Temperature-Leakage current study using 8-inch silicon sensors for CMS HGCAL

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on behalf of the CMS collaboration

University of Michigan Final Summer Student Presentations 2023

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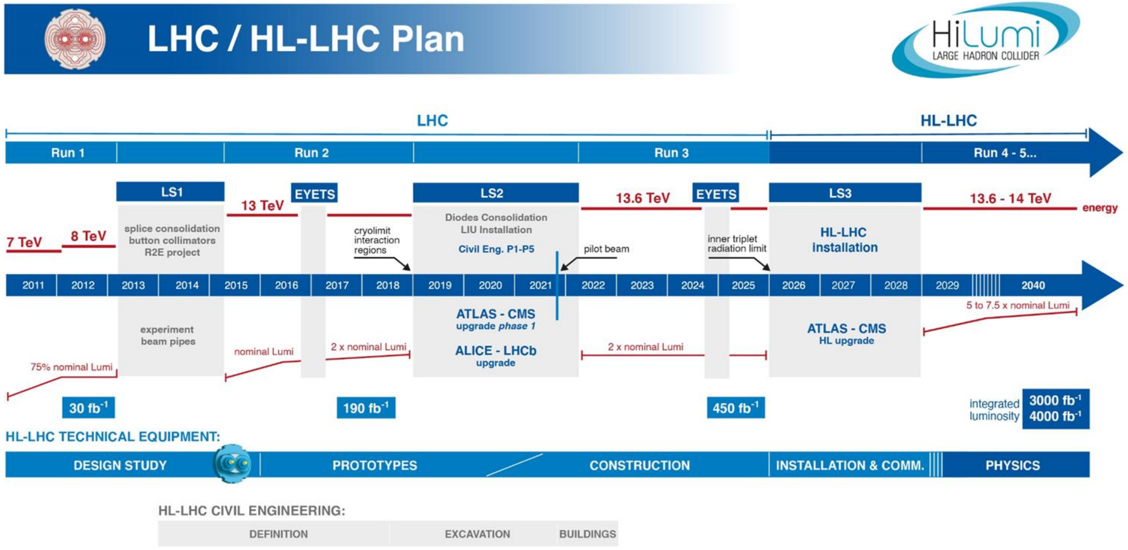
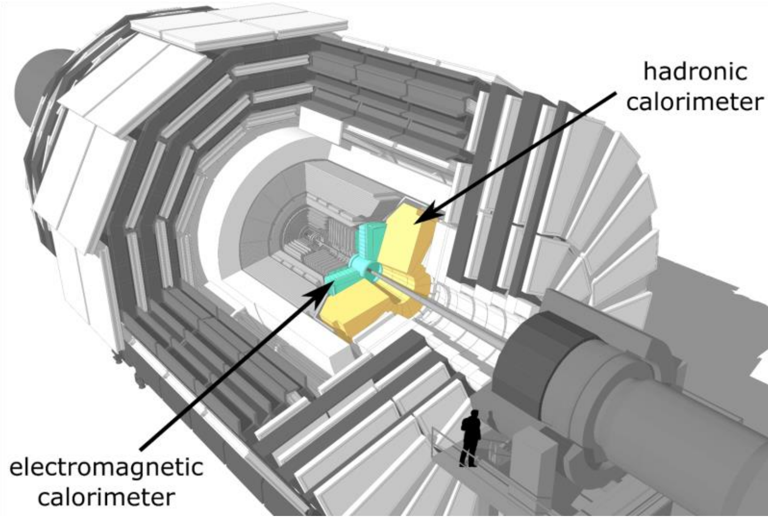
Compact Muon Solenoid HL Upgrade

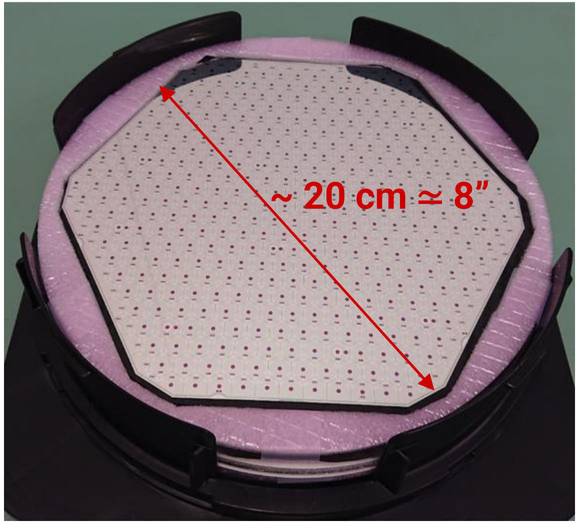




https://cds.cern.ch

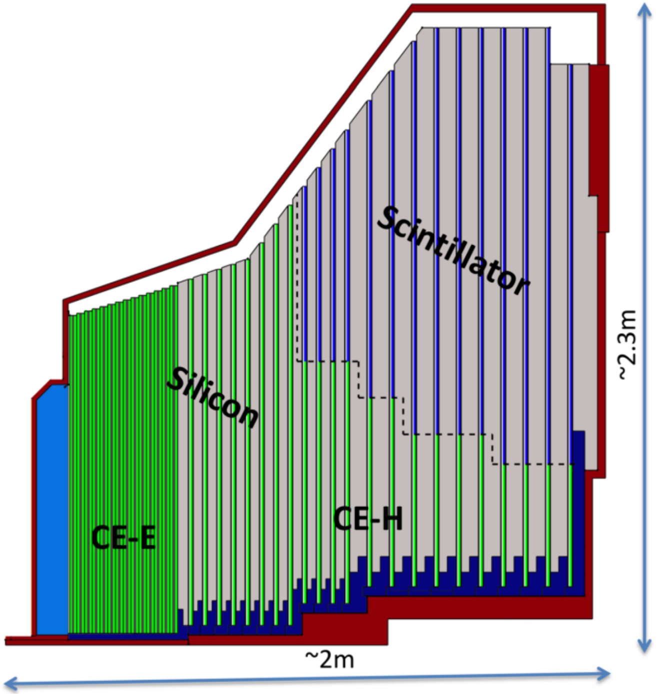
- Nearly 10x integrated luminosity increase
- Higher event rates require faster and more radiation hard detectors
- Silicon diodes will make up a large portion of the upgraded calorimeter (HGCAL)

High Granularity Calorimeter (HGCAL)



https://cds.cern.ch

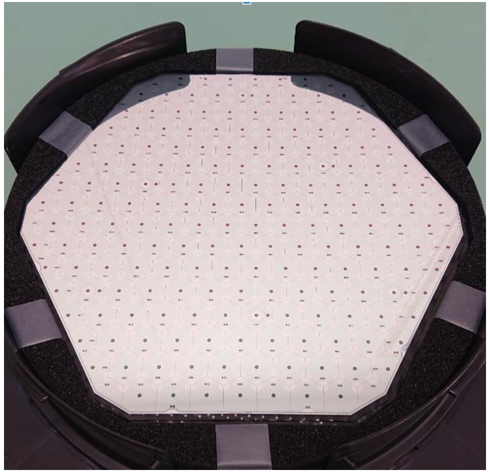
- Silicon sensors will have varying numbers of channels depending on their density and geometry
- Sensors will be of varying thickness



Electromagnetic calorimeter (**CE-E**):
Si, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**):
Si & **scintillator**, steel absorbers, 22 layers, ~8.5λ

- Scintillator can’t be used in the higher radiation regions
- Fully depleted silicon sensors used in both CE-E and CE-H

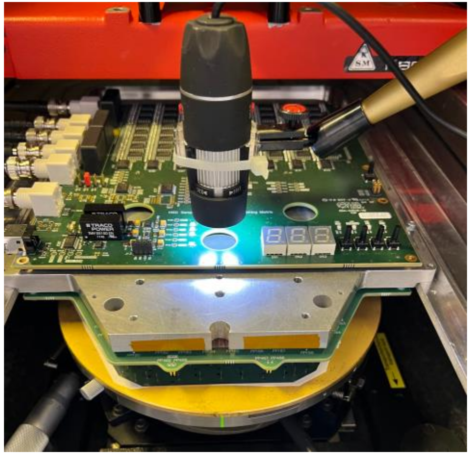
Sensor Parameters

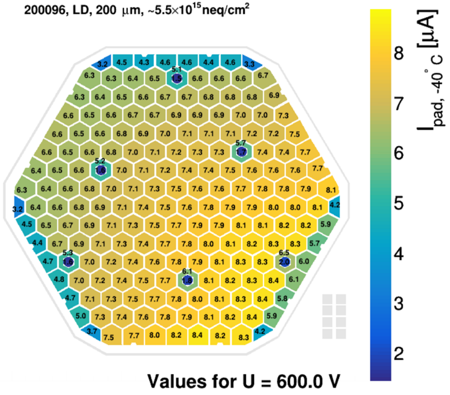


- Sensor 200096
- Low density type full sensor
- Thickness of 200 µm
- Fluence of 5.5e15 neq/cm²
- Anneal time 85 minutes

- Sensor 600003
- High density type partial sensor
- Thickness of 120 µm
- Fluence of 1e16 neq/cm²
- Anneal time 79 minutes

IV and CV Characterization





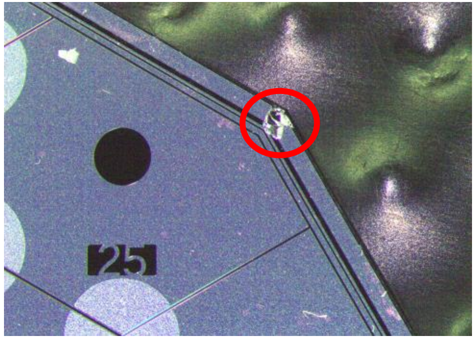
Optical inspection of sensors to ensure integrity of key components

Electrical testing performed by measurement station run with labview program

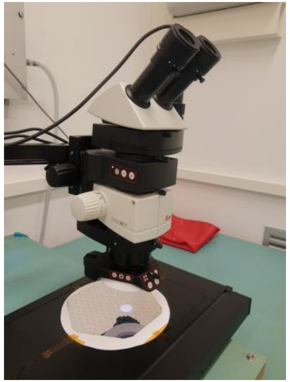
Example of IV output data

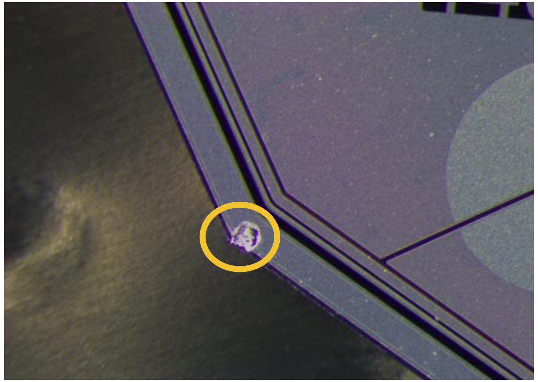
Visual inspection prior to post-irradiation IV+CV measurements

- 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

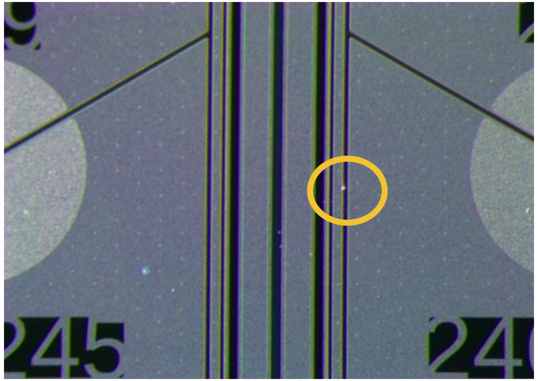


Chipped corner (CRITICAL)





Slightly chipped corner (Non-critical)



Dust particles (Non-critical)

Measurement Setup and Procedure: ALPS

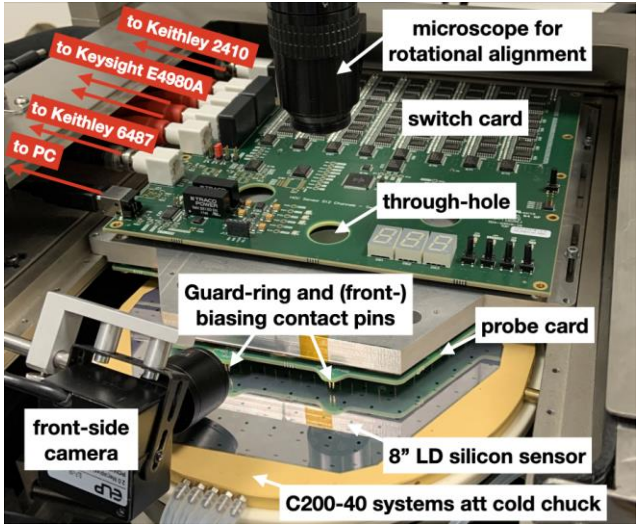
Storage and preparation

- Storage of the sensors at the temperature of -18°C
- Sensor identification with the scratch pad
- Optical inspection and cleaning performed for guard ring only, to avoid unnecessary annealing
- Identification of chipped corners and edges for some sensors

Measurement procedure

- Sensors were placed directly in ALPS on chuck (no backside protection, for better temperature control)
- The temperature range was chosen as: -40°C to -36°C
- The voltage was provided to the backside
- All channel IV was performed up to -850V

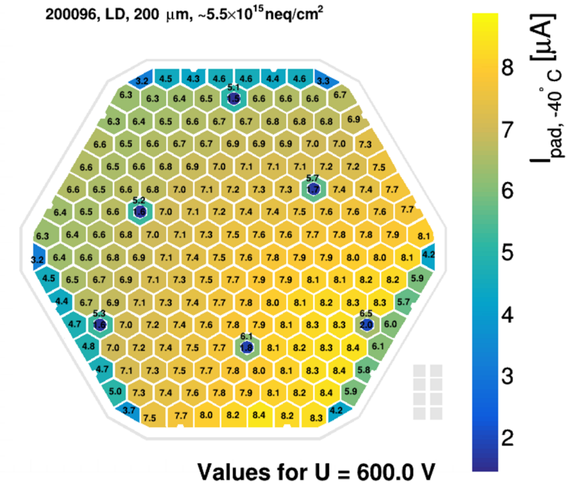
NO ANNEALING as the sensors received 80 minutes of annealing at 60 degrees in the RINSC reactor



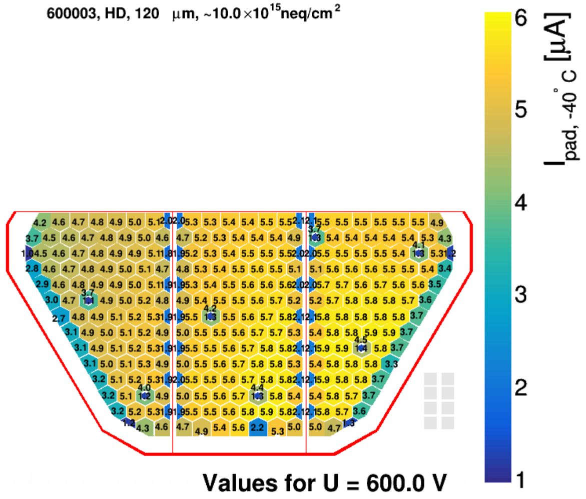
IV Voltage Range (negative)	0V - 850V
IV Voltage Steps	25V and 50V (to protect the setup)
Temperature points (°C)	-40, -39, -38, -37, -36

Leakage Current Hexplots

200096

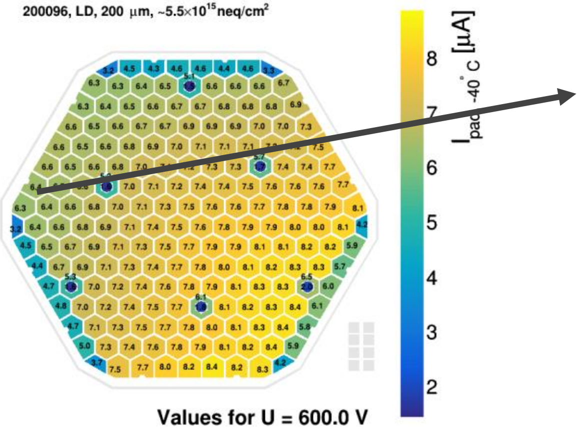


600003

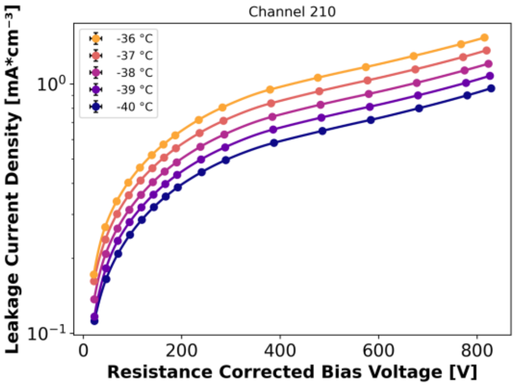


- Certain cells have different geometries and thus different leakage currents
- Observe fluence profile across sensor (consistent shape in 2 already measured sensors)

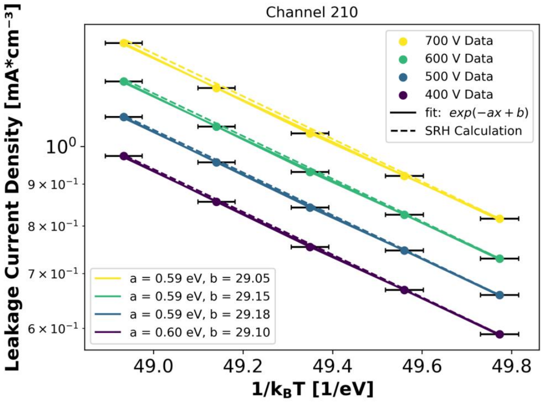
Data Analysis Workflow



- Leakage current vs voltage data for all channels at different temperatures

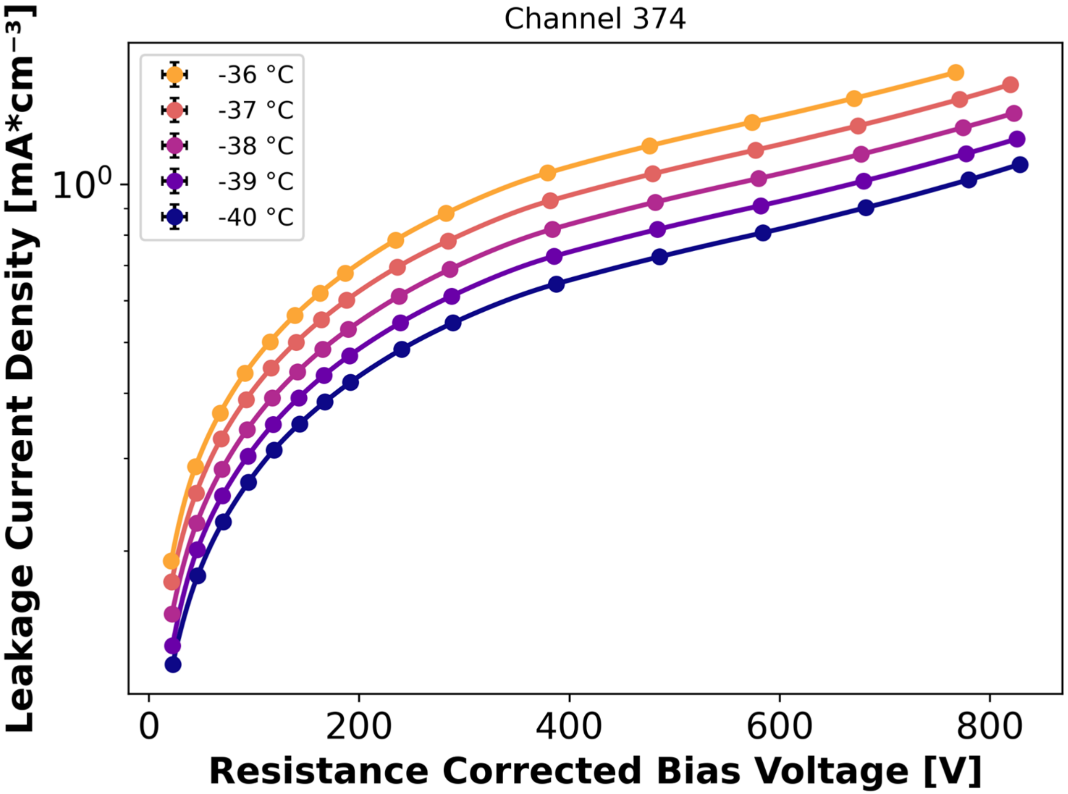


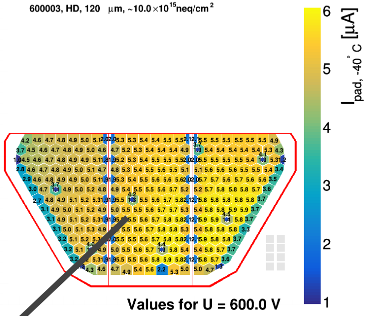
- Current density vs voltage Plot for one channel across range of temperatures



- Arrhenius plot at selected voltages

Example IV (600003)

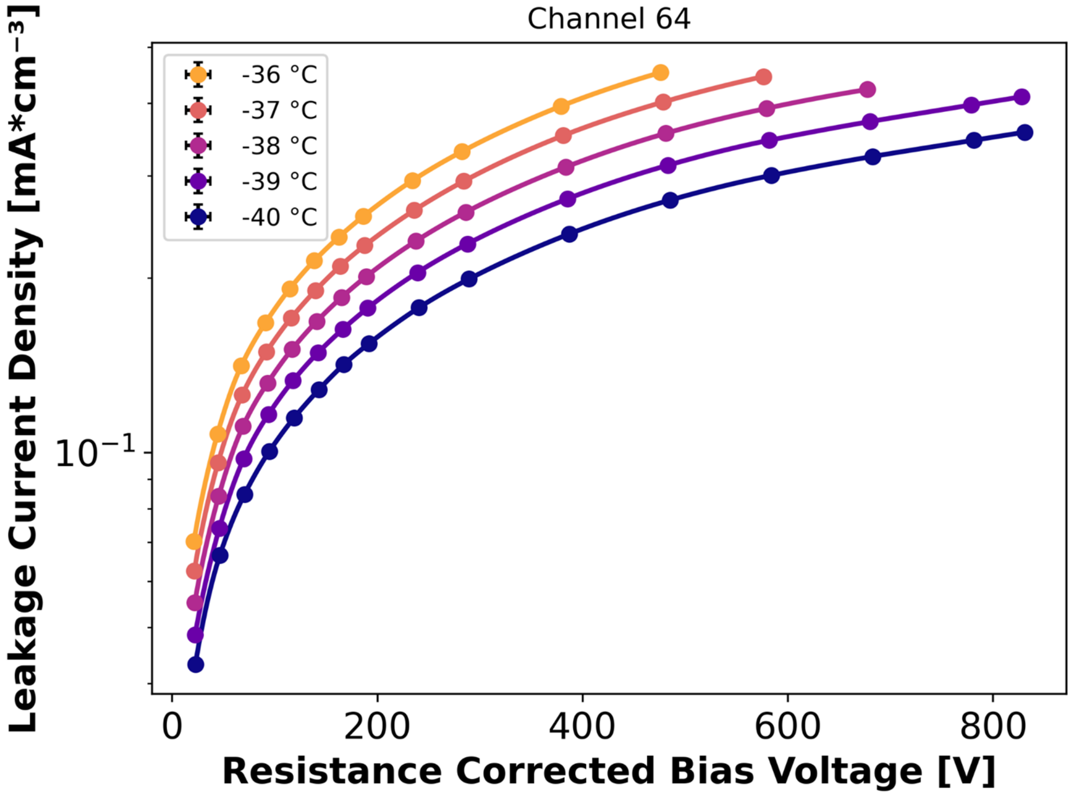


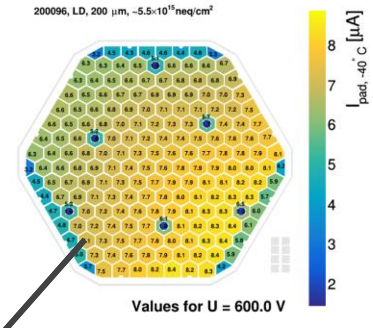


- Sensor 600003
- High density type partial sensor
- Thickness of 120 µm
- Fluence of 1e16 neq/cm²
- Anneal Time 79 minutes

- Real data is interpolated but not extrapolated
- This channel (and many others) were masked for high voltages at higher temperatures
- Follows the expected trend

Example IV (200096)

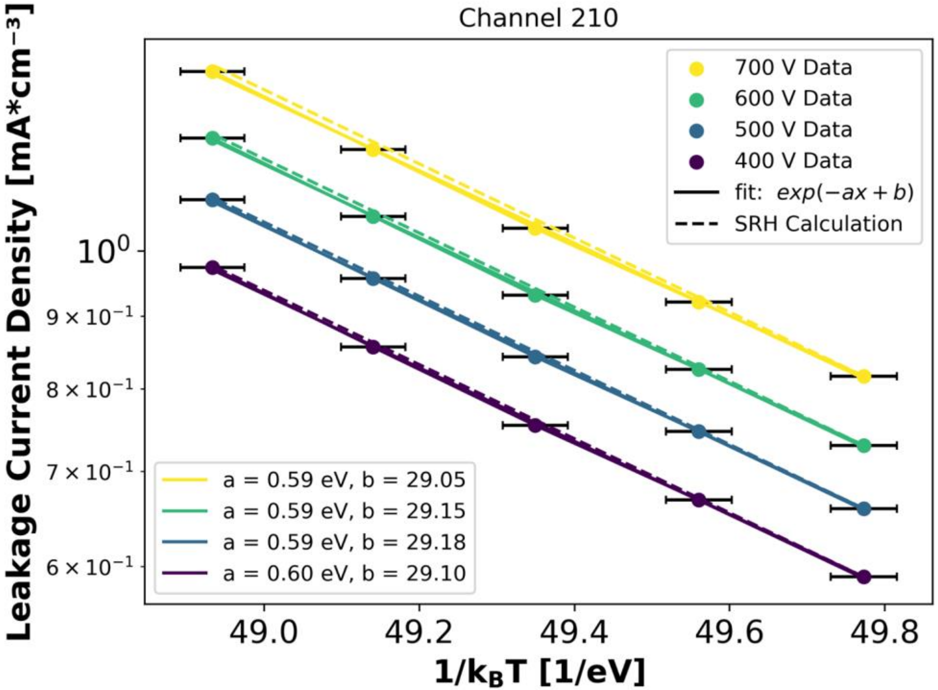




- Sensor 200096
- Low density type full sensor
- Thickness of 200µm
- Fluence of 5.5e15 neq/cm²
- Anneal Time 85 minutes

- Many more measurement points are masked despite lower current density
- Higher area pads results in higher pad current

Arrhenius Plot and SRH Calculation

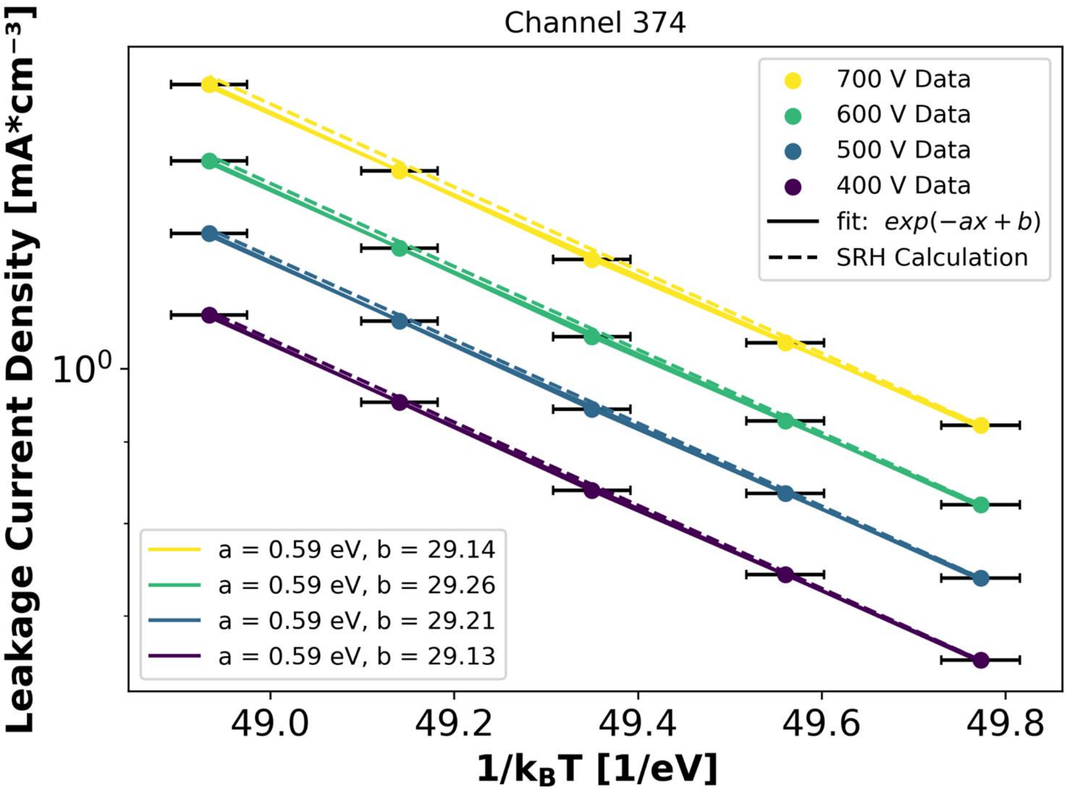


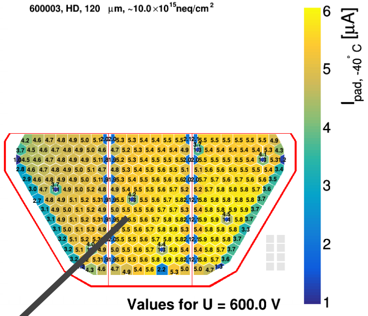
- Shockley Read Hall (SRH) calculation:

$$I(T)\alpha T^2 * e^{-1.12/2kT}$$

- Can help tell us where our dominant source of leakage current is
- Activation energy can be given by the slope of our current in log

Example Arrhenius (600003)

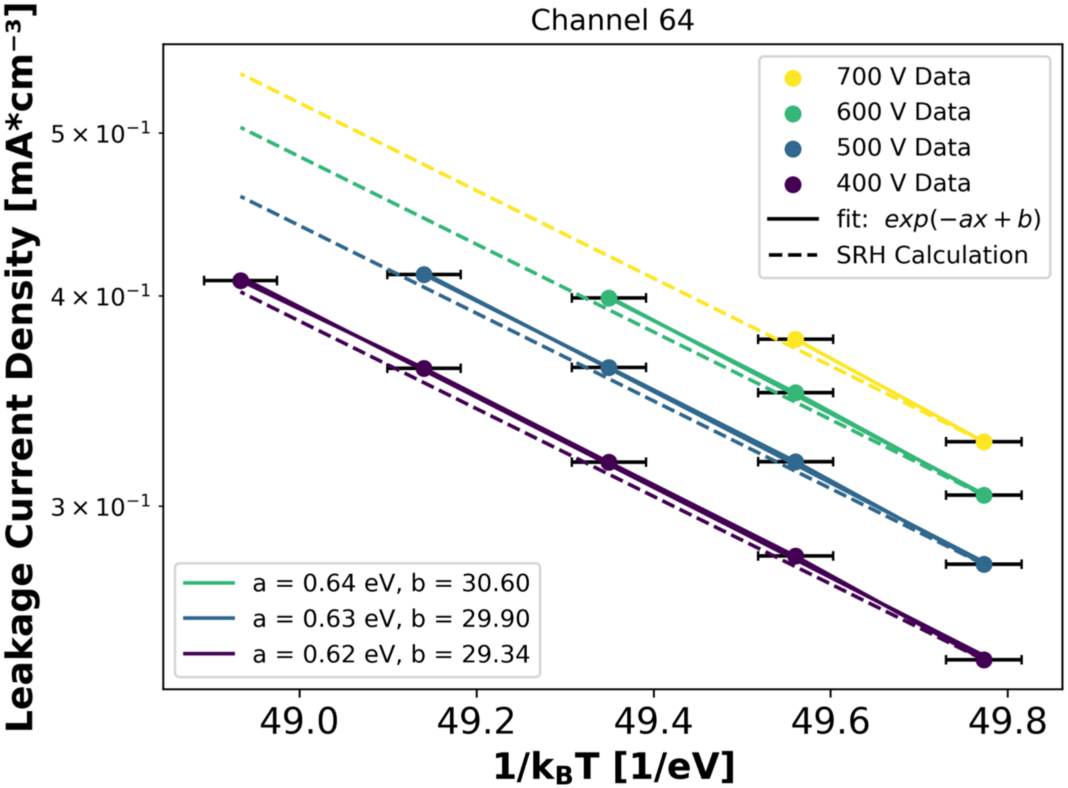


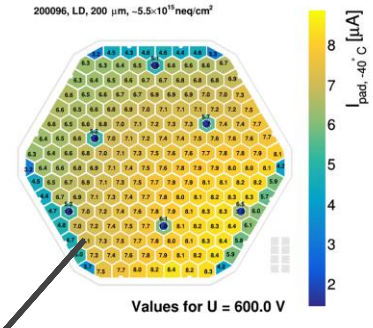


- Sensor 600003
- High density type partial sensor
- Thickness of 120 µm
- Fluence of 1e16 neq/cm²
- Anneal Time 79 minutes

- Fit Parameter “a” is the activation energy in eV
- SRH calculation fits data very well
- “Complete” set of data at all temperatures

Example Arrhenius (200096)

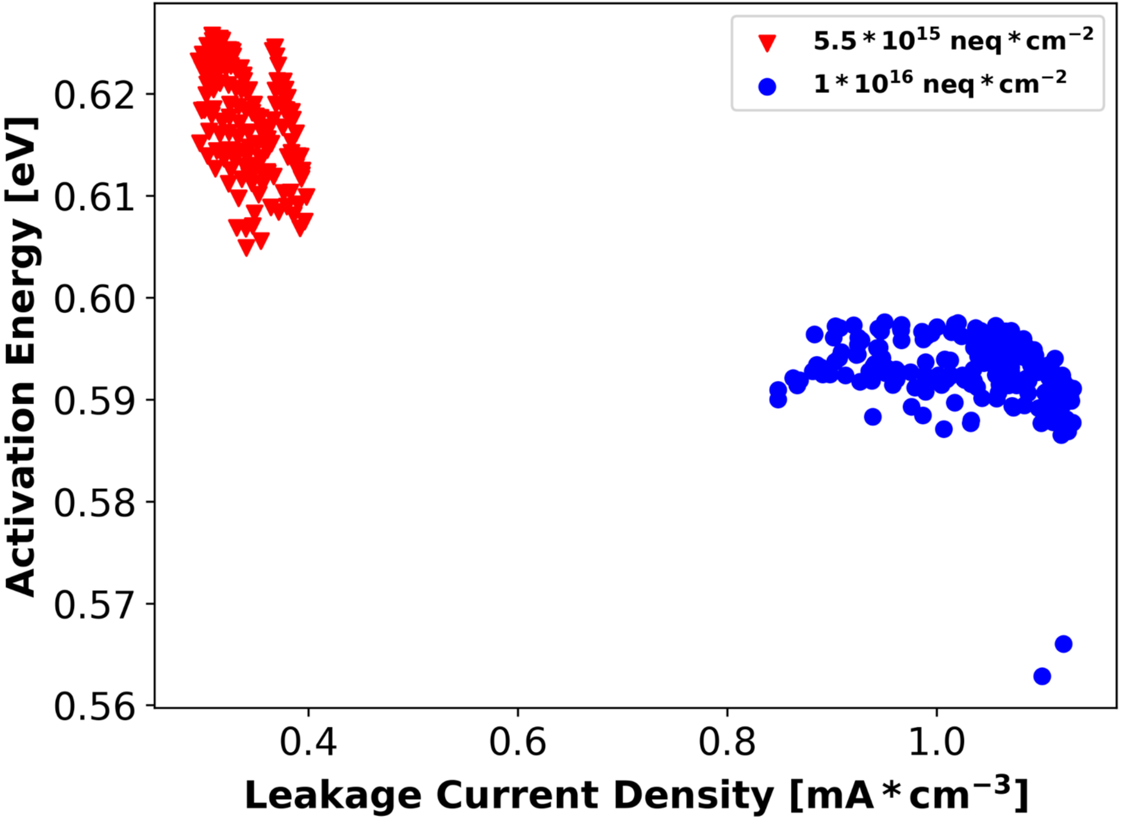




- Sensor 200096
- Low density type full sensor
- Thickness of 200μm
- Fluence of 5.5e15 neq/cm²
- Anneal Time 85 minutes

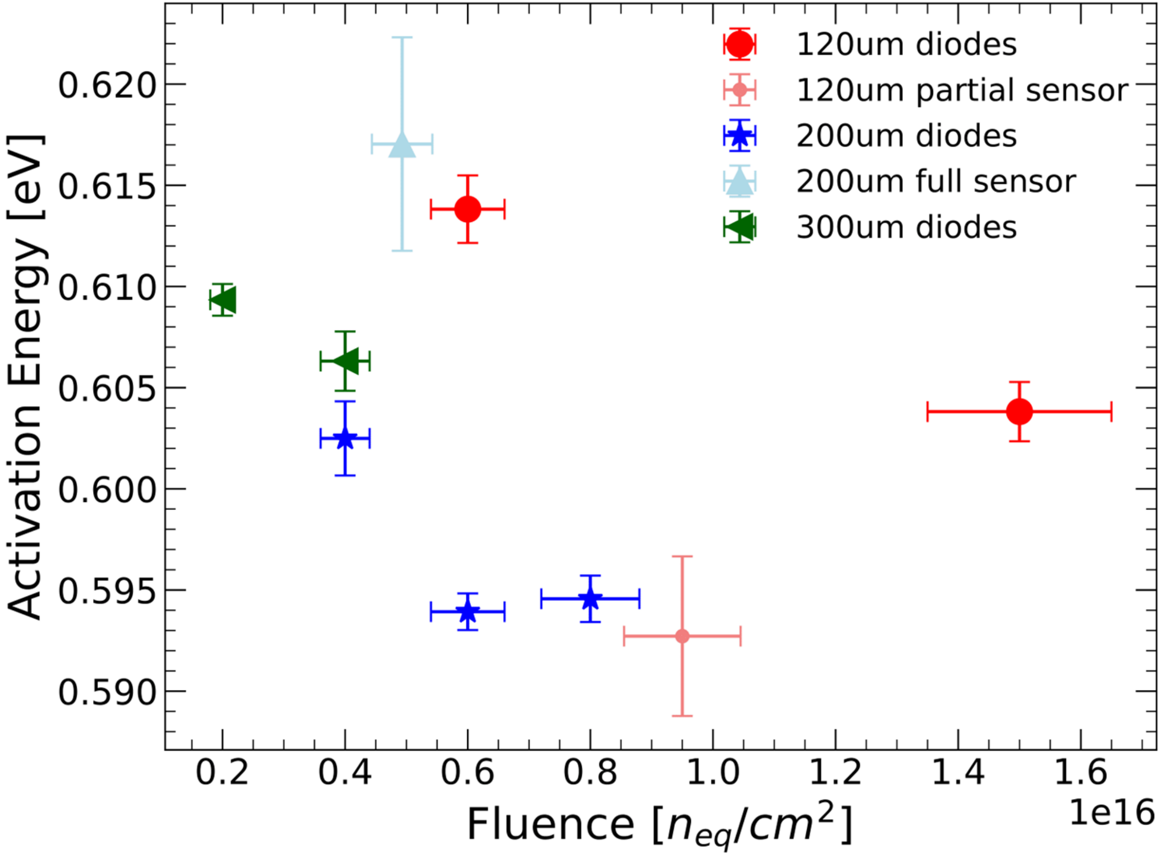
- SRH calculation fits data slightly less well
- Many more masked channels resulting in slightly less reliable extraction of activation energy

Activation Energy vs Fluence



- Taking leakage current density as a proxy for fluence
- We expect activation energy to decay exponentially with increasing fluence
- Wider range of fluences may tell us if activation energy has fluence dependance

Activation Energy vs Nominal Fluence



- For sensors mean activation energy is plotted for a nominal fluence
- At this point it is hard to say whether or not there is a clear trend

Summary

- Data appears to follow expected trends and Arrhenius plots seem to agree with literature thus far
- Activation energy may possibly be following expected trend (higher fluences corresponding to lower activation energy) but more work is needed to confirm

Outlook

- Include more sensors with different fluences in the activation energy analysis
- Plot activation energy on a hexplot of the sensor to investigate correlation with fluence profile
- More reading and investigation should be done to better understand the implications of SRH and activation energy determination

Backup

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

Round 1

Round 3

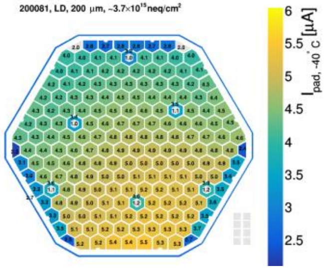
Round 4

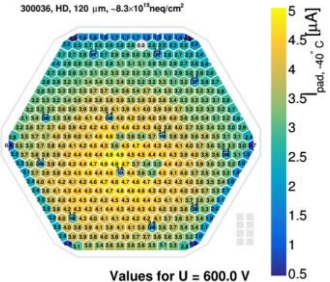
Round 5

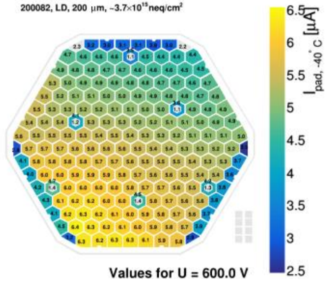
Round 6

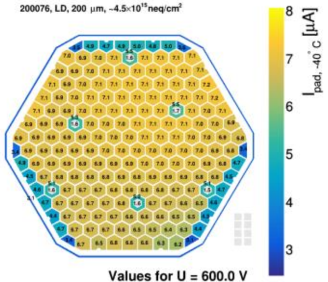
100082:
Chipped corner

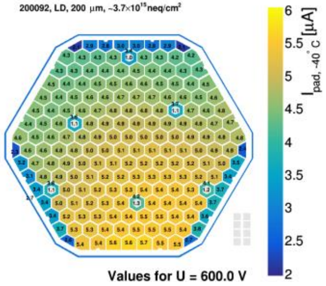
100076:
Chipped corner

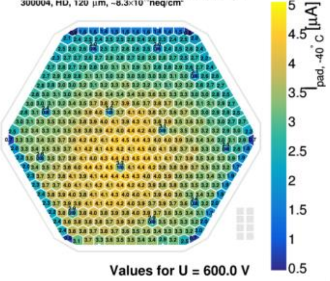


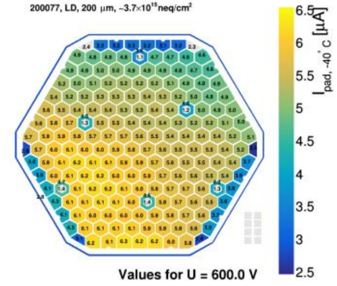


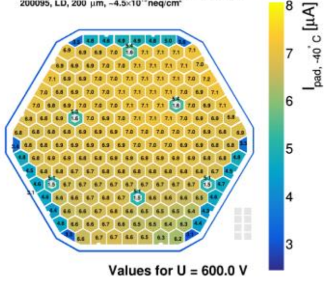


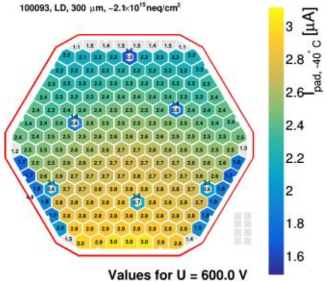


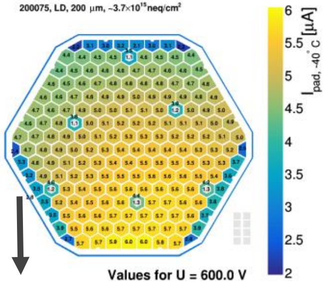


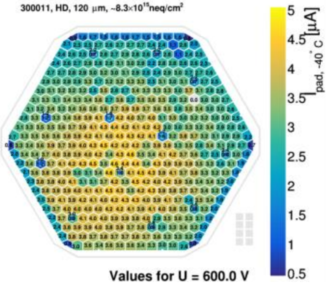


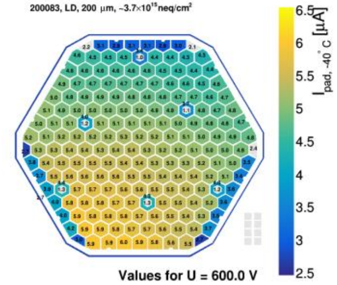








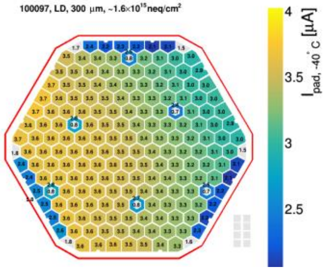


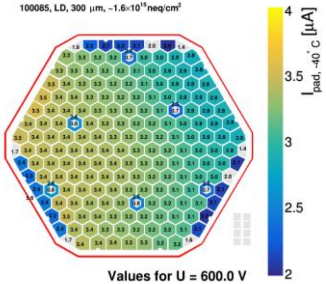


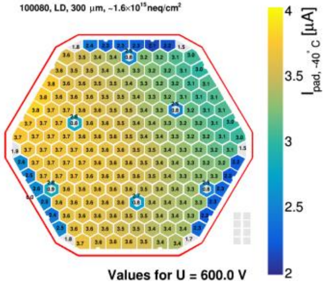
200093: over
annealed

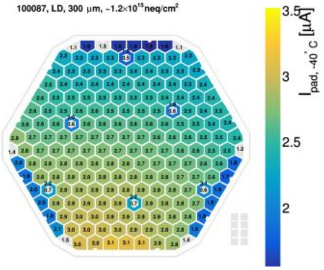
Reactor

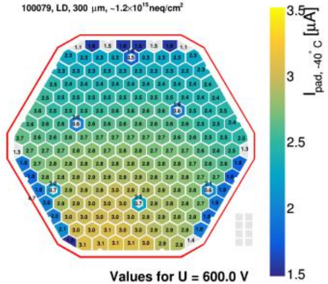
Compatible profiles for sensors of same round: **New rounds**

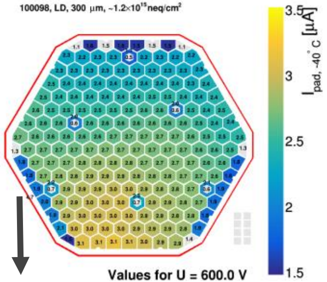




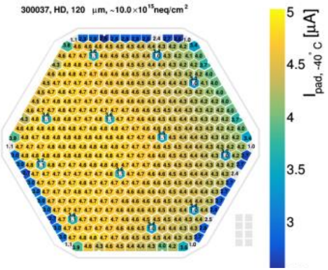


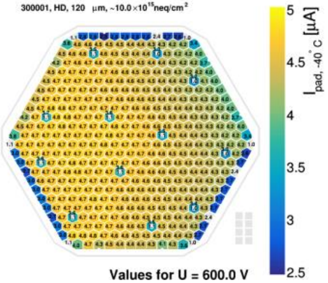


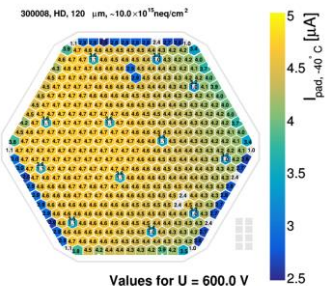




Reactor

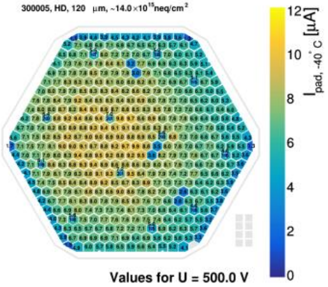


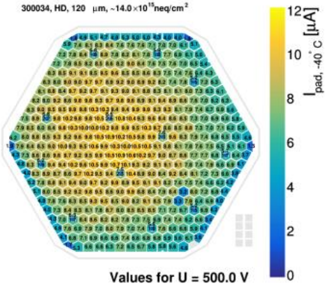


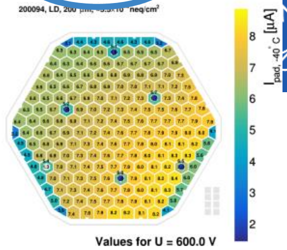


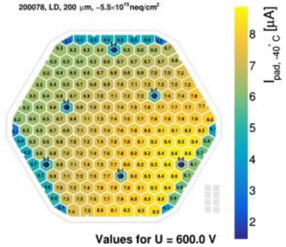
Round 10

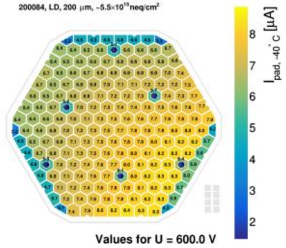
300009:
Chipped corner

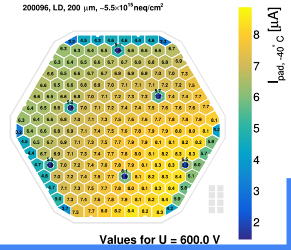






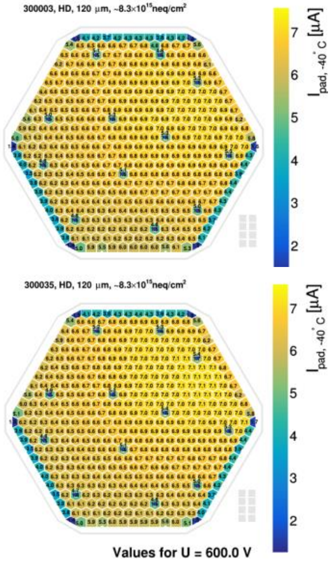






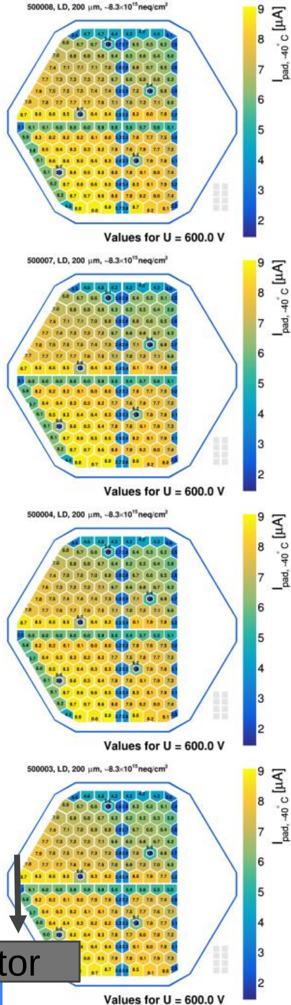
Compatible pro … sor … ound: **New rounds**

Round 12 (order unknown)

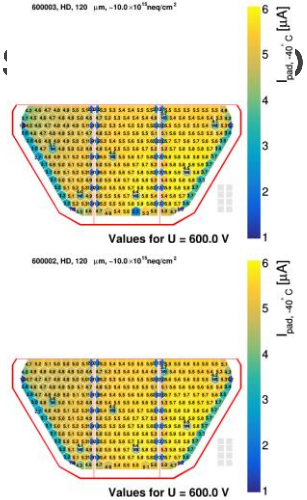


300010:
Chipped corner

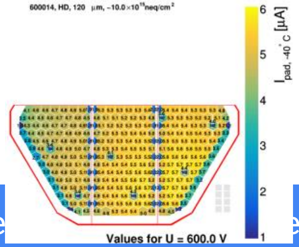
Round 13



Round 14

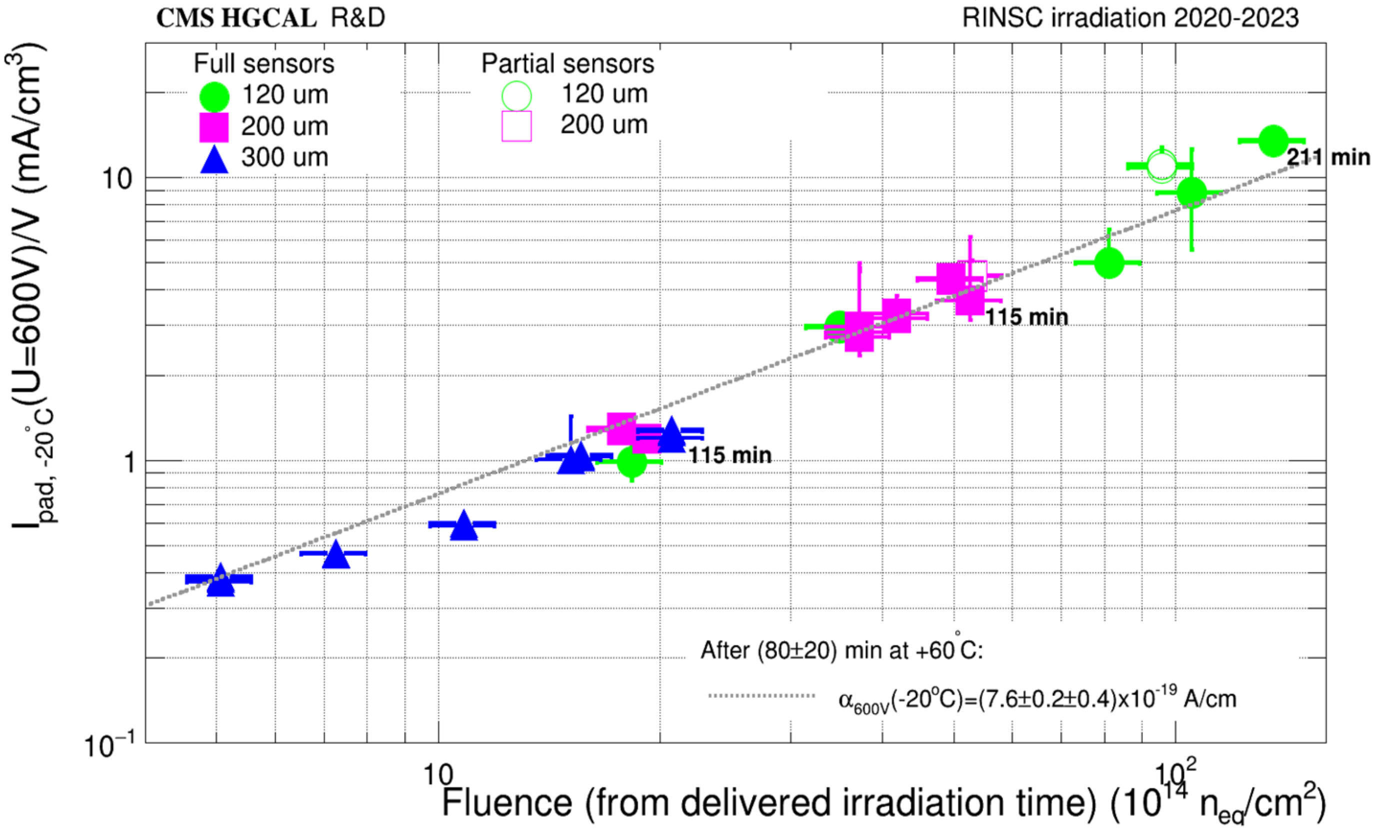


600015:
Chipped corner

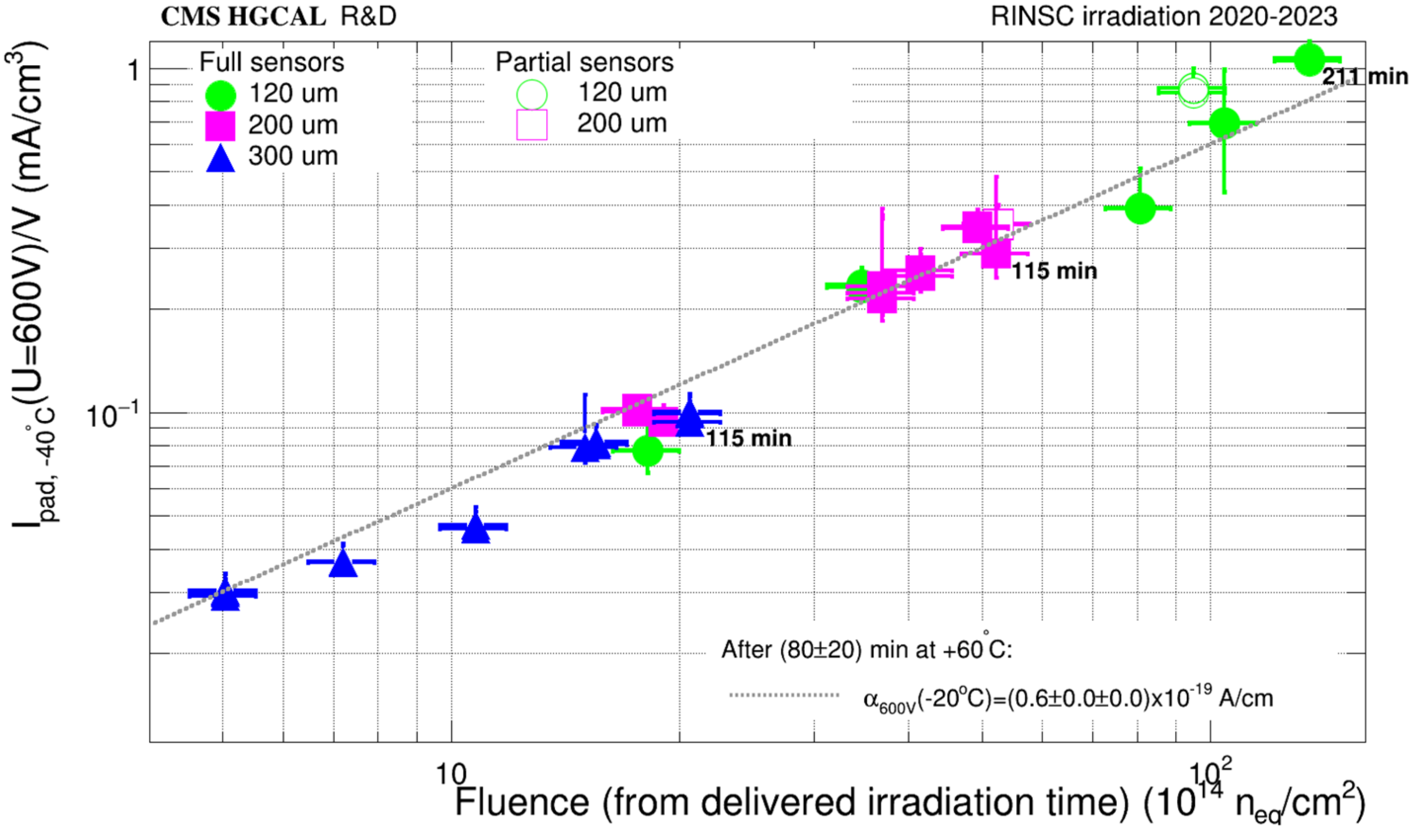


- Rounds 11, 12 and 14 have consistent fluence pattern
- I_{pad} mostly scales with cell size and delivered fluence, as expected.

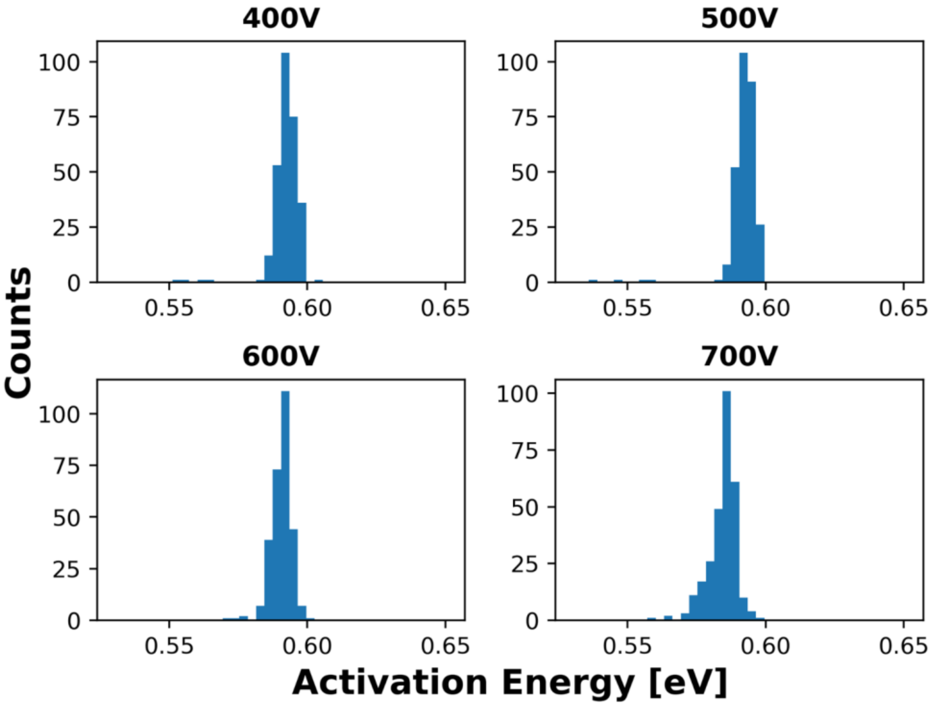
Current related damage rate (-20ºC)



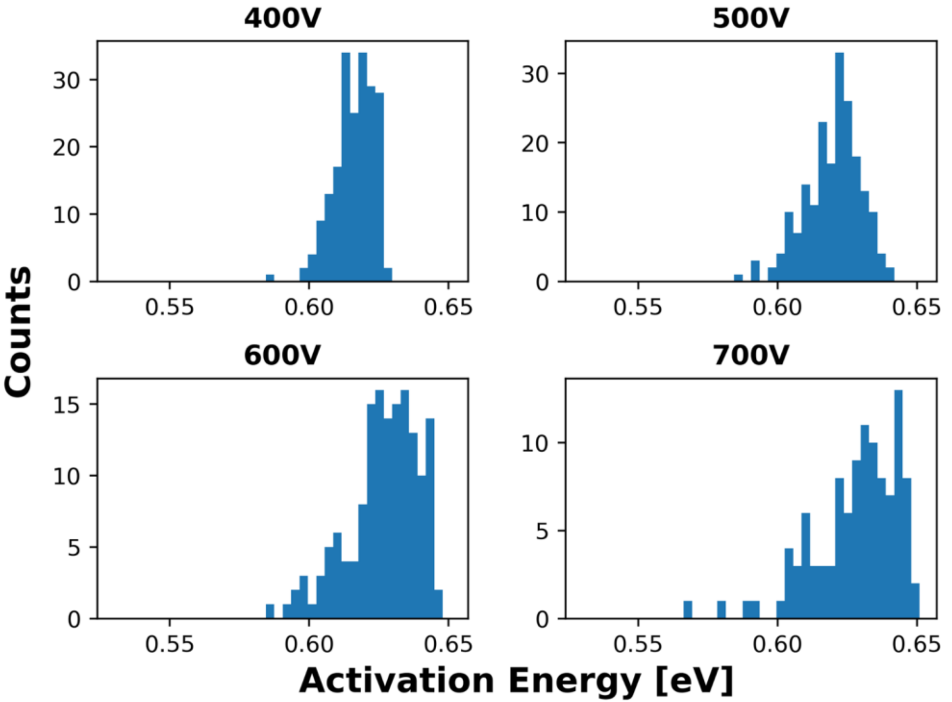
Current related damage rate (-40ºC)



Activation Energy Histogram



600003 1E16 neq/cm2, 120 um, 80 mins annealing



200096 5.5E15 neq/cm2, 200 um, 85 mins annealing

Target vs. delivered fluence

For the irradiation rounds, the irradiation time was set to a value based on the experience of the reactor personnel to meet the required target fluence, assuming that the reactor power is constant. For the alpha plot calculation, we used the delivered irradiation time as a proxy of the fluence, to make up for the possible variations of the delivered fluence vs target fluence. We used round 1 as the reference.

Round	Requested time [min]	Delivered time [minutes at 100% power]	Delivered time/Requested time	Target fluence [neq/cm^2]	Delivered fluence [neq/cm^2]	Delivered fluence/Requested fluence (%)
1	32	32.5	1.0	1.50E+15	1.50E+15	100.00
2	43	44.7	1.0	2.00E+15	2.06E+15	103.15
3	86	80.1	0.9	4.00E+15	3.70E+15	92.42
4	216	203.7	0.9	1.00E+16	9.40E+15	94.02
5	86	90.0	1.0	4.00E+15	4.15E+15	103.85
6	118	113.2	1.0	5.50E+15	5.22E+15	94.99
7	43	44.6	1.0	2.00E+15	2.06E+15	102.92
8	32	33.6	1.1	1.50E+15	1.55E+15	103.38
9	216	225.9	1.0	1.00E+16	1.04E+16	104.26
10	304	282.9	0.9	1.40E+16	1.31E+16	93.26
11	118	106.8	0.9	5.50E+15	4.93E+15	89.62
12	304	292.2	1.0	1.40E+16	1.35E+16	96.33
13	118	113.8	1.0	5.50E+15	5.25E+15	95.50
14	216	205.9	1.0	1.00E+16	9.50E+15	95.03