Radiation tolerance study
using test-structure diodes from 8-inch silicon sensors for CMS HGCAL

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with support from the CERN SSD group

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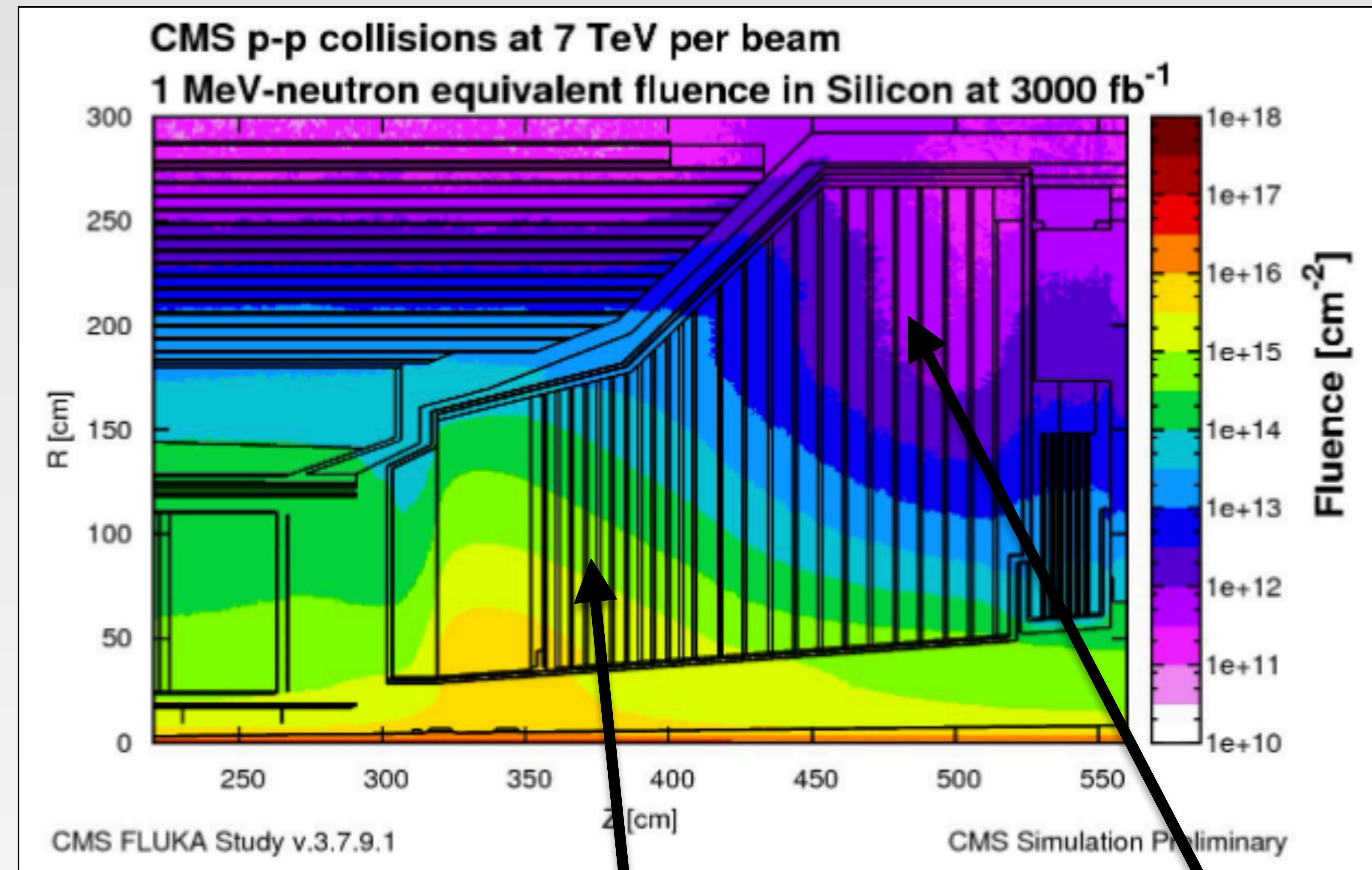
Introduction and Outline

- High fluences up to 10^16 neq/cm2
- Two different sensor types, different optimal annealing scenarios
- Large area to cover with Si sensors: **new production line for 8" wafers** [Full sensor results in Oliwia's talk]
- **Annealing behaviour has not been studied**
- Crucial input for operation and warming up scenarios



Silicon sensors (diodes)

Scintillator+ SiPMs

This talk: annealing behaviour of silicon bulk material

- Depletion voltage
- Leakage current
- Charge collection efficiency

Studied Samples

- Thickness and material
  - 300µm, 200µm FZ
  - 120µm EPI
- Fluences
  - 6.5e14 to 1e16 neq/cm2
  - Neutron irradiated at JSI

CV/IV

- 16 samples in total
- 9 Annealing points

➡ Approx 150 measurements

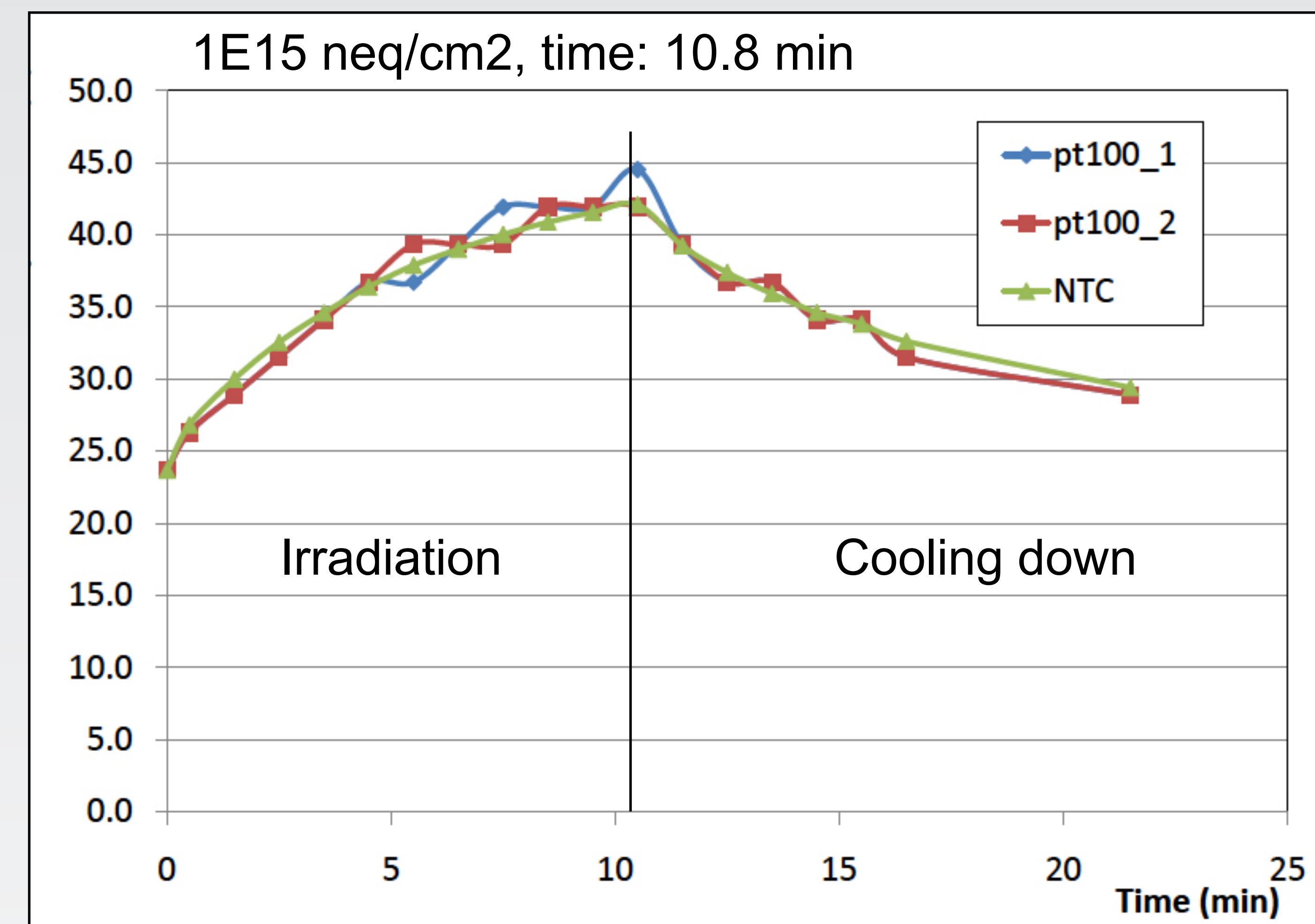
CCE

- 12 samples
- 6 Annealing points

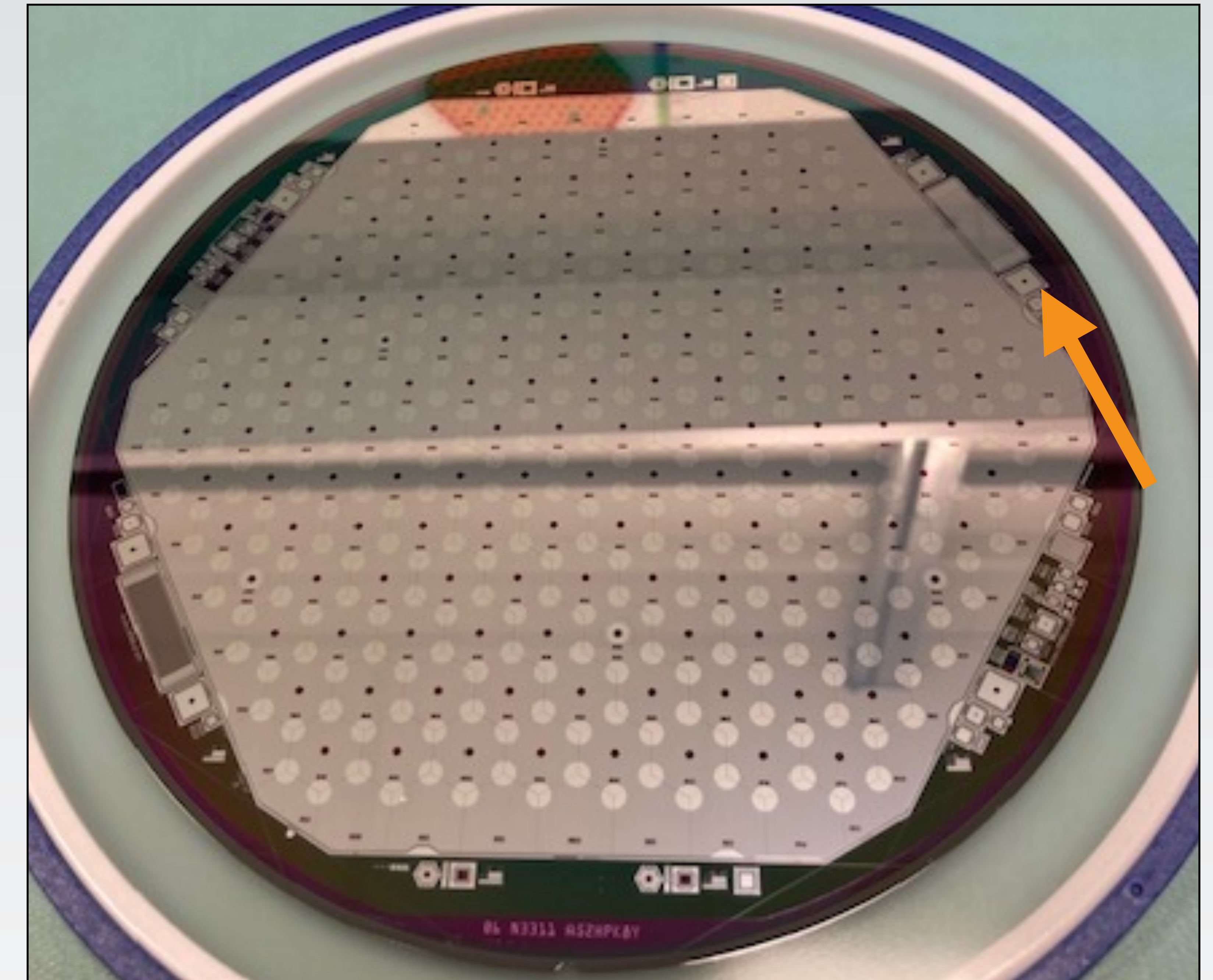
➡Approx 70 measurements

Annealing offset correction

- Assume homogenous linear increase in total accumulated fluence during irradiation
- Fold with recorded temperature profile: not expected to exceed +45˚C

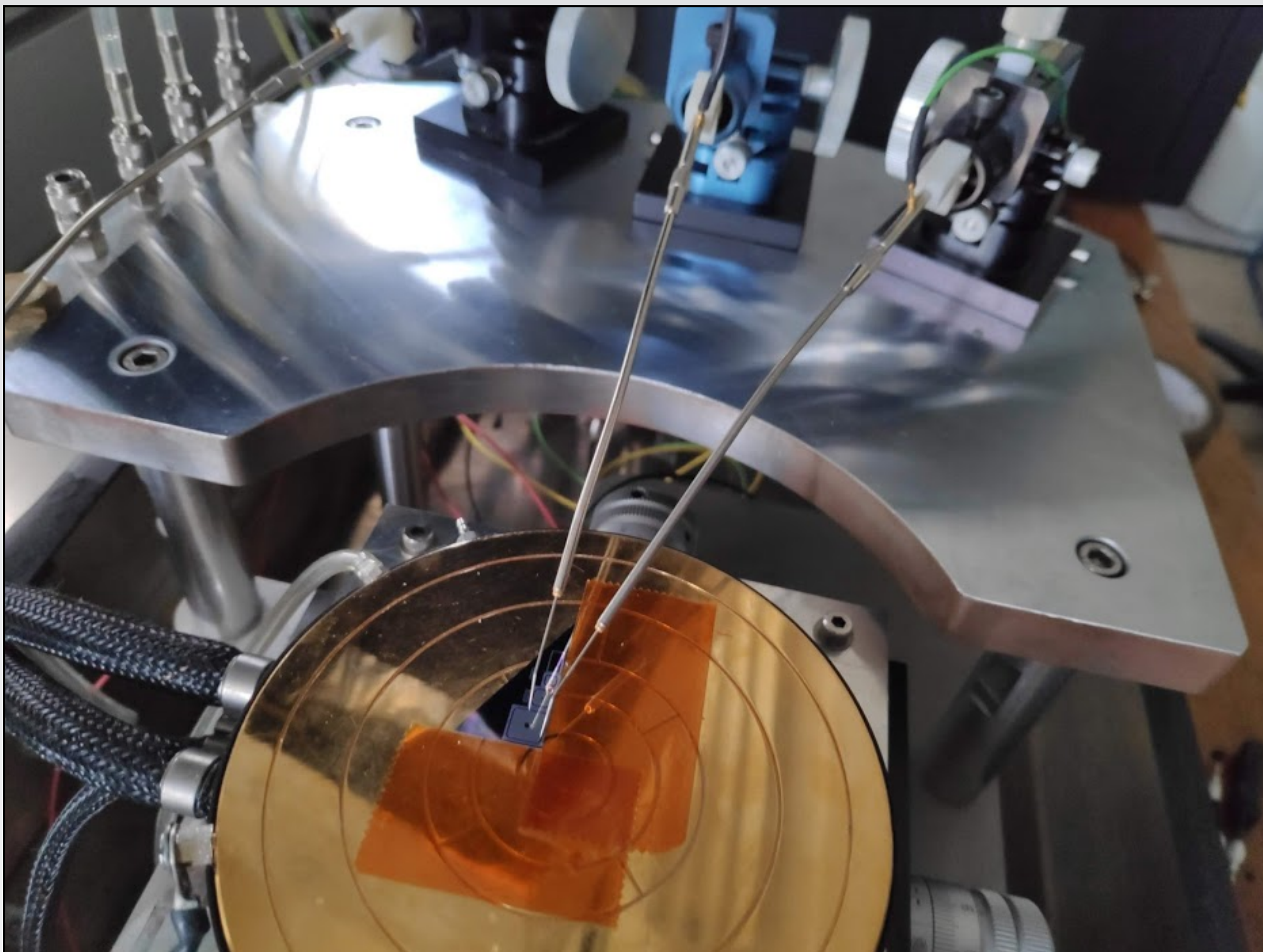


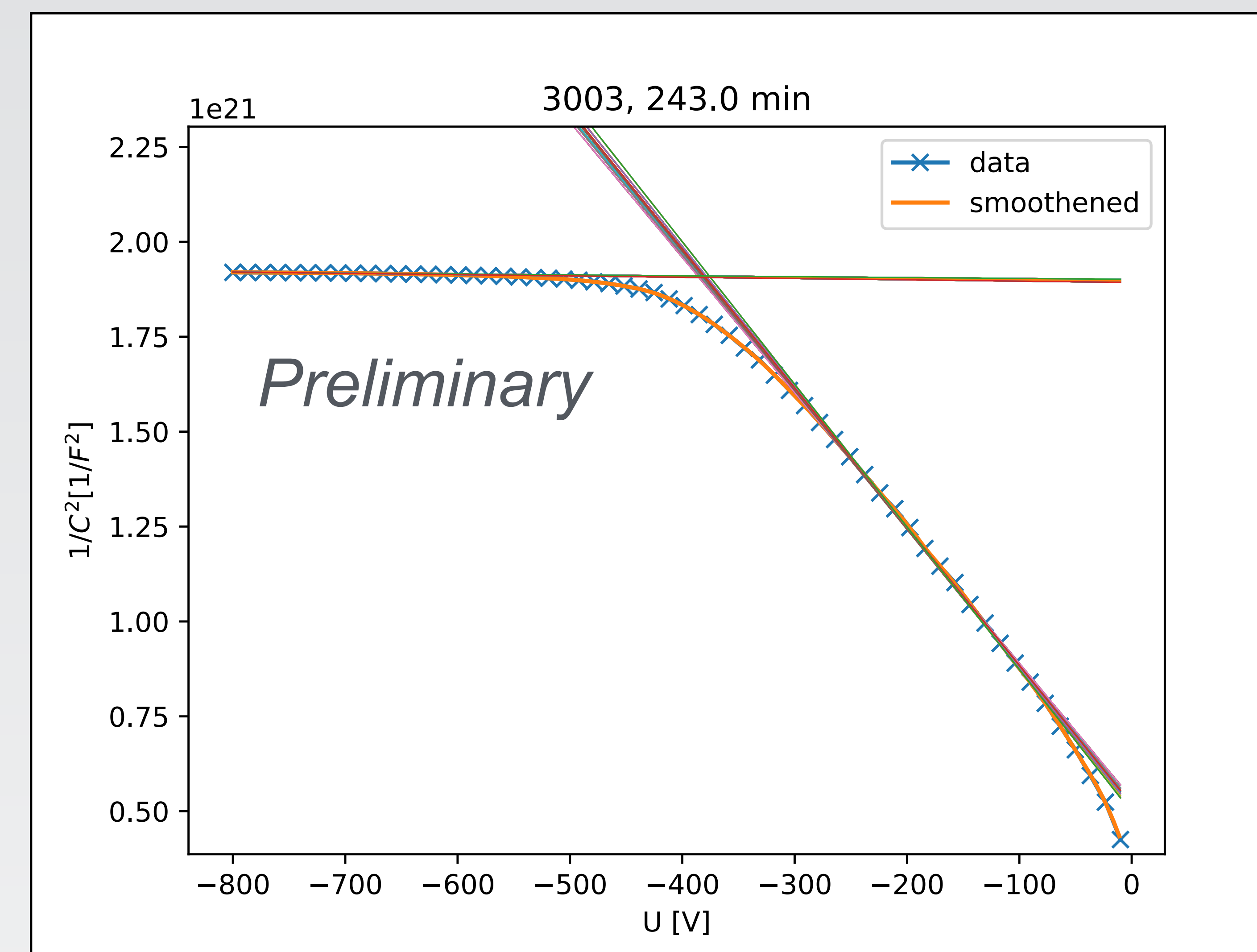
Cindro et al, NIMA

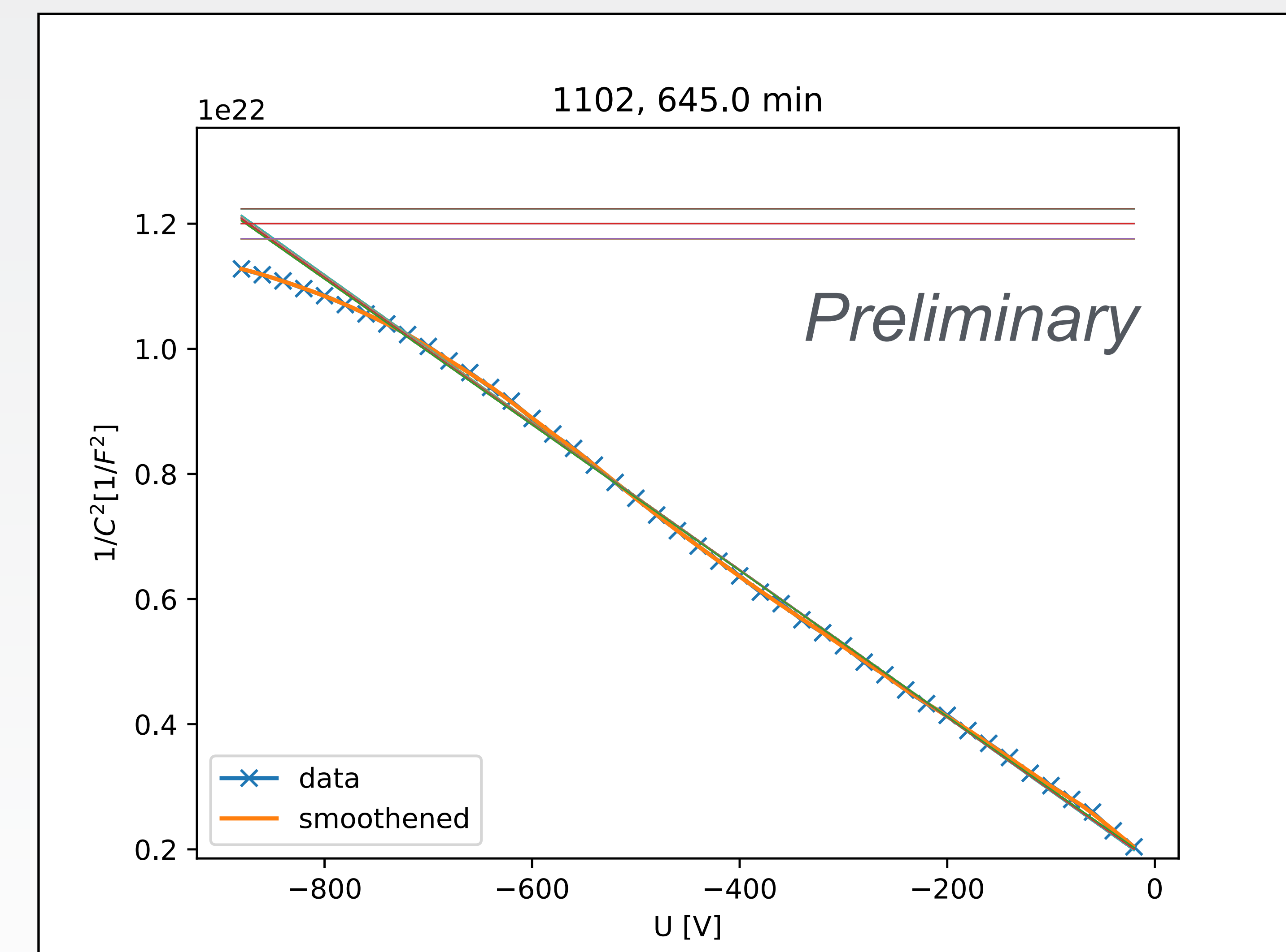


Thick- ness	Flat band volt.	Oxide quality	Proc.	Fluence [neq/cm2]
300	-2V	STD	FZ	6.50E+14
300	-2V	STD	FZ	1.00E+15
300	-2V	STD	FZ	1.50E+15
200	-2V	STD	FZ	1.00E+15
200	-2V	STD	FZ	1.50E+15
200	-2V	STD	FZ	2.50E+15
120	-2V	STD	EPI	1.00E+16
120	-2V	STD	EPI	2.50E+15
120	-2V	STD	EPI	1.50E+15

Capacitance and depletion voltage







- Measurements performed in the CERN SSD lab
  - 10kHz, 0.5 V
  - Temperature: -20˚C

- Fit straight lines
- Choose ranges by hand
  - Assign 10% uncertainty to range choice
- If plateau cannot be reached use expected end capacitance: extrapolation
  - Assign larger uncertainty

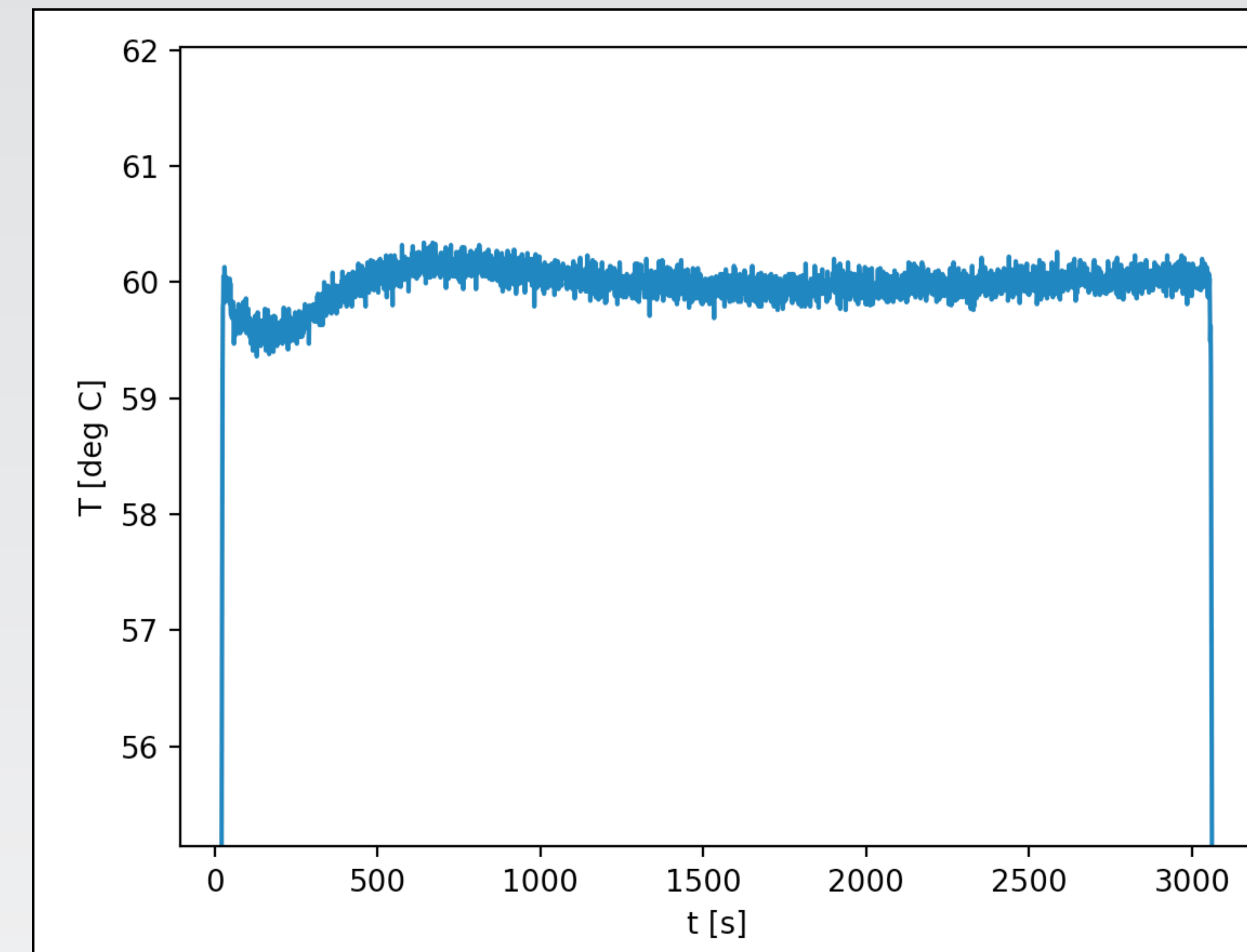
- Use as total uncertainty the envelope of all possible intersection points

CV/IV: Annealing Steps

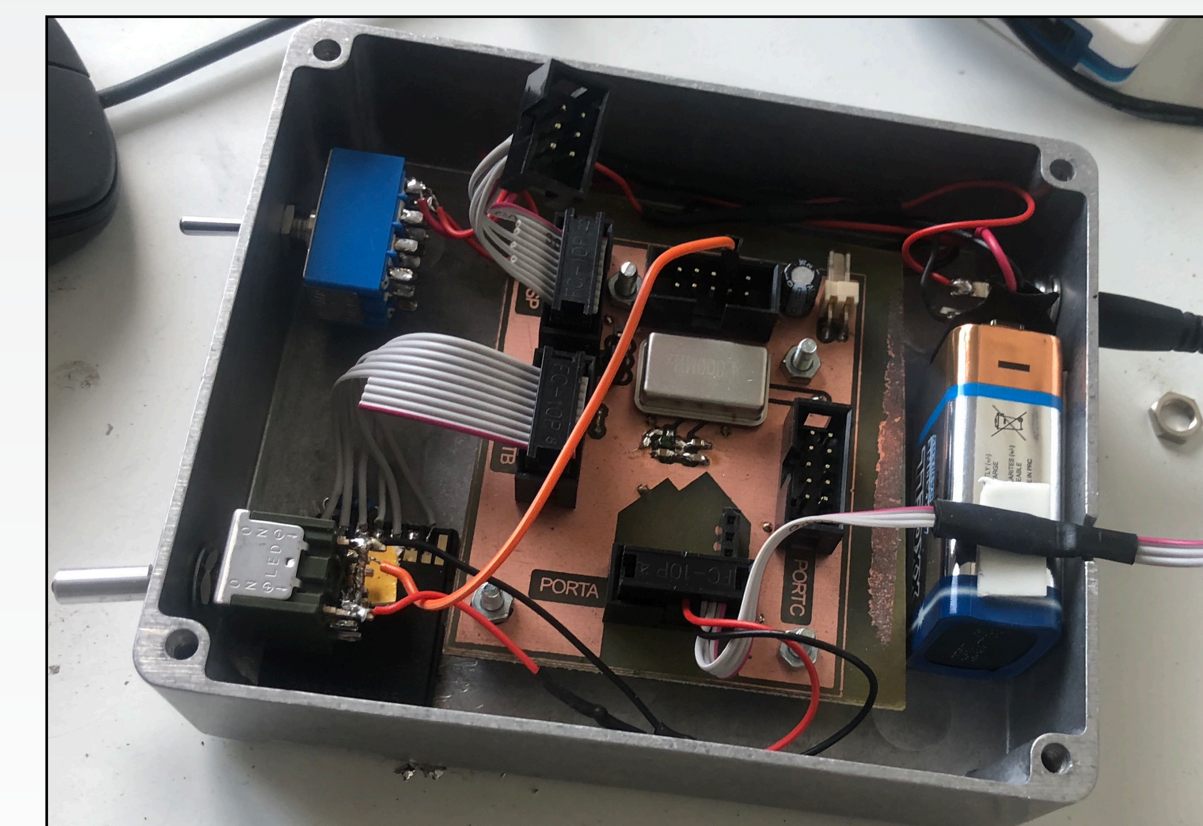
Step	Temperature °C	Time min	Eq. Time at RT days
1	60	**10**	3.8
2	60	20	6.9
3	60	40	13.3
4	60	80	27.9
5	60	100	53.7
6	60	140	100.0
7	80	25	203.1
8	80	57	407.4
9	80	120	824.1

↑ Δ step

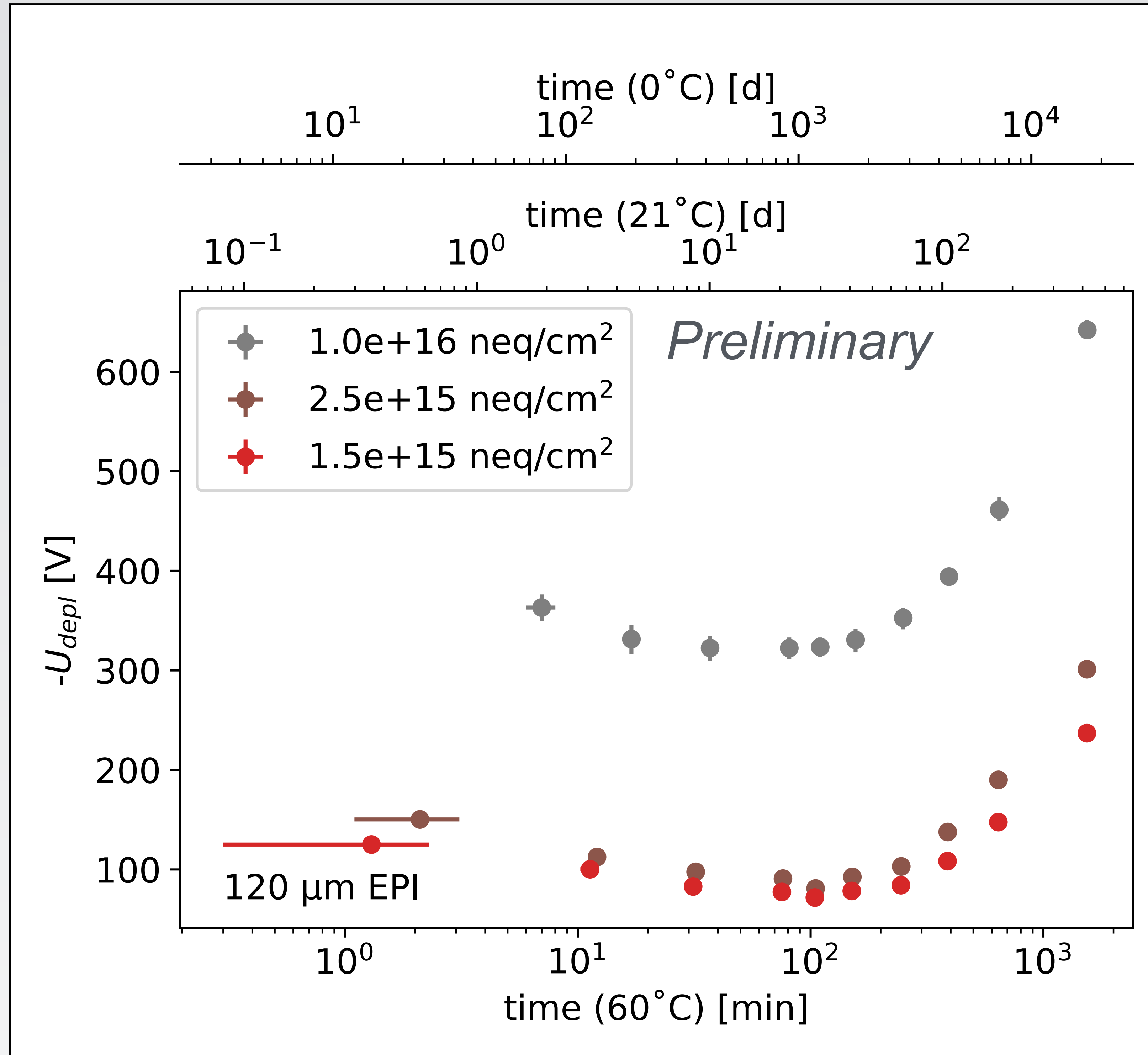
↑ Cumulative at room temperature

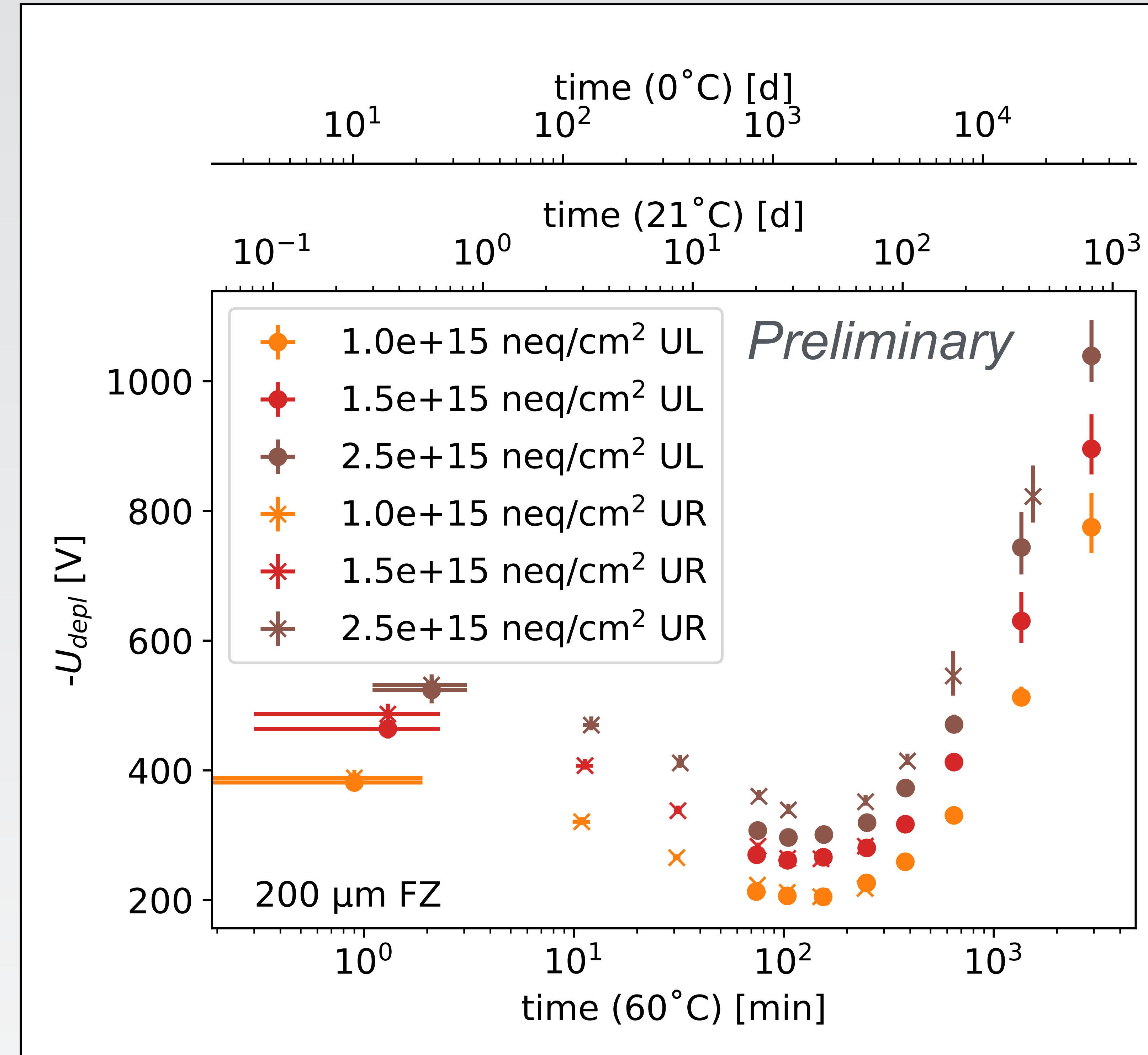


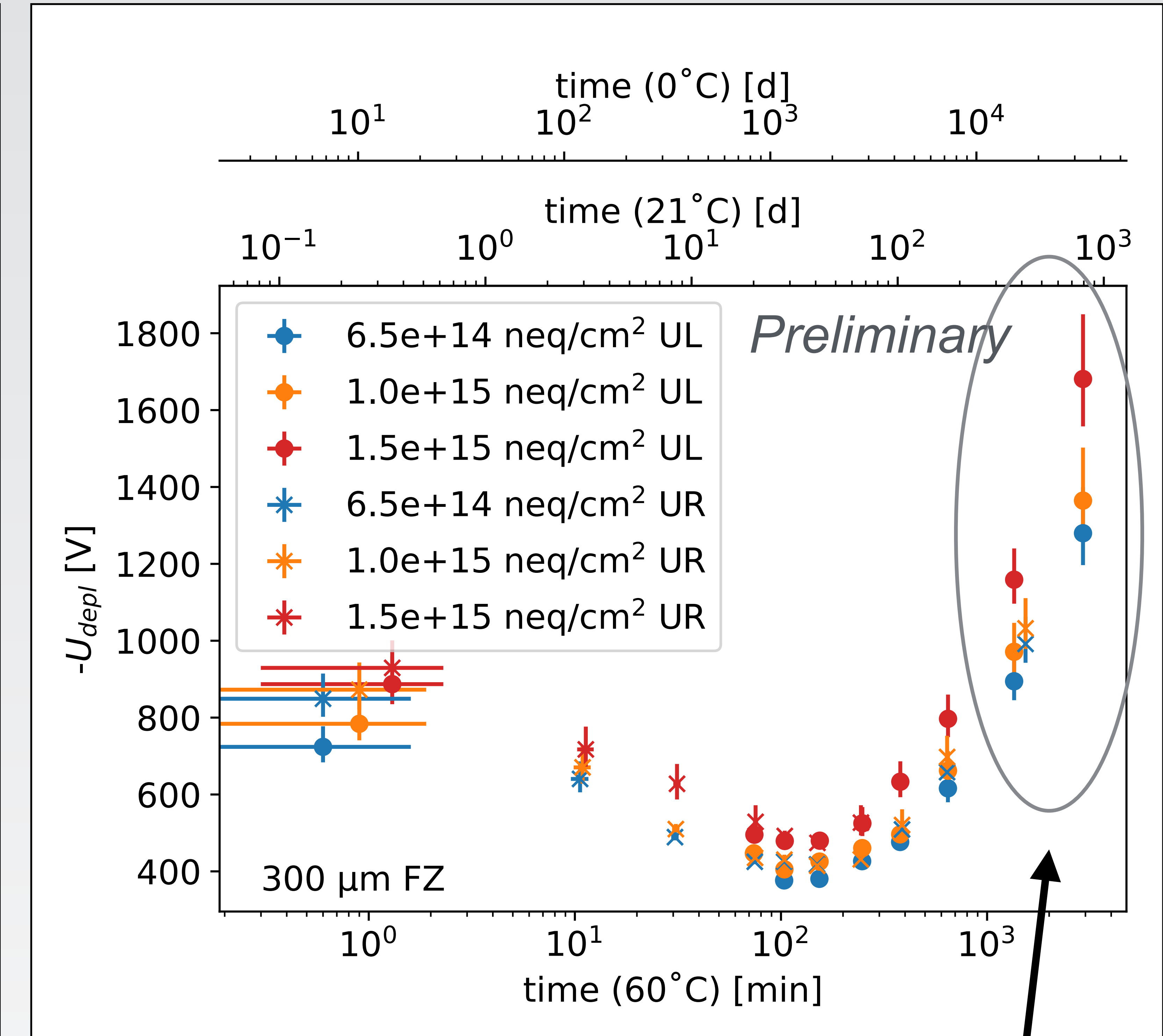
- Target annealing times between 10 minutes and about 2000min at 60˚C
- Anneal at 60˚C up to about 400 minutes, then change to 80˚C
- Temperature during annealing logged with 0.1˚C accuracy
  - Target annealing time and actual annealing times differ slightly



Depletion voltage







- Samples with same fluence and thickness mostly compatible (taking into account 10% fluence uncertainty)
- Beneficial and reverse annealing clearly visible

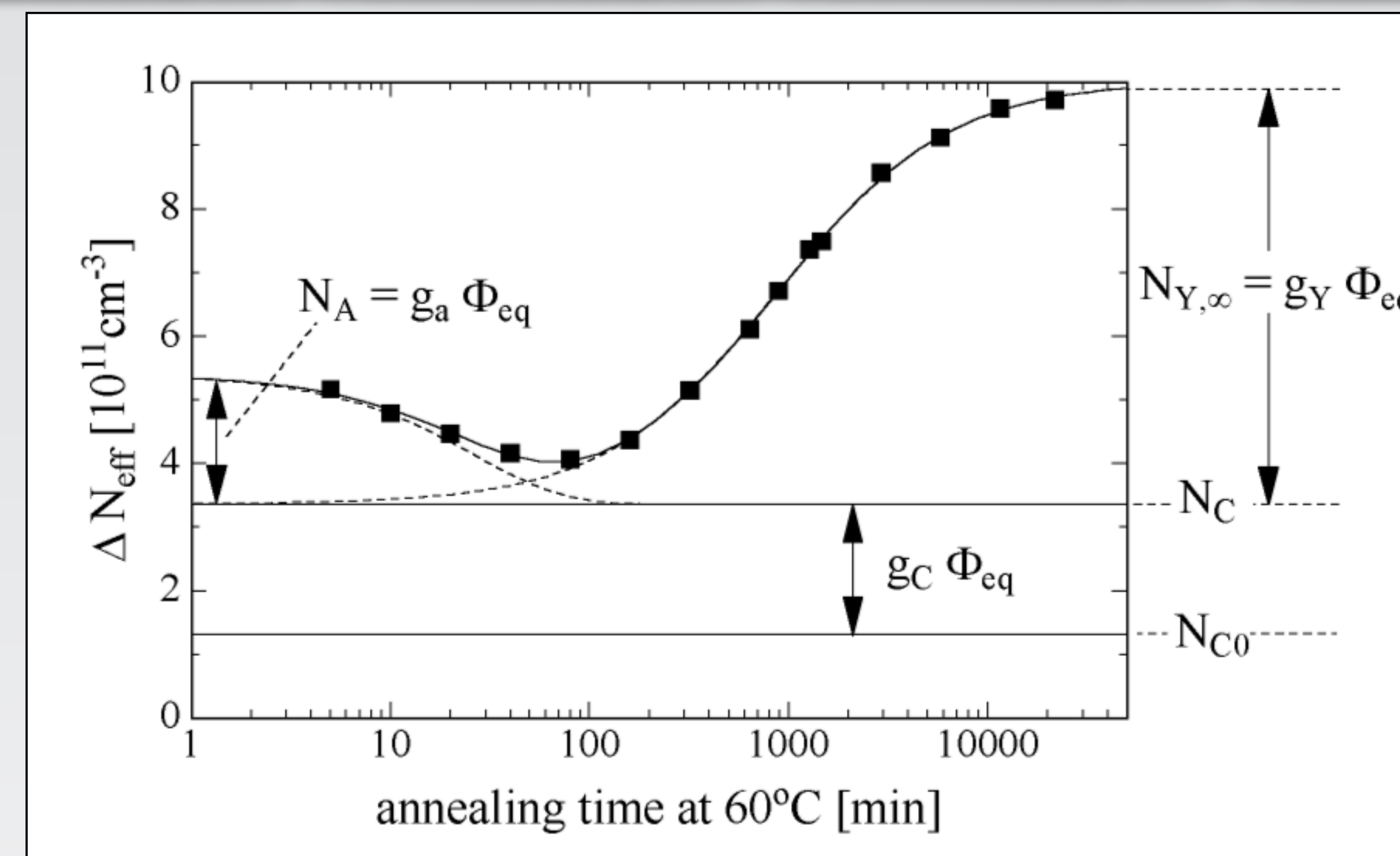
- For EPI material, minimum consistent with about 80 minutes at 60˚C
- For FZ material, minimum around 120 minutes at 60˚C

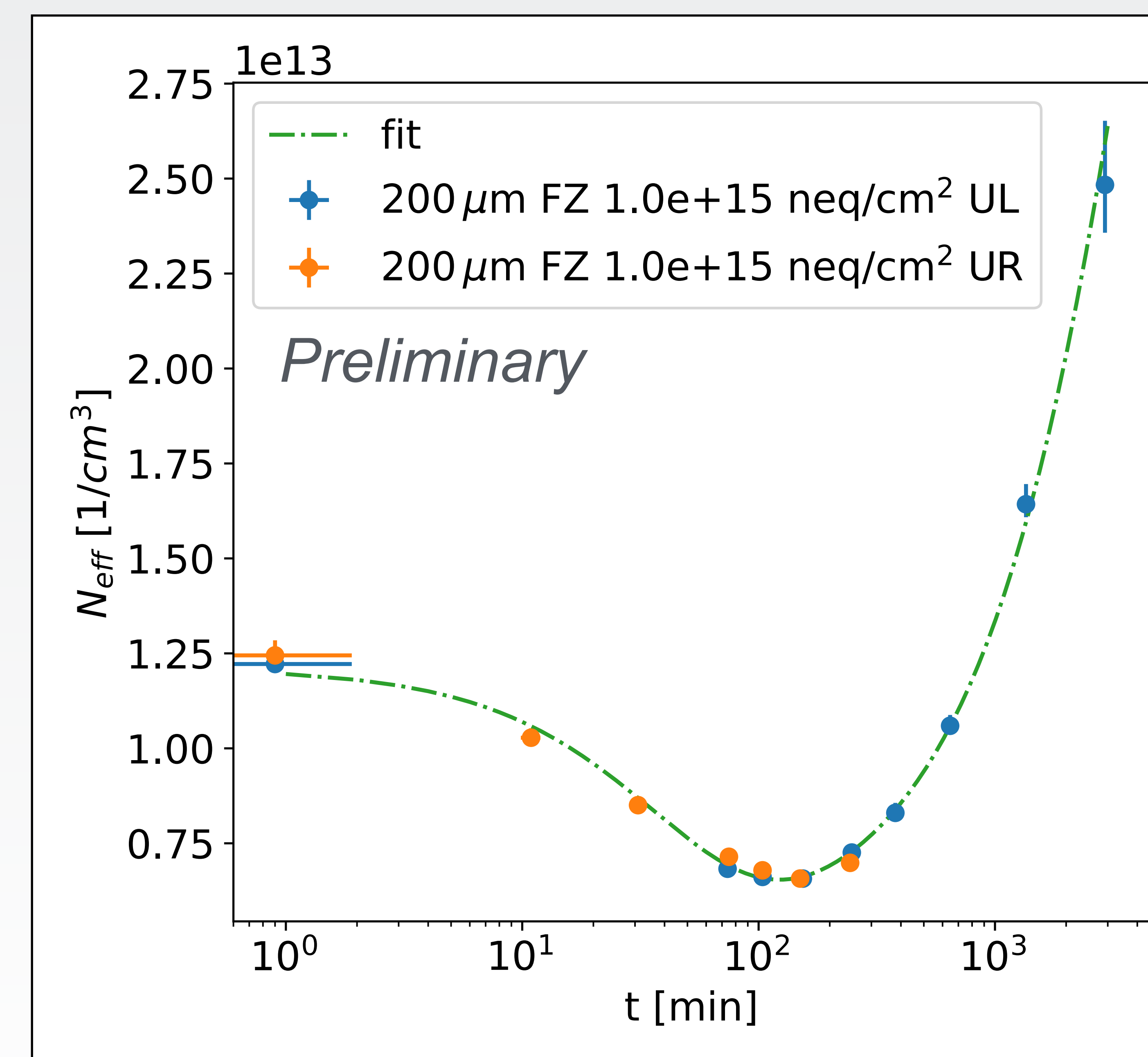
Extrapolation region

Fit of depletion voltage vs. Annealing time

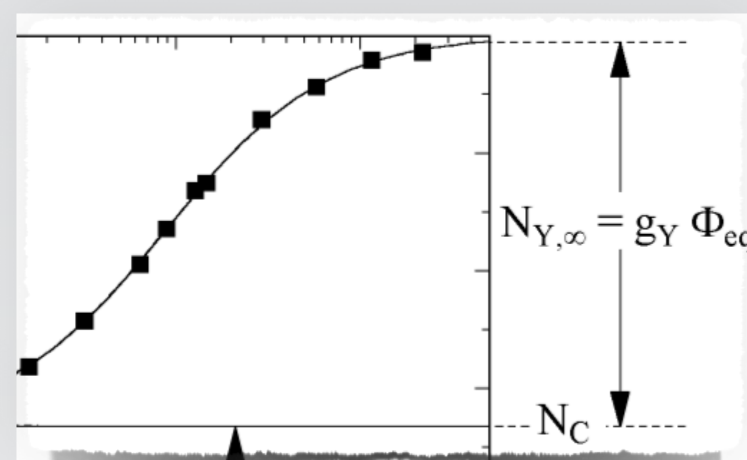
$$\Delta N_{eff}\left(\Phi_{eq}, t(T_a)\right) = N_A\left(\Phi_{eq}, t(T_a)\right) + N_C\left(\Phi_{eq}, t(T_a)\right) + N_Y\left(\Phi_{eq}, t(T_a)\right).$$

- Can be described by three terms
  - **N_A**: Beneficial annealing (exponentially falling)
    - Time constant τ_A
  - **N_C**: Constant radiation damage
    (here fitted as total constant offset: $N_C + N_{C0} + N_{Eff0}$)
  - **N_Y**: reverse annealing: $N_{Y,\infty}\left(1 - \frac{1}{1 + t/\tau_Y}\right)$
    - Time constant τ_Y
- Perform fit for each material and each fluence individually



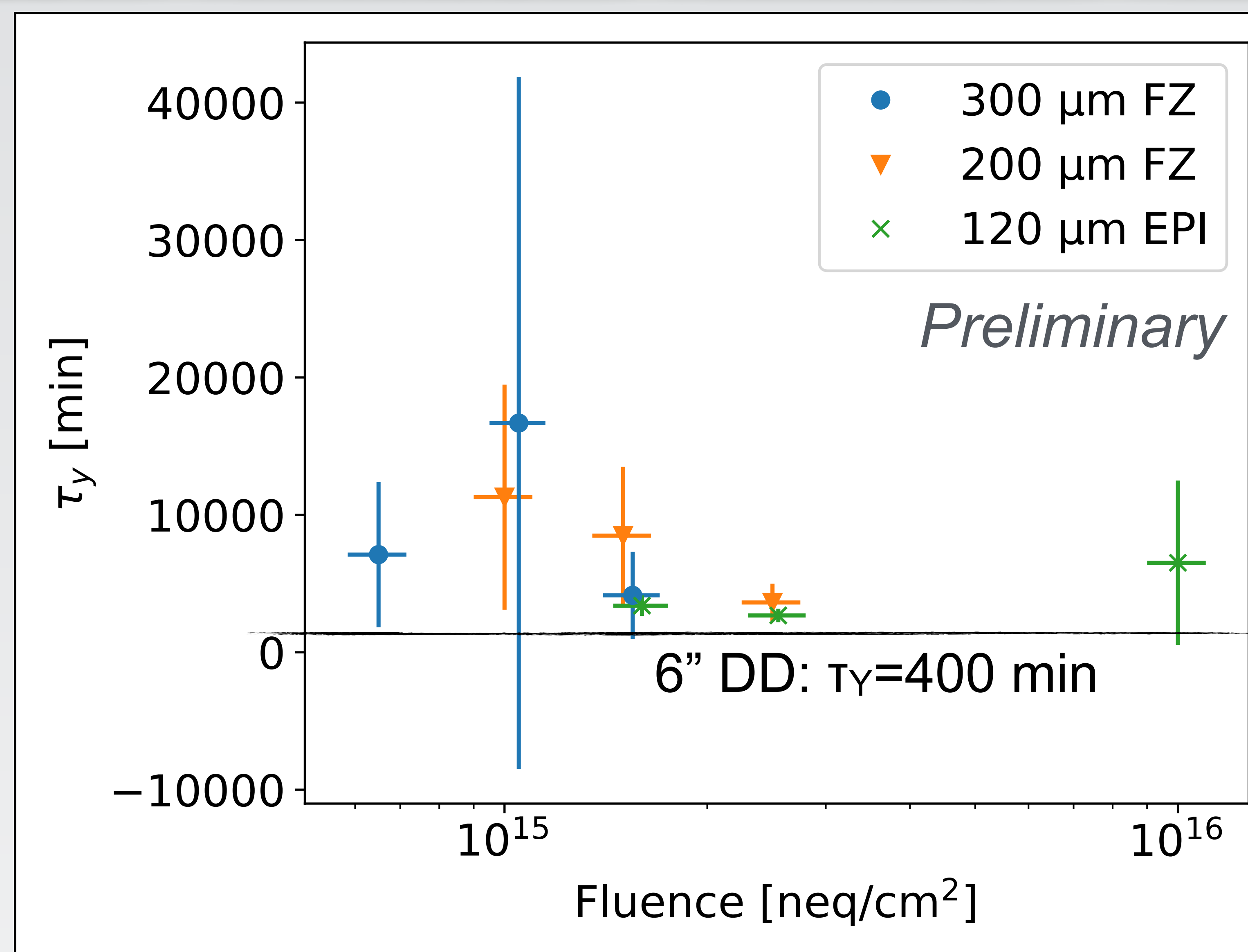


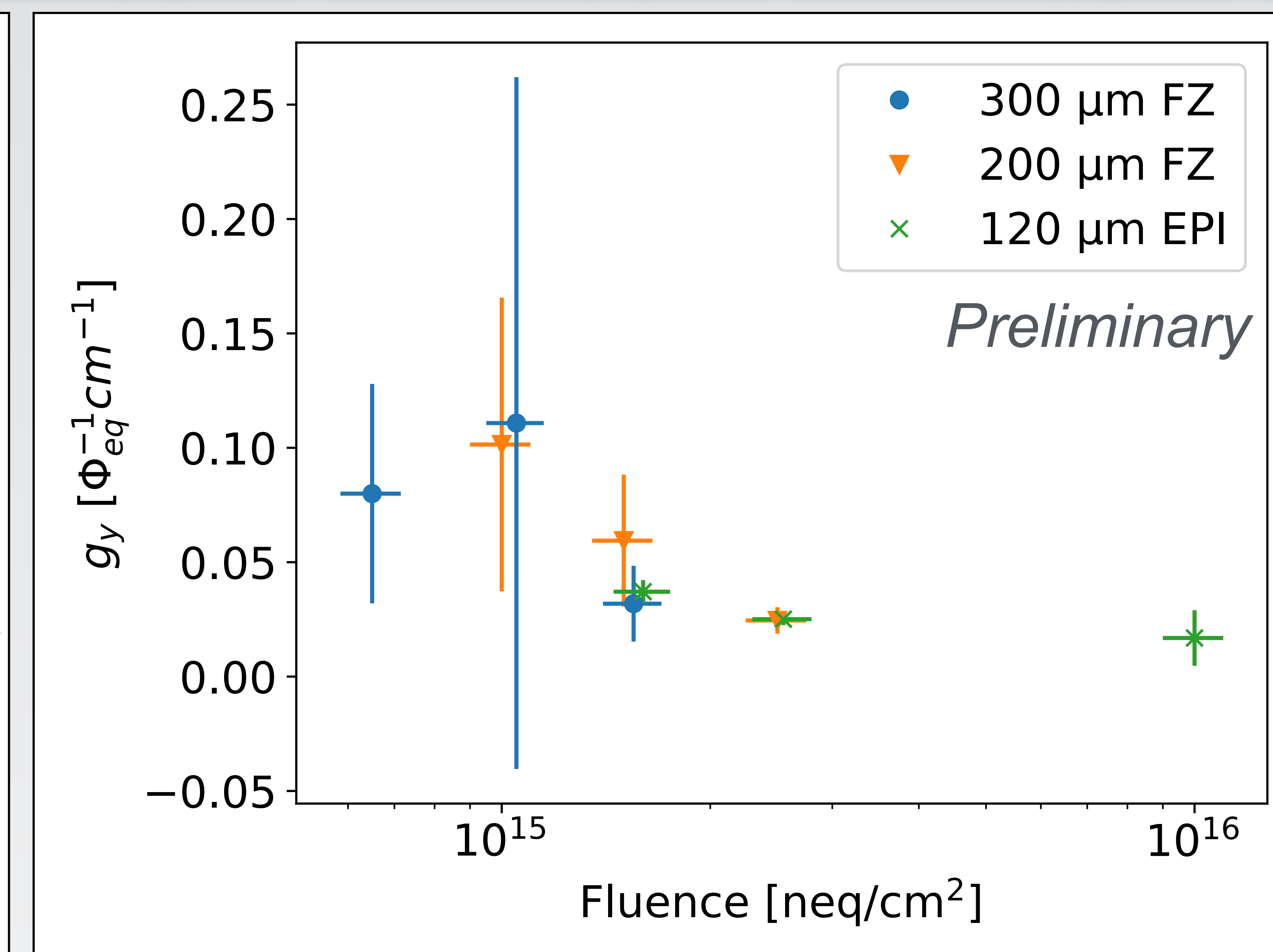
Parametrisation of beneficial and reverse annealing

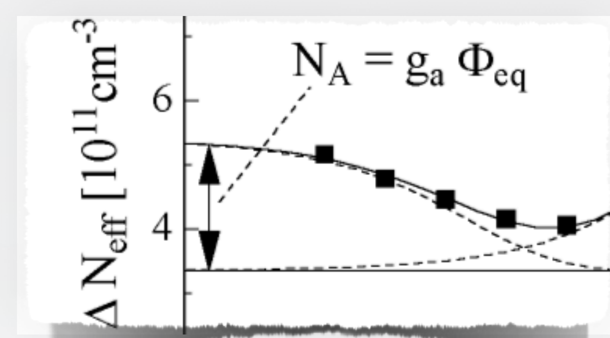


Reverse annealing

- Relatively large uncertainties
  - Not enough points at long annealing times
- Relatively large timing constant
- Slow reverse annealing compared to 6" DD sample
- g_Y almost constant as expected

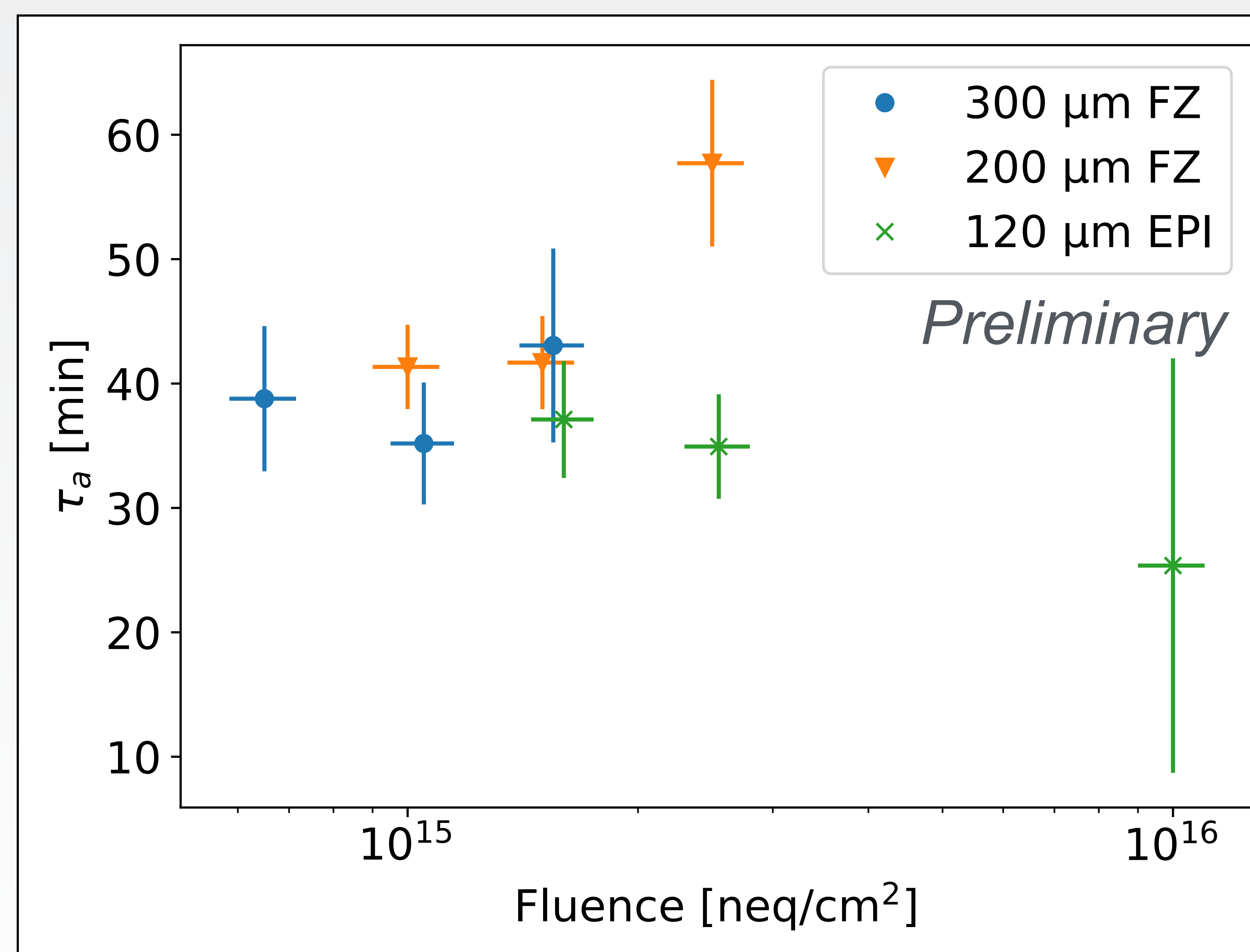


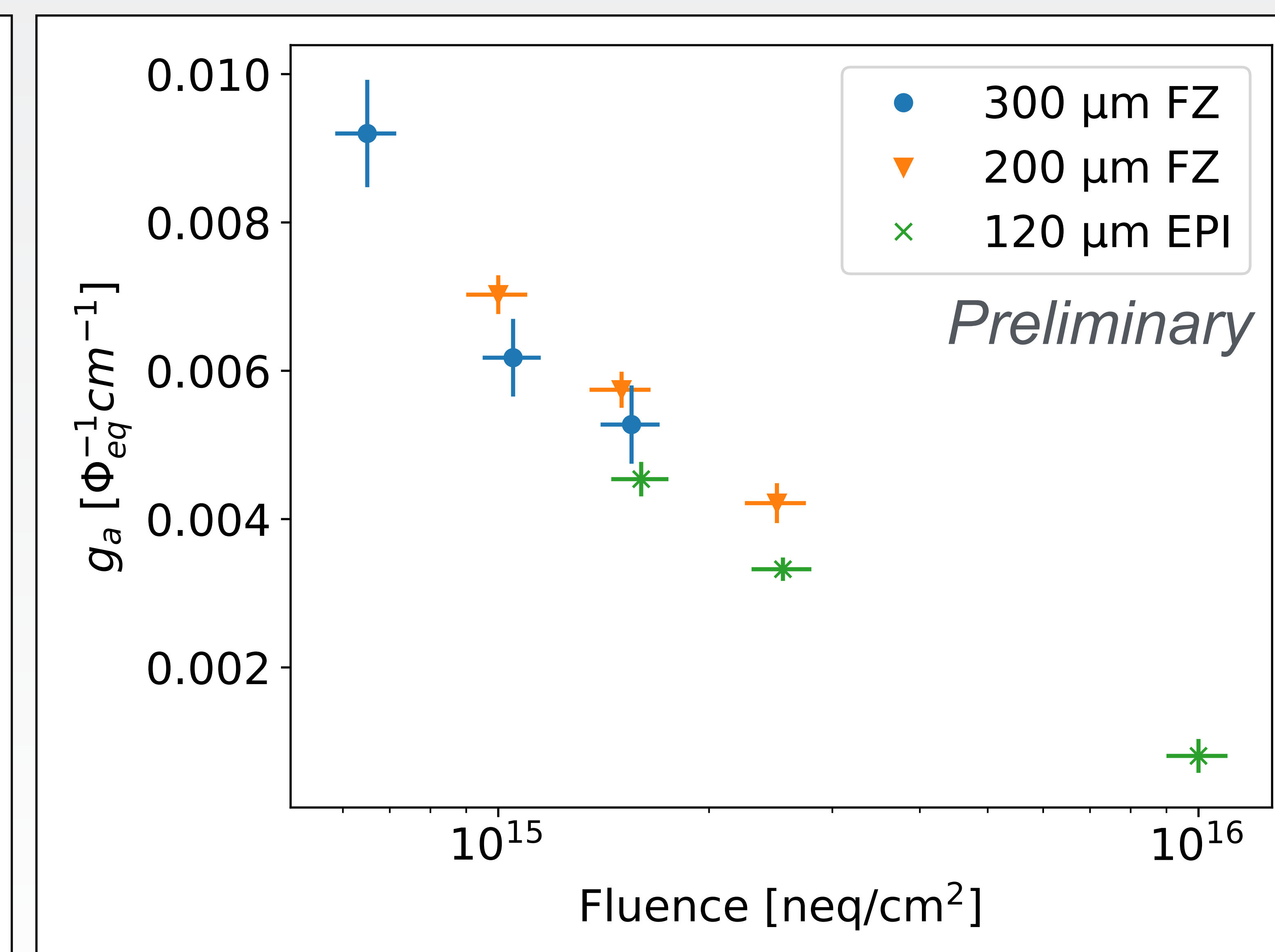




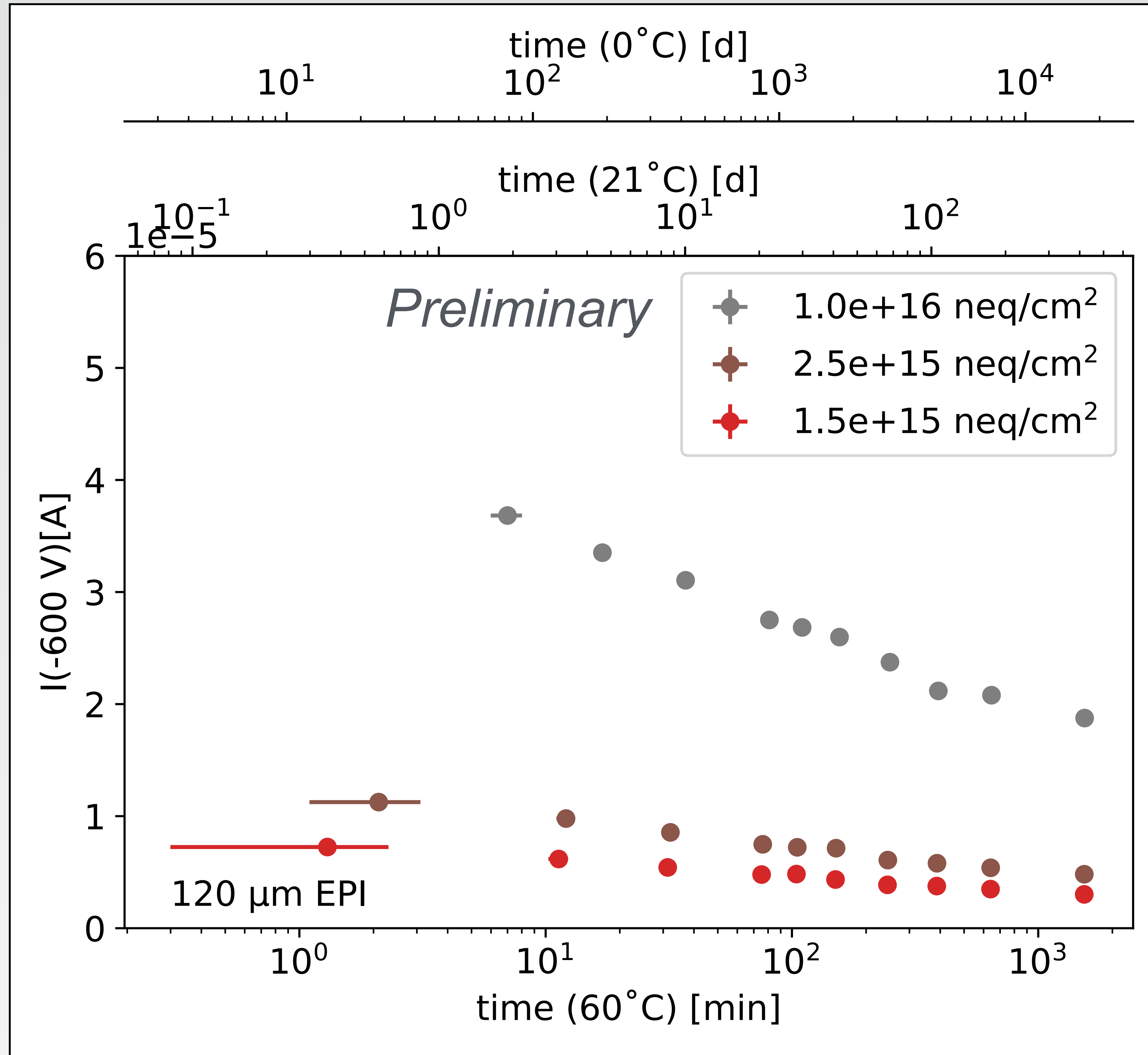
Beneficial annealing

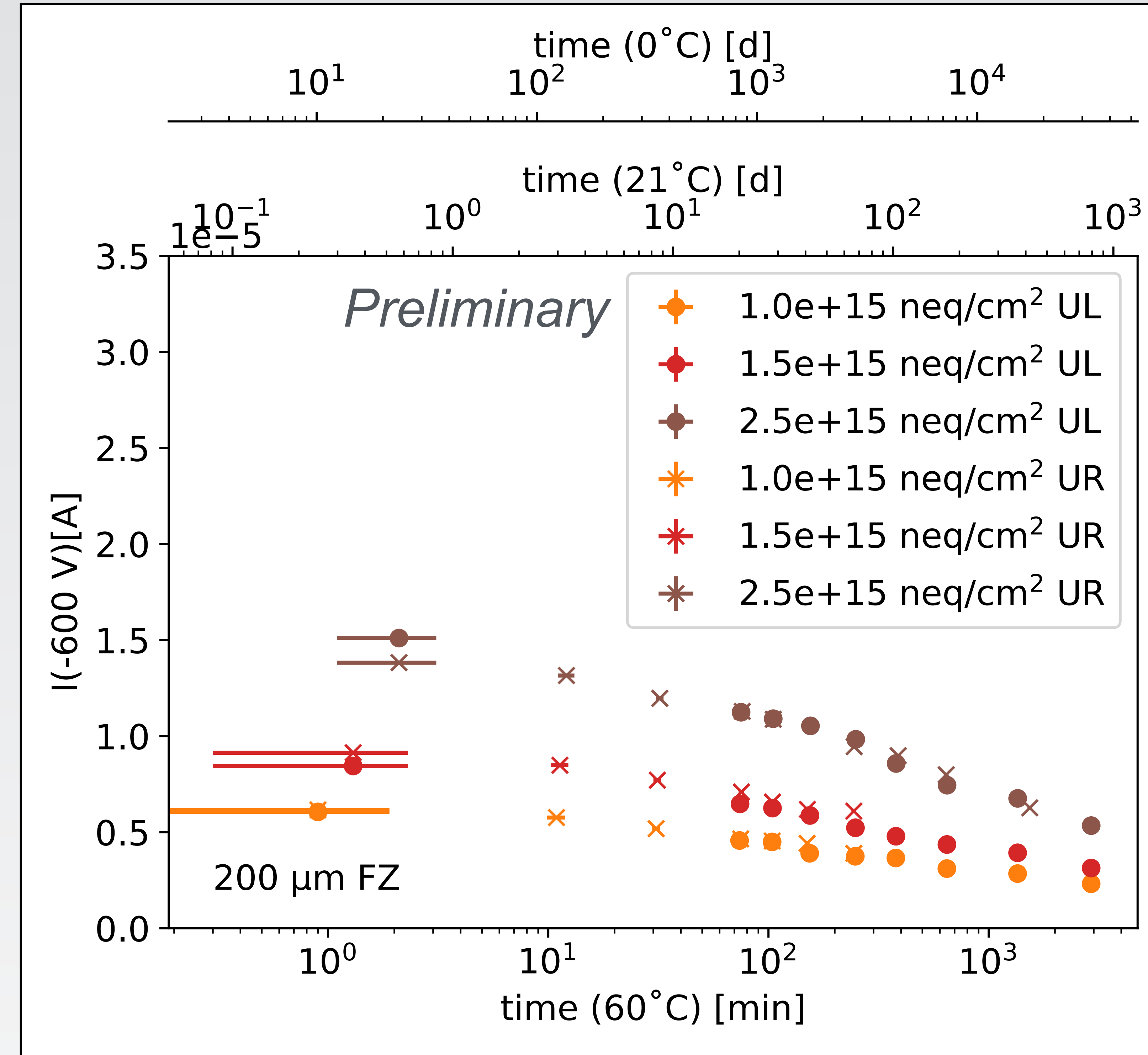
- Timing constant shows some spread
- Clear unexpected dependence of g_a on fluence contrary to constant expectation
  - Needs to be investigated

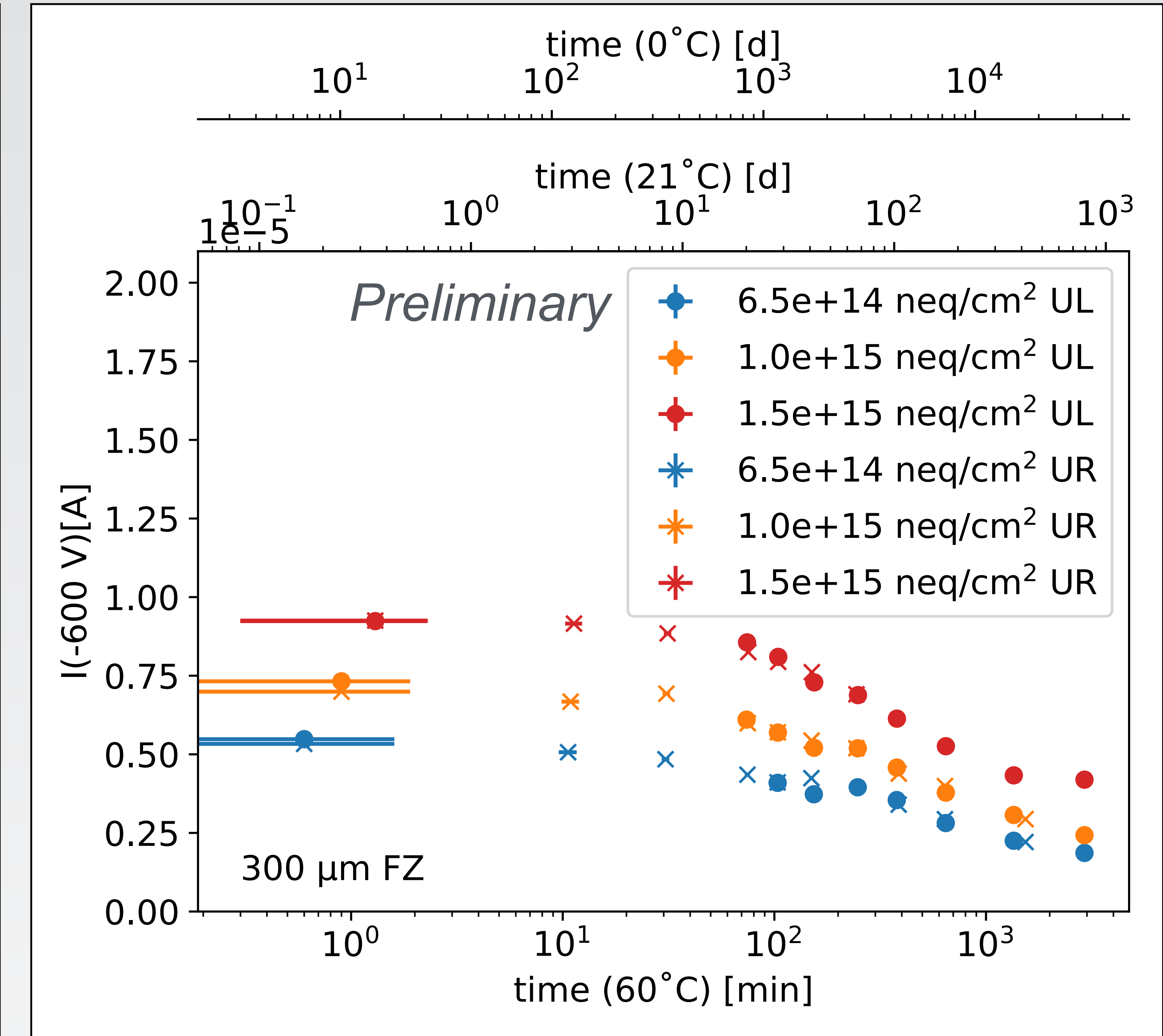




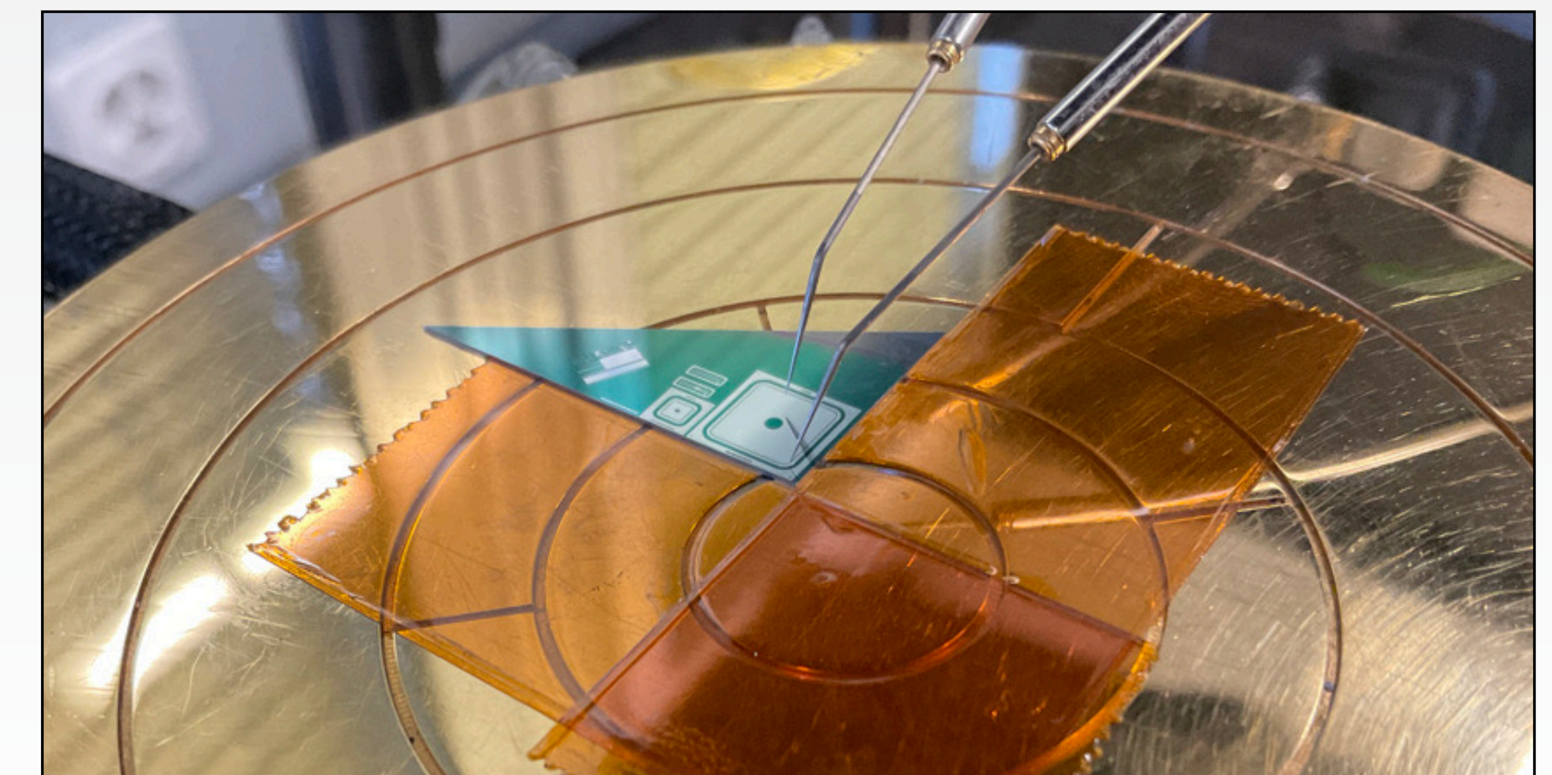
Leakage current



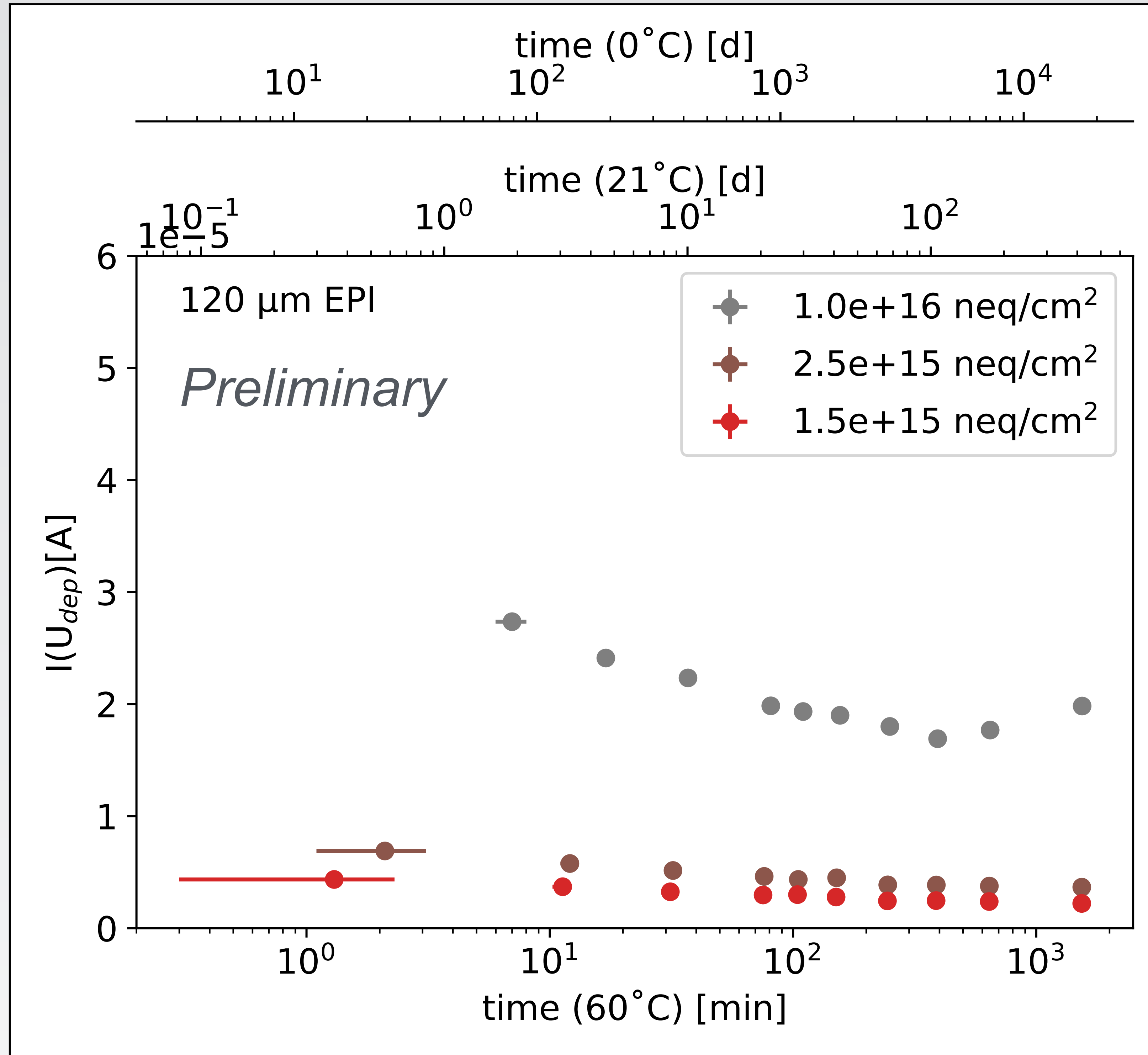


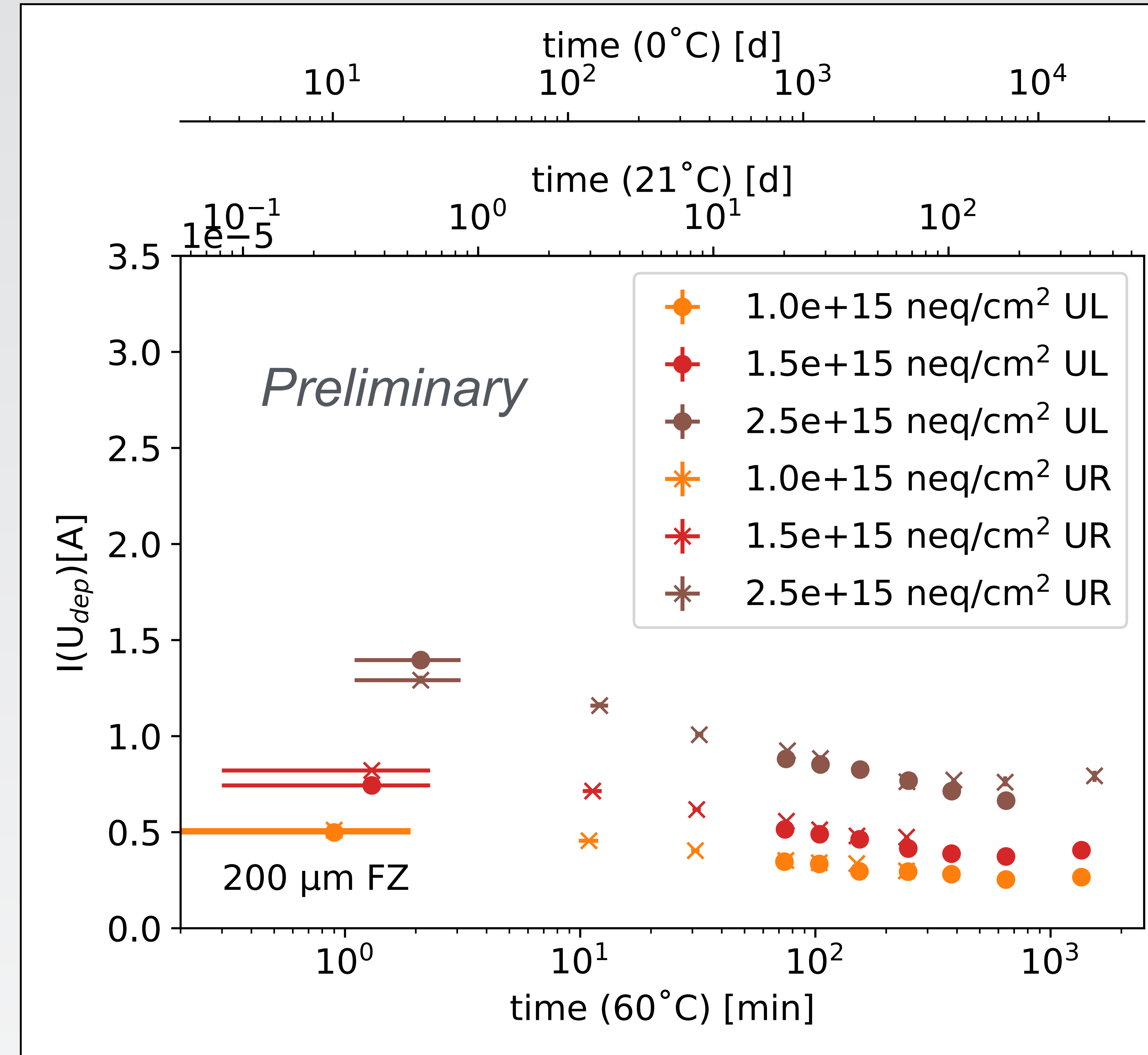


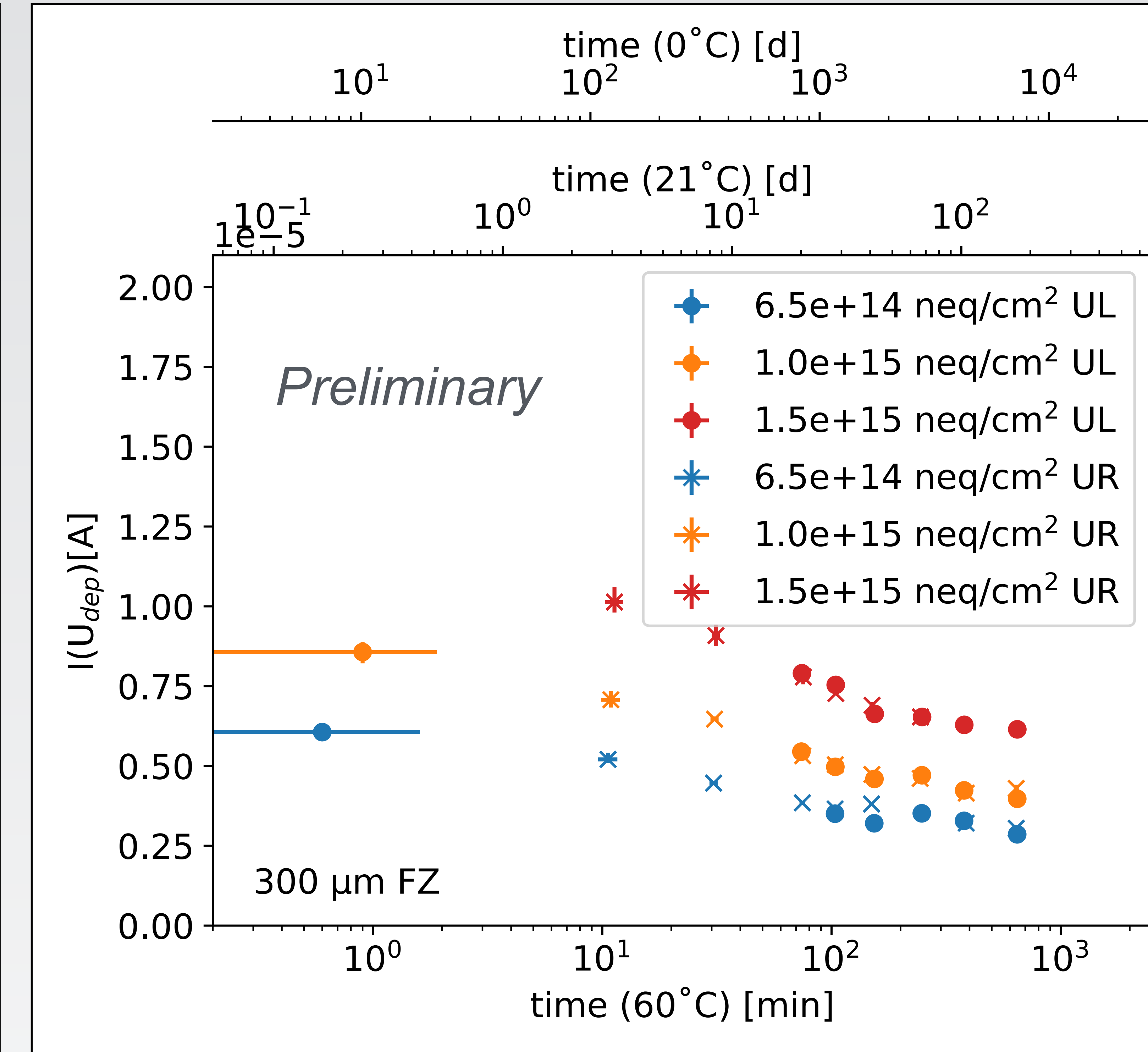
- Leakage current of the order of 10µA at -20˚C
- Samples with same fluence and thickness mostly compatible (taking into account 10% fluence uncertainty)
- Exponentially falling current (slight deviation for 300µm sensors)



Extraction of α

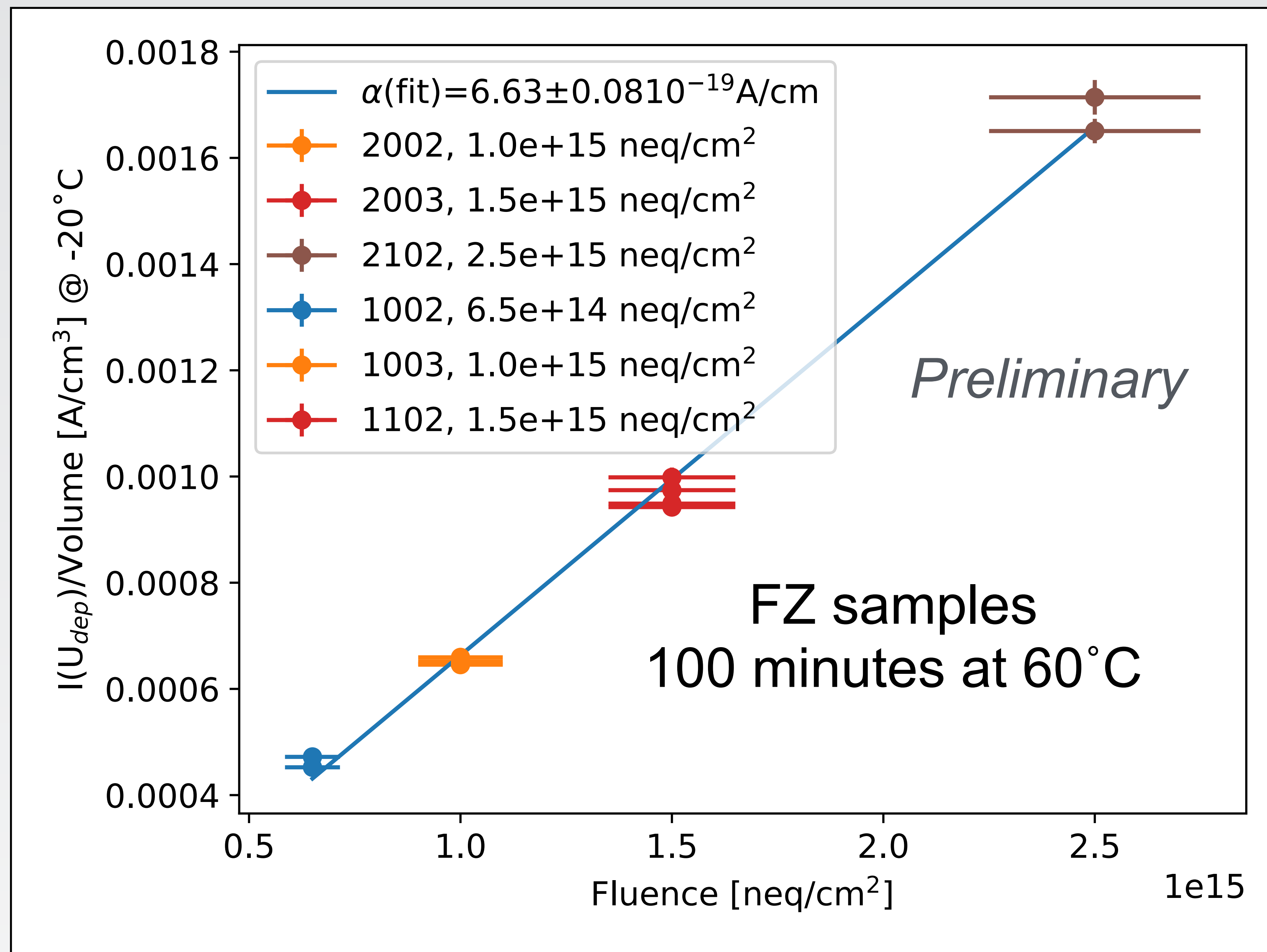




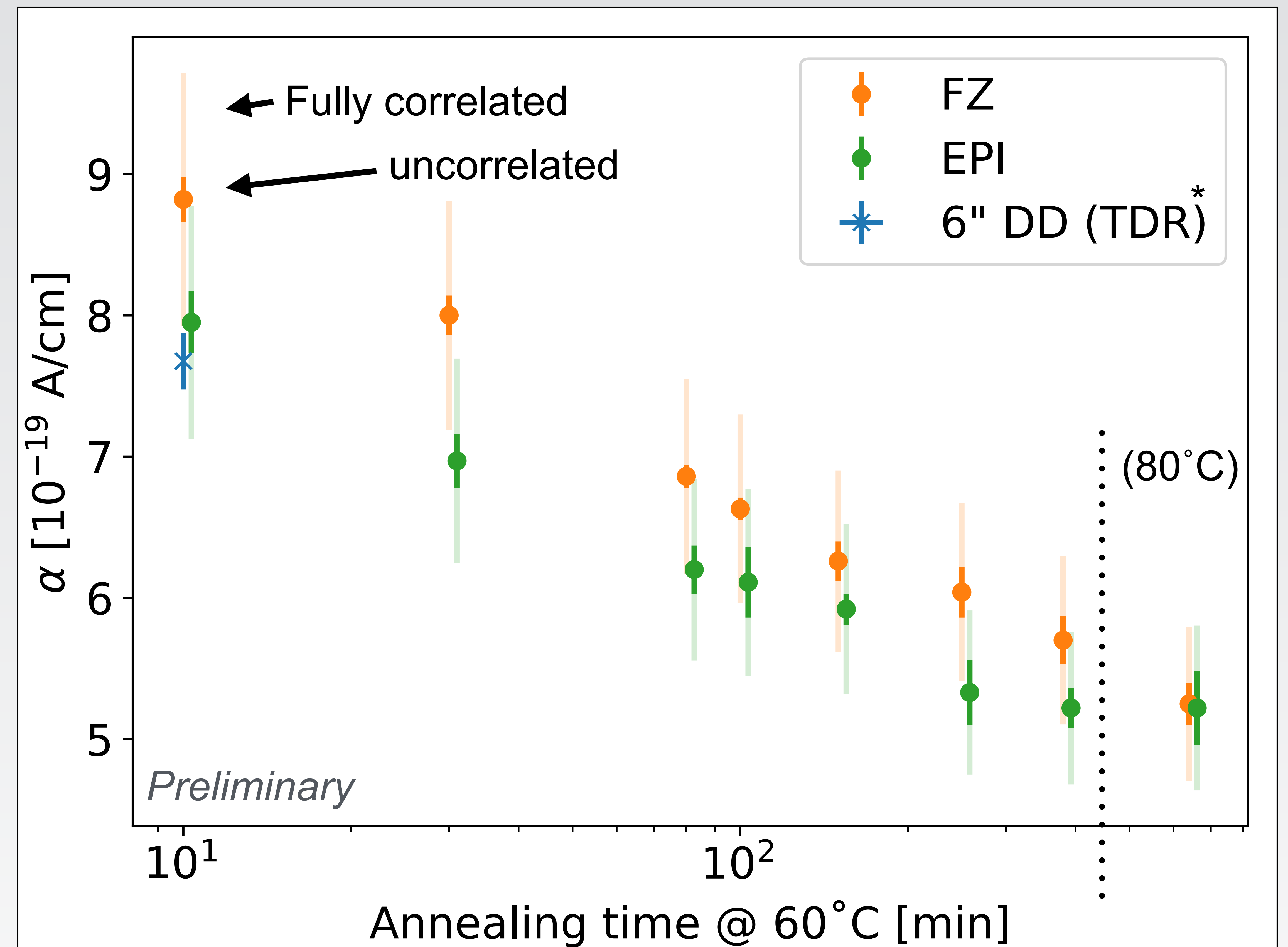


- $I(U_{dep})$ / thickness is a proxy for the slope of α
  - Should be universal, and not depend on thickness/diode type
  - Interpolation and smoothing of measured leakage current
- Mostly consistent picture, reverse annealing impact for large annealing time

α Fit



x16 →

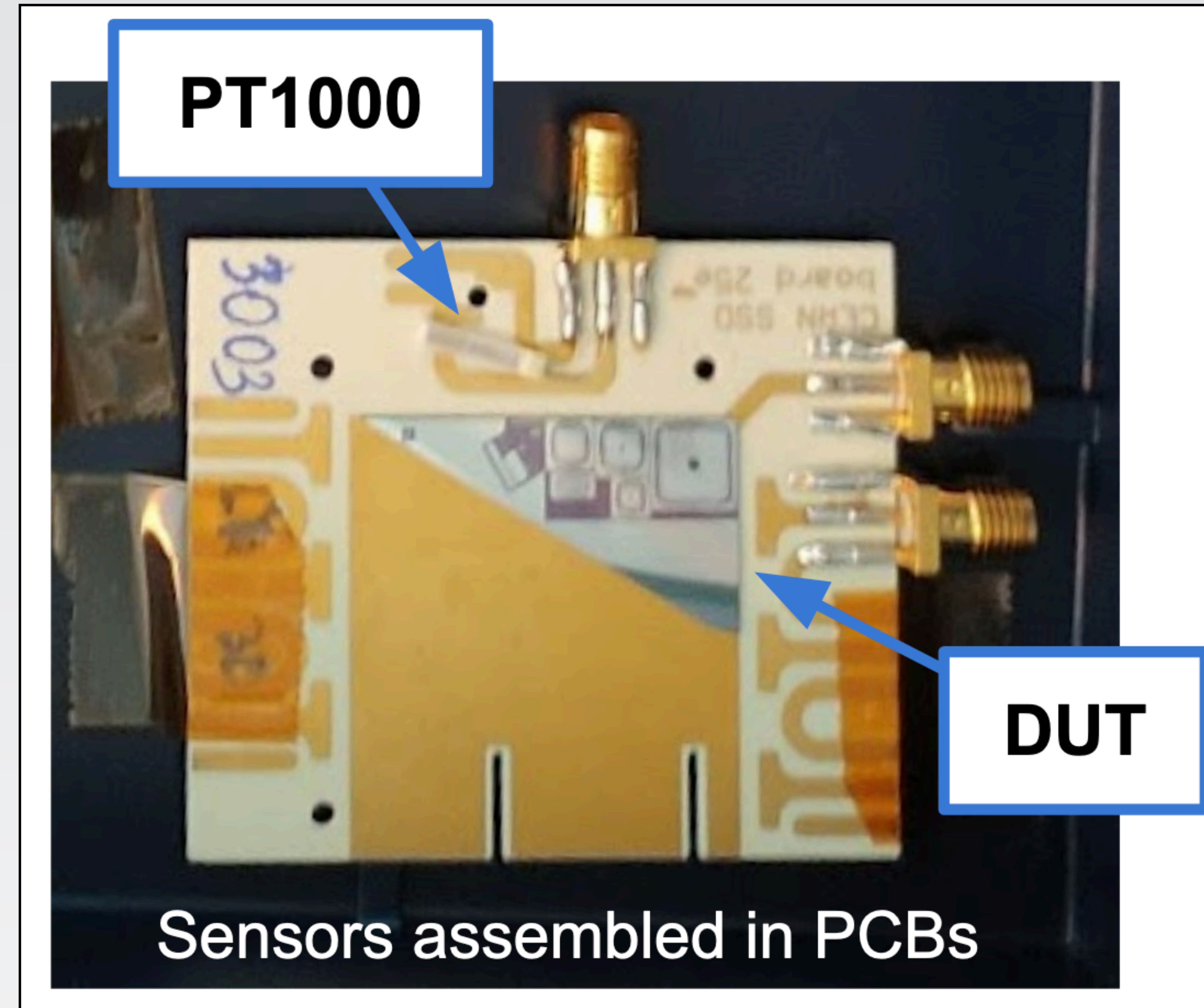


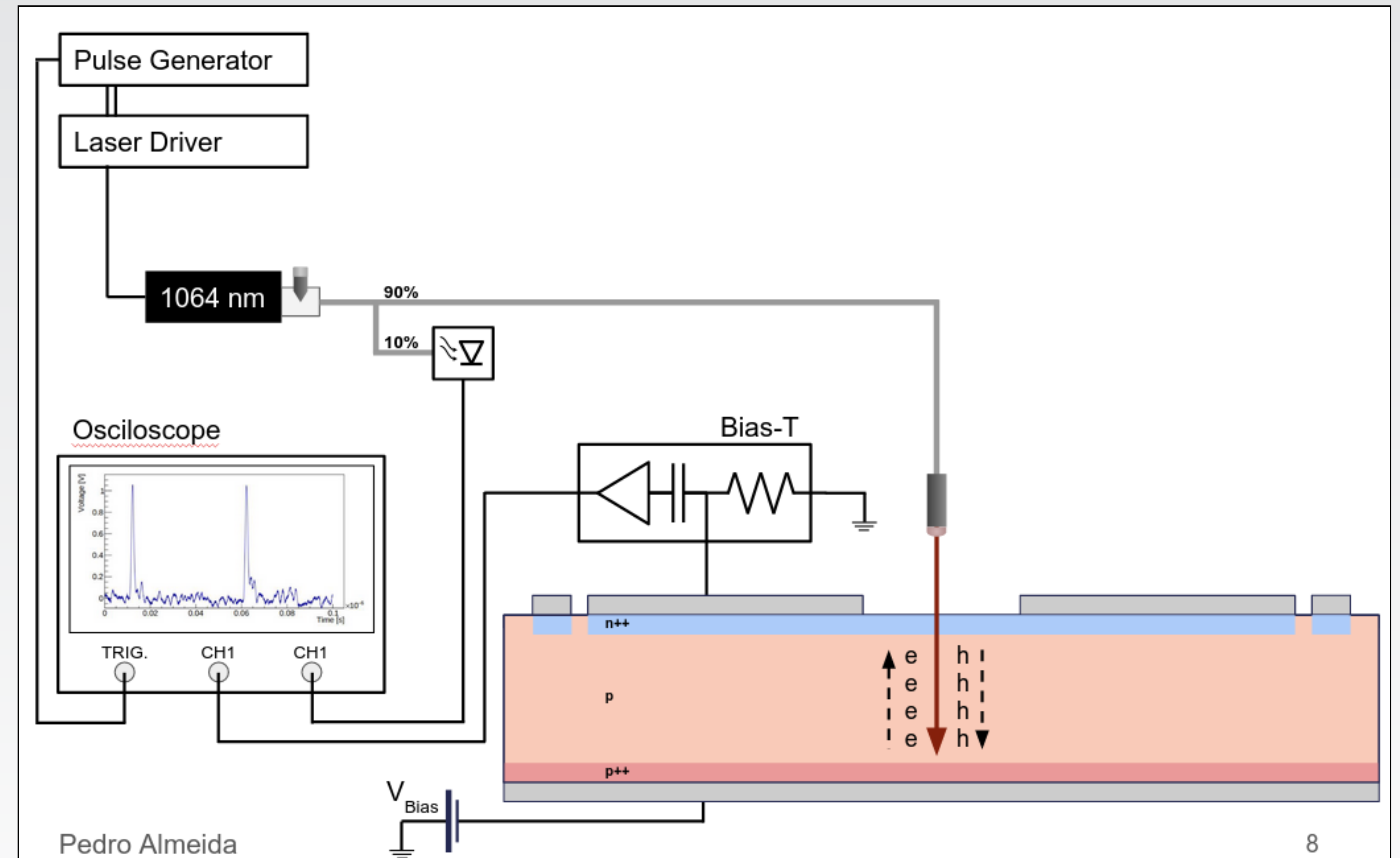
- Uncertainties from depletion voltage, time, and leakage current fully propagated
- Large uncertainty spread depending on the correlation of fluence uncertainties
- Expected exponential decay up to 600 minutes equivalent annealing time at 60˚C

- Compatible with previous studies from the HGCAL technical design report:
- Difference of 20% (understood) +20% (to be understood) w.r.t. full wafer measurements

*CERN-LHCC-2017-023

Charge Collection Efficiency

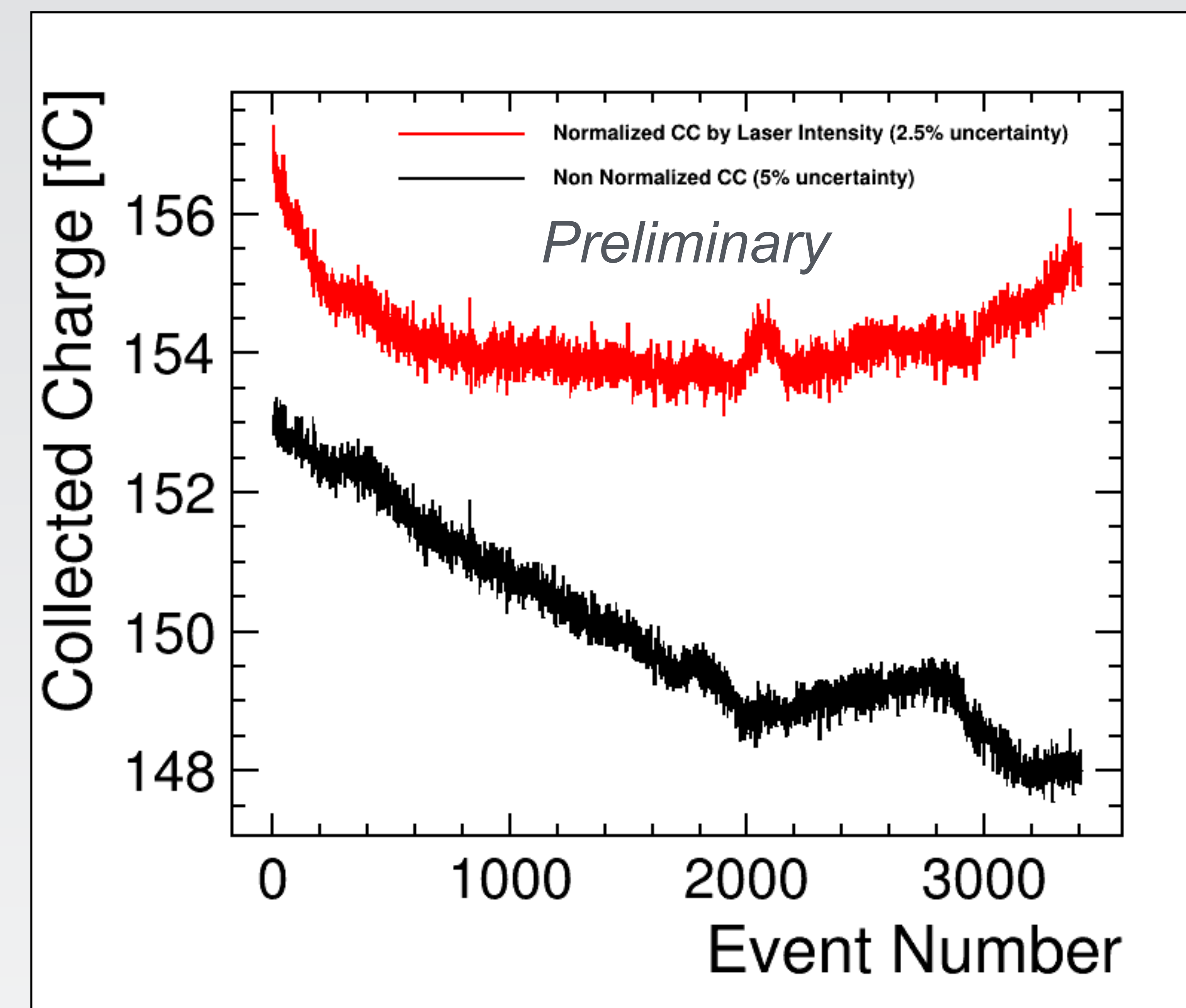


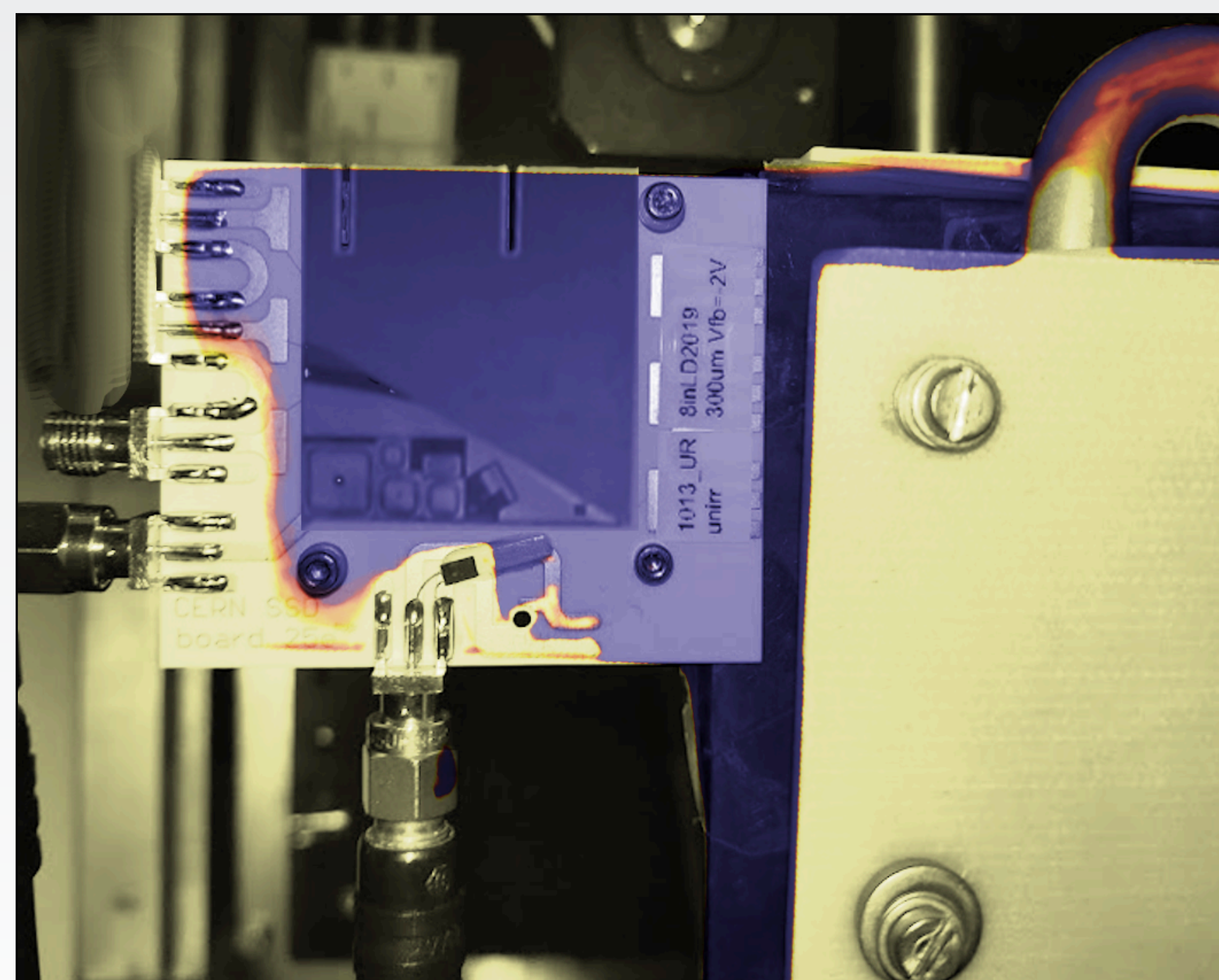


- 12 samples
  - Same fluences as CV/IV measurements
- 6 Annealing points
- Sensors assembled on PCB + wire bonded
- Laser intensity about 33 MIPs (300μm sensor)

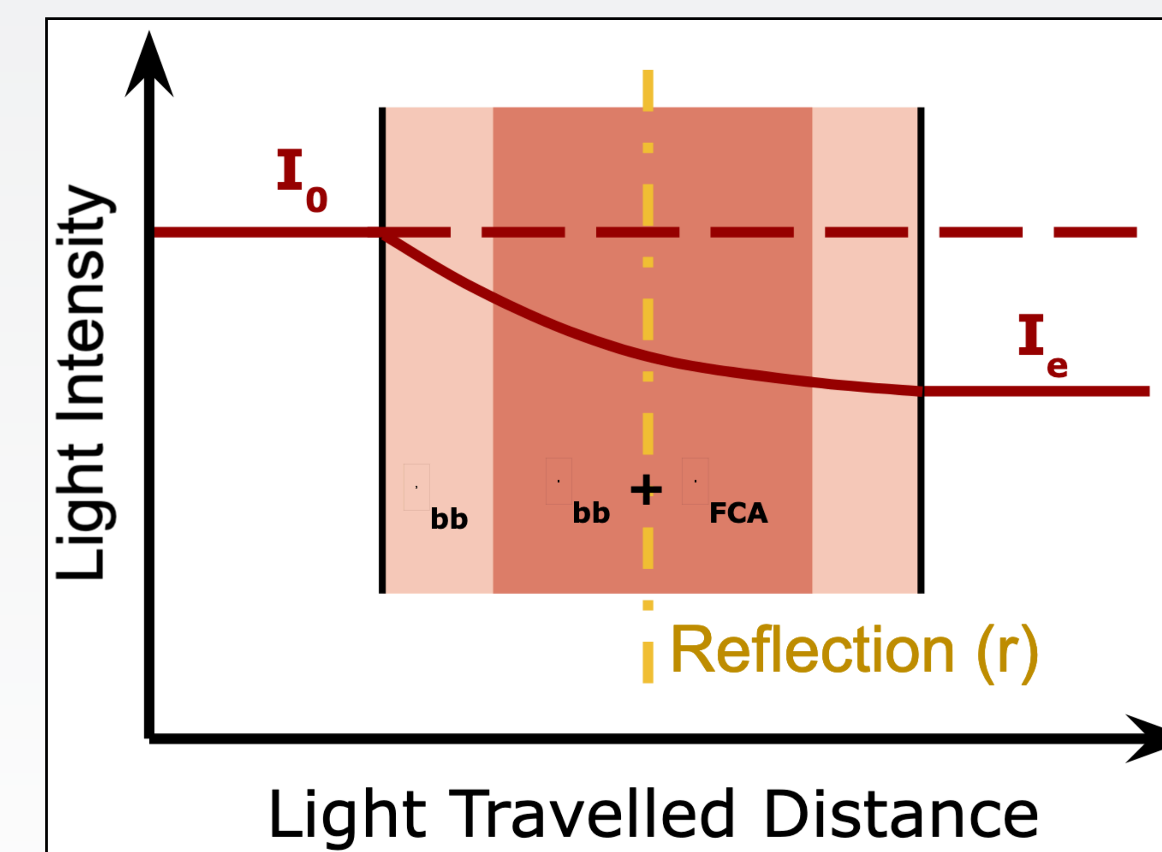
Uncertainties and corrections

- Drifts in the (not temperature controlled) reference diode
  - Calibrated over long measurement period with reference sensor
  - Assign 2.5% uncertainty
- Temperature across the PCB, in particular close to PT1000
  - Uncertainty +1 -5˚C
- Absorption depends on temperature [1]
  - Uncertainty of -1.8% + 7.1% in the charge collection



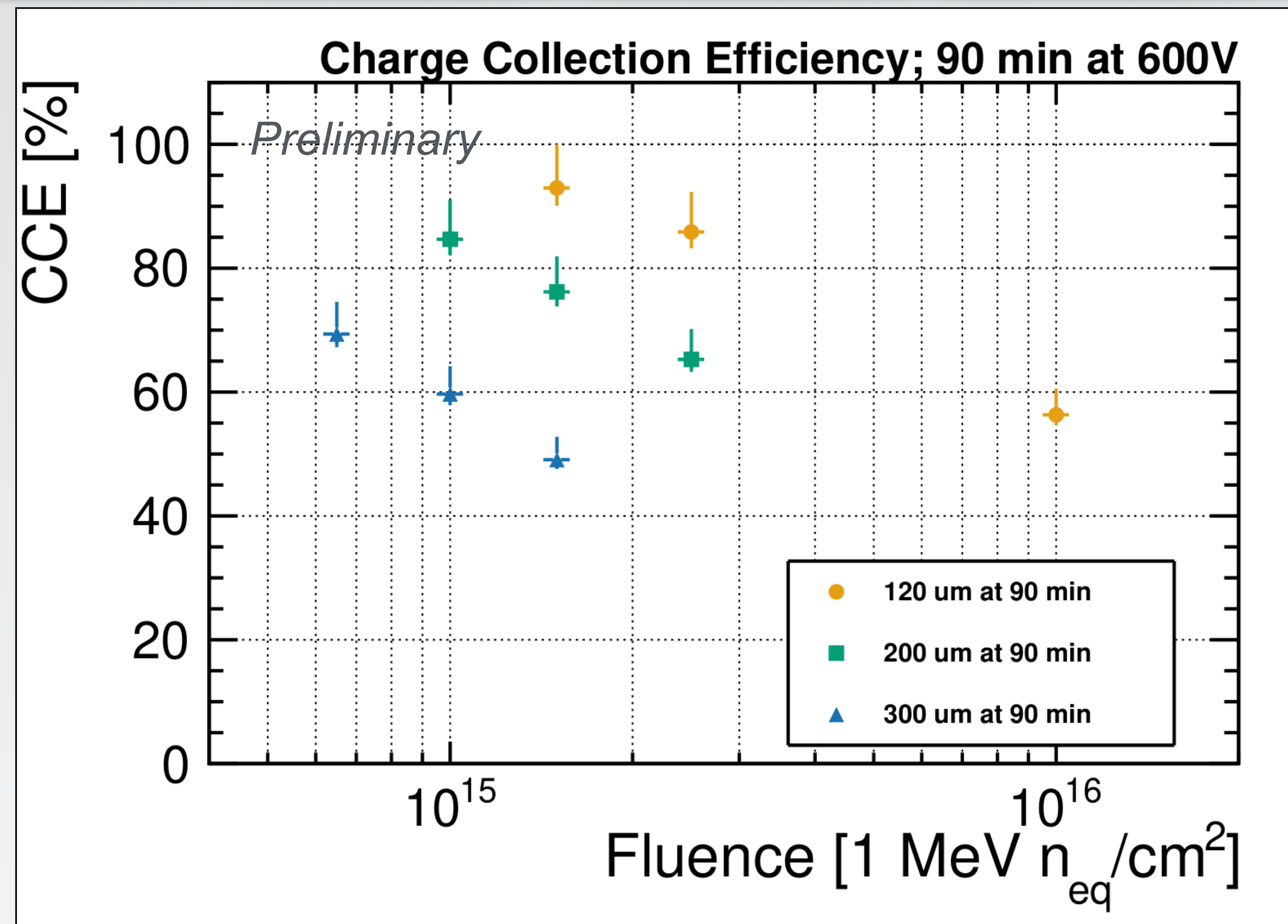


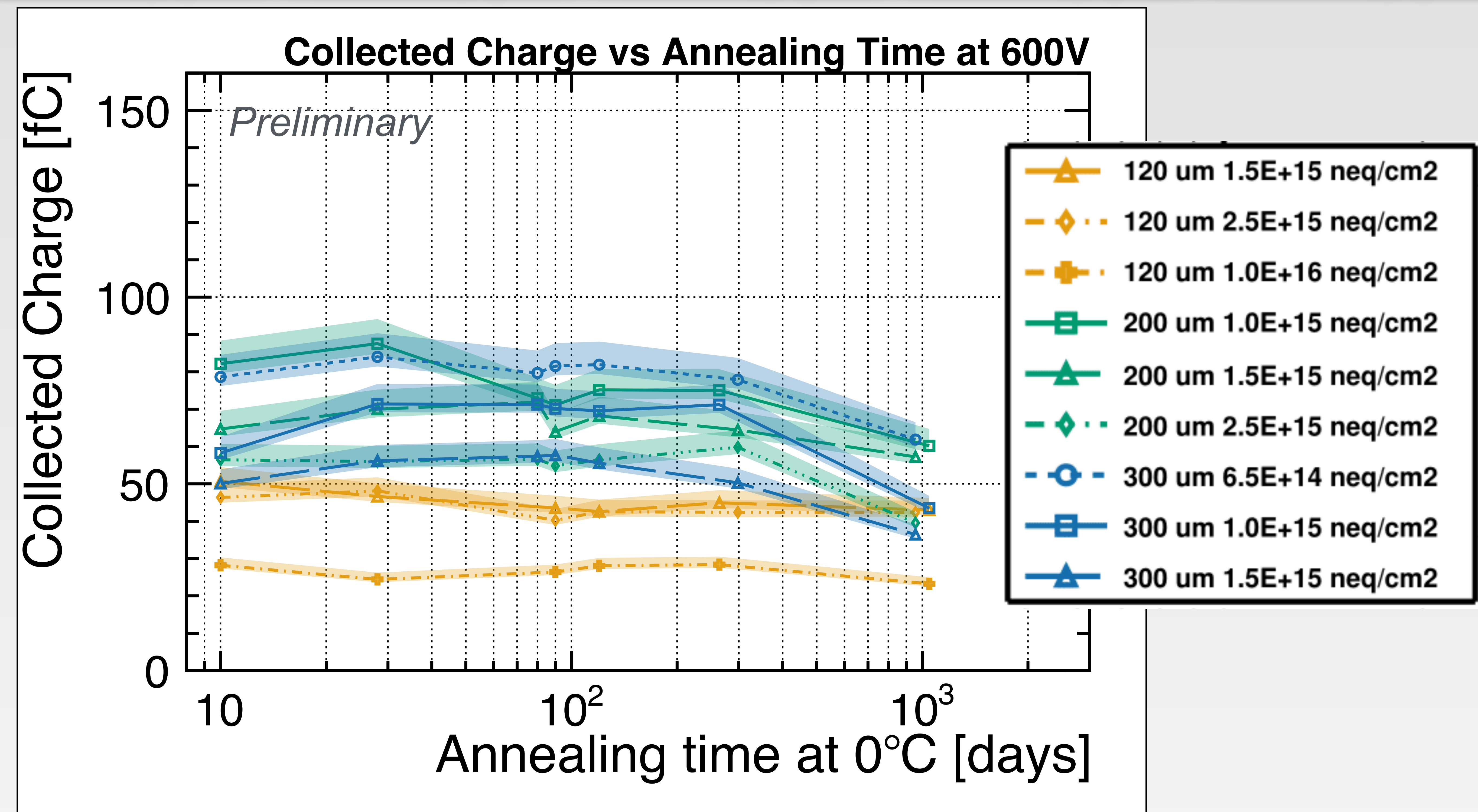
- Laser attenuation and reflection on backside
- Corrected for in results
- Associated uncertainties negligible



[1] Schinke et al.

Results





- Charge collection efficiency decreases with fluence
- Charge collection efficiency ~50% or higher at 600V for all fluences (approx +10% at 800V)
- No significant dependence on annealing time

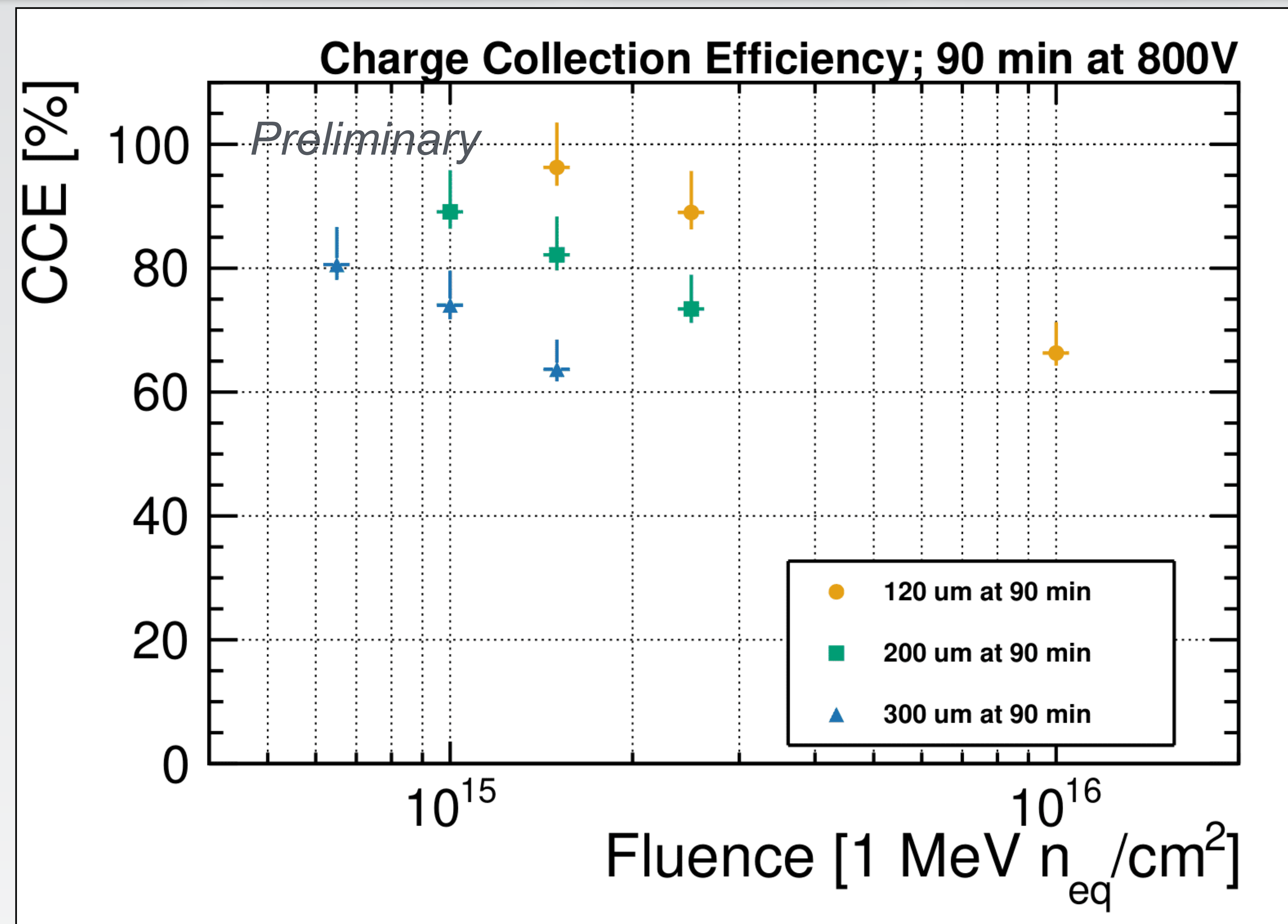
Summary

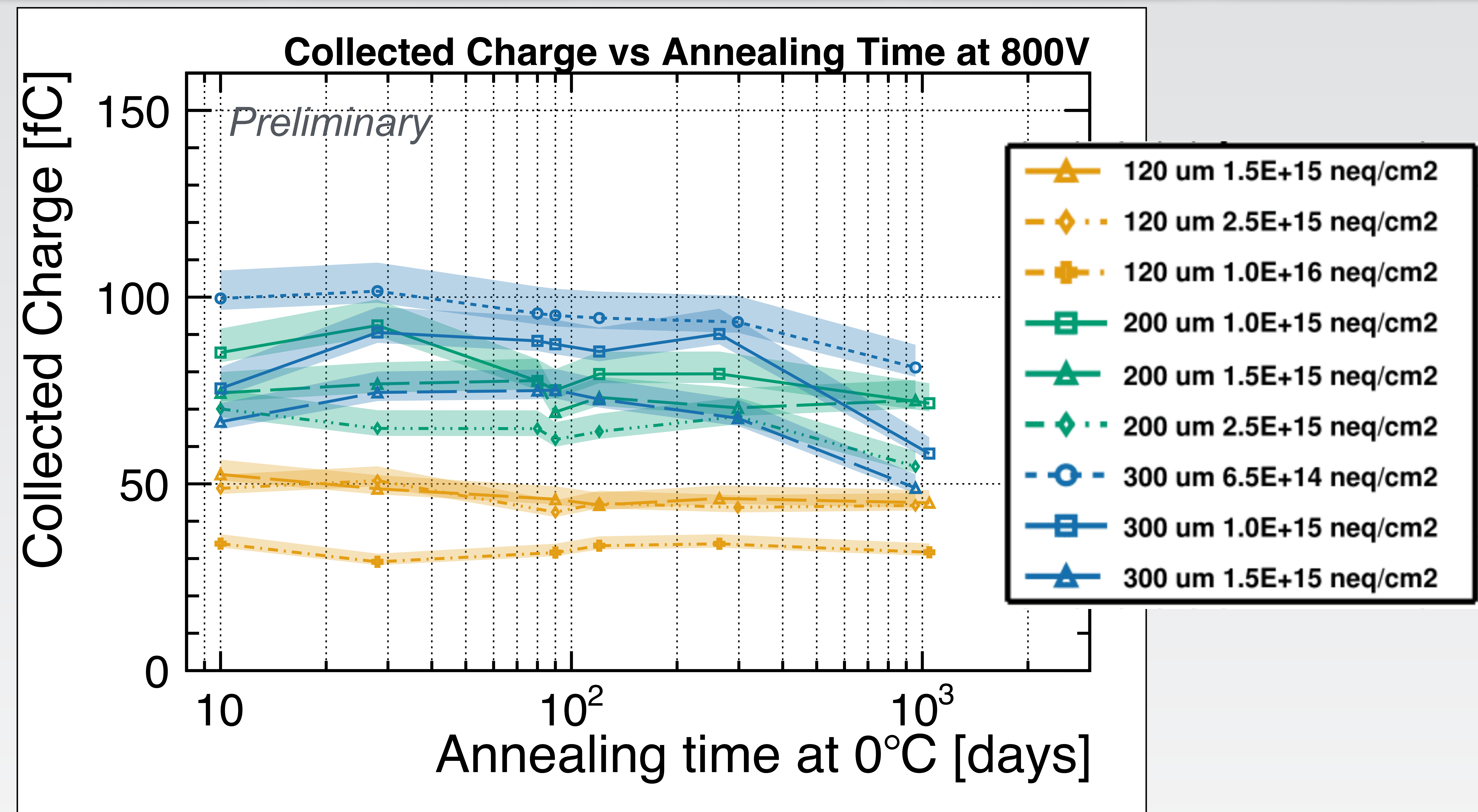
- An extensive annealing study on diodes from 8” wavers has been carried out
  - About 150 measurements of capacitance and leakage current
  - About 70 measurements to determine charge collection efficiencies
- Depletion voltage minimum seems to be around 120 minutes of annealing at 60˚C for FZ
  - Slightly lower for highly irradiated EPI material
- Seemingly slow reverse annealing
- Charge collection efficiencies (way) above 50% for all fluences
  - Working on cross-checks with Sr90 source
- No significant dependence or degradation with annealing time
- Results being used in simulation studies to for establishing an operation/annealing scenario for HGCal

Thanks to the CERN SSD group for their support

Backup

CCE Results at 800V





- Charge collection efficiency decreases with fluence
- Charge collection efficiency 60% or higher at 600V for all fluences (approx +10% at 800V)
- No significant dependence on annealing time