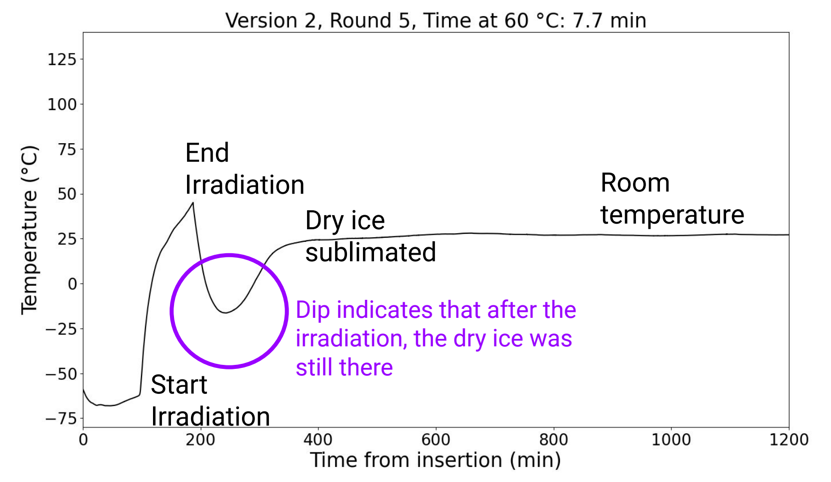


V1 round 6:
Puck melted
(annealing time likely
underestimated)

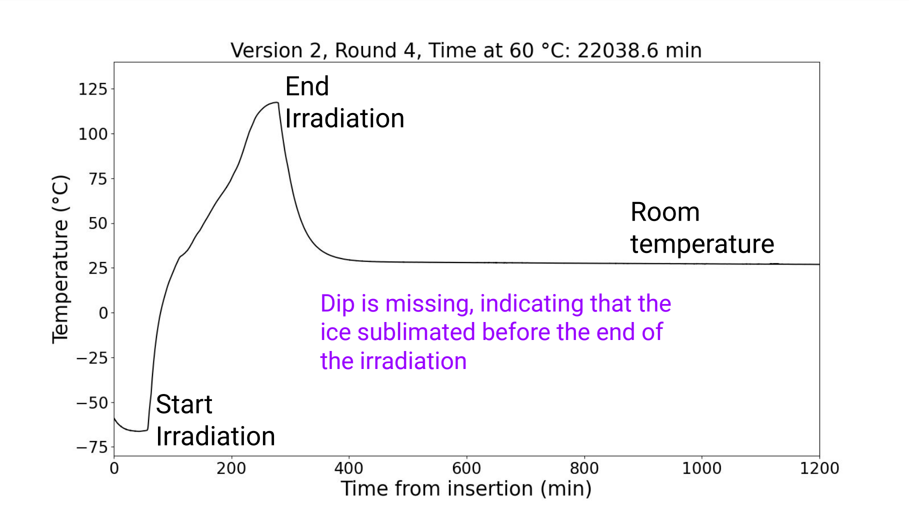
- Volume normalised leakage current over fluence -> equivalent to alpha calculated for one data point
  - No obvious impact of puck material visible

Dry ice sublimation analysis

- Drop of the temperature after irradiation to lower than the ambient temperature indicates that the dry ice was still present
- No drop visible in rounds v1: R3; v2: R3, R6, R10 (part I and part II), R11, R12 (part I and part II)
    - Dry ice fully sublimated during irradiation
- For some rounds we do not have the recordings, or they stopped (see backup)

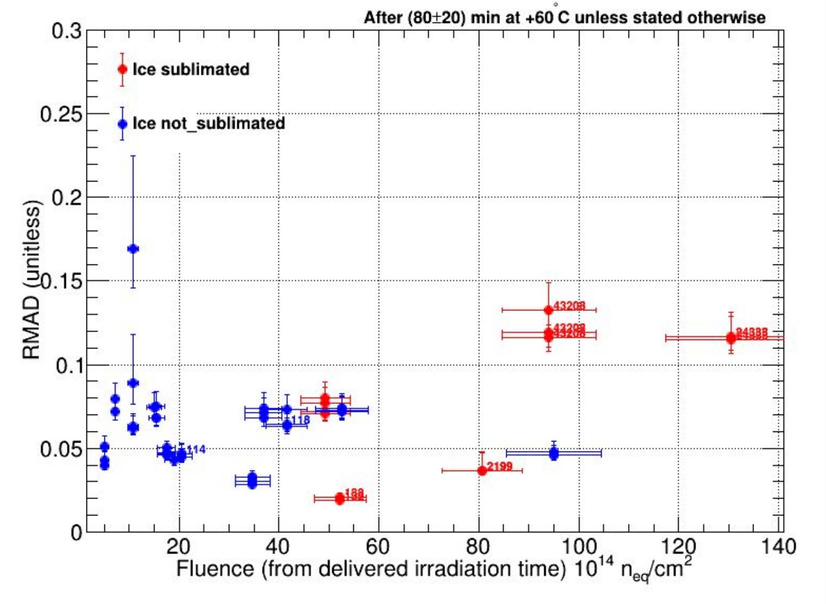


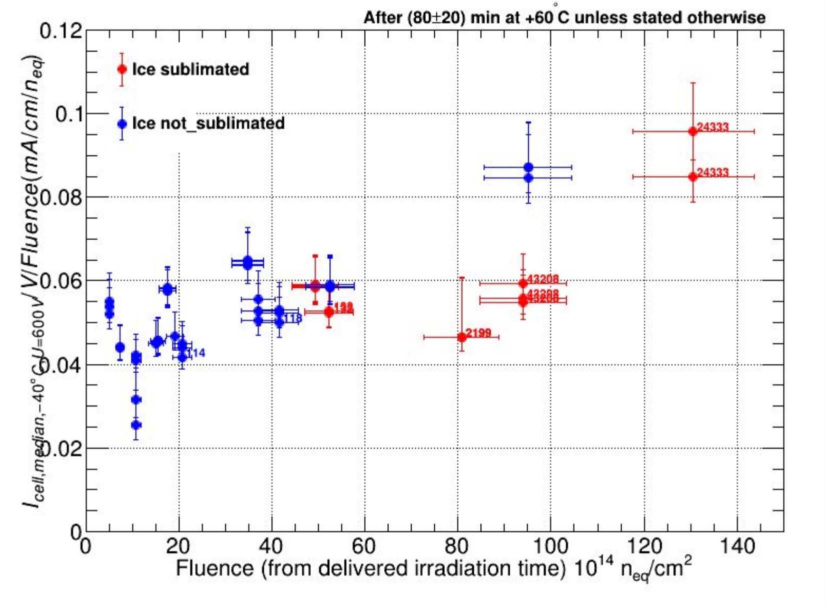
Dip indicates that after the irradiation, the dry ice was still there



Dip is missing, indicating that the ice sublimated before the end of the irradiation

RMAD and alpha: sublimated vs. non-sublimated ice





- No clear difference observed in RMAD for sublimated/non-sublimated ice
- Most data sets with fully sublimated ice have higher annealing times
  - Alpha for points with sublimated ice (=higher annealing) slightly lower, as expected

Version 2, round 9 (no data for one part),
assumed the ice not sublimated like in the first part

Summary

- 8-inch HGCAL silicon sensors were irradiated at the irradiation facility RINSC and they were electrically characterized

Temperature Study

- Temperature increase rate
  - Decreases with fluence
  - Difference between front and back highest for Acrylic, for which data is only available at low fluence (could be due to material or due to low fluence)
- Maximum temperature
  - Higher at reactor core side, as expected
  - Increases with duration of irradiation (= fluence), as expected
  - In aluminum and wood pucks lower than in acrylic pucks (extrapolated)
- Temperature difference front/back
  - Decreases with fluence
  - At same fluence, lower temperature difference in aluminum than in PEEK
- In-reactor annealing time per irradiation round
  - Increases with fluence
  - No dependence on puck material visible

Leakage current study

- Observe spread in volume normalized leakage current across full sensor
  - Could be linked to profiles in fluence and annealing time
- Observe no clear difference between puck materials, which could indicate annealing time impact
- Investigation of rounds with sublimated ice
  - Most data sets with melted ice have higher annealing times, as expected
  - Alpha for points with sublimated ice lower, as expected
  - No clear difference observed in RMAD for sublimated/non-sublimated ice

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 support and guidance during these studies.

Backup

Irradiation campaign overview

2020-2021, v1 prototypes

Version	Round	Sensor thick-ness [um]	Sensor layout	Target fluence [neq/cm2]	Puck material
1	1	300	full	6.50E+14	wood
1	2	200	full	2.50E+15	wood
1	3	120	full	1.0E+16	wood
1	4	200	full	2.50E+15	Acrylic
1	5	200	full	2.50E+15	Acrylic
1	6	120	full	1.0E+16	Acrylic
1	7	120	full	2.50E+15	Acrylic
1	8	120	full	5.00E+15	Acrylic
1	9	300	full	1.5E+15	Acrylic
1	10	300	full	1.00E+15	Acrylic
1	11	200	full	2.50E+15	Acrylic

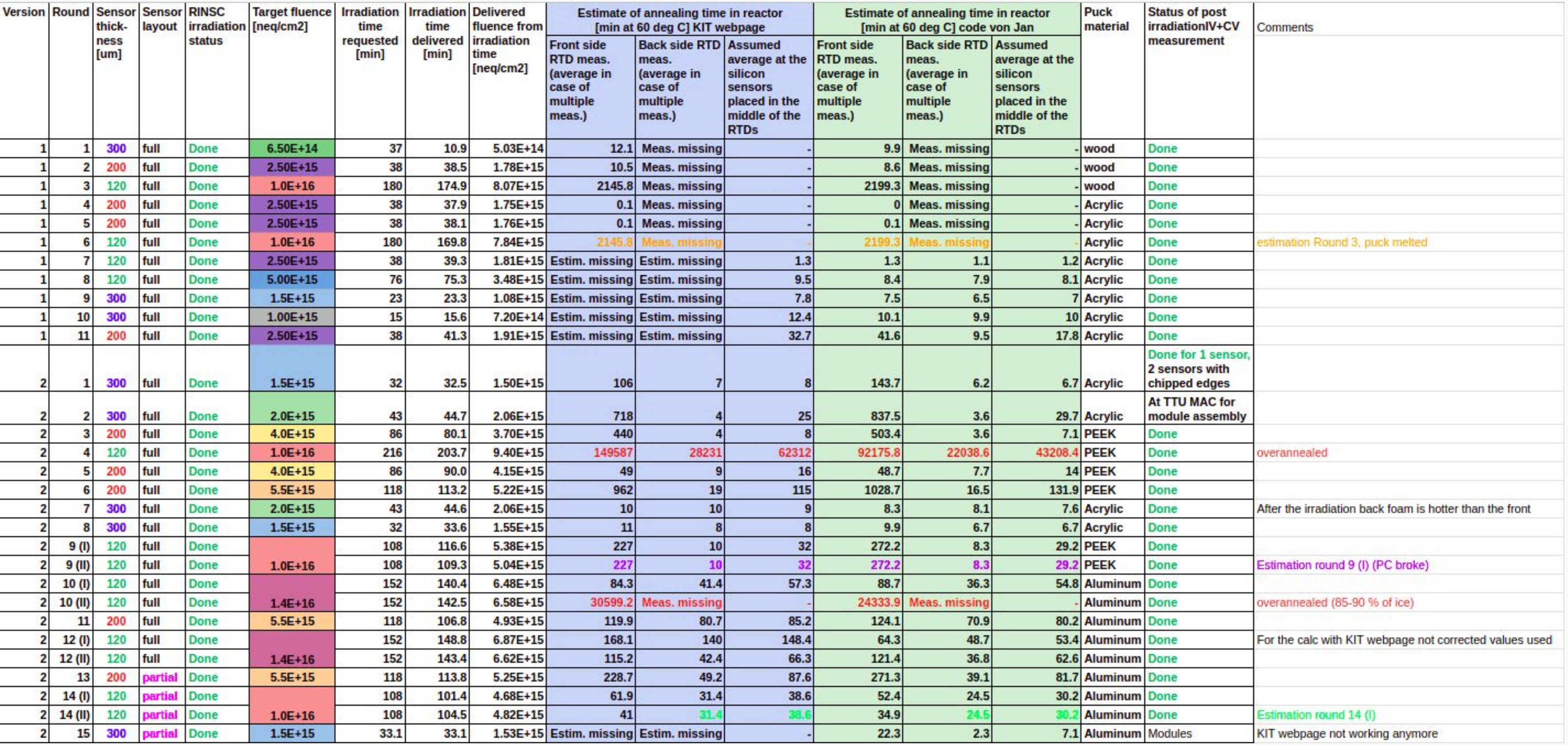
2021-2024, v2 prototypes (proto a)

Version	Round	Sensor thick-ness [um]	Sensor layout	Target fluence [neq/cm2]	Puck material
2	1	300	full	1.5E+15	Acrylic
2	2	300	full	2.0E+15	Acrylic
2	3	200	full	4.0E+15	PEEK
2	4	120	full	1.0E+16	PEEK
2	5	200	full	4.0E+15	PEEK
2	6	200	full	5.5E+15	PEEK
2	7	300	full	2.0E+15	Acrylic
2	8	300	full	1.5E+15	Acrylic
2	9 (I)	120	full	1.0E+16	PEEK
2	9 (II)	120	full		PEEK
2	10 (I)	120	full	1.4E+16	Aluminum
2	10 (II)	120	full		Aluminum
2	11	200	full	5.5E+15	Aluminum
2	12 (I)	120	full	1.4E+16	Aluminum
2	12 (II)	120	full		Aluminum
2	13	200	partial	5.5E+15	Aluminum
2	14 (I)	120	partial	1.0E+16	Aluminum
2	14 (II)	120	partial		Aluminum
2	15	300	partial	1.5E+15	Aluminum

Irradiations at similar reactor power:

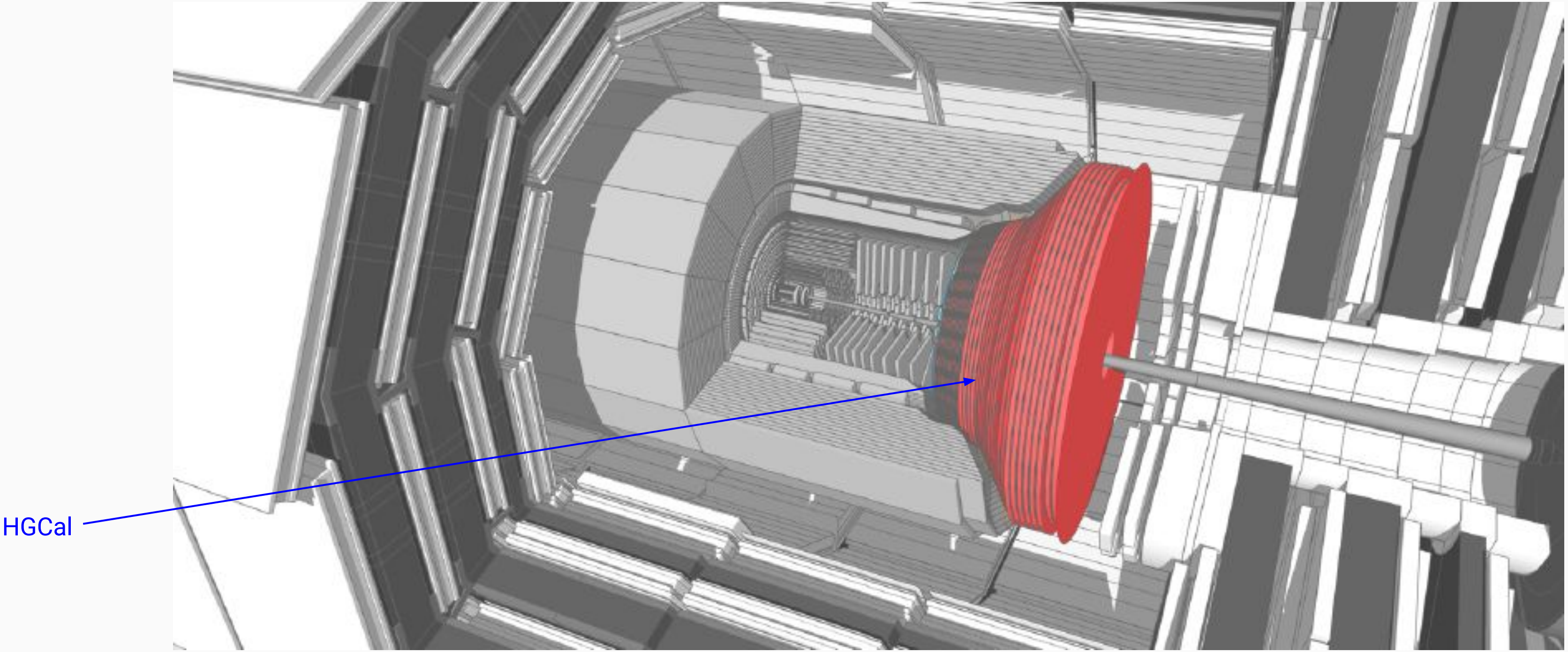
- 1 min ≙ 4.62E13 n_{eq}/cm^2
- Fluence also controlled with reference diodes and iron foils

Comparison annealing times from KIT webpage and package annealing_helpers



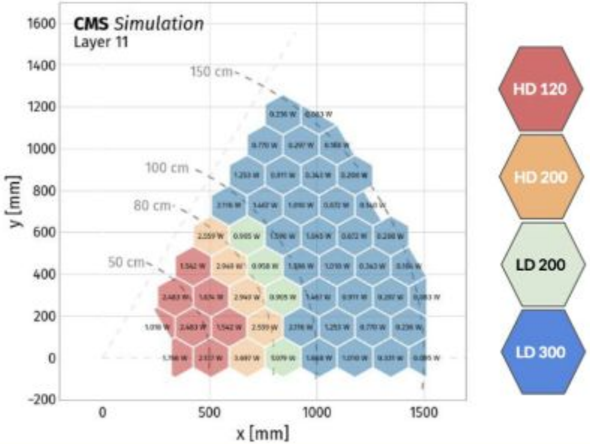
Version	Round	Sensor thick-ness [um]	Sensor layout	RINSC irradiation status	Target fluence [neq/cm2]	Irradiation time requested [min]	Irradiation time delivered [min]	Delivered fluence from irradiation time [neq/cm2]	Estimate of annealing time in reactor [min at 60 deg C] KIT webpage			Estimate of annealing time in reactor [min at 60 deg C] code von Jan			Puck material	Status of post irradiationIV+CV measurement	Comments
									Front side RTD meas. (average in case of multiple meas.)	Back side RTD meas. (average in case of multiple meas.)	Assumed average at the silicon sensors placed in the middle of the RTDs	Front side RTD meas. (average in case of multiple meas.)	Back side RTD meas. (average in case of multiple meas.)	Assumed average at the silicon sensors placed in the middle of the RTDs			
1	1	300	full	Done	6.50E+14	37	10.9	5.03E+14	12.1	Meas. missing	-	9.9	Meas. missing	-	wood	Done	
1	2	200	full	Done	2.50E+15	38	38.5	1.78E+15	10.5	Meas. missing	-	8.6	Meas. missing	-	wood	Done	
1	3	120	full	Done	1.0E+16	180	174.9	8.07E+15	2145.8	Meas. missing	-	2199.3	Meas. missing	-	wood	Done	
1	4	200	full	Done	2.50E+15	38	37.9	1.75E+15	0.1	Meas. missing	-	0	Meas. missing	-	Acrylic	Done	
1	5	200	full	Done	2.50E+15	38	38.1	1.76E+15	0.1	Meas. missing	-	0.1	Meas. missing	-	Acrylic	Done	
1	6	120	full	Done	1.0E+16	180	169.8	7.84E+15	2145.8	Meas. missing	-	2199.3	Meas. missing	-	Acrylic	Done	estimation Round 3, puck melted
1	7	120	full	Done	2.50E+15	38	39.3	1.81E+15	Estim. missing	Estim. missing	1.3	1.3	1.1	1.2	Acrylic	Done	
1	8	120	full	Done	5.00E+15	76	75.3	3.48E+15	Estim. missing	Estim. missing	9.5	8.4	7.9	8.1	Acrylic	Done	
1	9	300	full	Done	1.5E+15	23	23.3	1.08E+15	Estim. missing	Estim. missing	7.8	7.5	6.5	7	Acrylic	Done	
1	10	300	full	Done	1.00E+15	15	15.6	7.20E+14	Estim. missing	Estim. missing	12.4	10.1	9.9	10	Acrylic	Done	
1	11	200	full	Done	2.50E+15	38	41.3	1.91E+15	Estim. missing	Estim. missing	32.7	41.6	9.5	17.8	Acrylic	Done	
2	1	300	full	Done	1.5E+15	32	32.5	1.50E+15	106	7	8	143.7	6.2	6.7	Acrylic	Done for 1 sensor, 2 sensors with chipped edges	
2	2	300	full	Done	2.0E+15	43	44.7	2.06E+15	718	4	25	837.5	3.6	29.7	Acrylic	At TTU MAC for module assembly	
2	3	200	full	Done	4.0E+15	86	80.1	3.70E+15	440	4	8	503.4	3.6	7.1	PEEK	Done	
2	4	120	full	Done	1.0E+16	216	203.7	9.40E+15	149587	28231	62312	92175.8	22038.6	43208.4	PEEK	Done	overannealed
2	5	200	full	Done	4.0E+15	86	90.0	4.15E+15	49	9	16	48.7	7.7	14	PEEK	Done	
2	6	200	full	Done	5.5E+15	118	113.2	5.22E+15	962	19	115	1028.7	16.5	131.9	PEEK	Done	
2	7	300	full	Done	2.0E+15	43	44.6	2.06E+15	10	10	9	8.3	8.1	7.6	Acrylic	Done	After the irradiation back foam is hotter than the front
2	8	300	full	Done	1.5E+15	32	33.6	1.55E+15	11	8	8	9.9	6.7	6.7	Acrylic	Done	
2	9 (I)	120	full	Done	1.0E+16	108	116.6	5.38E+15	227	10	32	272.2	8.3	29.2	PEEK	Done	
2	9 (II)	120	full	Done		108	109.3	5.04E+15	227	10	32	272.2	8.3	29.2	PEEK	Done	Estimation round 9 (I) (PC broke)
2	10 (I)	120	full	Done	1.4E+16	152	140.4	6.48E+15	84.3	41.4	57.3	88.7	36.3	54.8	Aluminum	Done	
2	10 (II)	120	full	Done		152	142.5	6.58E+15	30599.2	Meas. missing	-	24333.9	Meas. missing	-	Aluminum	Done	overannealed (85-90 % of ice)
2	11	200	full	Done	5.5E+15	118	106.8	4.93E+15	119.9	80.7	85.2	124.1	70.9	80.2	Aluminum	Done	
2	12 (I)	120	full	Done	1.4E+16	152	148.8	6.87E+15	168.1	140	148.4	64.3	48.7	53.4	Aluminum	Done	For the calc with KIT webpage not corrected values used
2	12 (II)	120	full	Done		152	143.4	6.62E+15	115.2	42.4	66.3	121.4	36.8	62.6	Aluminum	Done	
2	13	200	partial	Done	5.5E+15	118	113.8	5.25E+15	228.7	49.2	87.6	271.3	39.1	81.7	Aluminum	Done	
2	14 (I)	120	partial	Done	1.0E+16	108	101.4	4.68E+15	61.9	31.4	38.6	52.4	24.5	30.2	Aluminum	Done	
2	14 (II)	120	partial	Done		108	104.5	4.82E+15	41	31.4	38.6	34.9	24.5	30.2	Aluminum	Done	Estimation round 14 (I)
2	15	300	partial	Done	1.5E+15	33.1	33.1	1.53E+15	Estim. missing	Estim. missing	-	22.3	2.3	7.1	Aluminum	Modules	KIT webpage not working anymore

HGCal



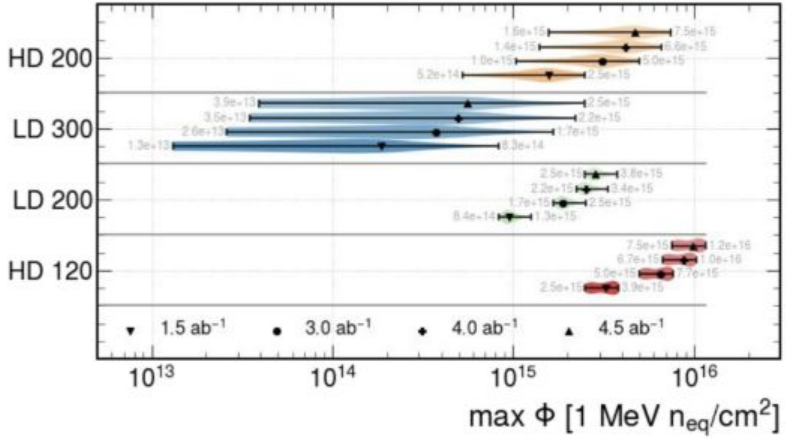
PRR for HD and all partial sensors

- Procurement Readiness Review (PRR) on 11 October 2023
- Presentations on strategy, sensor quality & radiation hardness, oxide variants, layout optimization and module measurements using irradiated sensors
- **Sensor designs validated** and adequate up to the required fluences
- **Formal approval** to start production of the 120µm HD sensors and all partial sensor types
- **Approval of layout optimisation of HGCAL silicon section**:
  - Deploy more thick sensors in higher radiation regions
    - HD: ~ 55% 200µm + ~45% 120µm
    - LD: ~ 85% 300µm + ~15% 200µm



HD 200µm: New variant

Fluence exposure after optimization



Recommendations

Recommendations for further irradiation rounds

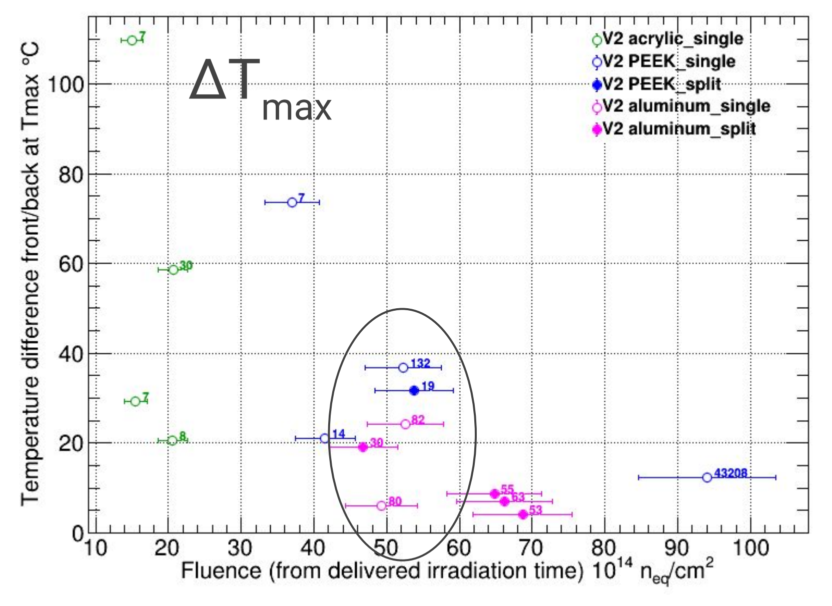
- Use more temperature sensors to mitigate potential system failure (no temperature data for 4 of 30 rounds, incomplete temperature data sets for 5 rounds)
    - If possible, add temperature sensors directly next to silicon sensors
    - Minimum 2 sensors in the front of the puck + 2 sensors in the back of the puck
    - Ideally use array of temperature sensors across wafer area

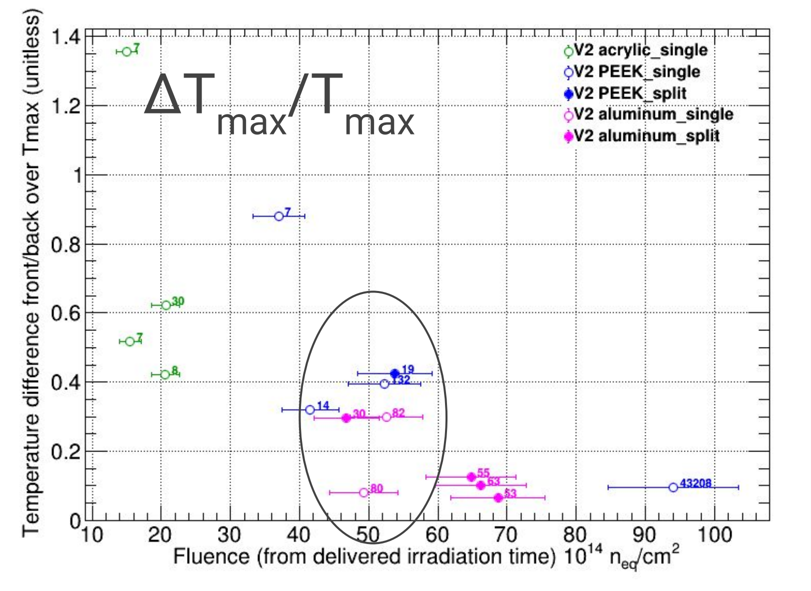
- Ensure that the recording time of the temperature sensors is long enough to cover the full time until the cylinders are placed in the freezer (1 of 30 rounds)
- Ensure consistent naming of the columns in the temperature recording file
- Use a single document to write down all changes to material, puck form, measurement method and measures which would potentially influence the irradiation method with a date, when this change was made

- In view of fluence inhomogeneities: for split rounds, ensure consistent orientation (rotation) of the sensors during the irradiation rounds
    - Sensor within puck
    - Puck orientation within the cylinder
    - Cylinder orientation in the beam port

Further studies of the temperature profiles

ΔT_{max} and $\Delta T_{max}/T_{max}$ vs. Fluence

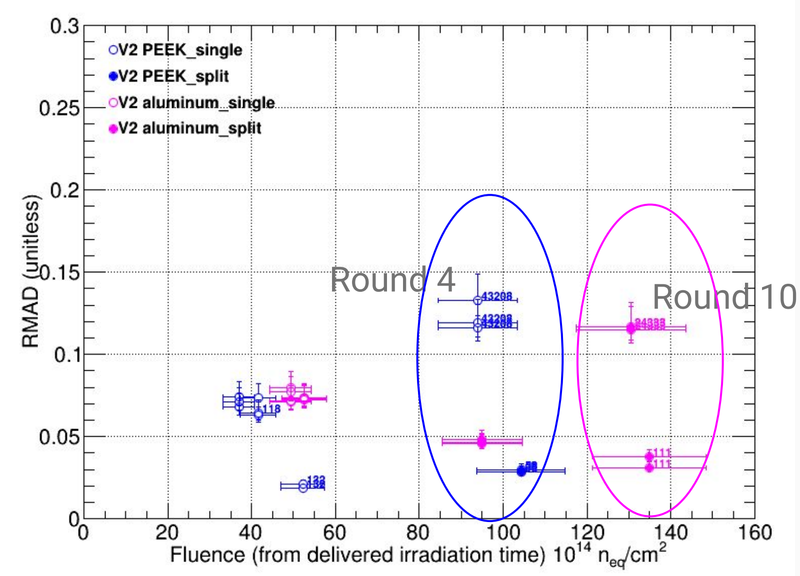




- Temperature difference decreases with fluence
- At same fluence, lower temperature difference in aluminium than in PEEK
    - Could be linked to better thermal conductivity of aluminium

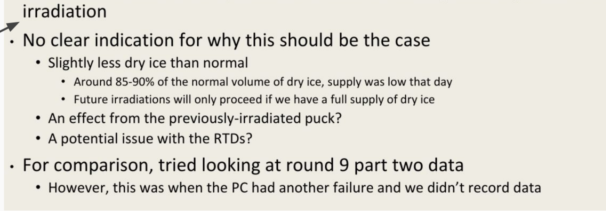
Split rounds enter twice at approximately half the target fluence
Included only results where back and front temperature data are present

RMAD: Split. vs single rounds



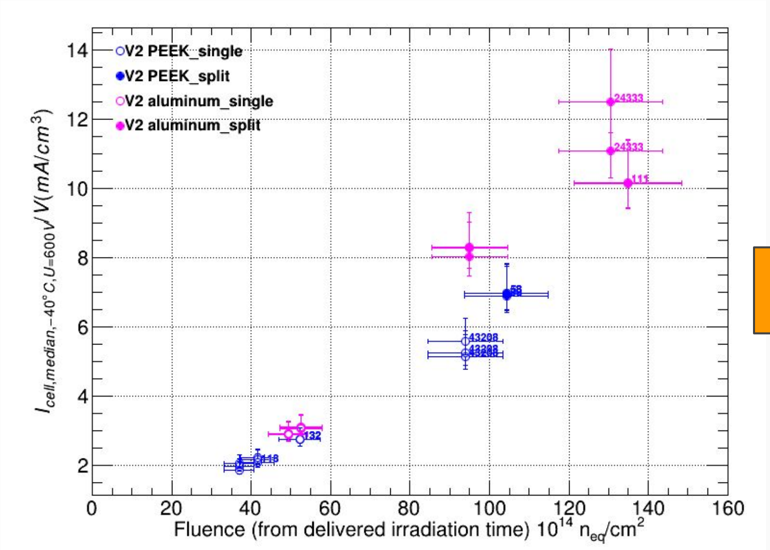
- Blue circle: Splitting reduced leakage current gradient
- Magenta circle: Similar difference in leakage current gradient observed in two separate split rounds
- No clear conclusion on reduction of gradient when using split rounds based on available data set
- Note: Suspicion that round 10 irradiation had problems

Round 10, comments of Nick:

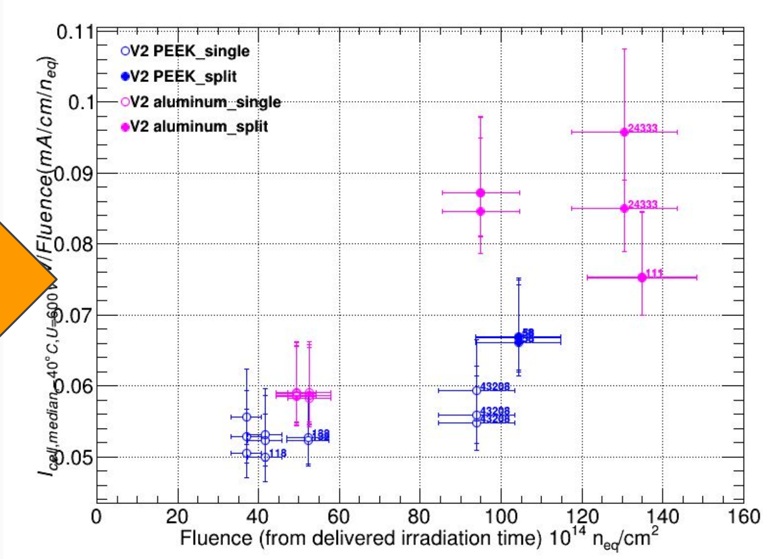


- **Dramatic** increase in temperatures measured during second part of the irradiation
- No clear indication for why this should be the case
  - Slightly less dry ice than normal
    - Around 85-90% of the normal volume of dry ice, supply was low that day
    - Future irradiations will only proceed if we have a full supply of dry ice
  - An effect from the previously-irradiated puck?
  - A potential issue with the RTDs?
- For comparison, tried looking at round 9 part two data
  - However, this was when the PC had another failure and we didn't record data

Relative current median: split vs. single rounds



Fluence normalised



- Volume normalised leakage current over fluence -> alpha
  - Would expect for data with higher annealing times to have lower alpha
    - Fulfilled for PEEK
    - Not fulfilled for aluminium
      - Potentially linked to temperature recording mistake in round 10 (a.k.a. 24333 min)

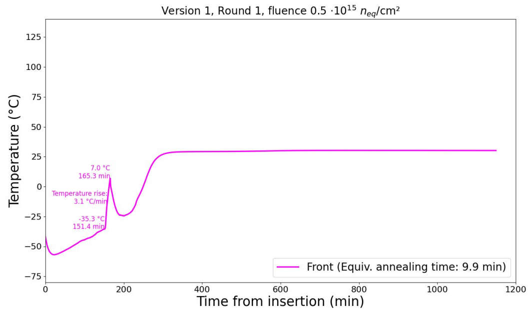
Annealing time error estimation

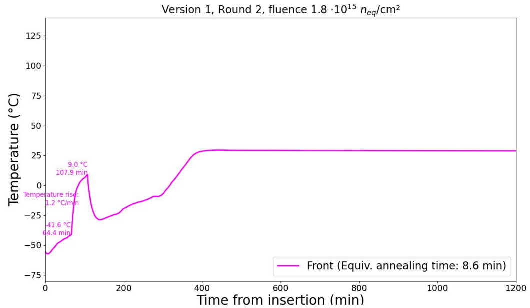
Sources of error:

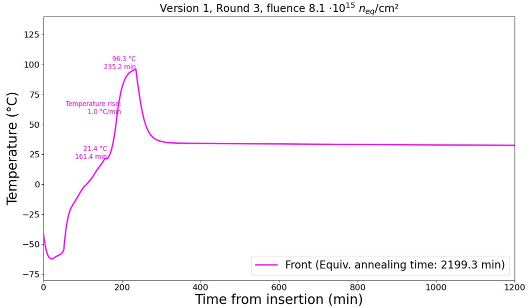
- Gross errors:
    - Missing measurement on the back side of the puck (v1: R1-5, v2: R10a) → uncertainty factor of 50 % of the estimated time for the front side ($time_{front}$): $\Delta_{missing\_back}$
    - Missing the measurement data set for the round: $\Delta_{missing\_round}$
        - v1: R6 → uncertainty factor of 100 % of the estimated average time of a similar round (v1: R3), because the puck material was different and the acrylic puck melted during this round
        - v2: R14b → uncertainty factor of 20% of the estimated average time of v2: R14a, as no unexpected events happened and there was still dry ice in the cylinder in both case, the puck material was the same
        - v2: R9b - dito
- Random error:
    - Time measurement error → 10% of the estimated average time ($time_{average}$): Δ_{time}
- Systematic errors:
    - Estimation error: 50% * ($time_{front}$ - $time_{average}$): $\Delta_{estimation\_front}$
    - Estimation error: 50% * ($time_{average}$ - $time_{back}$): $\Delta_{estimation\_back}$
- **Total error front:**
    - $\sqrt{(\Delta^2_{missing\_round} + \Delta^2_{time} + \Delta^2_{estimation\_front})}$
- **Total error back:**
    - $\sqrt{(\Delta^2_{missing\_back} + \Delta^2_{missing\_round} + \Delta^2_{time} + \Delta^2_{estimation\_back})}$

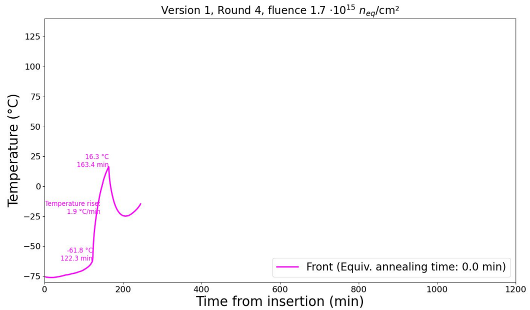
Table with errors

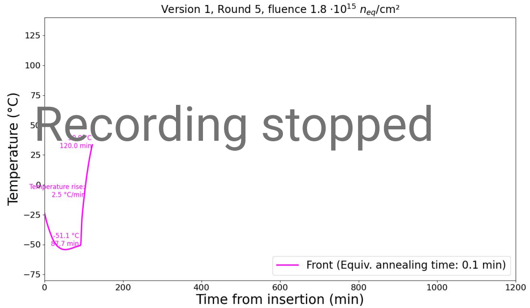
Temperature profiles of rounds



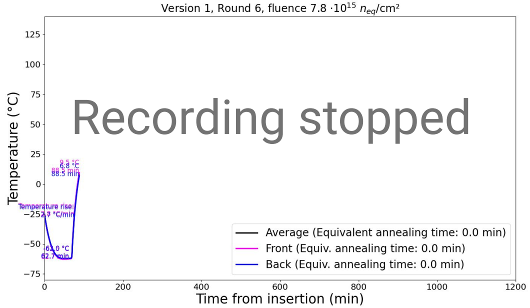




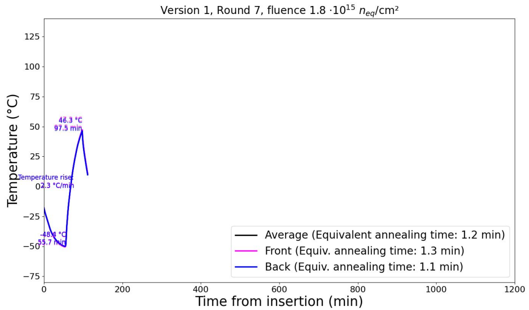


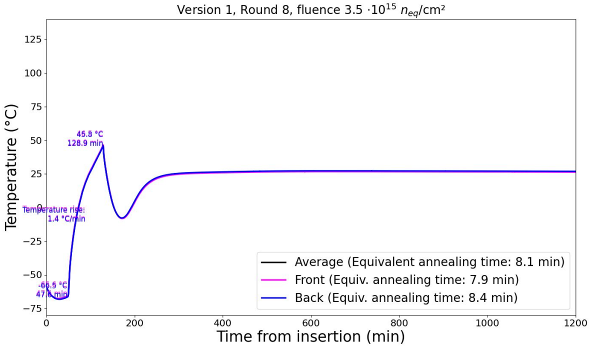


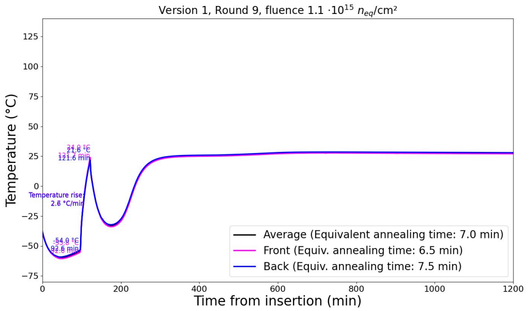
Recording stopped

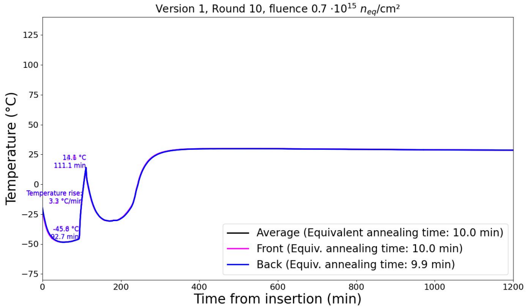


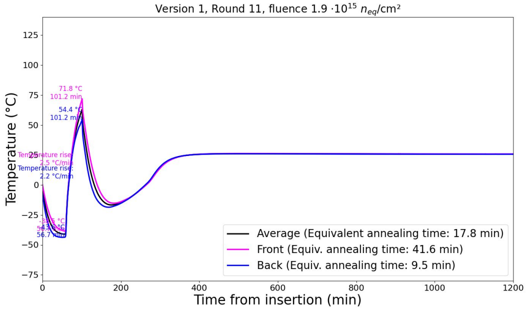
Recording stopped

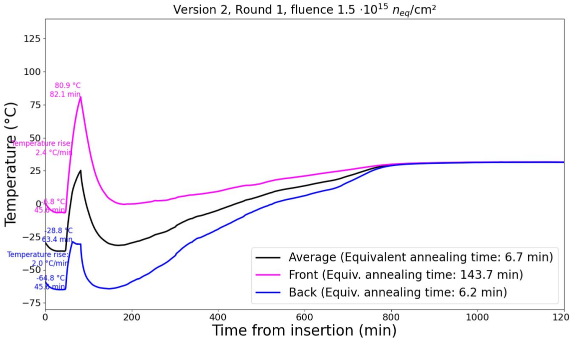


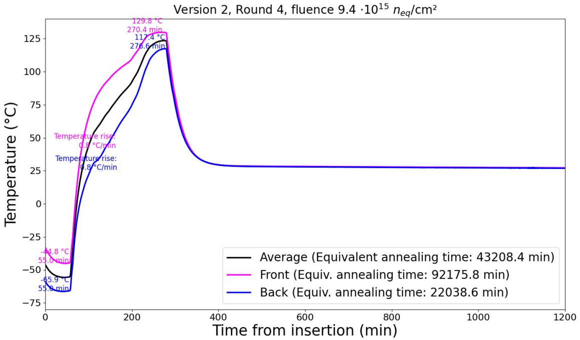


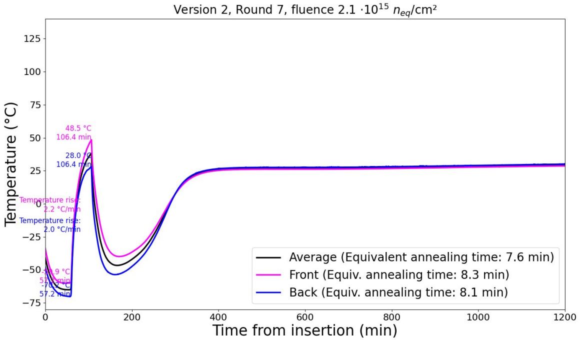

Version 1, Round 9, fluence 1.1 $\cdot 10^{15}$ n_{eq}/cm²

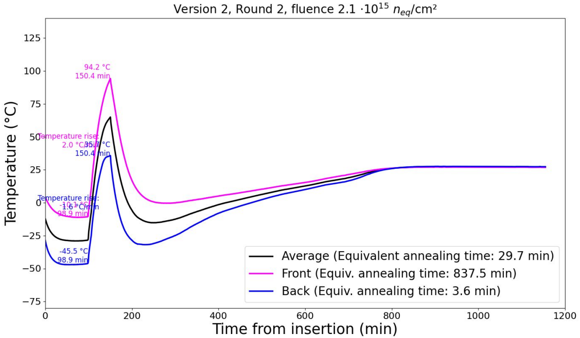

Version 1, Round 10, fluence 0.7 $\cdot 10^{15}$ n_{eq}/cm²

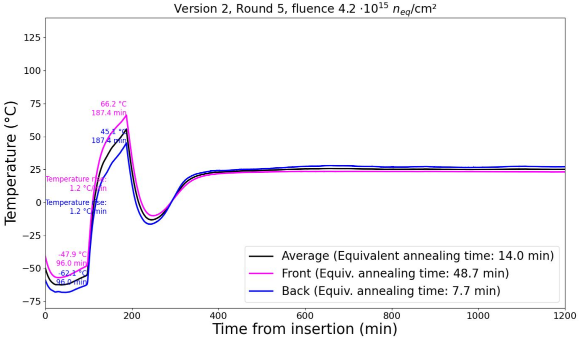

Version 1, Round 11, fluence 1.9 $\cdot 10^{15}$ n_{eq}/cm²

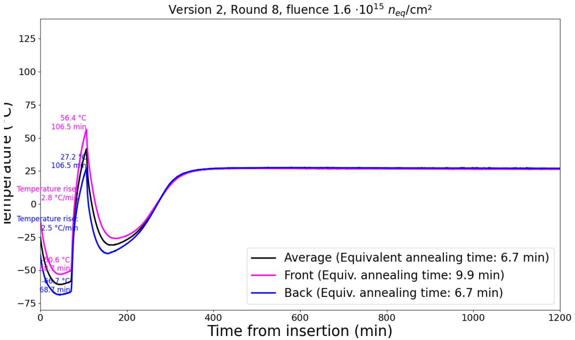

Version 2, Round 1, fluence 1.5 ·10^{15} n_{eq}/cm²

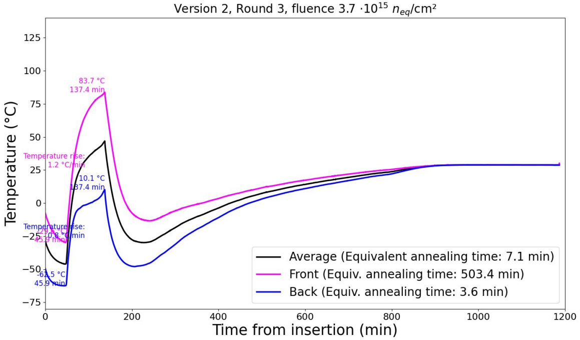

Version 2, Round 4, fluence 9.4 ·10^{15} n_{eq}/cm²

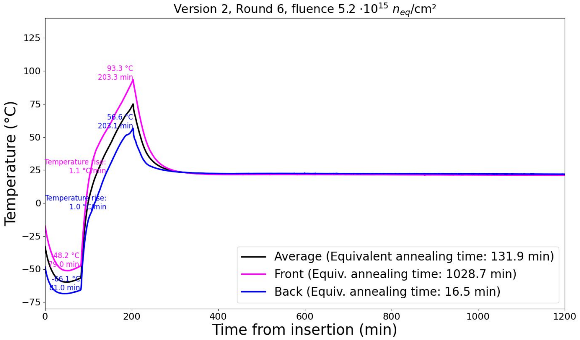

Version 2, Round 7, fluence 2.1 ·10^{15} n_{eq}/cm²


Version 2, Round 2, fluence 2.1 ·10^{15} n_{eq}/cm²

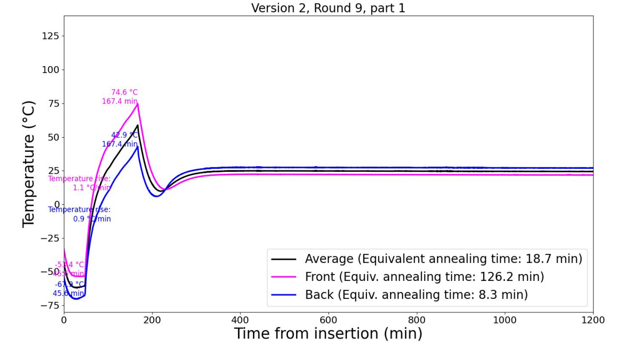

Version 2, Round 5, fluence 4.2 ·10^{15} n_{eq}/cm²


Version 2, Round 8, fluence 1.6 ·10^{15} n_{eq}/cm²

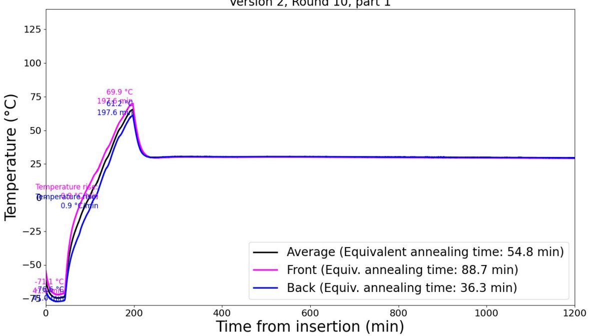

Version 2, Round 3, fluence 3.7 ·10^{15} n_{eq}/cm²

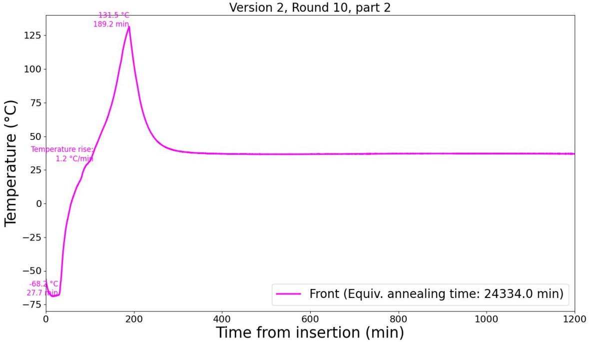

Version 2, Round 6, fluence 5.2 ·10^{15} n_{eq}/cm²

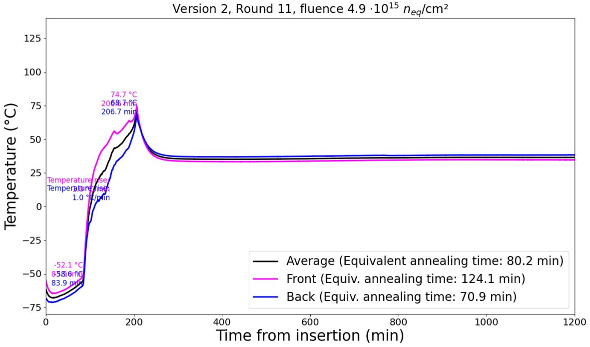
ons

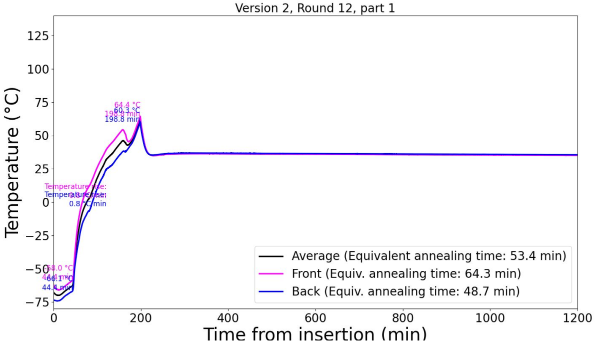


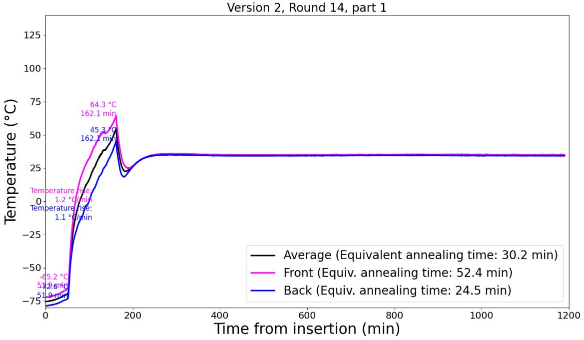
V2, R9, part 2
Recording stopped

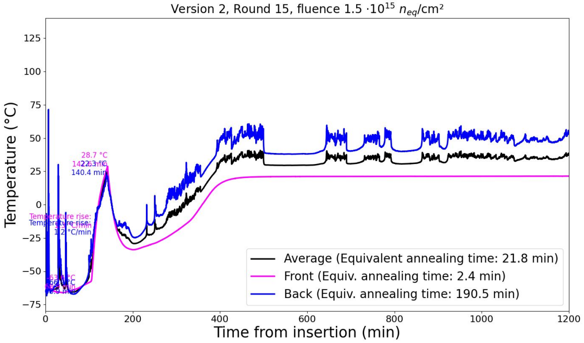


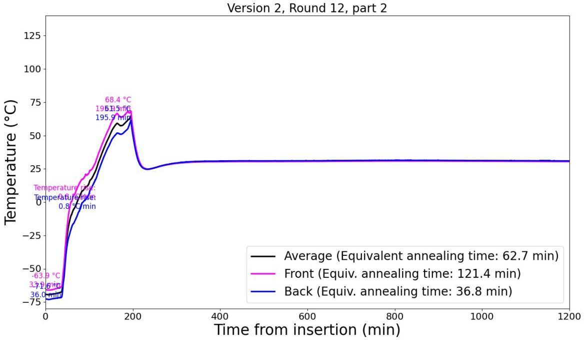


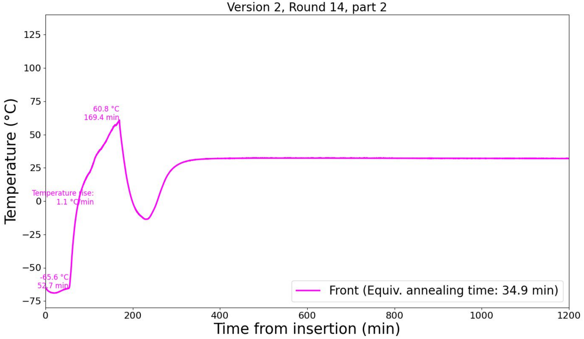


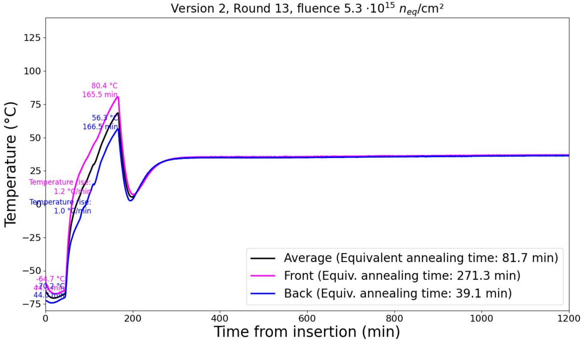

Version 2, Round 12, part 1
Temperature (°C)
Time from insertion (min)
64.4 °C
60.3 °C
198.8 min
Temperature rise:
0.8 °C/min
44.4 min
Average (Equivalent annealing time: 53.4 min)
Front (Equiv. annealing time: 64.3 min)
Back (Equiv. annealing time: 48.7 min)


Version 2, Round 14, part 1
Temperature (°C)
Time from insertion (min)
64.3 °C
162.1 min
45.3 °C
162.1 min
Temperature rise:
1.2 °C/min
Temperature rise:
1.1 °C/min
-65.2 °C
51.9 min
Average (Equivalent annealing time: 30.2 min)
Front (Equiv. annealing time: 52.4 min)
Back (Equiv. annealing time: 24.5 min)


Version 2, Round 15, fluence 1.5 ·10^15 n_eq/cm²
Temperature (°C)
Time from insertion (min)
28.7 °C
140.4 min
Temperature rise:
1.2 °C/min
Average (Equivalent annealing time: 21.8 min)
Front (Equiv. annealing time: 2.4 min)
Back (Equiv. annealing time: 190.5 min)


Version 2, Round 12, part 2
Temperature (°C)
Time from insertion (min)
68.4 °C
195.9 min
Temperature rise:
0.8 °C/min
-63.9 °C
36.0 min
Average (Equivalent annealing time: 62.7 min)
Front (Equiv. annealing time: 121.4 min)
Back (Equiv. annealing time: 36.8 min)


Version 2, Round 14, part 2
Temperature (°C)
Time from insertion (min)
60.8 °C
169.4 min
Temperature rise:
1.1 °C/min
-65.6 °C
52.7 min
Front (Equiv. annealing time: 34.9 min)


Version 2, Round 13, fluence 5.3 ·10^15 n_eq/cm²
Temperature (°C)
Time from insertion (min)
80.4 °C
165.5 min
56.3 °C
166.5 min
Temperature rise:
1.2 °C/min
Temperature rise:
1.0 °C/min
-64.7 °C
44.3 min
Average (Equivalent annealing time: 81.7 min)
Front (Equiv. annealing time: 271.3 min)
Back (Equiv. annealing time: 39.1 min)

Idea of CV annealing study to investigate annealing profile via optimal annealing time in Vdep

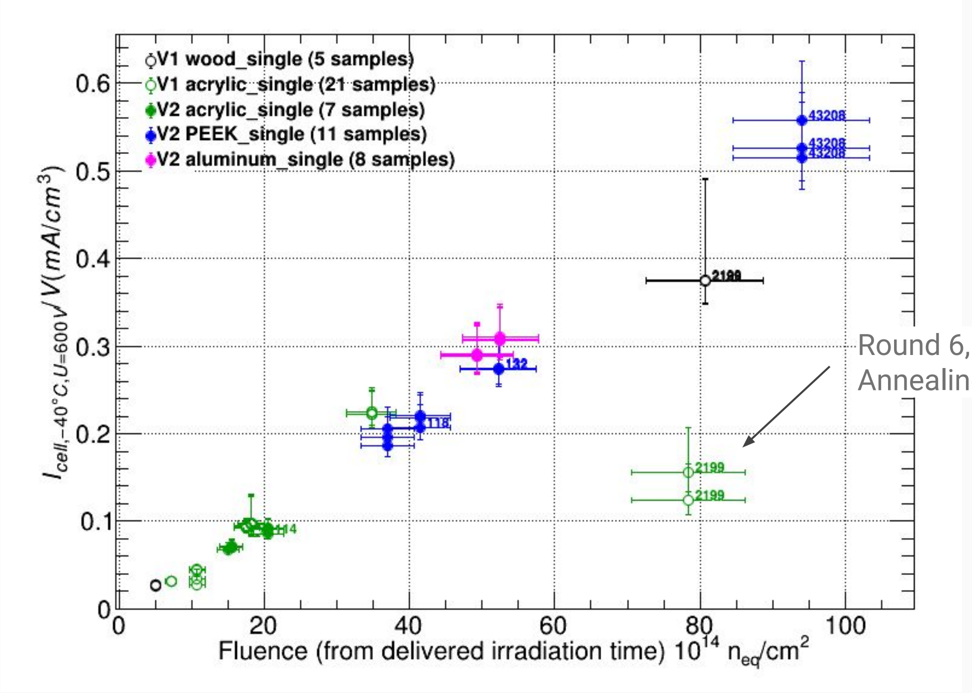
Recommendations for further CV studies

- Perform detailed CV annealing campaign
    - Plot Vdep vs annealing time for all cells across sensor
    - Extract optimal annealing time for all cells
    - Plot optimal annealing time as HexPlot

- Expect optimum to be at 90 (120) min for epi(FZ) sensors
    - If optimum for a epi sensor is found at 20 min, sensor has seen 70 min of annealing in reactor
    - If optimum for a epi sensor is found at 50 min, sensor has seen 40 min of annealing in reactor
    - If optimum for a epi sensor is found at 70 min, sensor has seen 20 min of annealing in reactor
- Gradient in optimal annealing time across sensor would hint at annealing time gradient

- Attention:
    - Vdep can only be estimated for low fluence rounds or thin sensors (measurement up to 1000V)
    - Propose to perform study with epi sensor

Comparison of puck materials (Median)



Round 6, puck melted
Annealing time likely underestimated

- Comparing rounds irradiated in a single step

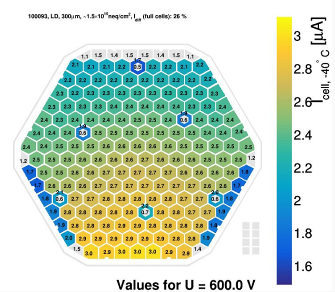
Hexplots of sensors irradiated at RINSC, currents not scaled with cell volume

Compatible profiles for sensors of same round

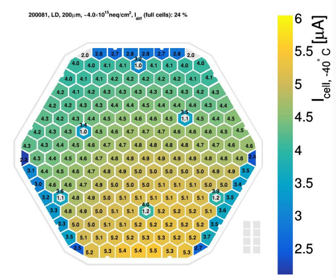
Round 1

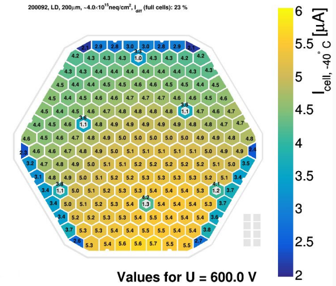
100082:
Chipped corner

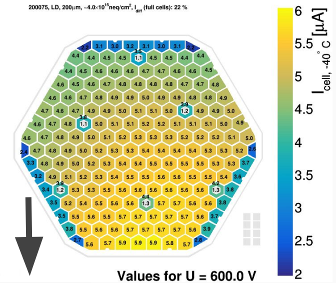
100076:
Chipped corner



Round 3

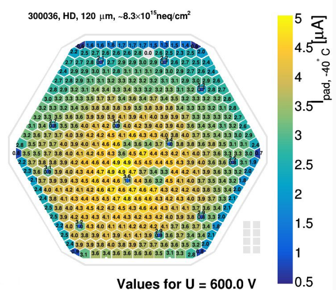


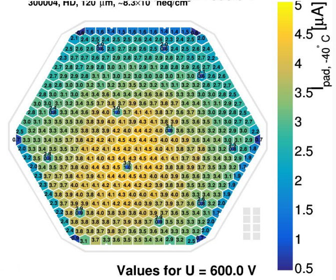


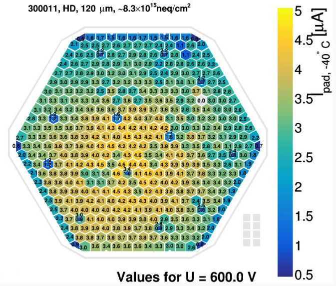


Reactor

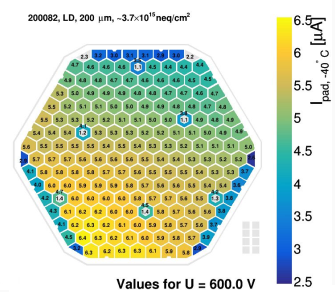
Round 4

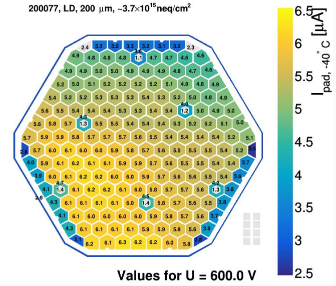


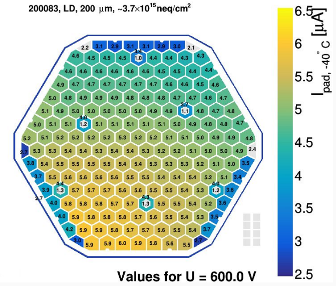




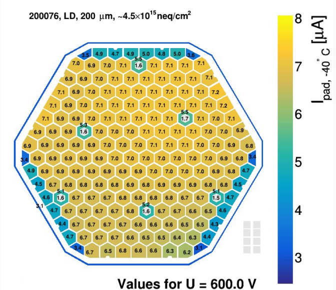
Round 5

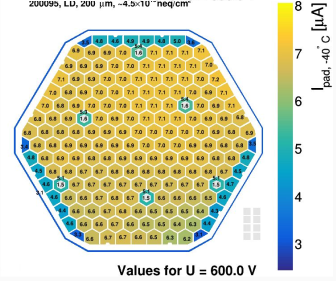






Round 6

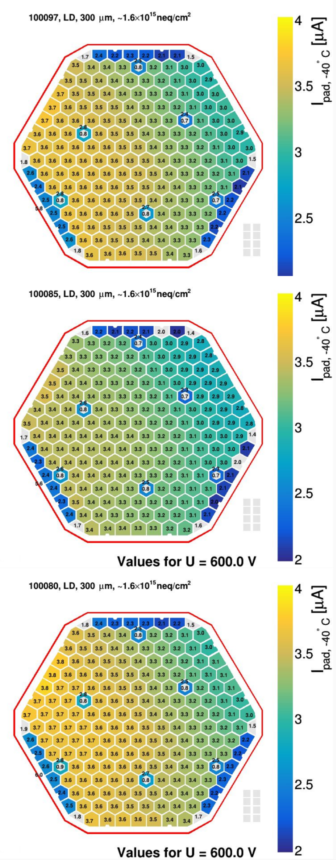




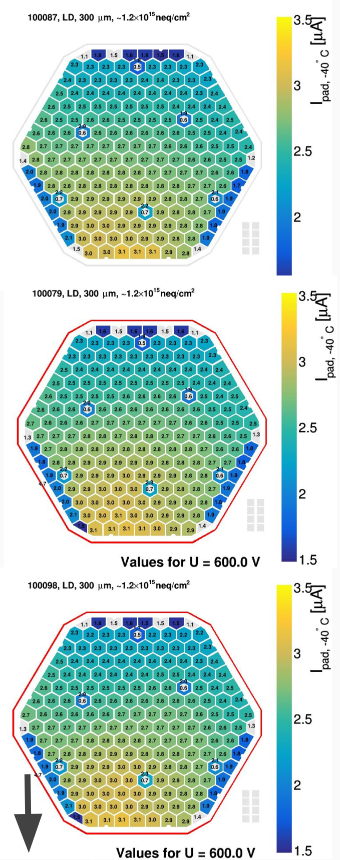
200093: over annealed

Compatible profiles for sensors of same round

Round 7

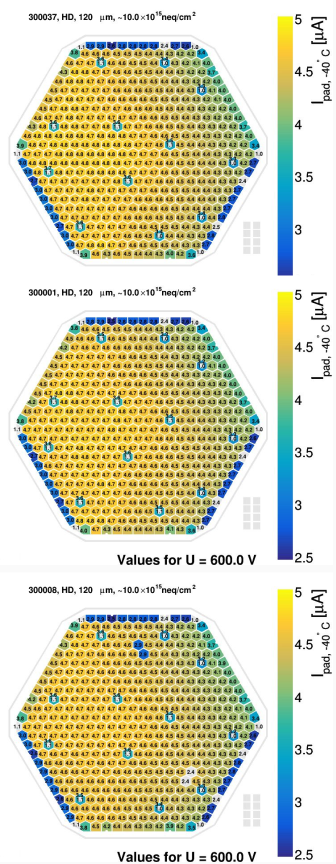


Round 8



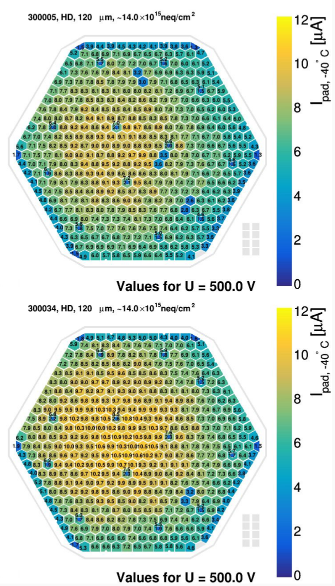
Reactor

Round 9

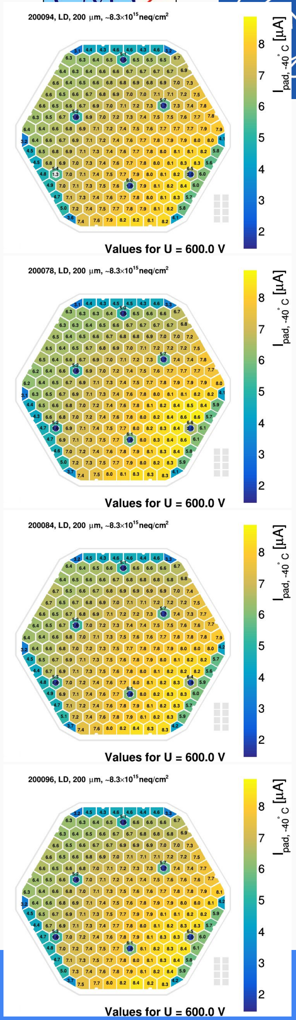


Round 10

300009:
Chipped corner

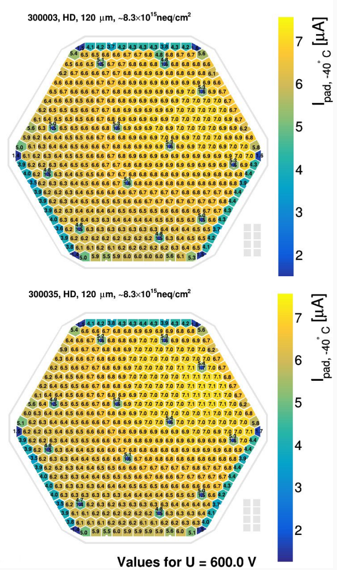


Round 11



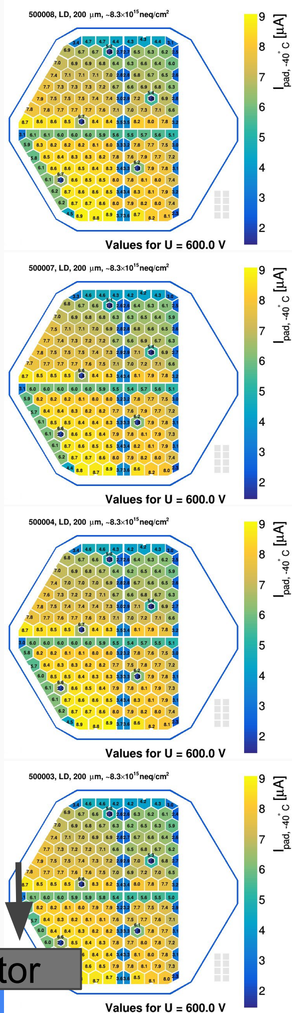
Compatible profiles for sensors of same round: **New rounds**

Round 12 (order unknown)



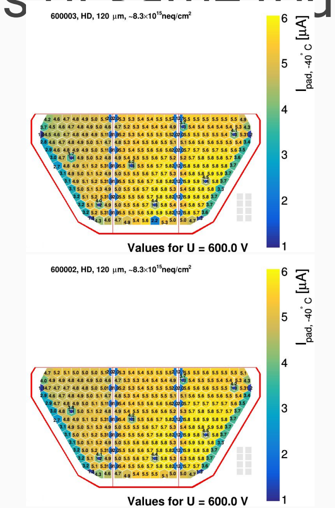
300010:
Chipped corner

Round 13

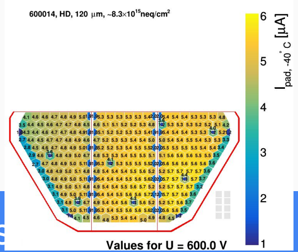


Reactor

Round 14



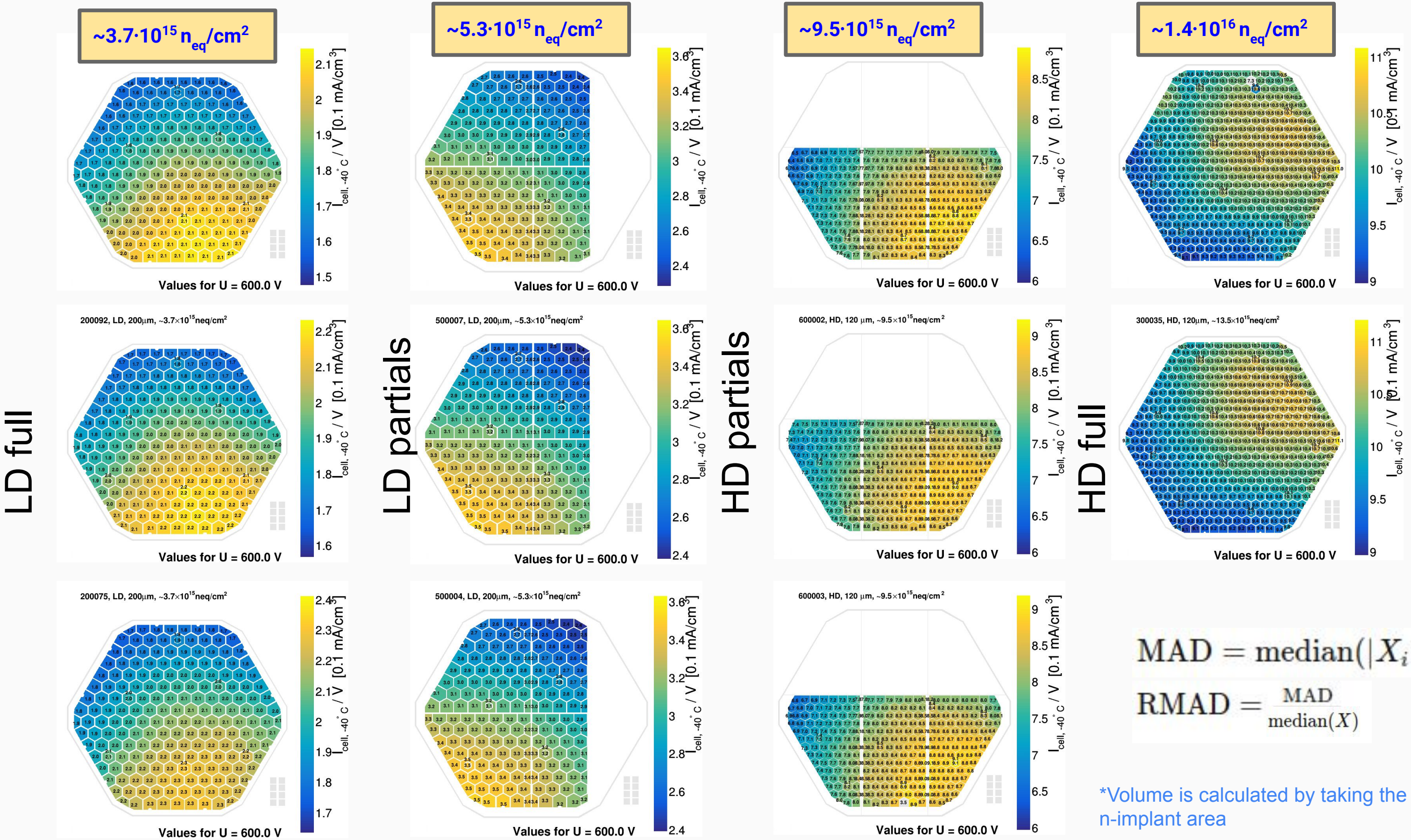
600015:
Chipped corner



- Rounds 11, 12 and 14 have consistent fluence pattern
- I_{pad} mostly scales with cell size and delivered fluence, as expected.

Hexplots of sensors irradiated at RINSC, currents scaled with cell volume

Leakage current gradient across wafer



~3.7·10^{15} n$_{eq}$/cm^2

~5.3·10^{15} n$_{eq}$/cm^2

~9.5·10^{15} n$_{eq}$/cm^2

~1.4·10^{16} n$_{eq}$/cm^2

LD full

LD partials

HD partials

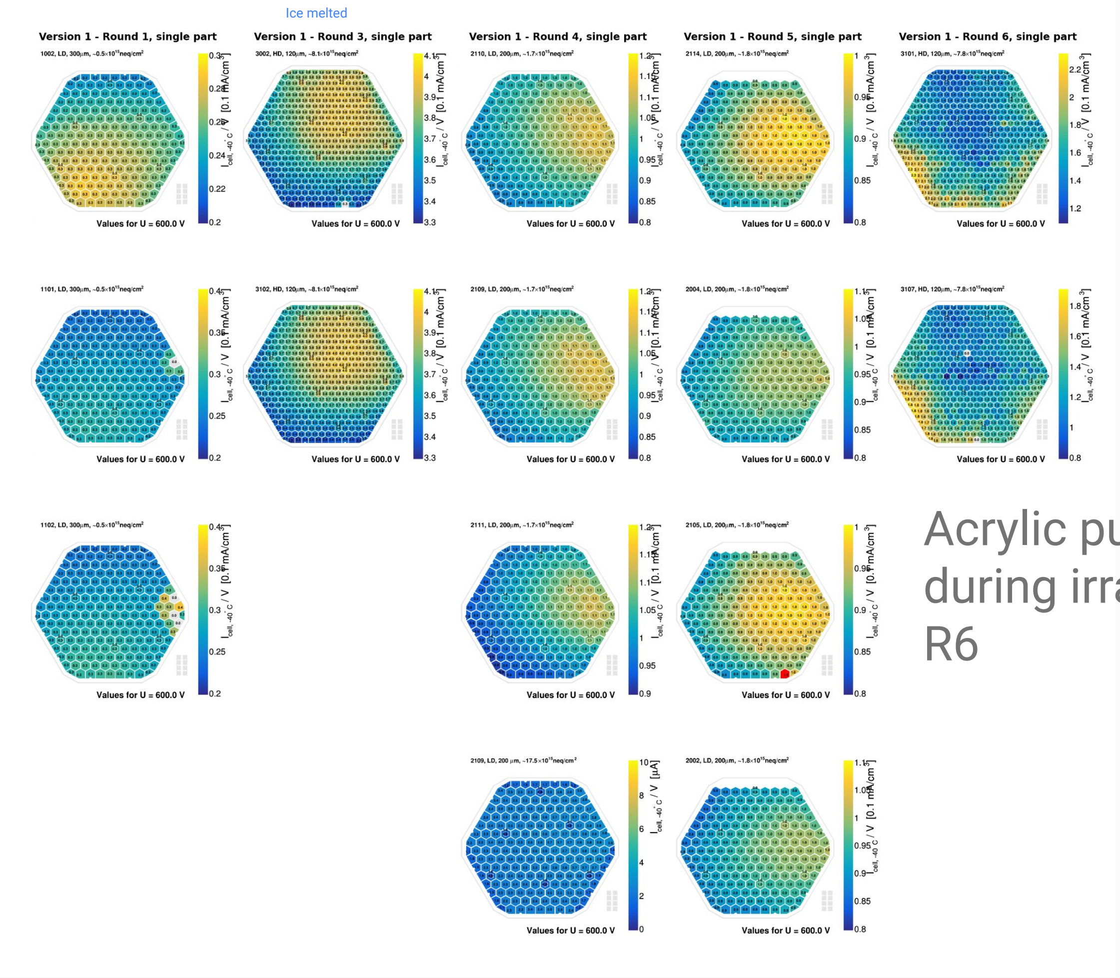
HD full

- Similar gradient between sensors of same irradiation round
- Quantify gradient by Relative Median Absolute Deviation (RMAD) is Median Absolute Deviation (MAD) divided by the median.

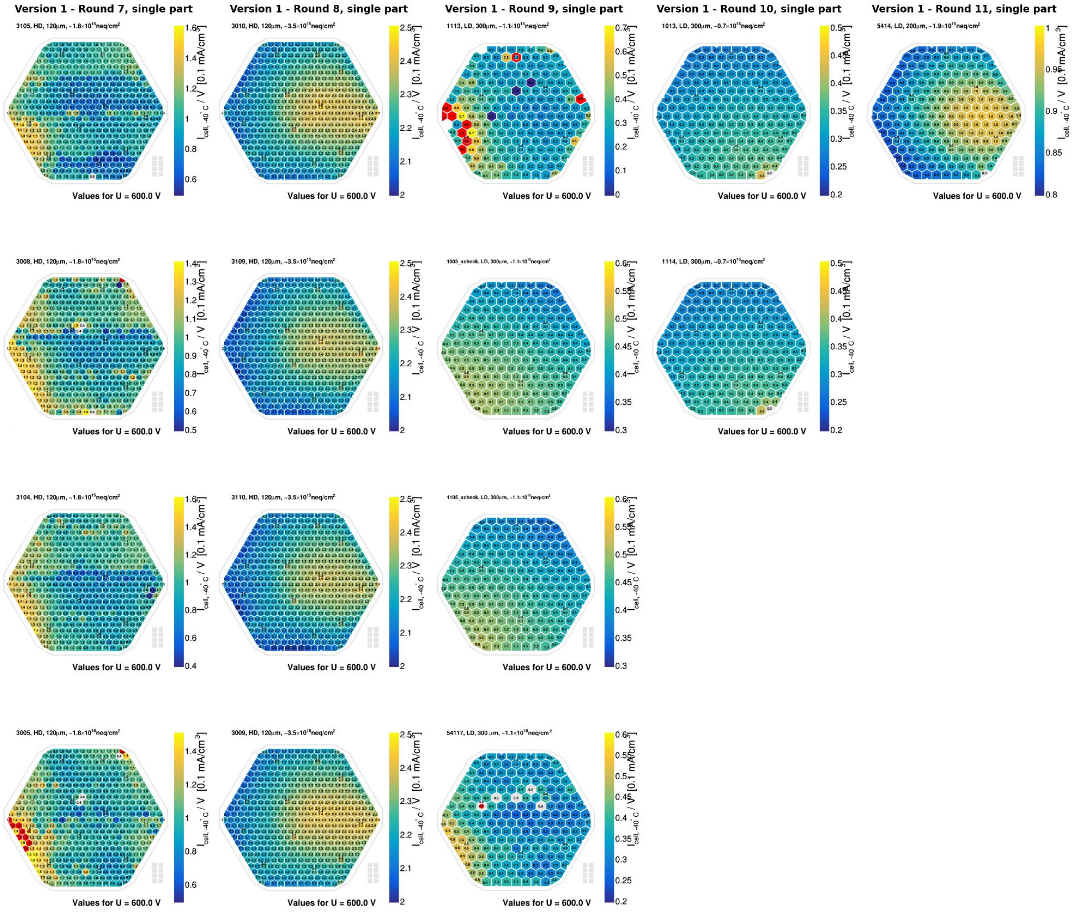
$$\mathrm{MAD} = \mathrm{median}(|X_i - \mathrm{median}(X)|)$$

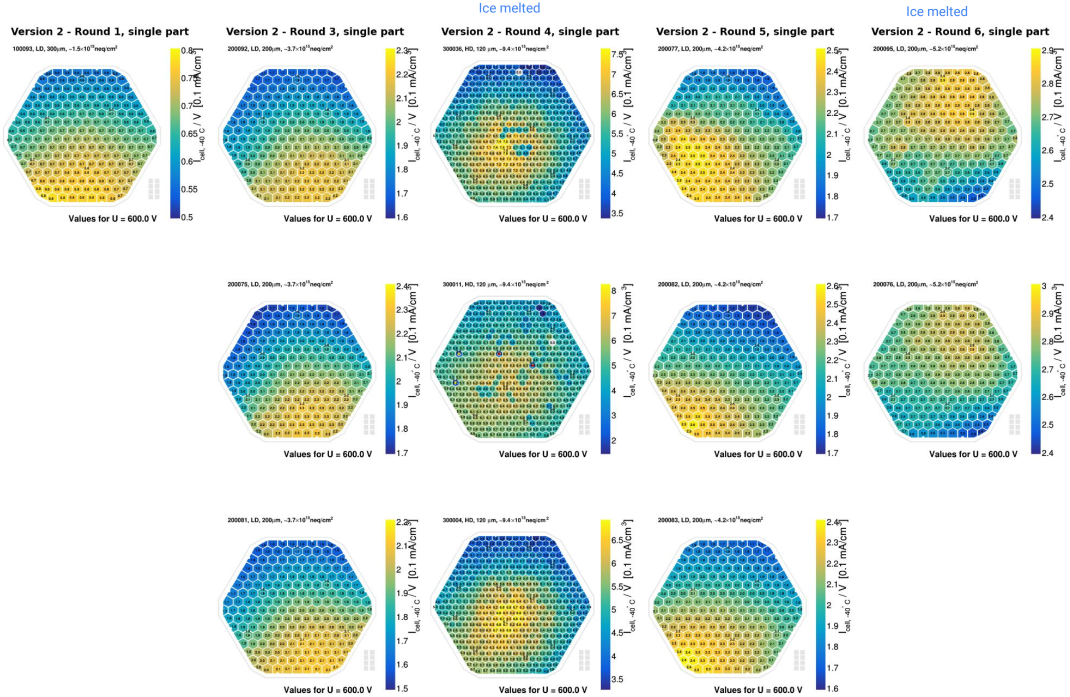
$$\mathrm{RMAD} = \frac{\mathrm{MAD}}{\mathrm{median}(X)}$$

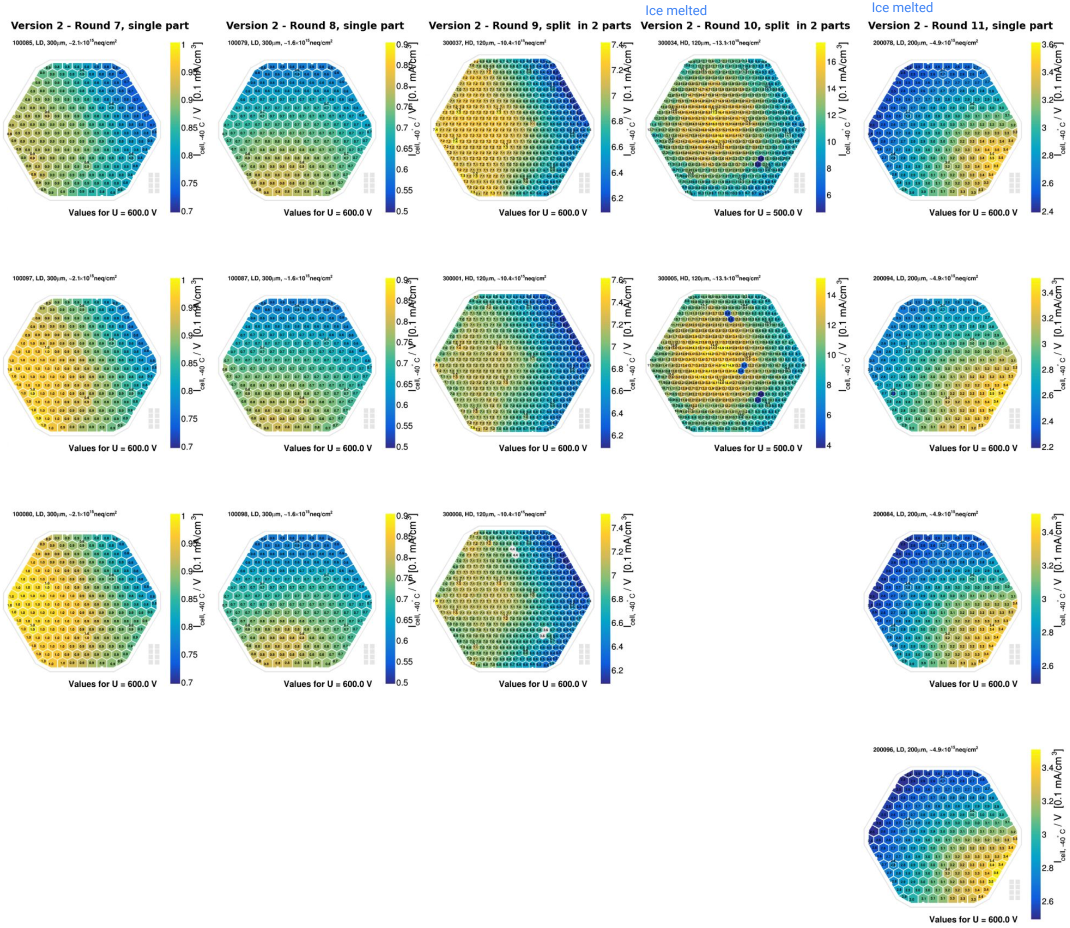
*Volume is calculated by taking the n-implant area



Acrylic puck melted during irradiation for R6

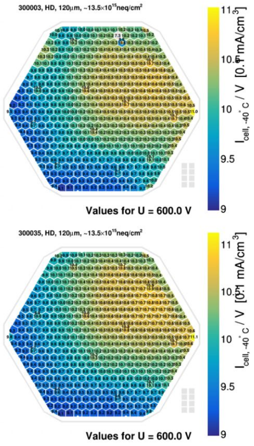

Version 1 - Round 7, single part
Version 1 - Round 8, single part
Version 1 - Round 9, single part
Version 1 - Round 10, single part
Version 1 - Round 11, single part
3105, HD, 120µm, ~1.8×10¹⁵neq/cm²
3010, HD, 120µm, ~3.5×10¹⁵neq/cm²
1113, LD, 300µm, ~1.1×10¹⁵neq/cm²
1013, LD, 300µm, ~0.7×10¹⁵neq/cm²
5414, LD, 200µm, ~1.9×10¹⁵neq/cm²
3008, HD, 120µm, ~1.8×10¹⁵neq/cm²
3109, HD, 120µm, ~3.5×10¹⁵neq/cm²
1003_xcheck, LD, 300µm, ~1.1×10¹⁵neq/cm²
1114, LD, 300µm, ~0.7×10¹⁵neq/cm²
3104, HD, 120µm, ~1.8×10¹⁵neq/cm²
3110, HD, 120µm, ~3.5×10¹⁵neq/cm²
1105_xcheck, LD, 300µm, ~1.1×10¹⁵neq/cm²
3005, HD, 120µm, ~1.8×10¹⁵neq/cm²
3009, HD, 120µm, ~3.5×10¹⁵neq/cm²
54117, LD, 300 µm, ~1.1×10¹⁵neq/cm²
I_cell, -40°C / V [0.1 mA/cm³]
Values for U = 600.0 V


Ice melted
Ice melted
Version 2 - Round 1, single part
Version 2 - Round 3, single part
Version 2 - Round 4, single part
Version 2 - Round 5, single part
Version 2 - Round 6, single part
100093, LD, 300μm, ~1.5×10^15neq/cm²
200092, LD, 200μm, ~3.7×10^15neq/cm²
300036, HD, 120 μm, ~9.4×10^15neq/cm²
200077, LD, 200μm, ~4.2×10^15neq/cm²
200095, LD, 200μm, ~5.2×10^15neq/cm²
200075, LD, 200μm, ~3.7×10^15neq/cm²
300011, HD, 120 μm, ~9.4×10^15neq/cm²
200082, LD, 200μm, ~4.2×10^15neq/cm²
200076, LD, 200μm, ~5.2×10^15neq/cm²
200081, LD, 200μm, ~3.7×10^15neq/cm²
300004, HD, 120 μm, ~9.4×10^15neq/cm²
200083, LD, 200μm, ~4.2×10^15neq/cm²
Values for U = 600.0 V
I_cell, -40°C / V [0.1 mA/cm³]
0.5 0.55 0.6 0.65 0.7 0.75 0.8
1.6 1.7 1.8 1.9 2 2.1 2.2 2.3
3.5 4 4.5 5 5.5 6 6.5 7 7.5
1.7 1.8 1.9 2 2.1 2.2 2.3 2.4 2.5
2.4 2.5 2.6 2.7 2.8 2.9
1.7 1.8 1.9 2 2.1 2.2 2.3 2.4
2 3 4 5 6 7 8
1.7 1.8 1.9 2 2.1 2.2 2.3 2.4 2.5 2.6
2.4 2.5 2.6 2.7 2.8 2.9 3
1.5 1.6 1.7 1.8 1.9 2 2.1 2.2
3.5 4 4.5 5 5.5 6 6.5
1.6 1.7 1.8 1.9 2 2.1 2.2 2.3 2.4

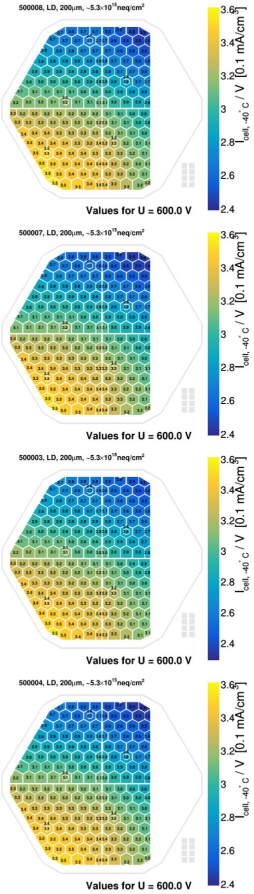

Ice melted
Ice melted
Version 2 - Round 7, single part
Version 2 - Round 8, single part
Version 2 - Round 9, split in 2 parts
Version 2 - Round 10, split in 2 parts
Version 2 - Round 11, single part
100085, LD, 300μm, ~2.1×10^15neq/cm²
100079, LD, 300μm, ~1.6×10^15neq/cm²
300037, HD, 120μm, ~10.4×10^15neq/cm²
300034, HD, 120μm, ~13.1×10^15neq/cm²
200078, LD, 200μm, ~4.9×10^15neq/cm²
100097, LD, 300μm, ~2.1×10^15neq/cm²
100087, LD, 300μm, ~1.6×10^15neq/cm²
300001, HD, 120μm, ~10.4×10^15neq/cm²
300005, HD, 120μm, ~13.1×10^15neq/cm²
200094, LD, 200μm, ~4.9×10^15neq/cm²
100080, LD, 300μm, ~2.1×10^15neq/cm²
100098, LD, 300μm, ~1.6×10^15neq/cm²
300008, HD, 120μm, ~10.4×10^15neq/cm²
200084, LD, 200μm, ~4.9×10^15neq/cm²
200096, LD, 200μm, ~4.9×10^15neq/cm²
$I_{cell, -40^\circ C}$ / V [0.1 mA/cm³]
Values for U = 600.0 V
Values for U = 500.0 V

Ice melted

Version 2 - Round 12, split in 2 parts



Version 2 - Round 13, single part



Version 2 - Round 14, split in 2 parts