Radiation tolerance and annealing studies using test-structure diodes from 8-inch silicon sensors for CMS HGCAL

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on behalf of the CMS Collaboration

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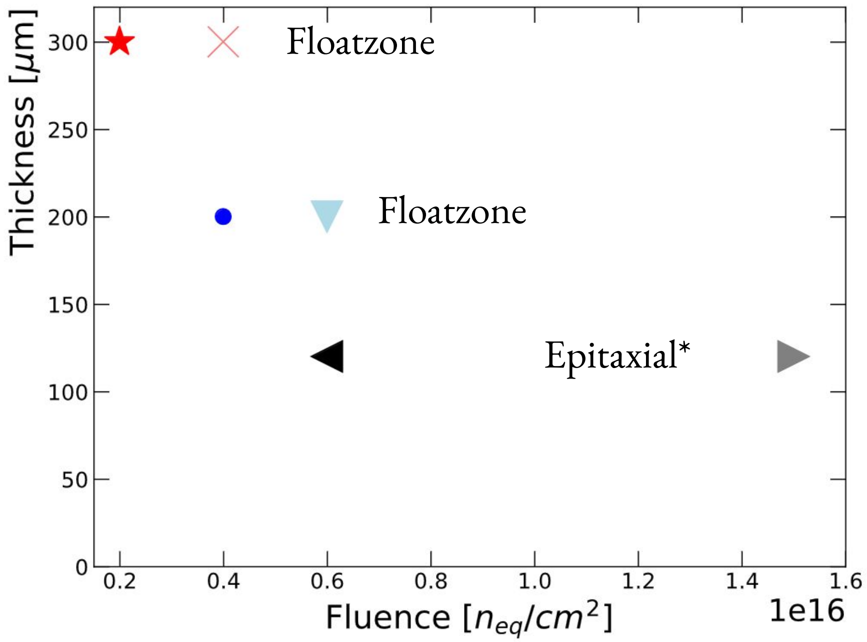
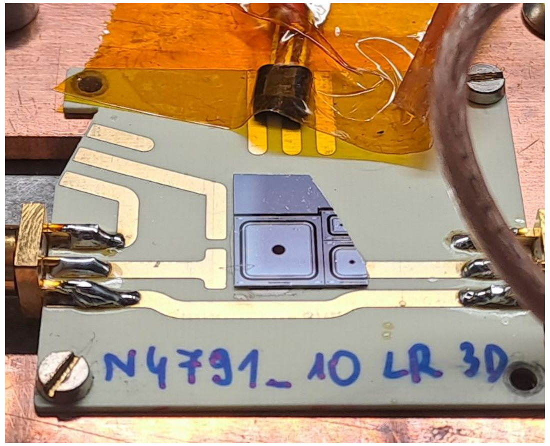
CERN

Campaign overview

- Planar, high resistivity (>3 kΩcm) pad diodes with 0.5x0.5 cm^2 active area, cut from 8-inch wafers
- Neutron irradiation at JSI (Jozef Stefan Institute), Ljubljana, Slovenia
- Annealing at 5 temperatures: 60°C, 40°C, 30°C, 20.5°C and 6.5°C
- 60°C, 20.5°C and 6.5°C started Sep 23, 40°C started June 24 and 30°C started Oct 24
- Annealing ongoing: For 30°C and 6.5°C annealing not progressed enough yet for Hamburg model fit



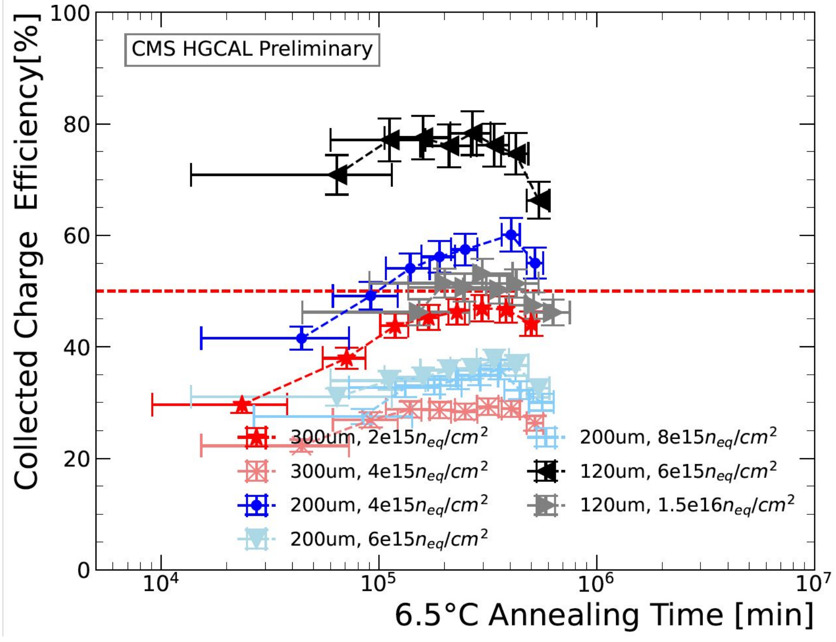


- Leakage current and capacitance vs voltage (IV/CV) and charge collection (CC vs voltage, TCT using IR laser) measurements
- **Goal:** Revisit the Hamburg model for p-type material and extrapolate to lower temperatures, as input for HGCAL operation scenario (0°C)
- High fluences: Concept of depletion voltage not applicable: Extracting a "saturation voltage" from CV measurements instead

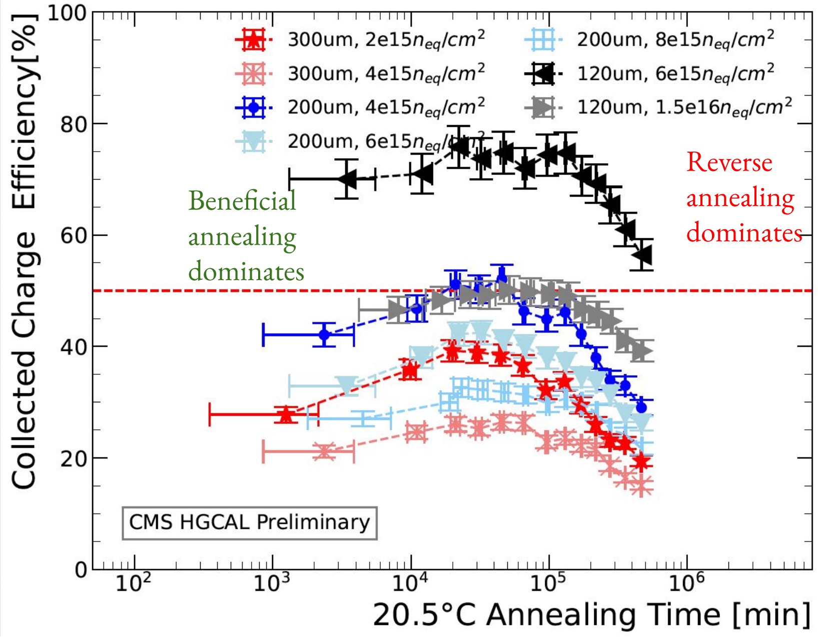
** 180um handling wafer, physical thickness 300um*

Charge collection efficiency at 600V

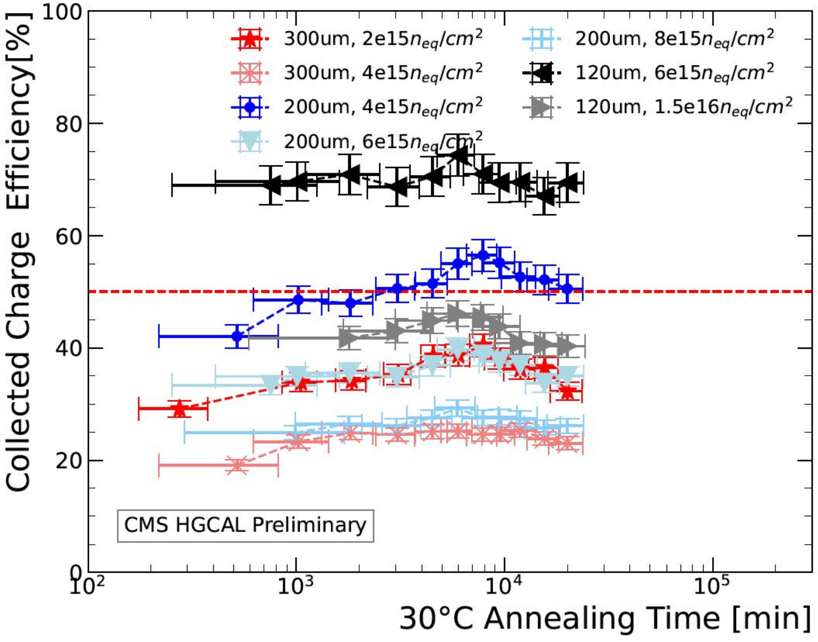
6.5°C annealing



20.5°C annealing



30°C annealing



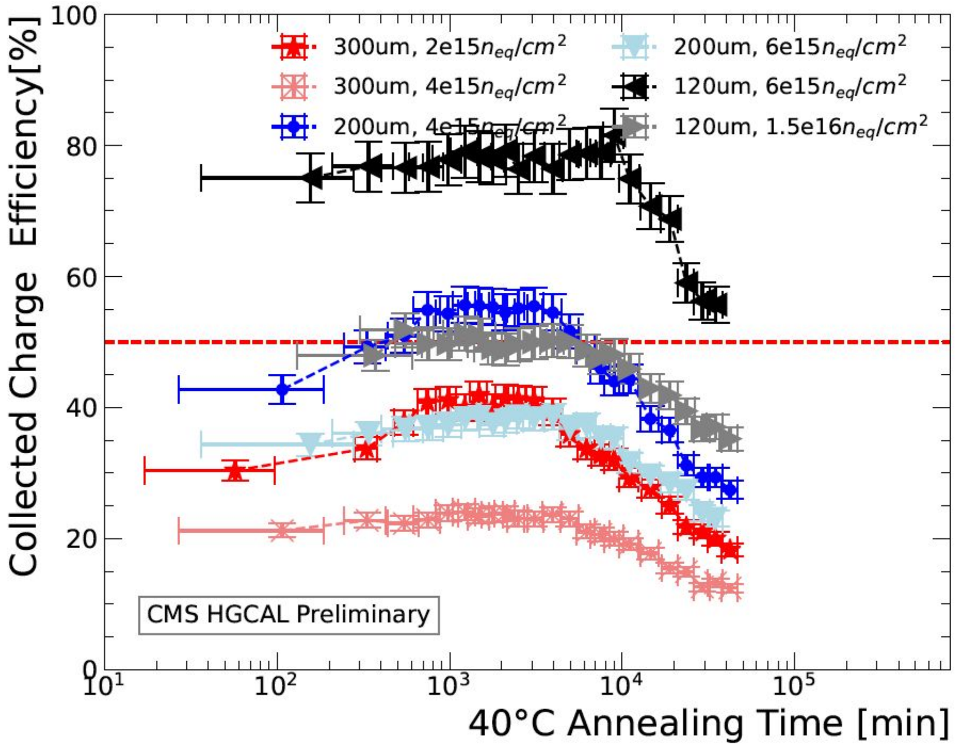
- Maximum around 140 days (epi) and 250 days (FZ)
- Slow annealing: Just entered region dominated by reverse annealing

- Maximum around 250 hours (epi) and 580 hours (FZ)
- Reverse annealing already further progressed

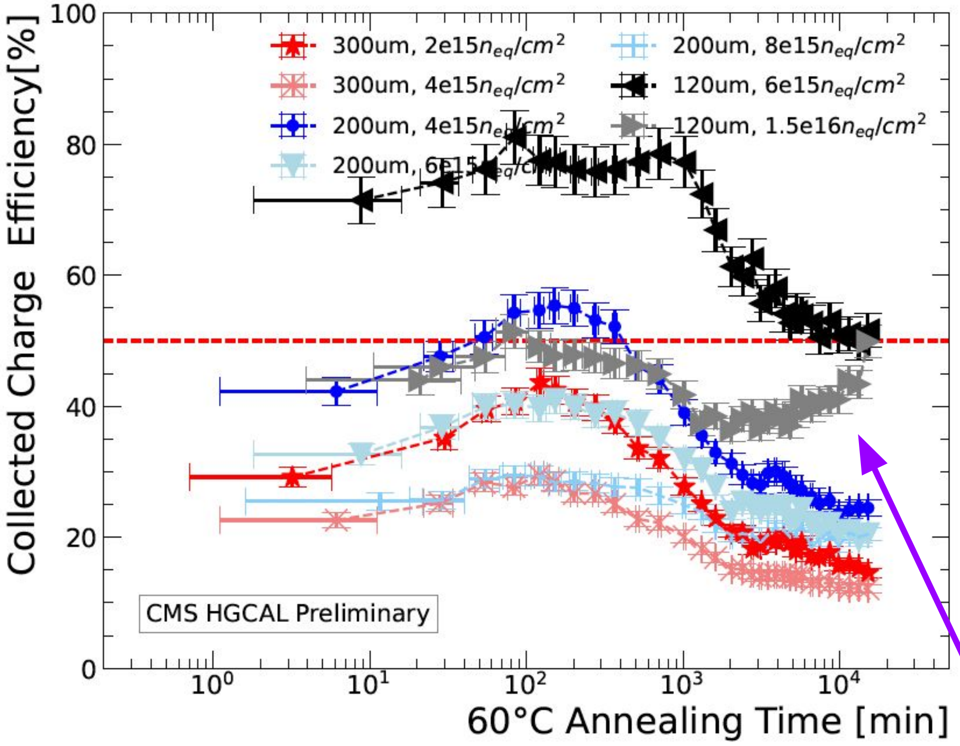
- Started annealing only 60 days ago: Not far into reverse annealing yet
- Maximum around 8000 min for FZ, hard to identify for EPI

Charge collection efficiency at 600V

40°C annealing



60°C annealing



- Maximum around 1000 min (epi) and 1700 min (FZ)
- Clear second maximum in 120um 6e15 n_{eq}/cm^2 data, also visible for other temperatures

- Maximum around 90 min (epi) and 120 min (FZ)
- Charge multiplication for the thin sensors at high annealing times, especially at 1.5e16 n_{eq}/cm^2

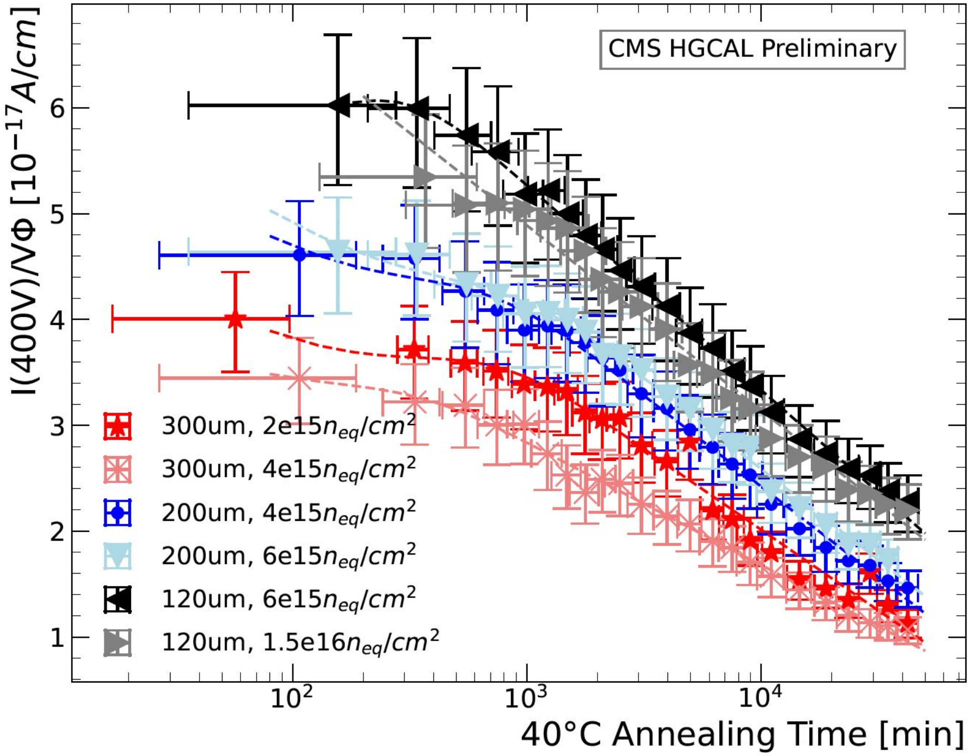
Current related damage rate at 400V

Hamburg model:

$$\alpha(t) = \alpha_I^* \exp(-t/\tau_I) + \alpha_0 - \beta^* \ln(t/t_0)$$

- Calculating the damage parameter α from the measured leakage current for each sensor individually
- Extremely sensitive fits:
  - Changes for 20.5°C and 30°C expected with further measurements
  - Data points influenced by the onset of charge multiplication had to be excluded
- Already visible here: Higher fluence does not mean necessarily higher damage parameter
  - Influence of the fixed voltage instead of depletion voltage - also influencing the dependence on thickness
  - Split for further analysis by fluence and material (next slide)

Damage parameter α: $\frac{I}{V} = \alpha \cdot \phi$



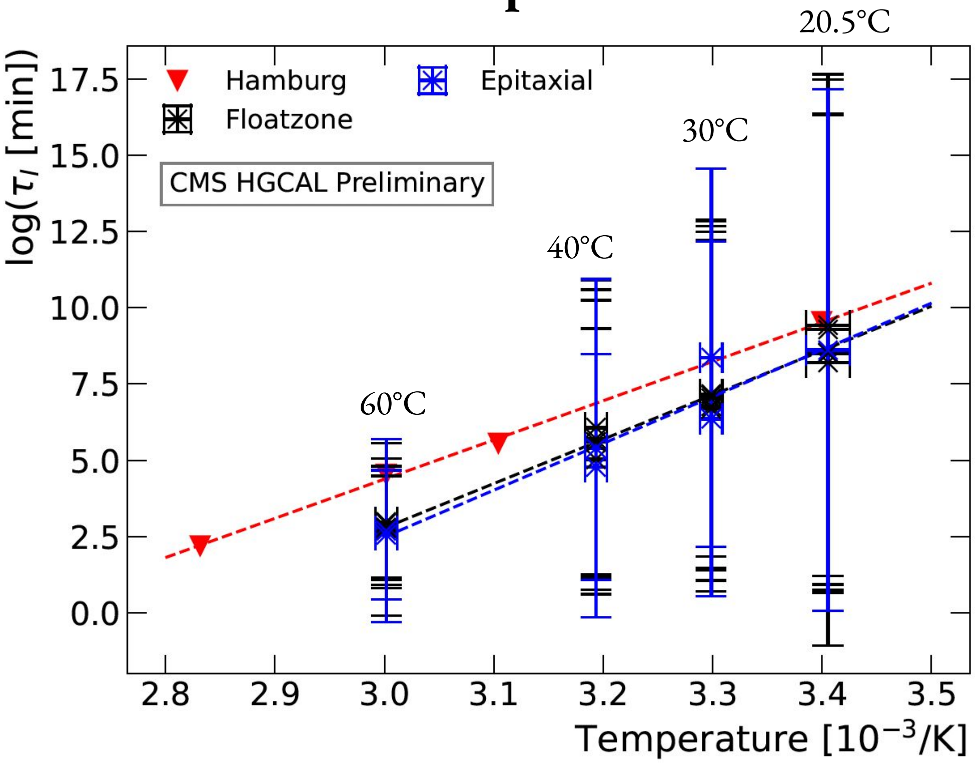
** Uncertainties not included into some fits (not converging, work in progress)*

Not split for the averaged values:

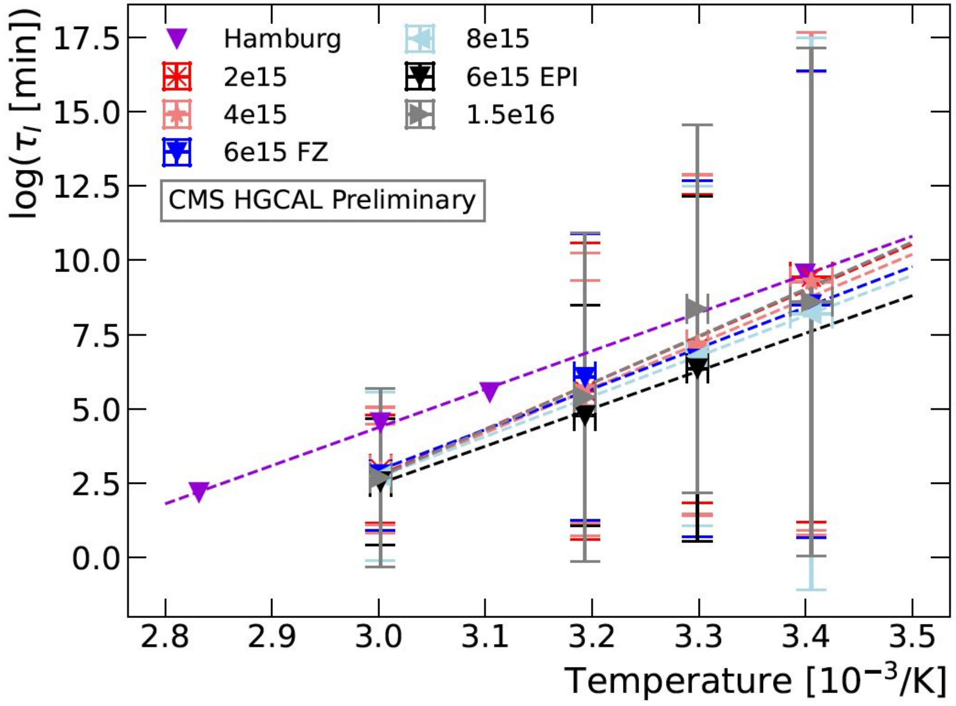
	Hamburg	This campaign (all sensors)
β $[10^{-18}$A/cm]:	3.07±0.18	6.26±0.06
α_I $[10^{-17}$A/cm]:	1.23±0.06	1.55±0.42

Current related damage rate at 400V

Material dependence

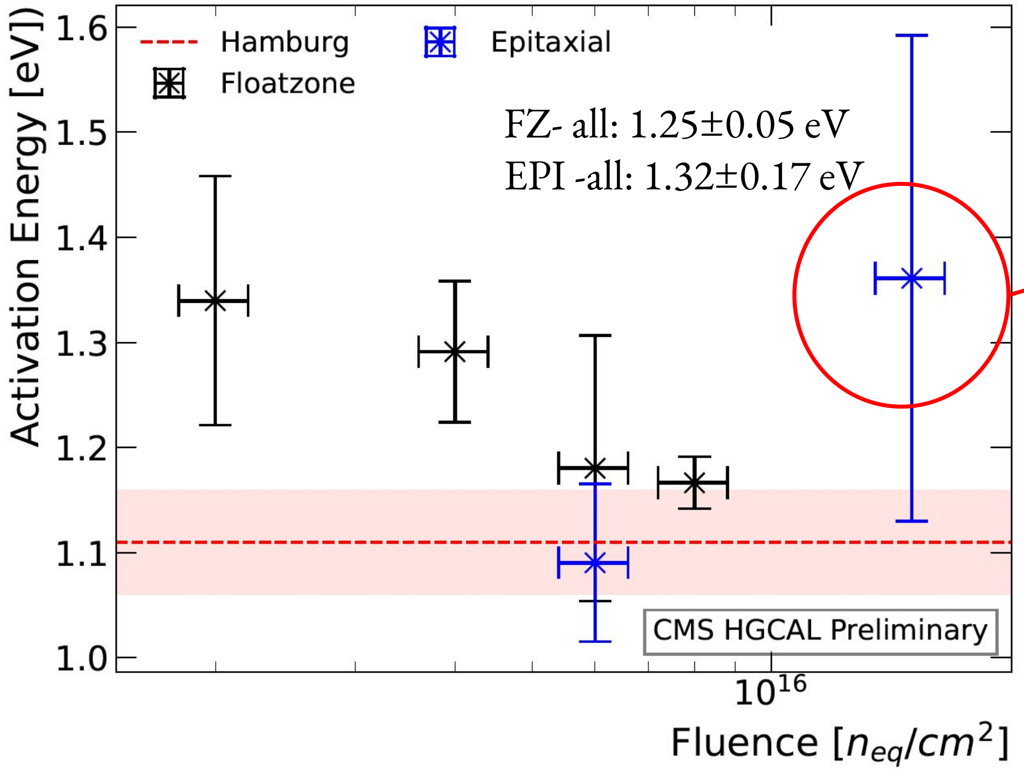


Fluence dependence

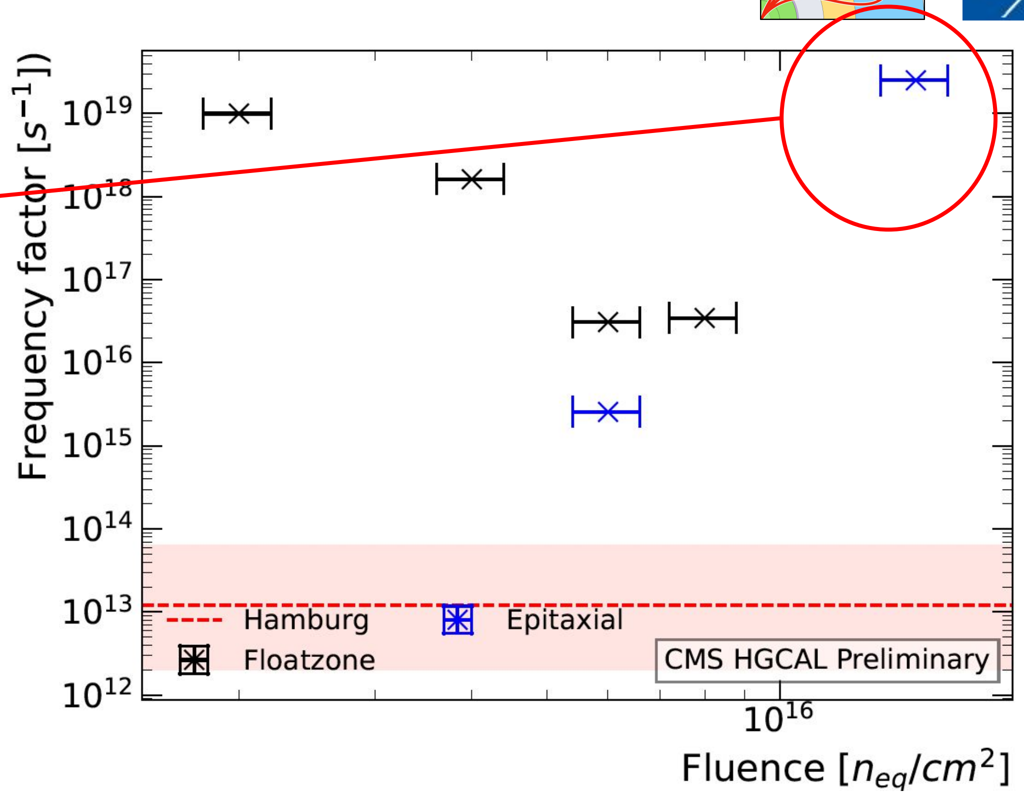


- Large deviation still from Hamburg model - but also large uncertainties on many extracted values
- Differences in slope and absolute values for different fluences and materials - outliers influence fits
- Thickness dependence hard to evaluate: Just two samples for floatzone, one for epitaxial - deviation between epitaxial and floatzone material prevents direct comparison of all three thicknesses

Current related damage rate at 400V



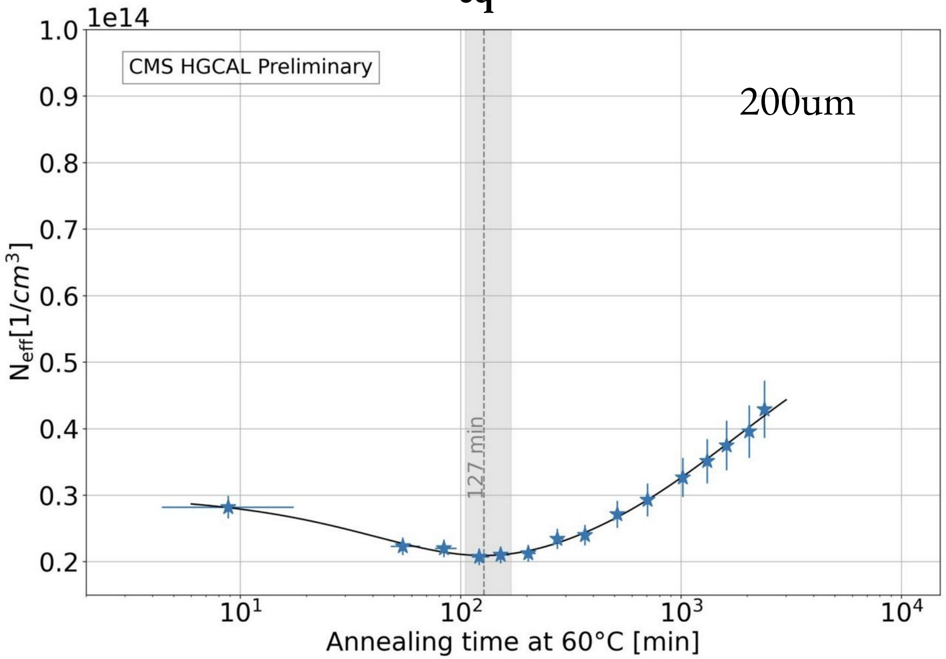
Worst fits. Highest fluence, other effects starting to dominate? Handling wafer having an influence?



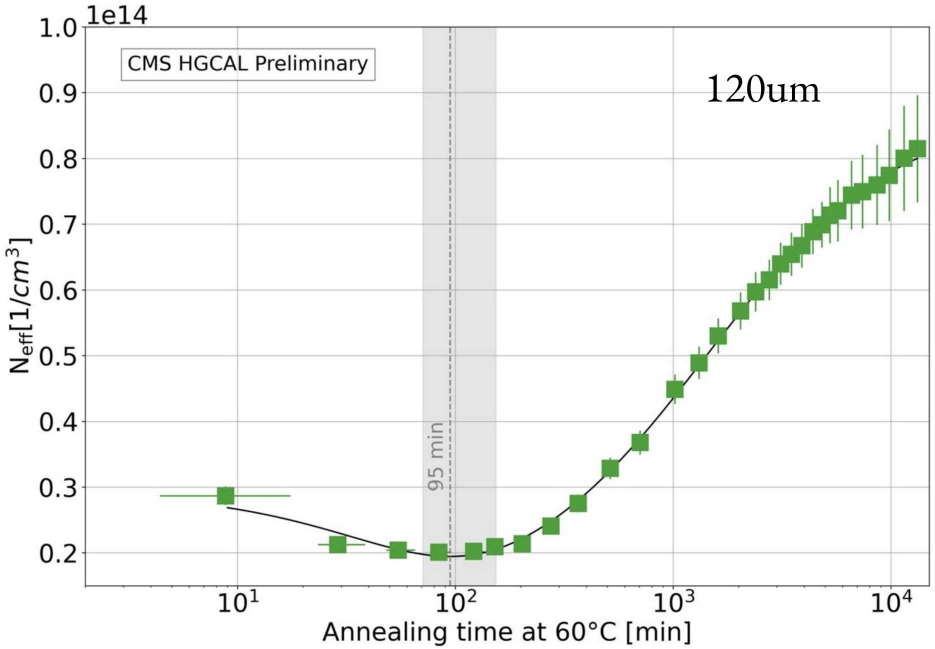
- Small decrease with fluence of activation energy and frequency factor for floatzone sensors
- Increase with fluence of both parameters for epitaxial sensors - but fits for highest fluence have large uncertainty
- Values at 6e15 n_{eq}/cm^2 similar for the different materials, slightly lower for epitaxial sensor
- In average, higher activation energy and significantly higher frequency factor than the Hamburg model values
- This would mean faster annealing for higher fluences for floatzone, opposite for epitaxial, but in general slower than assumed from Hamburg model

Effective Doping concentration

Floatzone, 6e15n_{eq}/cm^2, 60°C annealing



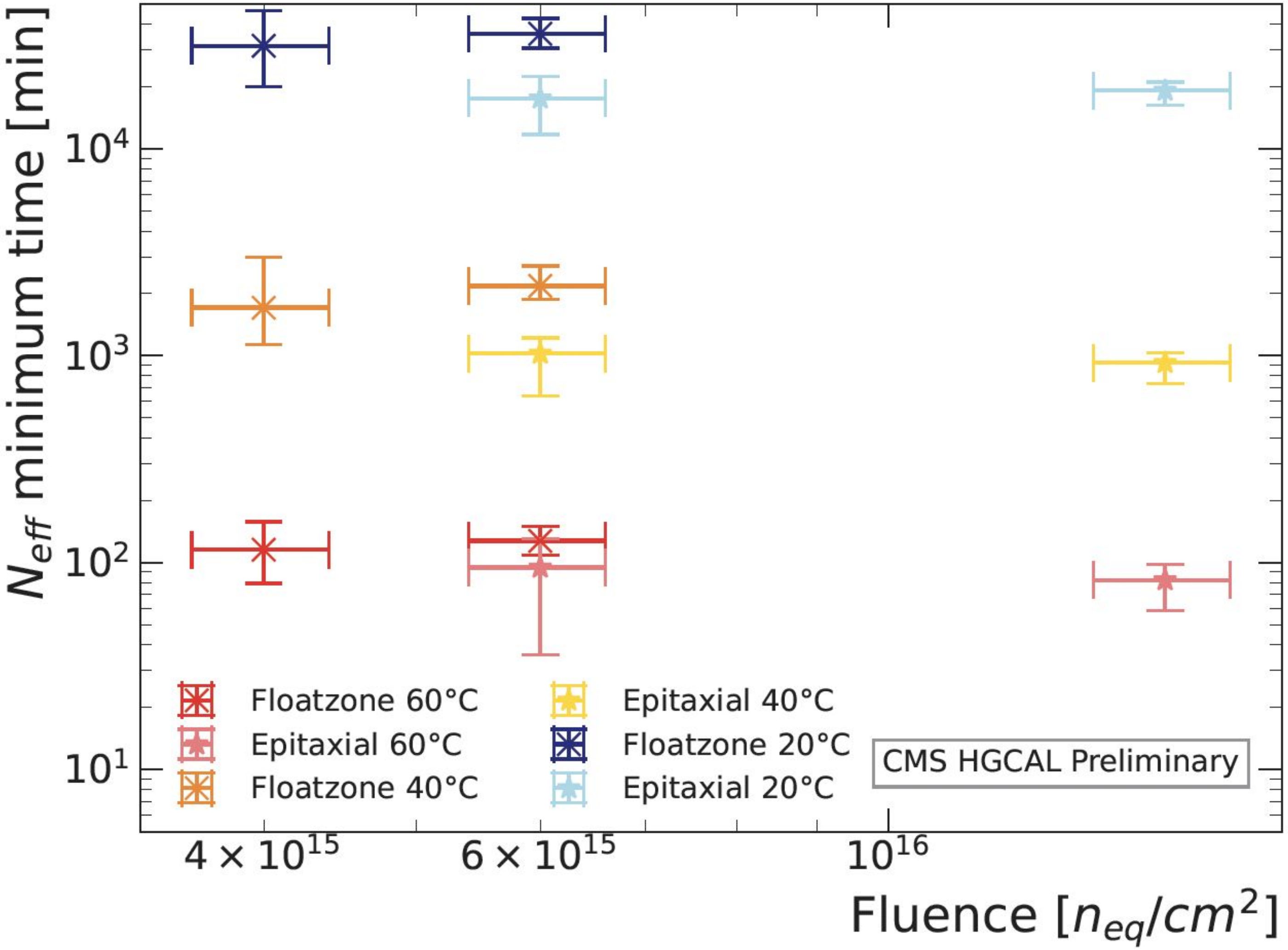
Epitaxial, 6e15n_{eq}/cm^2, 60°C annealing



- Saturation voltage in FZ sensors exceed measurement limit after some annealing time: Less points to fit for FZ
- Clear difference in minimum location and increase rate after minimum between FZ and epitaxial sensors visible
- Parameters of interest:
  - Timing of minimum, beneficial and reverse annealing time constants
  - Acceleration/ scaling factors for all three parameters for temperature scaling

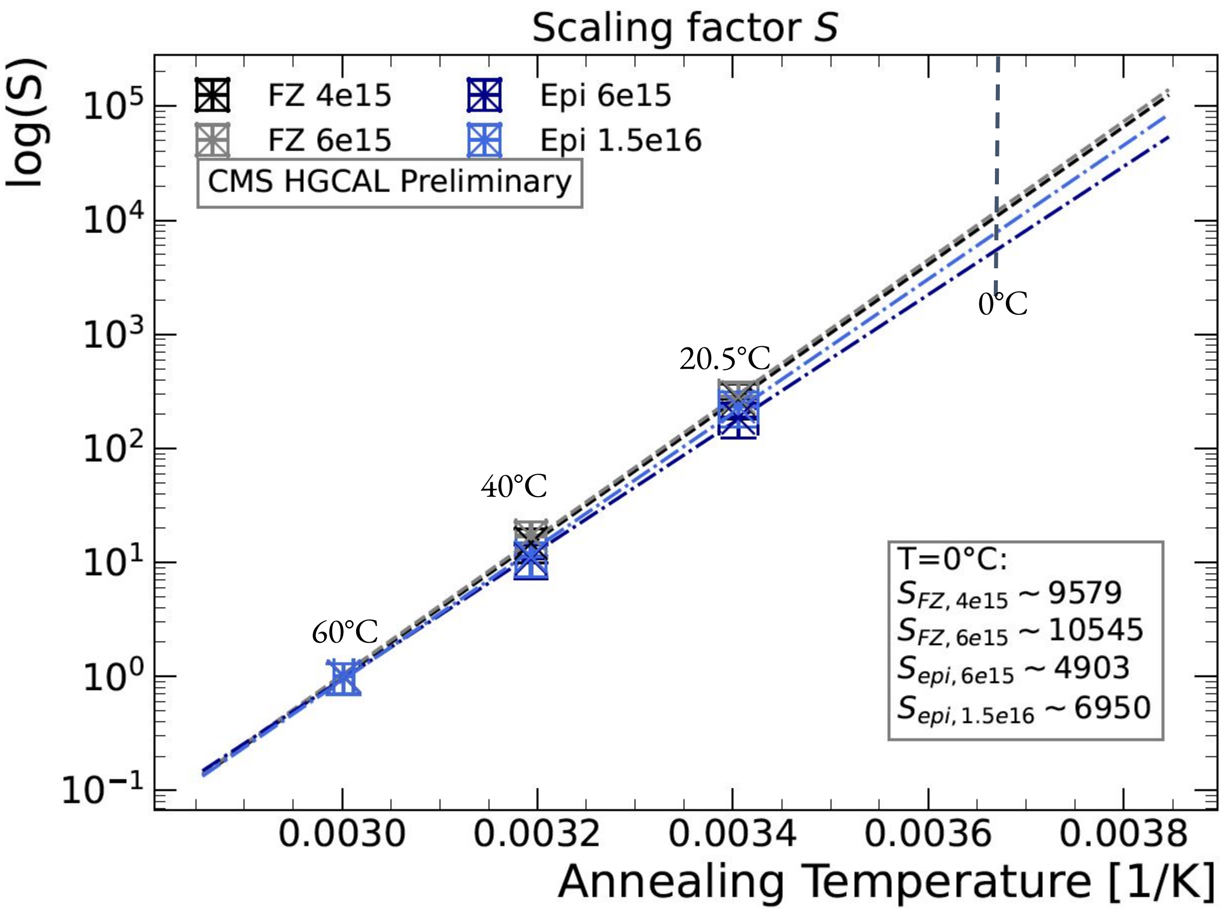
**Extracted parameters and fits for other sensors and temperatures in the backup (slides 23-26)*

N_{eff} minimum time vs fluence



- Trend: Increase in time with increase in fluence for floatzone
- Not as clear for epitaxial: very similar values, sometimes longer, sometimes shorter for higher fluence
- Unclear how much this is affected by the initial calculation of the in-reactor annealing times

Scaling: Time of the N_{eff} minimum



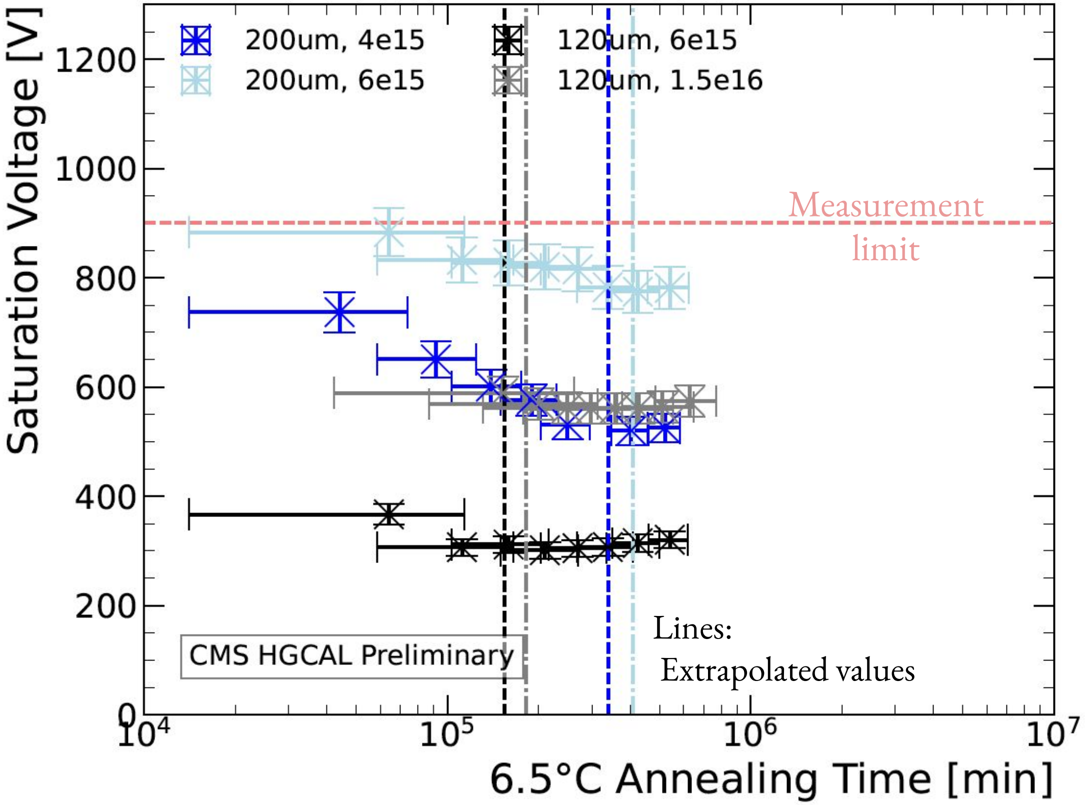
Example fit parameters - 4e15 n_{eq}/cm^2 FZ:
$\log(S) = 13888 \pm 85 * 1/T_a - 41.6$

- Scaling of time of N_{eff} minimum with respect to 60°C
- Significant difference between samples:
  - Same fluence: FZ factor two higher than EPI at 0°C
    - *material or thickness dependence?*
  - Same material and thickness:
    10–15% difference for different fluences
- 6.5°C will be used to crosscheck, 30°C data will be added to improve fits as soon as enough data is available

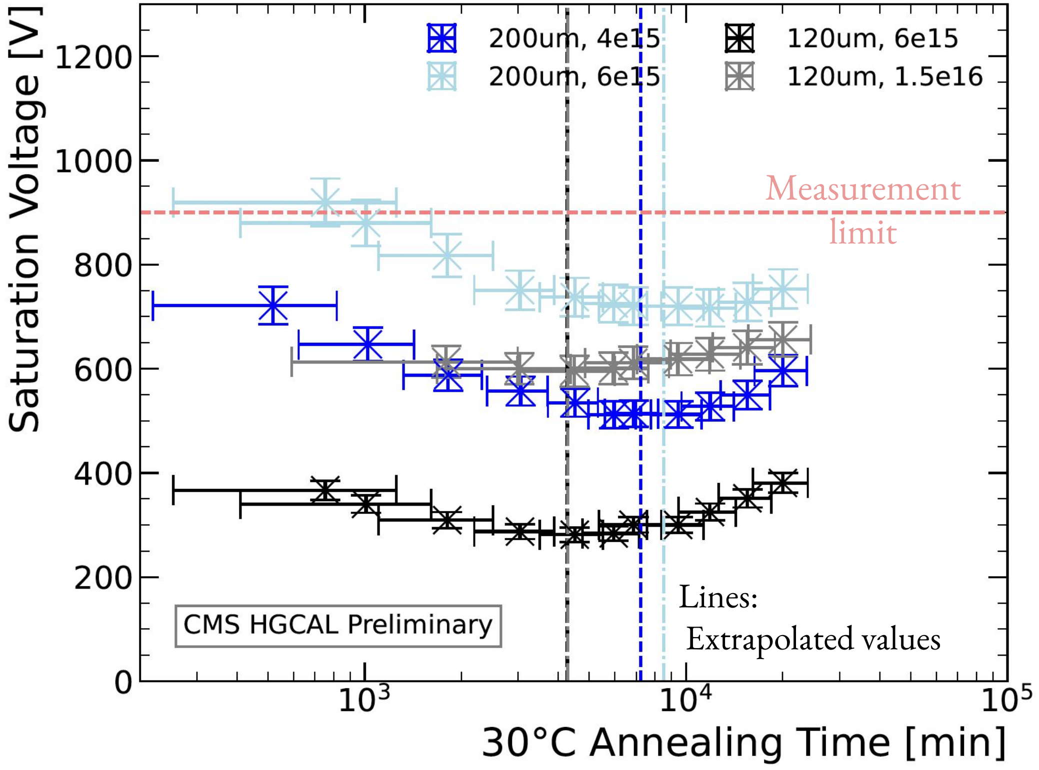
Extrapolated t_{min}	FZ 4e15	FZ 6e15	EPI 6e15	EPI 1.5e16
0°C	767 days	932 days	322 days	397 days
6.5°C	235 days	284 days	107 days	126 days
30°C	5 days	6 days	3 days	3 days

Scaling: Minima - Crosscheck

6.5°C Annealing



30°C Annealing

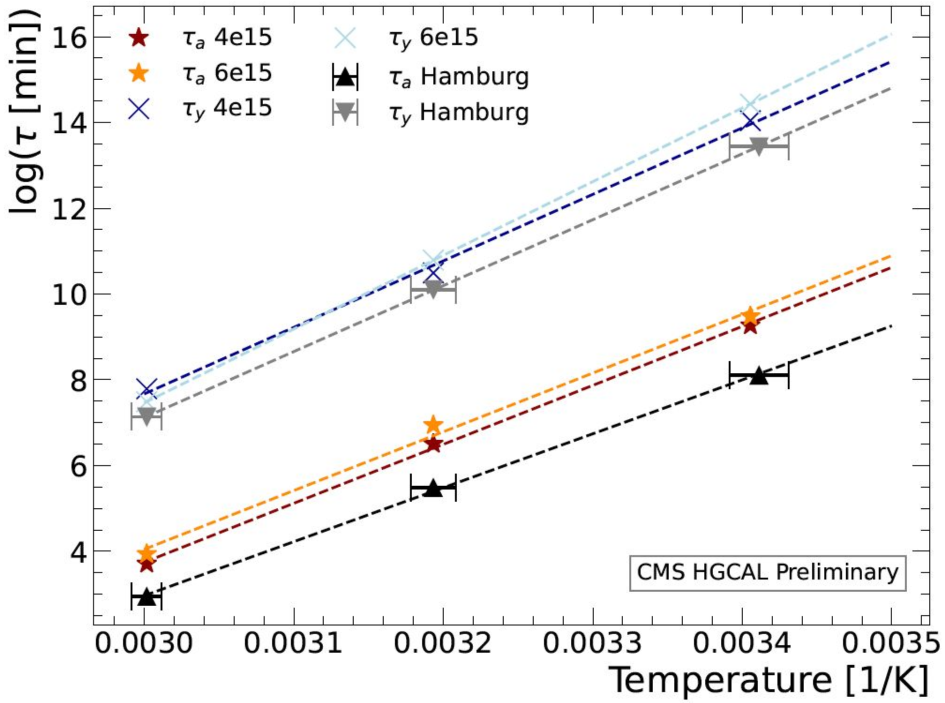


- Very good agreement between preliminary and extrapolated from scaling from other temperatures
- One exception: 1.5e16 n_{eq}/cm^2 120um sensor at 6.5°C - potentially caused by in-reactor annealing time calculation uncertainty - *based on Hamburg model using parameters found to deviate now*

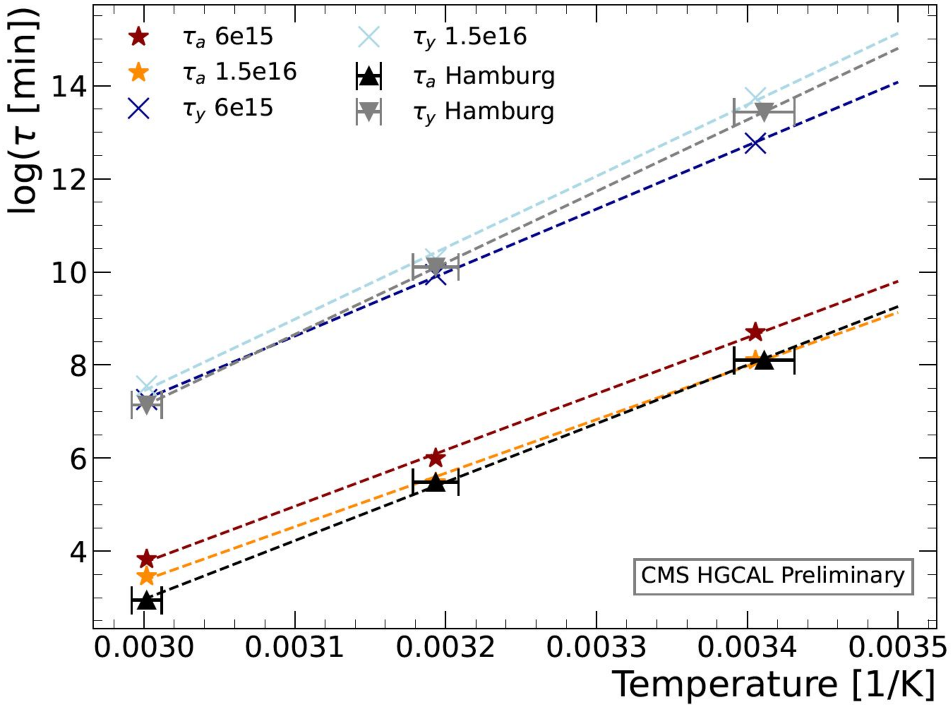
**Saturation voltages just below or just above the measurement limit have been extracted using the end-capacitance assumption after observing no change of it with annealing time*

Annealing time constants

Floatzone



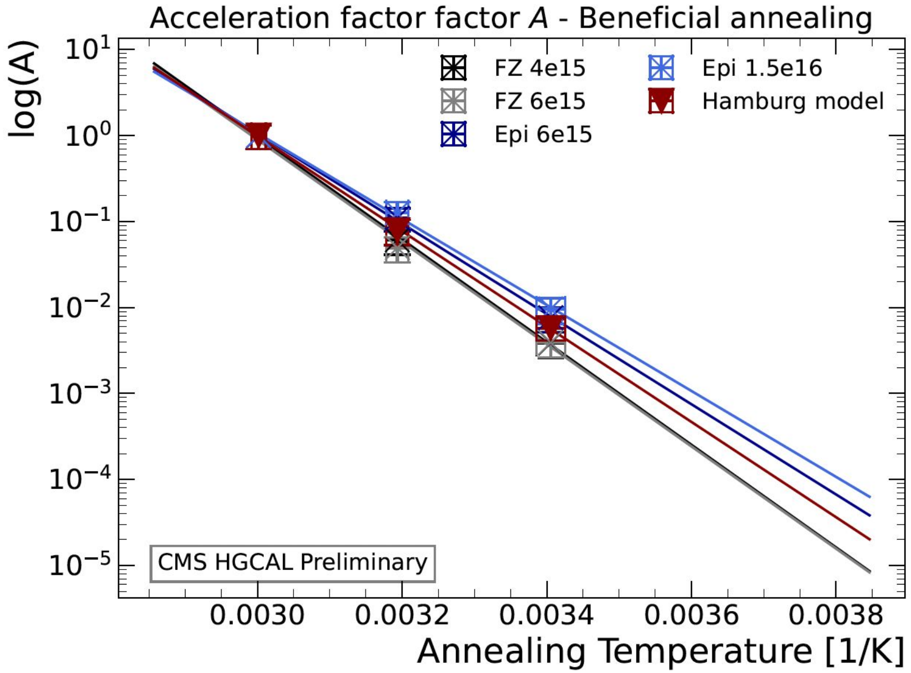
Epitaxial

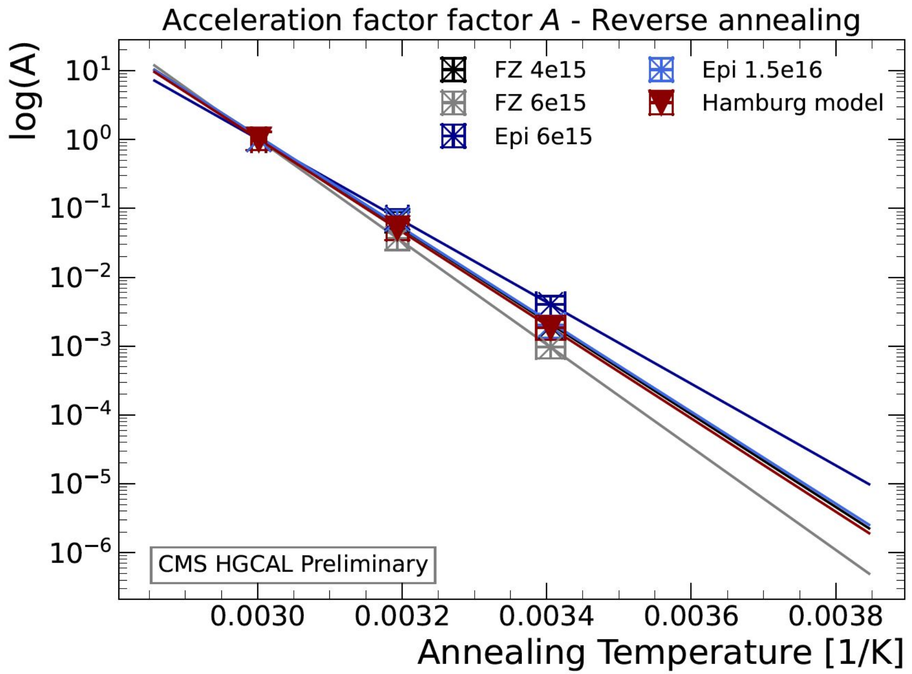


- Beneficial annealing: Same temperature dependence for different fluences, but deviation from temperature dependence compared to Hamburg model (slope + offset)
- Reverse annealing: Significant fluence dependence in the temperature dependence, higher fluences seem to be closer to Hamburg model
- For higher fluence slower reverse annealing expected at lower temperatures

Acceleration factors of annealing time constants

Normalized to 60°C

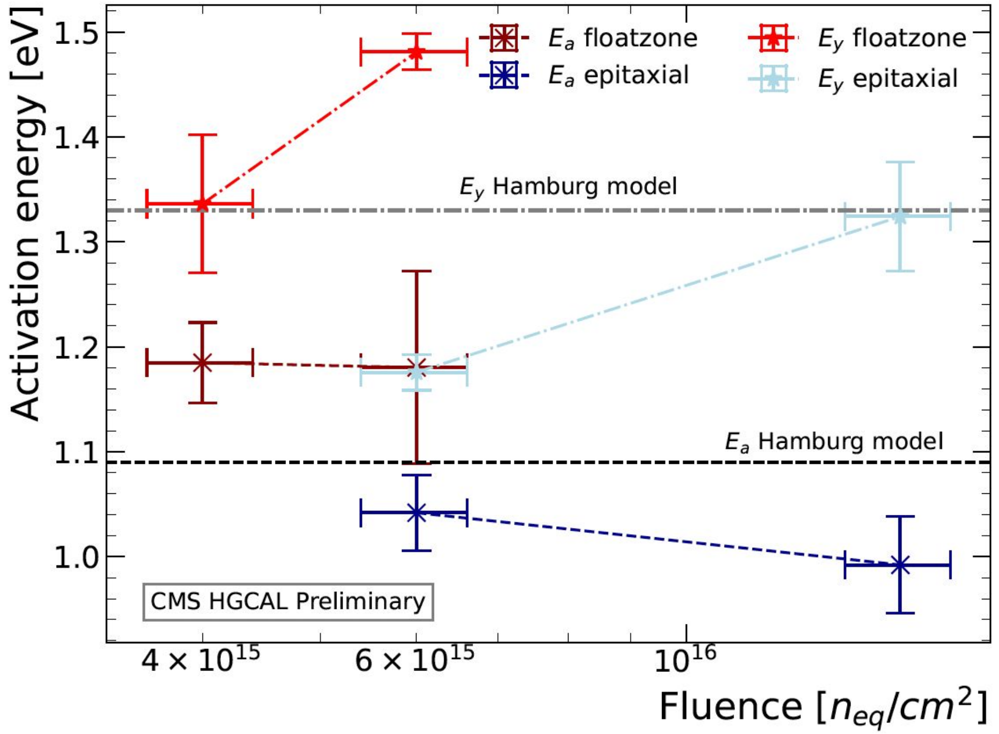


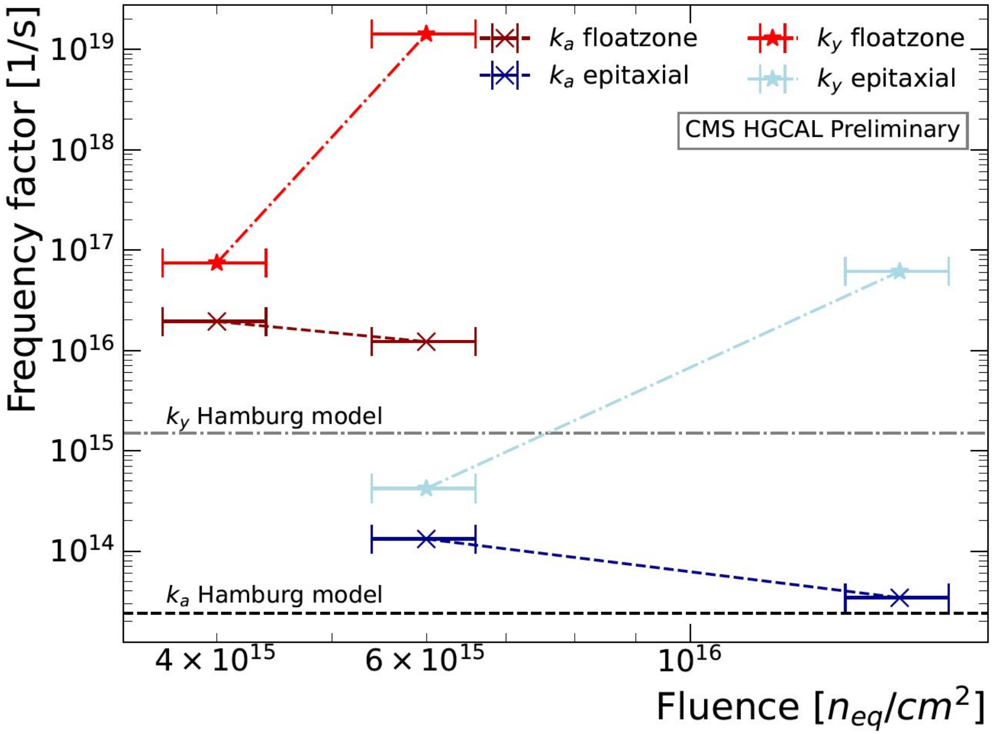


- No strong fluence dependence in the beneficial annealing for floatzone, slightly more for epitaxial
- Larger deviations in reverse annealing - only in agreement with the Hamburg model for one of two fluences
- Extrapolated acceleration factors at 0°C:

[10^{-4}]	Hamburg	4e15 FZ	6e15 FZ	6e15 EPI	1.5e16 EPI
Beneficial annealing	2.14428	1.09443	1.05093	3.588	5.30665
Reverse annealing	0.344539	0.398387	0.11957	1.23564	0.43577

Activation energy and frequency factor





- Decrease of beneficial annealing parameters E_a, k_a with fluence, increase of reverse annealing parameters E_y, k_y - hard to verify for reverse annealing (only two fluences), same decrease seen for beneficial in leakage current
- Both epitaxial and floatzone values differ from Hamburg model values - epitaxial is closer
- This means at 0°C:
  Floatzone: Beneficial and reverse annealing slower than expected from Hamburg model
  Epitaxial: Beneficial and reverse annealing faster than expected from Hamburg model

Conclusions

- General annealing behaviour as expected for all temperatures
- Deviations from the n-type based default Hamburg model values especially for FZ sensors

- Apparent dependencies of time constants, activation energy and frequency factor on material, fluence and potentially sensor thickness
  - Is it still valid to use a 'one model for all' approach at high fluences?
  - This campaign can not fully test all dependencies (e.g. thickness) - will be considered for a coming low fluence campaign
- **All results are preliminary** - still more data to collect, fits to be improved, and further analysis parameters to be evaluated (e.g. the annealing amplitudes N_a,N_y/ g_a,g_y showing fluence dependence)

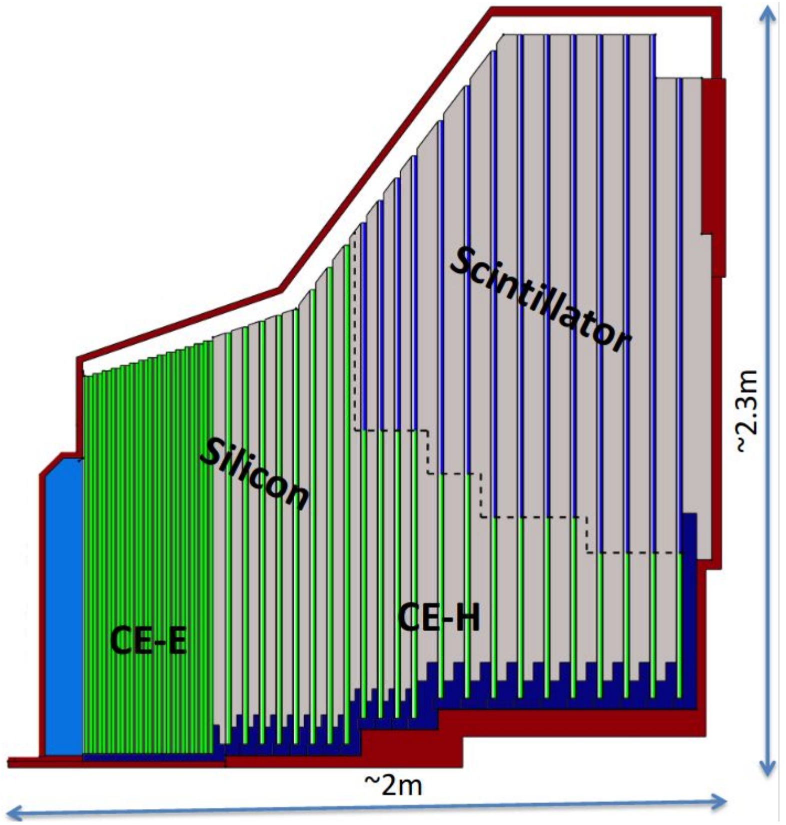
- The annealing for floatzone sensors seems to be slower: Minimum expected only after about 800 days at 0°C instead of 400 days as assumed previously by Hamburg model - but for epitaxial sensors the minimum would be expected after already 350days
- However, it takes about 150-200 min more until N_{eff} is similar to the value without additional annealing: Assuming 40 months of shutdown at 0°C: Even the worst case (lower E_y extracted from 6e15n_{eq}/cm^2 sensor) scenario this means about **800-1000 additional days** until the sensor is in the same state (N_{eff}, CC) **as without annealing** , with improved I_{leak} - no drastic reverse annealing effects are expected

BACKUP

Short reminder of HGCAL

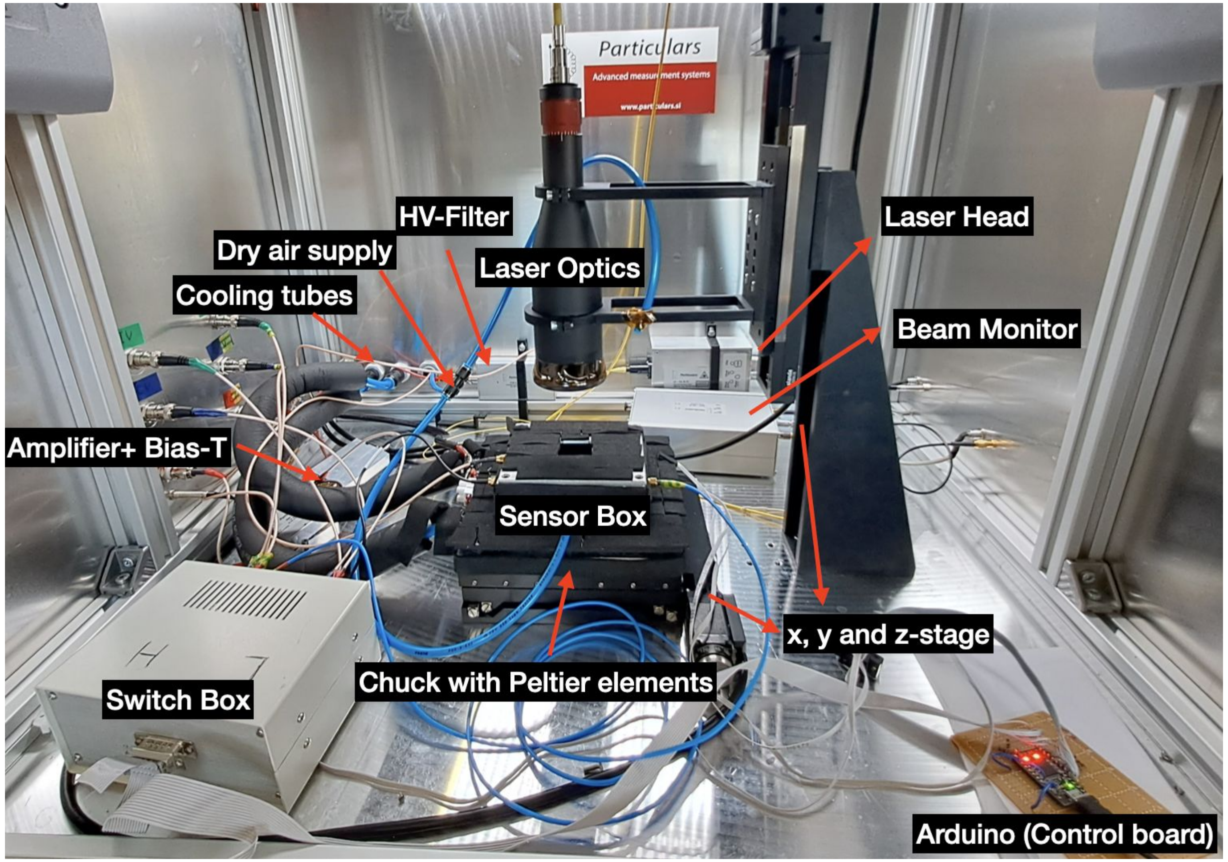
- CMS will replace Calorimeter Endcaps (CE) for HL-LHC operation
- CE to be implemented in HGCAL (High Granularity Calorimeter) concept
- Silicon sensors will be used for the electromagnetic section and high radiation regions of the hadronic section of the CE
- ~620 m2 silicon sensors produced on 8-inch wafers
- 3 different thicknesses: 300 µm, 200 µm (Float zone) and 120 µm (Epitaxial) - thinner sensors in high fluence regions
- Fluences of up to 1e16 neq/cm

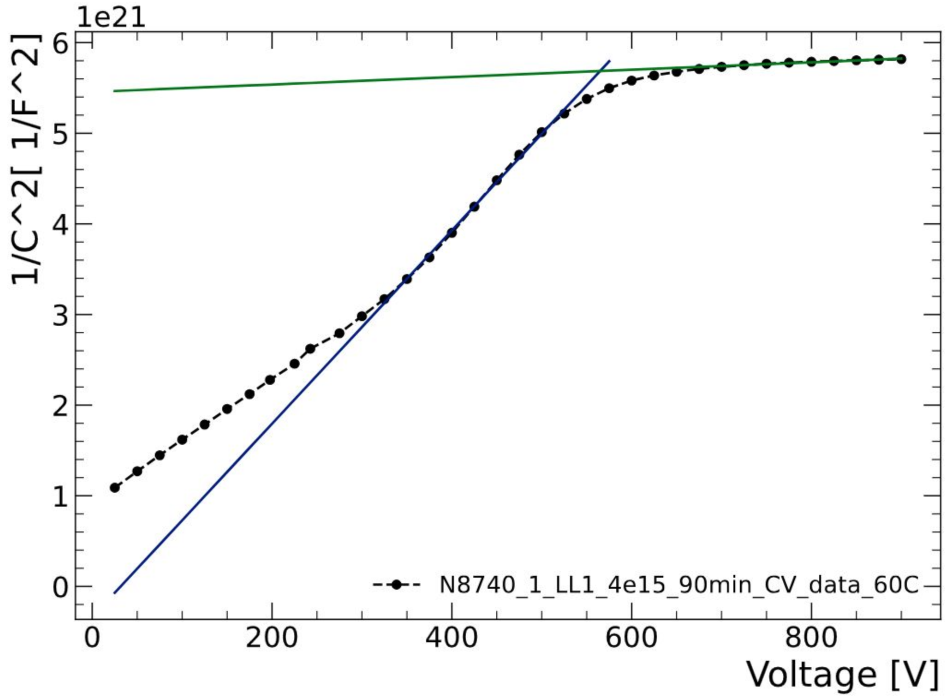
Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



Experimental setup

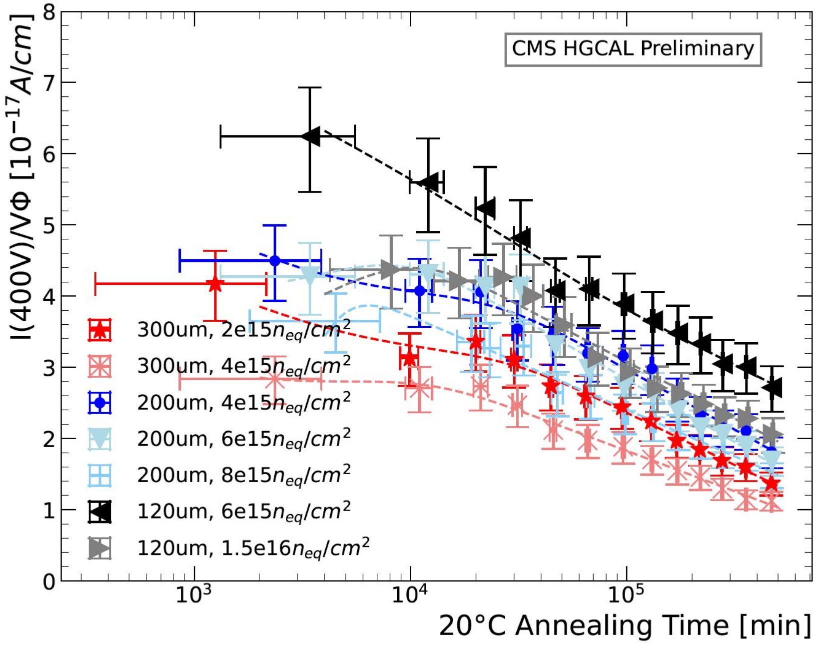
- Particulars TCT setup upgraded it to IV+CV+TCT setup
- Switchbox to change measurement type automatically
- Sensors are glued and wirebonded to a PCB, placed on a cooled copper holder, connected via SMA connectors



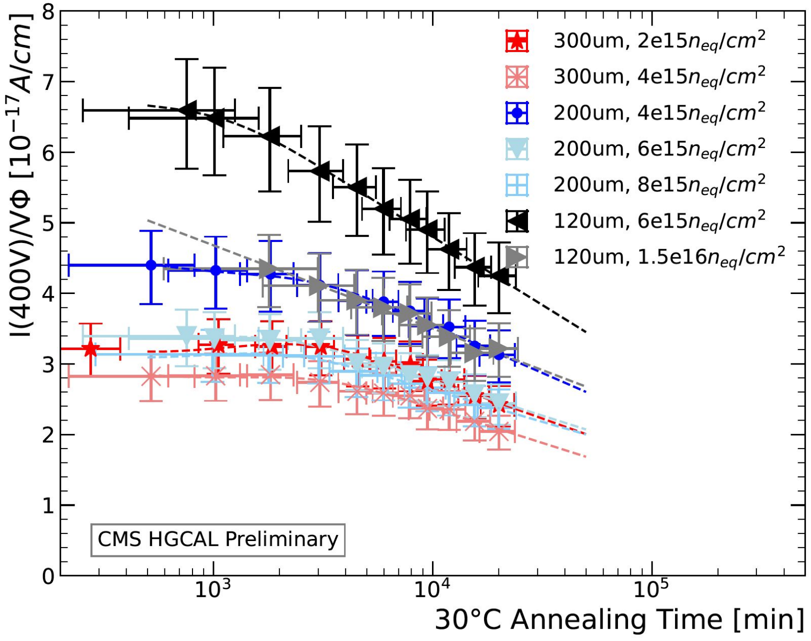


- Saturation voltage extraction
- Measured at 2kHz, -20°C
- Constant capacitance beyond saturation independent of
- annealing time: End-capacitance assumption for saturation voltages around/just above the measurement limit

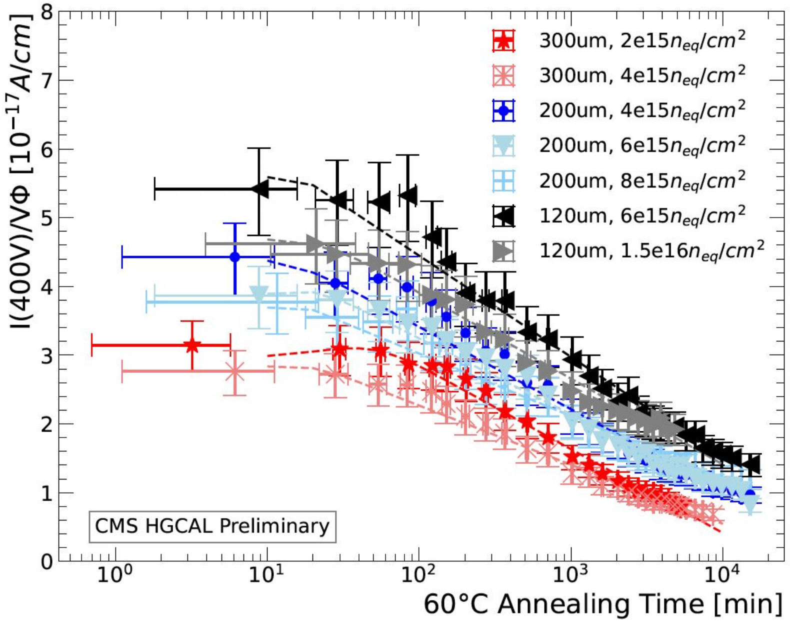
Current related damage rate: 400V



Annealing in progress: Changes in the fits with more data possible

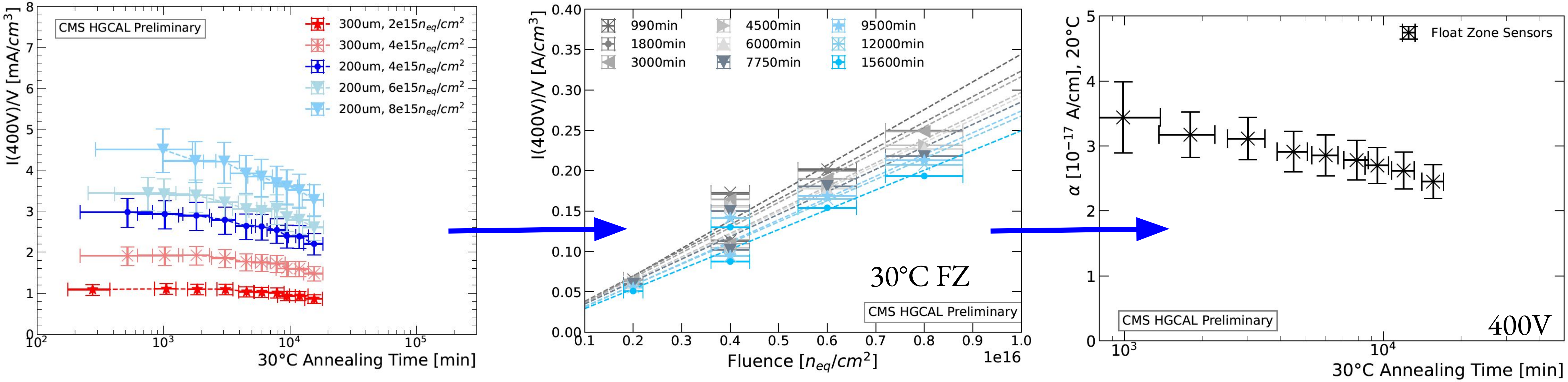


Annealing just started. Largest changes expected for 30°C with more data



Onset of charge multiplication: Last data points omitted for high fluence sensors

Current related damage rate: Example for 30°C at 400V



Damage parameter α: $\frac{I}{V} = \alpha \cdot \phi$

- Damage parameter extraction from leakage current measurements
- Split analysis between Floatzone and Epitaxial sensors
- Difference in normalised current visible for 200um/300um at 4e15 n_{eq}/cm^2
  - potential dependencies on fluence and thickness to be investigated
- Individual data sets (6.5°C, 20.5°C) not brought to identical annealing times - interpolation needed.

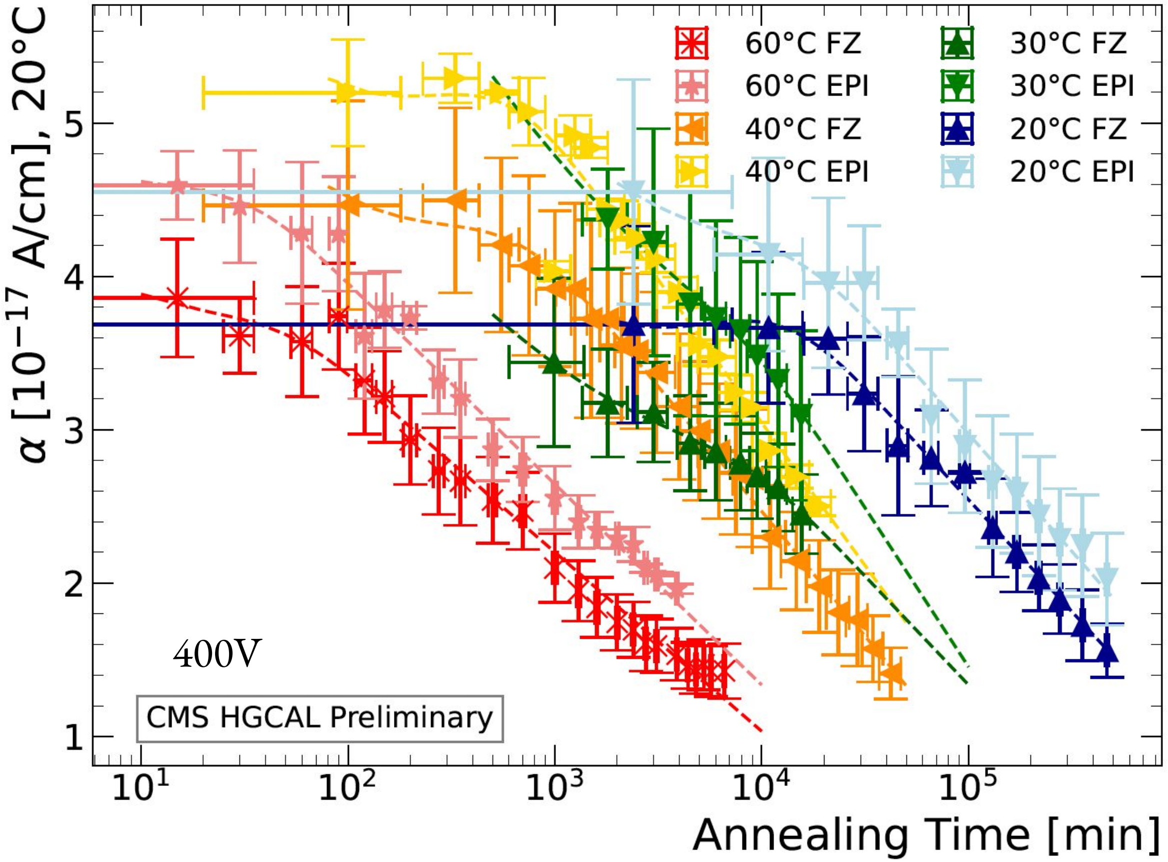
Current related damage rate at 400V

Hamburg model - based on n-type sensors and fluences up to 1e15 n_{eq}/cm^2:

$$\alpha(t) = \alpha_I * \exp(-t/\tau_I) + \alpha_0 - \beta * \ln(t/t_0)$$

"short term" "long term"

- Extremely sensitive fits:
  - Changes for 20.5°C and 30°C expected with further measurements
  - Data points influenced by the onset of charge multiplication had to be excluded
- Differences between Floatzone and Epitaxial: Fluence, thickness or material dependence?
  - Can we still use a "one model for all sensors" approach?
  - Extremely large uncertainties on extracted values
  - Long-term annealing seemingly better described than short-term annealing



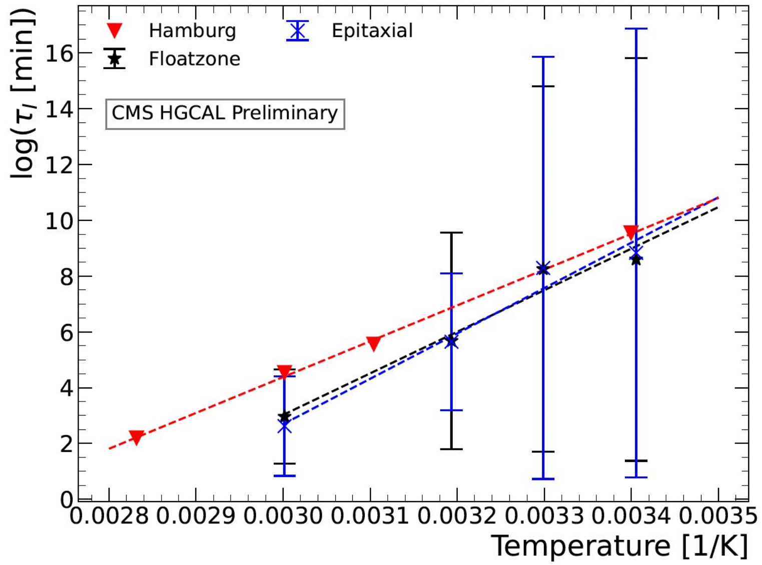
Current related damage rate at 400V

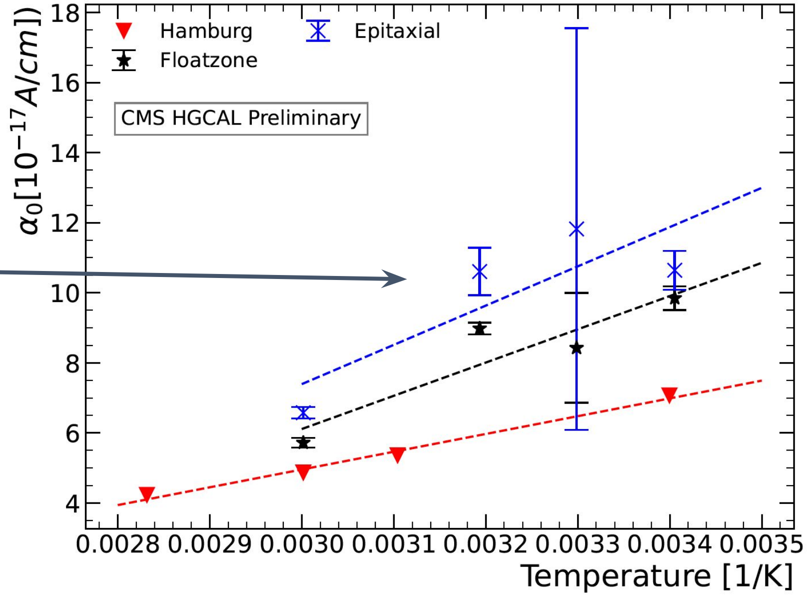
$$\alpha(t) = \alpha_I * \exp(-t/\tau_I) + \alpha_0 - \beta * \ln(t/t_0)$$

$1/\tau_I = k_{0I} * \exp(-E_I/k_B T_a)$

$\alpha_0 = -a + b/T_a$

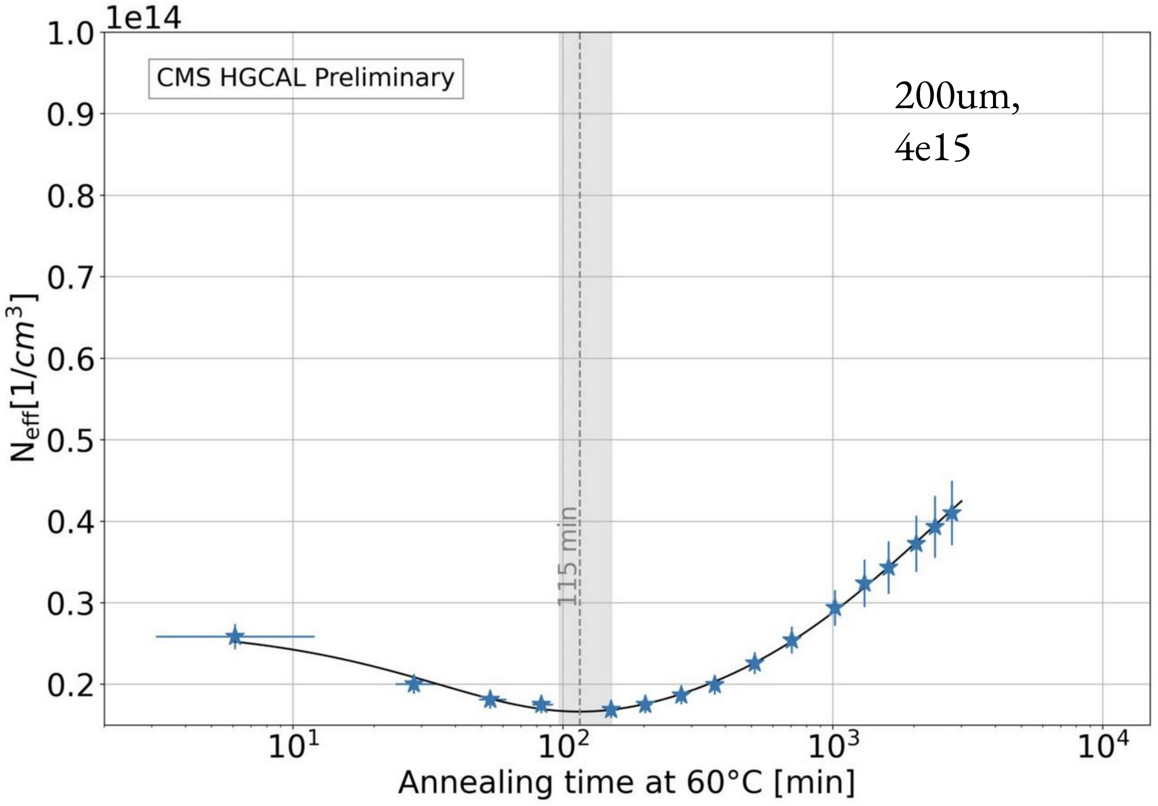
	Hamburg	Floatzone	Epitaxial
α_I [10^{-17}A/cm]	1.23±0.06	1.40±0.39	1.35±0.23
k_{0I} [s^{-1}]	1.2 * 10^{13}	8.46 * 10^{16}	8.04 * 10^{19}
E_I [eV]	1.11±0.05	1.20±0.08	1.40±0.18
β [10^{-18}A/cm]	3.07±0.18	6.23 ±0.14	6.57 ±0.33
a [10^{-17}A/cm]	8.9±1.3	22.35±9.44	26.23±16.49
b [10^{-17}A/cm]	4600±400	0.82±0.25	0.97±0.44

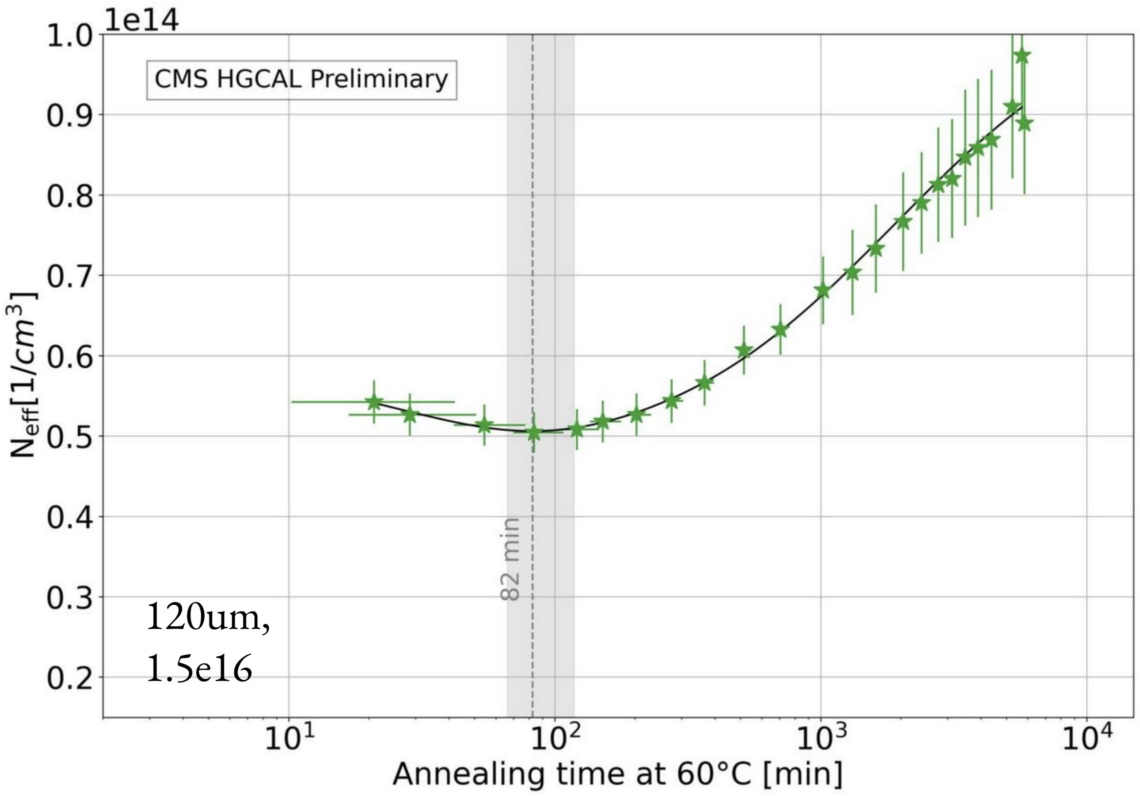




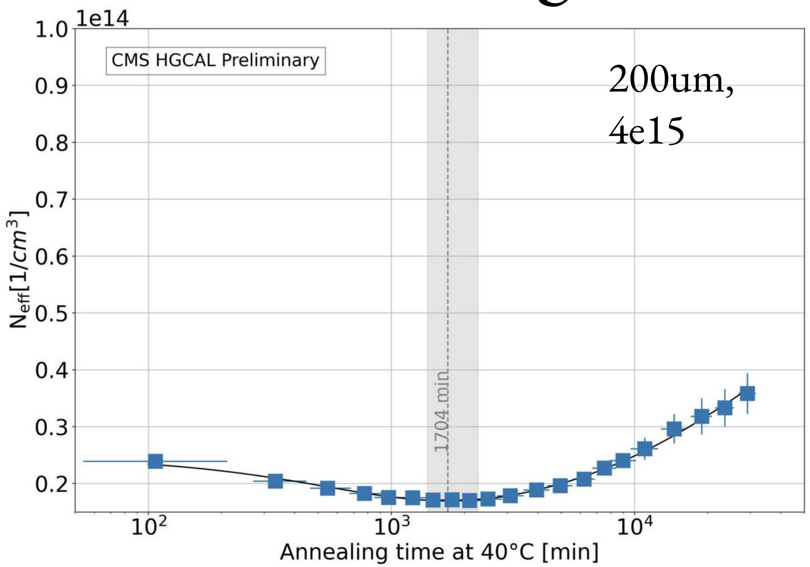
- Difficult to interpret due to large uncertainties and deviations
- Generally: Higher activation energy leads to slower annealing

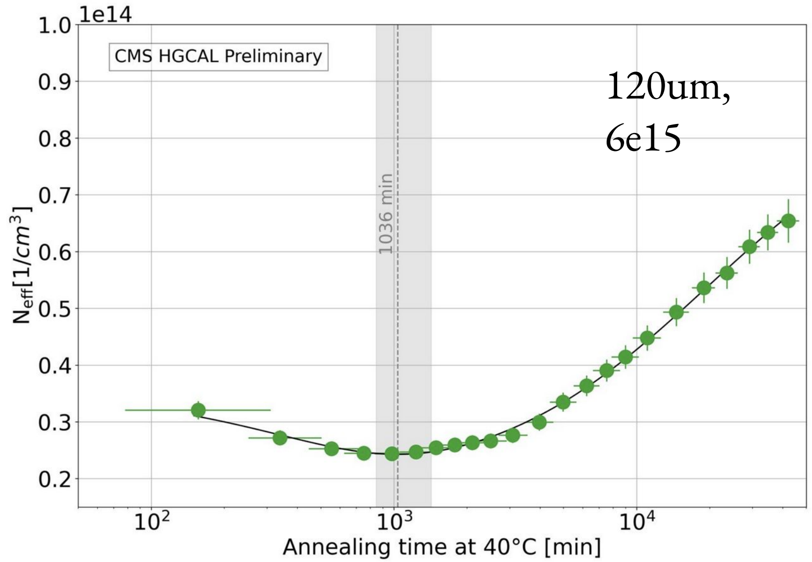
Neff: Hamburg model fits 60°C

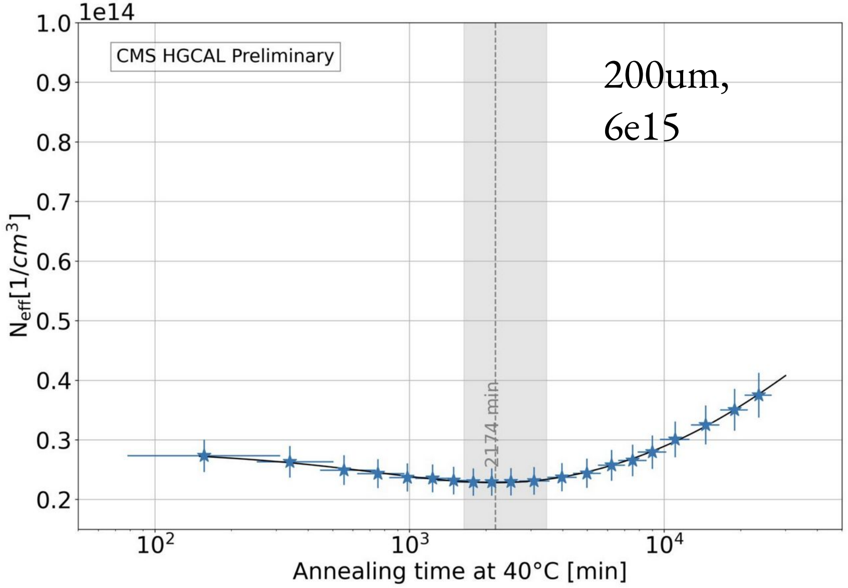


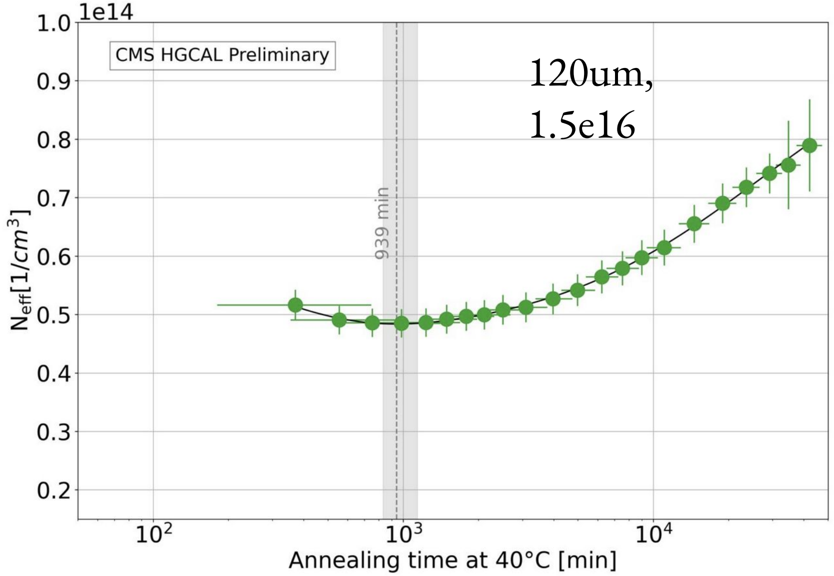


Neff: Hamburg model fits 40°C

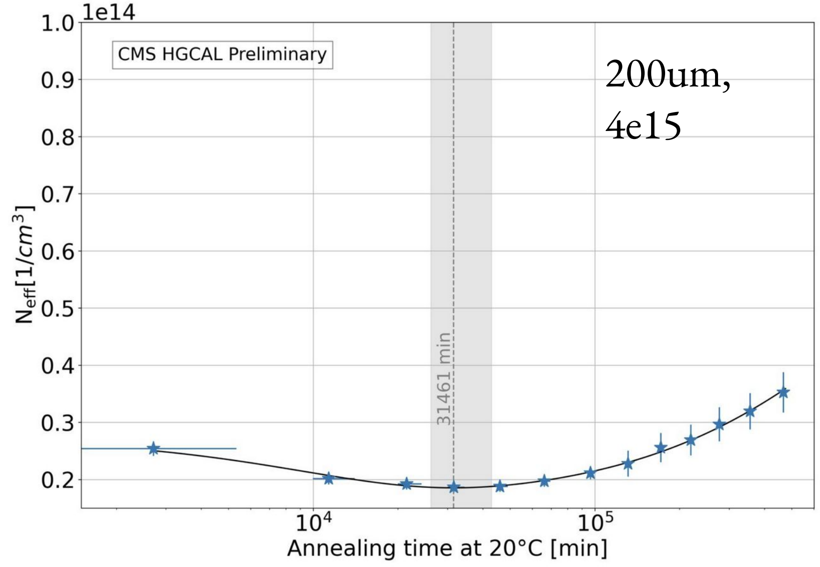


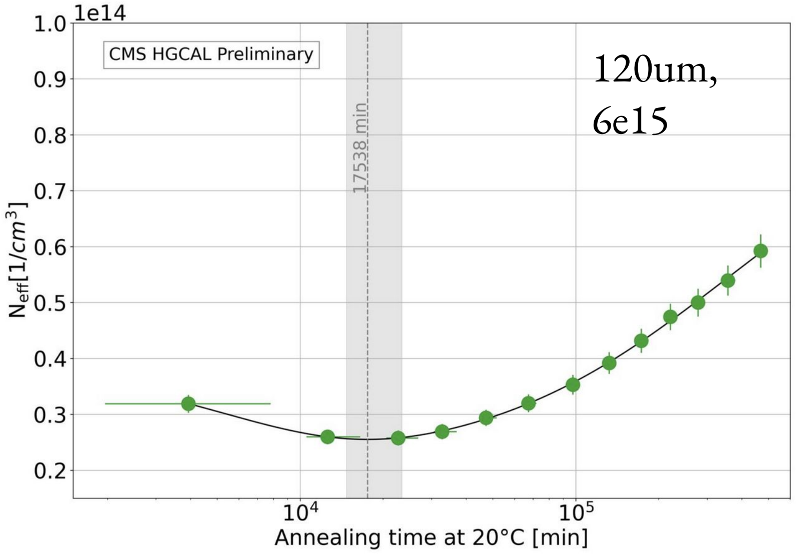


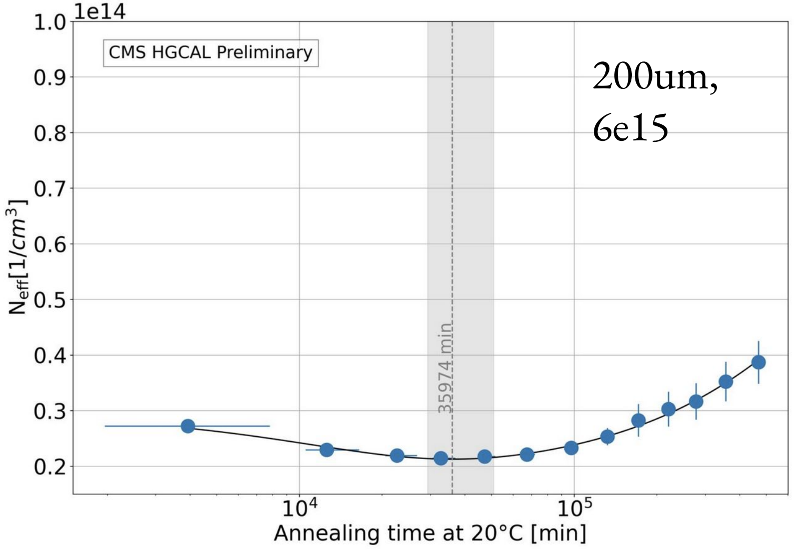


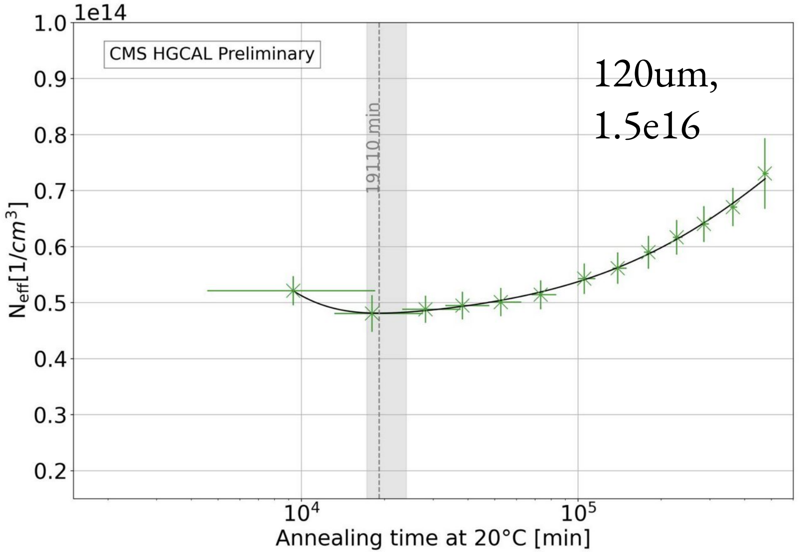


Neff: Hamburg model fits 20.5°C









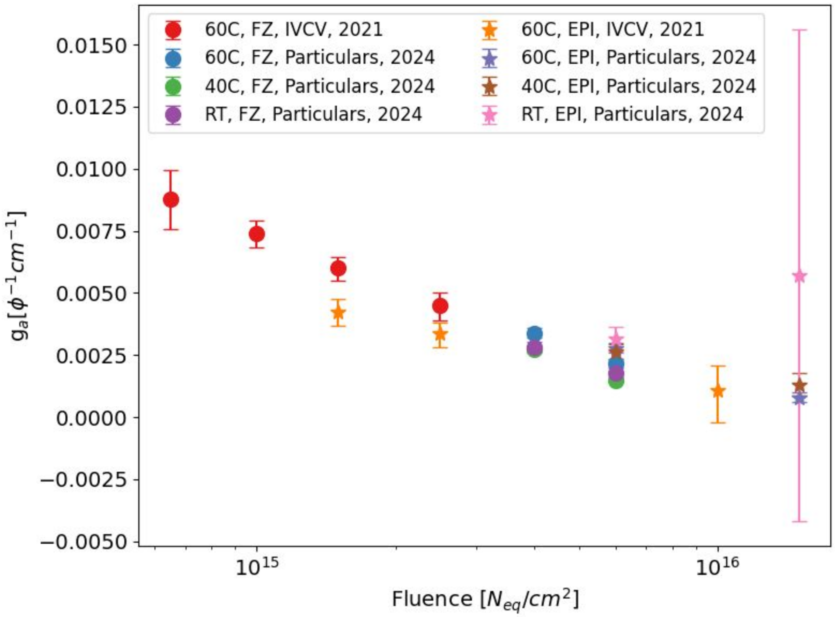
Neff: Extracted fit parameters

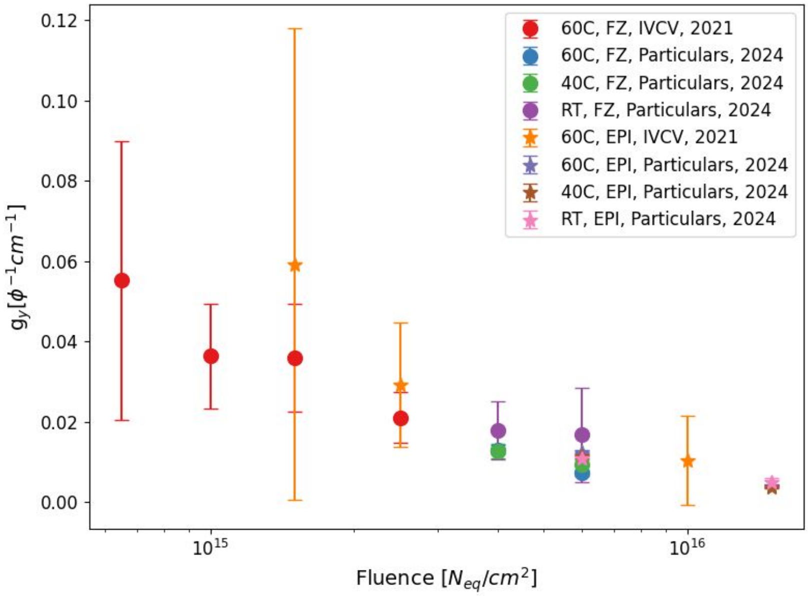
60°C	FZ 4e15	FZ 6e15	EPI 6e15	EPI 1.5e16
g_a	0.0034	0.0022	0.0028	0.0008
τ_a	40.983	51.389	45.854	31.747
g_c	0.0027	0.0024	0.0015	0.0029
g_y	0.0131	0.0073	0.0124	0.0039
τ_y	2416	1789	1417	1897
t_{min}	115_{-19}^{+36}	127_{-22}^{+42}	95_{-24}^{+59}	82_{-16}^{+36}

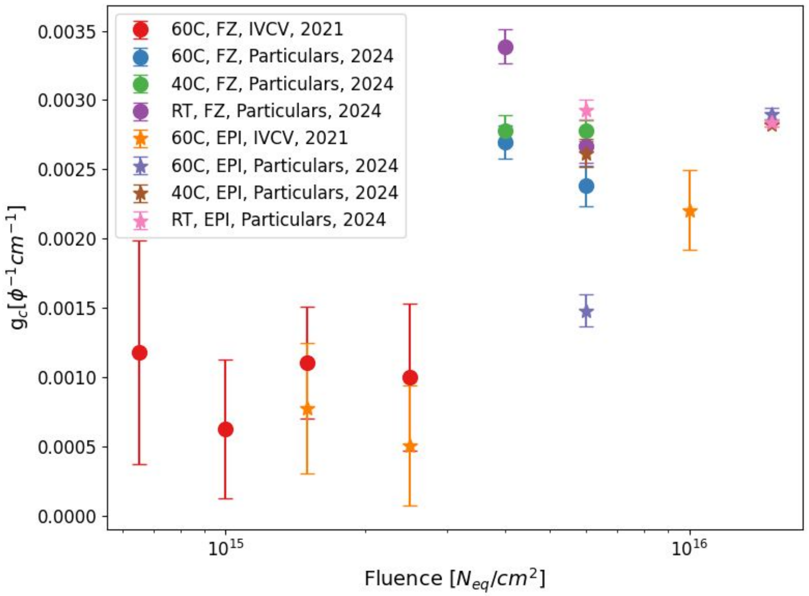
40°C	FZ 4e15	FZ 6e15	EPI 6e15	EPI 1.5e16
g_a	0.0027	0.0015	0.0026	0.0013
τ_a	669.8	1036.7	418.4	251.7
g_c	0.0028	0.0028	0.0026	0.0028
g_y	0.0127	0.0094	0.0114	0.0036
τ_y	36027	48595	19325	27130
t_{min}	1704_{-298}^{+570}	2174_{-539}^{+1279}	1036_{-193}^{+386}	939_{-109}^{+199}

20°C	FZ 4e15	FZ 6e15	EPI 6e15	EPI 1.5e16
g_a	0.0028	0.0018	0.0031	0.0057
τ_a	10615	13119	6015	3295
g_c	0.0034	0.0027	0.0029	0.0028
g_y	0.0179	0.0169	0.0109	0.0051
τ_y	1253601	1846859	350705	931928
t_{min}	31461_{-5321}^{+11492}	35974_{-6718}^{+14966}	17538_{-2833}^{+5827}	19110_{-1880}^{+4869}

Neff: Extracted fit parameters g_a, g_c, g_y





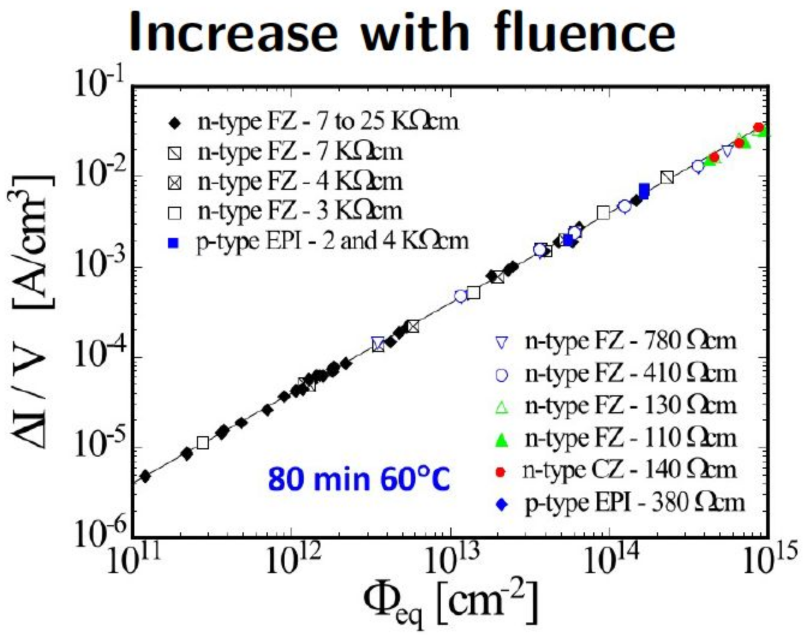


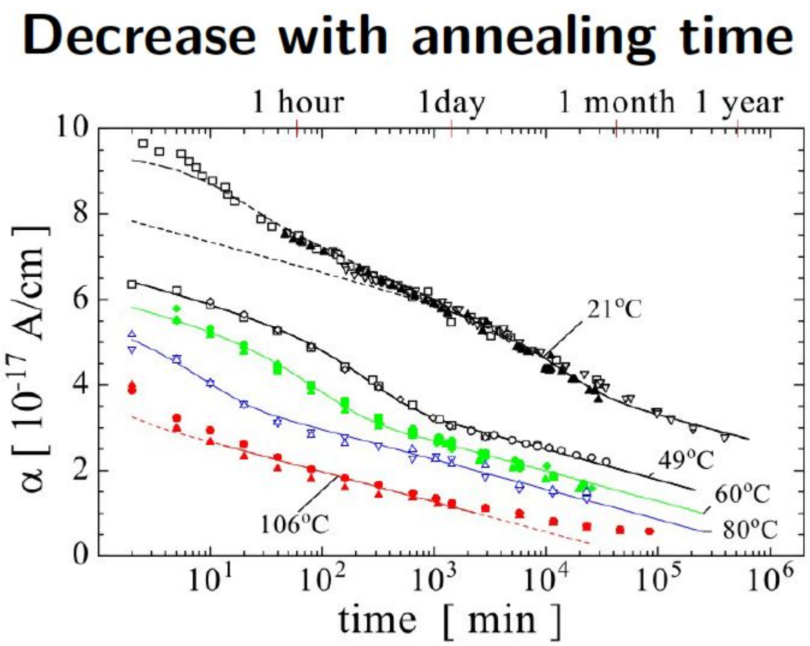
- Decrease with fluence
- In agreement with previous study
- Hamburg model: $(1.81\pm0.14)*10^{-2}cm^{-1}$ -> lower fluences, extrapolating would lead to values in that order

- Decrease with fluence
- In agreement with previous study
- Hamburg model: $(5.16\pm0.09)*10^{-2}cm^{-1}$ -> in agreement with the lowest fluence measured here

- No clear fluence dependence
- Shift for higher fluences
- Hamburg model: $(1.49\pm0.04)*10^{-2}cm^{-1}$ -> one magnitude larger than measured

Leakage current





Current related damage factor

$$\alpha = \frac{\Delta I}{V\Phi_{eq}}$$

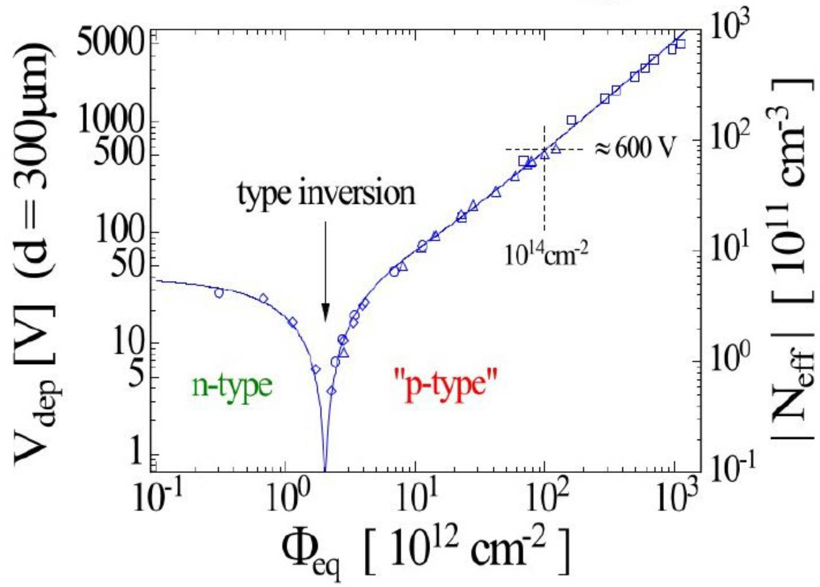
Current increase is independent of silicon production process (FZ, Epi, Cz) and impurity concentration types and concentration.
It can be a fluence indicator.

No reverse annealing for the leakage current.
Annealing is strongly temperature dependent.

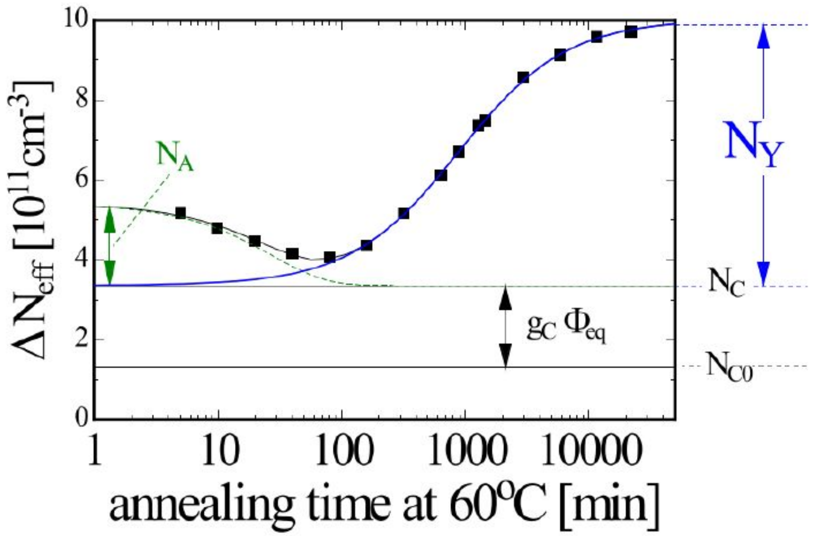
M.Moll, Bethe Forum on Detector Physics 2014

Change of effective doping concentration

with fluence Φ_{eq}



with annealing



- For n-type sensors: Type inversion, N_{eff} changes from positive to negative, electric field building up from the backside
- Reason to change to p-type sensors at HL-LHC detectors

- Short term: Beneficial annealing
- Long term: Reverse annealing
- Time constants are temperature dependent
  → Detectors need to be cooled to avoid entering reverse annealing

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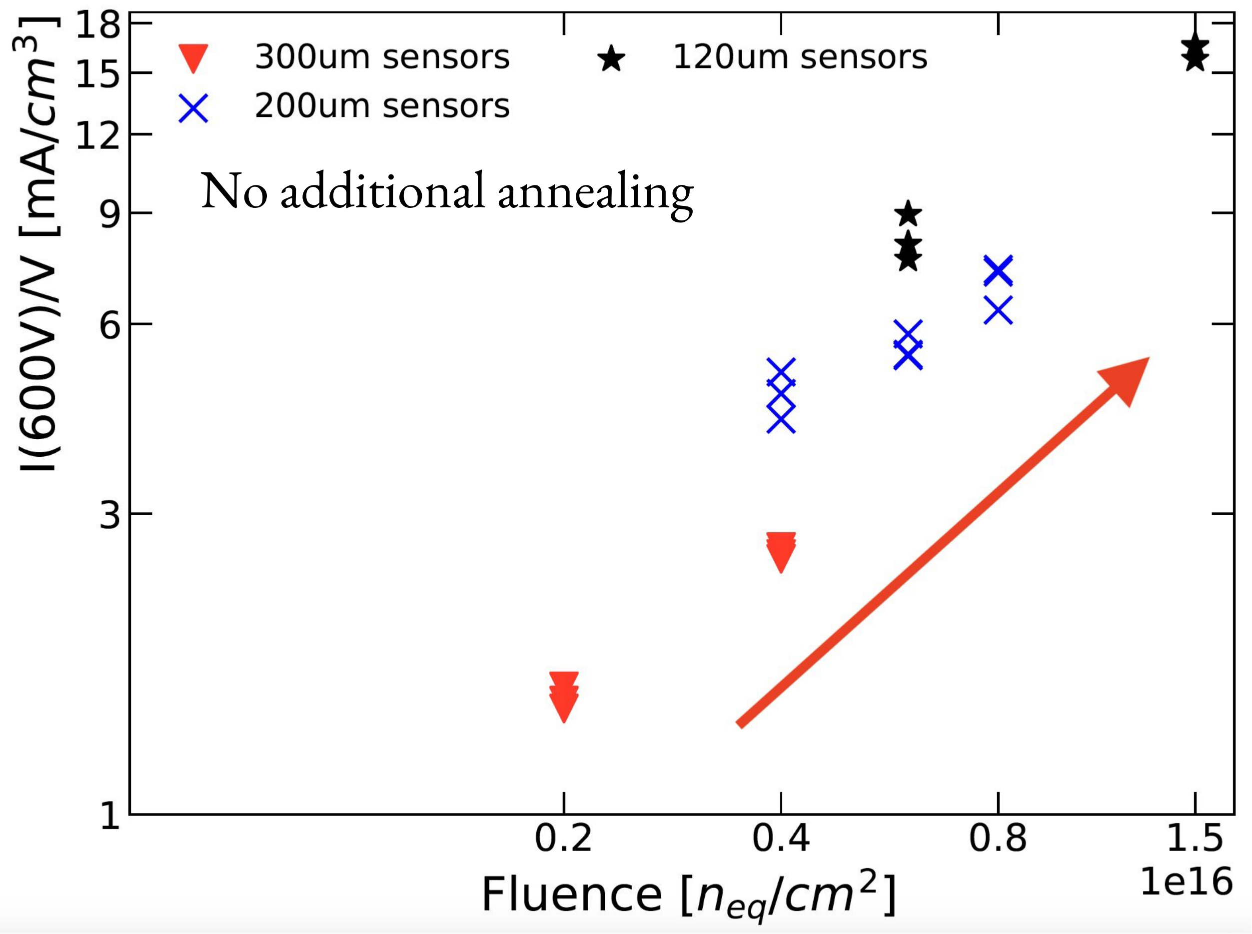
Potential thickness dependence in leakage current



Acceleration factor w.r.t. 20°C