Charge multiplication in radiation-damaged epitaxial silicon detectors

Jörn Lange[1], Alexandra Junkes[1], Julian Becker[1], Eckhart Fretwurst[1], Robert Klanner[1], Gunnar Lindström[1], Ioana Pintilie[2]

[1] University of Hamburg
[2] NIMP Bucharest

12th Vienna Conference on Instrumentation, February 2010

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Bundesministerium für Bildung und Forschung

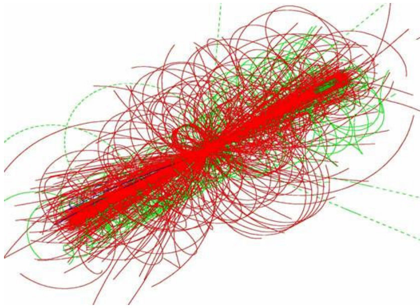
In the framework of the CERN RD50 Collaboration

Introduction

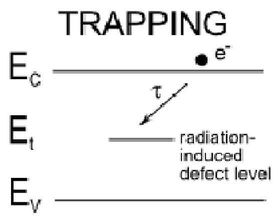
- Upgrade: LHC → S-LHC

	LHC	S-LHC
Luminosity	$10^{34}cm^{-2}s^{-1}$	→ $10^{35}cm^{-2}s^{-1}$
Fluence $\Phi_{eq}(r=4cm)$	$3x\ 10^{15}cm^{-2}$	→ $1.6x\ 10^{16}cm^{-2}$

⇒ very radiation hard detectors needed!

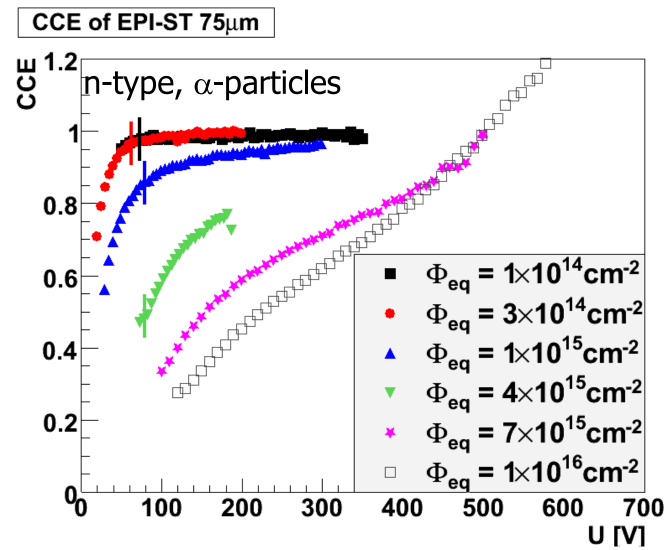


- Bulk radiation damage in Si detectors
  - Increasing depletion voltage (U_{dep}) at high fluences
  - Increasing leakage current (I_{rev}) ⇒ more noise and power consumption
  - Less charge collection efficiency (CCE) due to trapping ⇒ less signal



Introduction

- Trapping: most limiting factor at S-LHC fluences
  ⇒ Degradation of Charge Collection Efficiency (CCE)
- But at high fluences and voltages: CCE>1
  ⇒ Trapping overcompensated by Charge Multiplication (CM)
- Can CM be used for highly damaged S-LHC detectors?
  ⇒ Detailed understanding of the formation and properties of CM in irradiated sensors needed
- Questions to be answered:
  1) Why/how is the CM region formed?
  2) Where is the CM region located?
  3) Is the measured charge linear to the deposited one?
  4) Is CM uniform over the detector area?
  5) Is the operation of a detector in the CM regime stable in time?
  6) How does CM affect the charge spectrum or the noise?



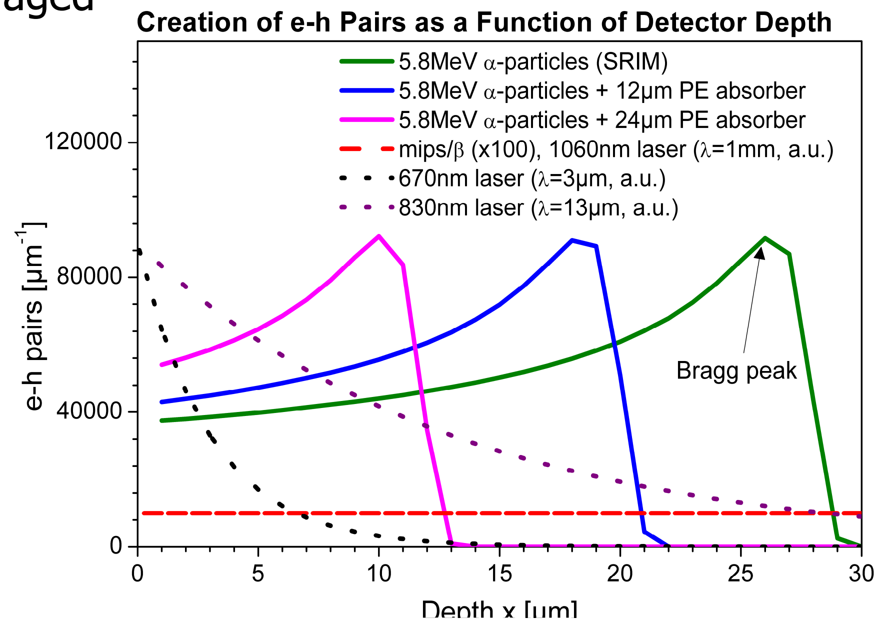
Investigated Material

- Epitaxial (Epi) Si on Cz substrate: candidate for superior radiation hardness
  - *Device Engineering:* thin (25-150µm)
  - *Defect Engineering:* high O concentration in standard material (ST): $<[O]>=9.3 \times 10^{16} cm^{-3}$
    further O enrichment possible (DO): $<[O]>=6 \times 10^{17} cm^{-3}$

- n-type
- 75µm, 100µm, 150µm thickness
- Pad detectors produced by CiS:
  $5 \times 5 mm^2$ and $2.5 \times 2.5 mm^2$
- 24GeV/c proton irradiation (CERN PS)
  up to $\Phi_{eq}=10^{16} cm^{-2}$
- 30 min at 80°C annealing if not stated otherwise
- Standard sample here: EPI-ST 75µm, $10^{16} cm^{-2}$

Experimental Methods

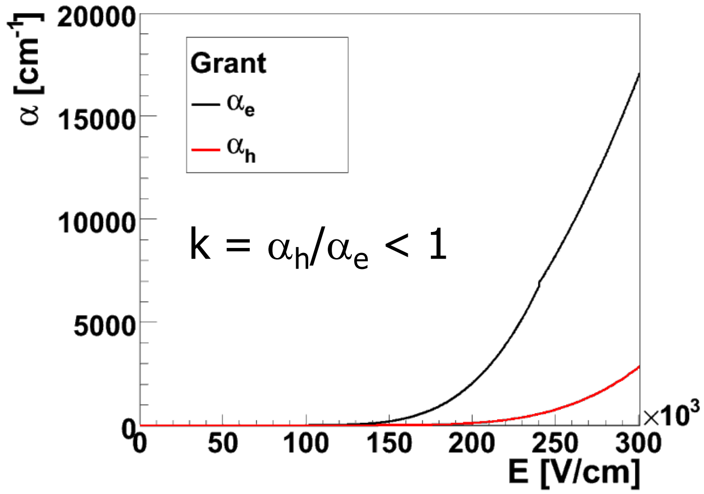
- CV at room temperature, 10 kHz → U_{dep}, N_{eff}
- Thermally Stimulated Current (TSC) → microscopic defect concentrations
- Transient Current Technique (TCT) → CCE
  - No time-resolved pulses below 150 µm
    ⇒ only integral of current pulse (i.e. collected charge Q) evaluated
  - Charge collection efficiency obtained by normalising Q wrt. unirradiated diode: $CCE = \frac{Q}{Q_0}$
  - Measured at -10°C to reduce leakage current, nitrogen atmosphere
  - If not stated otherwise, 512 pulses were averaged
  - Radiation with different penetration:
    - 5.8 MeV α-particles with different polyethylene (PE) absorber layers between source and diode (CCE precision ~3%, self-trigger)
    - 670, 830, 1060 nm laser light (CCE precision ~2%, external trigger)



Charge Multiplication and Electric Field

Described by ionisation coefficient $\alpha(E)$:

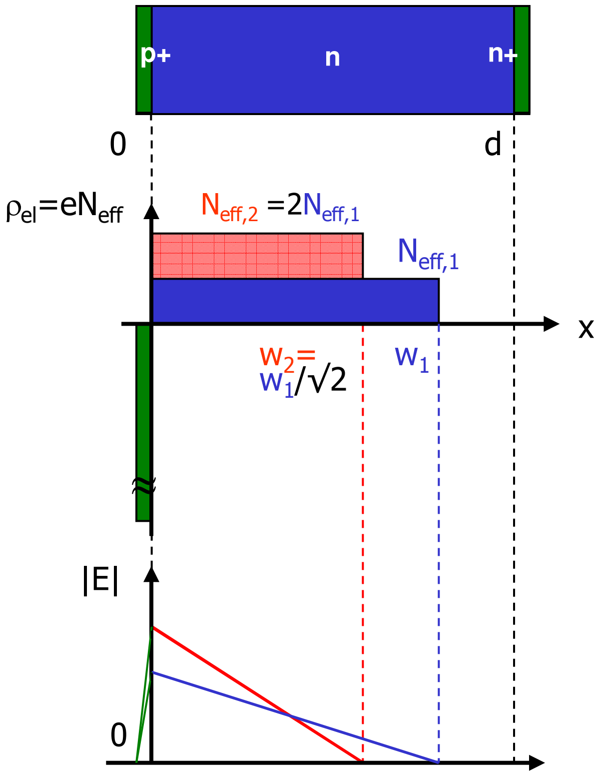
$$dN = N\,\alpha(E)\,dx$$



⇒ high electric fields needed

($E > 1.5 \times 10^5$ V/cm)

Linear field model (N_{eff}=const)



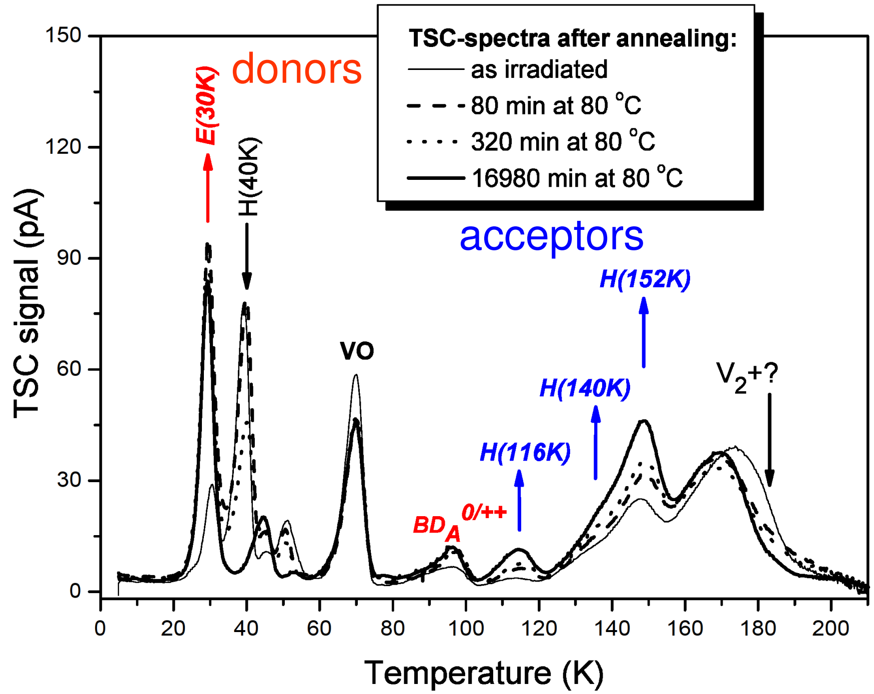
N_{eff} increases → E_{max} increases

N_{eff} from Microscopic Defects

Thermally Stimulated Current (TSC):
Current due to emission from filled traps ⇒ defect concentrations

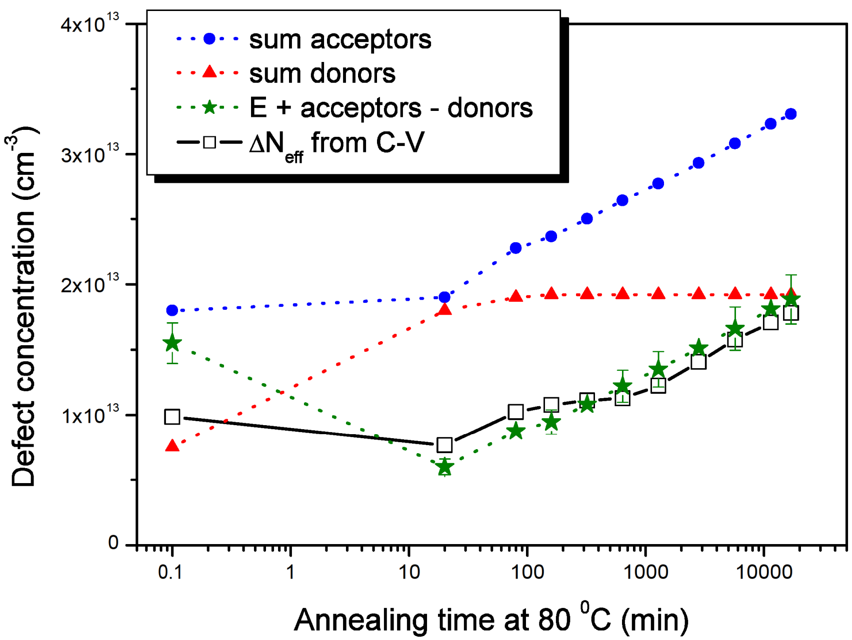
Defect concentrations by TSC

EPI-DO 75 µm, 2×10^{14} cm^{-2}



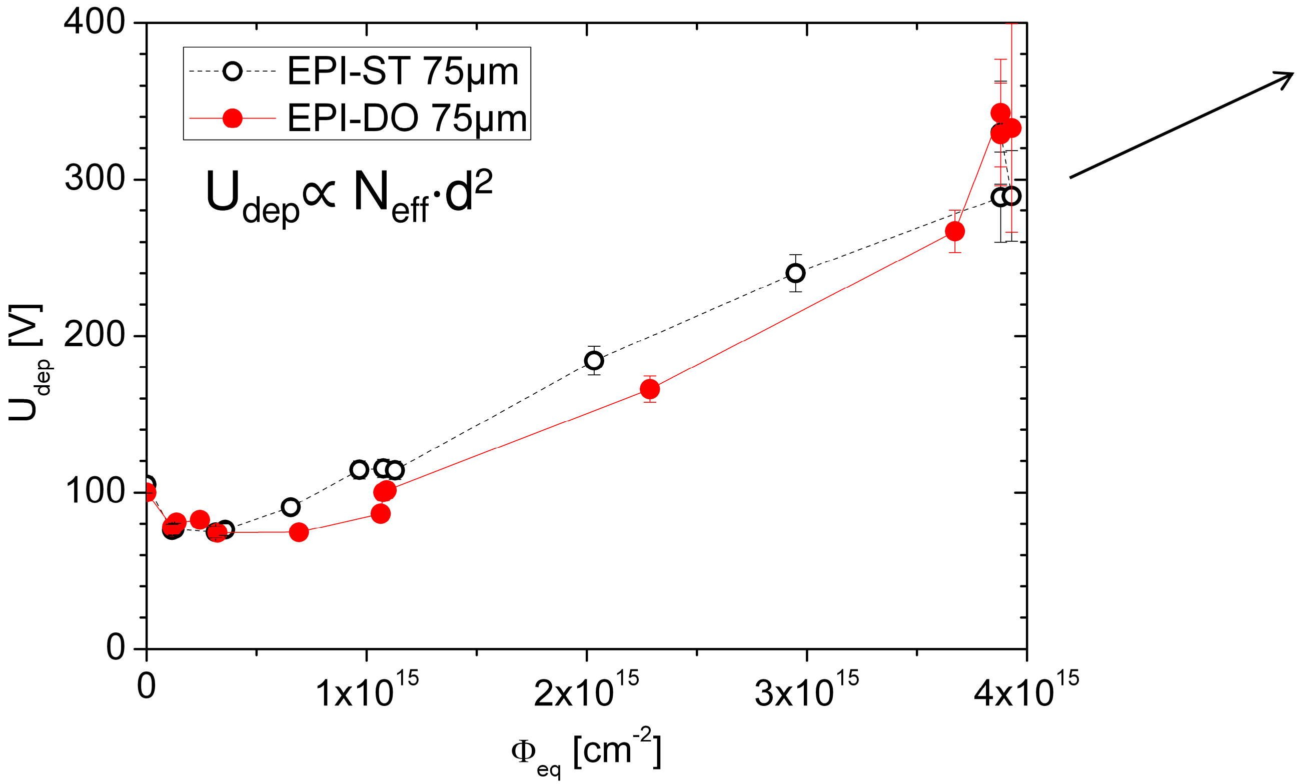
High donor concentration after p-irradiation

Microscopic vs. macroscopic



Long-term annealing can be explained

Development of U_{dep}, N_{eff}



Stable Damage (8 min at 80°C):

Partial donor removal of initial P-doping

Predominant donor introduction at high fluences

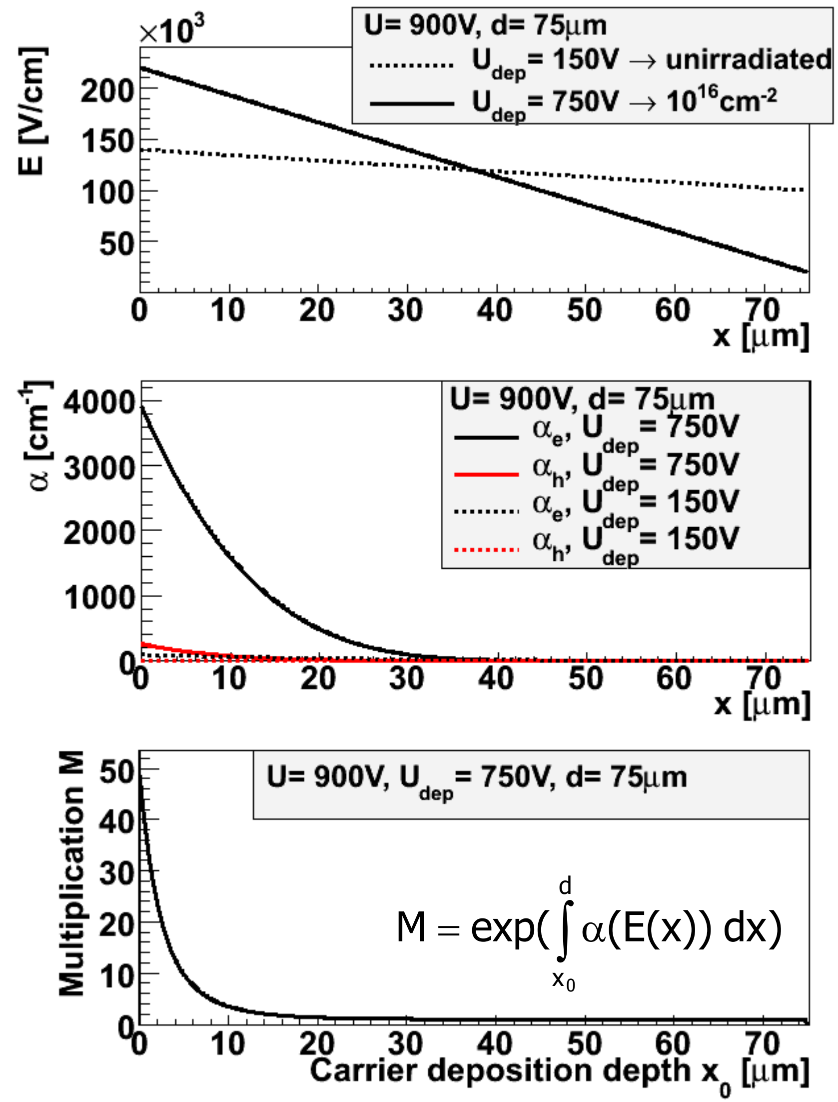
⇒ No space charge sign inversion (SCSI) in EPI after p-irradiation

Simple Model of Radiation-Induced CM Region

Simplified model for n-EPI-ST 75µm, $10^{16}cm^{-2}$:

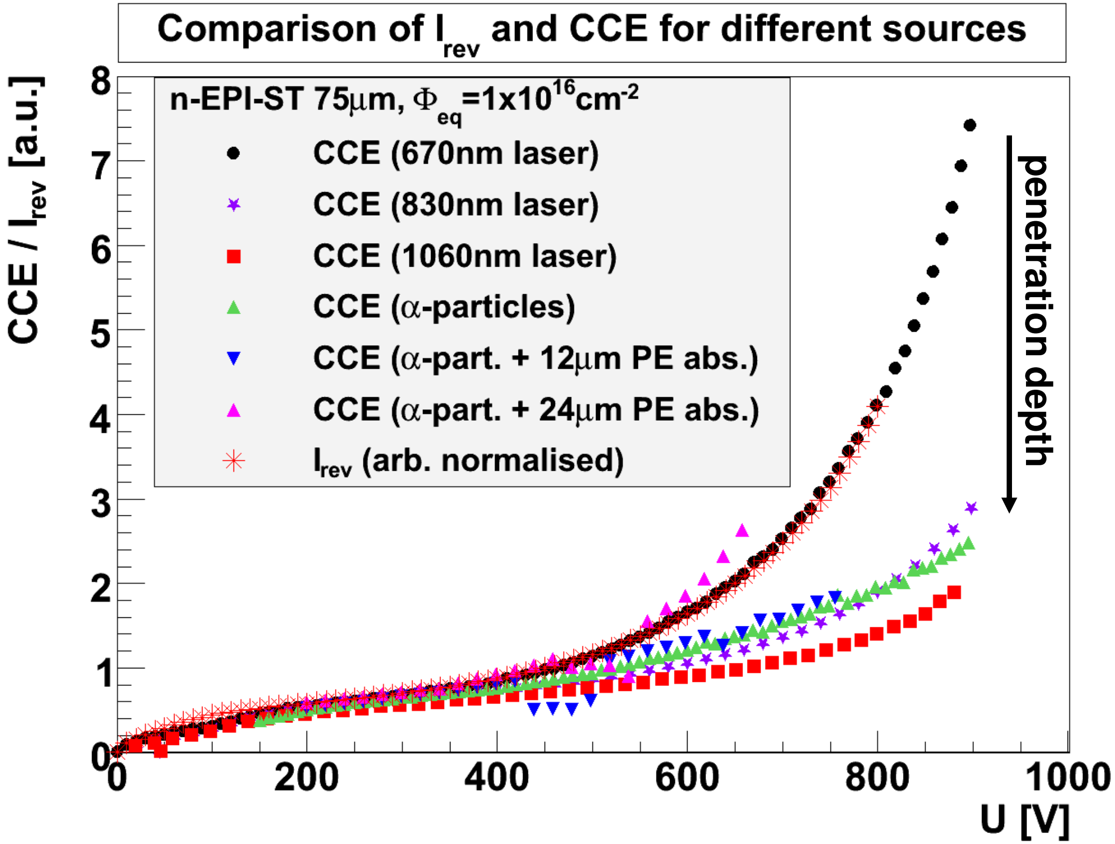
- Extrapolated U_{dep}: 750 V
- Linear field*
- No trapping
- Only e multiplication

$\Rightarrow$ CM region expected at the front side



*Warning: At high fluences significant modifications due to high I_{rev} (e.g. double peak)

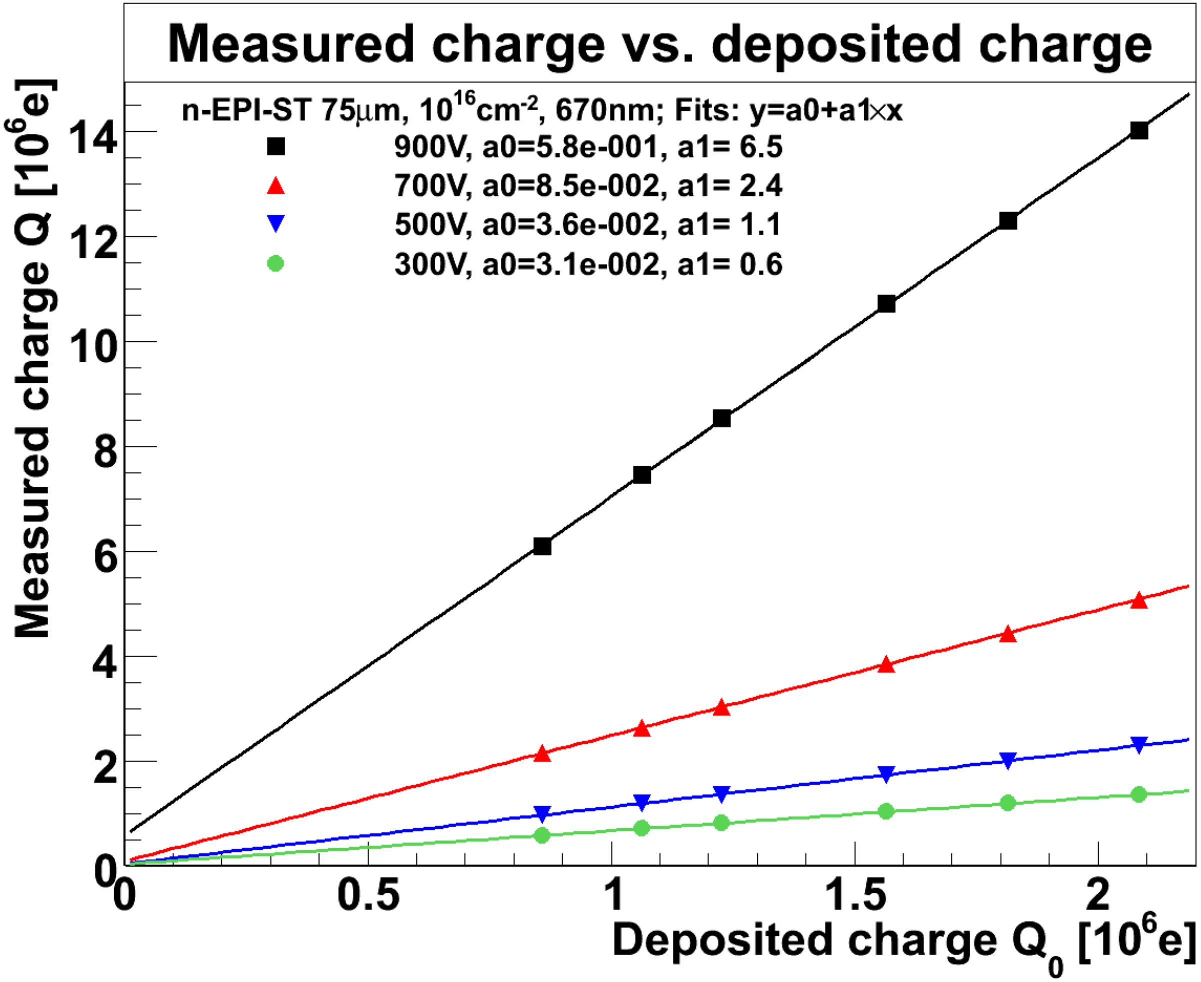
Localisation of CM region



Smaller penetration depth
→ stronger CM

⇒ CM region located at the front side

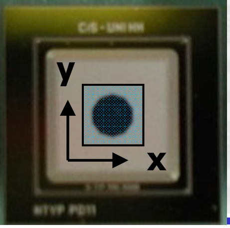
Linearity of Measured Charge



⇒ Linear mode

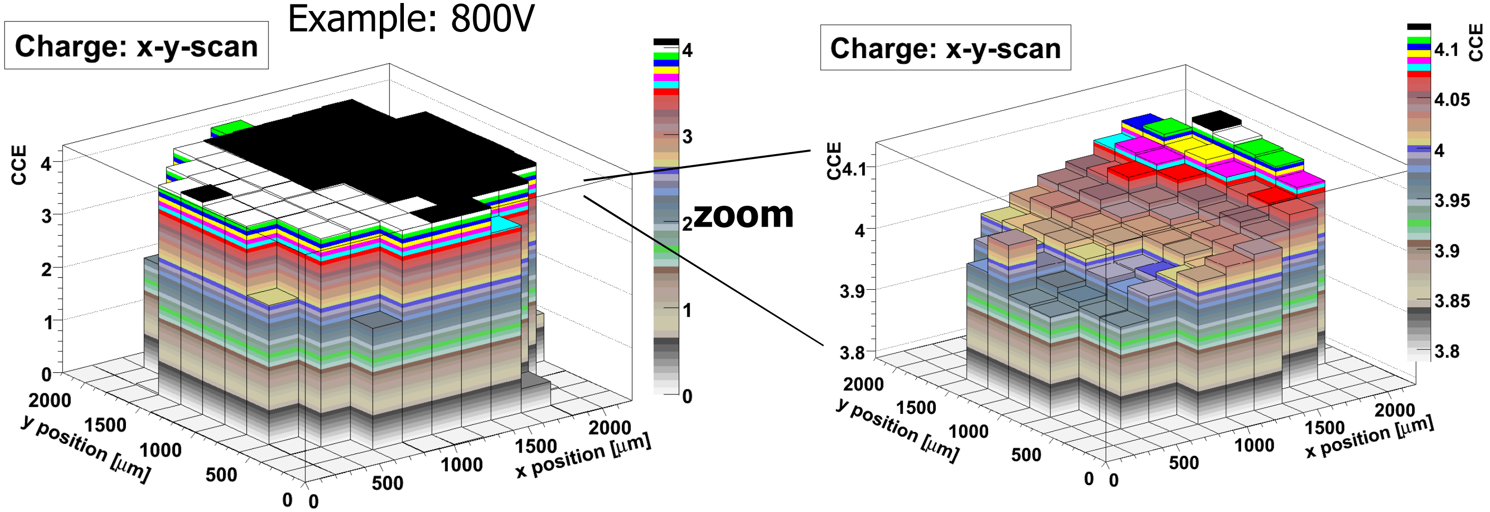
not Geiger mode

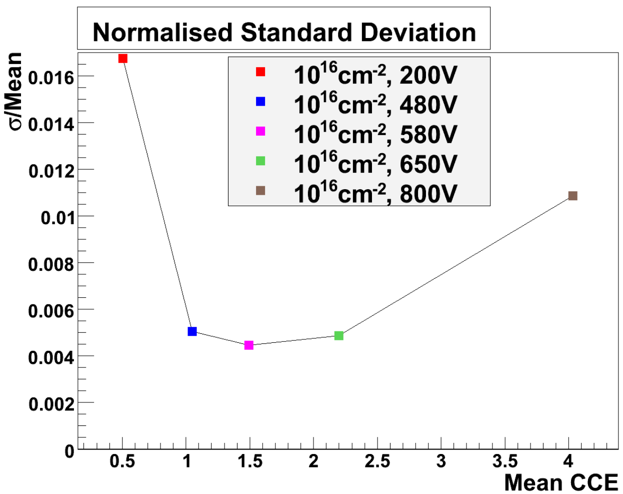
$k = \alpha_h/\alpha_e << 1$



Spatial Uniformity: x-y-scan

Example: 800V





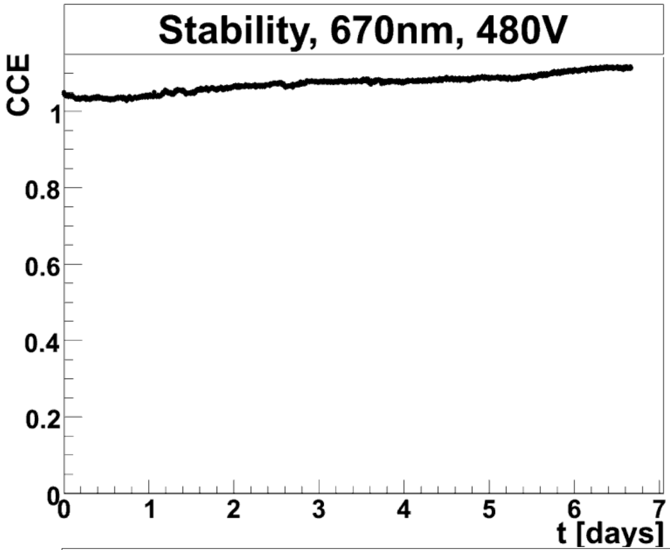
- x-y-scan with 660 nm laser:
  beam spot σ_{beam}=20 μm, 200 μm step width

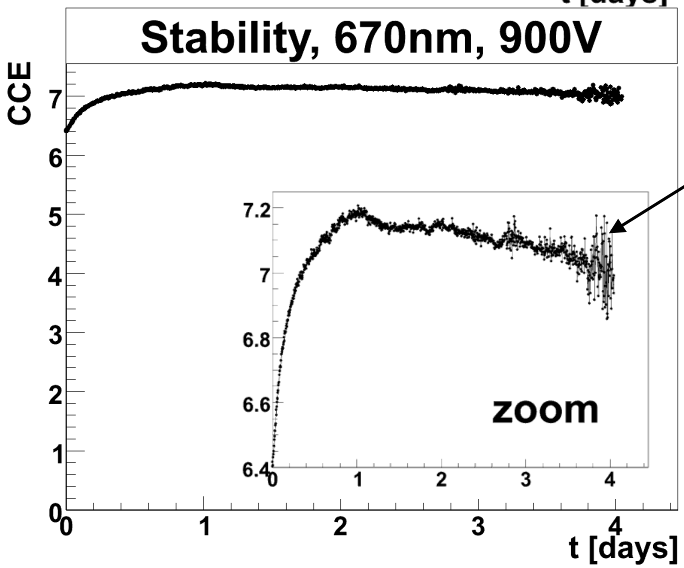
  → very uniform
  (~0.5 - 1% deviation, slightly increasing with CCE)

- Zoom:

  → systematic linear slope in x-direction
  (0.5 - 2%/mm, increasing with CCE)
  → possible reason: non-uniform irradiation?

Long-Term Stability





- Uninterrupted long-term measurement
  - constant voltage and temperature
  - 512 averages, every 5min
- CCE (CM) stable for days
- At high voltages limited by micro discharges
  - can occur randomly at high voltages
  - but: also in unirradiated diodes at high voltages
  - ⇒ improve device technology

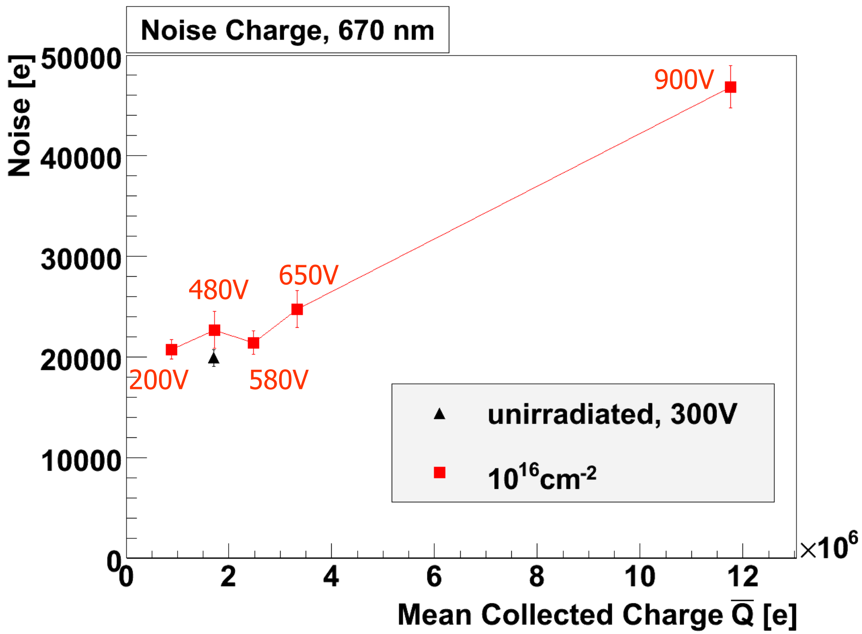
Influence of CM on Noise

- Results shown so far obtained by averaging 512 signals
- S/N separation event by event needed → Effects of CM on charge spectrum and noise studied for 300 single pulses

Noise:

- Shot noise due to I_{rev}: $\sigma_{shot} \sim M' \cdot \sqrt{F(M')}$

  with excess noise factor F(M) describing statistical fluctuations of CM (depends on k)
- $\sigma_{noise} = \sqrt{\sigma^2_{shot}(M') + \sigma'^2}$ ⇒ CM improves S/N when $\sigma_{shot}(M')$ is not yet dominating



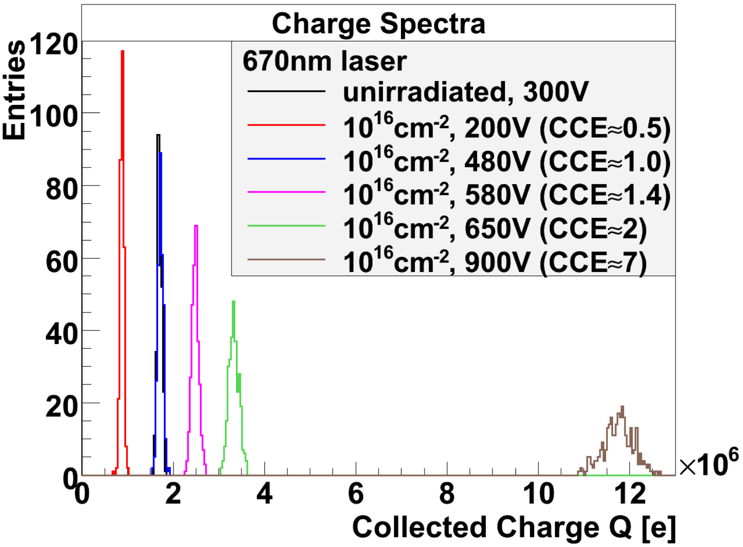
TCT baseline noise

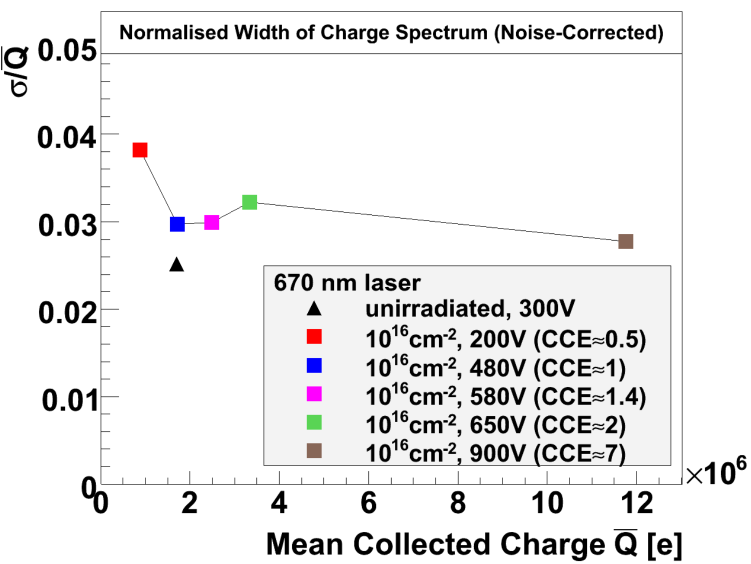
(same integration interval as signal)

- Increase at high voltages
- Signal (670nm) grows faster than noise
- But here:
  - M(U) increases fast for 670nm
  - TCT setup with high intrinsic noise (20000e)

⇒ What about MIPs and low noise charge readout?

Influence of CM on the Charge Spectrum



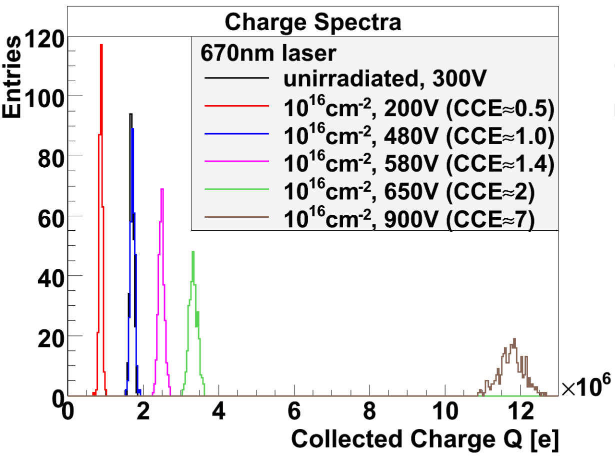


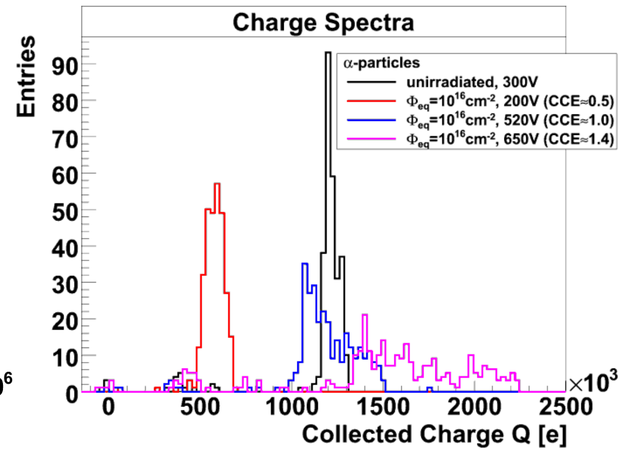
Total width: $\sigma \sim M \cdot \sqrt{F(M)}$

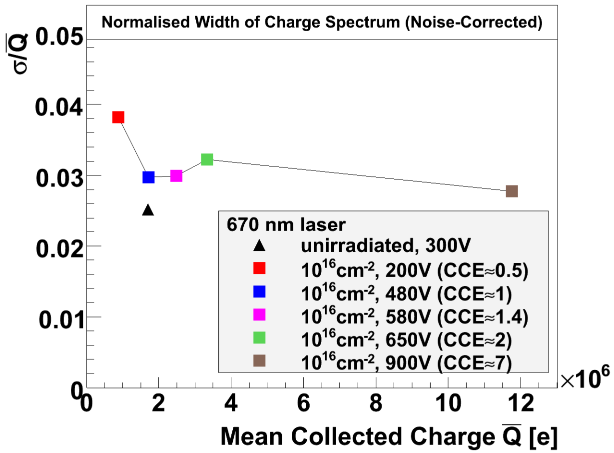
Normalised width:

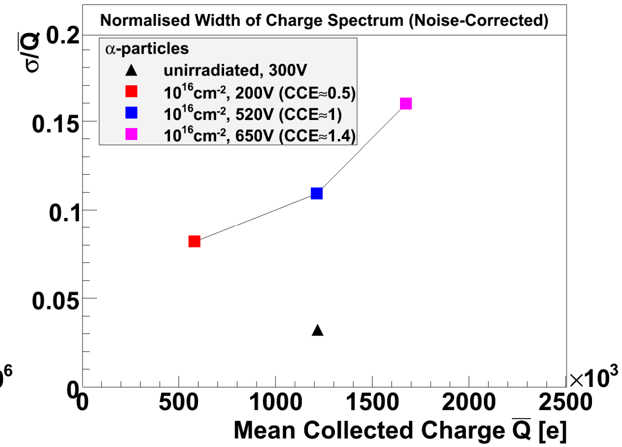
- Almost constant for laser light (670, 830, 1060nm)
  $\Rightarrow$ Fluctuations in CM process not dominant

Influence of CM on the Charge Spectrum









Total width: $\sigma \sim M \cdot \sqrt{F(M)}$

Normalised width:

- Almost constant for laser light (670, 830, 1060nm)
  ⇒ Fluctuations in CM process not dominant
- Increases for α-particles
  ⇒ Fluctuations in fraction of charge deposited in CM region?

  Possible reasons:
  - Low-energy particles with shallow penetration
  - Divergence of α-beam

⇒ What about MIPs?

- Landau fluctuations

Summary and Outlook

- Charge Multiplication in highly irradiated n-EPI diodes:
  - High field at the front side due to radiation-induced predominant donor introduction
  - Linear mode
  - Uniform over the detector area, stable in time
  - Noise increase slower than signal growth (TCT with 670nm laser)
  - No significant fluctuations in CM process

- Open issues:
  - S/N for MIPs and charge readout
    $\Rightarrow$ Charge measurements with beta-setup in progress
  - Can micro discharges at high voltages be reduced and controlled?
  - Possible effects on position resolution $\rightarrow$ segmented sensors

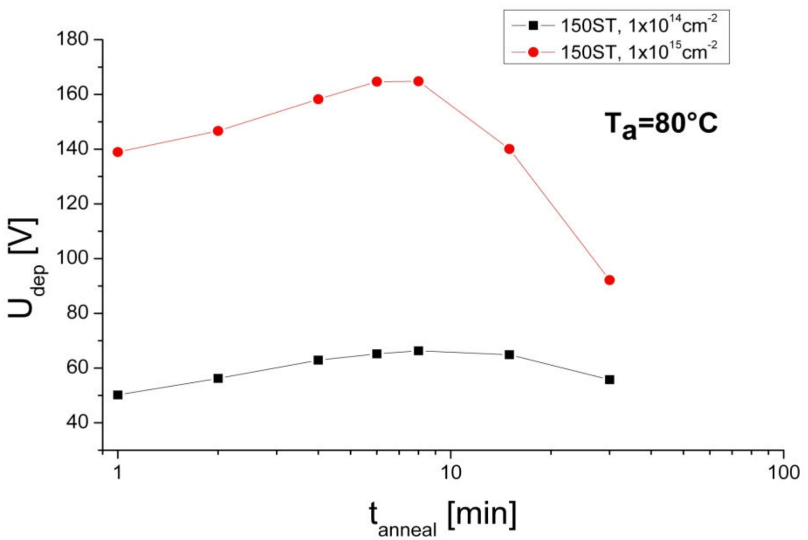
Charge multiplication seems to be a promising candidate to overcome trapping in highly irradiated detectors

BACKUP SLIDES

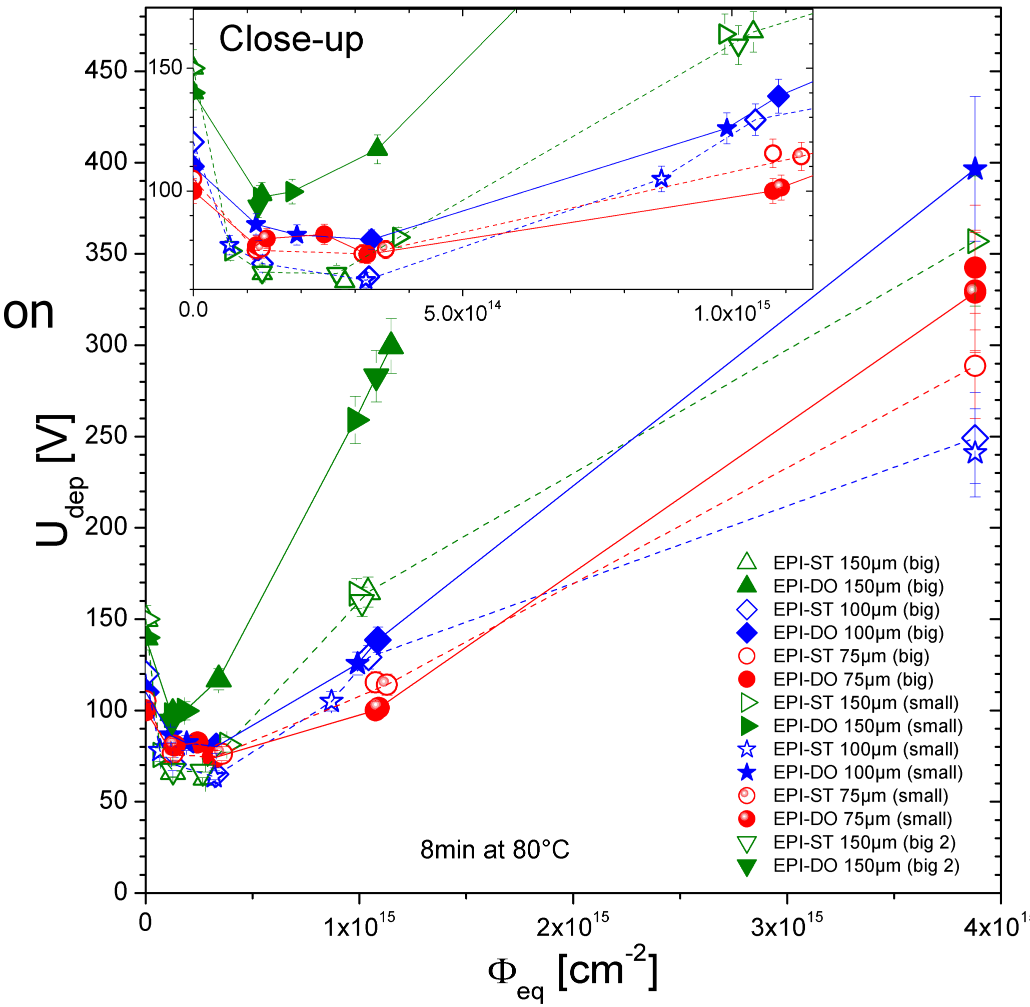
Depletion Voltage (from CV at 10 kHz)

- CV/IV measurable up to 4x10^{15} cm^{-2} at room temperature
- Annealing curve at 80°C (isothermal) → no type inversion
- Stable Damage (8 min at 80°C): first donor removal, then donor introduction with g_C(DO)>g_C(ST)

Annealing curve:

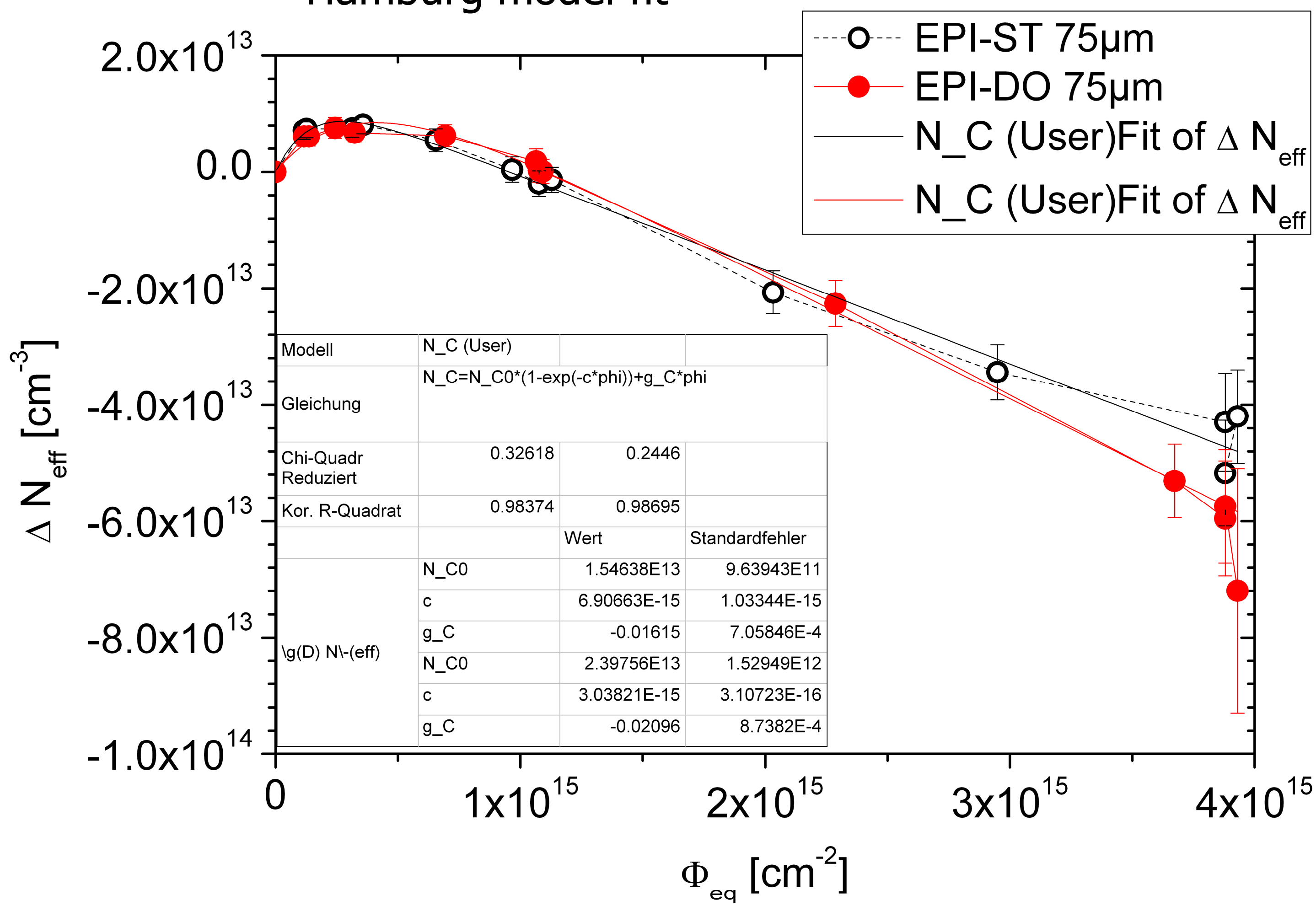


Stable Damage:



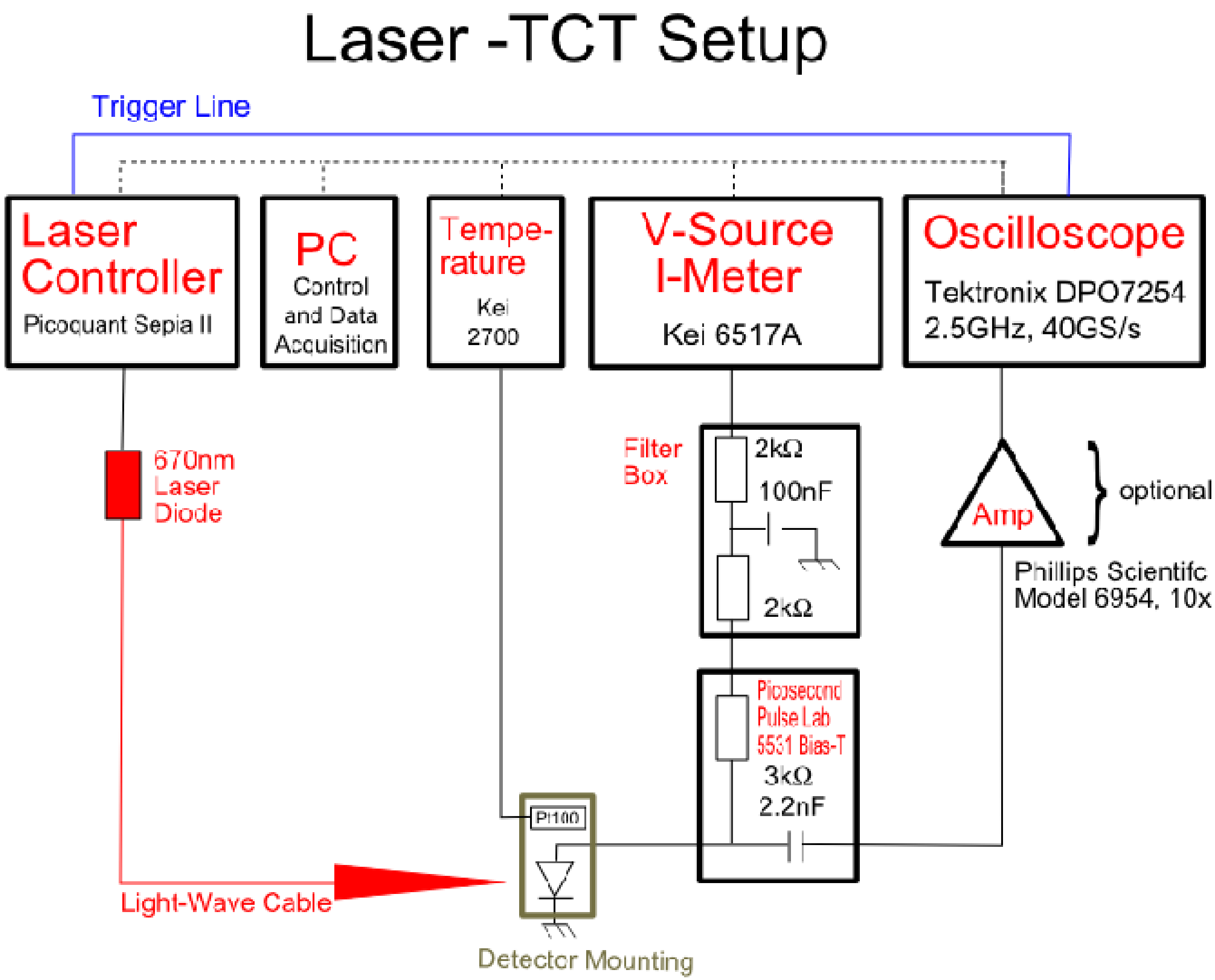
Determination of g_C

Hamburg model fit



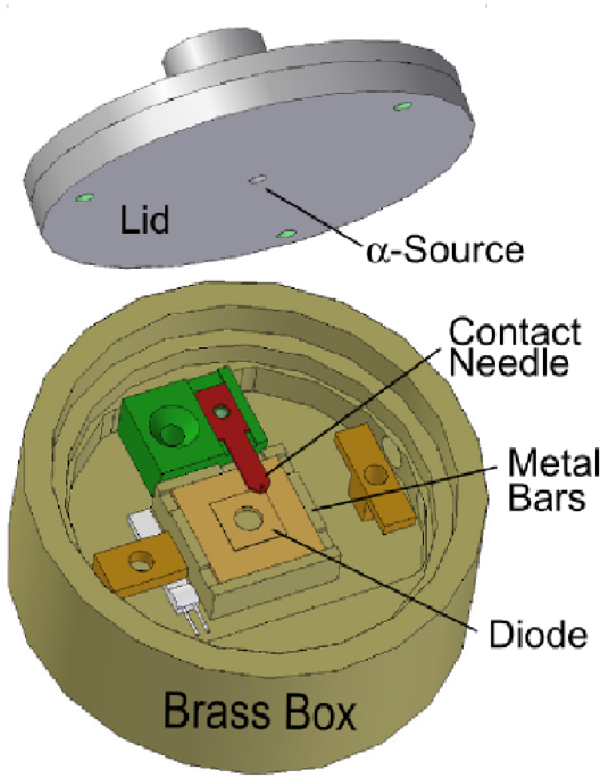
Modell	N_C (User)		
Gleichung	N_C=N_C0*(1-exp(-c*phi))+g_C*phi		
Chi-Quadr Reduziert	0.32618	0.2446	
Kor. R-Quadrat	0.98374	0.98695	
		Wert	Standardfehler
\g(D) N\-(eff)	N_C0	1.54638E13	9.63943E11
	c	6.90663E-15	1.03344E-15
	g_C	-0.01615	7.05846E-4
	N_C0	2.39756E13	1.52949E12
	c	3.03821E-15	3.10723E-16
	g_C	-0.02096	8.7382E-4

MTCT Laser-TCT Setup

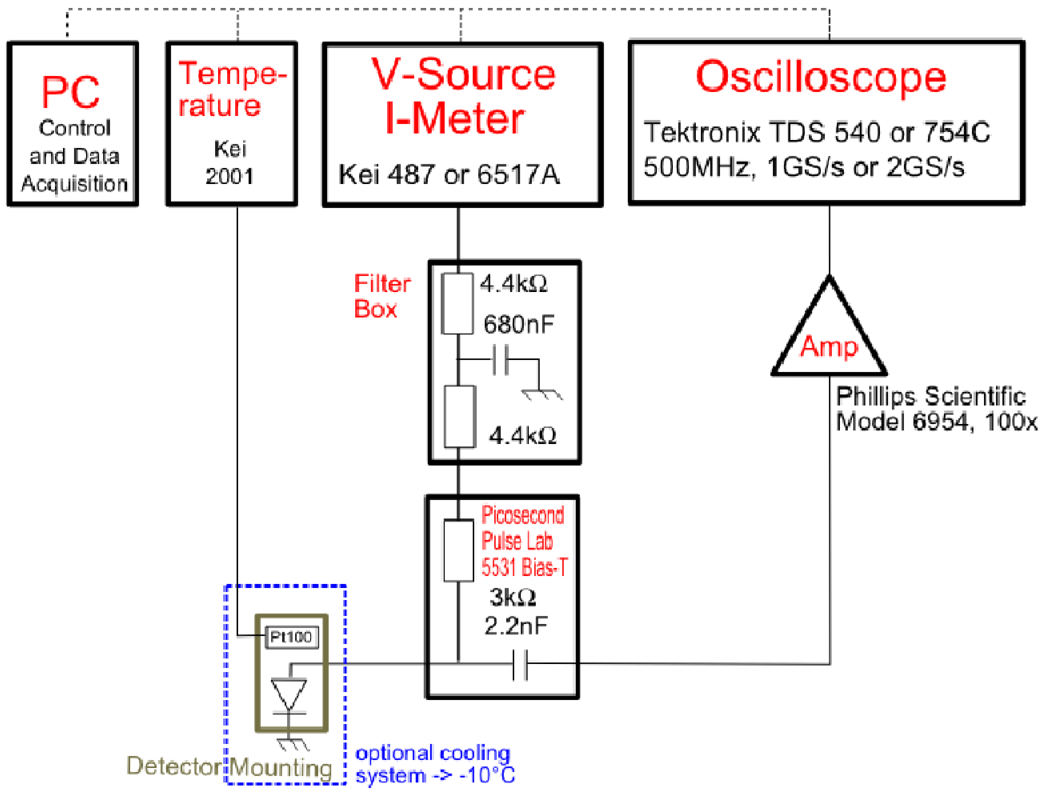


Alpha-TCT Setup

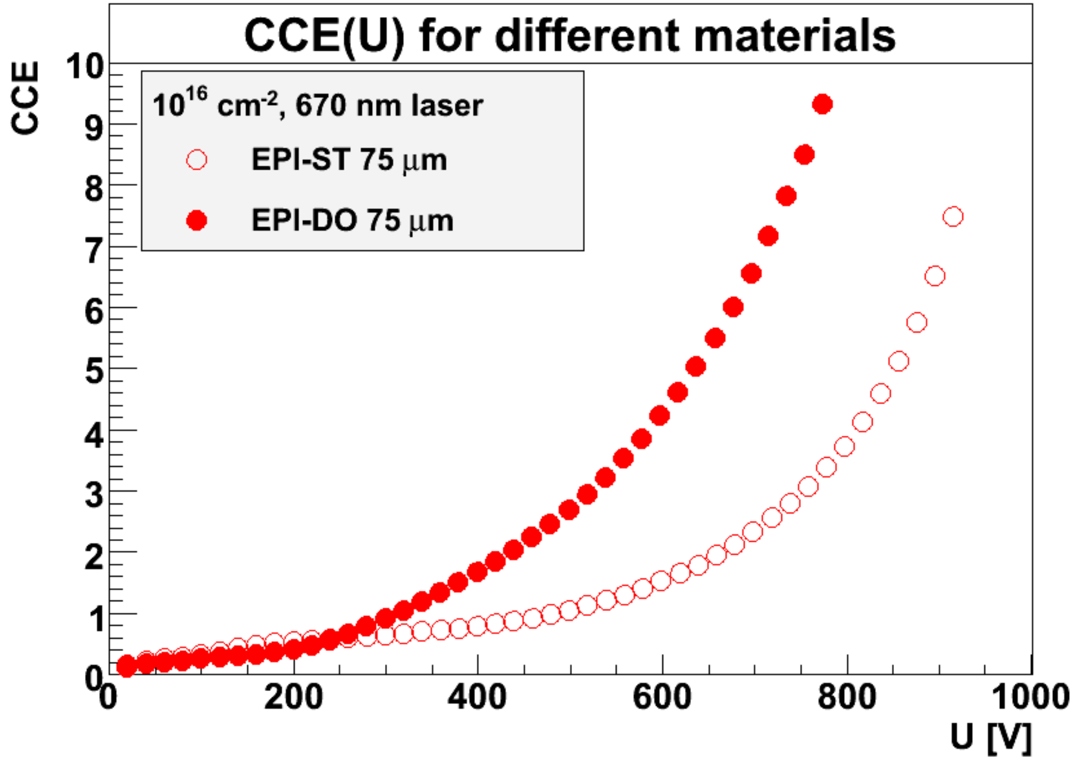
Detector Mounting



α -TCT Setup



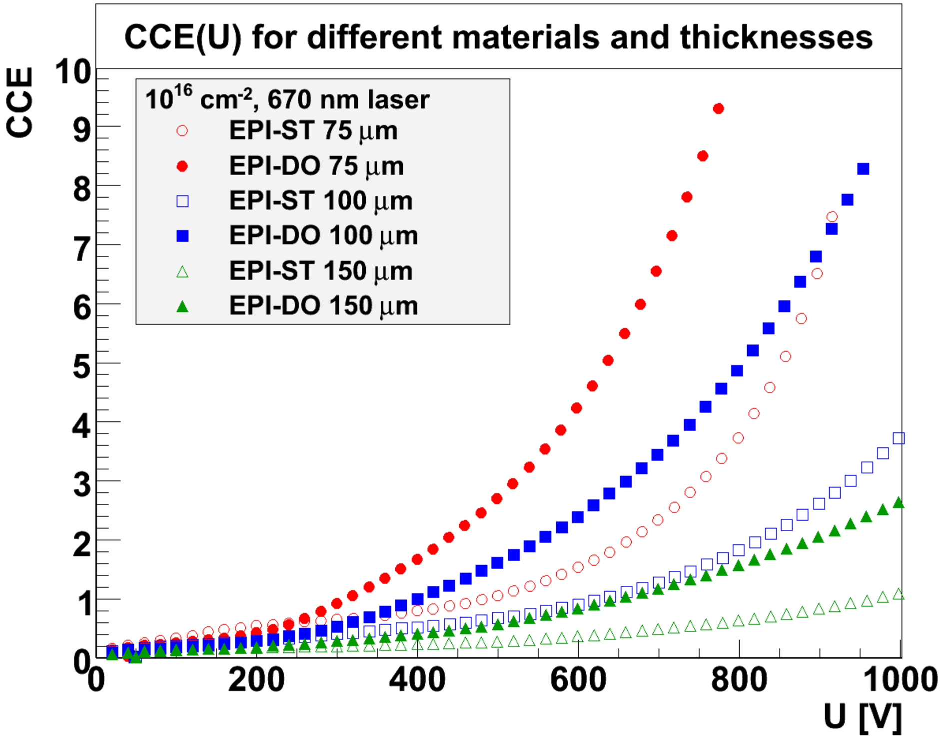
CCE dependence on material (75µm only)



In the CM regime:

- CCE(DO) > CCE(ST)
  → higher CM in DO due to larger $|g_C|$

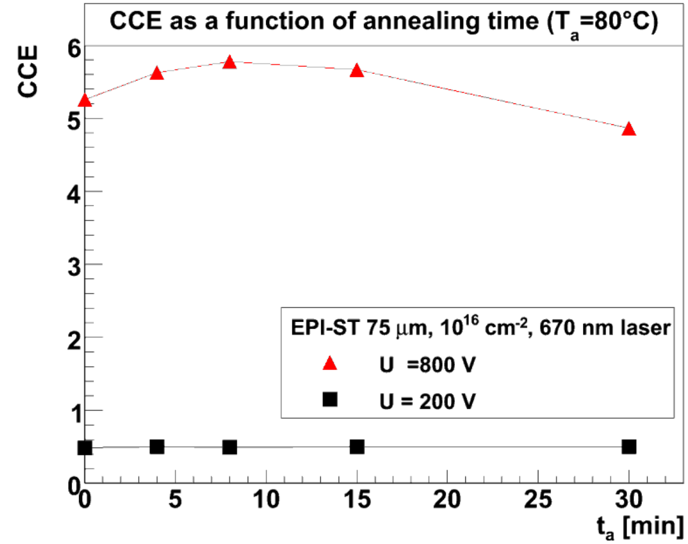
CCE for different materials and thicknesses

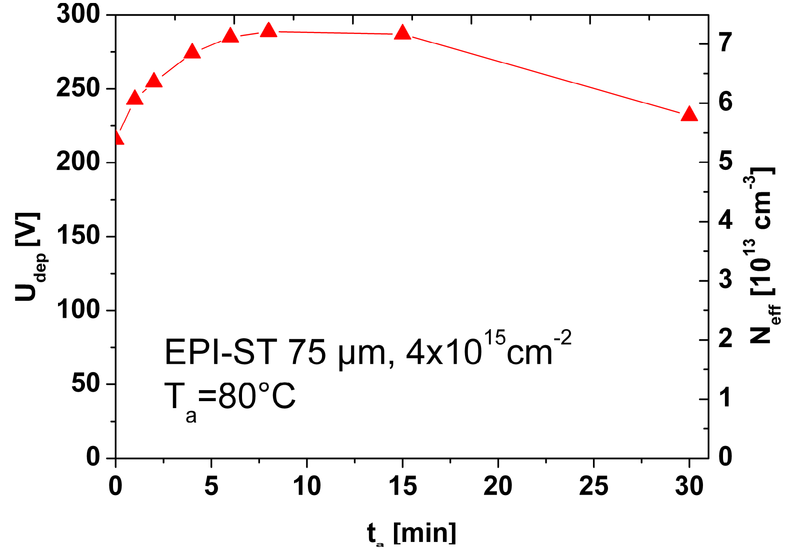


In the CM regime:

- CCE(DO)>CCE(ST)
  → higher CM in DO due to larger g_C
- Increasing CCE for decreasing thickness
  Possible reasons:
  → higher CM in thin diodes due to higher field? But extrapolation: all U_{dep}>600V
  → higher CM in thin diodes due to larger g_C as [O] is higher in thin samples
  → less influence of trapping on CCE in thin samples

CCE dependence on annealing



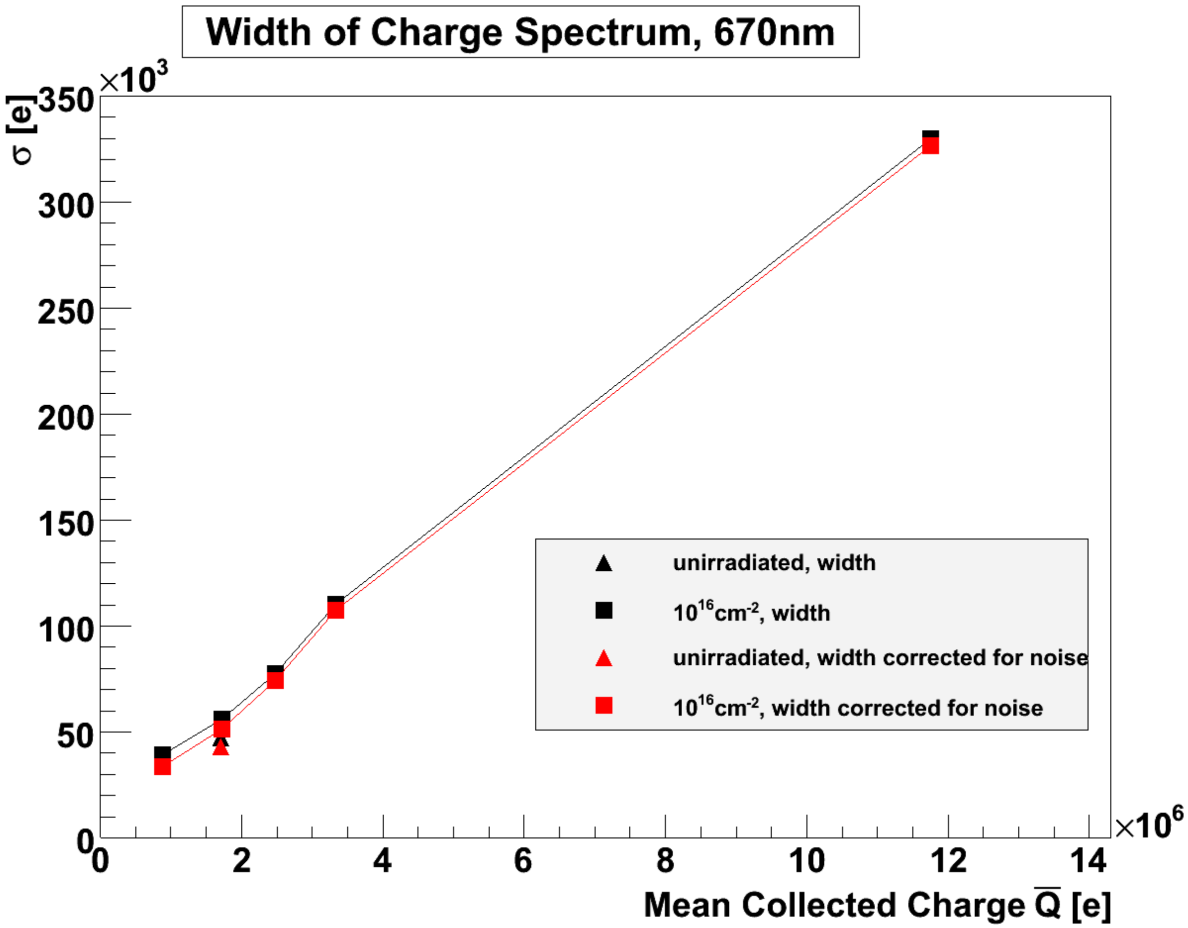


In the CM regime:

- CCE annealing curve shows the same behaviour as the one of U_{dep}, N_{eff}

$\Rightarrow$ higher N_{eff} $\rightarrow$ higher E_{max} $\rightarrow$ higher CM

Absolute width of charge spectrum
Comparison: uncorrected - corrected



Broadening of Charge Spectrum