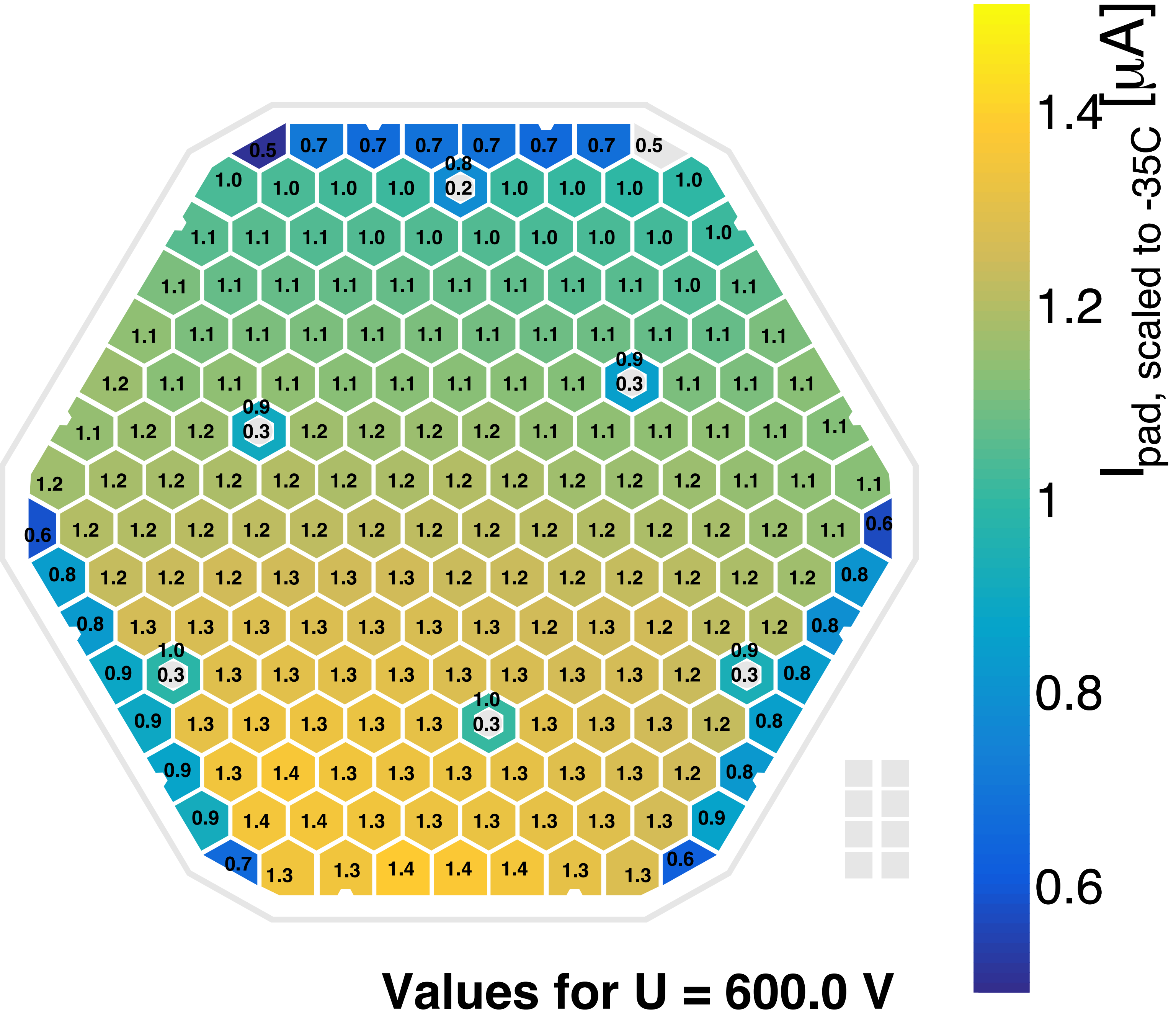
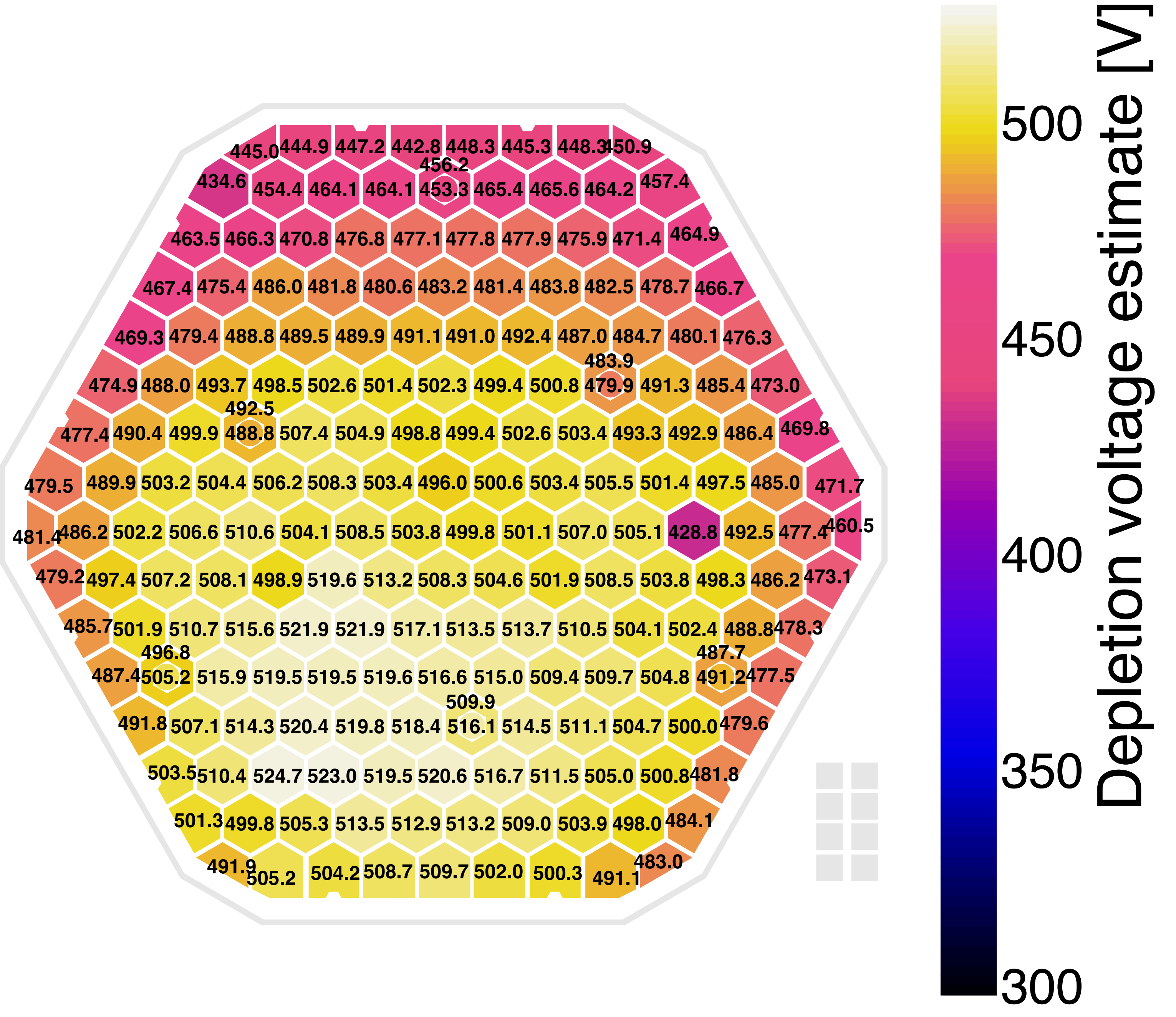
08th July 2021

IV+CV results from full sensor neutron irradiation campaign

Thorben Quast on behalf of the CMS HGCAL Silicon Group at CERN





Prototype sensors irradiated at RINSC and 26/38 characterised at CERN

Round	ID	Temp.	P-Stop	Thickness	Geometry	Flat band voltage	P-Stop conc.	Oxide quality	Mat- erial	Target fluence [neq/cm2]	RINSC Irradiation
Round 1	1004	-30°C & -40°C	ind.	300µm	LD	-5V	STD	STD	FZ	6.5E+14	26 Aug 2020
	1002					-2V					
	1101		com.			-5V					
	1102					-2V					
	IV+CV results presented on: 10 November 2020 (link)										
Round 3	3002	-40°C	ind.	120µm	HD	-2V	0.5*STD	STD	epi	1E+16	20 Oct 2020
	3102		com.				0.5*STD				
	3003		ind.				STD				
	3103		com.				STD				
	IV+CV results presented on: 09 February 2021 (link)										
Round 4	2109	-40°C	com.	200µm	LD	-5V	STD	Type B	FZ	2.5E+15	21 Jan 2021
	2110							Type C			
	2111							Type D			
	2112							Type E			
Round 5	2004		ind.					STD			28 Jan 2021
	2002					-2V					
	2105		com.			-5V					
	2114					-2V					
	IV+CV results presented on: 11 May 2021 (link)										
Round 8 New!	3009	-40°C	ind.	120µm	HD	-2V	STD	STD	epi	5E+15	11 March 2021
	3010										
	3109		com.								
	3110										
	IV+CV results shared here: https://indico.cern.ch/event/1048048/contributions/4425700/attachments/2276308/3867081/120mum_LD_5E15_round8_June2021.pdf										
Round 10 New!	1013	-40°C	ind.	300µm	LD	-2V	STD	STD	FZ	1E+15	15 April 2021
	1114		com.								
	N0538 WNo.3		ind.			-5V					
	N0538 WNo.25		com.			-2V	Type C				
	IV+CV results shared here: https://indico.cern.ch/event/1048048/contributions/4425700/attachments/2276308/3867083/300mum_LD_1E15_round10_June2021.pdf										
Round 11 New!	N0541 WNo.4	-40°C	ind.	200µm	LD	-5V	STD	STD	FZ	2.5E+15	06 May 2021
	N0538 WNo.10					-2V	Type C	STD	FZ		
	IV+CV results shared here: https://indico.cern.ch/event/1048048/contributions/4425700/attachments/2276308/3867082/200mum_LD_2p5E15_round11_June2021.pdf										

8-step post-irradiation characterisation procedure

1. **Visual inspection** of the sensors.
   - Identification of mechanical defects (e.g. chipped corners, cracks, …).
   - Removal of dust, particular focus on guard ring (GR) area.

~10min - 60min

2. **"Fine"** leakage current vs. bias voltage (**IV**) measurement at -40°C.
   - Total leakage current below compliance of 2mA up to highest voltages?
   - O(1) channels tested, increase bias voltage by 10V up to 850V or I_{tot}=2mA.

~30min

3. All-channel **IV measurement at -40°C.**.
   - All channels, coarser voltage increments up to 850V or I_{tot}=2mA.

~1.5hr - 3hr

4. All-channel capacitance vs. bias voltage (**CV**) **measurement at -40°C.**.
   - All channels, sensor geometry-dependent voltage increments up to 850V or I_{tot}=2mA.

~2.5hr - 5hr

5. Additional **sensor annealing**.
   - Up to equivalent of **80min at 60°C.**

~1.5hr

6. All-channel **IV measurement at -40°C.**.
   - All channels, coarser voltage increments up to 850V or I_{tot}=2mA.

~1.5hr - 3hr

7. All-channel capacitance vs. bias voltage (**CV**) **measurement at -40°C.**.
   - All channels, sensor geometry-dependent voltage increments up to 850V or I_{tot}=2mA.

~2.5hr - 5hr

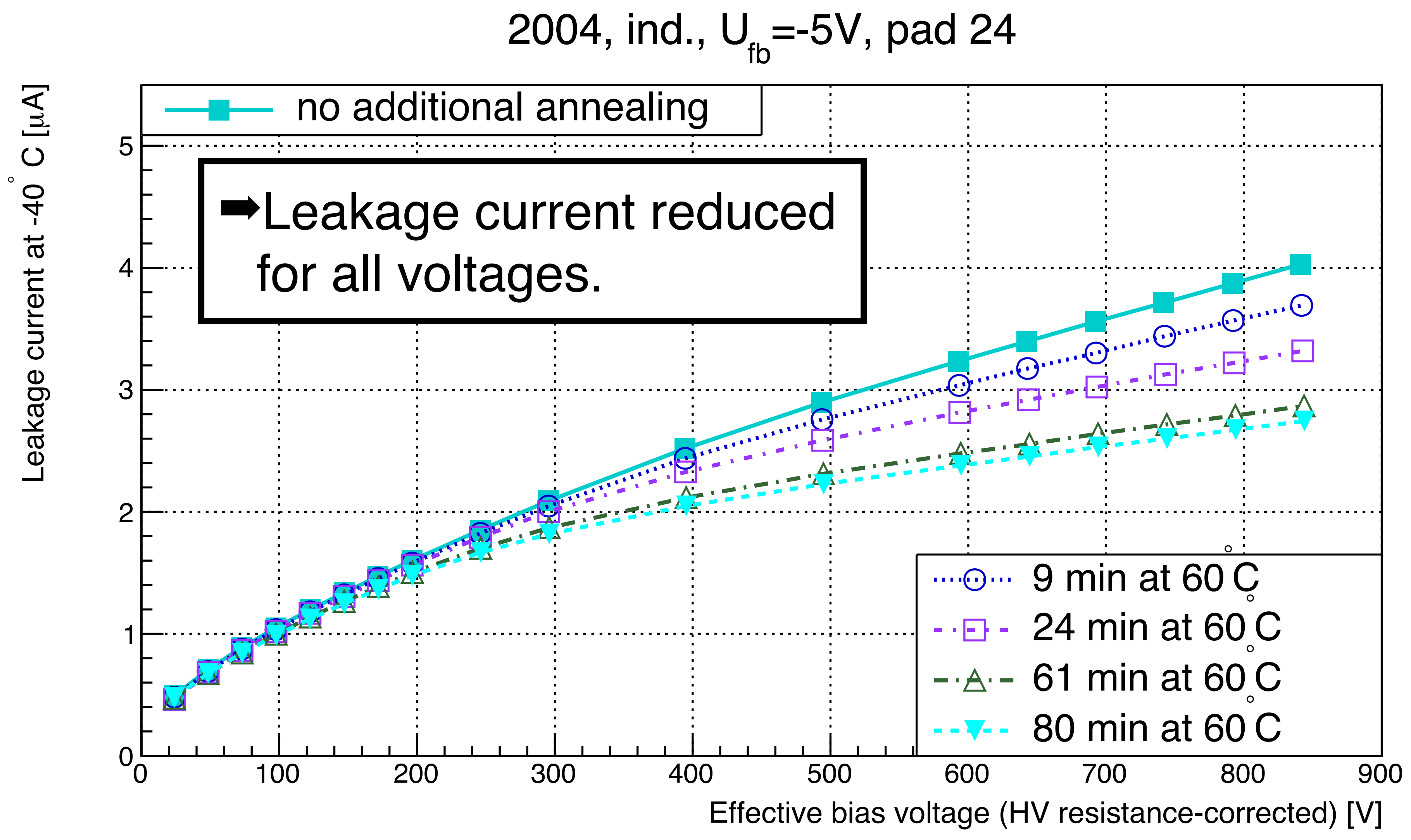
8. Additional visual inspection in case of signs of breakthroughs.

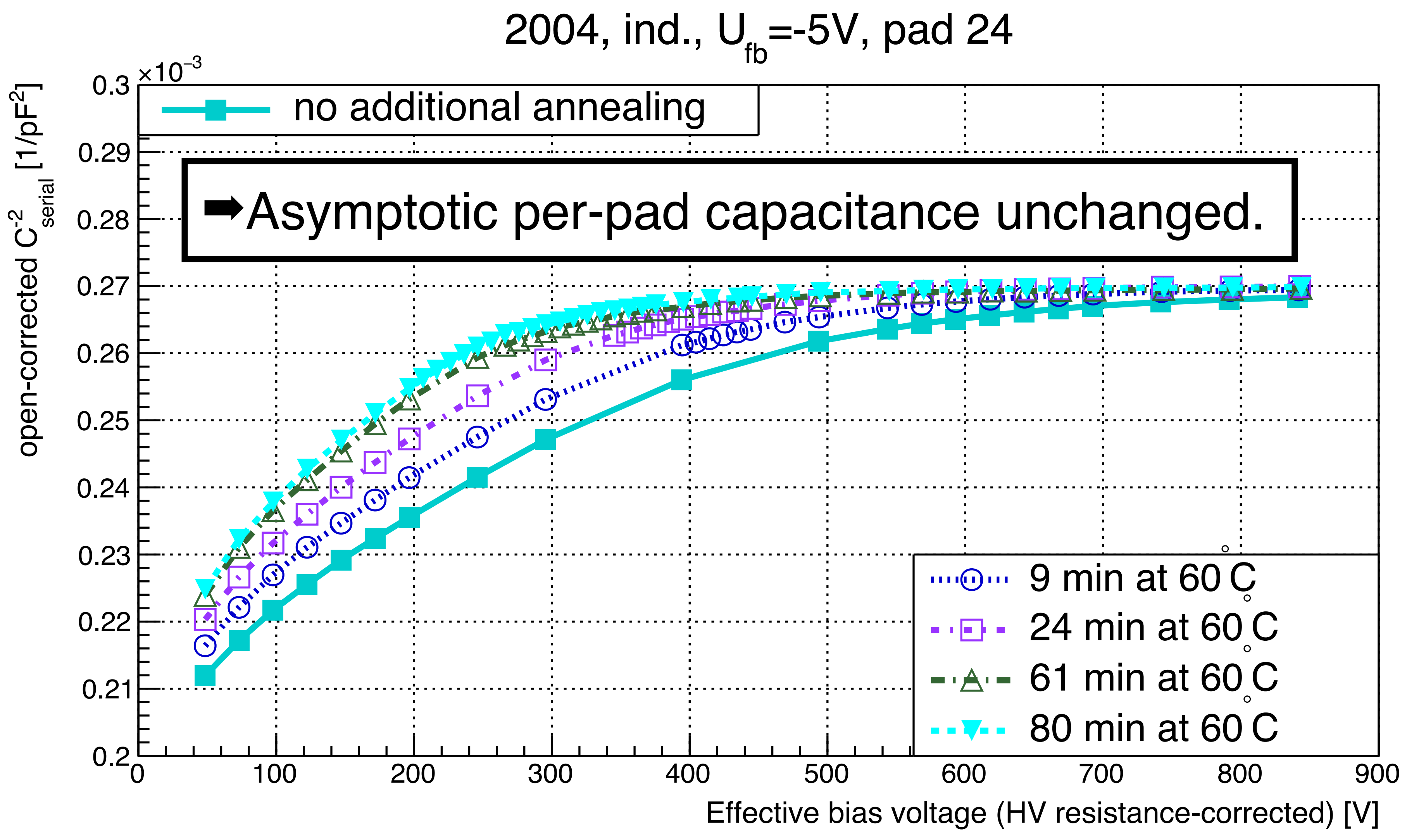
~10min

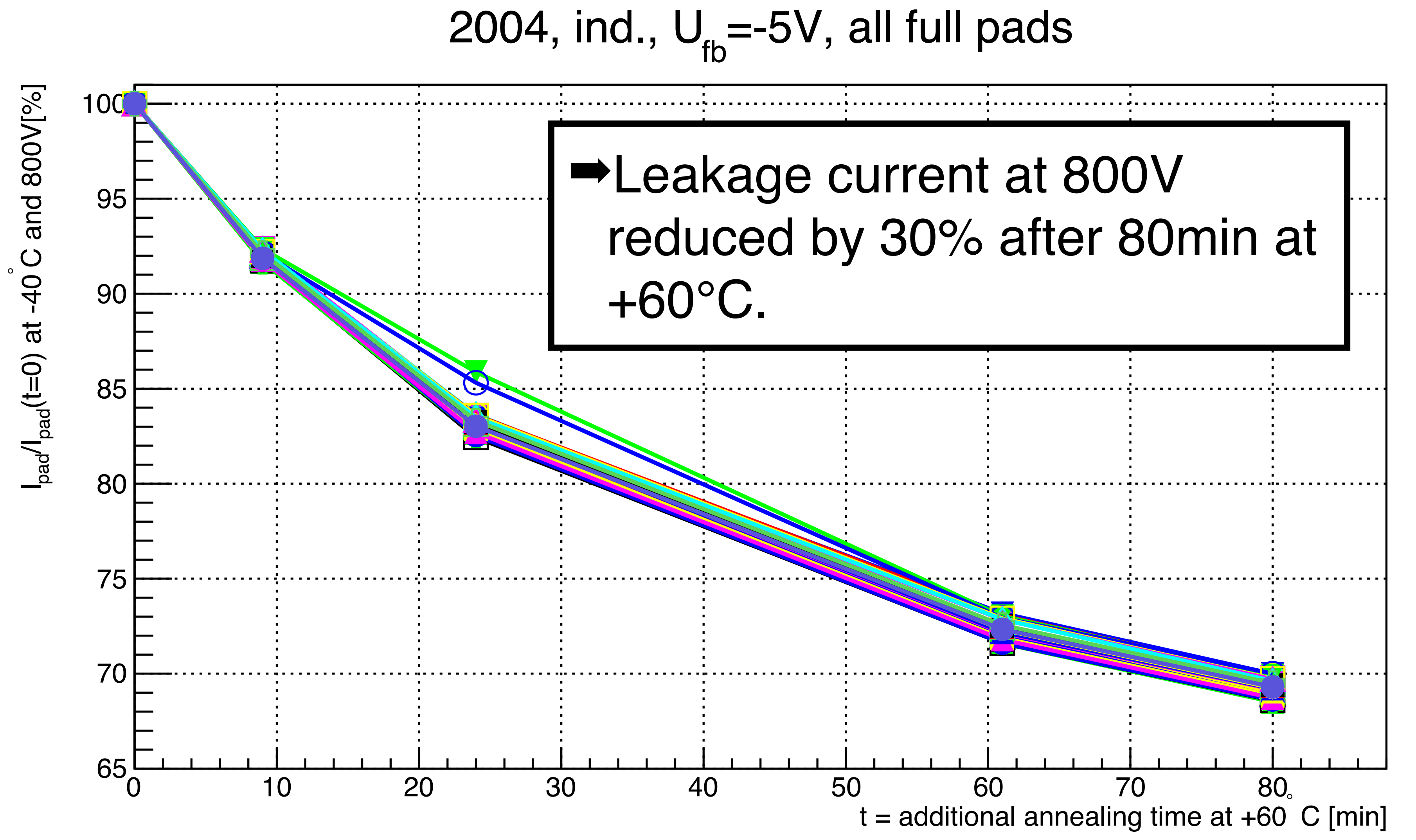
10(19)hrs per LD(HD) sensor

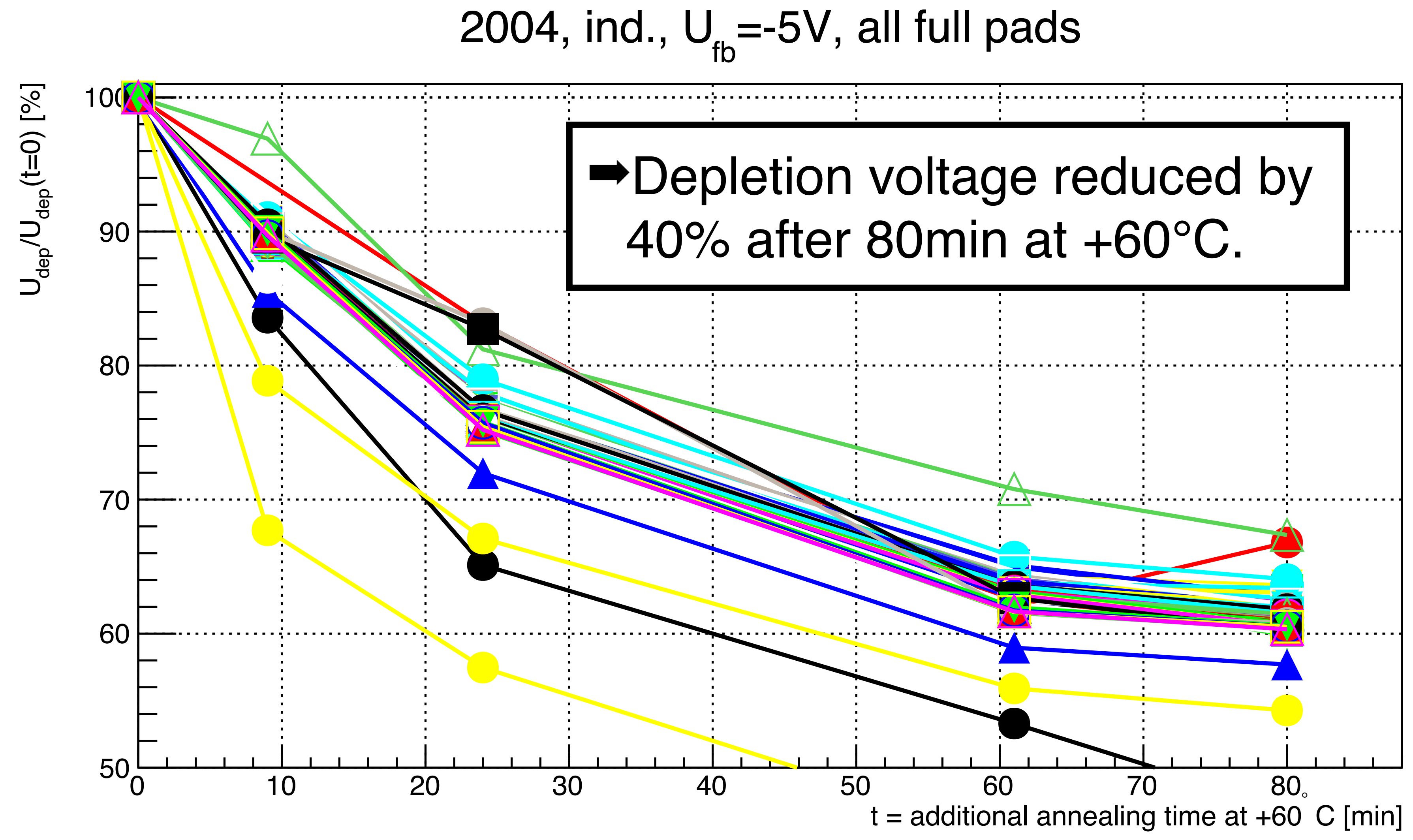
Additional annealing lowers leakage current and depletion voltage

- Annealing of sensor 2004 (200µm, LD, 2.5neq/cm²) paused for intermediate IV+CV measurements.







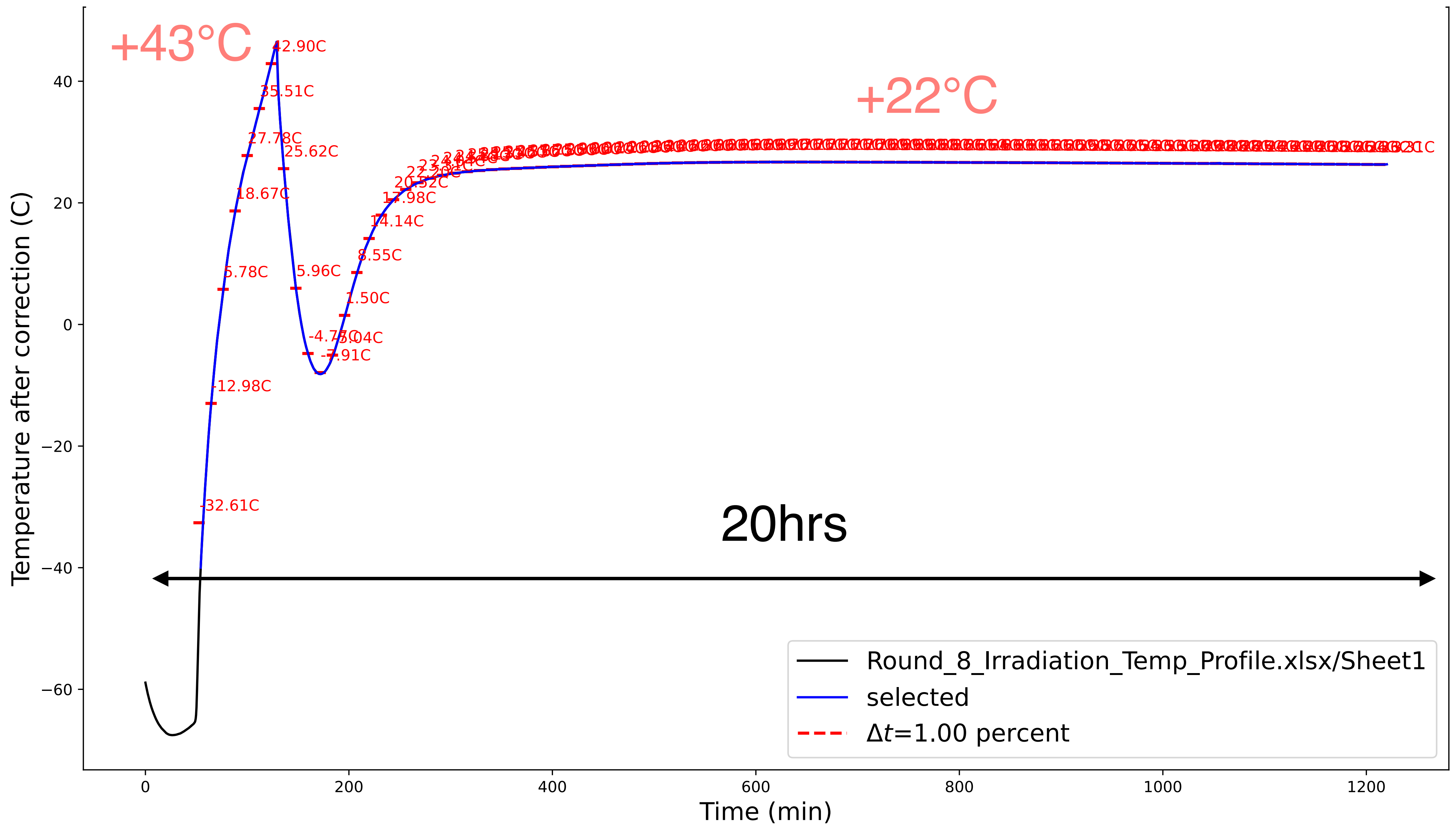


~~Due to annealing: Temperature during irradiation matters~~

- Temperature recorded during irradiation at RINSC.
- Data provided by Nick Hinton.

- Temperature recording stopped too early for some runs (e.g. rounds 4 and 5).
- Intervals where irradiation took place matter.

Temperature recording during RINSC irradiation round 8:



- Annealing time calculation: https://annealing.cms-ka.fzk.de
- So far, we have assumed that temperature was recorded AFTER irradiation:

  ➡Annealing time estimates on the left can be understood as upper limits of the actual effective annealing at +60°.

Target fluence [neq/cm2]	RINSC Irradiation	Estimated annealing time at +60°C
6.5E+14	Round 1 (26 Aug 2020)	**12.1 min**
1E+15	Round 10 (15 April 2021)	**12.4min**
2.5E+15	Rounds 4 & 5 (21 & 28 Jan 2021)	**<0.1min**
2.5E+15	Round 11 (06 May 2021)	**32.7min**
5E+15	Round 8 (11 March 2021)	**9.5min**
1E+16	Round 3 (20 Oct 2020)	**O(100min)***

* no additional annealing performed at CERN

Leakage current strongly temperature dependent

- Measurement mostly taken with a chuck temperature of -40°C.
- Leakage current (I) can be scaled to different temperatures (T).
- Scaling law:

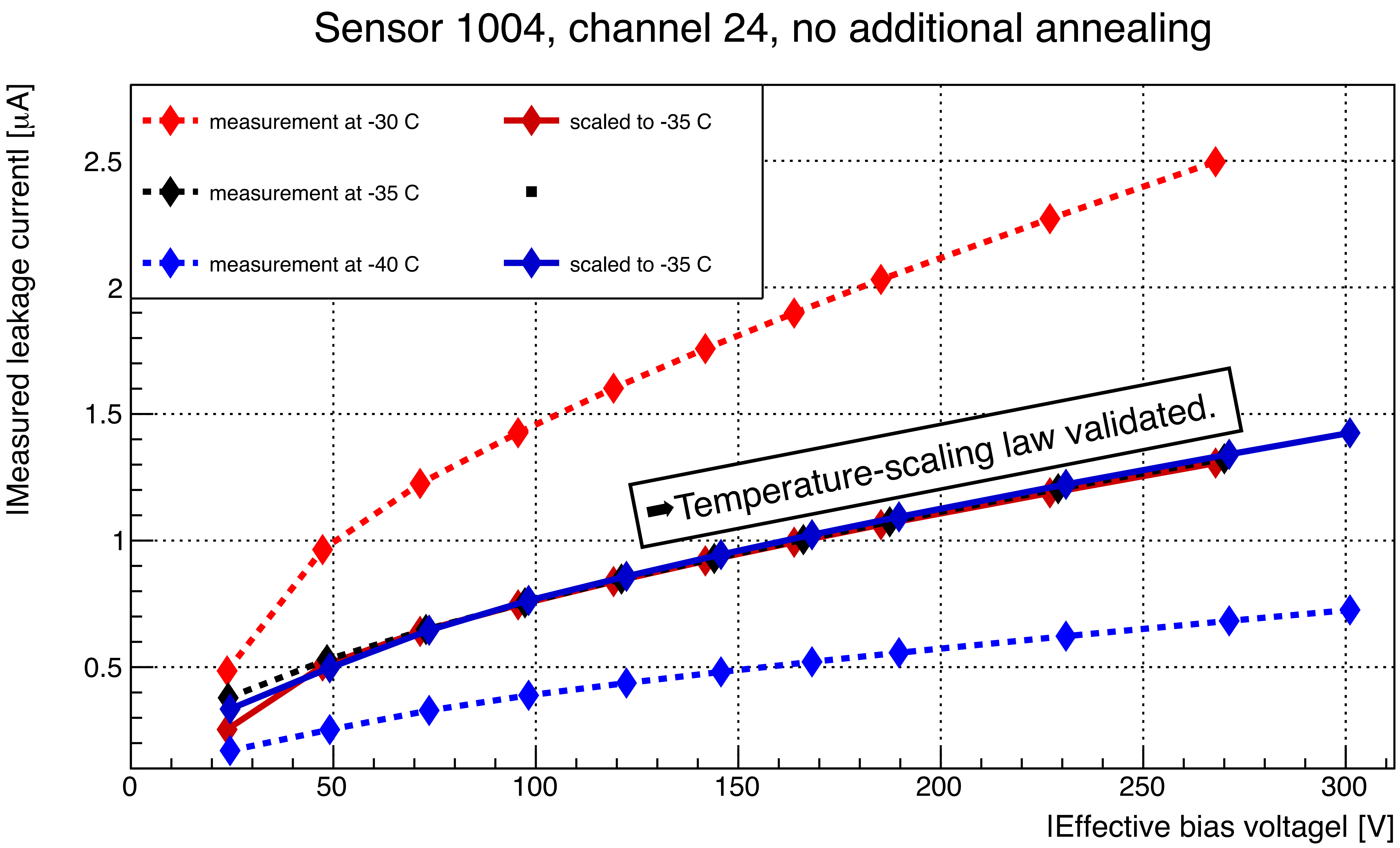
$$\frac{I}{T^2} \cdot \exp \frac{E_g}{2 \cdot k_b \cdot T} \equiv \text{const.}$$

1.21 eV

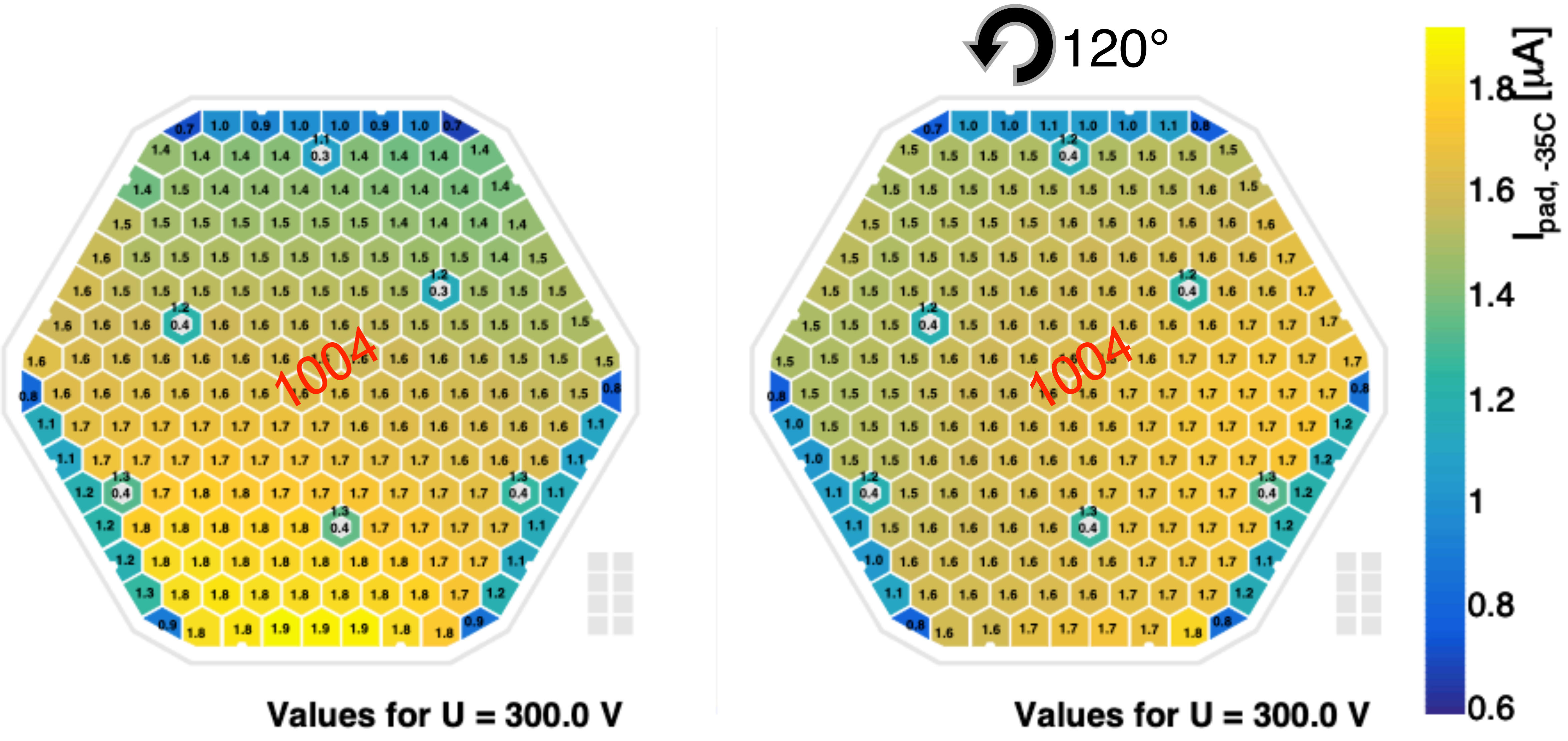
8.62e-5 eV/K

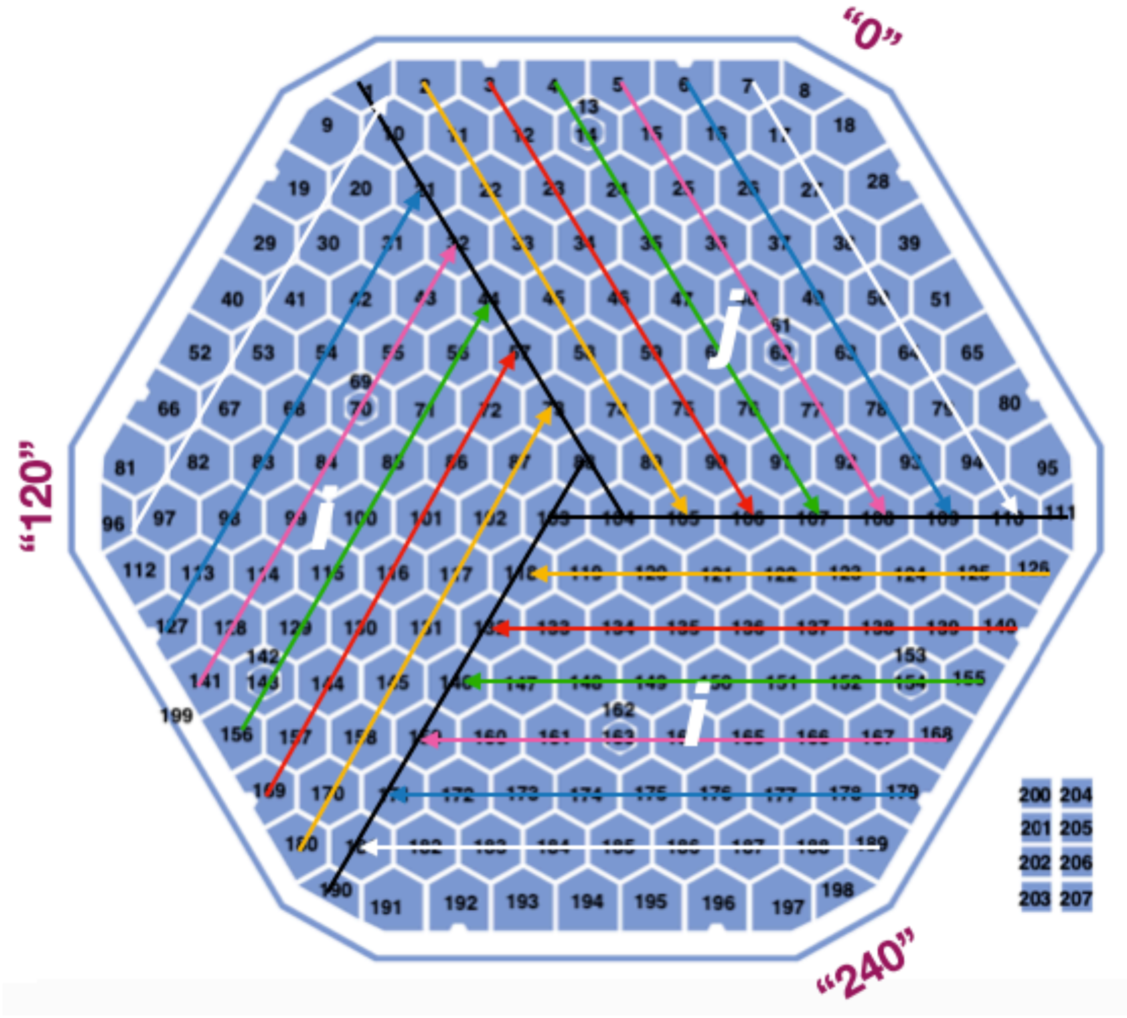
➡ <u>Practical rule-of-thumb for the summer:</u>

I(T=+24°C) = 1000x I(T=-40°C)



Cold chuck at CERN with a +/-0.7 °C temperature variation

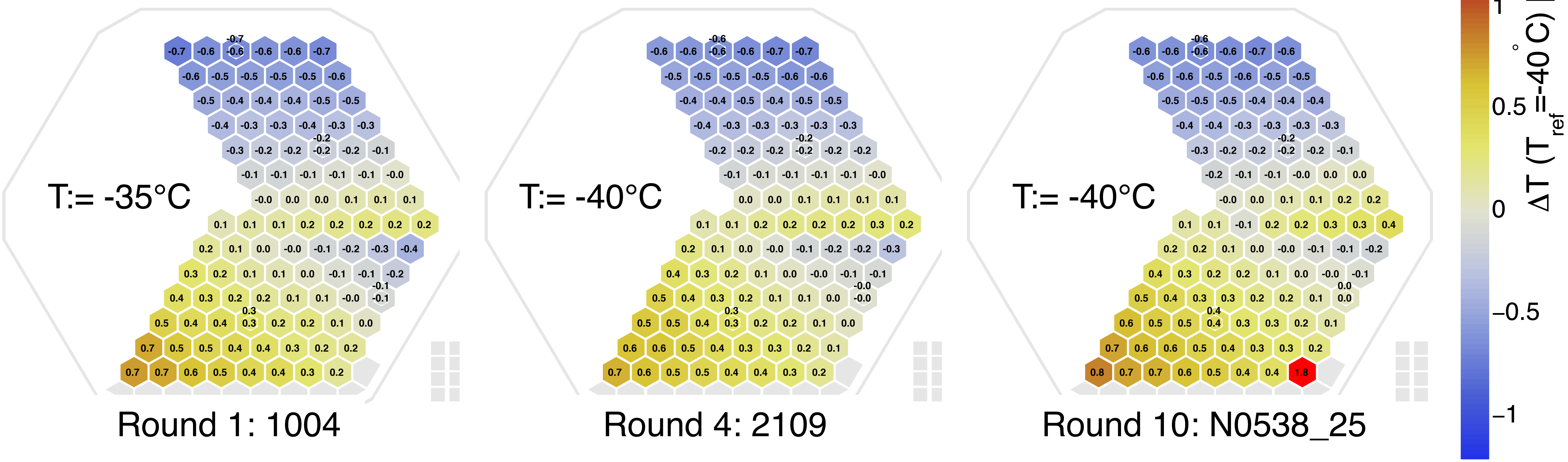




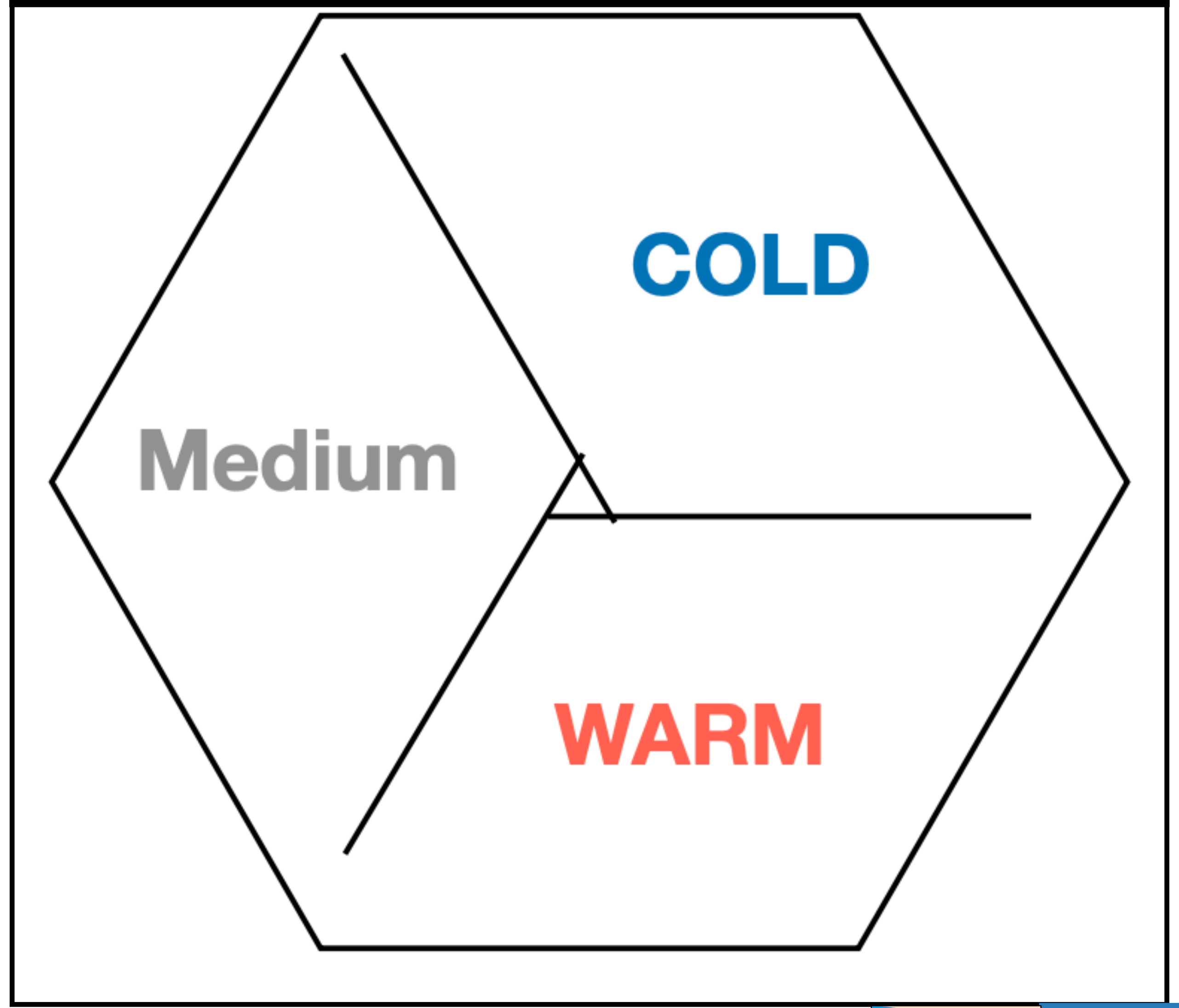
- Infer temperature(T) non-uniformity based on leakage current differences at different positions i, j.
- Can compare T at three positions **w.r.t. each other**.

$$\frac{\delta I_{i,j}}{I_j} = \frac{\delta T_{i,j}}{T_j}\cdot\left(2+\frac{E_g}{2\cdot k_b\cdot T_j}\right)$$

Measurement performed for three different sensors (and different times): **Consistent results**.



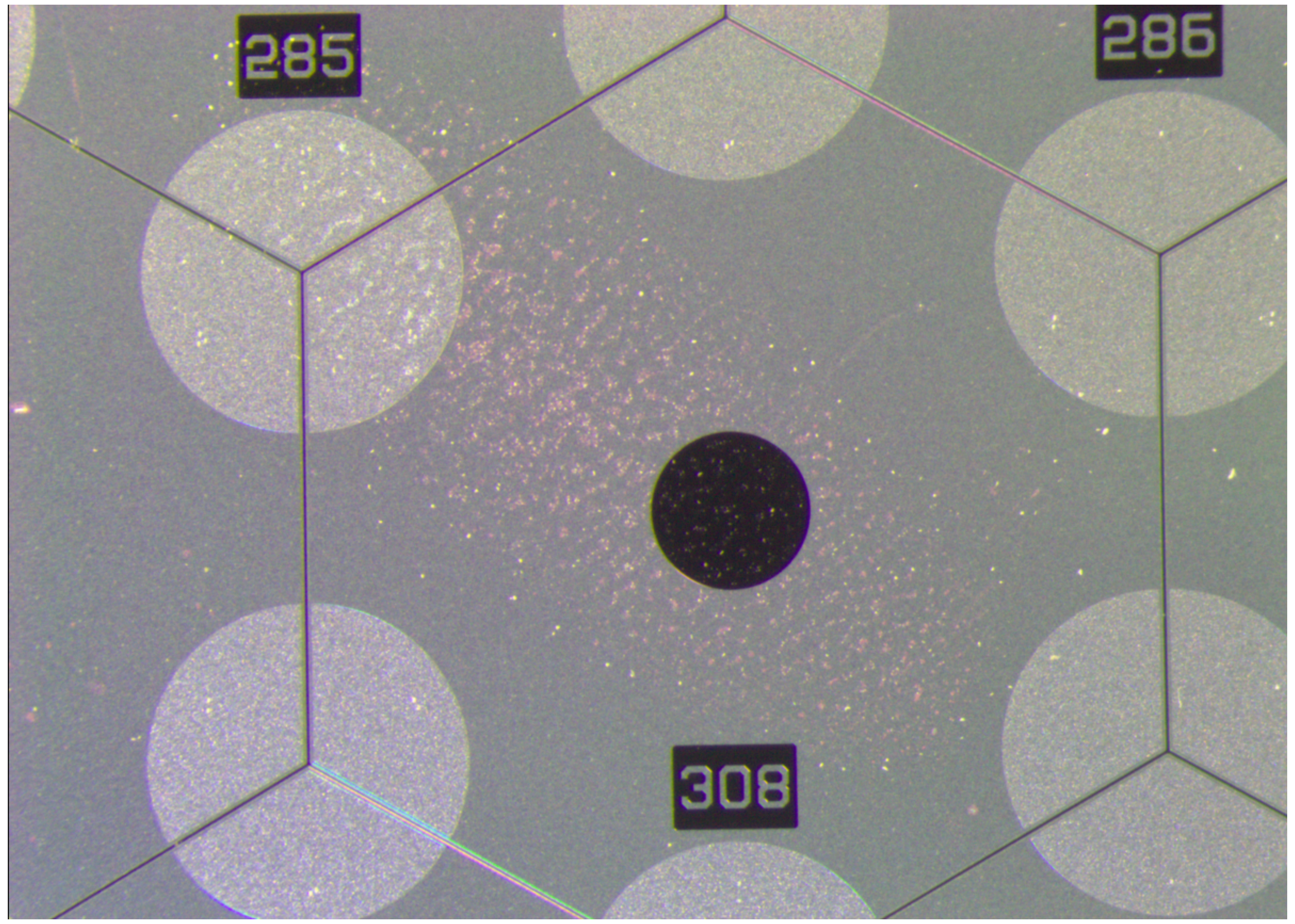
➡Chuck temperature profile schematic.



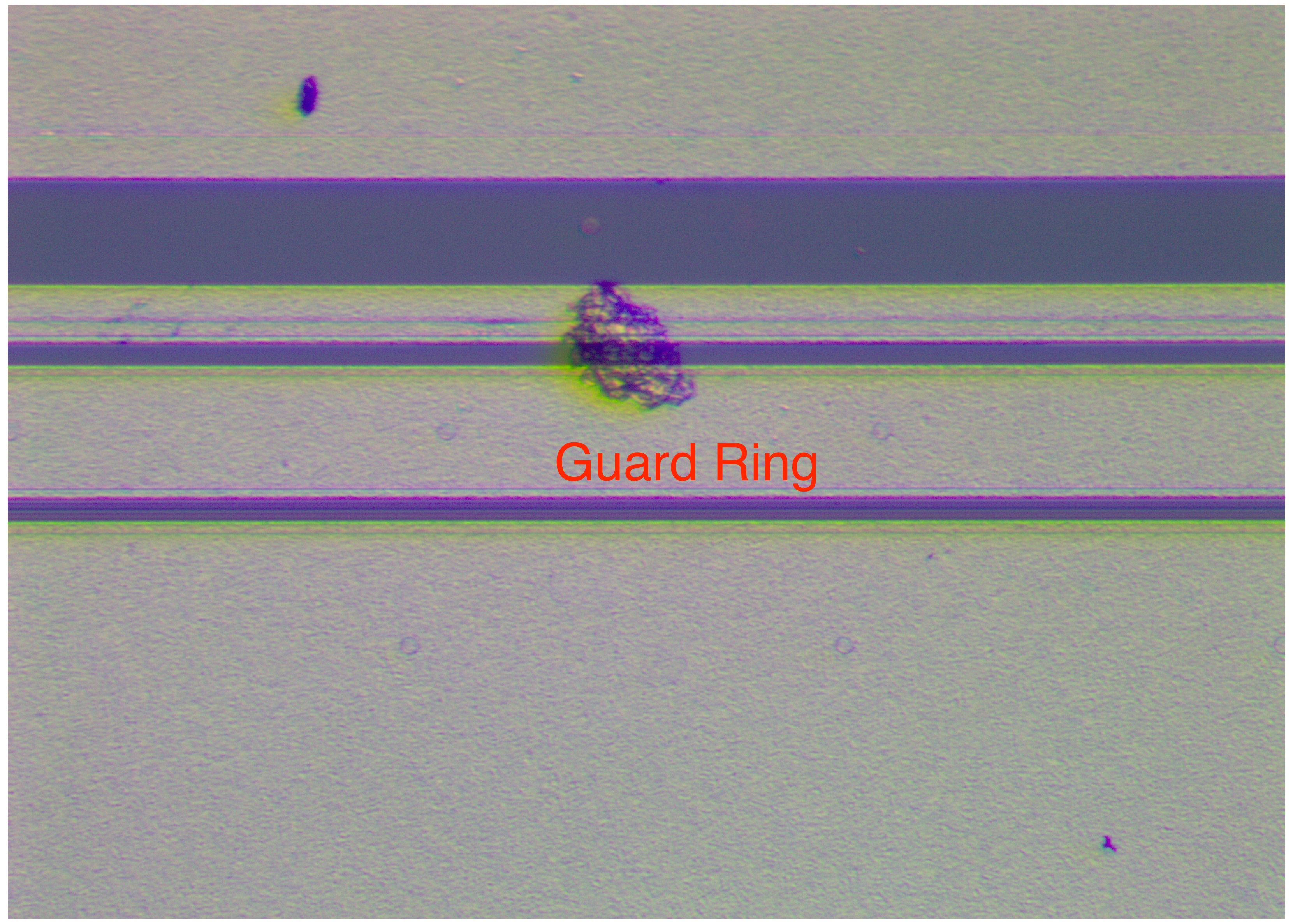
Visual inspection is important

- Visual inspection of the sensors before each measurement:
  - Identification of mechanical defects (e.g. chipped corners, cracks, …).
  - Removal of dust, particular focus on guard ring (GR) area.
- Time-intensive: 10-60min.
- Currently working on automatising parts of the inspection, using a programmable xy-stage.
- Broad range of features present on irradiated sensors:

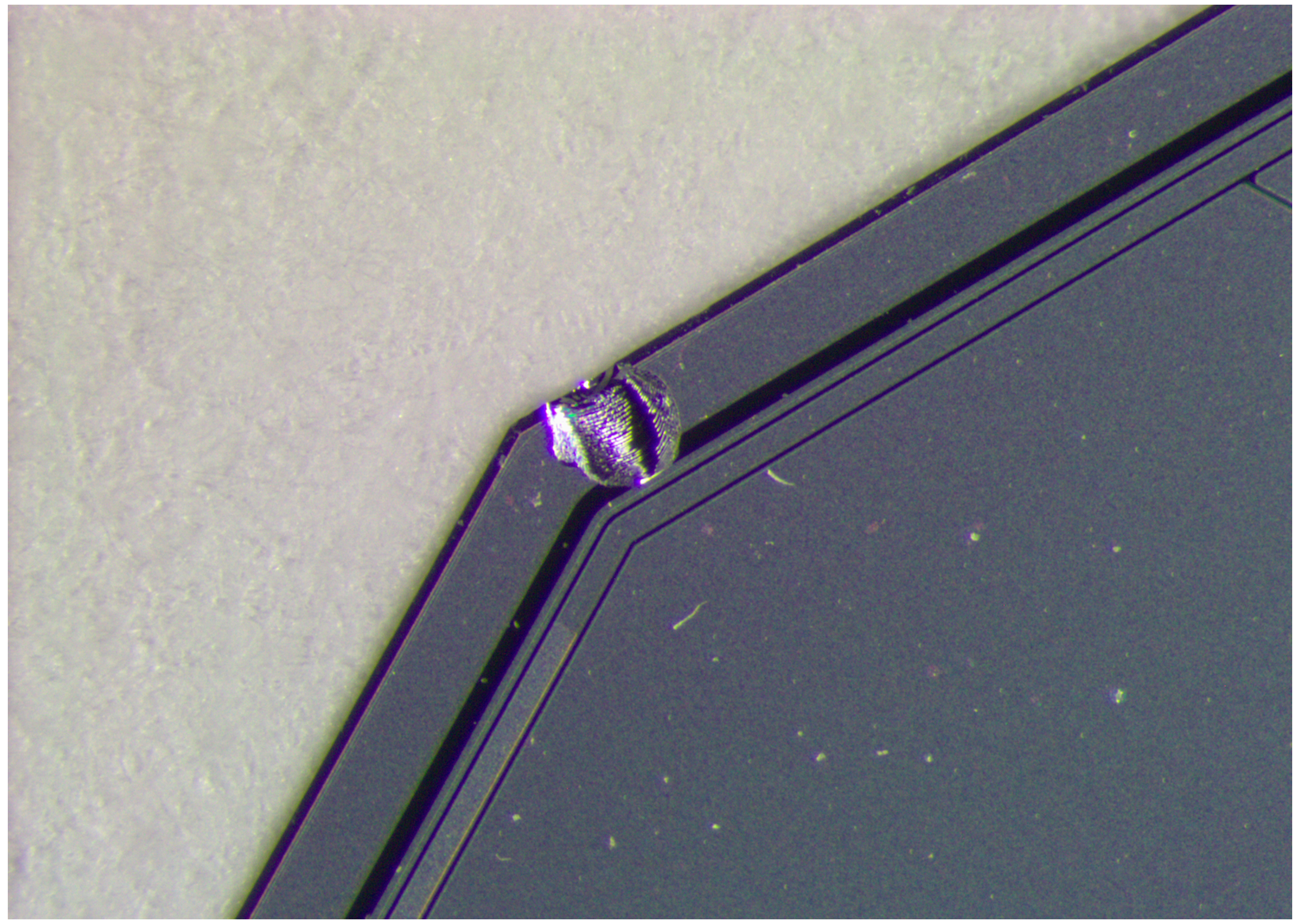
e.g. water residual



e.g. dust particles

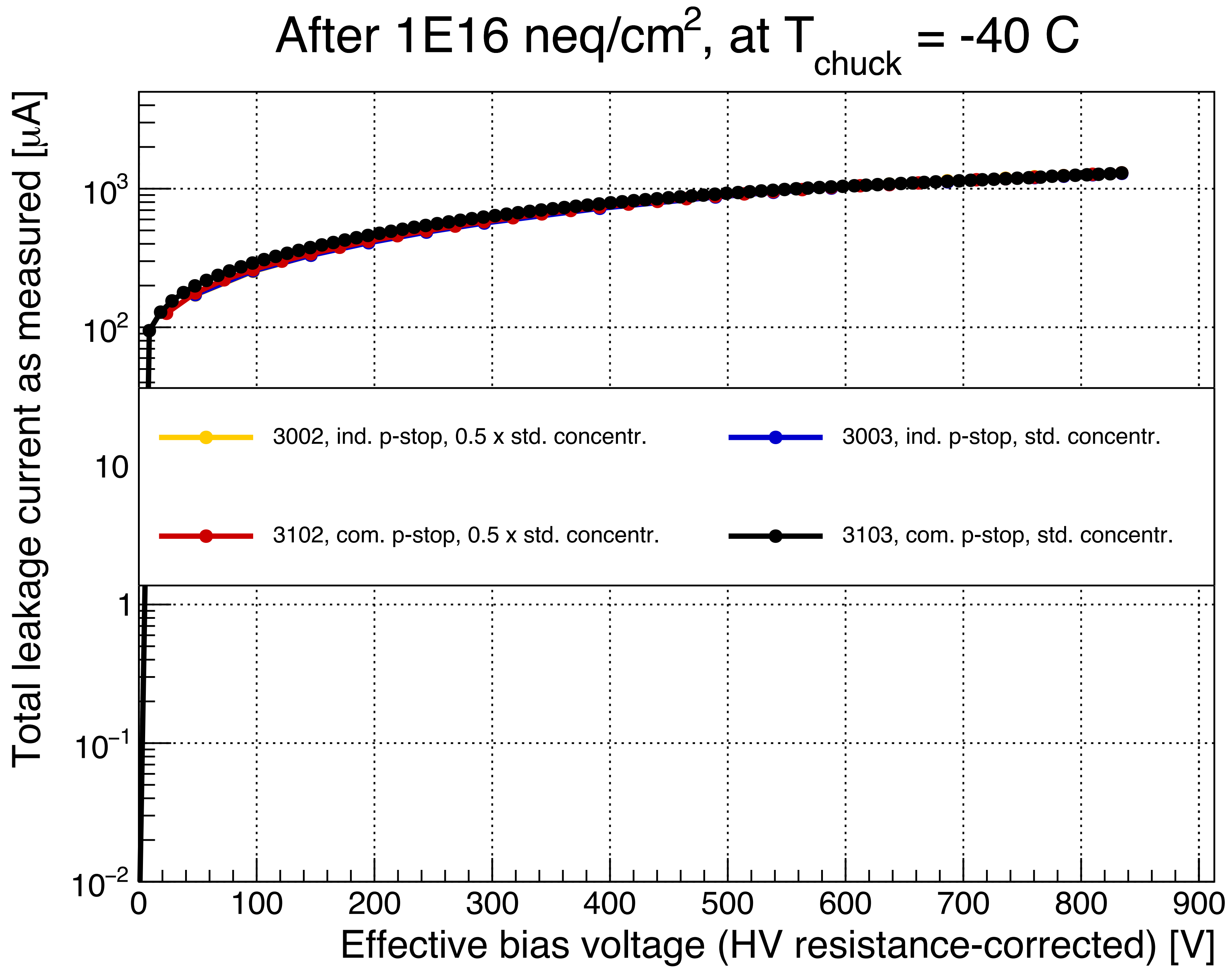


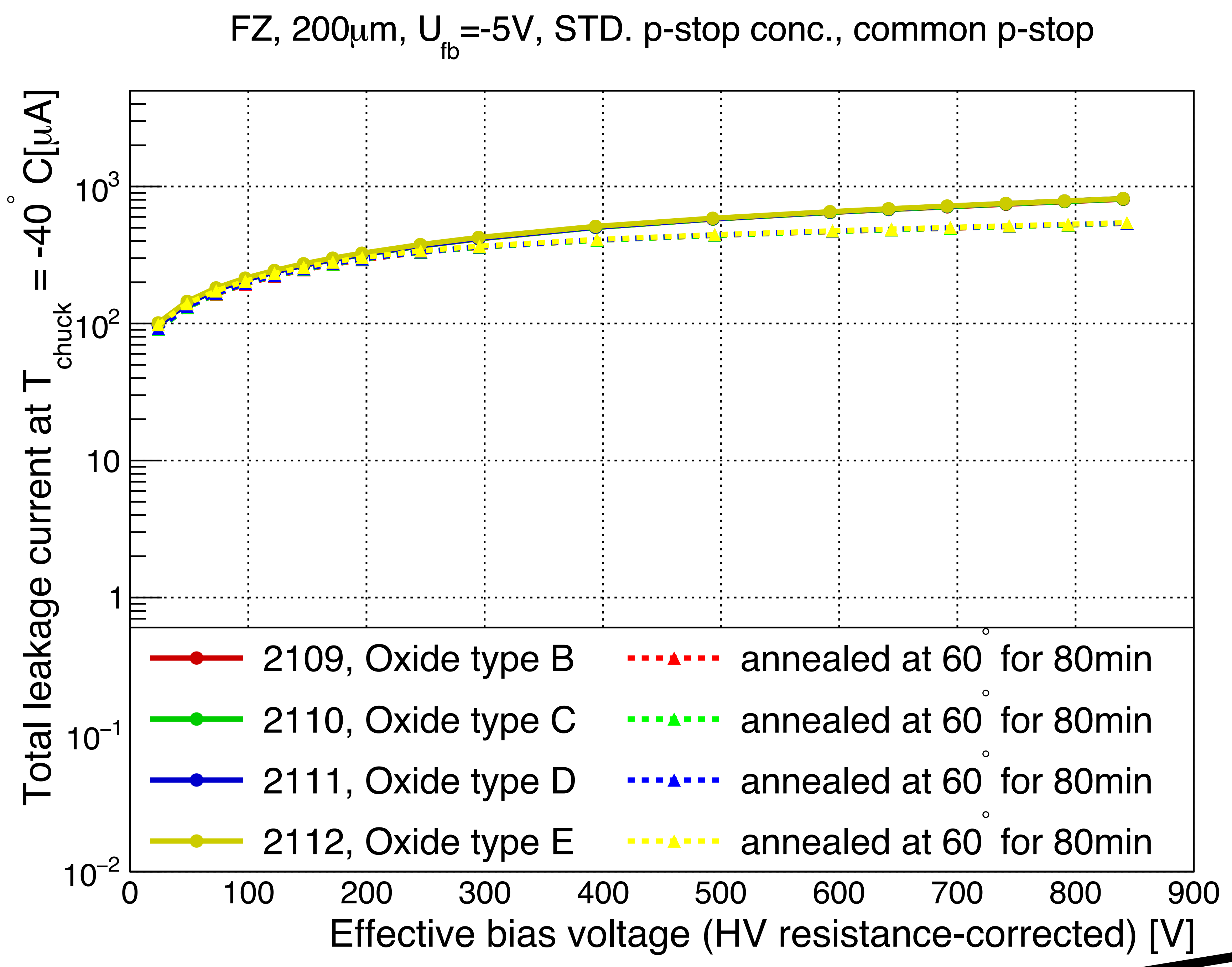
e.g. chipped corners



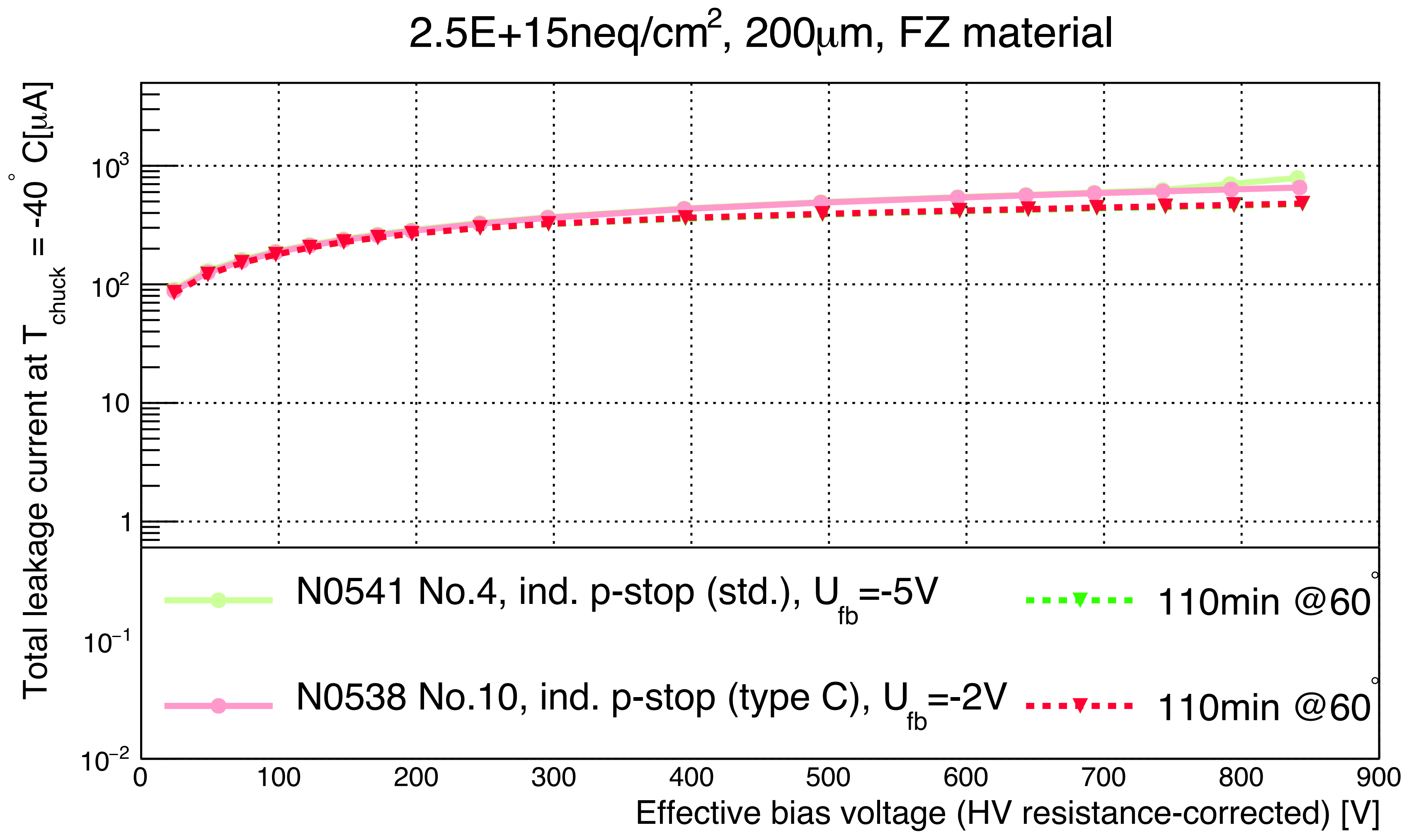
Harmless ⟷ Dangerous

Total leakage currents below 2mA for 20/26 sensors



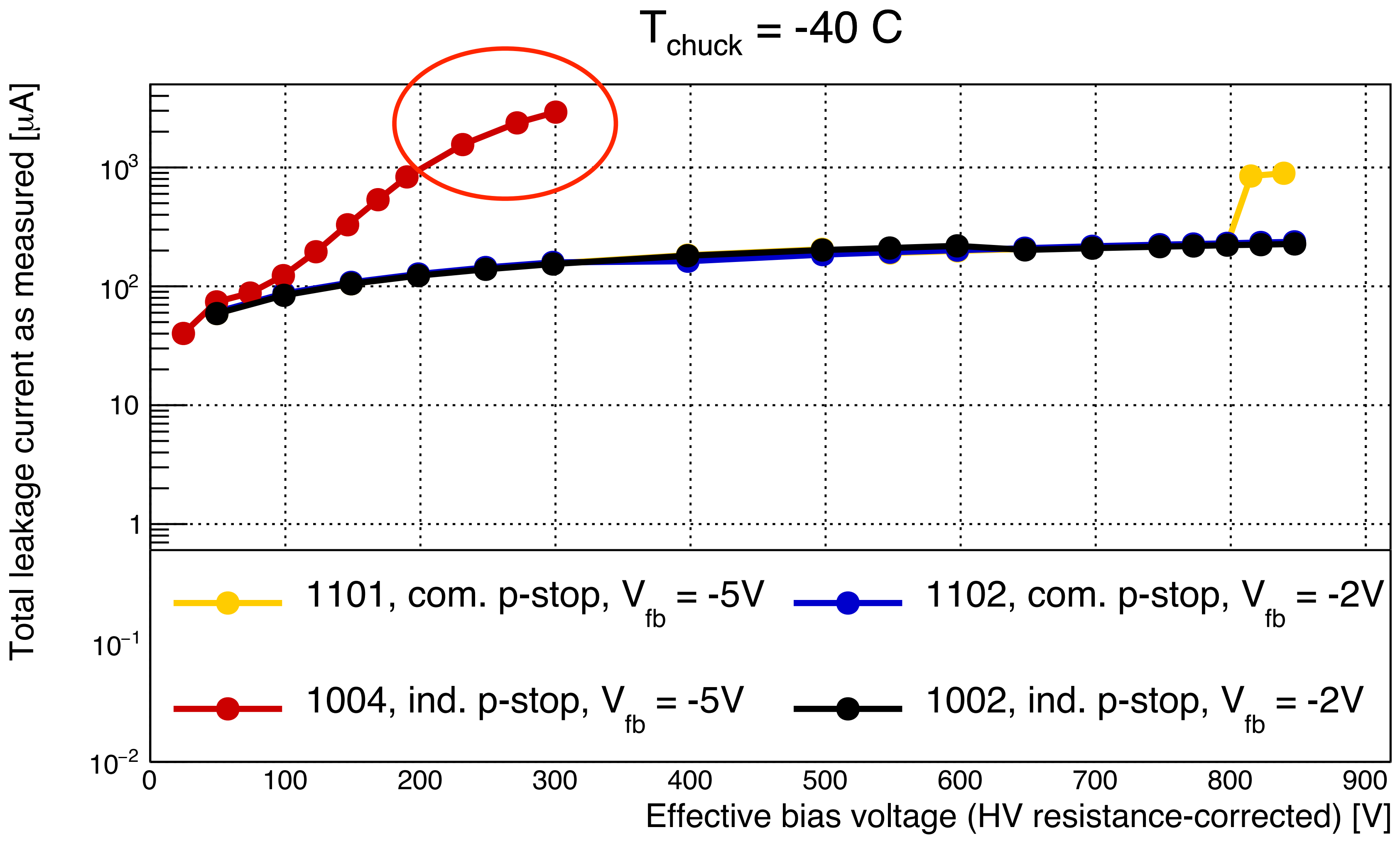


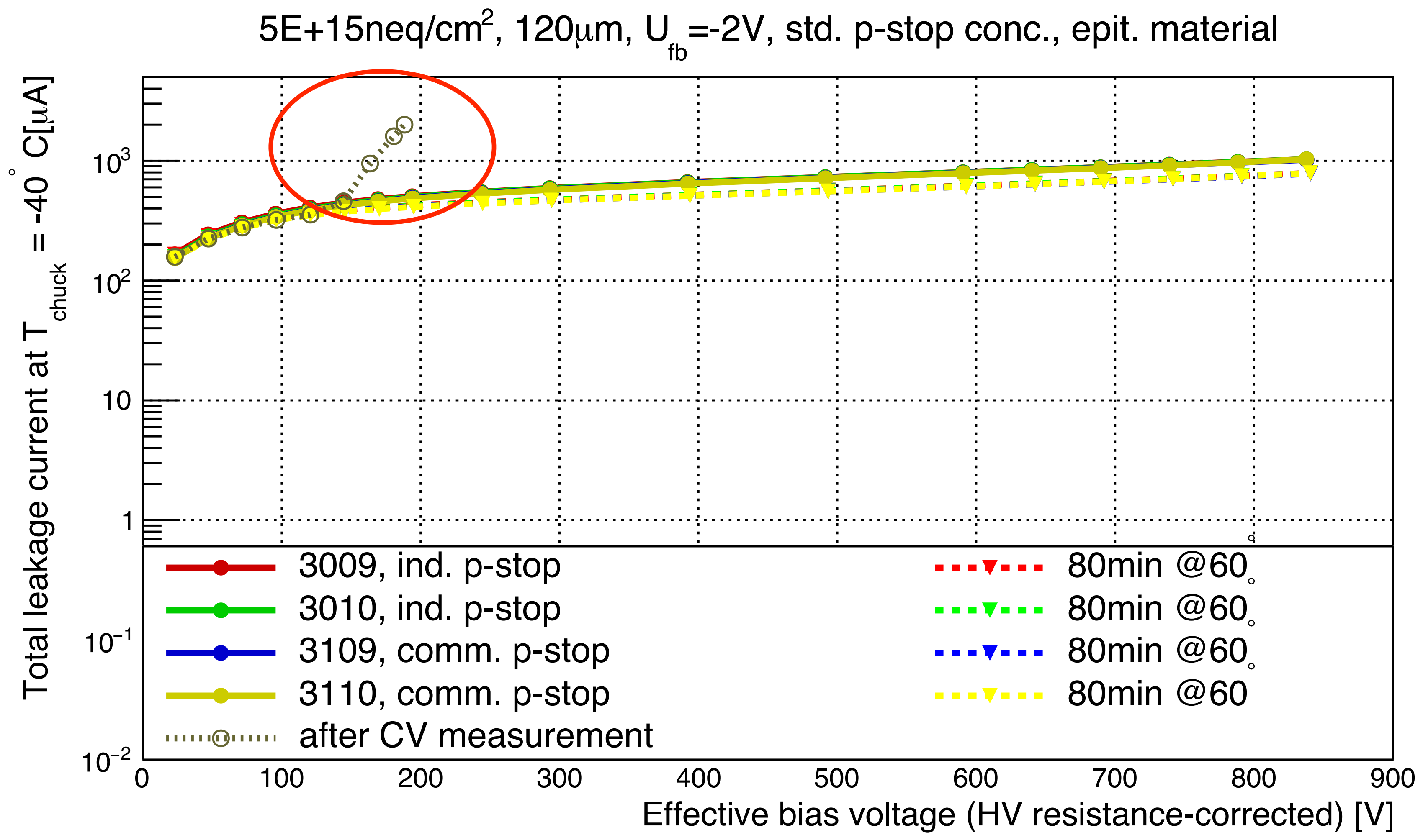
✓Total leakage current across full sensor at -40°C well within our (system-defined) current compliance of 2mA.

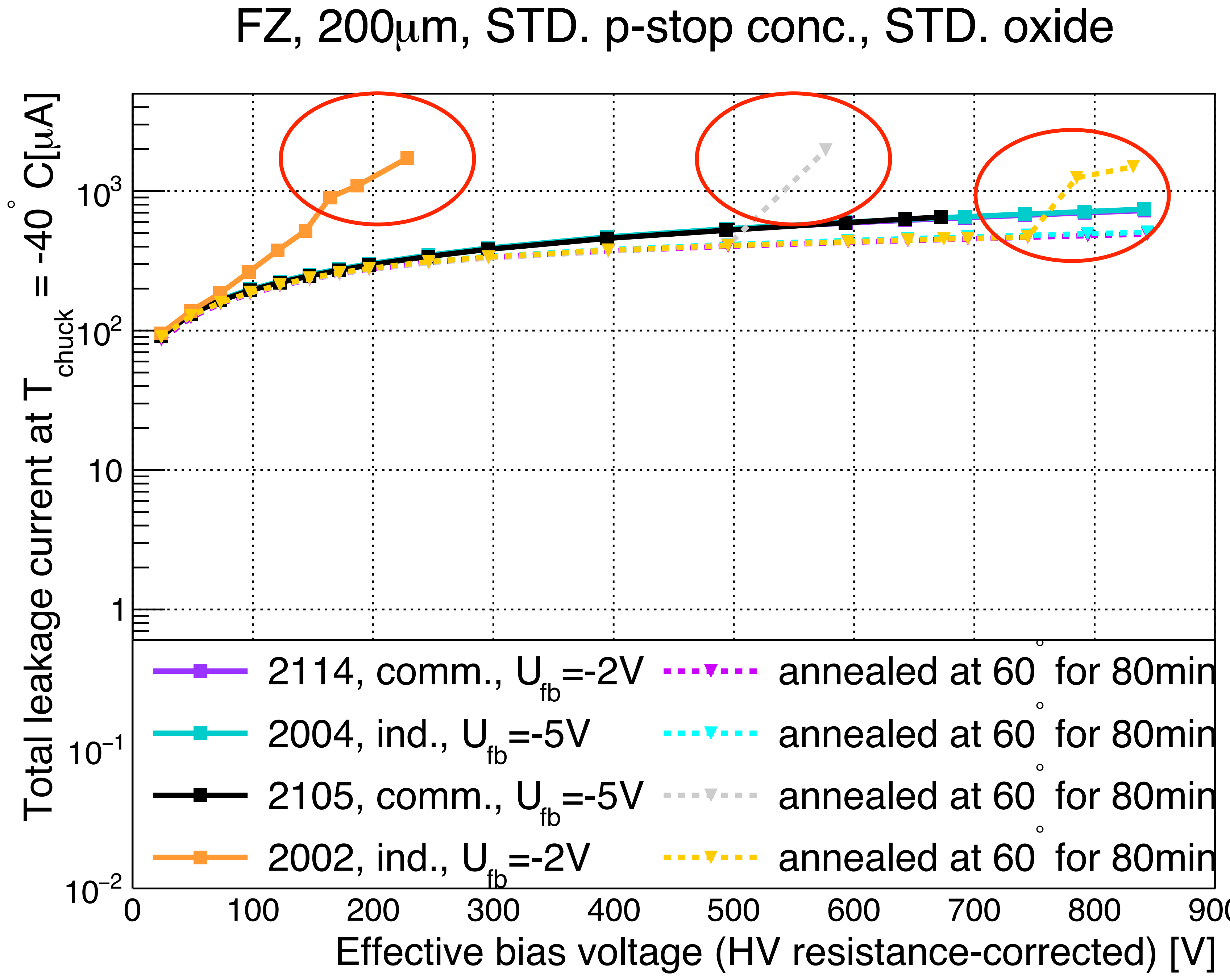


3002	ind.	120μm	-2V	0.5*STD	STD	1E+16
3102	com.			0.5*STD		
3003	ind.			STD		
3103	com.			STD		
2109	com.	200μm	-5V	STD	Type B	2.5E+15
2110					Type C	
2111					Type D	
2112					Type E	
N0541 WNo.4	ind.	200μm	-5V	STD	STD	2.5E+15
N0538 WNo.10			-2V	Type C	STD	

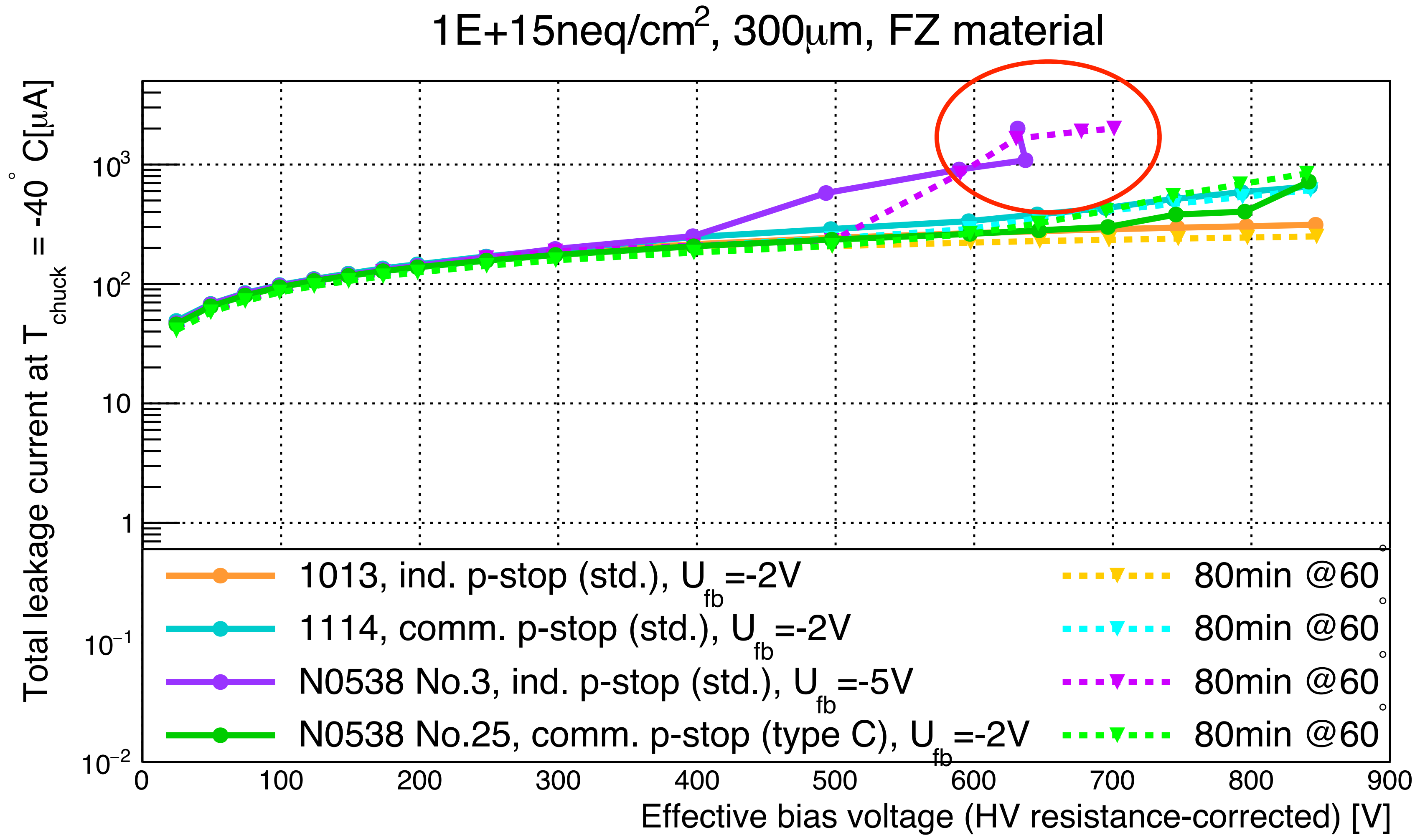
Total leakage currents above 2mA for 6/26 sensors







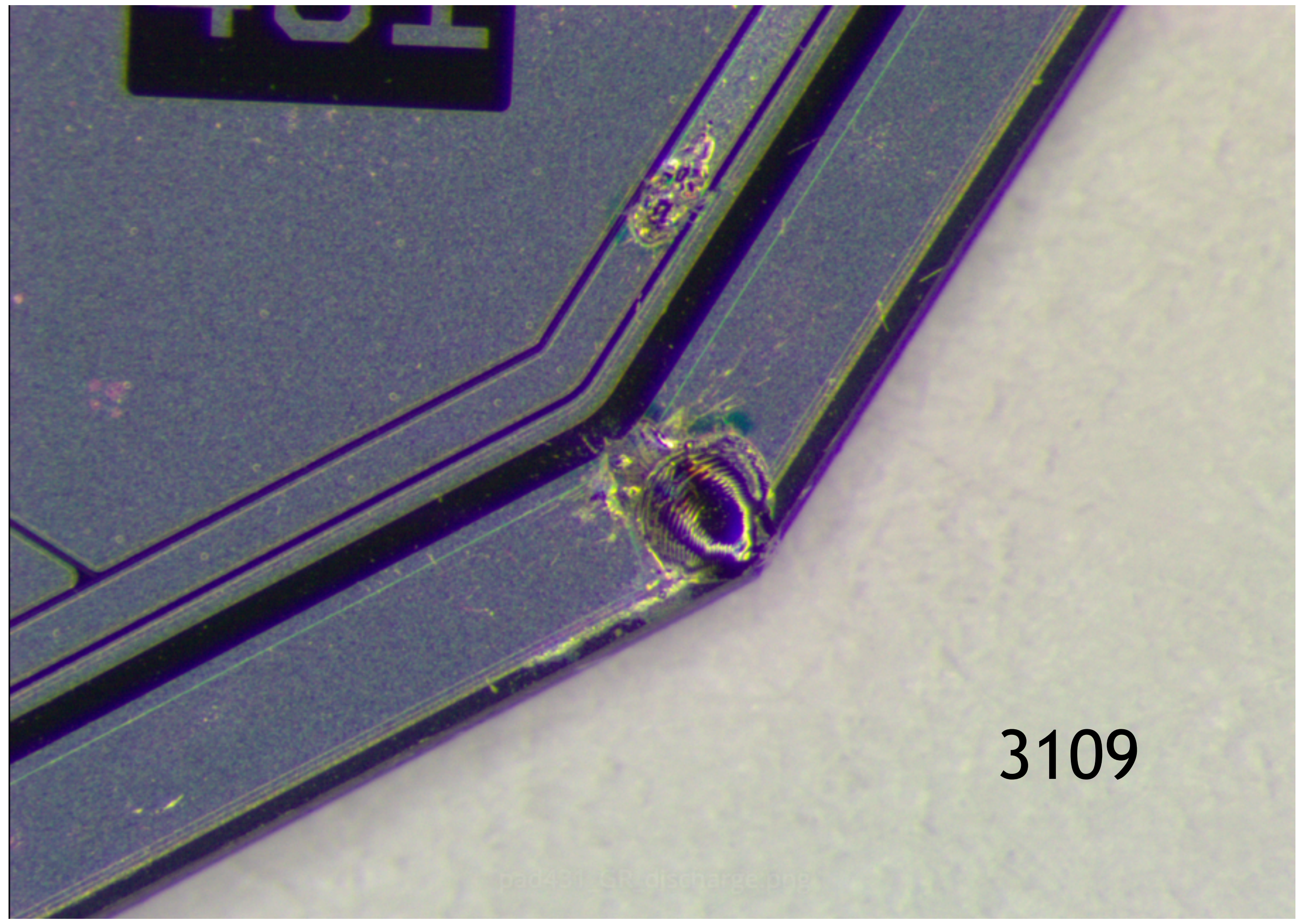
* 3109 analogous to 3110 after post-annealing CV measurement.

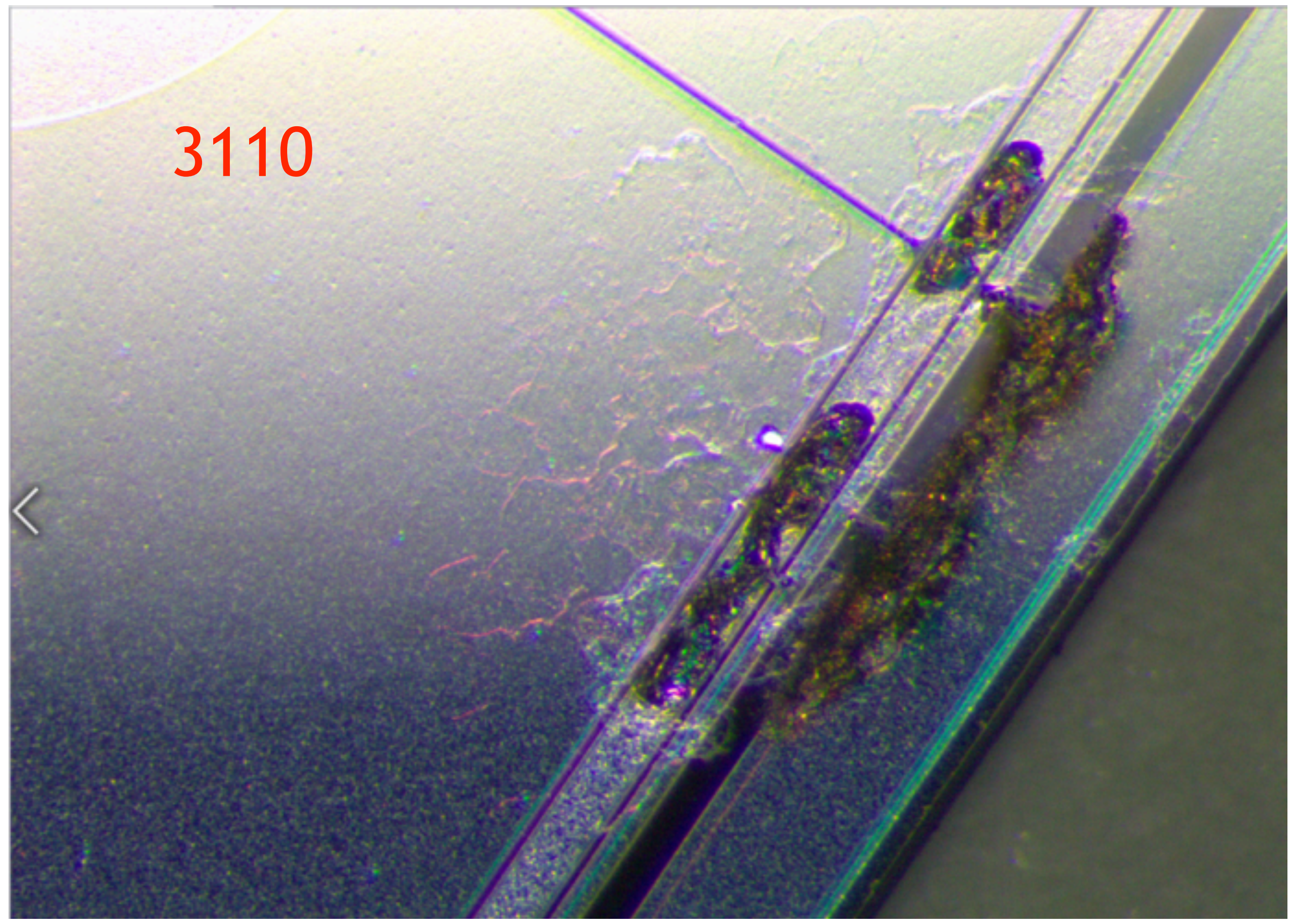


x Total leakage current across full sensor at -40°C exceeds 2mA.

1004	ind.	300µm	-5V	STD	STD	6.5E+14
1002			-2V			
1101	com.		-5V			
1102			-2V			
2004	ind.	200µm	-5V	STD	STD	2.5E+15
2002			-2V			
2105	com.		-5V			
2114			-2V			
3009	ind.	120µm	-2V	STD	STD	5E+15
3010						
3109*	com.					
3110						
1013	ind.	300µm	-2V	STD	STD	1E+15
1114	com.					
N0538 WNo.3	ind.		-5V			
N0538 WNo.25	com.		-2V	Type C		

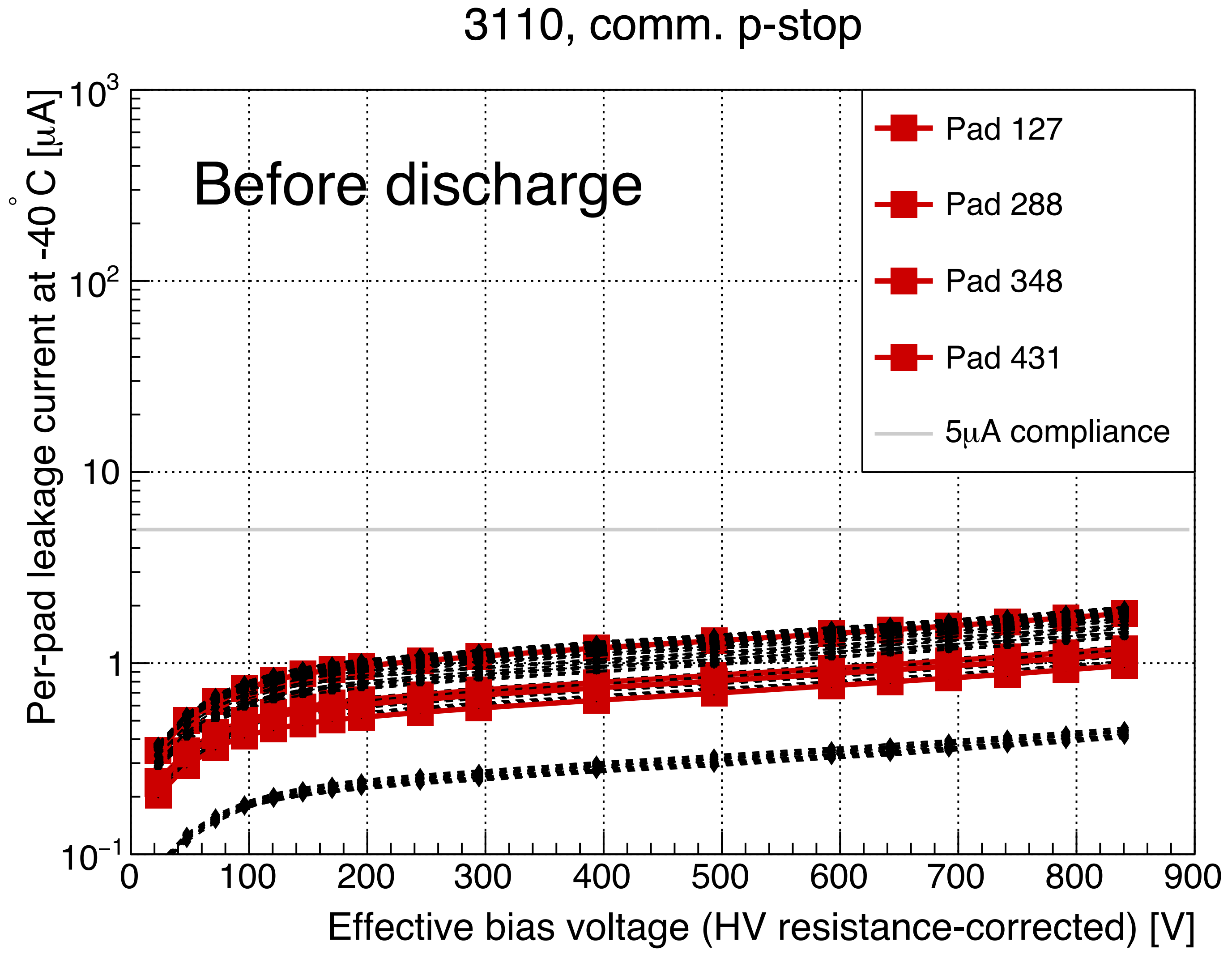
Multiple new discharge marks observed during the characterisation

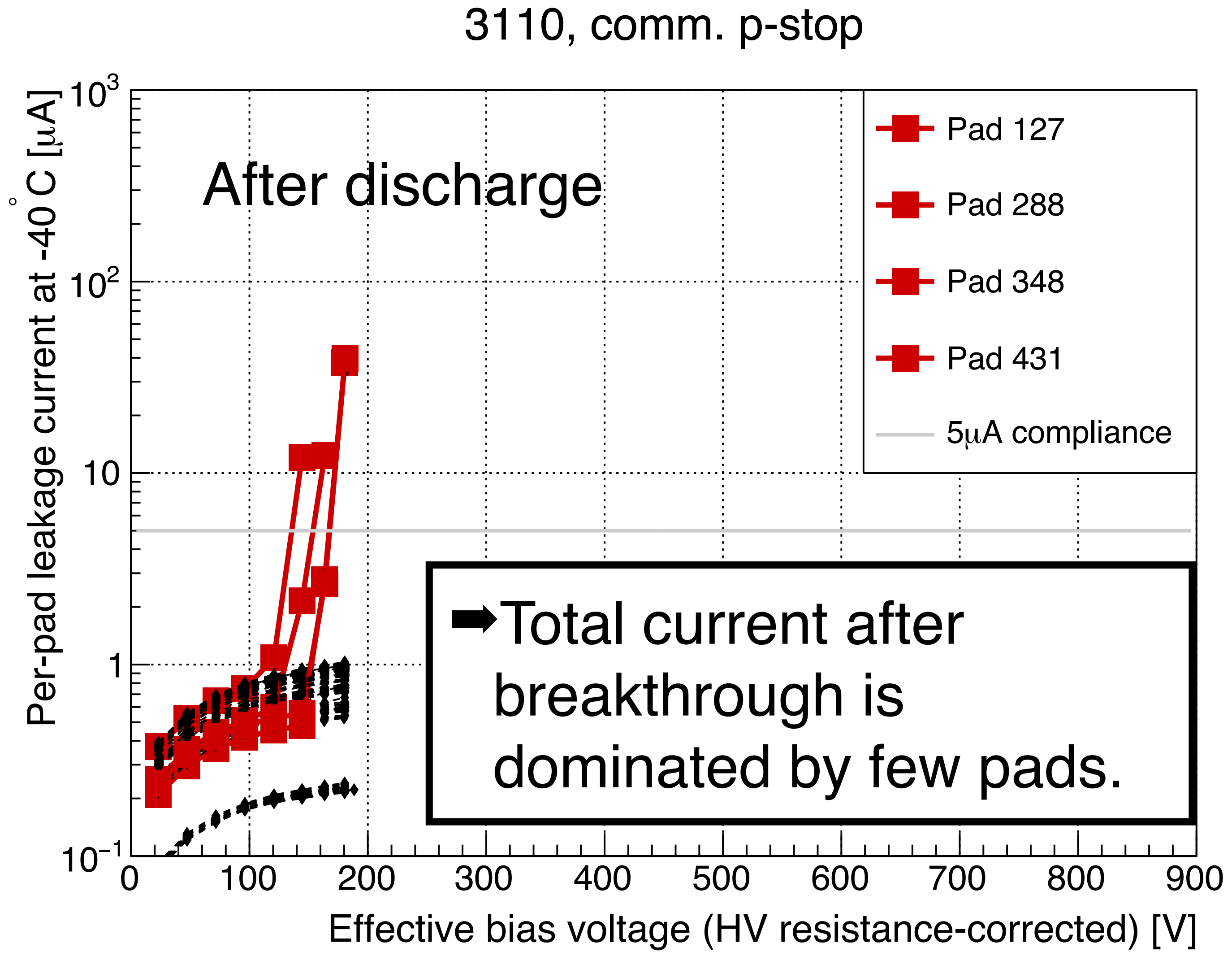




ID	Previous visible defects	Location of discharge mark
1004	-	Pad 81, HV edge ring and grounded GR
2002	Chipped corner	Pad 196, HV edge ring and grounded GR
2105	Discharge mark during pre-irrad. measurement	Pad 197, HV edge ring and grounded GR
3109	Chipped corner	Pads 417 and 431, HV edge ring and grounded GR
3110	-	Pad 287, HV edge ring and grounded GR
N0538 WNo.3	-	Pad 6, HV edge ring and grounded GR, ***no passivation in grounded GR***

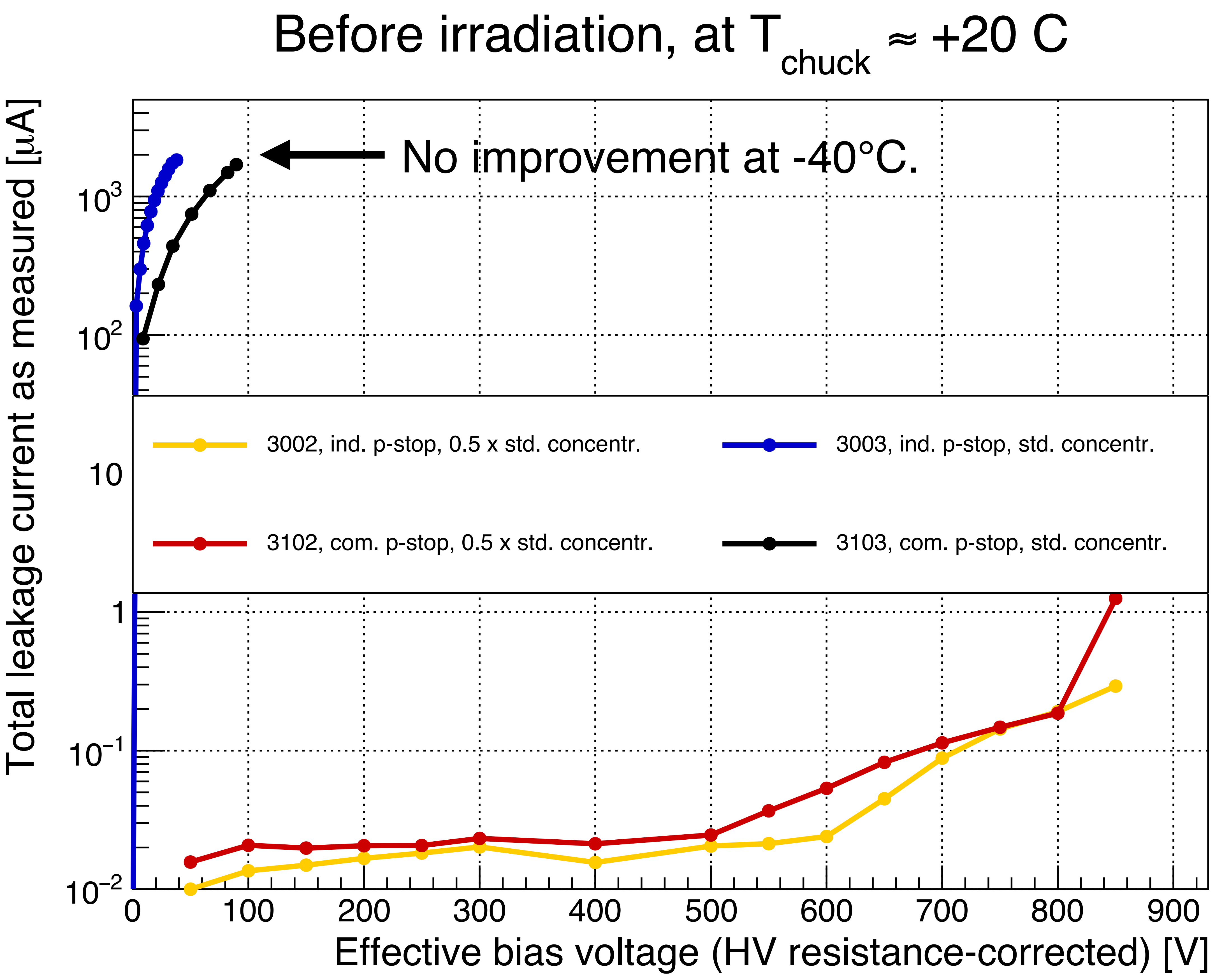
New discharge marks without previous defects visible.

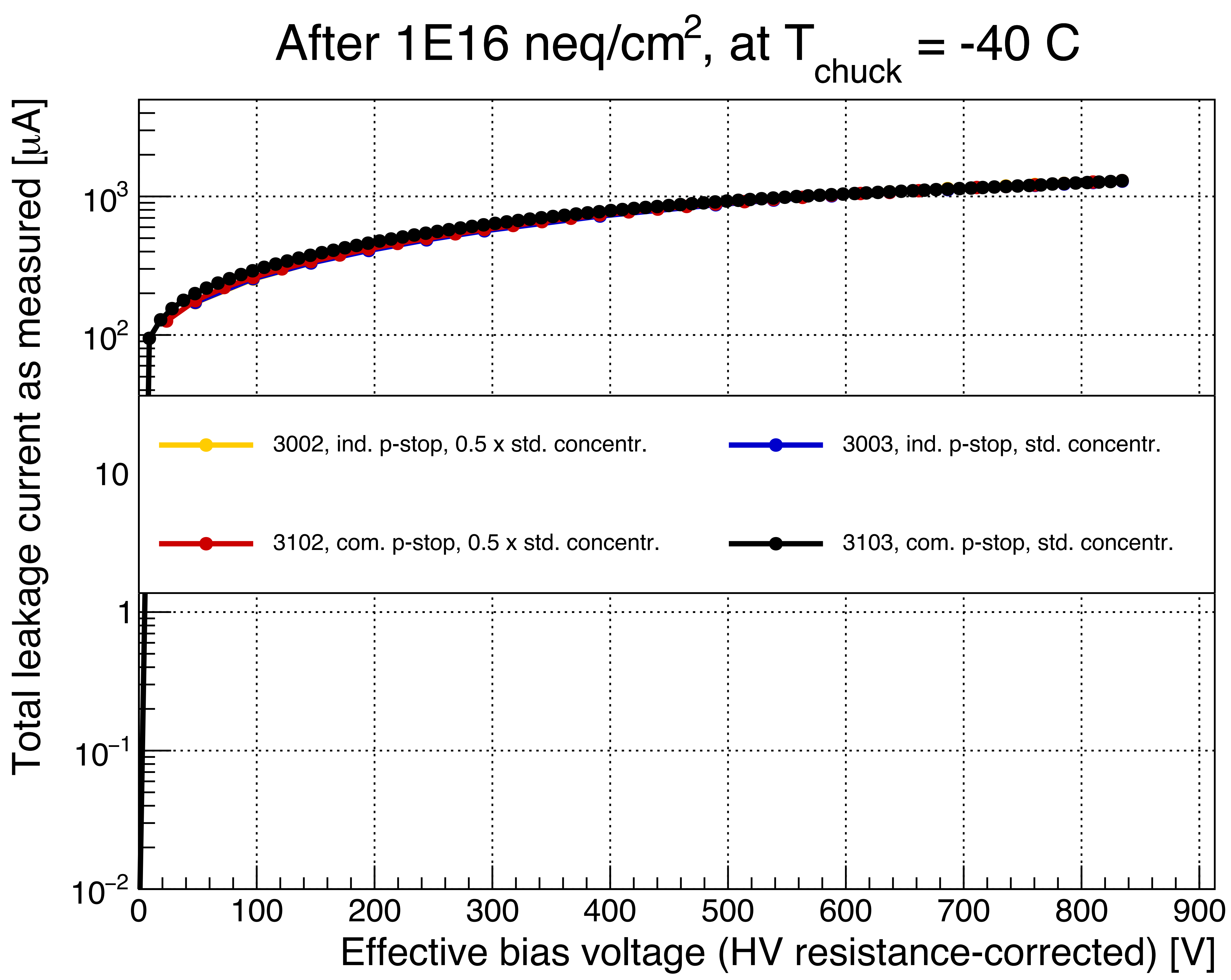




- Discharges occurred at different stages of the characterisation procedure.
- Some sensors with discharges could be partially characterised.

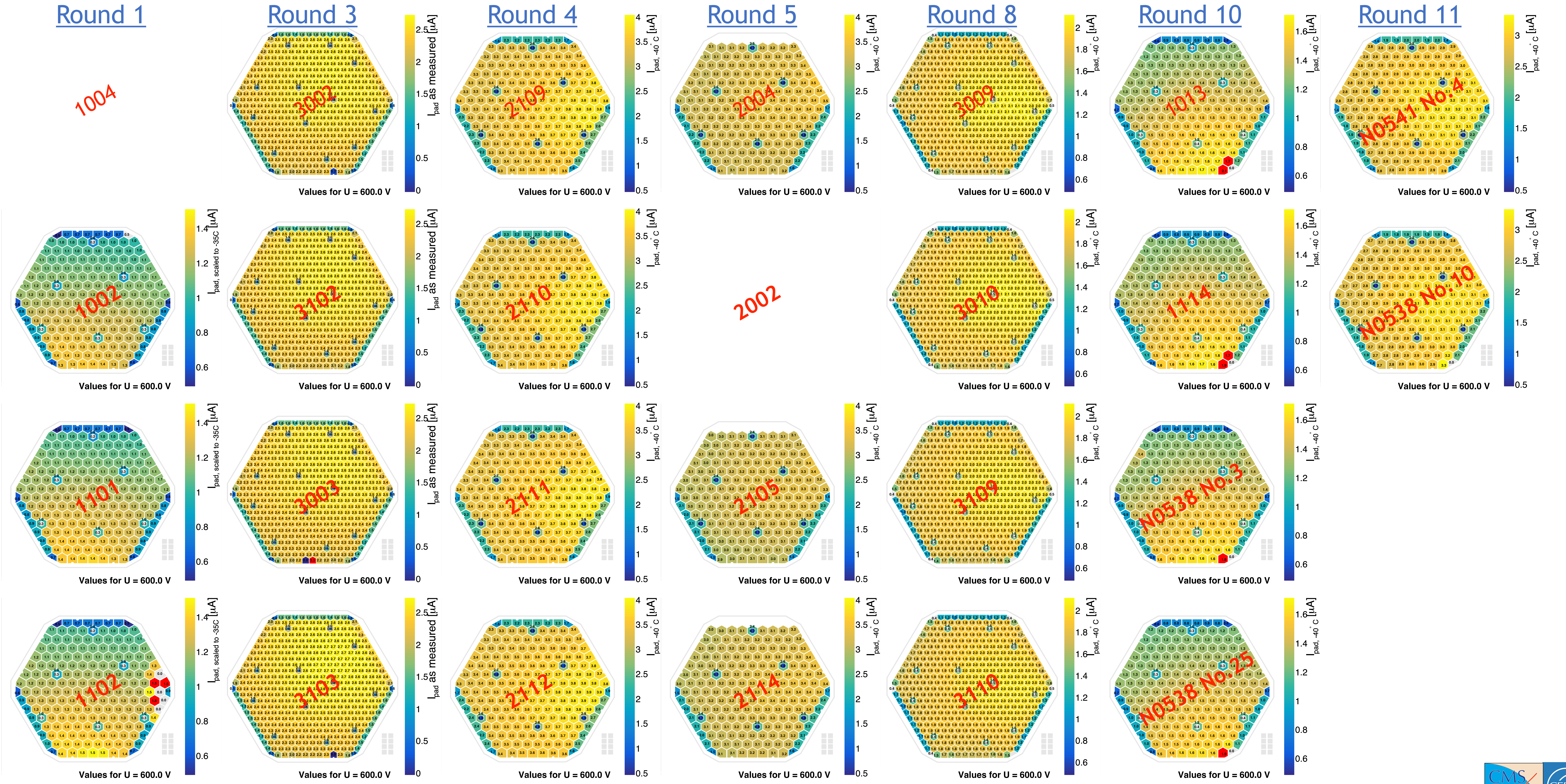
Some sensors “cured” during irradiation





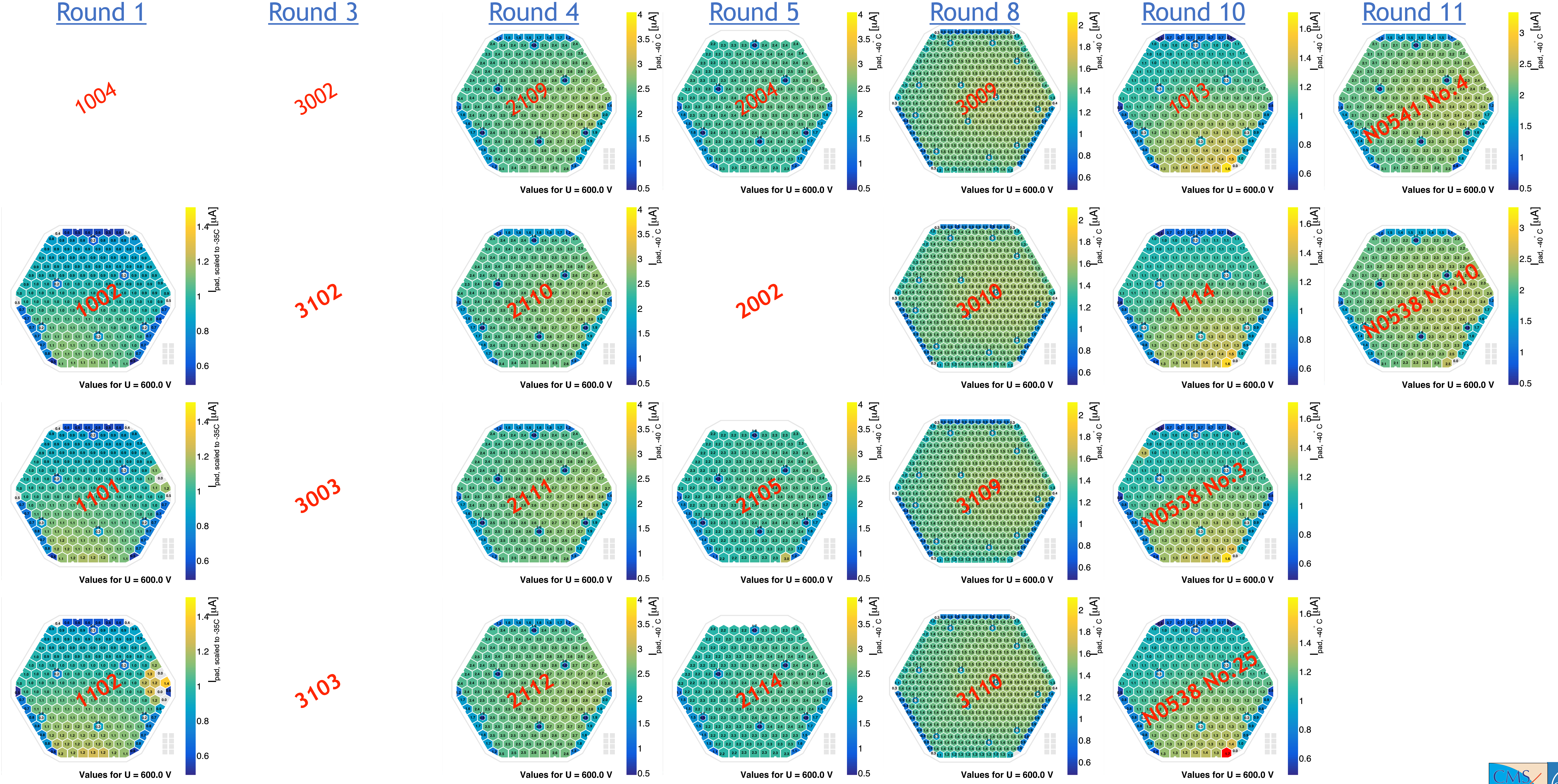
- Leakage current of sensors 3003 and 3103 dominated by few pads with high leakage current before irradiation.
- Total leakage current of same sensors after irradiation consistent with 3002 and 3102.
- Similar “recovery” effect also seen for round 8 sensors.

Leakage currents *before* our additional annealing at 600V



Leakage currents *after* our additional annealing at 600V

Round 1 | Round 3 | Round 4 | Round 5 | Round 8 | Round 10 | Round 11



RINSC fluence profile seen in data

Model: Measured leakage current (I) proportional to exposed fluence (ɸ) during irradiation.

- Per-pad leakage current interpolated to 600V.
- Sensors before our additional annealing.
- Use leakage currents from full hexagonal pads only.
- Quantify fluence profile as a 2D Gaussian with arbitrary orientation.

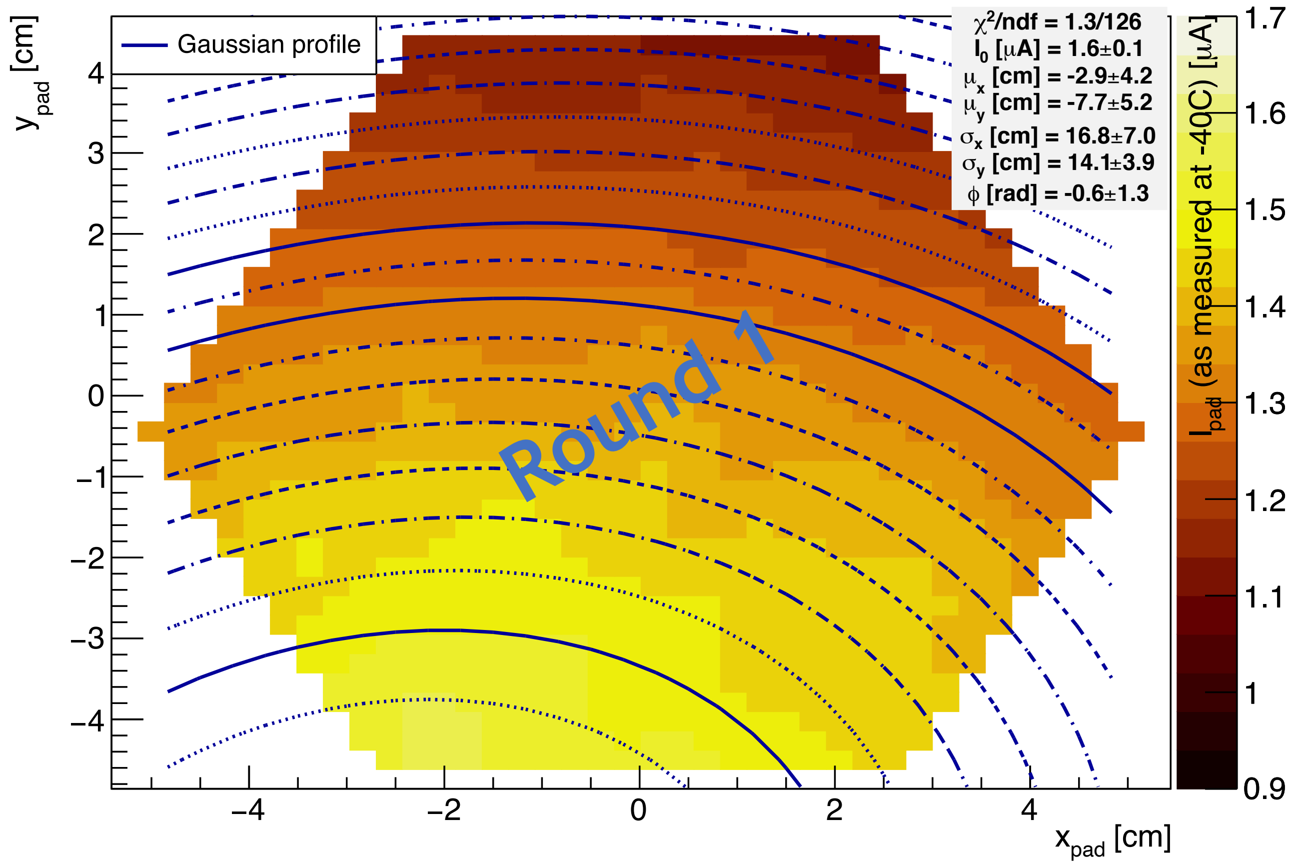
✓Consistent profiles within the same round (not shown here).

➡Sensor orientations differed between irradiation rounds.

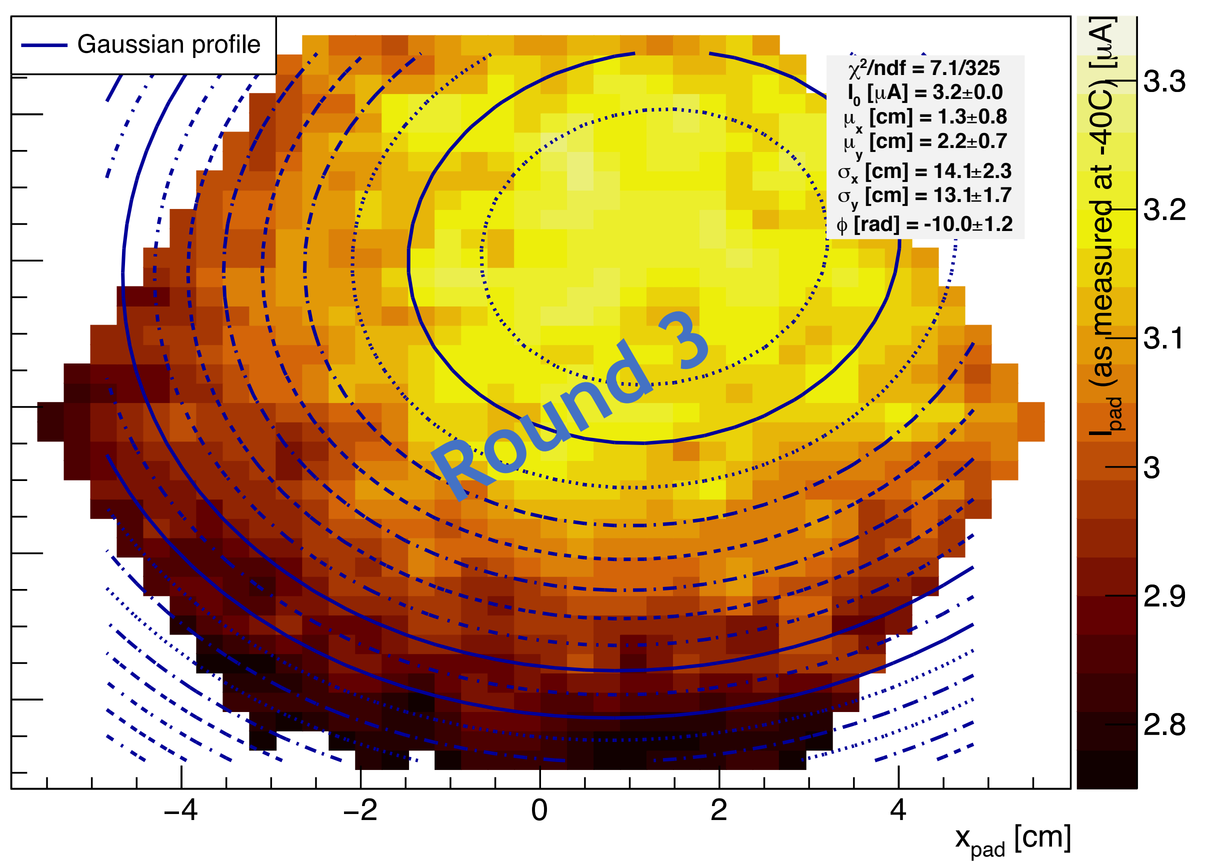
➡Beam not centred on sensor.

➡Fluence profile width: σ~8”—> **ΔΦ/Φ=ΔI/I~20%.**

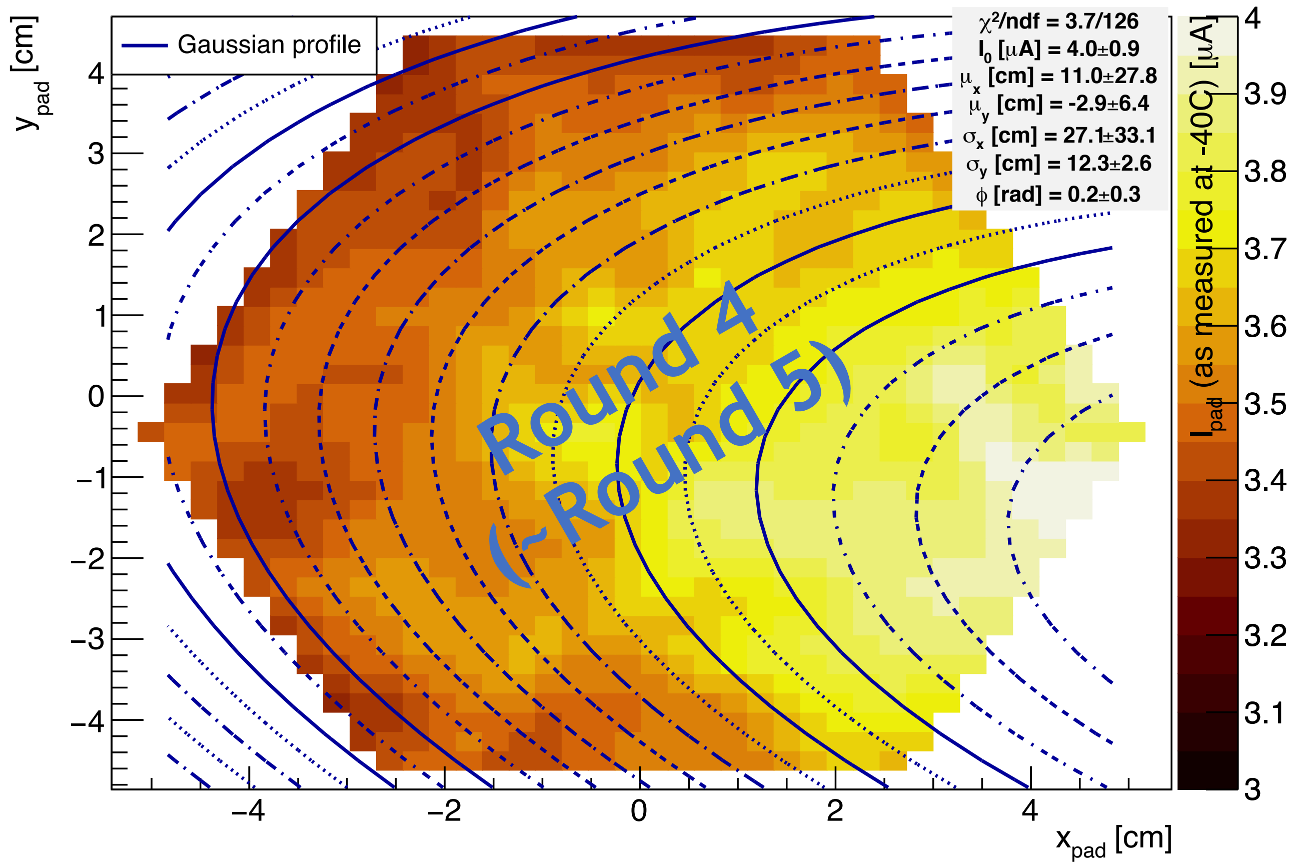
Fluence profile estimate for sensor: 1002



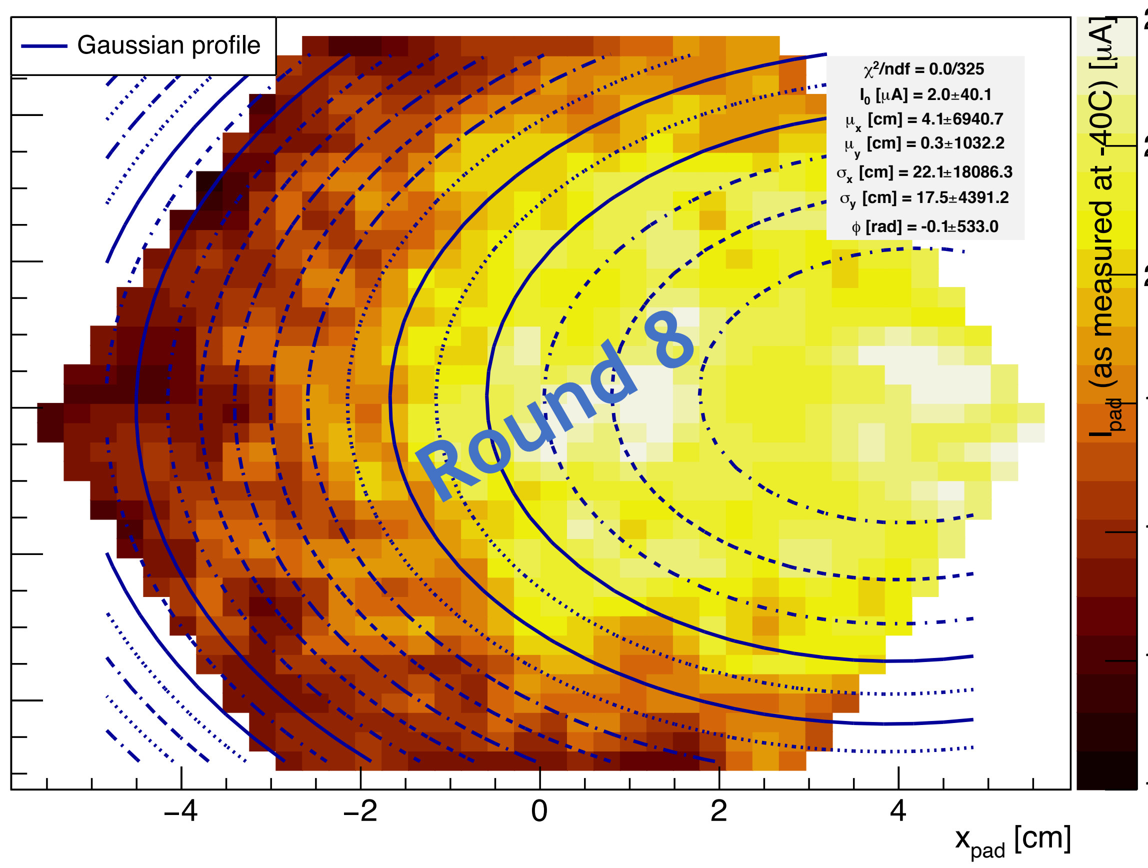
Fluence profile estimate for sensor: 3002



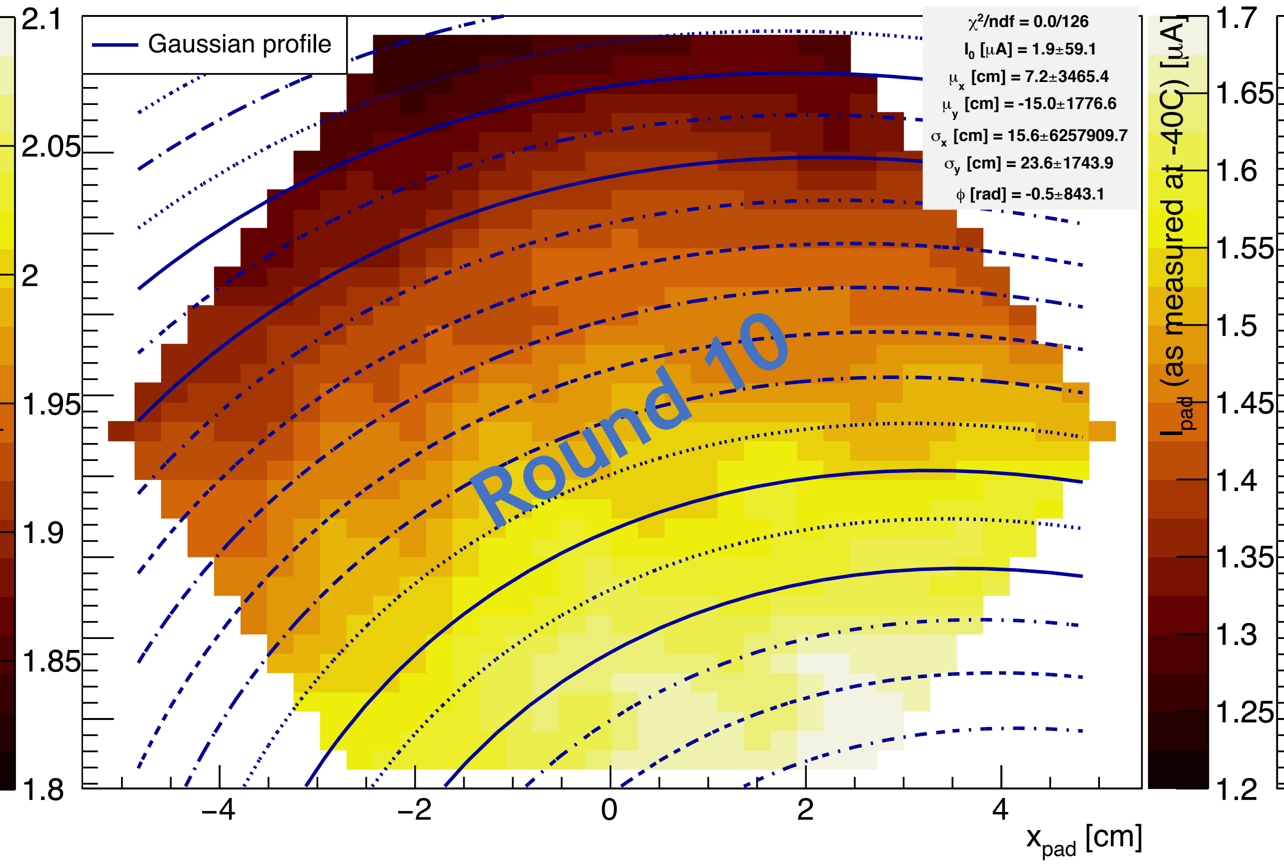
2110, Oxide type C



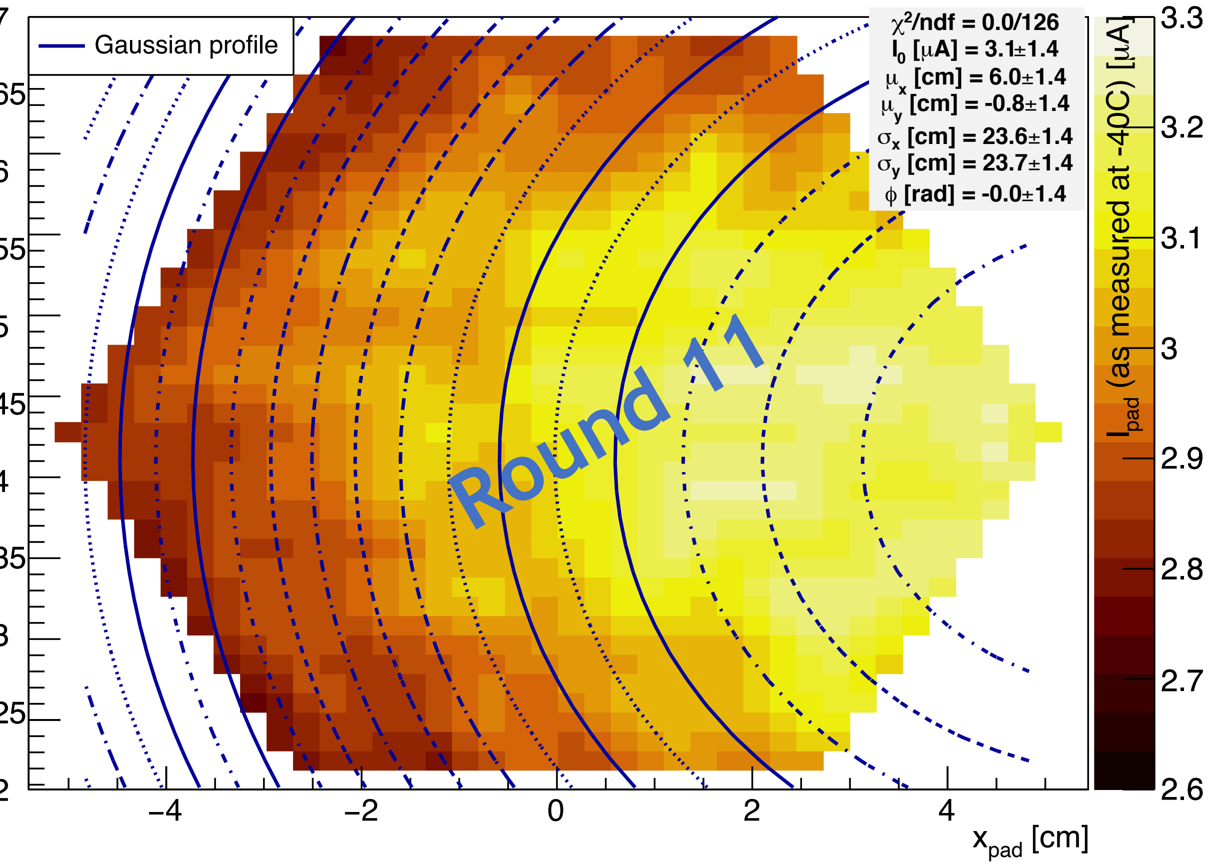
Round8, 3009, ind. p-stop



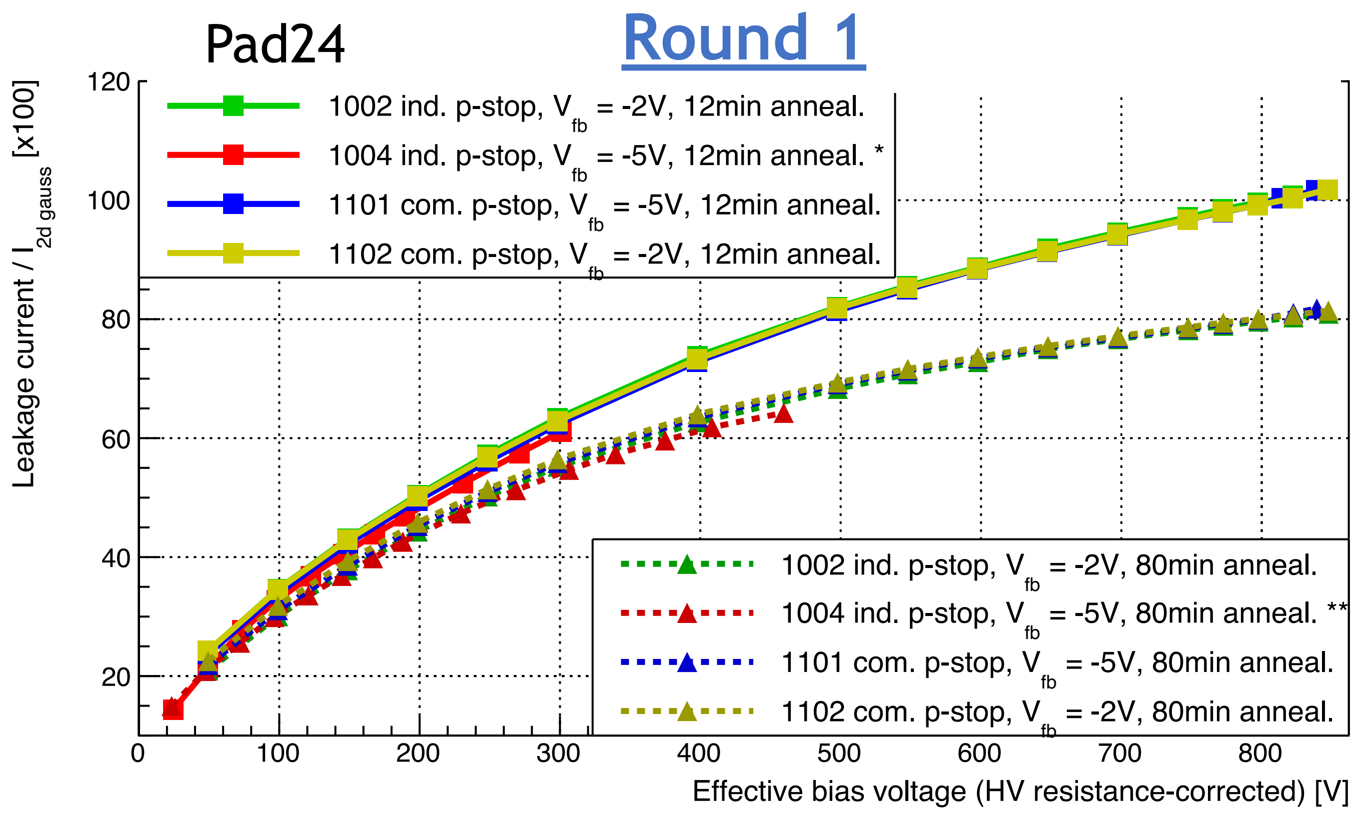
Round10, 1013, ind. p-stop (std.), U_{fb}=-2V

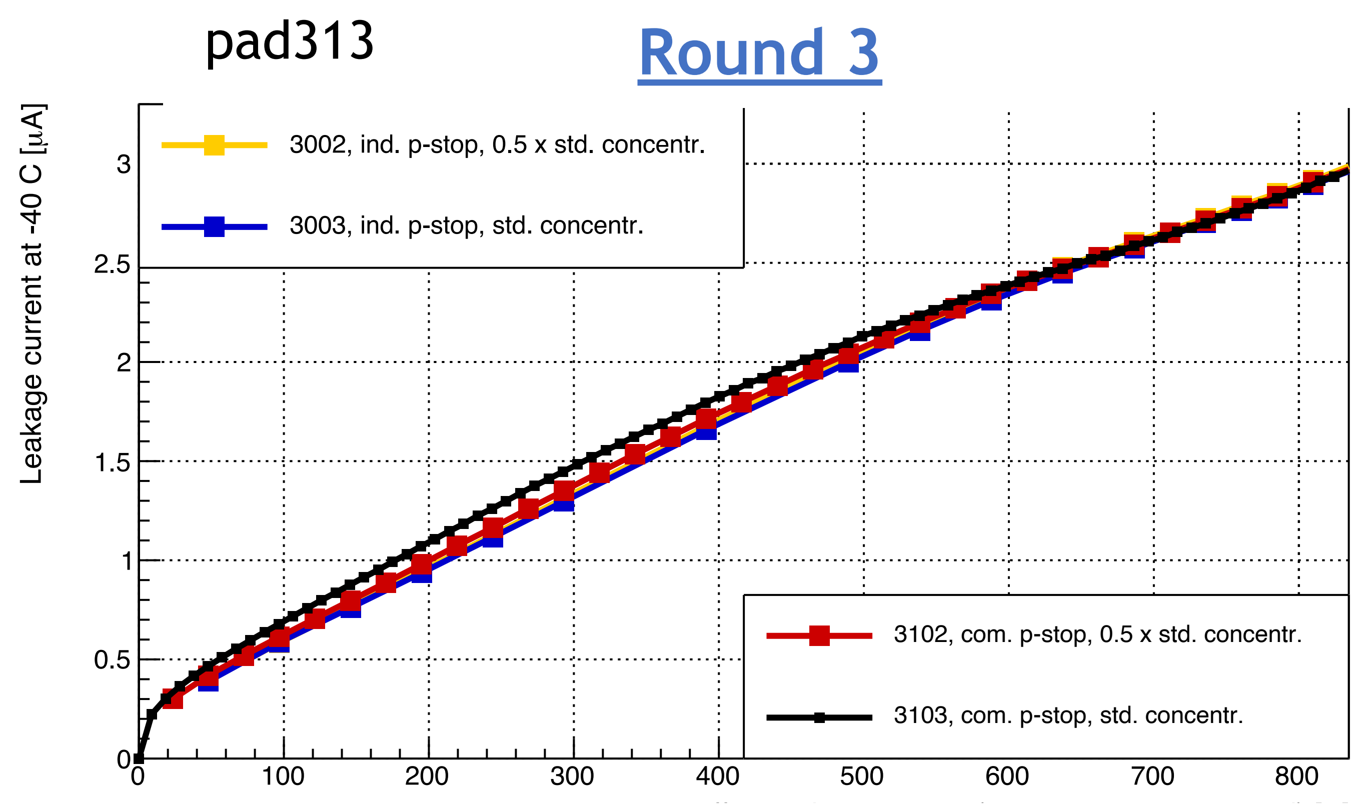


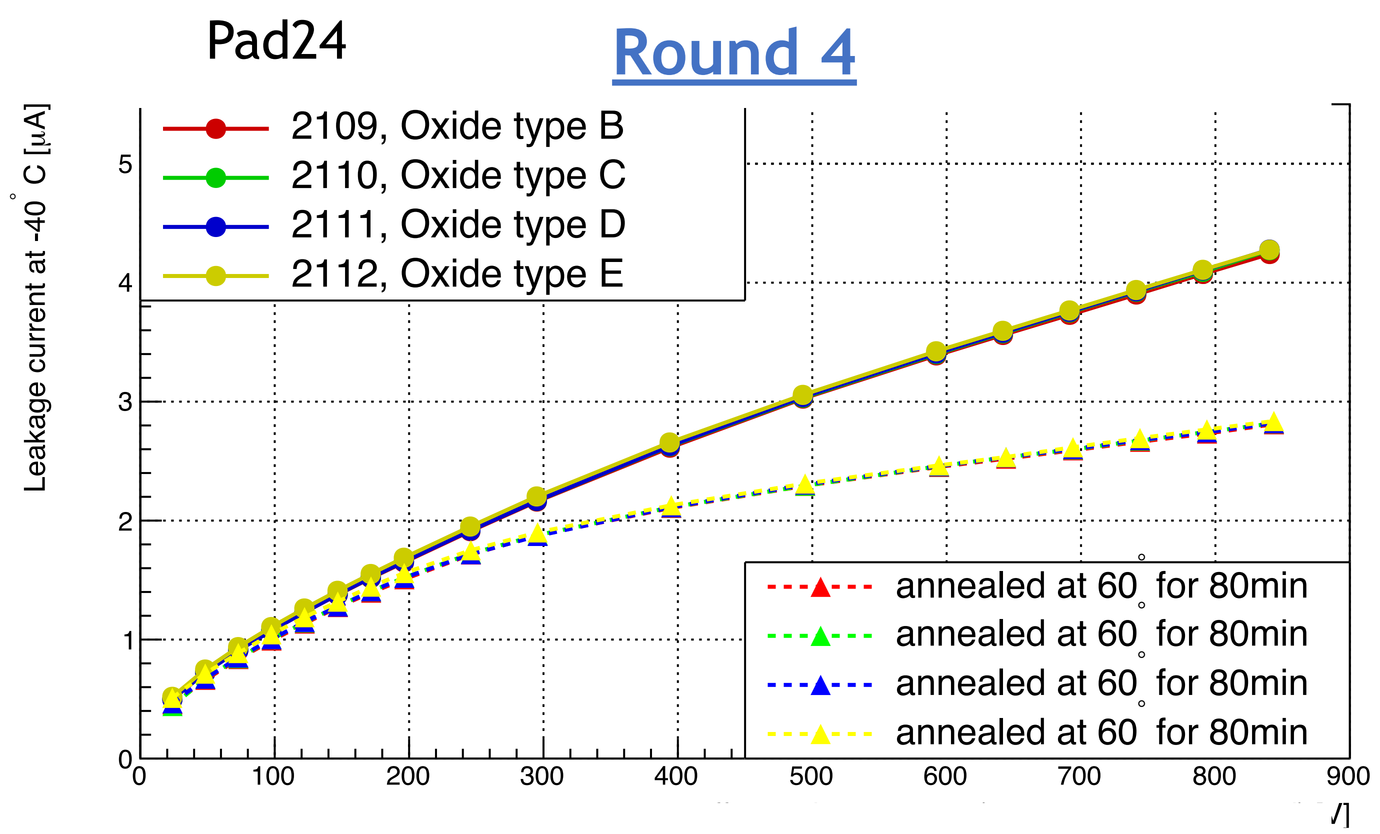
Round11, N0541 No.4, ind. p-stop (std.), U_{fb}=-5V

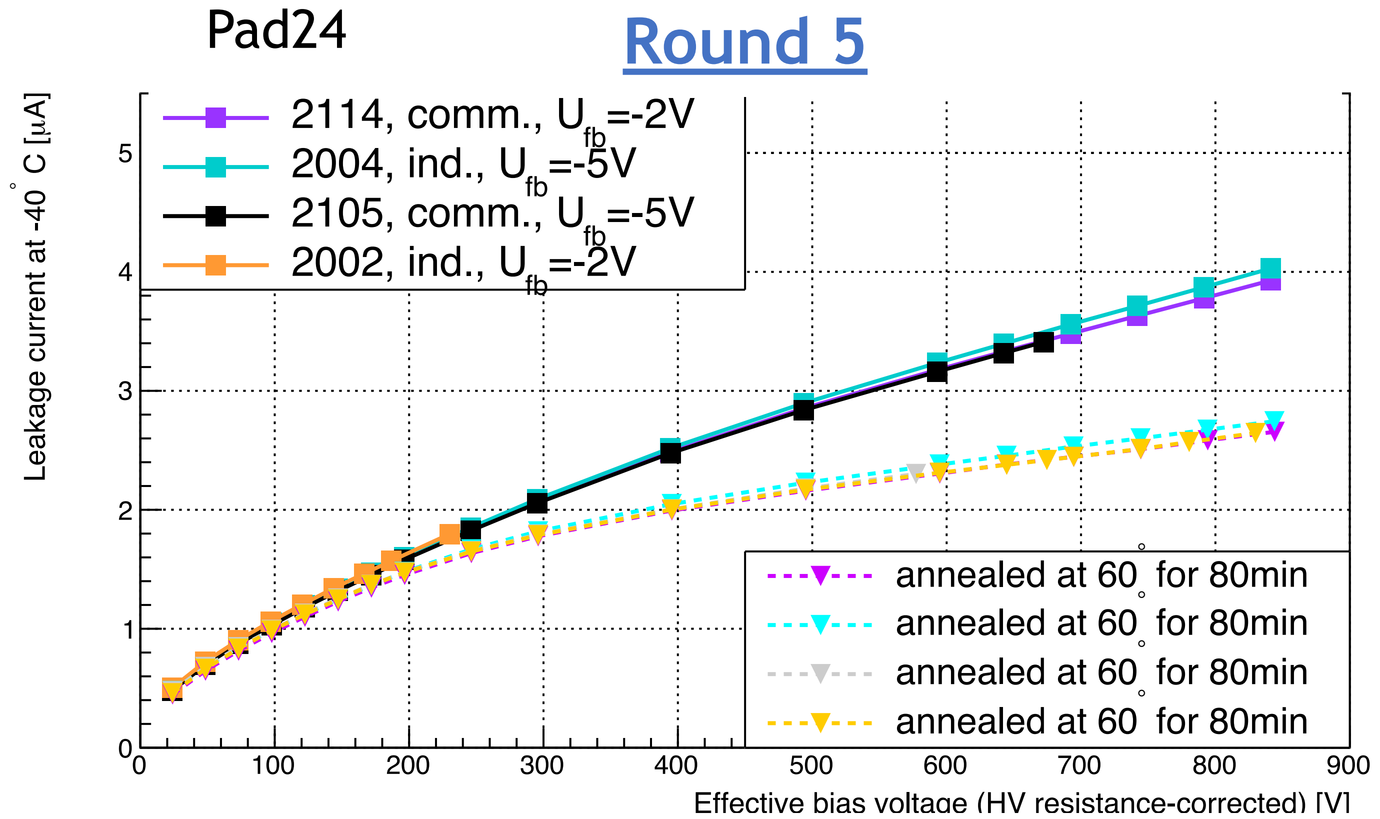


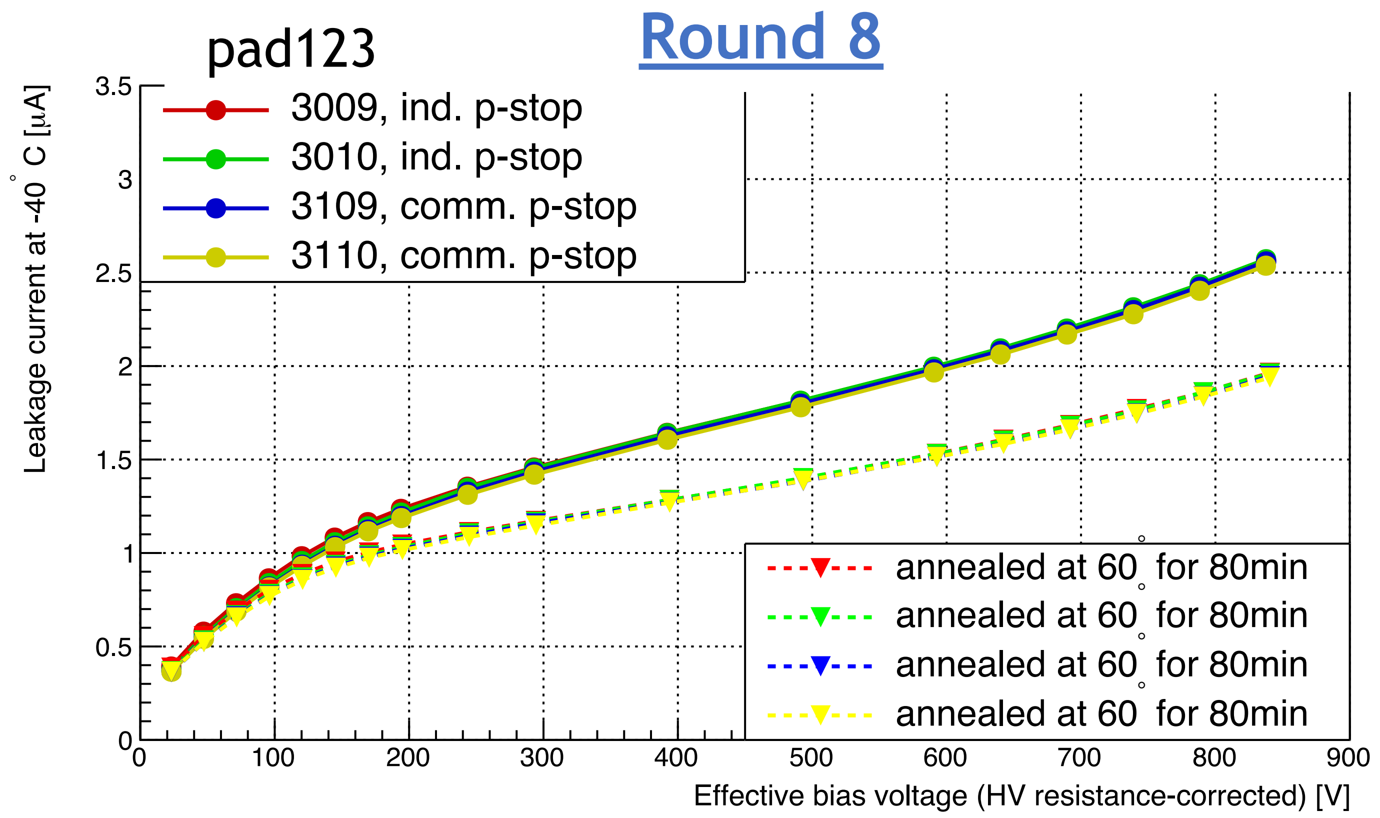
No sizeable difference in leakage current between process parameters

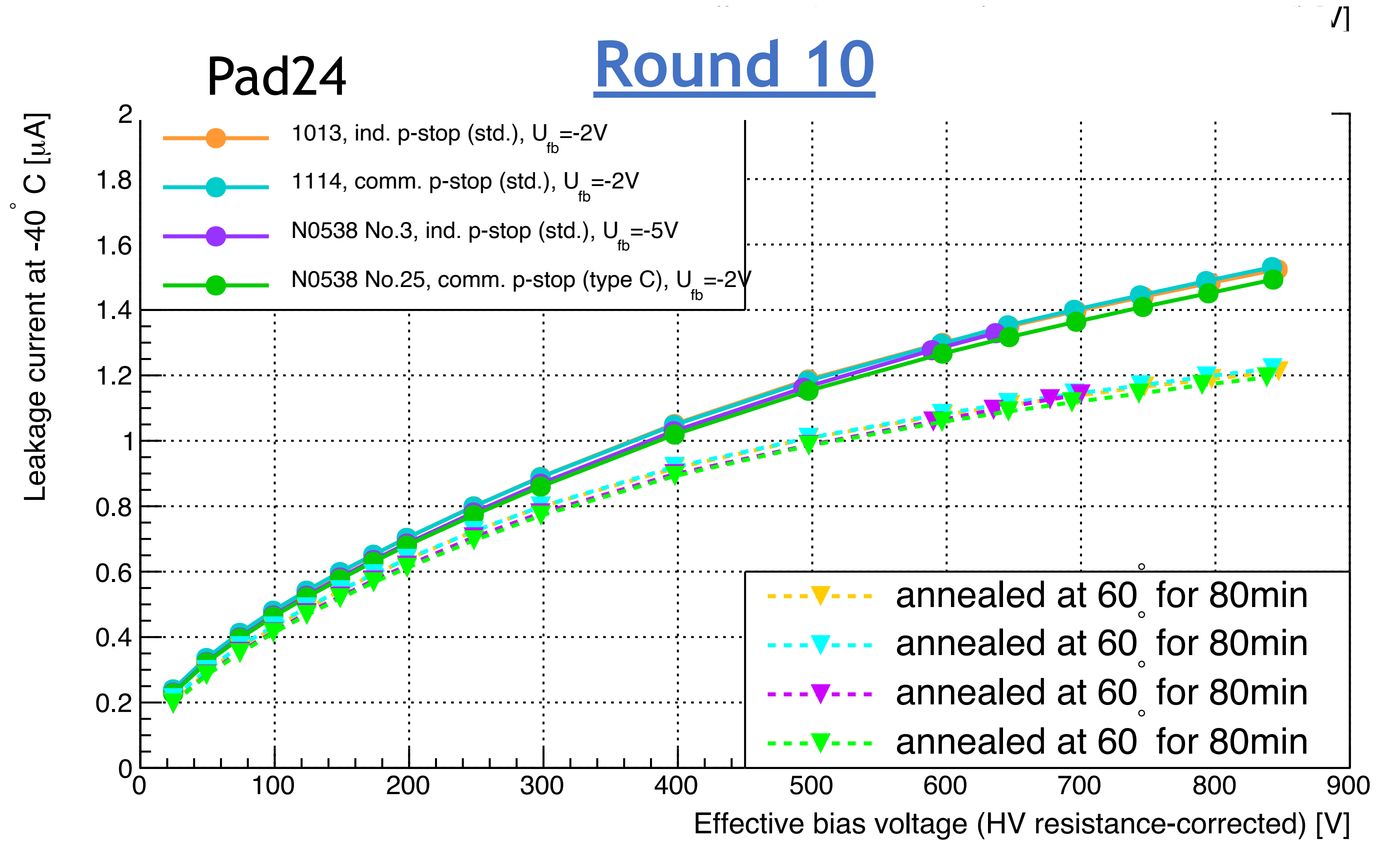


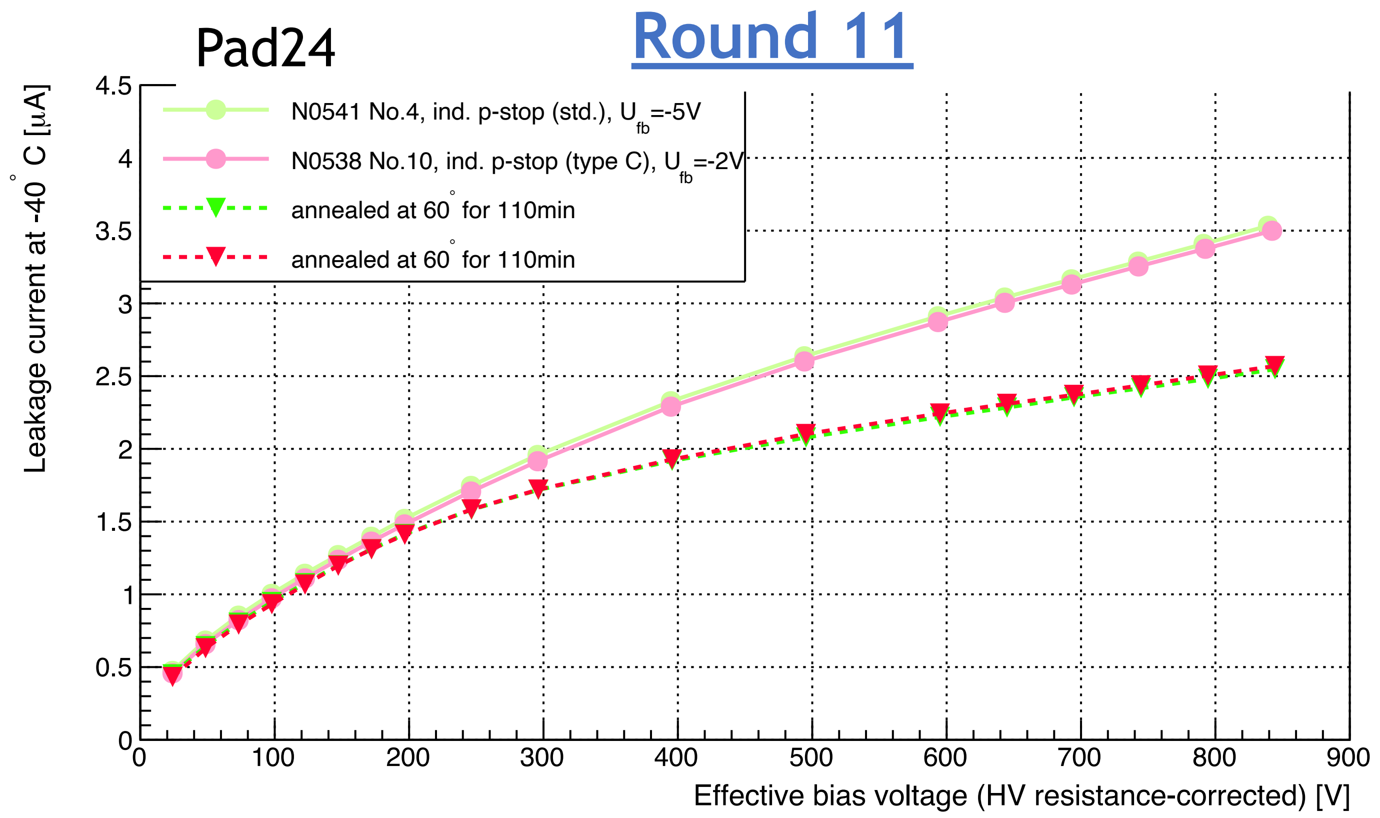








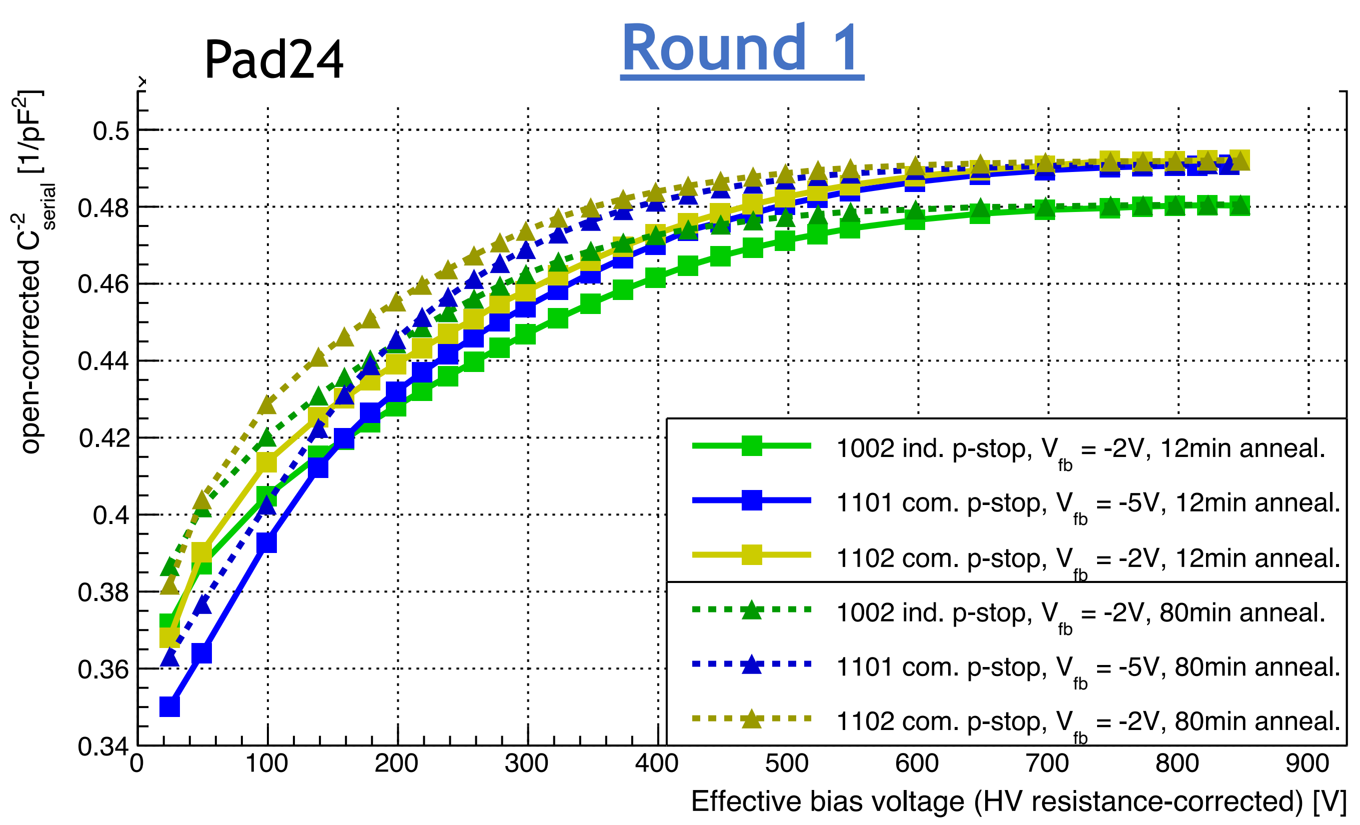


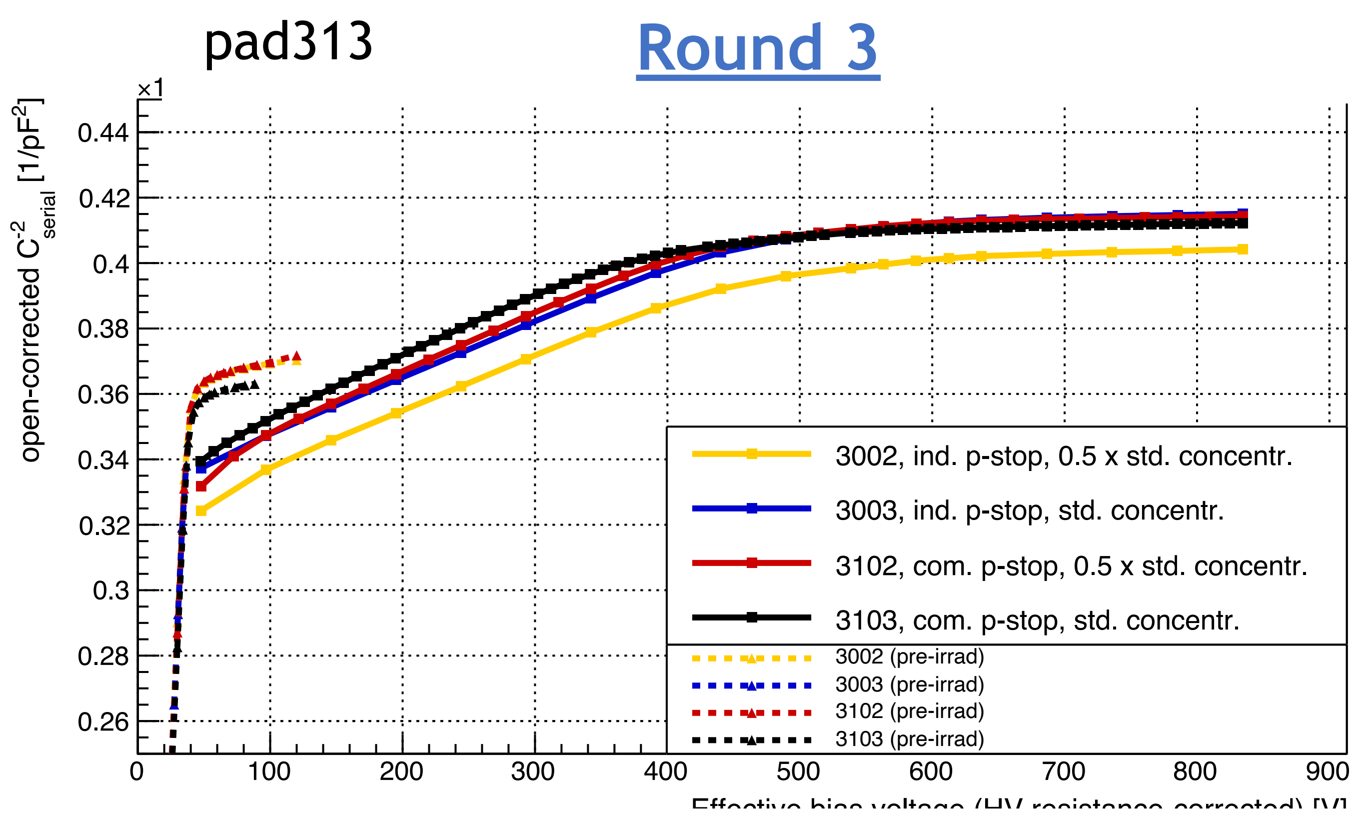


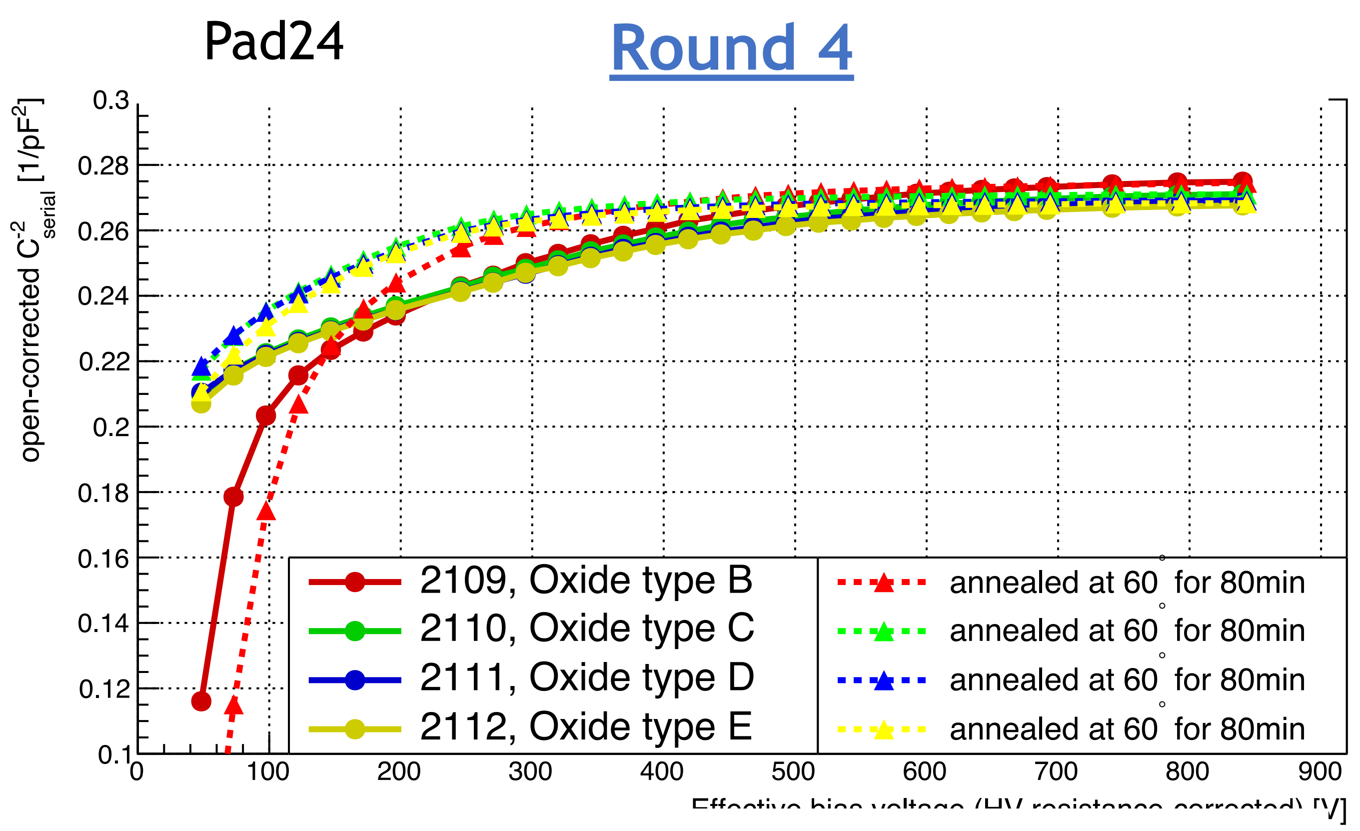
- Shown IV curves for the chosen pads representative for all pads on the sensors:
- IV curves of different process parameters overlap at the O(1%) level.

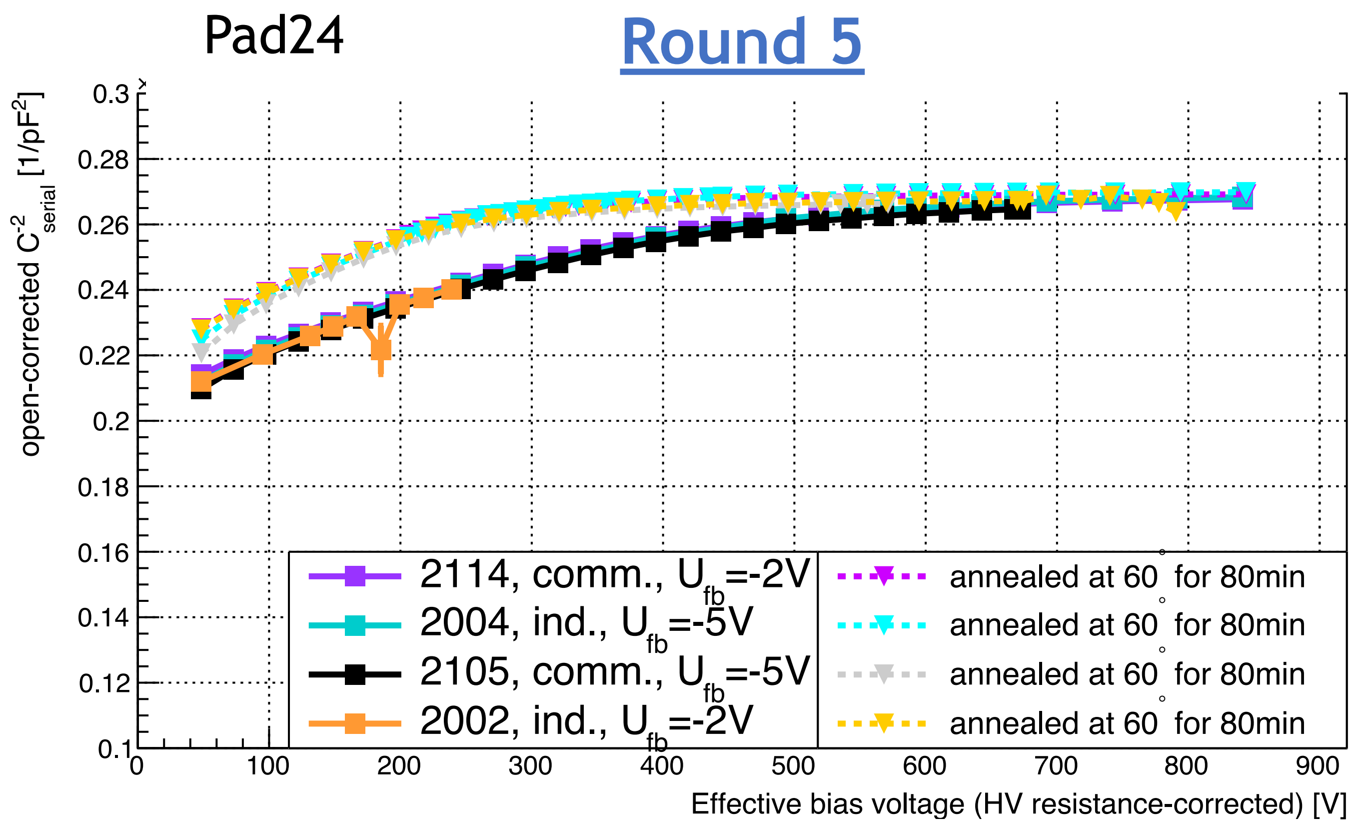
➡**Leakage current after irradiation and at -40°C unaffected by choice of process parameters.**

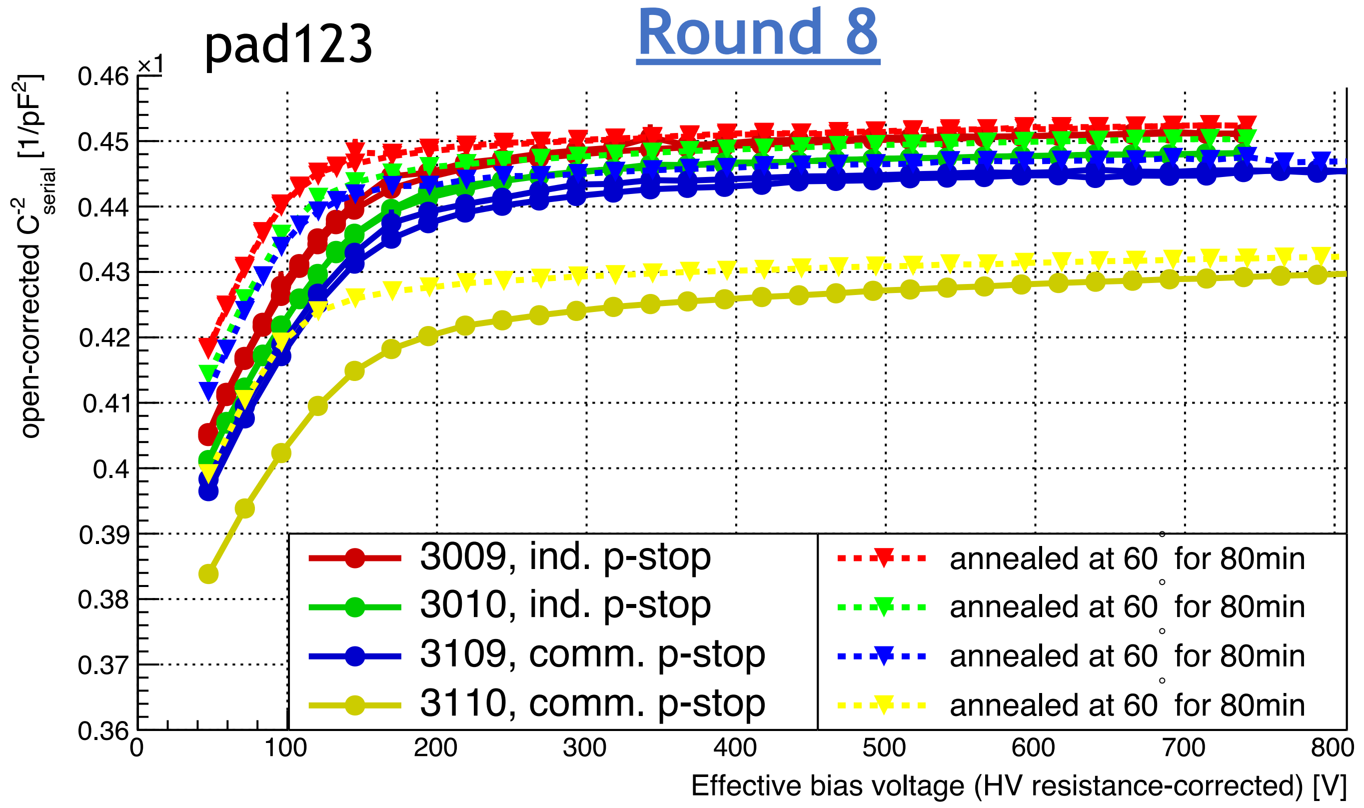
Differences in capacitances between process parameters

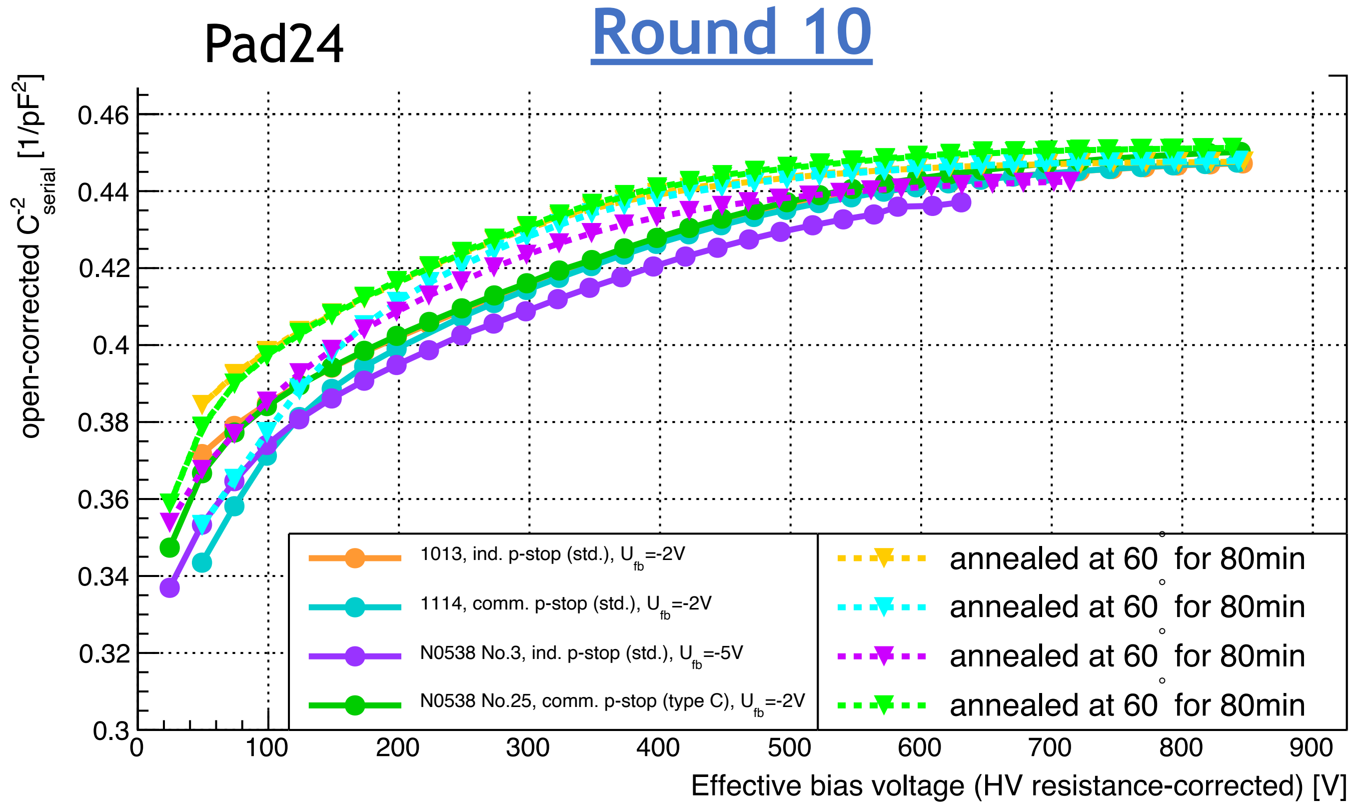


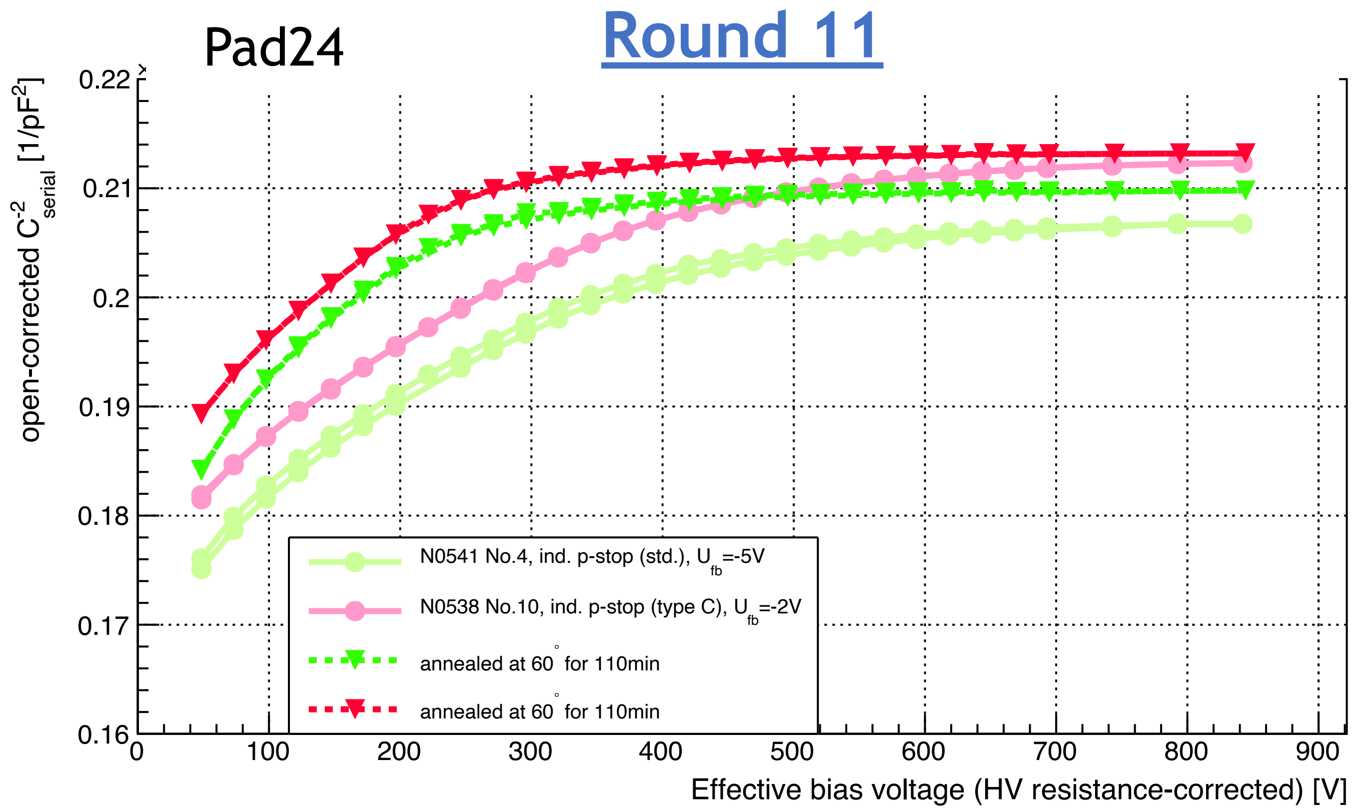












- Shown C^{-2} vs. V curves for the chosen pads representative for all pads on the sensors:
- C^{-2} vs. V curves of different process parameters with visible difference.

➡**Capacitance affected by choice of of process parameters.**

- ***Further specification and quantification of differences still to be done…***

Depletion voltage estimation

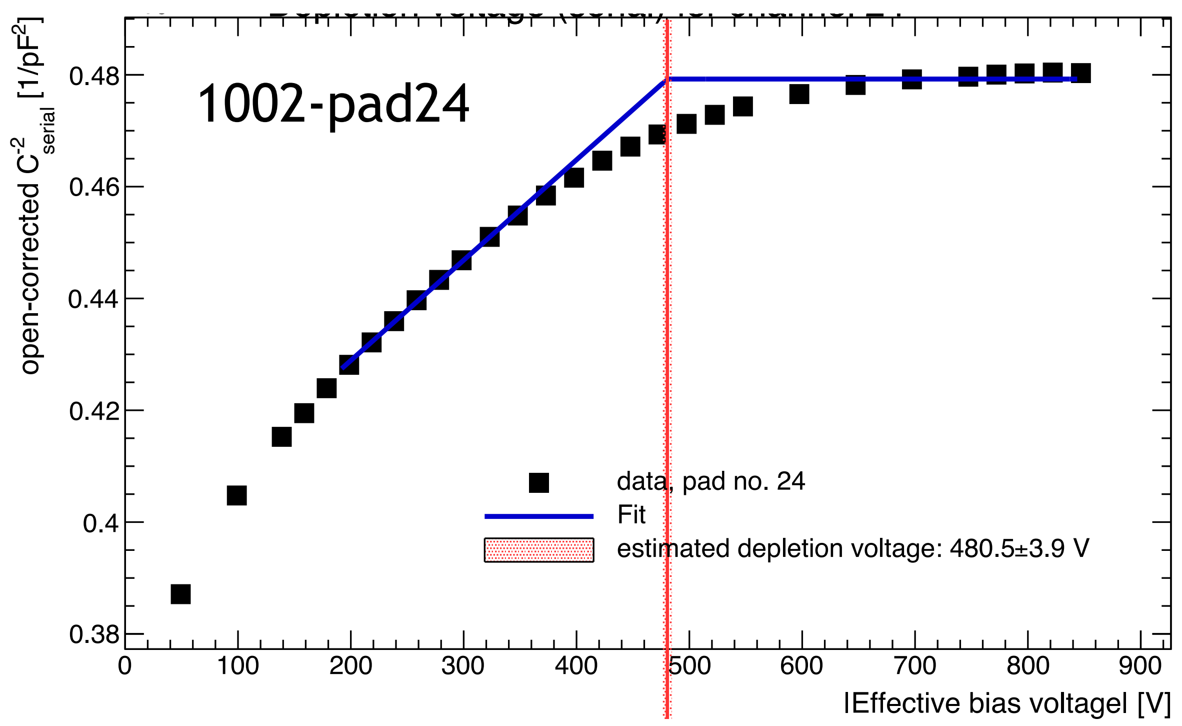
Depletion voltage (U_{dep}) definition

- Based on squared-inverse of open-corrected serial capacitance (same as on slide 16).
- U_{dep} intersection of plateau at high voltages and straight-line fit to rising part.

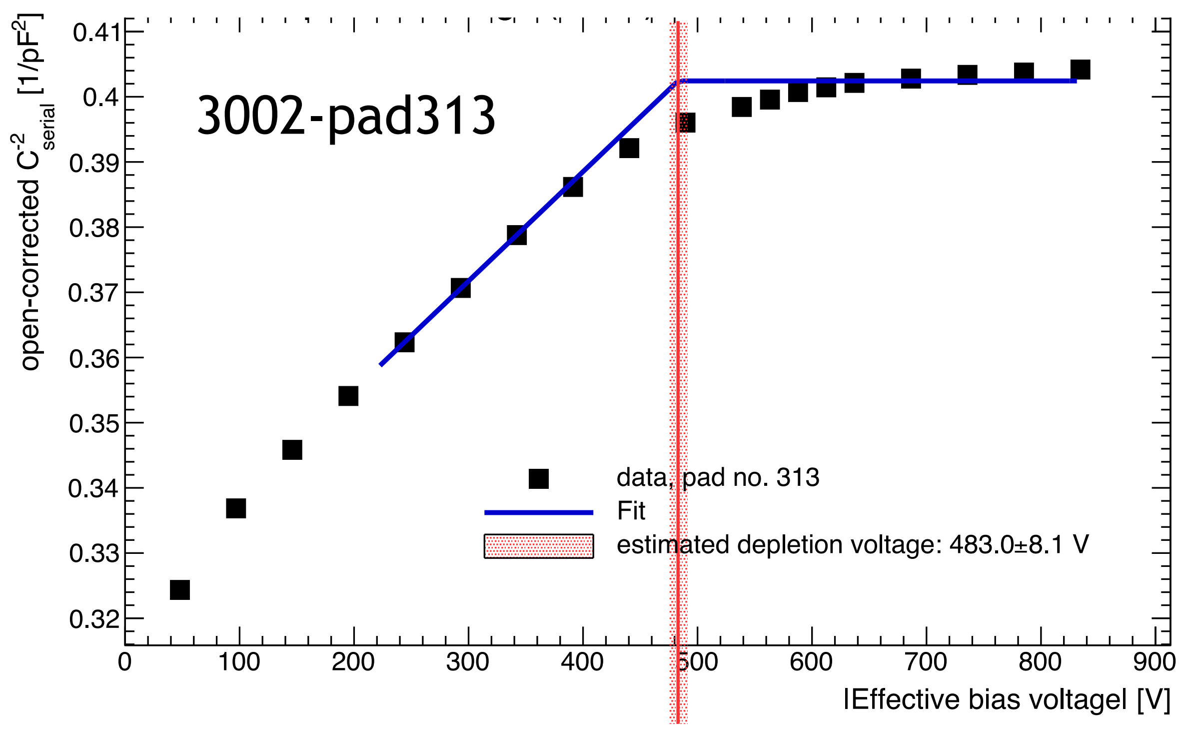
Note: This is only an estimate!

- U_{dep} affected by choice of rising part and sampling of voltages therein.

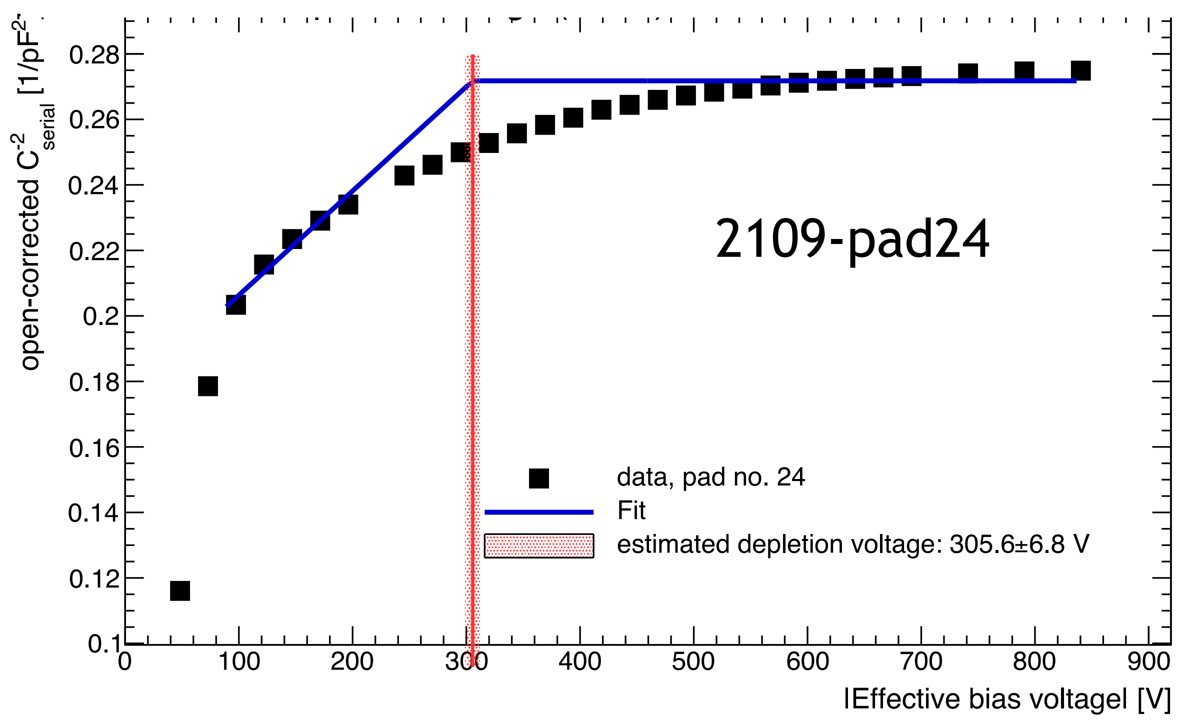
e.g. round 1



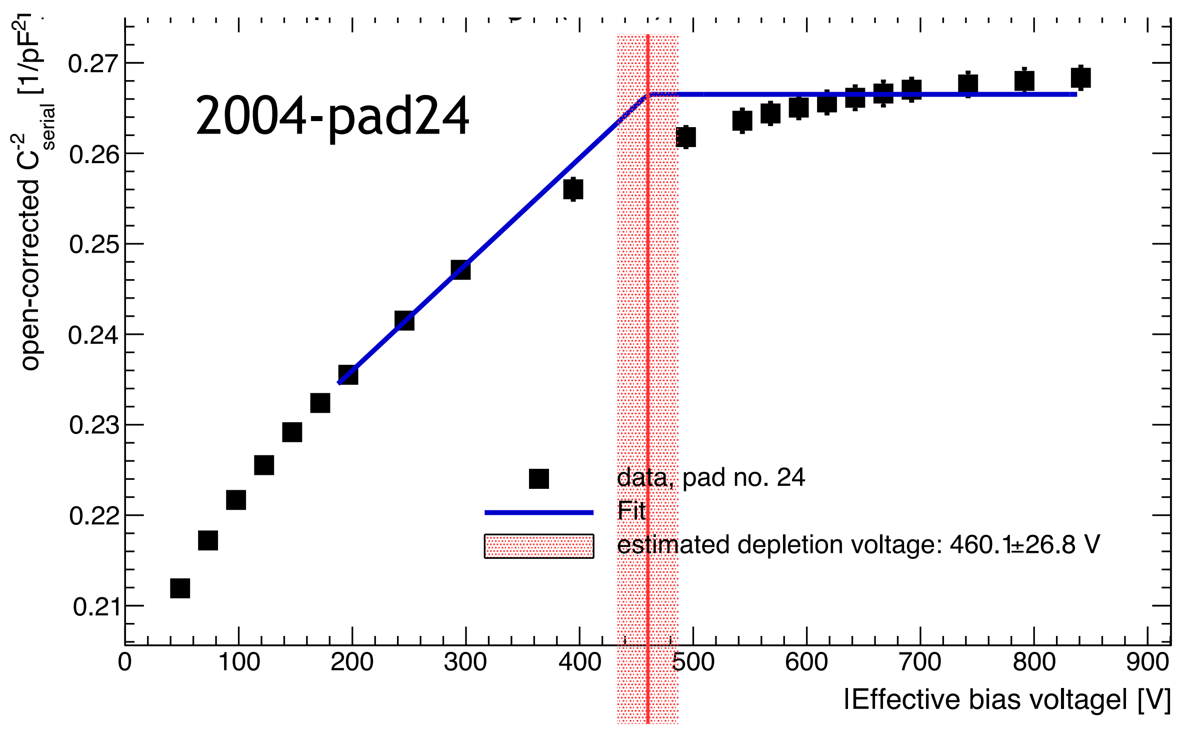
e.g. round 3



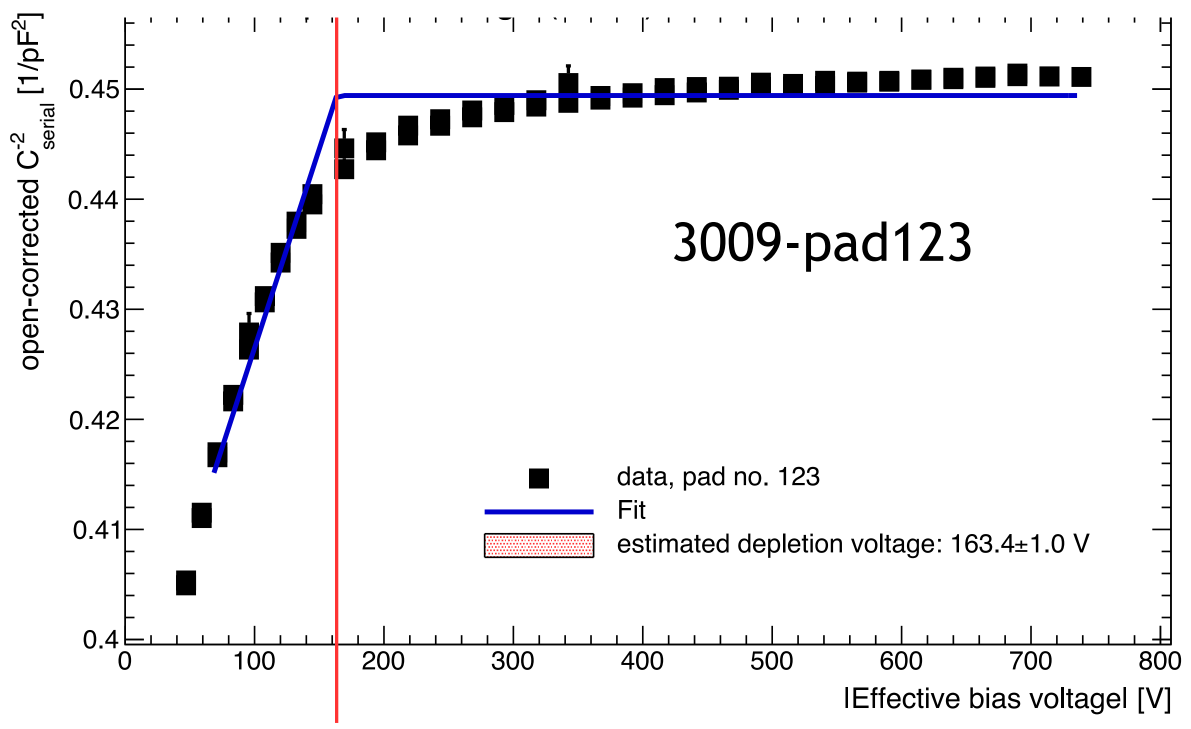
e.g. round 4



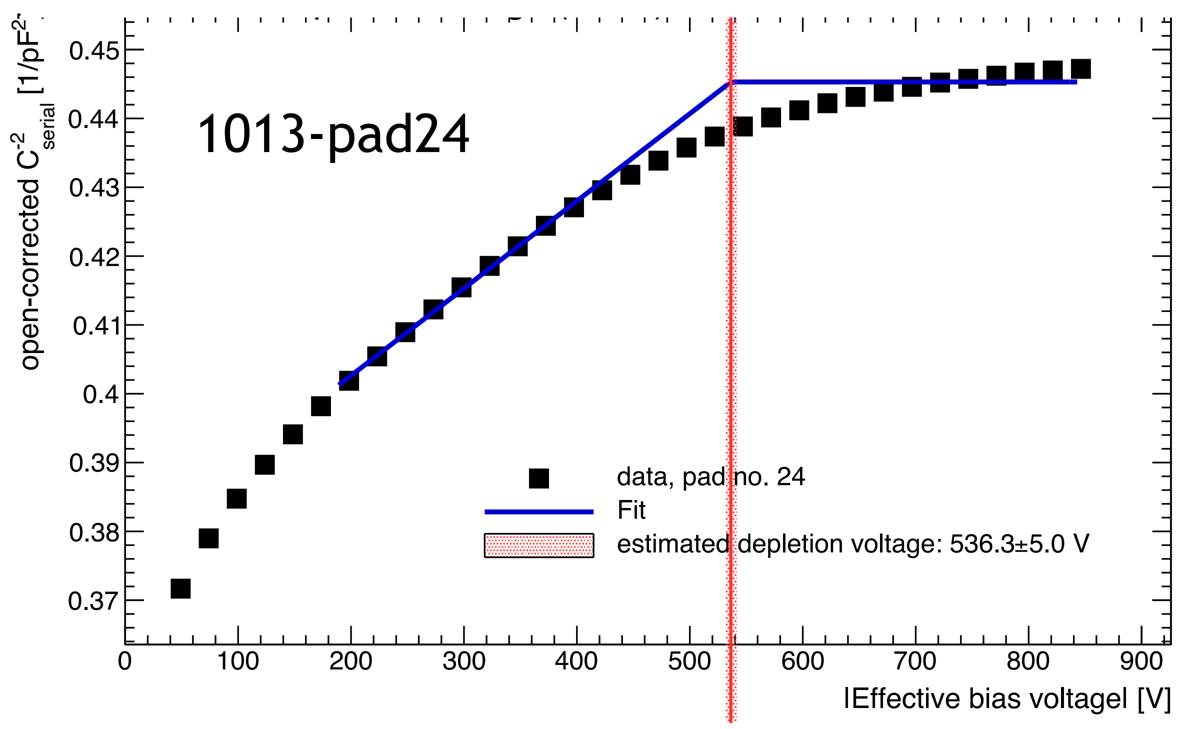
e.g. round 5



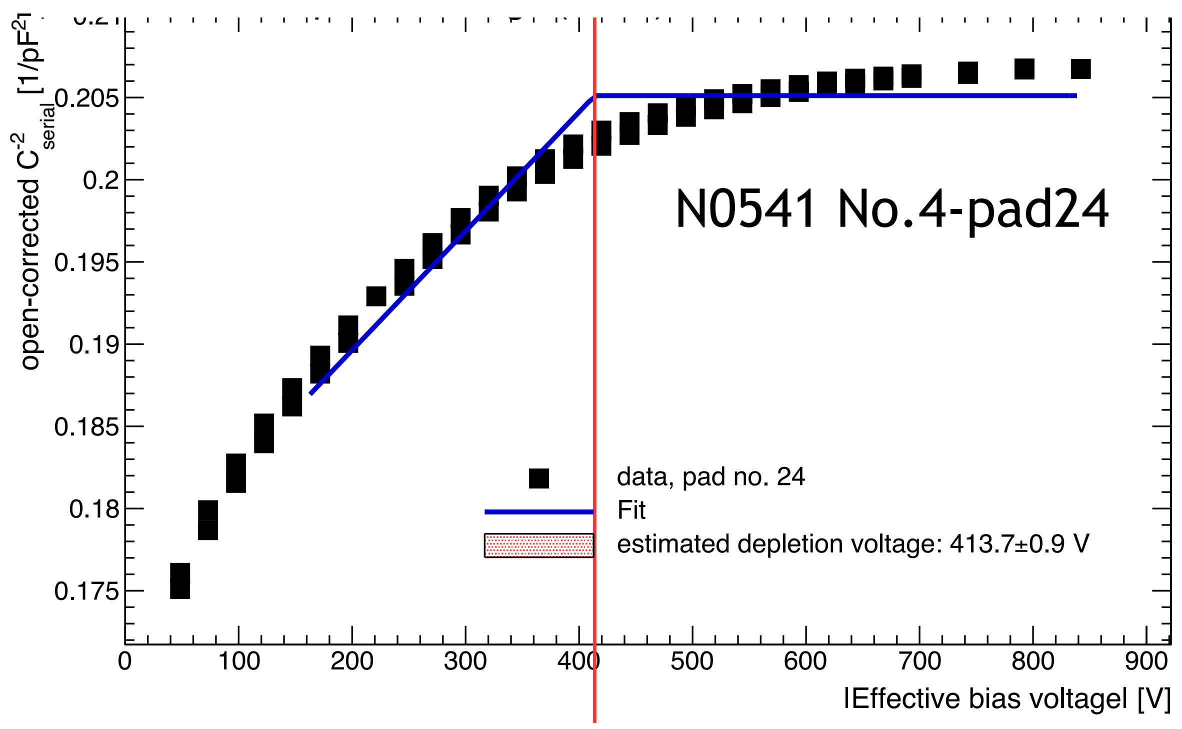
e.g. round 8



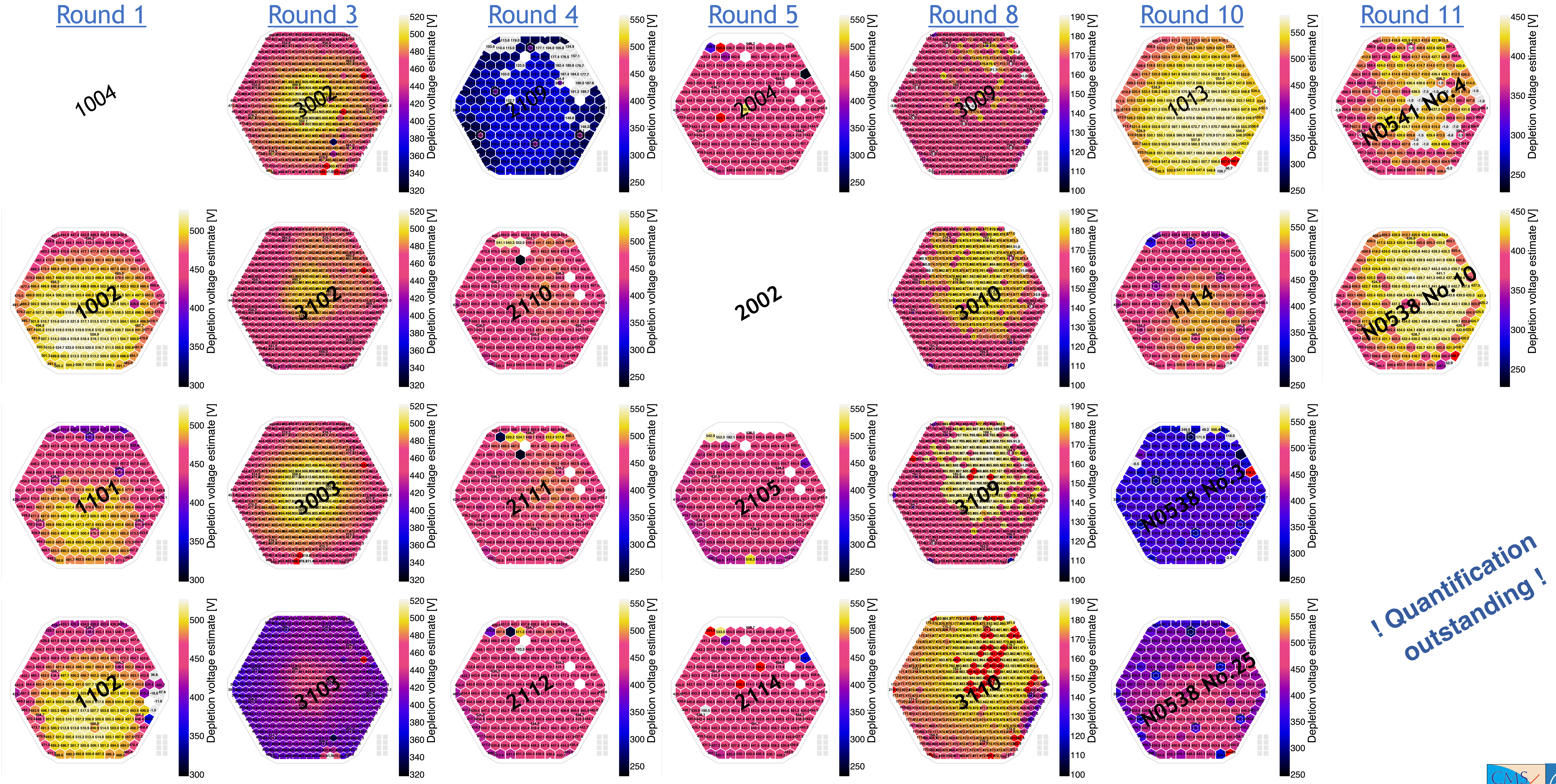
e.g. round 10



e.g. round 11

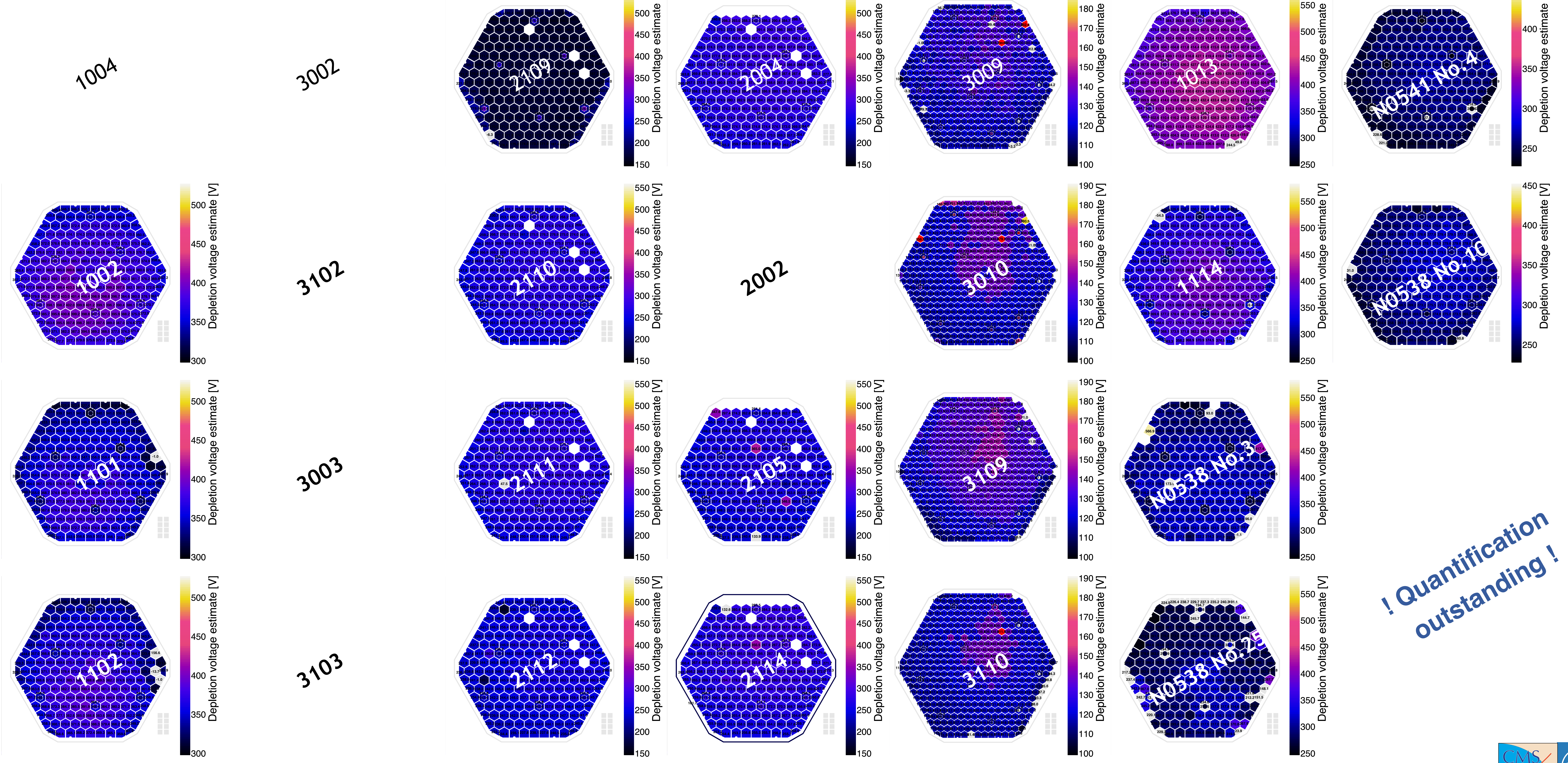


Estimated depletion voltages *before* our additional annealing



~~Estimated depletion voltages *after* our additional annealing~~

Round 1 | Round 3 | Round 4 | Round 5 | Round 8 | Round 10 | Round 11



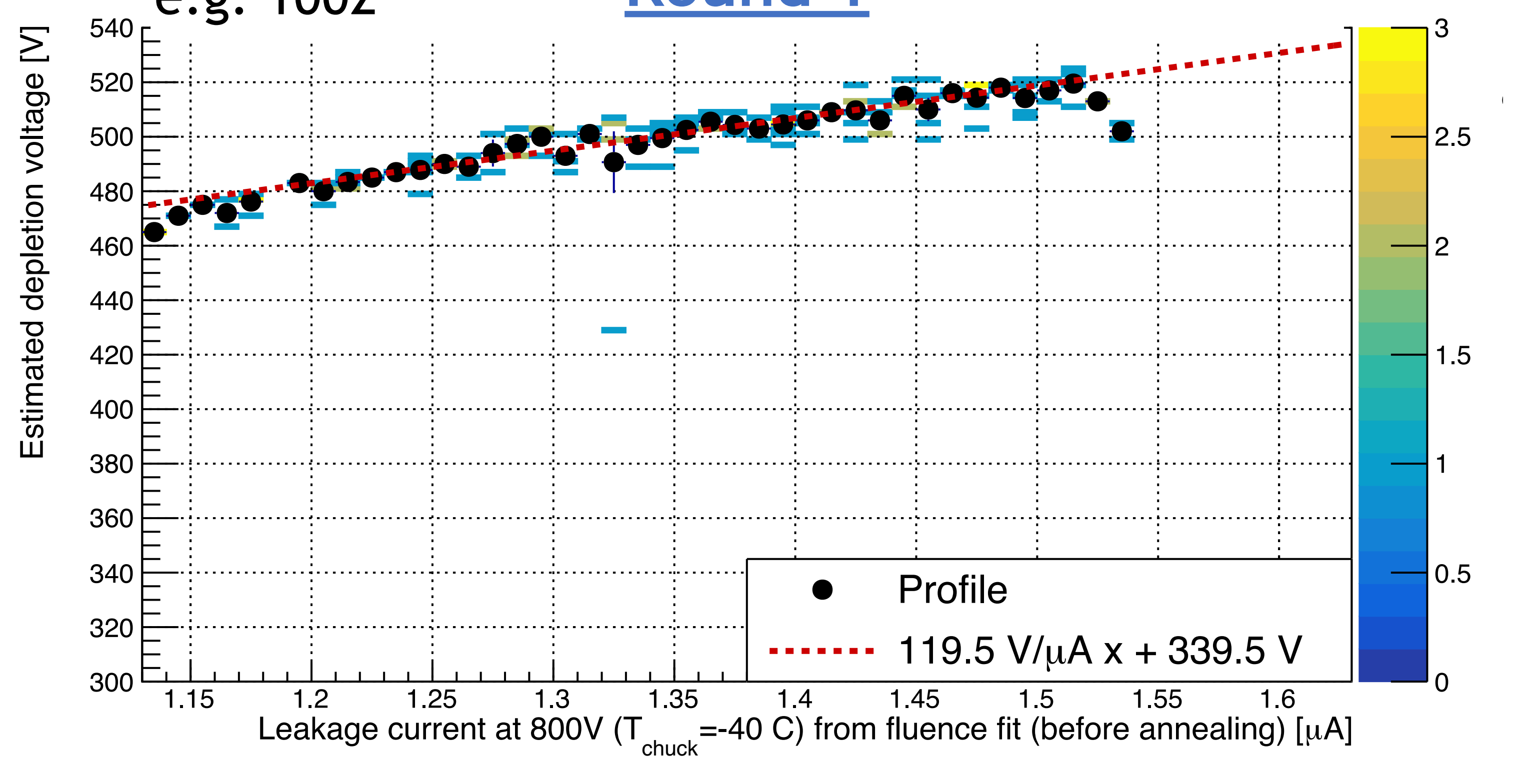
! Quantification outstanding !

Positive correlation between fluence and depletion voltage

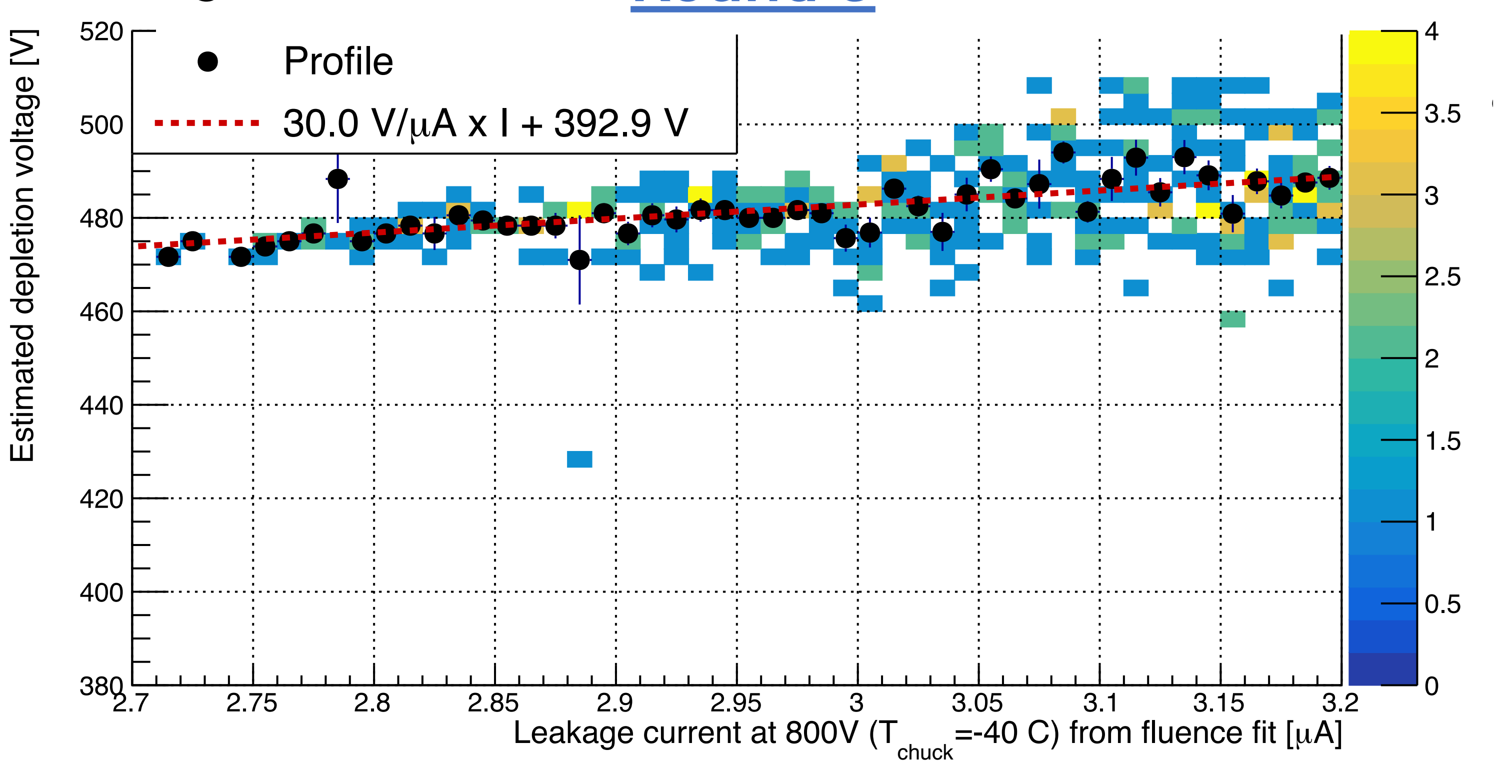
- X-axis: Leakage currents as measured (before additional annealing) at 600(800) V as proxy for neutron fluence during irradiation.
- Y-axis: Depletion voltage assessment (before additional annealing).
- Only full hexagonal pads studied here.
- Displayed slope representative for other sensors of the same irradiation round.

➡**Higher depletion voltage correlates to higher leakage current (~fluence).**

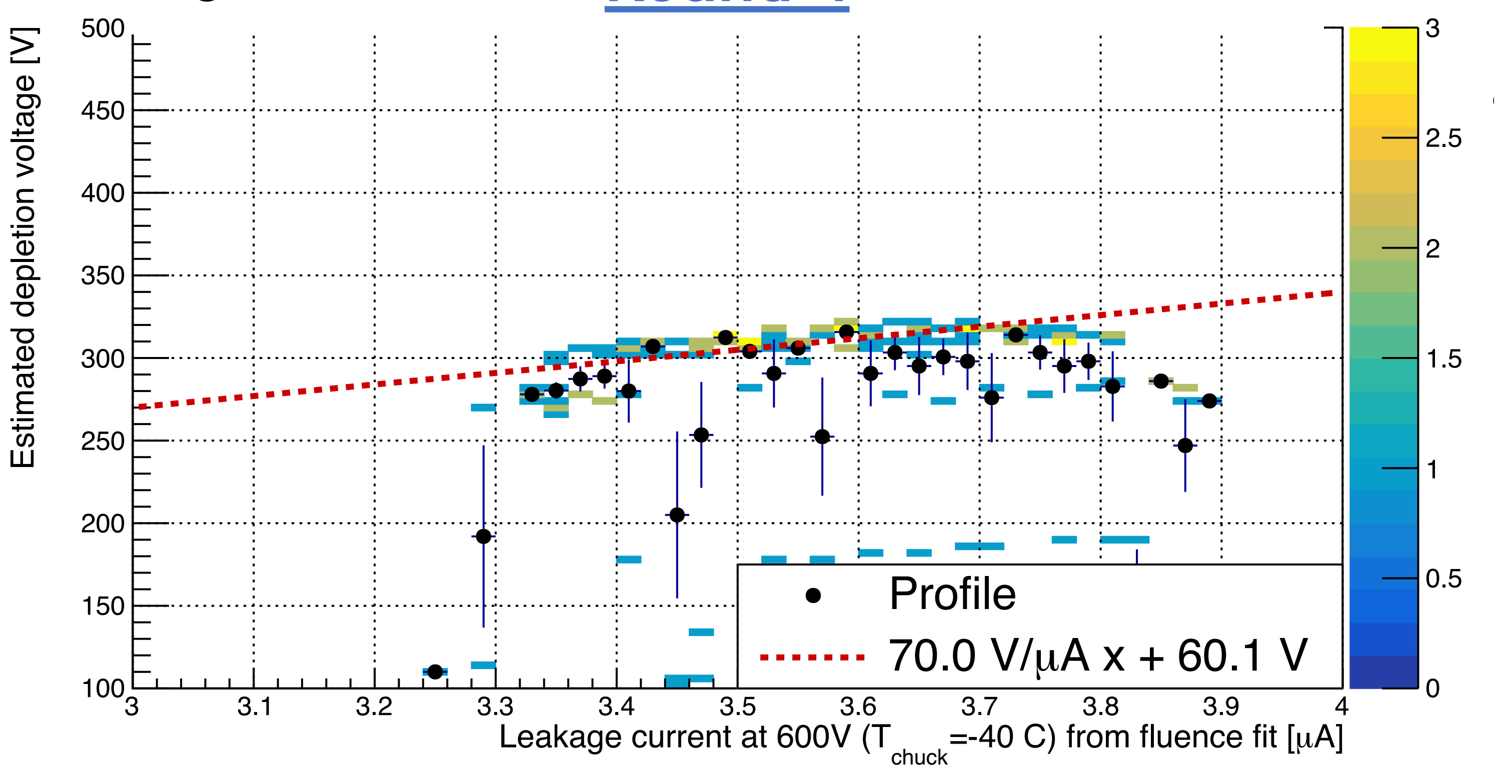
e.g. 1002 Round 1



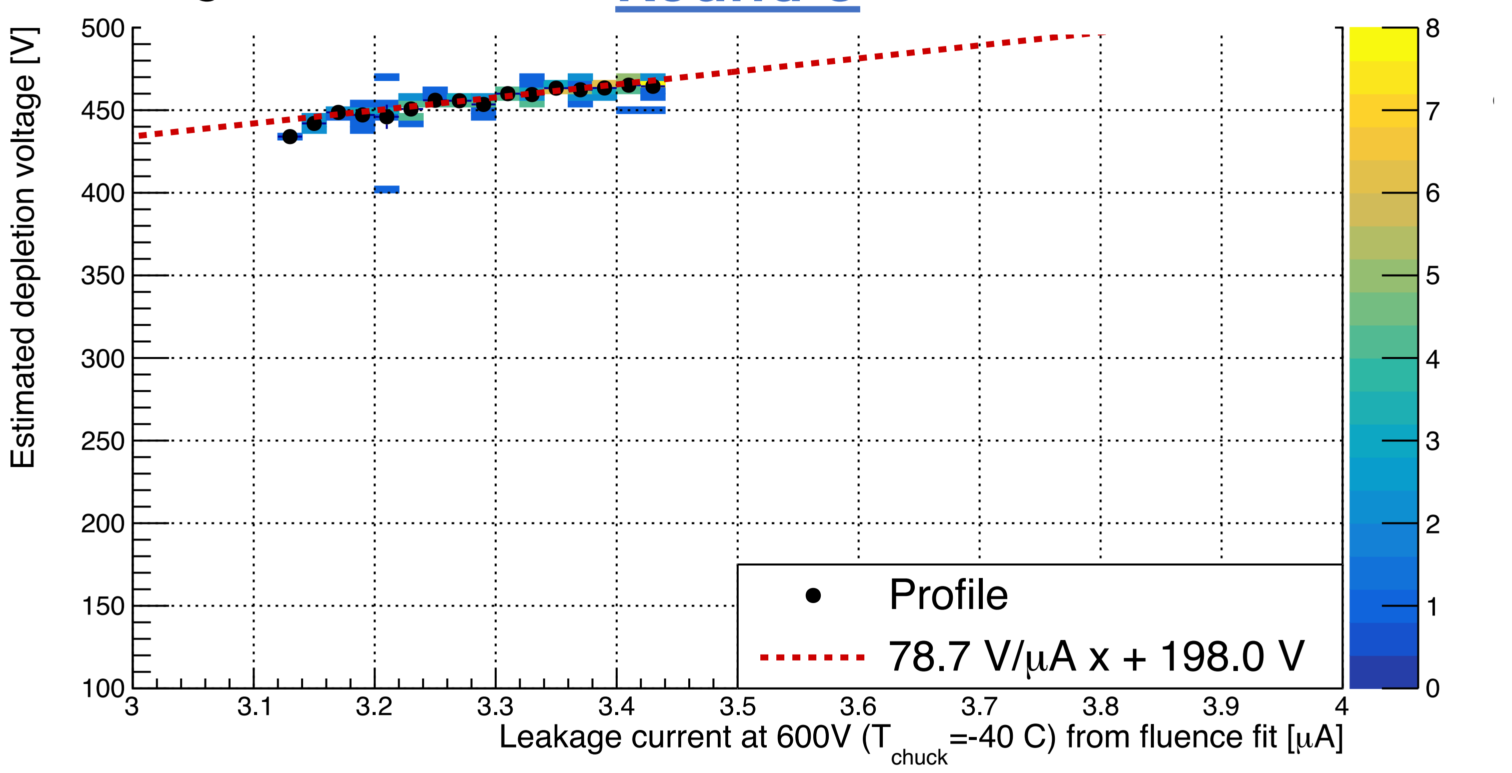
e.g. 3002 Round 3



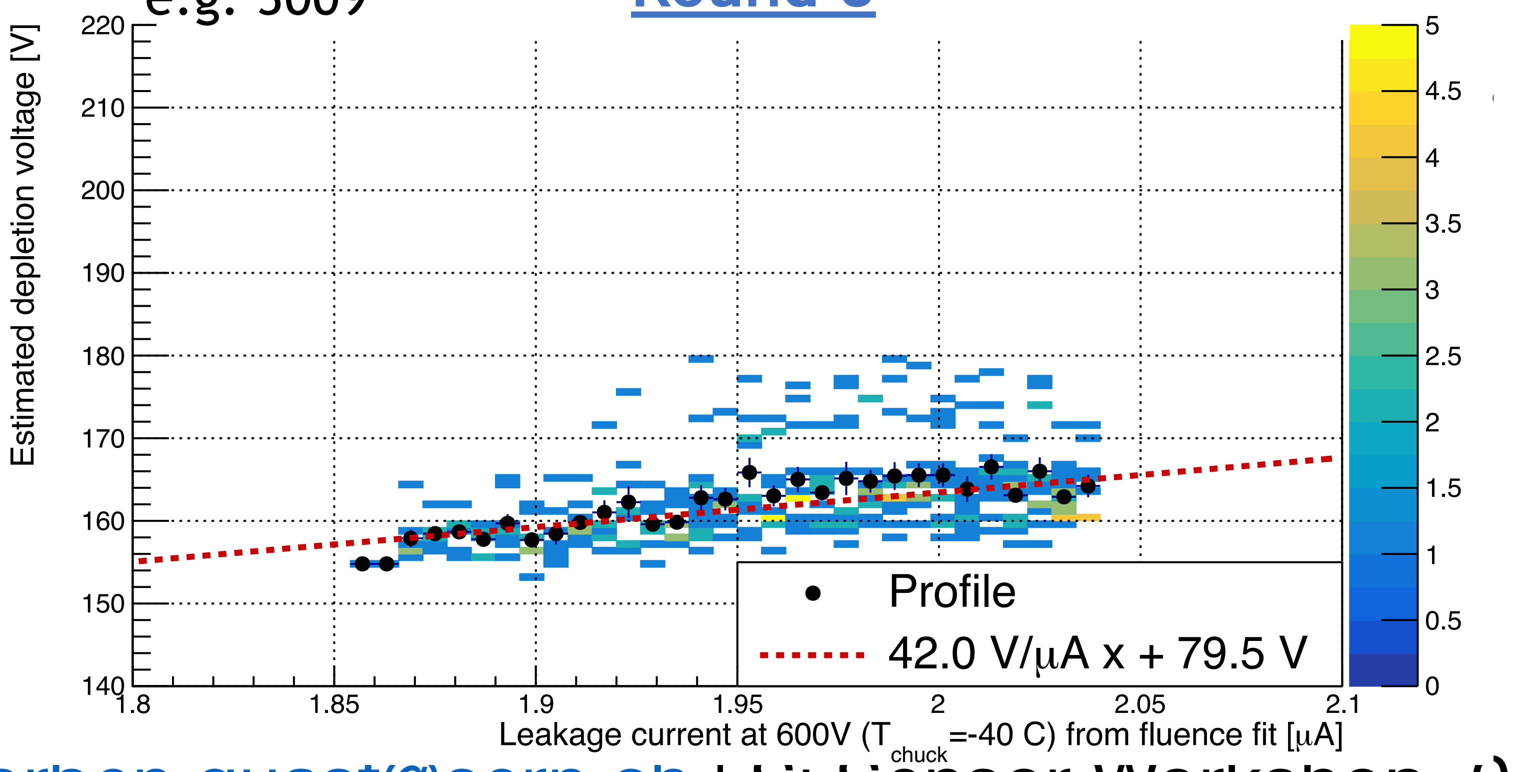
e.g. 2109 Round 4



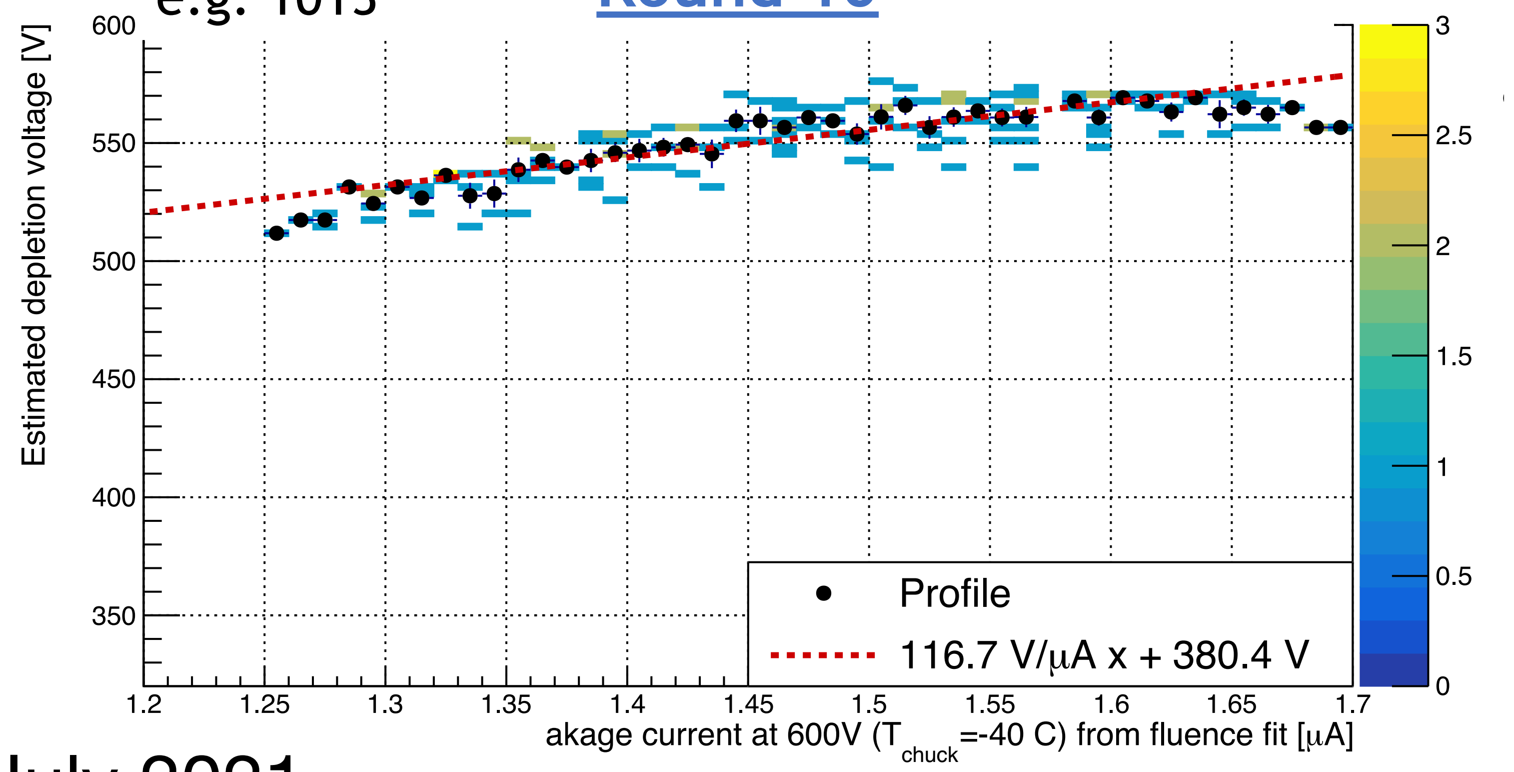
e.g. 2004 Round 5



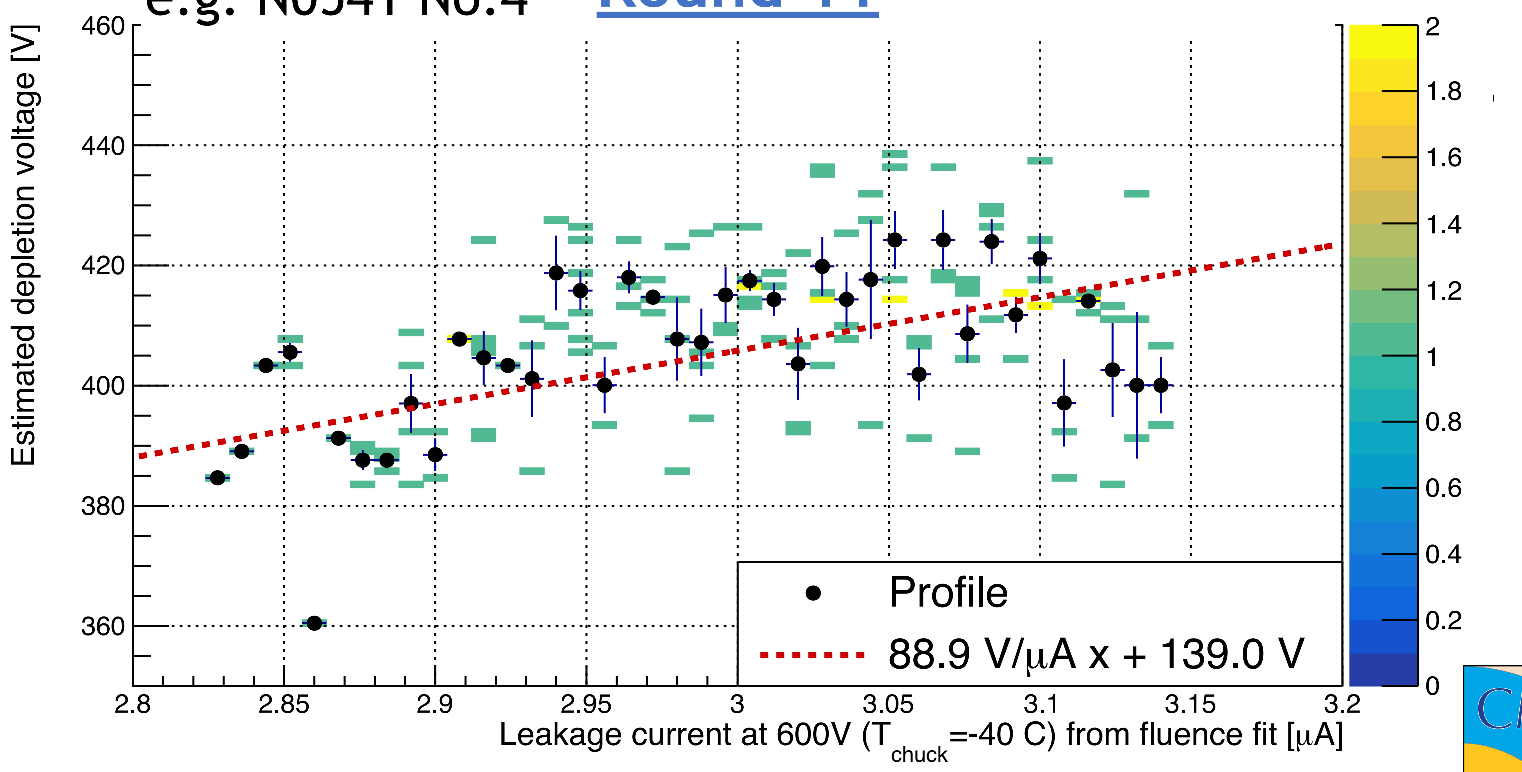
e.g. 3009 Round 8



e.g. 1013 Round 10



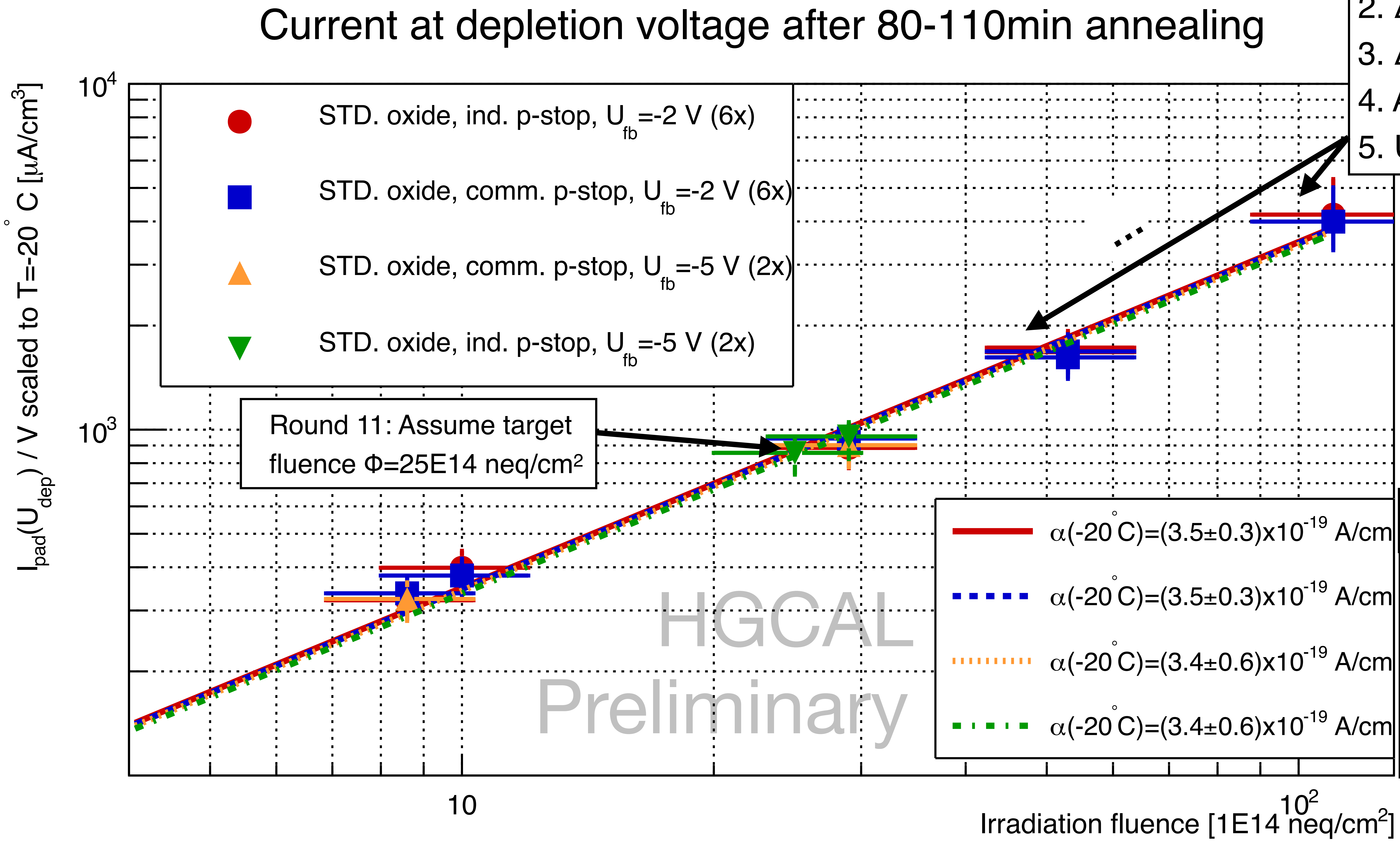
e.g. N0541 No.4 Round 11



~~Extraction of full-wafer alpha-value with 16/26 sensors~~

Per-pad leakage current per volume proportional to neutron-fluence

At depletion voltage



<u>Systematic uncertainties</u>

1. ΔΦ/Φ := 20%.
2. $\Delta U_{dep}/U_{dep}$:= 20%.
3. ΔI(ΔT, T)/I(T) := 7%.
4. Add. annealing: ΔI/I<20%
5. Uncertainty on thickness negligible.

<u>ΔI / V = α x Φ ?</u>

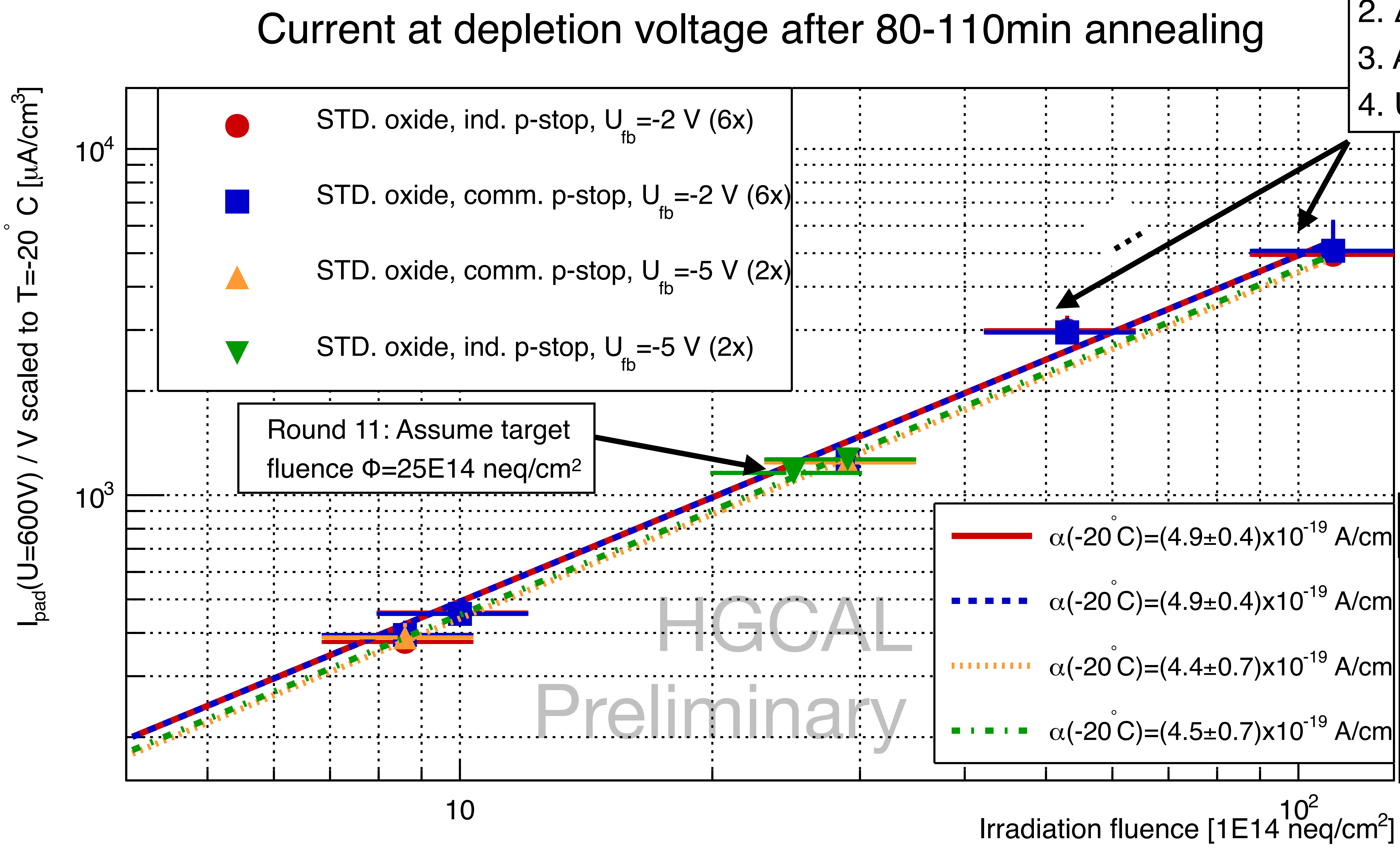
➡ **Yes.**

Preliminary α after additional annealing at $U_{bias} = U_{dep}$ = (3.5 +/- 0.3) x 10^{-13} μA/cm

~~Extraction of full-wafer alpha-value with 16/26 sensors~~

Per-pad leakage current per volume proportional to neutron-fluence

At 600V



Systematic uncertainties

1. ΔΦ/Φ := 20%.
2. ΔI(ΔT, T)/I(T) := 7%.
3. Add. annealing: ΔI/I<20%
4. Uncertainty on thickness negligible.

ΔI / V = α x Φ ?

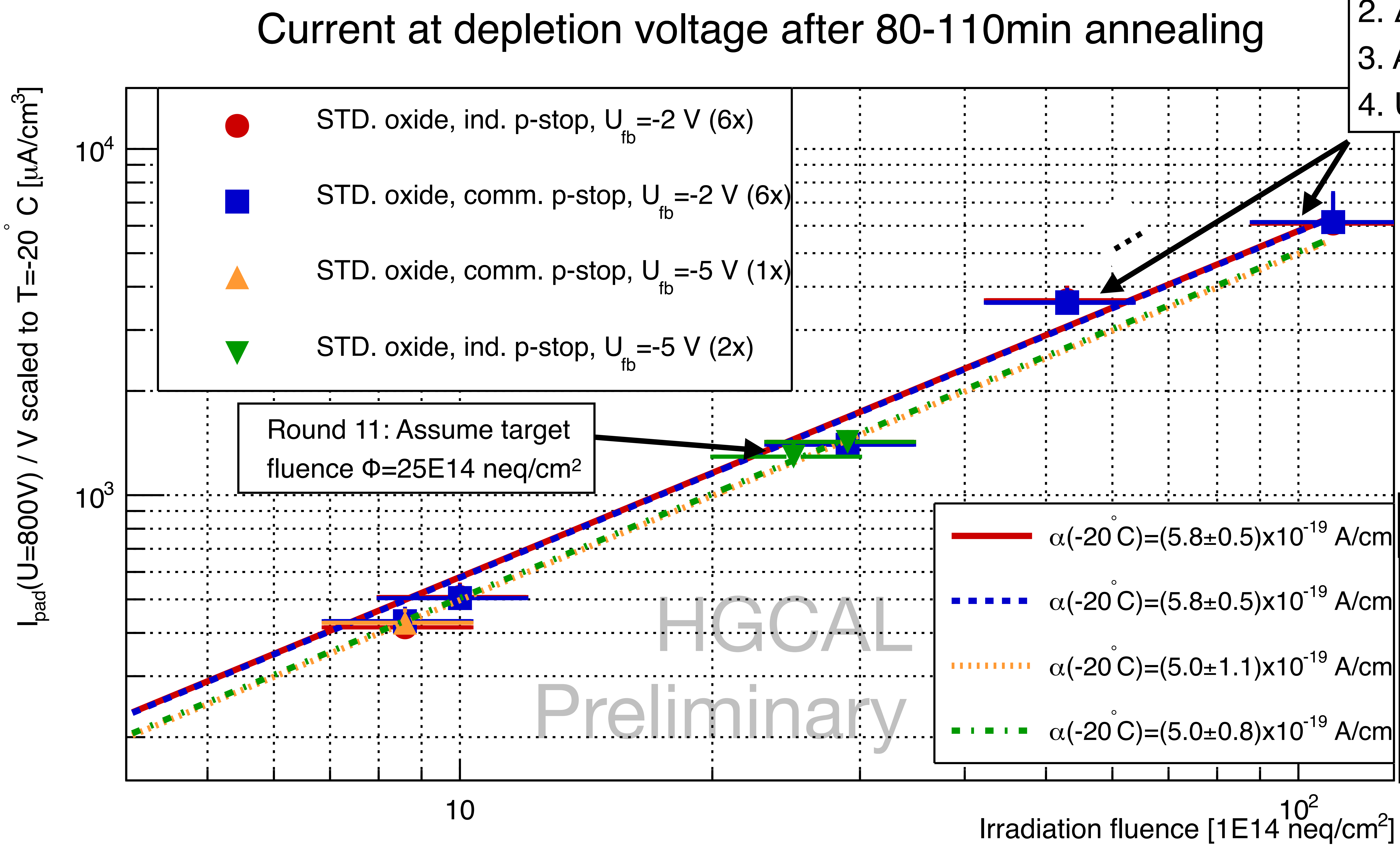
➡ **Yes.**

Preliminary α after additional annealing at U_{bias} = 600V = (4.9 +/- 0.4) x 10^{-13} μA/cm

Extraction of full-wafer alpha-value with 16/26 sensors

Per-pad leakage current per volume proportional to neutron-fluence

At 800V



Systematic uncertainties

1. $\Delta\Phi/\Phi$:= 20%.
2. $\Delta I(\Delta T, T)/I(T)$:= 7%.
3. Add. annealing: $\Delta I/I<20\%$
4. Uncertainty on thickness negligible.

$\Delta I / V = \alpha \times \Phi$?

➡ **Yes.**

Preliminary α after additional annealing at U_{bias} = 800V = $(5.8 +/- 0.5) \times 10^{-13}$ μA/cm

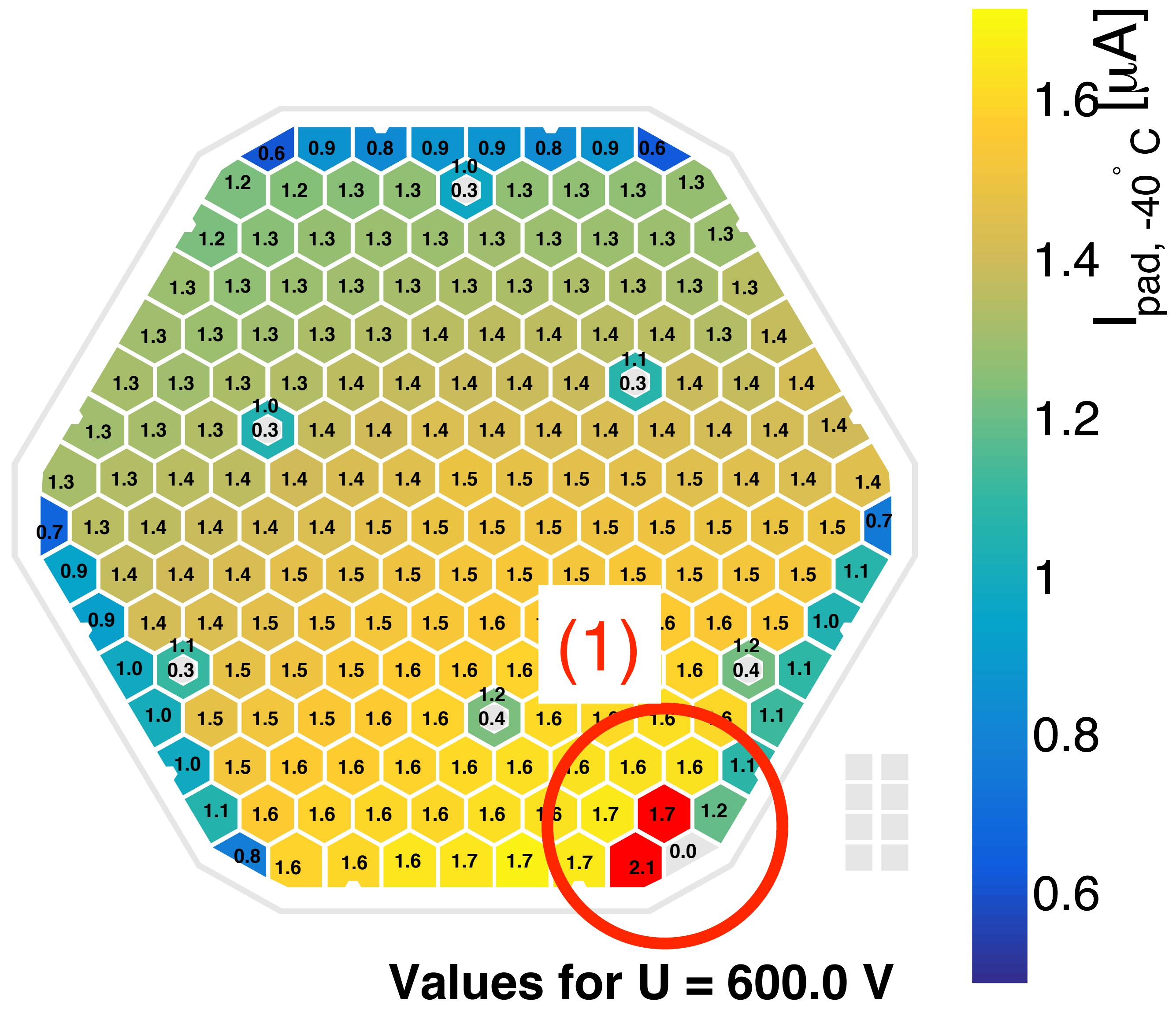
Last but not least: ~~Real-life measurement~~ experiences

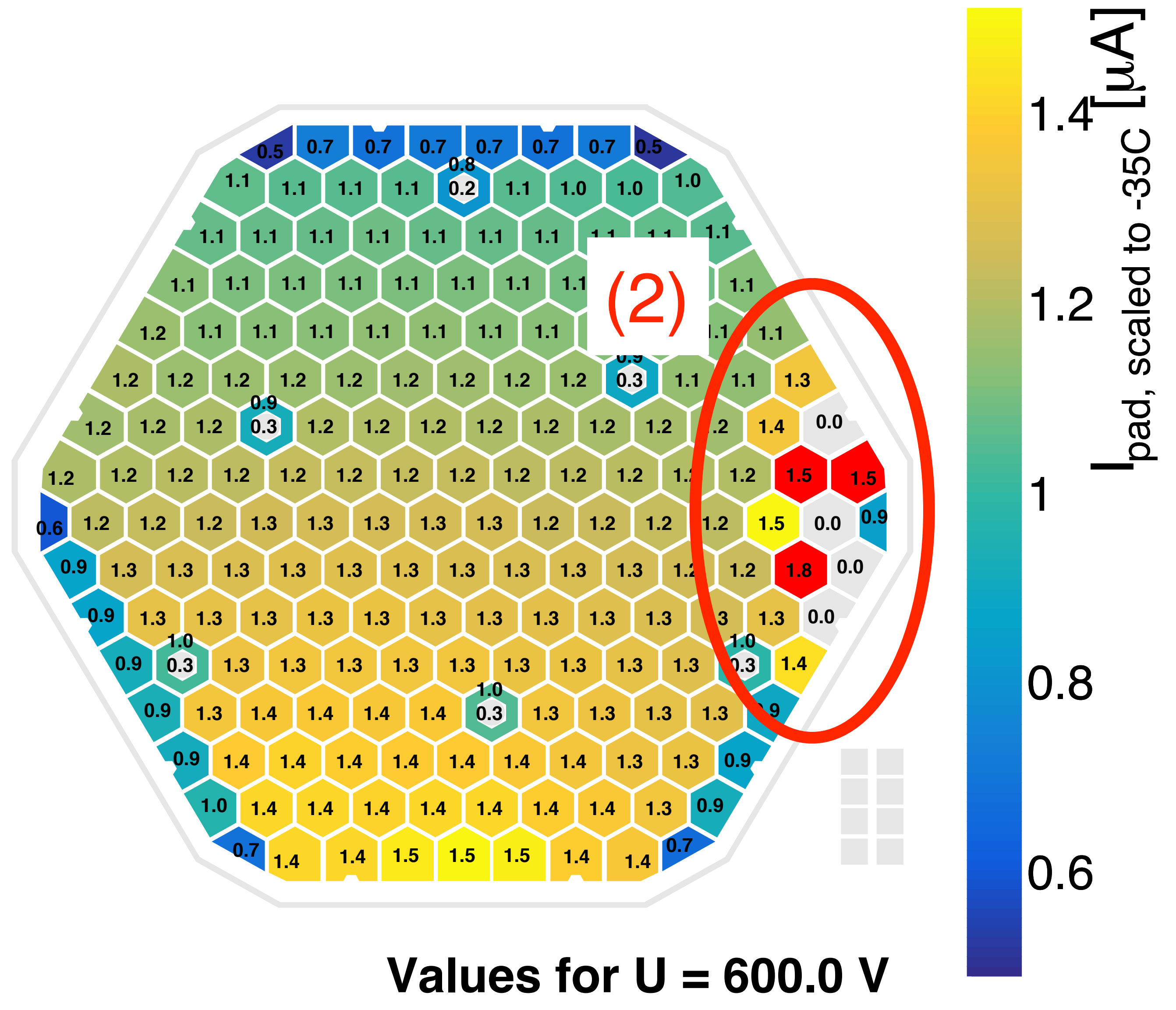
- **Overall, stable operation of CERN setup with cold chuck.**
  - No switch card broke in this campaign (2mA total current and 5µA per-pad compliance).
  - Changing sensor design = change of probe card exercised multiple times without major problems.

- Most common problem is bending (1) and even detachment (2) of pogo pins from probe card.

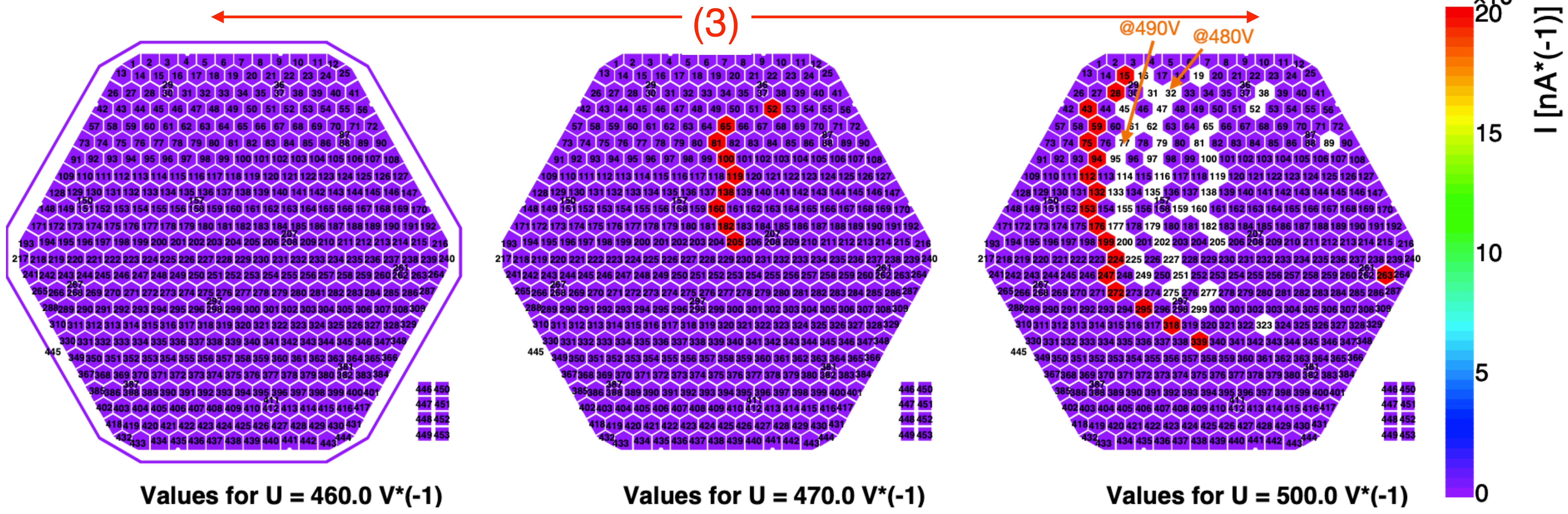
- "Exotic" problems can cause headaches, e.g. malfunctioning picoammeter (3):
  - Potential issue observed on [14 January 2021]
  - Cause finally identified on [26 January 2021]

- **CERN group is ready for IV+CV characterisations of further irradiated HGCAL silicon sensors in 2021.**





Only 400V - 500V in steps of 10V, all pads with, 10s waiting time between channel switches



Summary of this summary

- 26 out of 38 HGCAL prototype silicon sensors irradiated at RINSC were characterised at CERN since October 2020.
- 8-step IV+CV characterisation procedure incl. additional annealing can take up to 19hrs per sensor.
- Visual sensor inspection is important. Typical features seen: Harmless water residuals, dust (to be removed), chipped corners.

- Due to high temperatures in the reactor: Annealing takes place during irradiation - temperature important to monitor.
- RINSC irradiation profile seen in the data. Beam not centred on the sensors?

- Leakage current vs. temperature scaling law experimentally validated.
- CERN cold chuck with +/- 0.7°C temperature variation.

- Total leakage current well within (system-defined) compliance of 2mA for 20/26 sensors.
- 6 sensors with discharges. 3/6 with previously visible defects, unspecified cause for the other 3/6 sensors.
- Peculiar: Total leakage current behaviour improved after irradiation for some 120µm sensors.

- Post-irradiation annealing at +60°C for 80min: Leakage current reduced by ~30%, depletion voltage reduced by ~40% (200µm sensor).
- Per-pad leakage current independent of process parameters.

- Depletion voltage estimate with difference between process parameters. *To be clarified by further analysis: Are differences systematic?*
- Depletion voltage and leakage current (as proxy for the fluence) positively correlated.

- **$\Delta I / V = \alpha \times \Phi$, $\alpha_{preliminary} = (3.5 \pm 0.3) \times 10^{-13}$ µA/cm**

- *Measurements and results to be documented in a note / paper.*