UNIVERSITY OF LIVERPOOL

27th RD50 workshop, CERN

IV-characterization of silicon sensors irradiated up to 2E16n_{eq}/cm^2

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IV Measurement Aim

- Current scaling:

$$\frac{I(T_2)}{I(T_1)} = \left(\frac{T_2}{T_1}\right)^2 exp\left(\frac{-E_{eff}}{2k_B}\frac{T_1 - T_2}{T_1 T_2}\right)$$

E_{eff}: effective energy (1.214±0.014eV [1]); T_1: measurement temperature, T_2: scaling temperature; k_B: Boltzmann constant

Use for scaling of current to different temperatures, determination of E_{eff} from measurement

- Investigate behaviour of current for irradiated sensors

$$\frac{I\left(\Phi_{eq}\right) - I(\Phi_0)}{V} = \alpha\Phi_{eq}$$

V: depleted volume; Φ_{eq}: equivalent fluence; $I(\Phi_0)$: nonirradiated current ; α: current related damage rate

Determination of α from measurements,

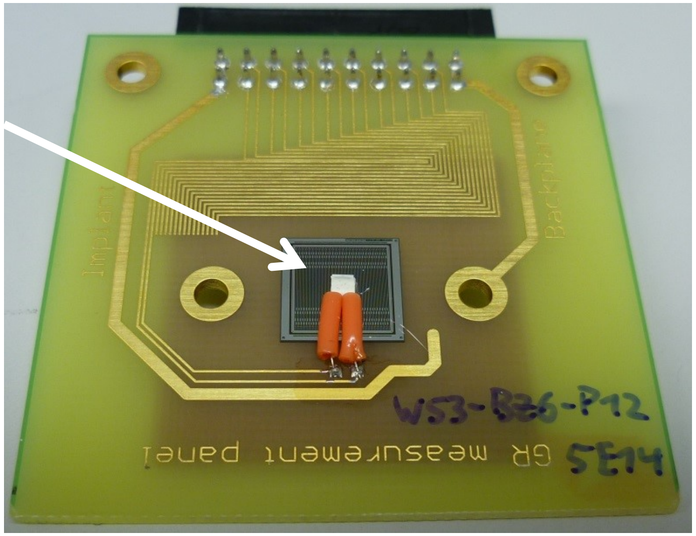
α depends on the sensor annealing time

[1]: A. Chilingarov; *Temperature dependence of the current generated in Si bulk*; **2013_JINST_8_P10003**

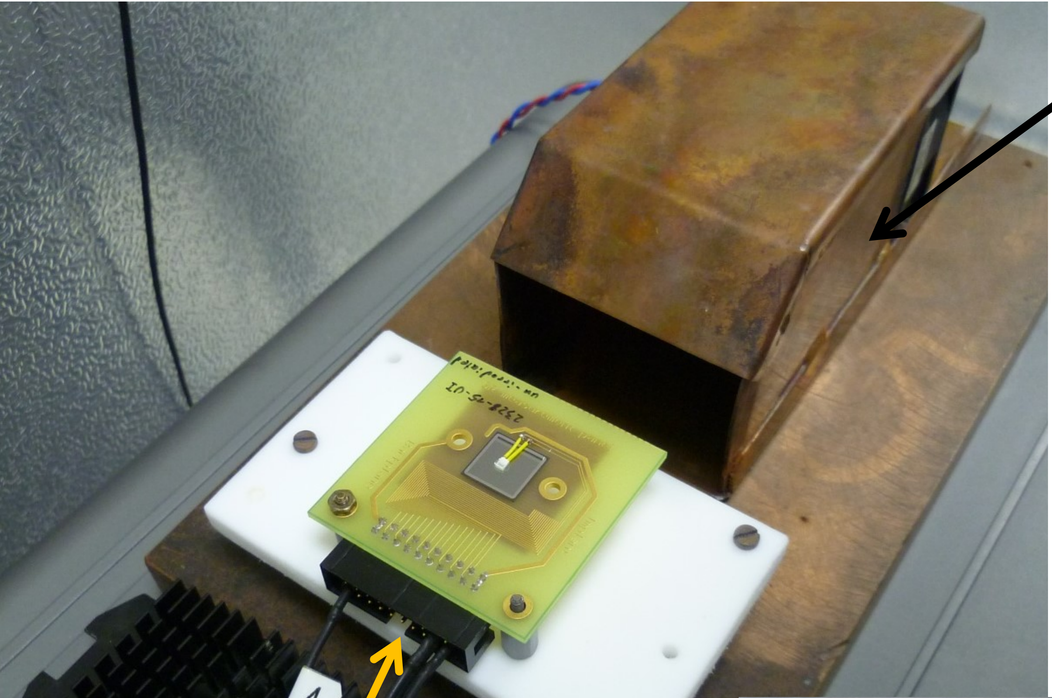
Sensors/Measurements

- Irradiate silicon sensors to different fluences
  - Protons (Birmingham):
    - ATLAS07 MINI (293µm): 1×10^{12} to 1×10^{15} n_{eq}/cm^2
  - Neutrons (Ljubljana):
    - ATLAS07 MINI (293µm): 5×10^{15} to 2×10^{16} n_{eq}/cm^2
    - Micron 2437 (143µm): 5×10^{15} to 2×10^{16} n_{eq}/cm^2
    - Micron 2923 (108µm): 5×10^{15} to 2×10^{16} n_{eq}/cm^2
    - Micron 2923 (108µm): 5×10^{15} to 2×10^{16} n_{eq}/cm^2 measured at CERN
    - Micron 3107 (50µm): 1×10^{15} to 2×10^{16} n_{eq}/cm^2

- Glued PT1000 temperature sensor on sensor
- Perform IV/CV measurements in a freezer at different temperatures from -23°C to -15°C (at least 2 per sensor)
- Room temperature annealing in nitrogen cabinet to total annealing times of 10d and 30d



Old Liverpool Setup



Fan for air flow

PCB just placed in freezer

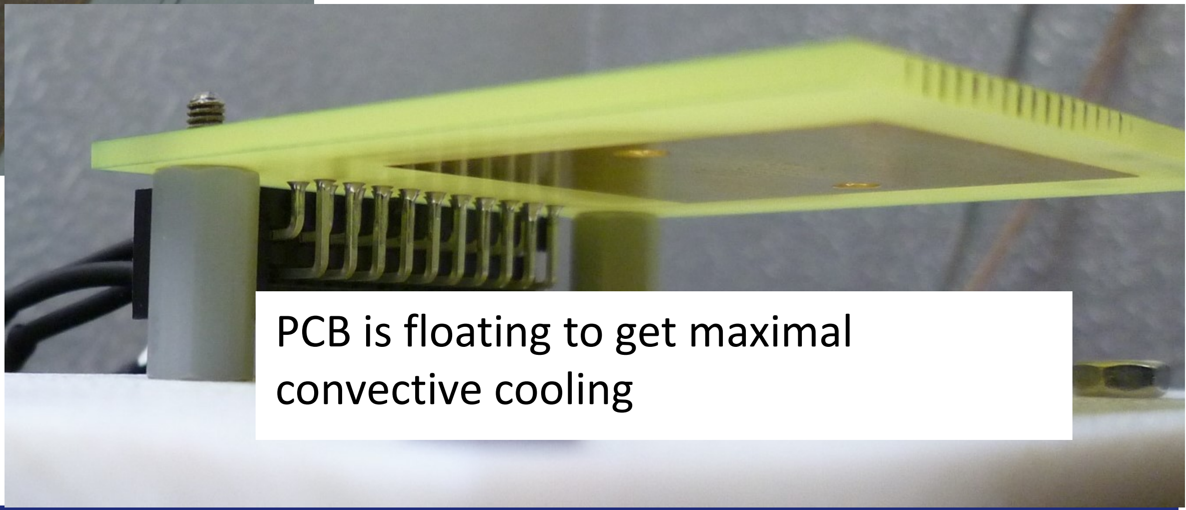
Fan for air circulation

Limited by freezer:

If freezer is constantly running a temperature of -23°C can be reached

For higher temperatures a oscillation can be observed due to the freezer not being constantly on

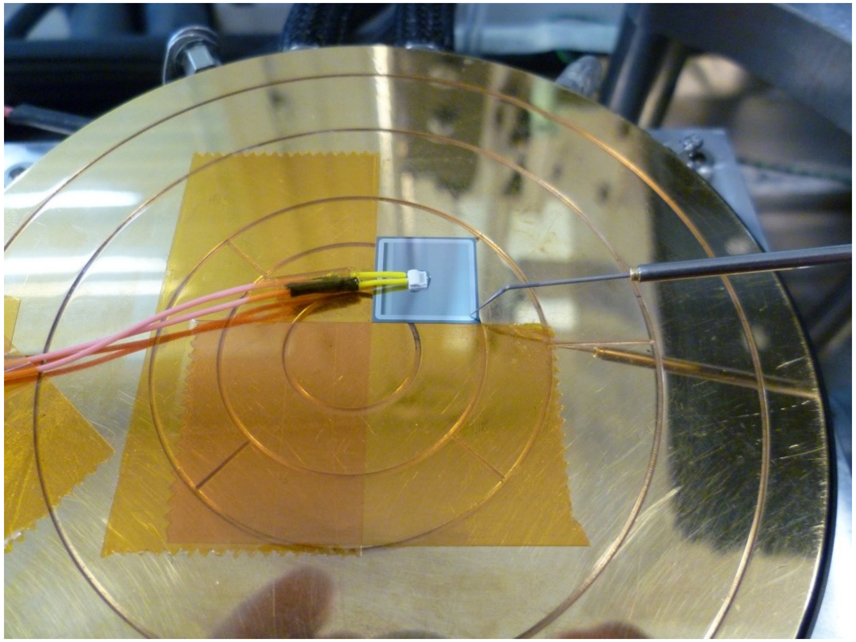
HV and PT1000 read out



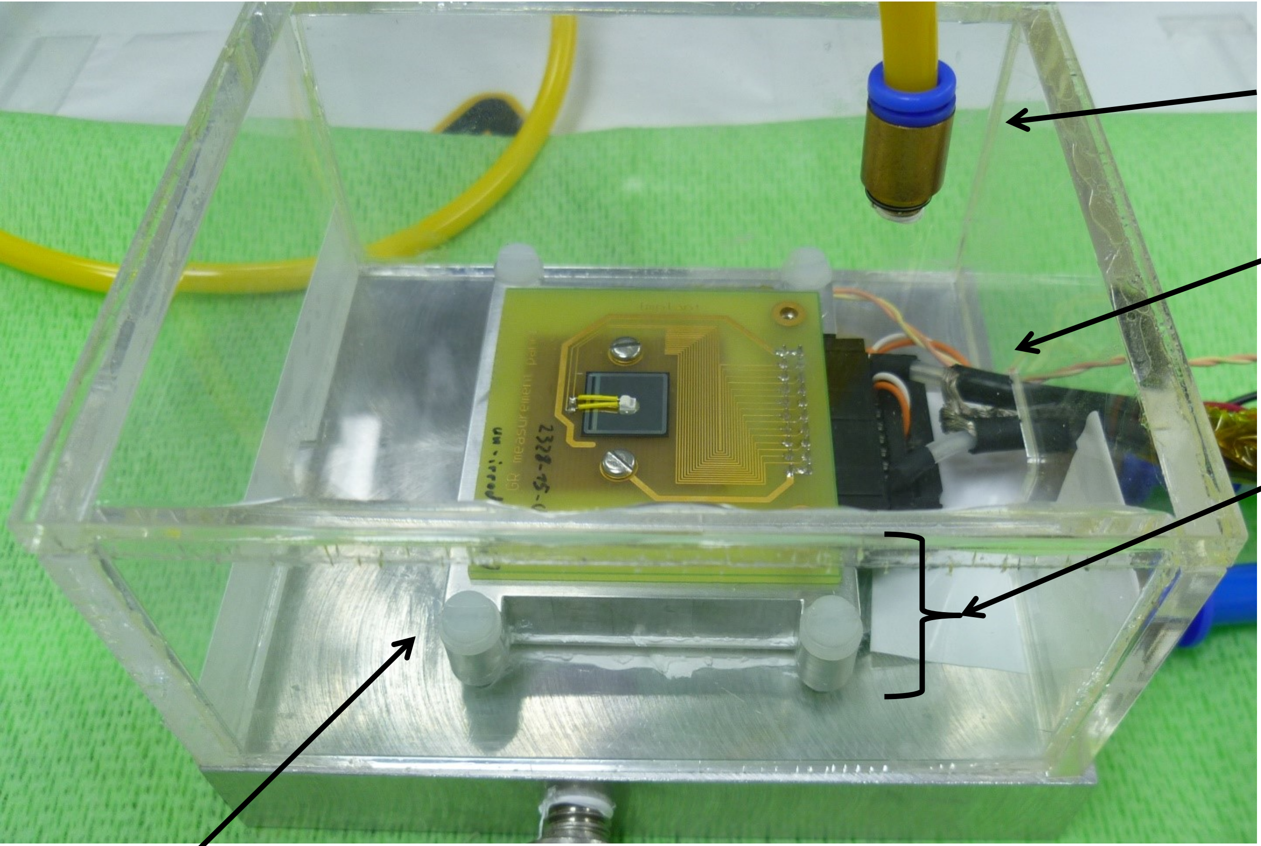
PCB is floating to get maximal convective cooling

CERN setup

- Cold chuck, cooled by chiller and peltier
- PT1000 glued onto sensor for temperature measurement



New Liverpool setup



Perspex cover with Nitrogen inlet

HV and PT1000 connector

PCB
Mounting Plate
Peltier
Chuck cooled to chiller

Use Nylon screws to prevent heat loop

Sufficient flow of dry air / nitrogen is very important to prevent ice on sensor

Measurements with new setup

- Same method used in Freiburg
  - Start at highest voltage and ramp down
  - Measurements at -25°C and -20°C (PT1000 at chuck)
  - Setup not in freezer
  - Chiller set to +5°C to prevent ice at tubes; Peltier power set to 15V (3A)
    - At -25°C use 90% of Peltier power
    - Peltier can cope with higher voltage (up to 29.8V, 6A), but this require a modification of the PID controller

- Cooling with new setup much faster
- PID parameters not optimal, but for first measurements they are acceptable

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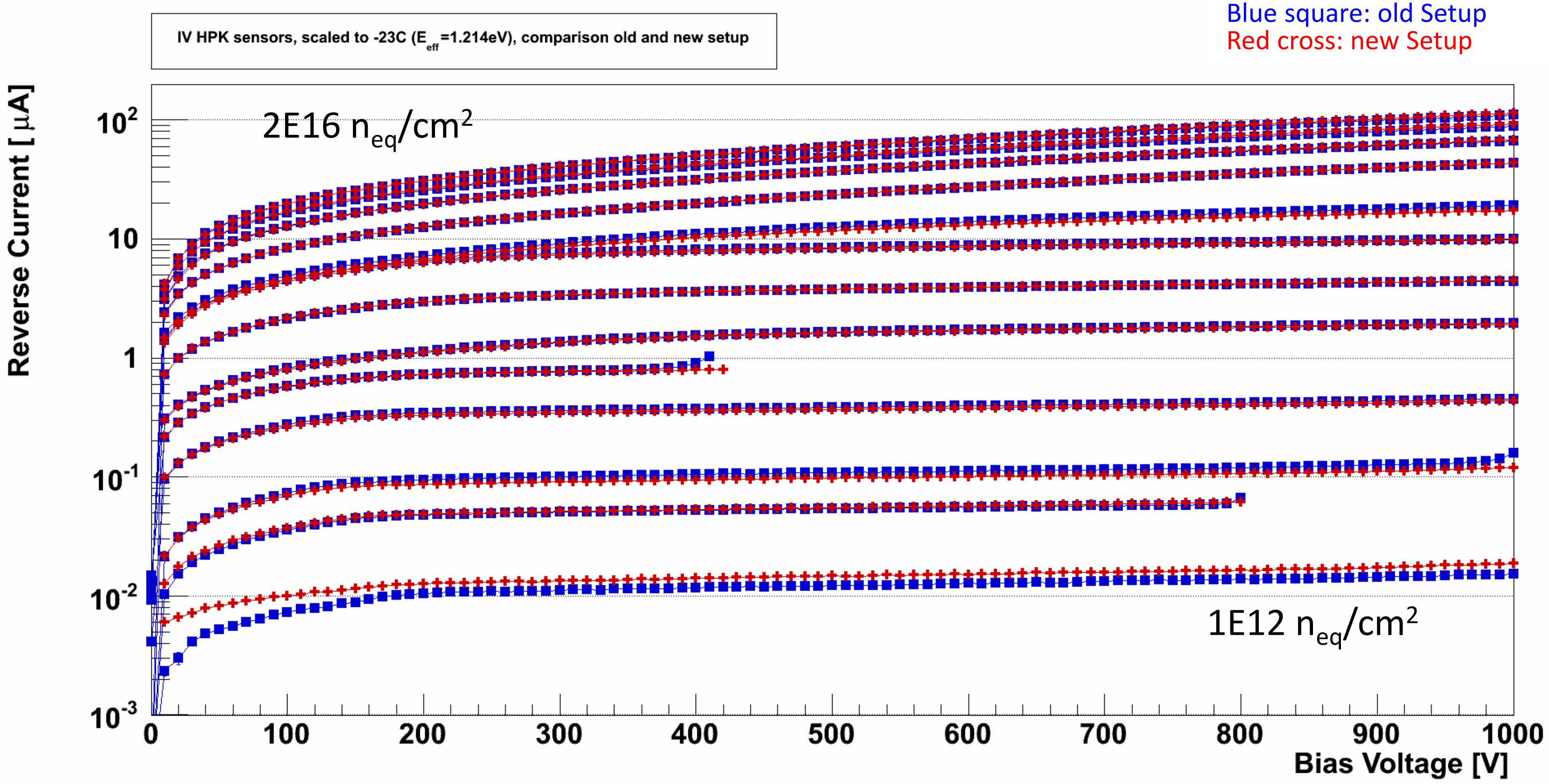
Comparison of Current

293µm sensors (HPK), 1E12 -> 2E16 n_{eq}/cm^2

Blue square: old Setup
Red cross: new Setup



PT1000

$$R_t = R_0[1 + AT + BT^2 + C(T - 100°\mathrm{C})T^3]$$

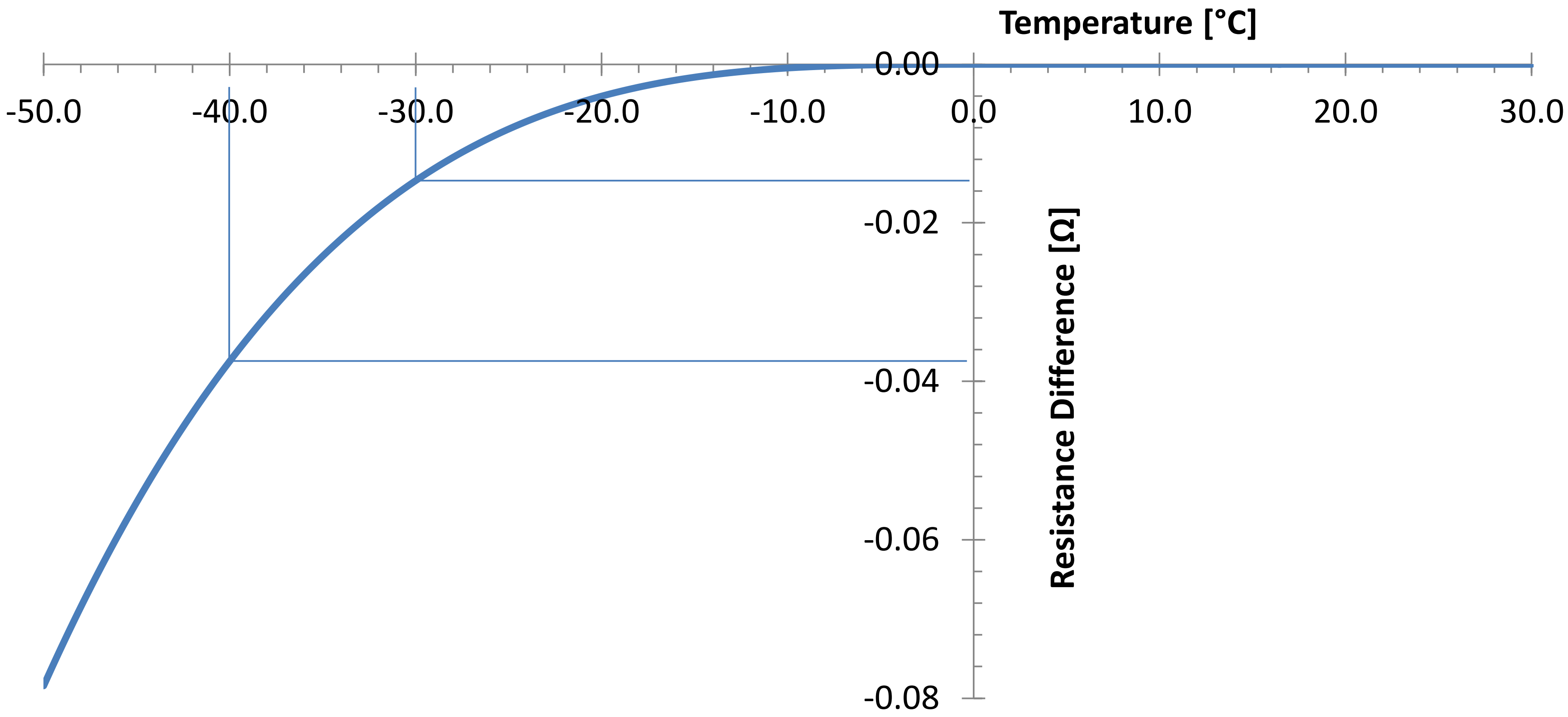
- T: temperature
- $R_0 = 1000\Omega$
- $A = 3.9083 \cdot 10^{-3} °\mathrm{C}^{-1}$
- $B = -5.775 \cdot 10^{-7} °\mathrm{C}^{-2}$
- $C = \begin{cases} -4.183 \cdot 10^{-12} °\mathrm{C}^{-4} & -200°\mathrm{C} \leq T \leq 0°\mathrm{C} \\ 0 & 0°\mathrm{C} \leq T \leq 850°\mathrm{C} \end{cases}$

For temperatures < 0°C there is no analytical solution for this equation

- Possible to use a numerical method: calculate resistance for small temperature steps and compare with measured resistance. If values agree within a certain margin, use this temperature
- Use same format as for temperatures > 0°C (up to quadratic term), but there is a small deviation

PT1000

PT1000 difference quadratic to total



Temperature difference between full equation and “quadratic” approximation

Up to -40°C the difference is less than 0.04Ω

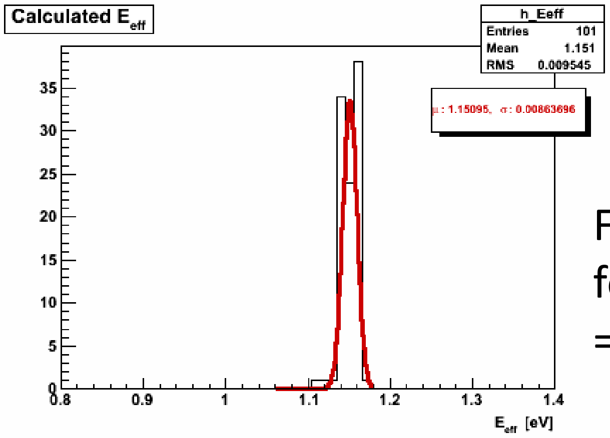
- Measurement by hand: $\sigma_R = 0.1\Omega$
- Automatic measurement: $\sigma_R \leq 0.02\Omega$

E_{eff} and α determination

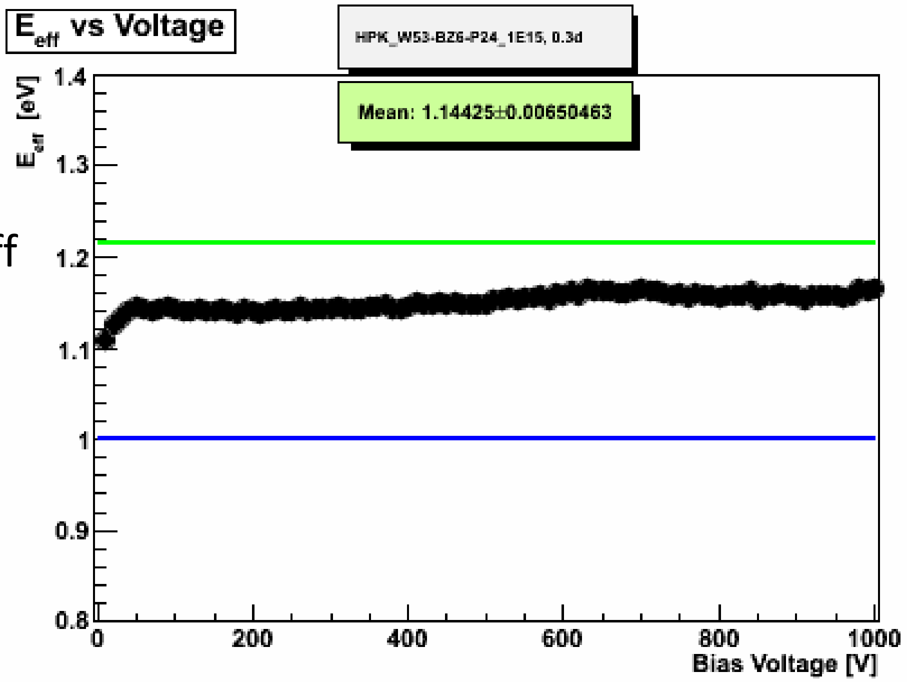
E_{eff} determination

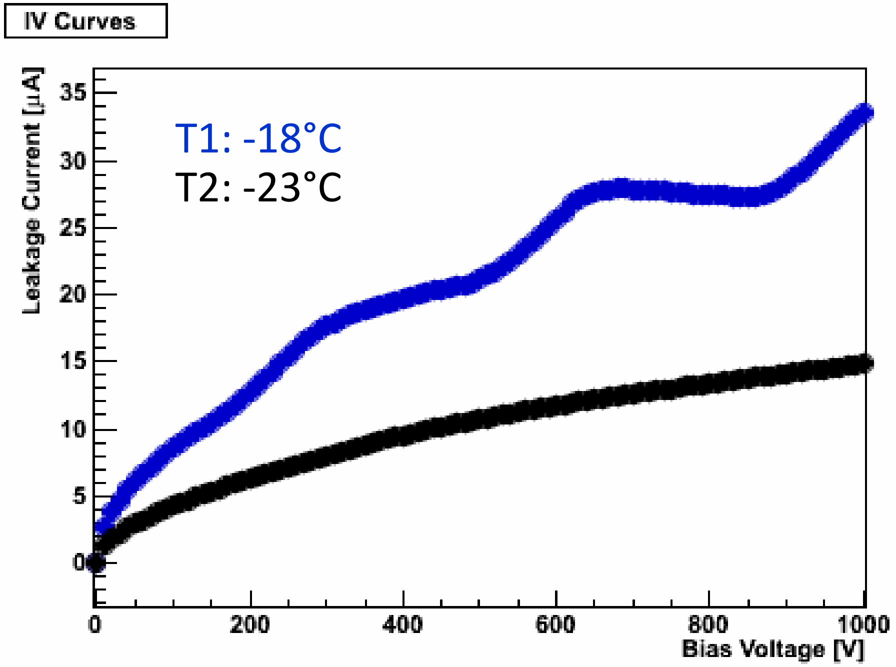
- Calculate E_{eff} for IV measurements
  - E_{eff} value for each measured voltage
    - Fill data in Histogram
    - Fit with Gauss function
  - Calculate average value
- Fit E_{eff} vs Fluence with straight lines
  - Low energy (no slope): $f(x) = a$
  - High energy: $f(x) = a - b\log_{10}(x)$

293µm, 1E15n_{eq}/cm^2, 0.3d

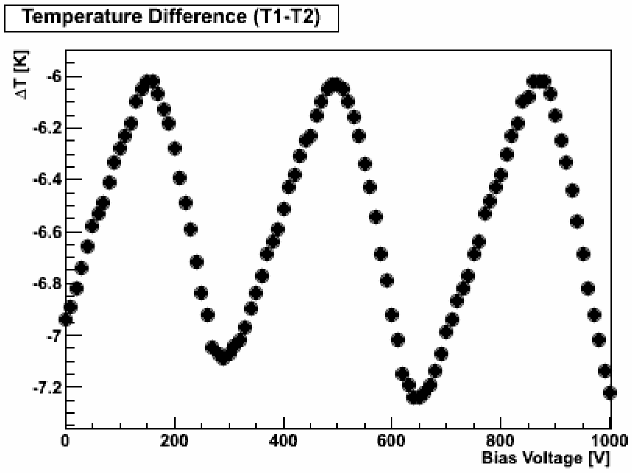


Fairly constant Eeff for all voltages
=> Good Gauss fit

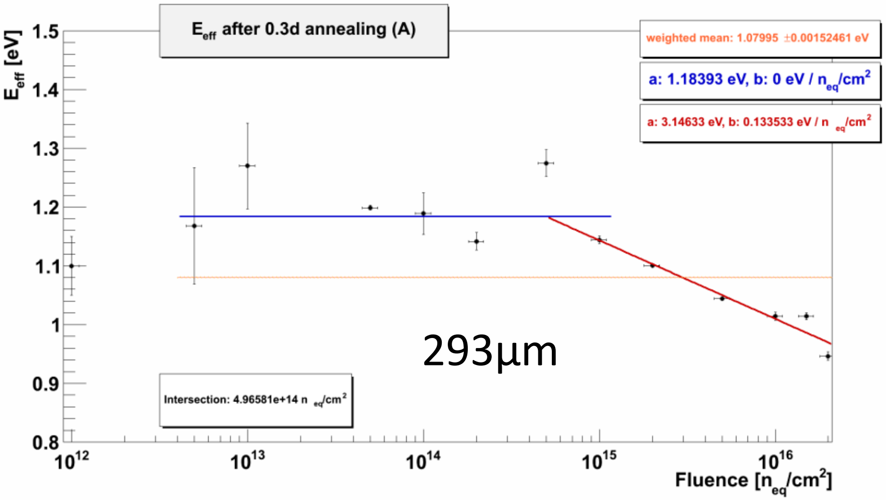


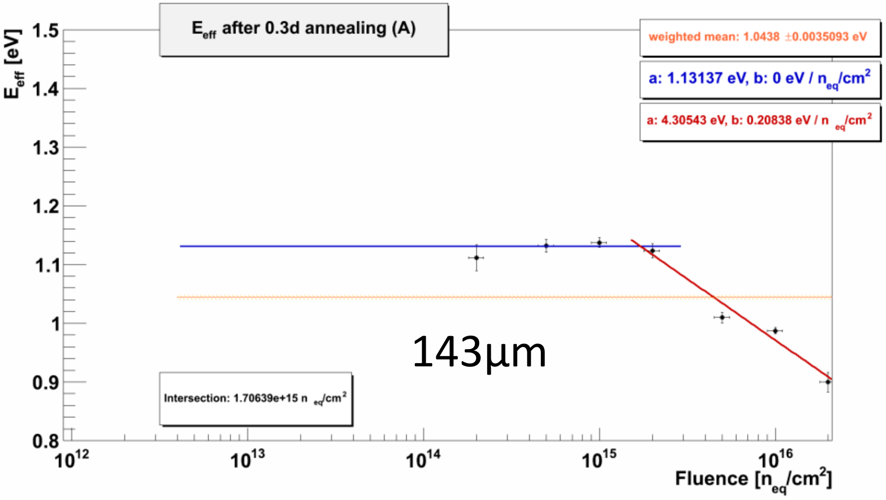


Temperature oscillations due to freezer -> can be seen as well in current

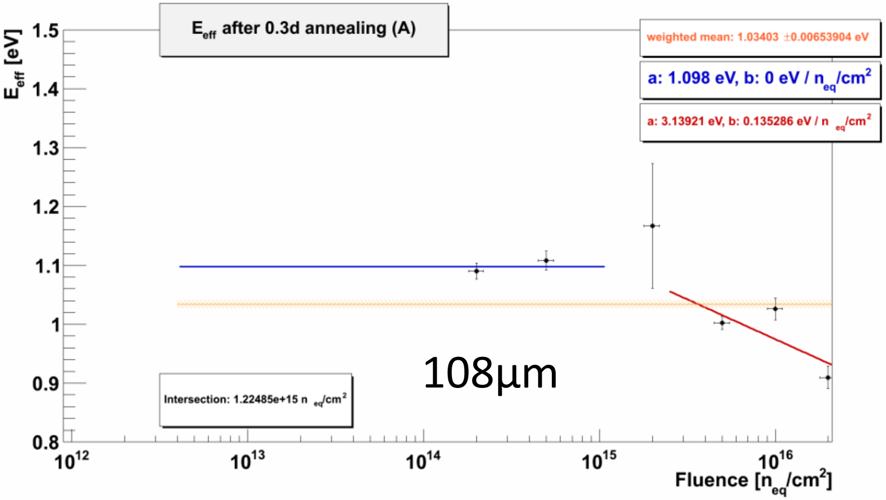


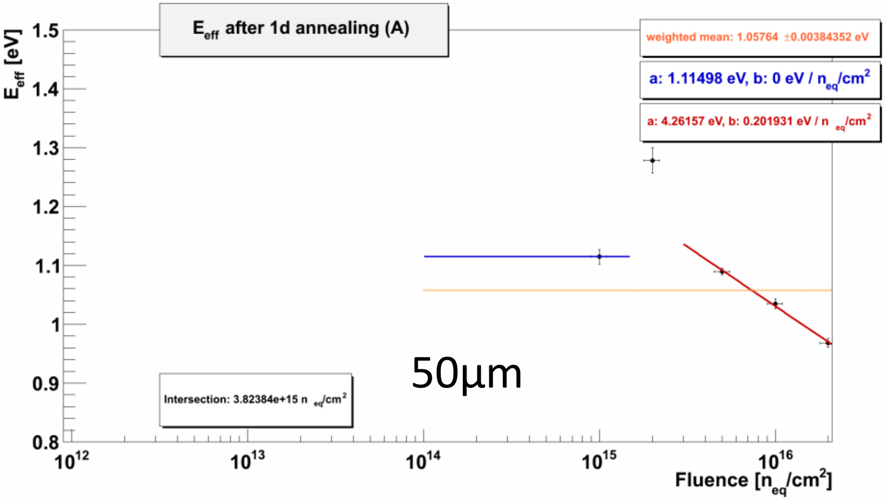
E_{eff} for different thickness



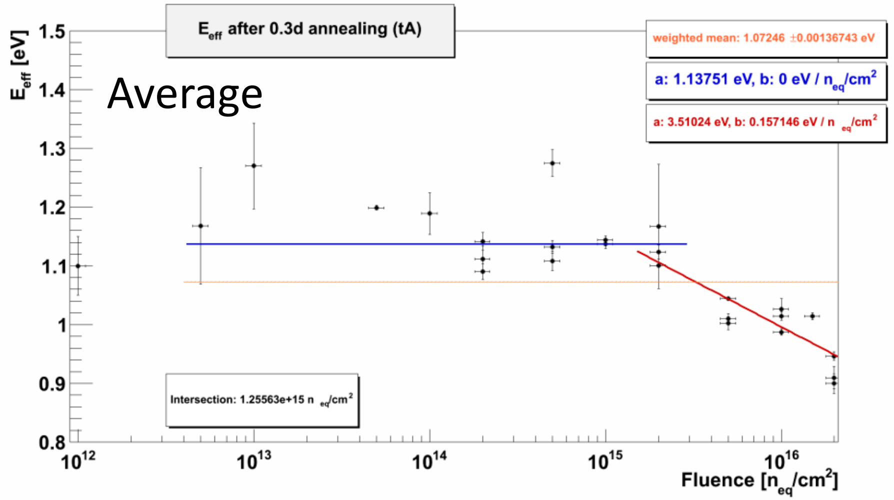


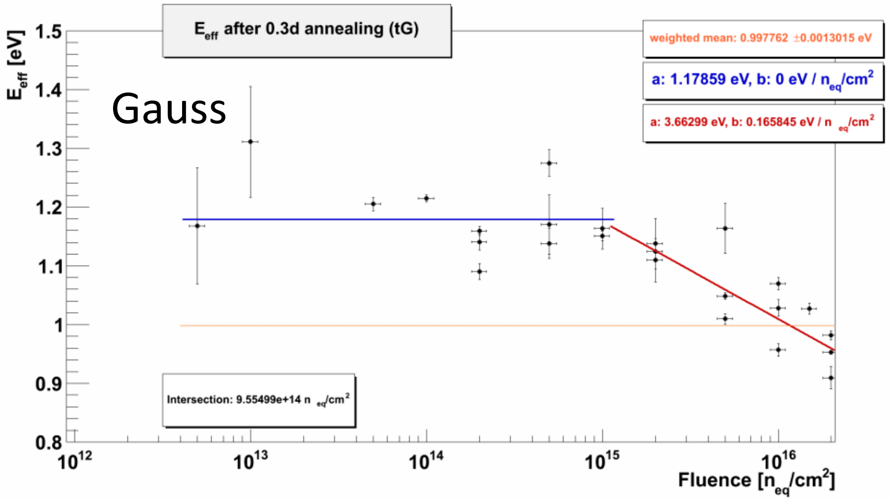
For high fluences (>1E15 / 2E15 n_{eq}/cm^2) E_{eff} decreases with increasing fluence





Gauss vs Average

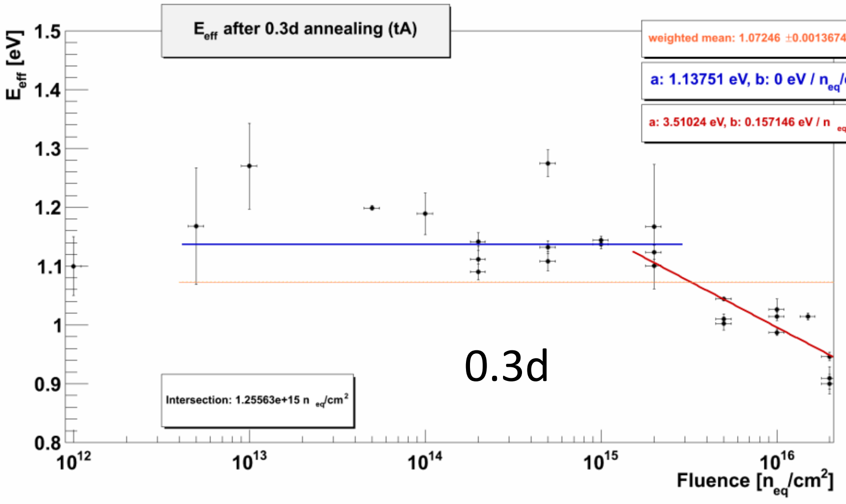


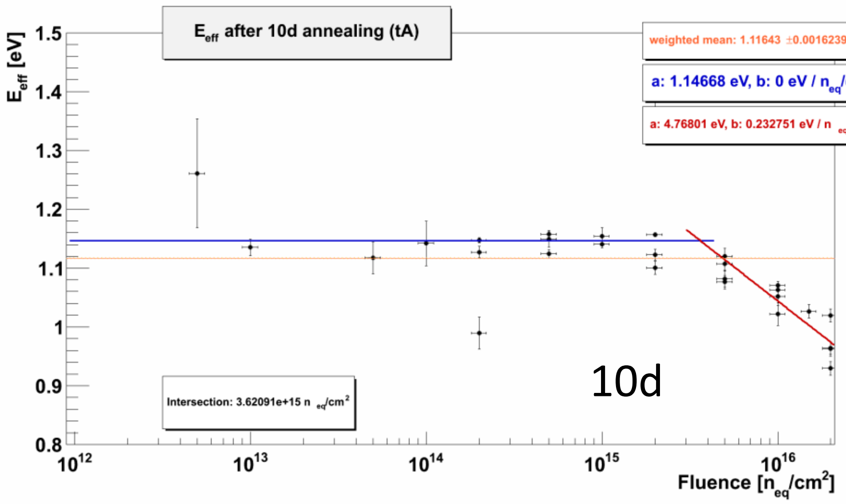


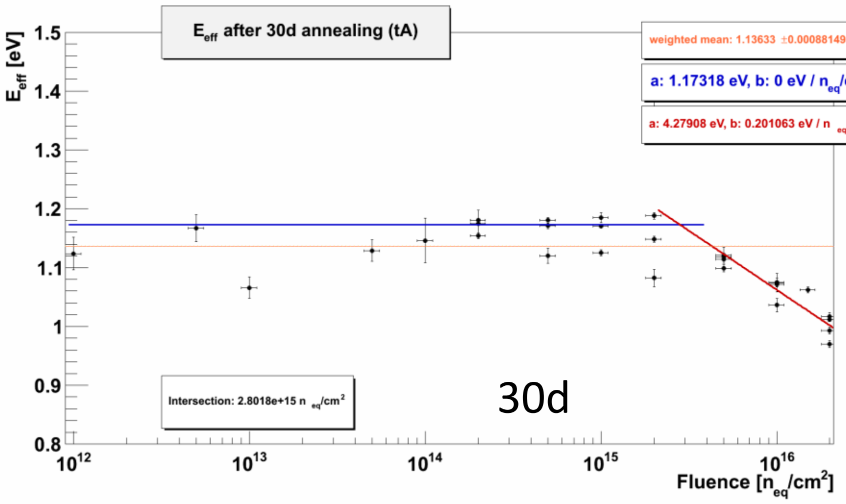
- Small difference between gauss and average E_{eff} determination
  - Fit of gauss distribution not always possible

		a	σ_a	b	σ_b
Low fluence	Average	1.138	0.002		
	Gauss	1.179	0.003		
High fluence	Average	3.51	0.16	0.16	0.01
	Gauss	3.7	0.2	0.166	0.013

Average values after annealing

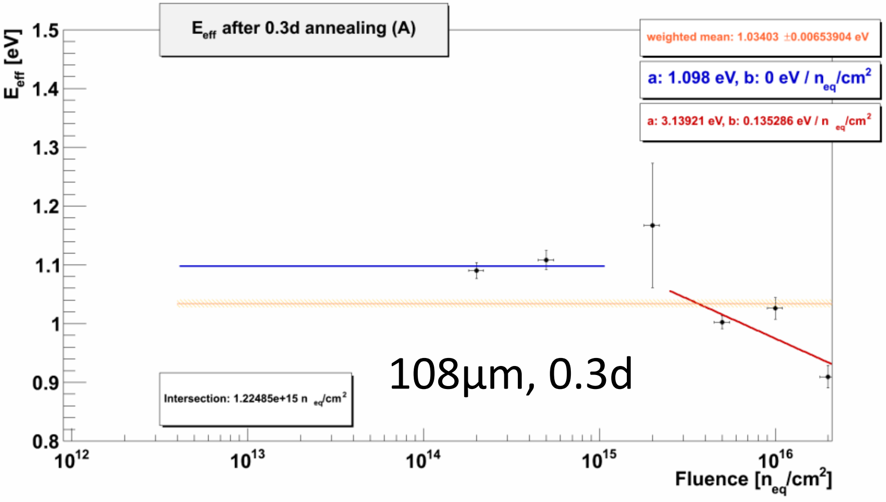




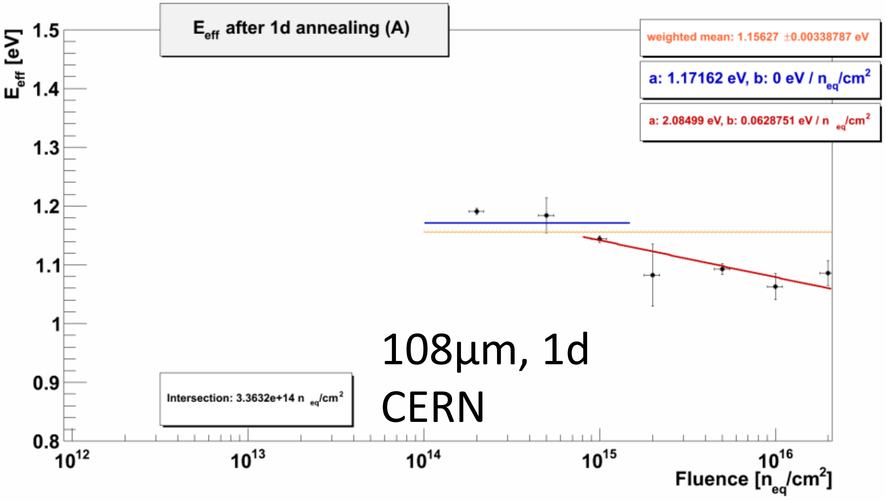


- Small increase of E_{eff} values with increasing room temperature annealing time

Compare freezer with cold chuck

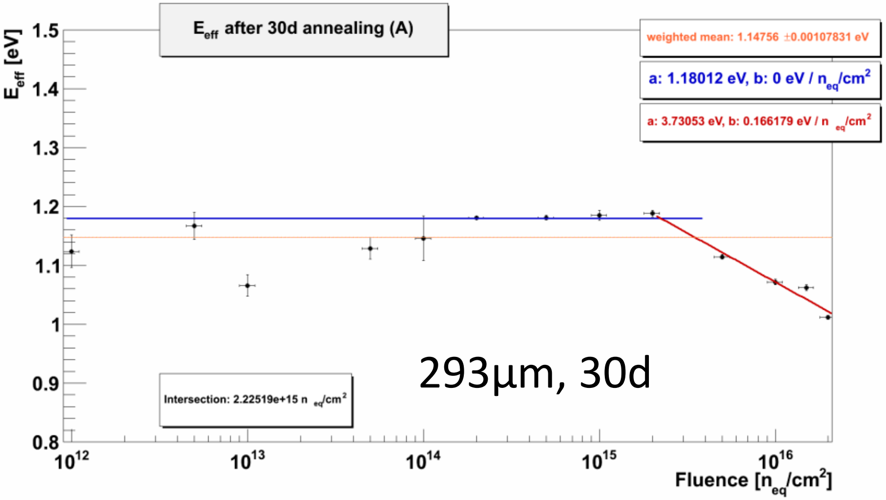


108µm, 0.3d

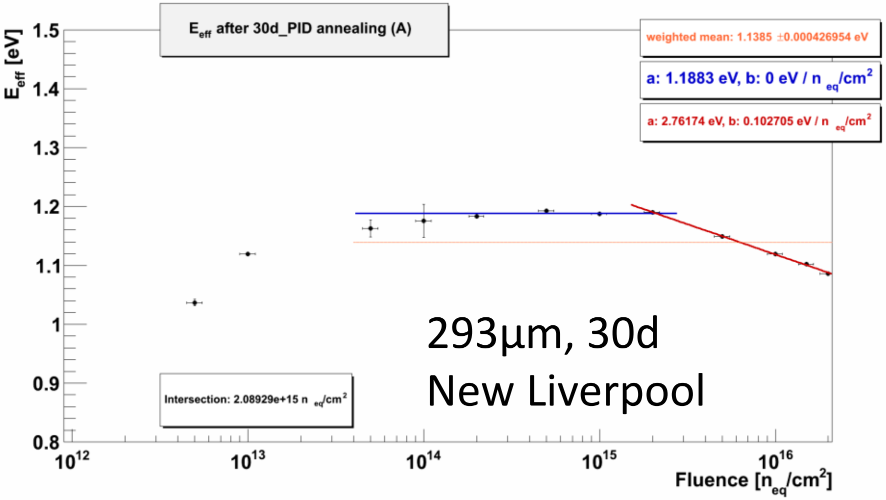


108µm, 1d
CERN

- Cold chuck method reduces E_{eff} decrease at high fluences a bit



293µm, 30d

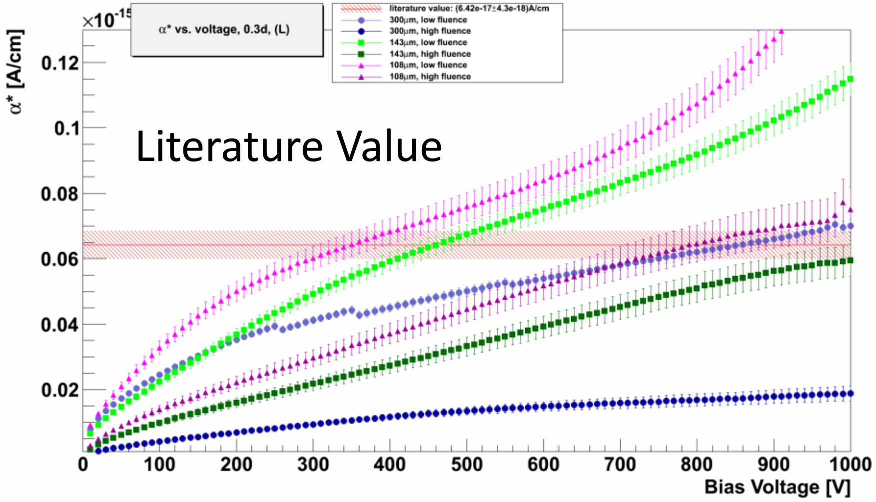


293µm, 30d
New Liverpool

α determination

- Scale current to 21°C
  - Use different E_{eff} values
    - Literature value
    - For each sensor
      - Gauss value (from measurement of that sensor or from fit)
      - Average value (from measurement of that sensor or from fit)
      - Total Gauss / Average (fit using E_{eff} values from all sensors)
  - Fit straight line in ΔI/V vs Φ plot
    - low irradiation fluence ($\leq$ 1E15n_{eq}/cm^2)
    - high irradiation fluence ($\geq$ 5E15 n_{eq}/cm^2)
- But: sensors not fully depleted (particularly at high fluences)
  - Geometric current related damage rate α*:
    - Instead of unknown depleted volume use the geometric volume
    - For fully depleted volume it is equal to the standard definition of α

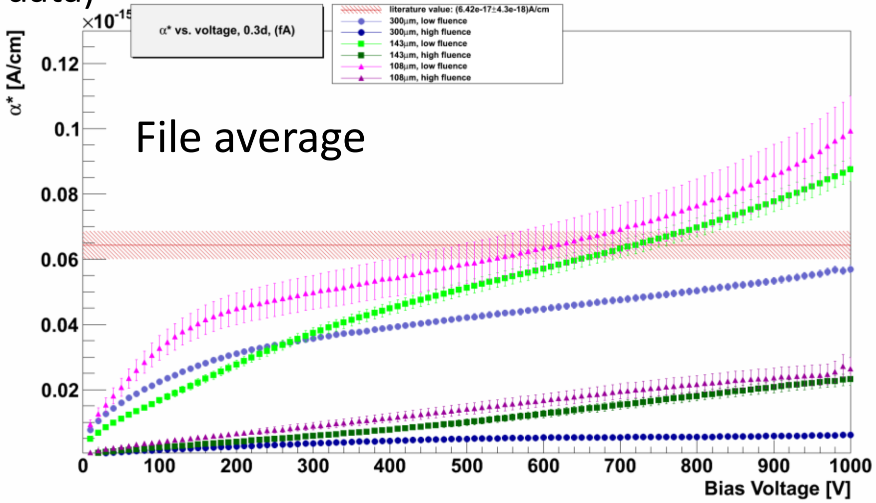
Which E_{eff} value to use



Literature Value

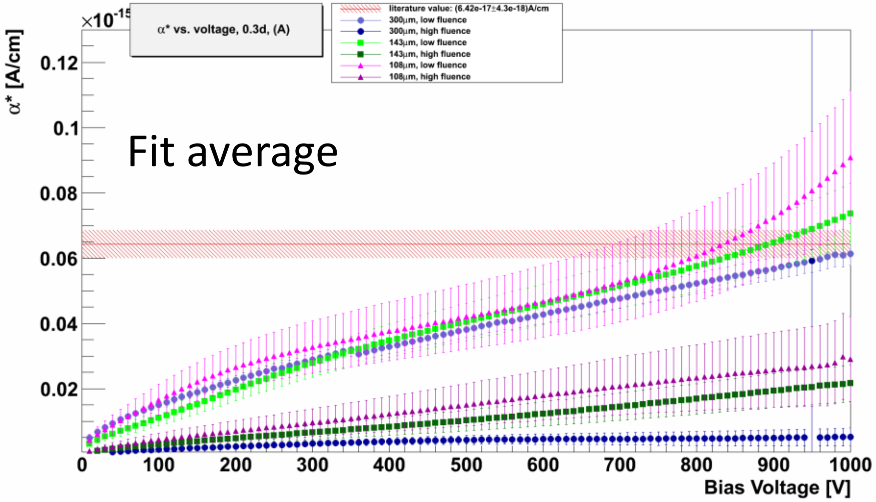
- Using literature value for scaling results in too high α^* values
- Using the determined values improves this
  - Using the fit data of all sensors the error bars increase due to the high spread of the values

Using separate E_{eff} values for each sensor (form IV data)



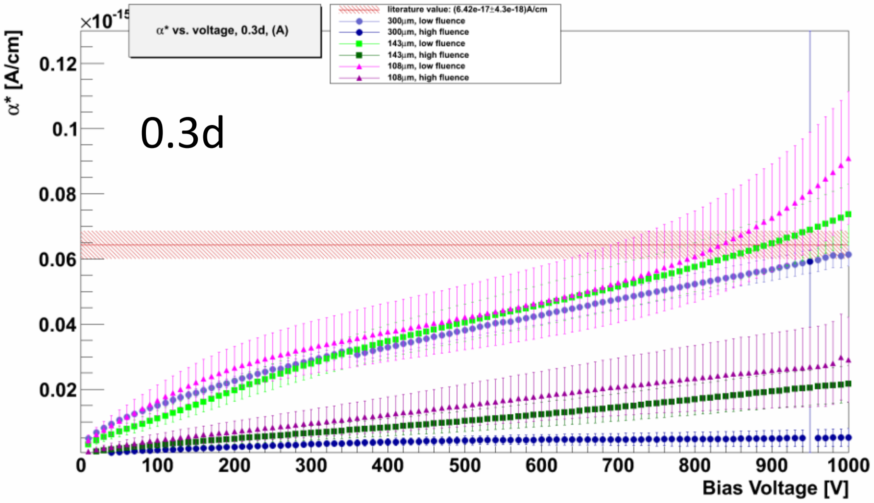
File average

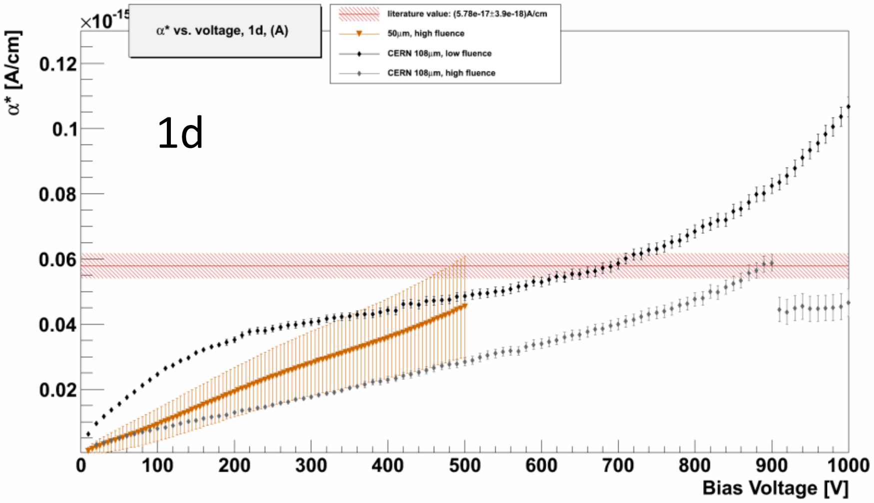
Using function from fit of all average E_{eff} values



Fit average

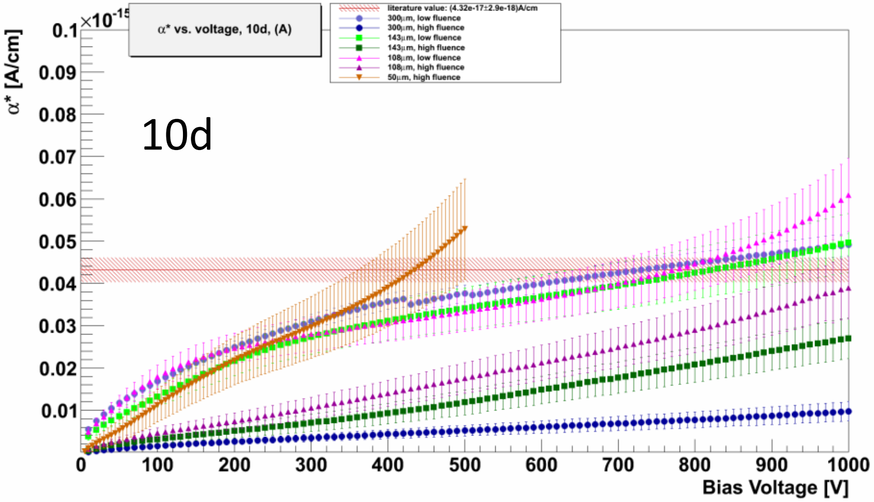
α^* after annealing

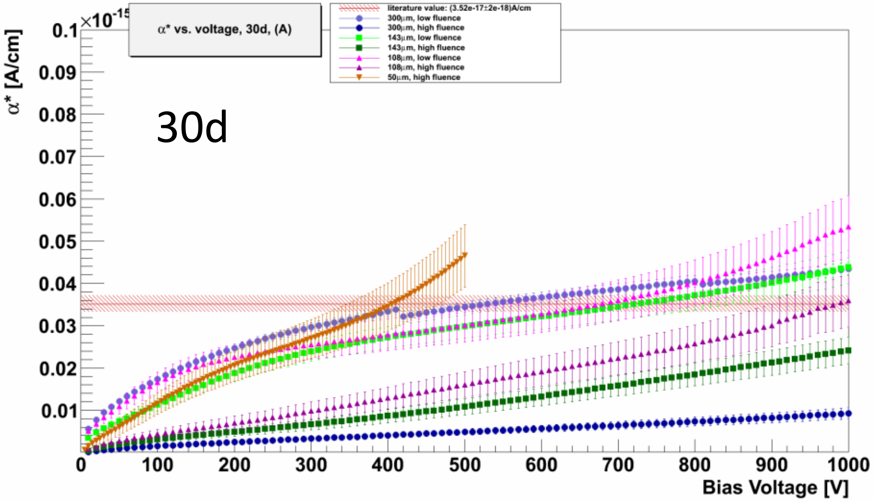




Large error bars due to large uncertainties for E_{eff} value from fit (high fluence scaled by factor 0.2 for better overview)

With increasing annealing time the high fluence values increase further towards literature value



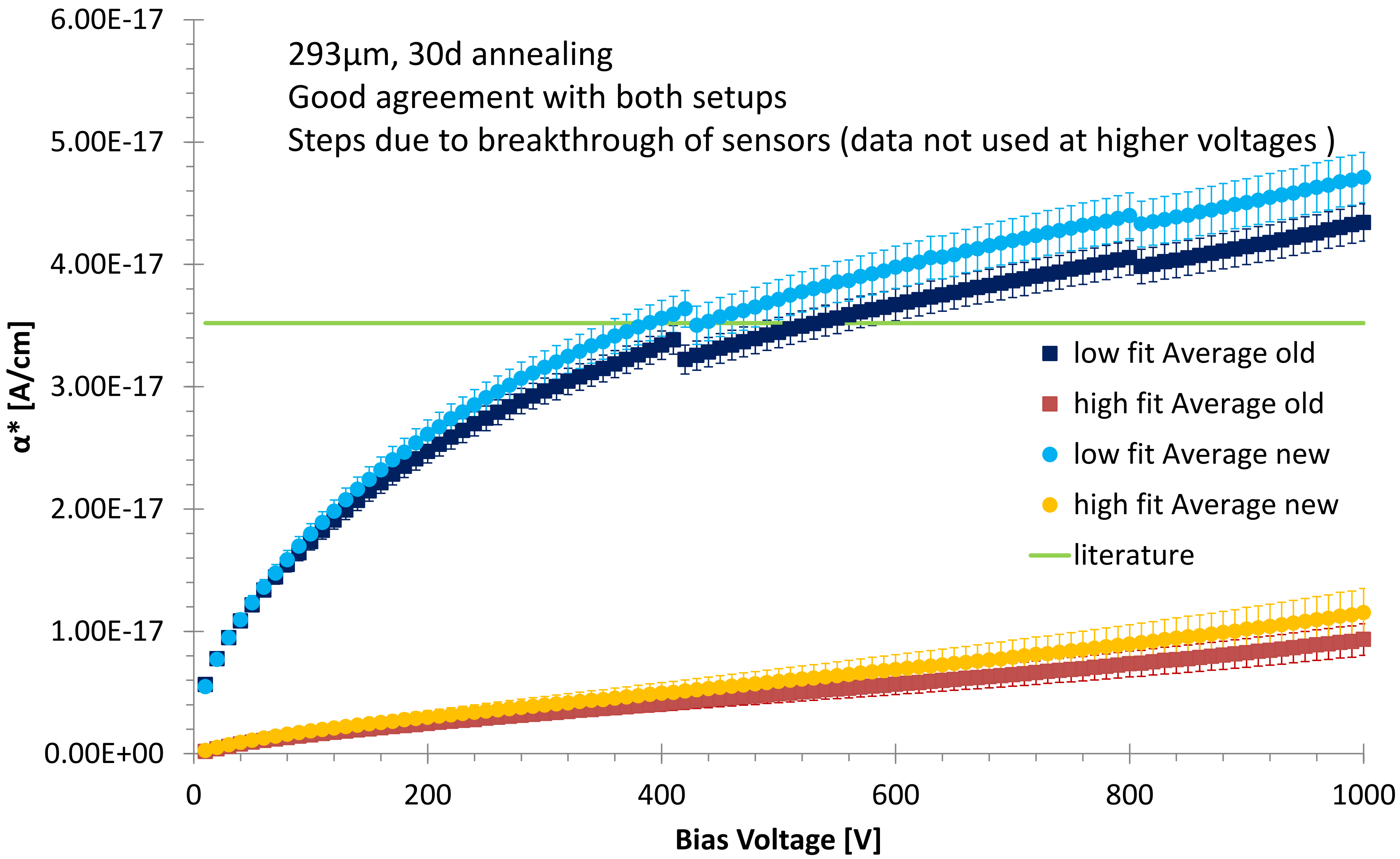


Comparison freezer <-> cold chuck

293µm, 30d annealing

Good agreement with both setups

Steps due to breakthrough of sensors (data not used at higher voltages)



Summary

- Computing E_{eff} from IV measurements it can be seen that at fluences > 2E15n_{eq}/cm^2 the value decrease with increasing fluence
  - Same behaviour after room temperature annealing up to 30d
- Measurements with a cold chuck
  - Fast reach of target temperature
  - Can actively counter self heating
- For α^* determination the appropriate E_{eff} has to be used
  - For high fluences the literature value is not reached, but α^* is still increasing with increasing voltage => sensor not fully depleted

Backup

Alpha Literature I

Short term annealing

$$\alpha(t,T_a) = \alpha_\infty \sum_i \frac{b_i}{b_\infty} exp\left(-\frac{t}{\tau_i(T_a)}\right)$$

t: annealing time; T_a: annealing temperature

[2,3]

	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = \infty$
τ_i $[min]$	$(1.78\pm0.10)\times10^1$	$(1.19\pm0.03)\times10^2$	$(1.09\pm0.01)\times10^3$	$(1.48\pm0.01)\times10^4$	$(8.92\pm0.59)\times10^4$	∞
b_i	0.156±0.038	0.116±0.003	0.131±0.002	0.201±0.002	0.093±0.007	0.303±0.006

$\alpha_\infty = (2.86\pm0.18)\times10^{-17}$ A/cm [4]

[2]: M. Moll; *Radiation Damage in Silicon Particle Detectors*; **PHD Thesis**

[3]: R. Wunstorf; *Systematische Untersuchung zur Strahlenresistenz von Silizium-Detektoren für die Verwendung in Hochenergiephysik-Experimenten*; **PHD Thesis**

[4]: A. Chilingarov; *Radiation studies and operational projections for silicon in the ATLAS inner detector*; **NIM A 360 (1995) 432-437**

Alpha Literature II

Long term annealing

$$\alpha(t) = \alpha_I exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \ln\left(\frac{t}{t_0}\right)$$

t: annealing time

Parameter for annealing at 21°C from fit

α_I=1.23×10^{-17} A/cm, α_0=7.07×10^{-17} A/cm

τ_I=1.4×10^{4} min, t_0=1 min

β=3.29×10^{-18} A/cm

α_I and β vary slightly with annealing temperature, average values:

$\langle\alpha_I\rangle$=(1.23±0.06)×10^{-17} A/cm, $\langle\beta\rangle$=(3.07±0.18)×10^{-18} A/cm

α_0 depend on annealing temperature => value from parameterization:

α_0=(6.74±0.06)×10^{-17} A/cm

[2]: M. Moll; *Radiation Damage in Silicon Particle Detectors*; **PHD Thesis**

Alpha Values Literature

- Using equations to calculate theoretical alpha values
- Annealing temperature of 20°C (room temperature)

- Sample preparation: ~470min (0.3d) for all sensors
- Room temperature annealing of sensors in Nitrogen box

Annealing time	Short term annealing	Long term annealing	Long term annealing (average)
t [min]	α [10^{-17}A/cm]		
0.3d (=470 min)	**6.40±0.43**	6.24	6.04±0.14
10d (=14400min)	**4.32±0.29**	4.36	4.24±0.18
30d (=43220min)	**3.50±0.23**	3.61	3.52±0.20

↑

bold: “theoretical value” for comparison

α determination

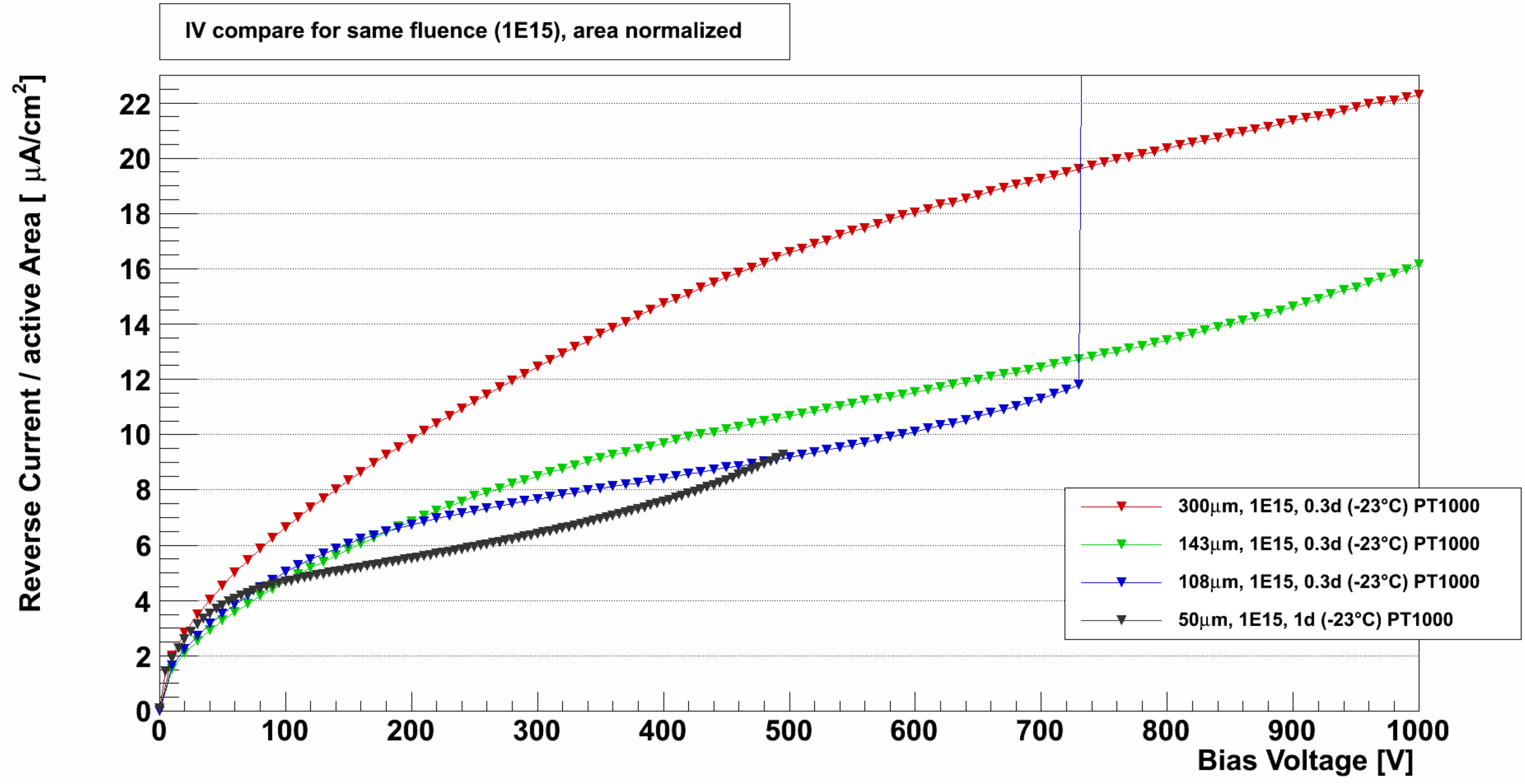
$$\sigma_{I(T_2)}^2 = I(T_2)^2 \left[\left(\frac{\sigma_{I(T_1)}}{I(T_1)} \right)^2 + \left(2 + \frac{E_{eff}}{2k_B T_1} \right)^2 \left(\frac{\sigma_{T_1}}{T_1} \right)^2 + \left(2 + \frac{E_{eff}}{2k_B T_2} \right)^2 \left(\frac{\sigma_{T_2}}{T_2} \right)^2 + \left(\frac{1}{2k_B} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right)^2 \sigma_{E_{eff}}^2 \right]$$

- Major source for uncertainty: E_{eff} fit for high fluences
  - $\frac{\sigma_{E_{eff}}}{E_{eff}}$ is up to 10% for high fluences, which results in large uncertainties of the scaled current and therefore large uncertainties of the straight line fit
  - Had to scale $\sigma_{E_{eff}}$ down by factor 0.2 to get a reasonable size of the error bars in the graph

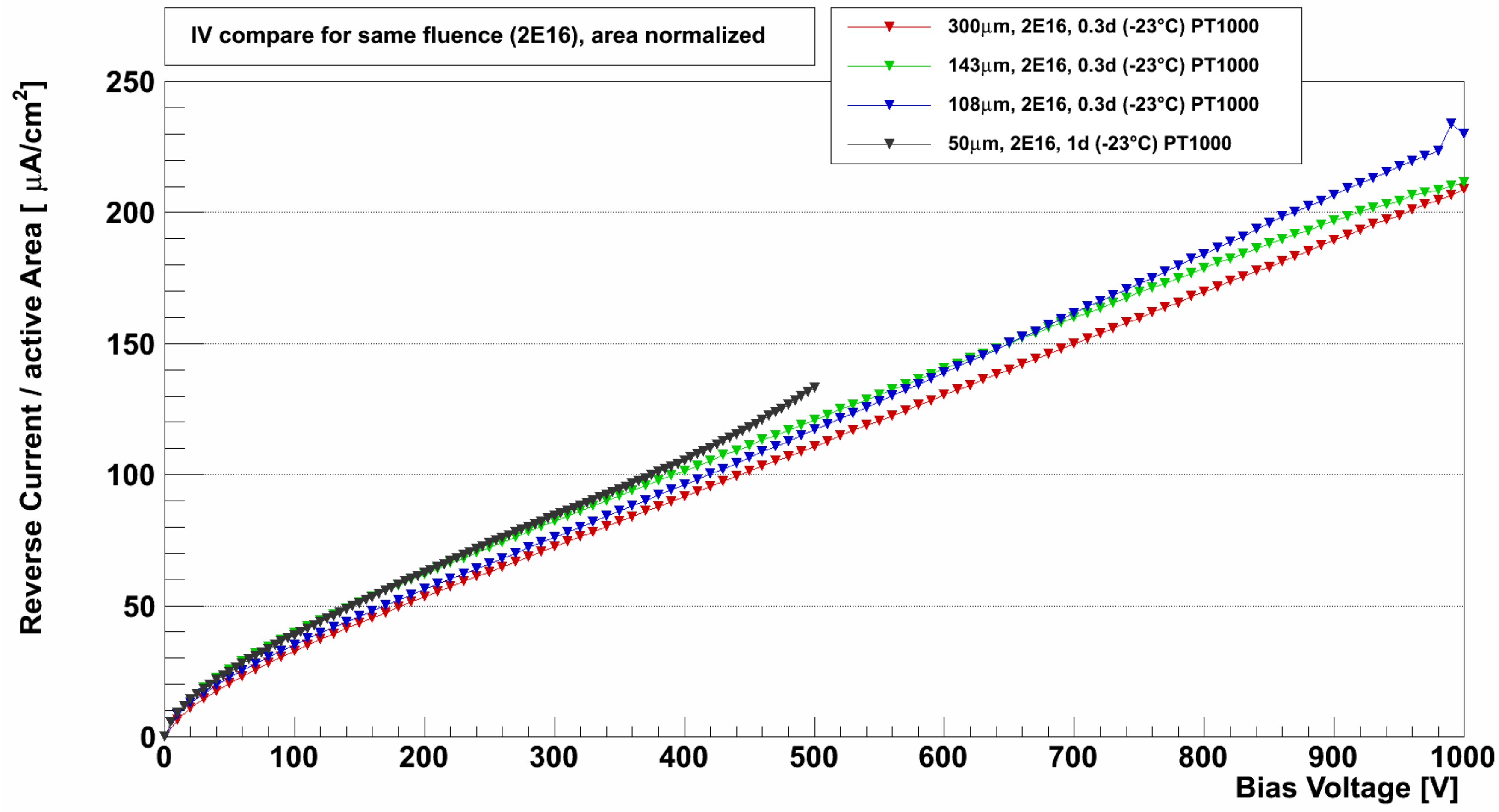
Leakage Current at different fluences

FOR SENSORS WITH DIFFERENT THICKNESS

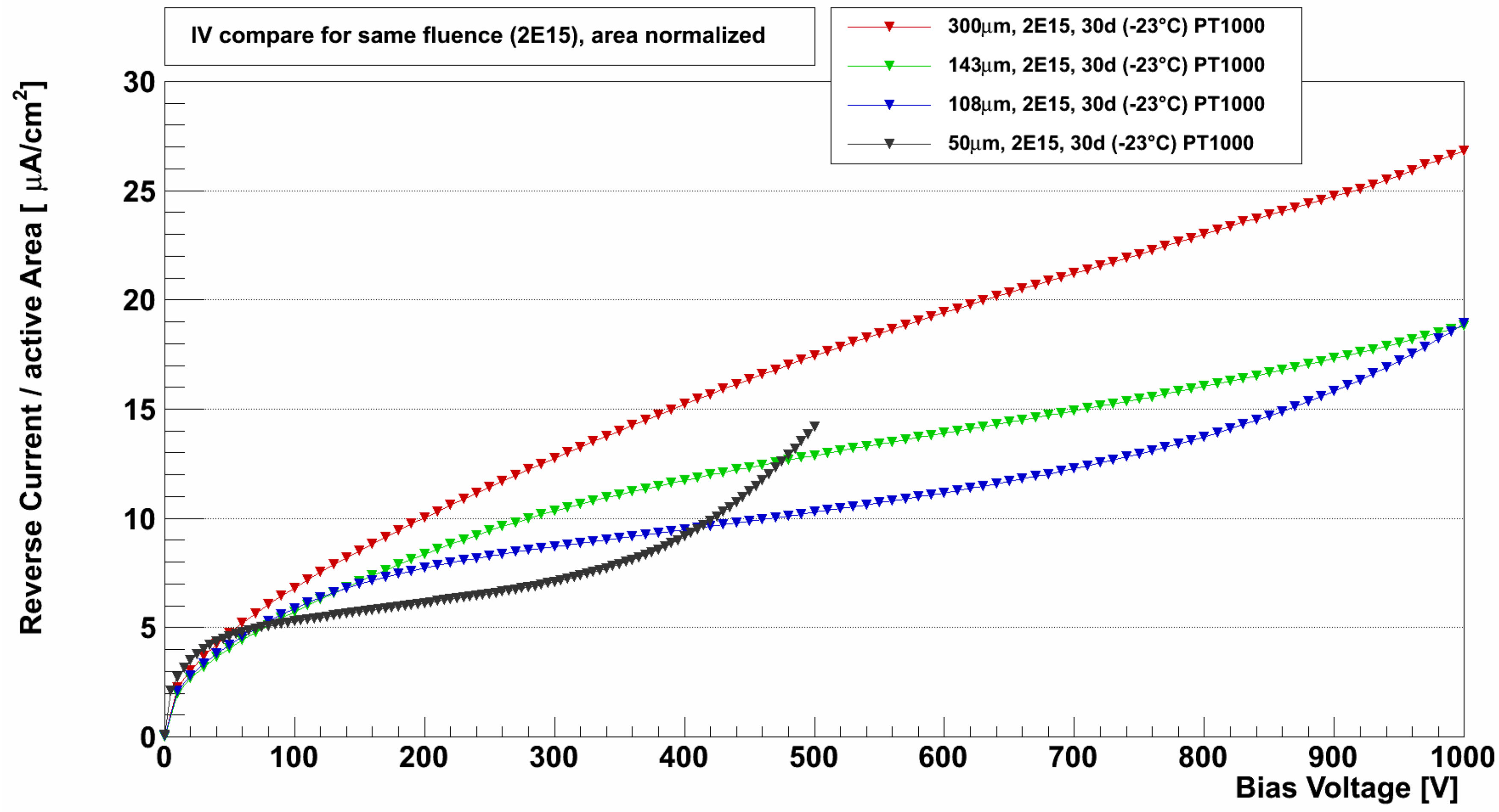
0.3d, 1E15 n_{eq}/cm^2



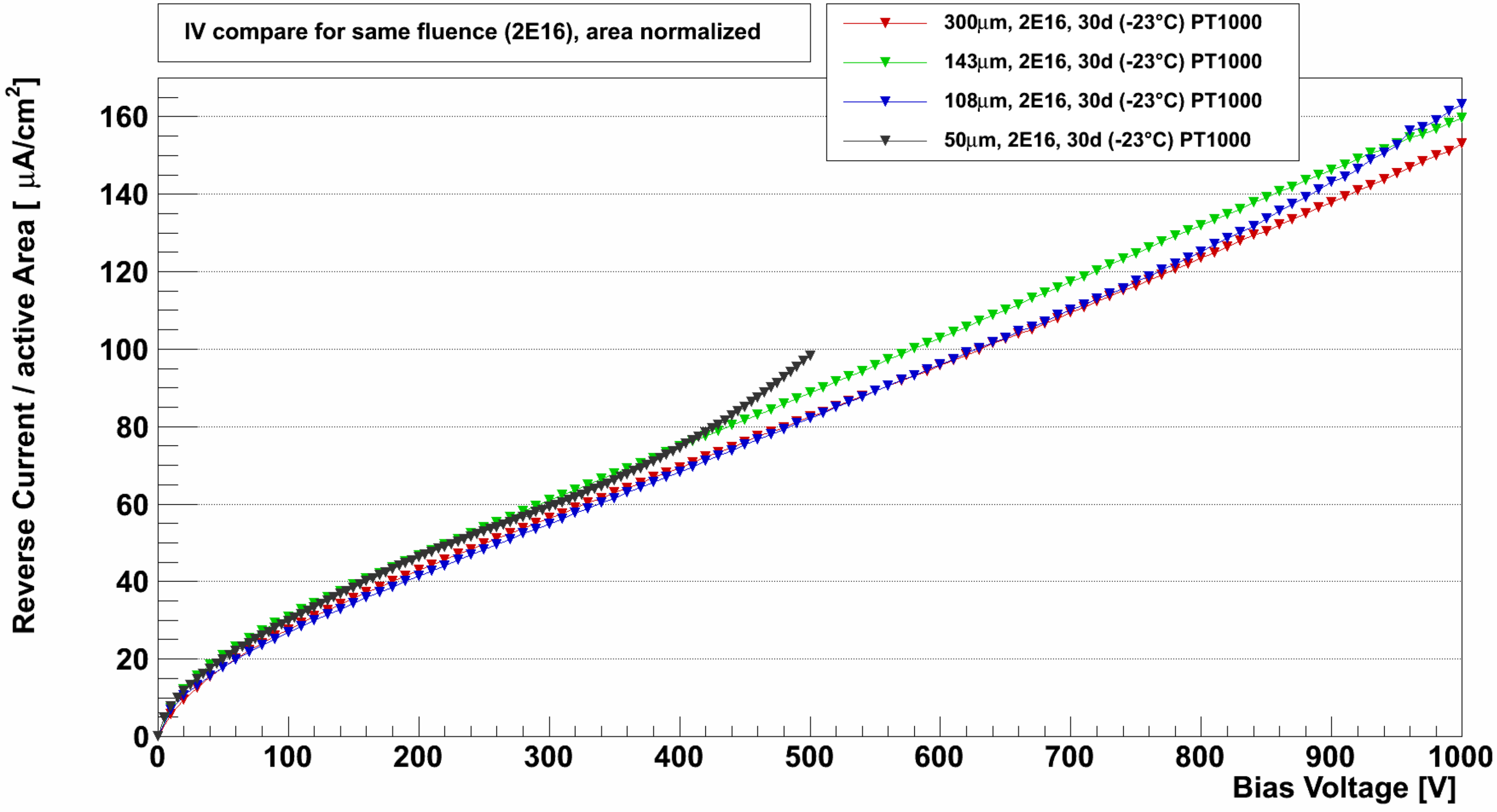
0.3d, 2E16 n_{eq}/cm^2



30d, 2E15 n_{eq}/cm^2



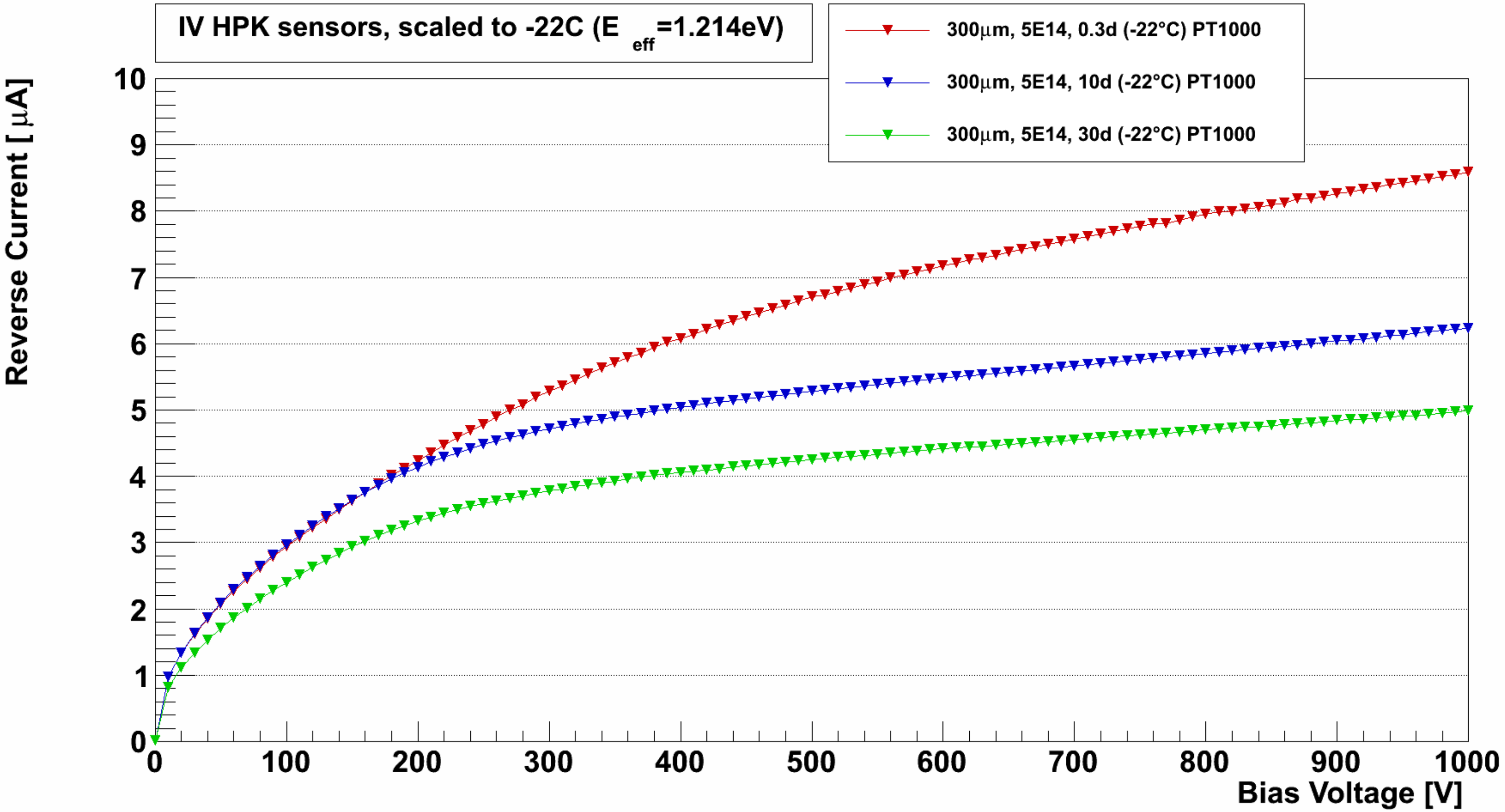
30d, 2E16 n_{eq}/cm^2



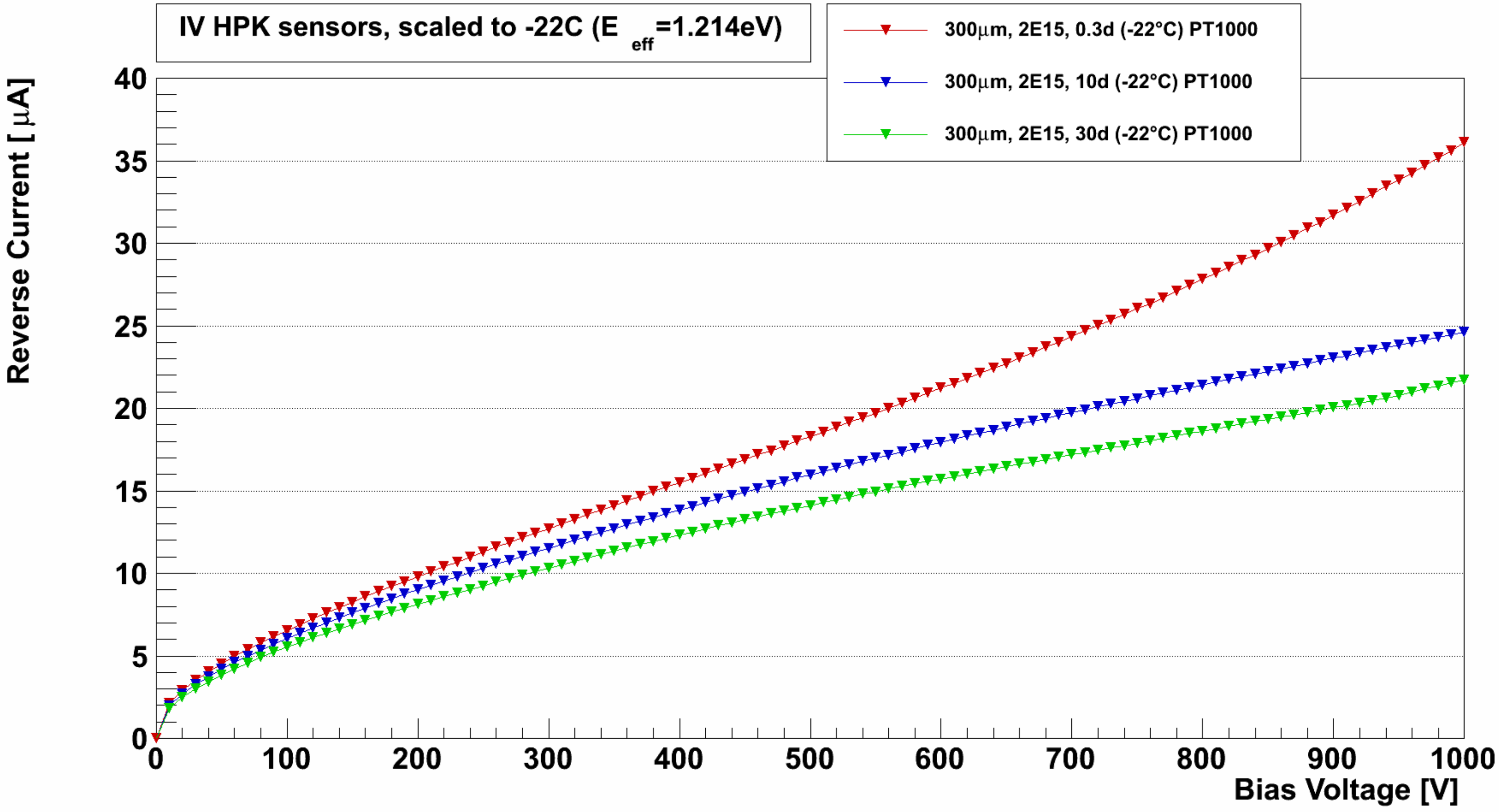
Leakage Current at different annealing steps

FOR SAME SENSOR

5E14 n_{eq}/cm^2


IV HPK sensors, scaled to -22C (E_{eff}=1.214eV)
300µm, 5E14, 0.3d (-22°C) PT1000
300µm, 5E14, 10d (-22°C) PT1000
300µm, 5E14, 30d (-22°C) PT1000
Reverse Current [µA]
0
1
2
3
4
5
6
7
8
9
10
Bias Voltage [V]
0
100
200
300
400
500
600
700
800
900
1000

2E15 n_{eq}/cm^2

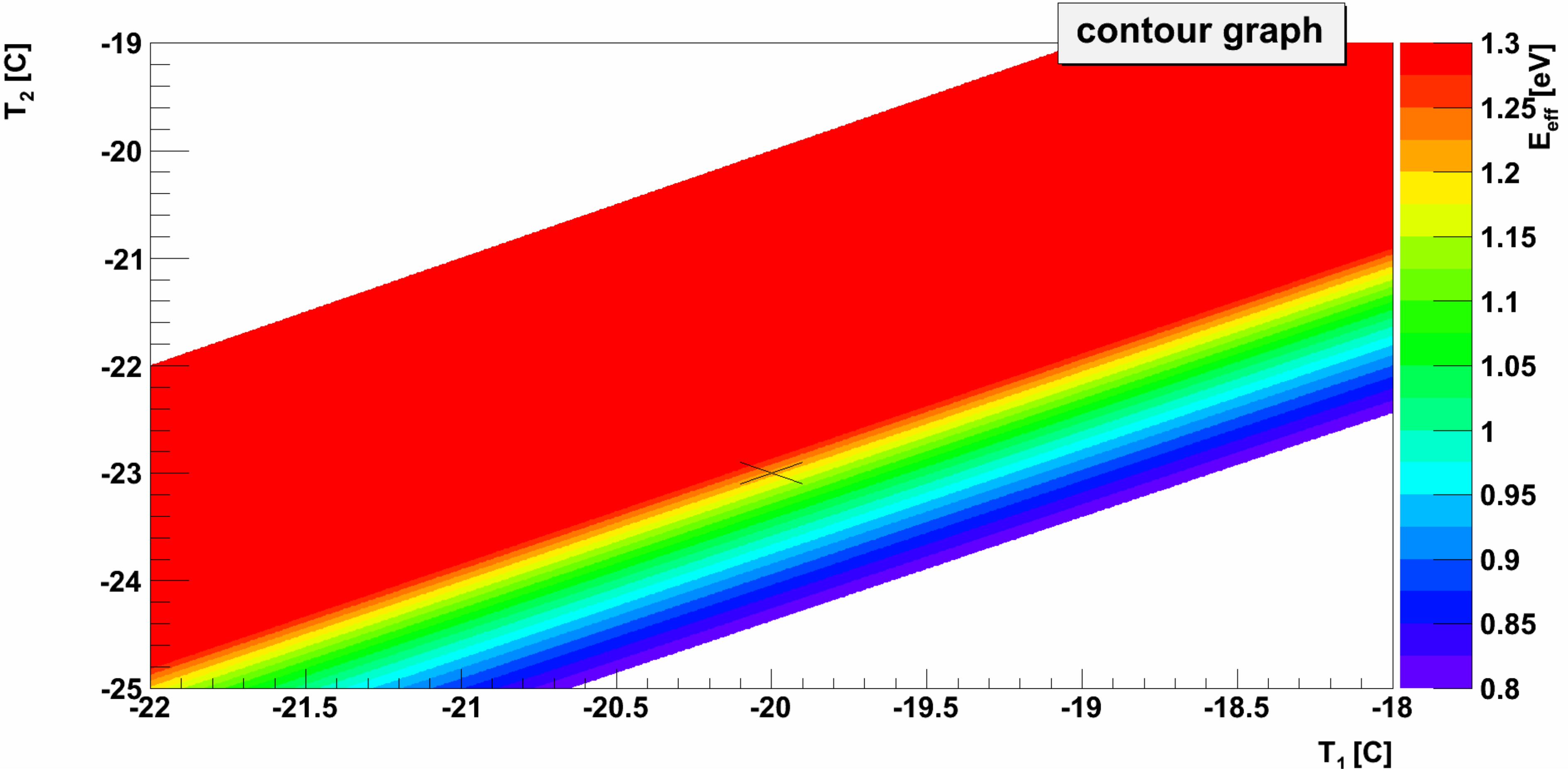

IV HPK sensors, scaled to -22C (E_{eff}=1.214eV)
300µm, 2E15, 0.3d (-22°C) PT1000
300µm, 2E15, 10d (-22°C) PT1000
300µm, 2E15, 30d (-22°C) PT1000
Reverse Current [µA]
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
700
800
900
1000
Bias Voltage [V]

Simulations and Error reflection

E_{eff} variation

- In formula two possible causes of variation in E_{eff}:
  - Wrong temperature measurement (not only temperature of sensor, also temperature of freezer => temperature measured too cold)
  - Wrong current measurement
- Simulation of influence from both effects on E_{eff} with:
  - Current measurement correct, only temperature variation
  - Temperature measurement correct, only current variation
- Chosen parameters:
  - T_1 = -20.0°C, T_2 = -23.0°C
  - I_1 = 20.0µA, I_2 = 13.99µA
    - Value of I_2 calculated from other parameters with E_{eff} = 1.214eV

Temperature Variation



Temperature measurement on the sensor could be affected by environment. The environment can be warmer than the sensor due to PID cooling, or the sensor can be warmer than the environment due to self heating. Either way the measured temperature is not the actual silicon temperature.