Charge Multiplication Properties in Highly Irradiated Thin Epitaxial Silicon Diodes

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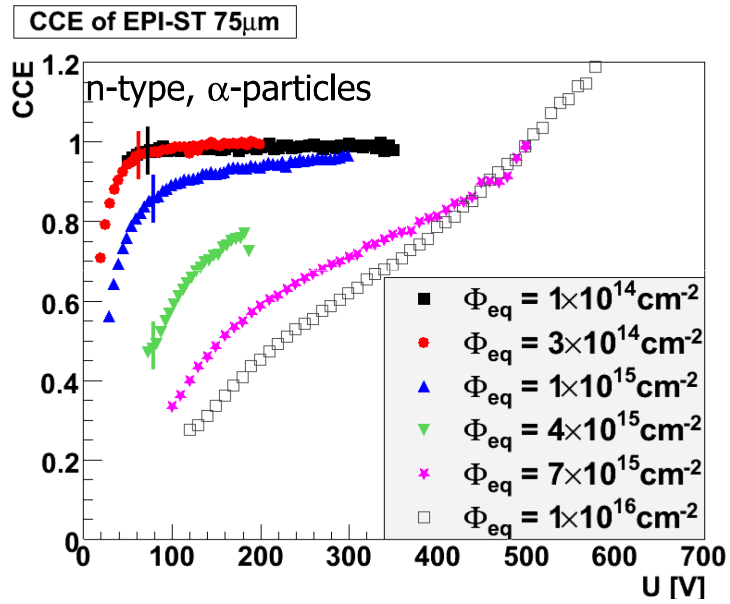
In the framework of the CERN RD50 Collaboration

Introduction

- Trapping: most limiting factor at S-LHC fluences
  $\Rightarrow$ Degradation of Charge Collection Efficiency (CCE)
- But at high fluences and voltages: CCE>1
  $\Rightarrow$ Trapping overcompensated by Charge Multiplication (CM)
- Can CM be used for highly damaged S-LHC detectors?
  $\Rightarrow$ Detailed understanding of the formation and properties of CM in irradiated sensors needed



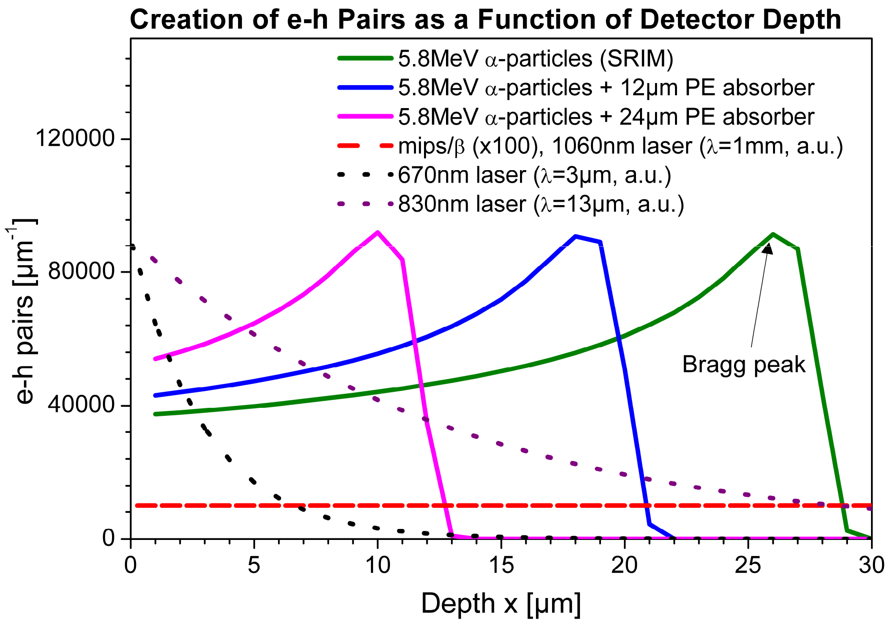
- Questions to be answered:
  1) Where is the CM region located?
  2) Is the measured charge proportional to the deposited one?
  3) Do fluctuations of the CM process affect the charge spectrum or the noise?
  4) Is CM homogeneous over the detector area?
  5) Is the operation of a detector in the CM regime stable in time?
  6) … (position resolution etc.)

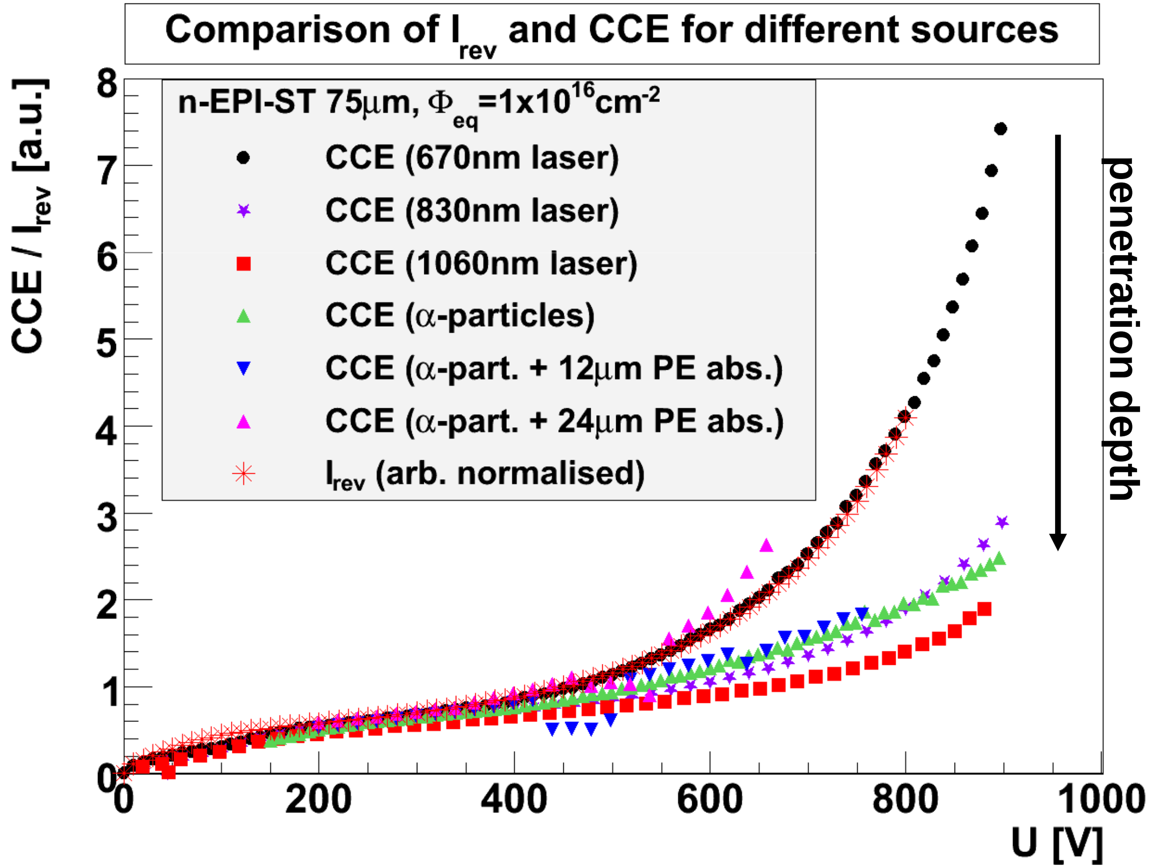
Investigated Diode and Method

- Material: Epitaxial Si pad-detectors on Cz-substrate produced by ITME/CiS
- Here: focus on sample with the most extreme multiplication values: 8364-03-50
  $\rightarrow$ highest available fluence, smallest thickness
  - n-EPI-ST 75 µm
  - [O] = 9x10^{16} cm^{-3}, $N_{eff,0}$ = 2.6x10^{13} cm-3, <111> orientation
  - 5 x 5mm^2
  - Φ_{eq} = 10^{16} cm^{-2} (24 GeV/c protons, CERN PS)
  - 30 min at 80°C annealing

- Method: Transient Current Technique (TCT)
  - No time-resolved pulses for 75 µm
    $\Rightarrow$ 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
  - Different TCT setups with different properties:
    - 5.8 MeV α-particles with different polyethylene (PE) absorber layers between source and diode
    - 670, 830, 1060 nm laser light (new ALS lasers $\rightarrow$ improved stability/CCE precision)
    - MTCT setup with 660nm laser: x-y-scan, (time-resolved measurements in 150 µm EPI diodes)

CCE for Different Sources with Different Penetration



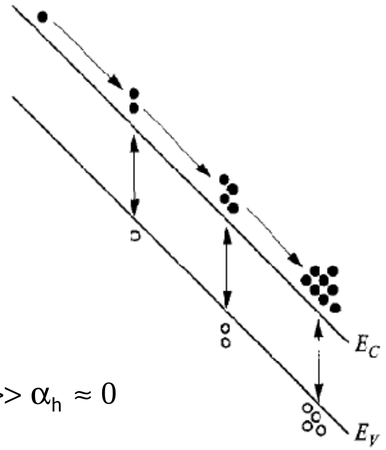


Smaller penetration depth
→ stronger CM

⇒ CM region located at the front side

Charge Multiplication due to Impact Ionisation

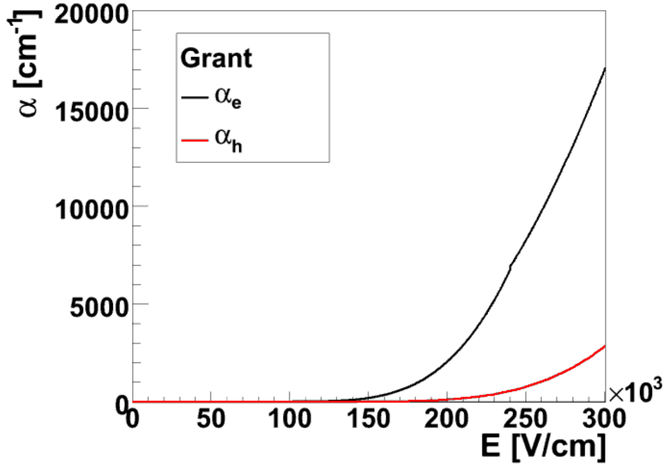
Impact ionisation



$\alpha_e \gg \alpha_h \approx 0$

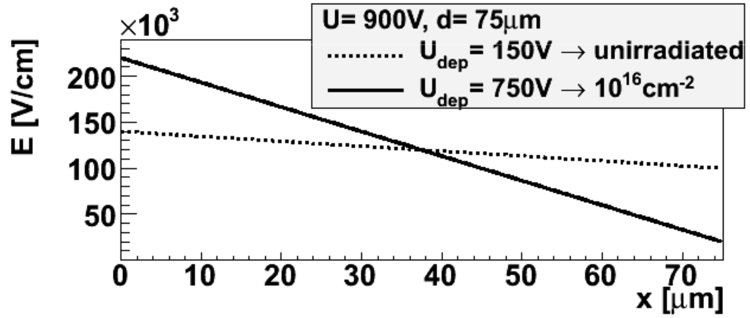
Described by ionisation coefficient $\alpha(E)$:

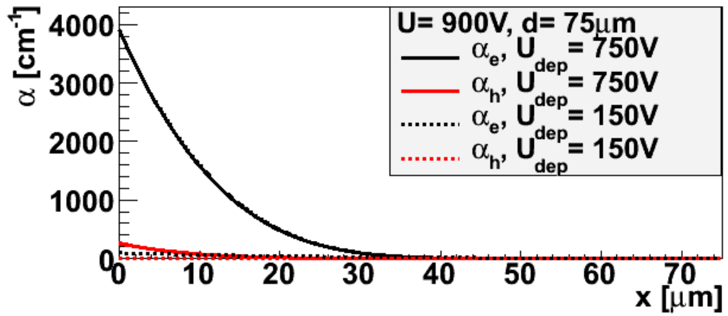
$$dN = N\,\alpha(E)\,dx$$

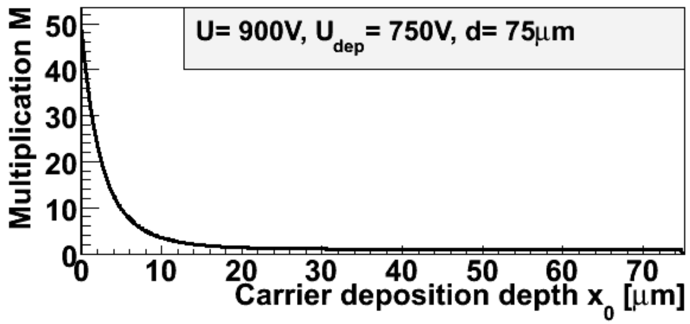


Simplified model for n-EPI ST 75µm, $10^{16}cm^{-2}$:

- Linear field with extrapolated U_{dep}
- No trapping

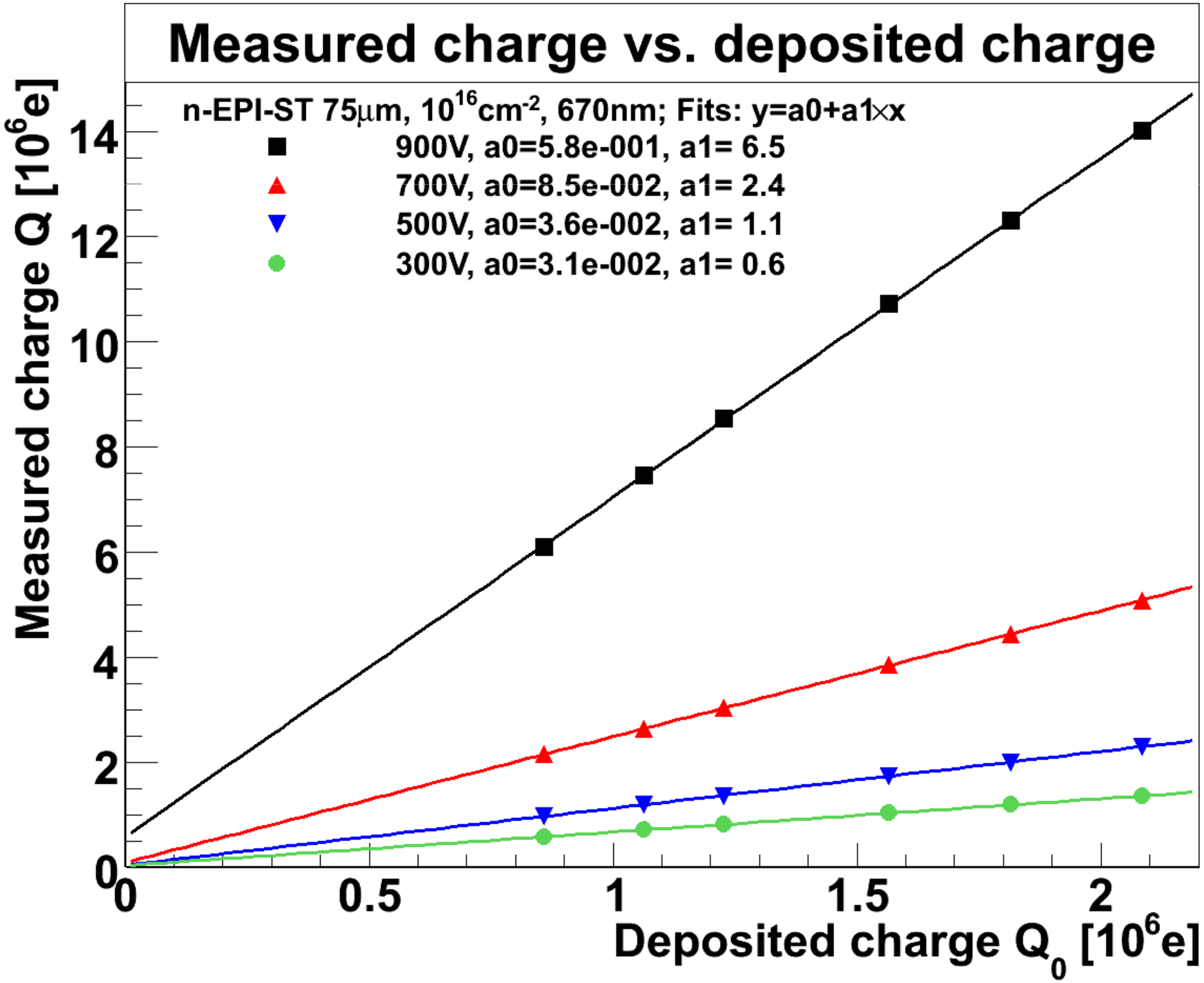






$$M = \exp\left(\int_{x_0}^{d} \alpha(E(x))\,dx\right)$$

Proportionality of Measured Charge



Linear

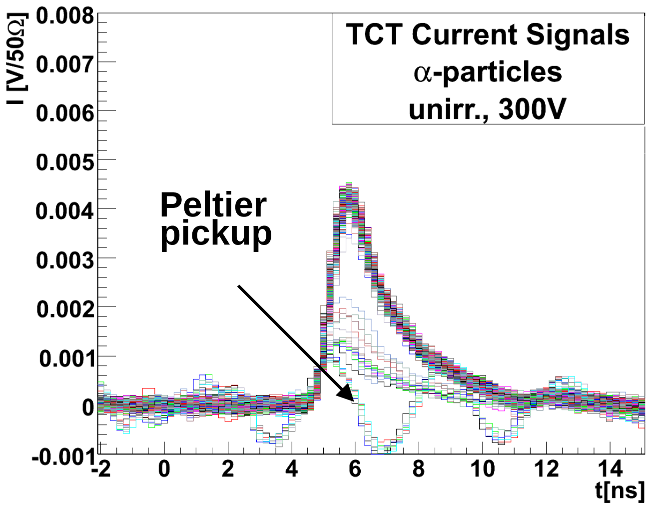
(almost proportional)

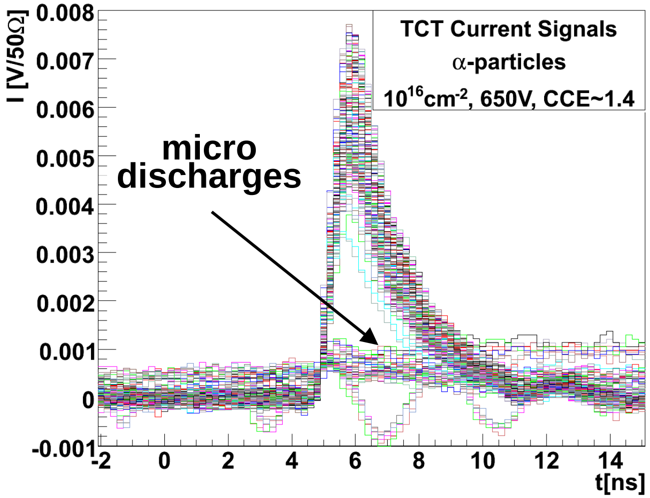
⇒ proportional mode

not Geiger mode

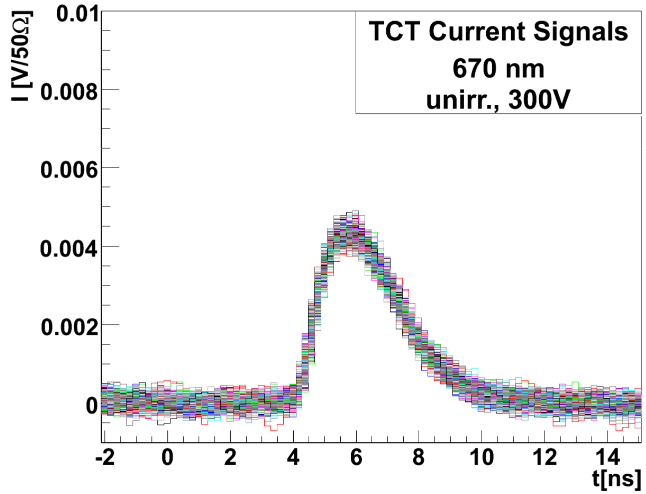
Single TCT Pulses - with and without Charge Multiplication

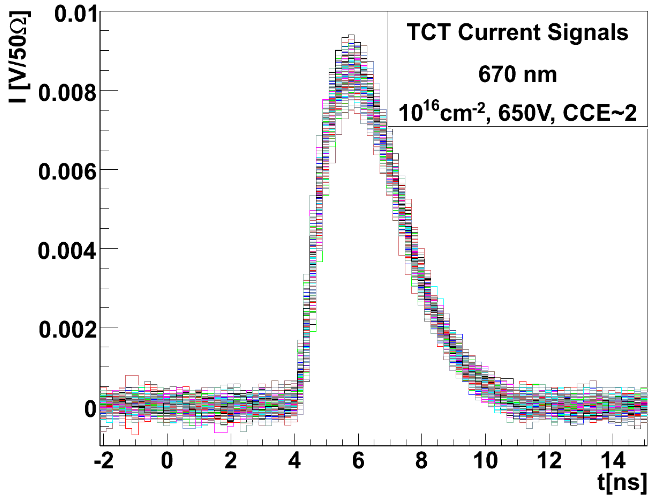
α-particles





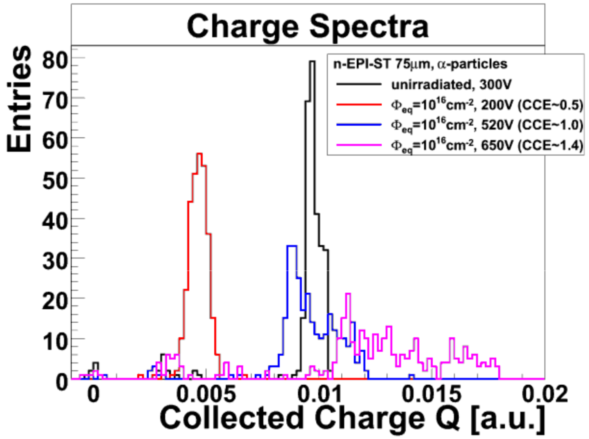
Laser light

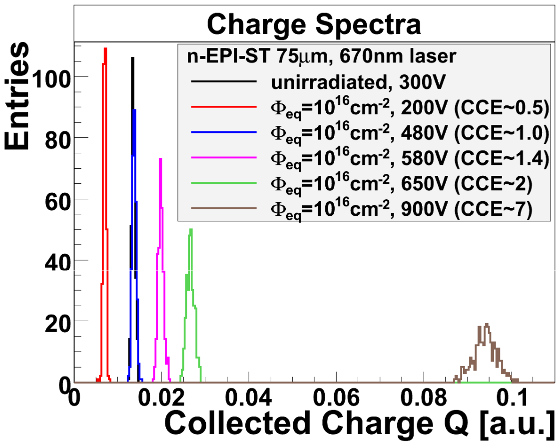


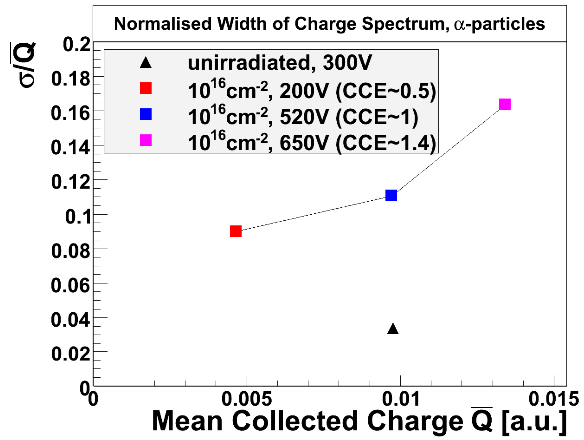


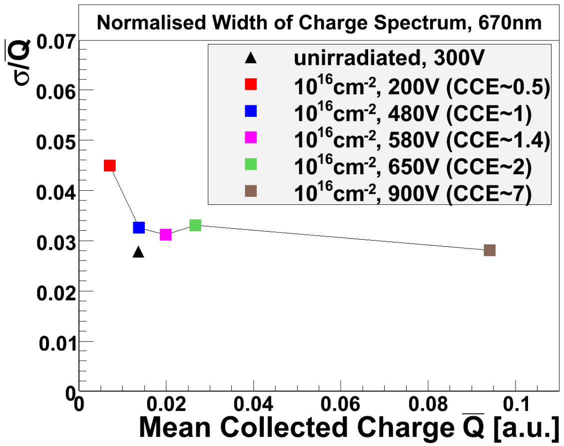
- Results before obtained by averaging 512 signals to reduce noise
- What about single TCT pulses – event by event?
- 300 single TCT pulses taken
  - α-particles: self-triggered
  - Laser: external trigger (50 Hz)
- Micro discharges
  - can occur randomly at high voltages
  - can fake a signal above the trigger threshold (if self-triggered)
  - but: also in unirradiated diodes at high voltages
  - ⇒ improve Si technology

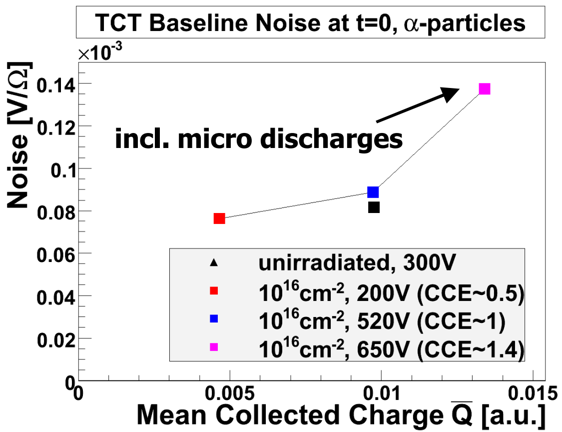
Charge Spectrum and Baseline Noise - with and without Charge Multiplication

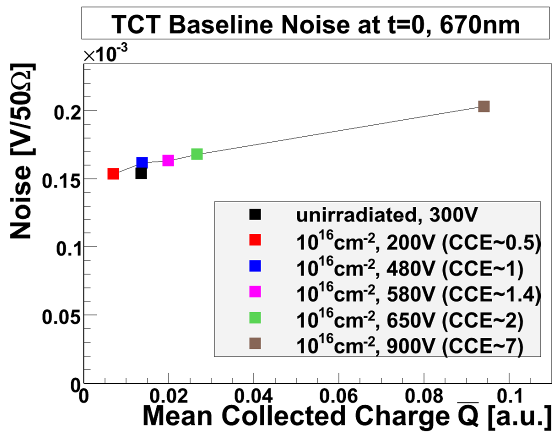






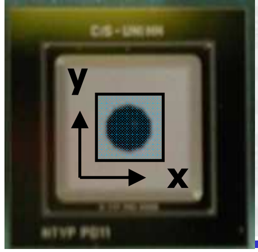






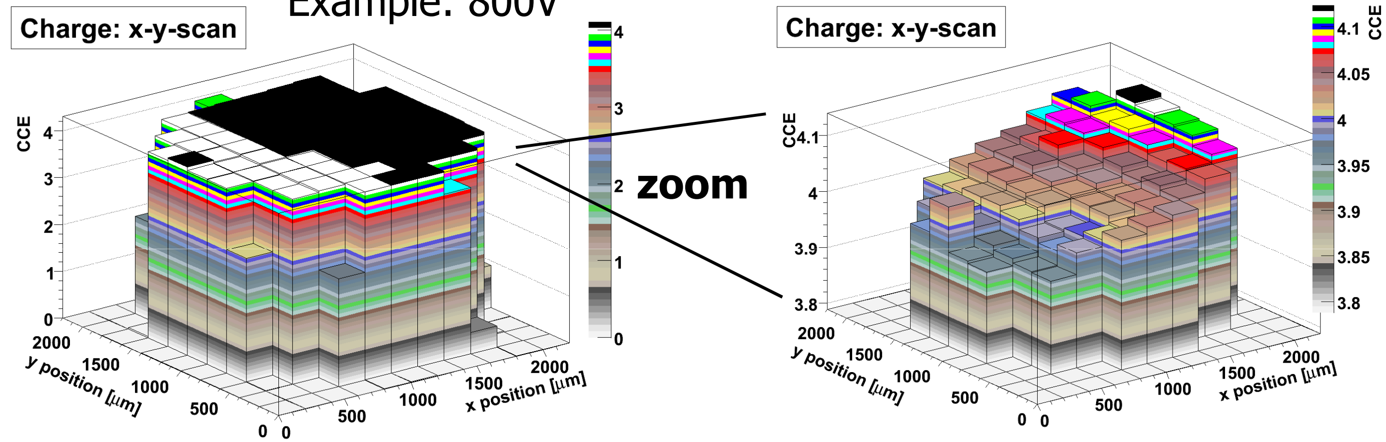
- Normalised width of charge spectrum:
  - increases for α-particles
  - almost constant for laser light (670, 830, 1060nm)
- ⇒ fluctuations in CM process not dominant
- ⇒ α-particles: fluctuations in fraction of charge deposited in CM region?
- ⇒ what about MIPs?

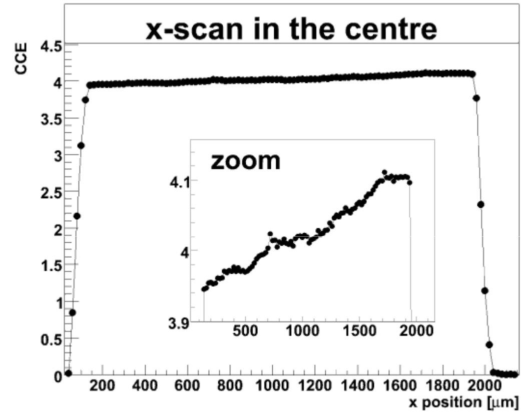
- TCT baseline noise
  - only slight increase in absence of micro discharges despite high I_{rev} increase
  - but here: TCT setup
- ⇒ what about low noise charge readout?

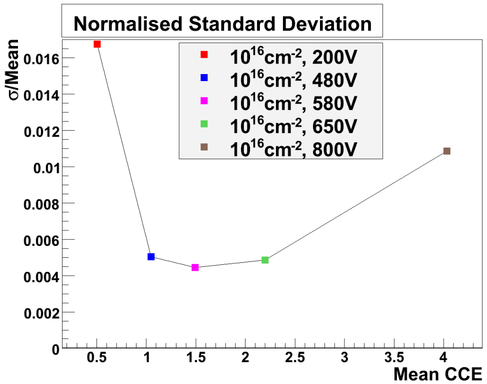


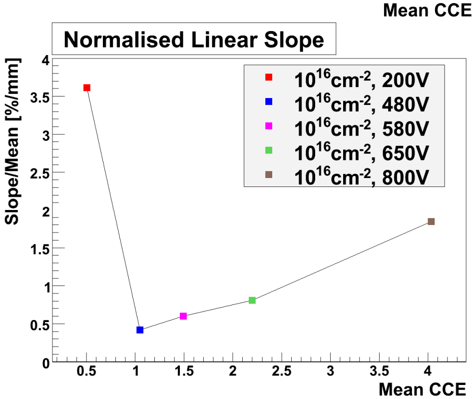
Spatial Homogeneity: x-y-scan

Example: 800V









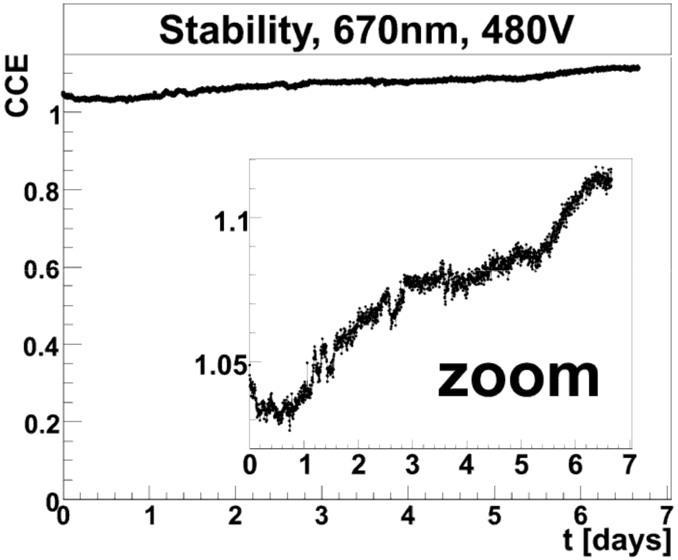
- x-y-scan with 660nm laser:
  beam spot σ_{beam}=20μm, 200μm step width

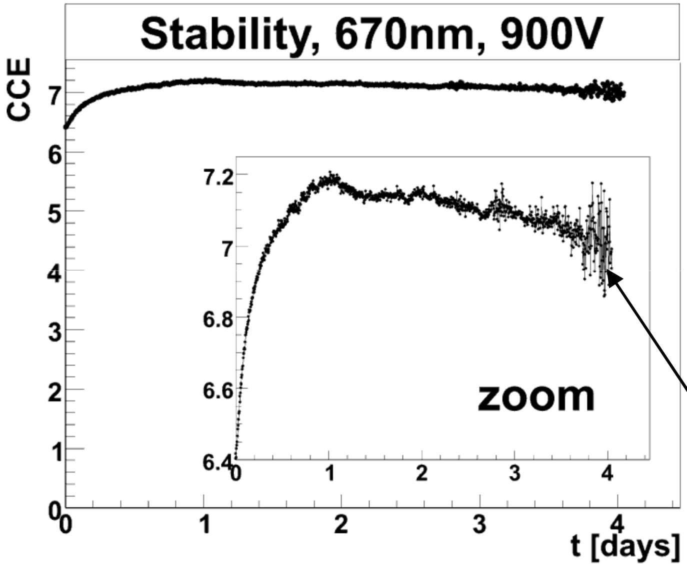
  → very homogeneous
  (~0.5-1% deviation, slightly increasing with CCE)

- But: zoom and x-scan (10μm step width)

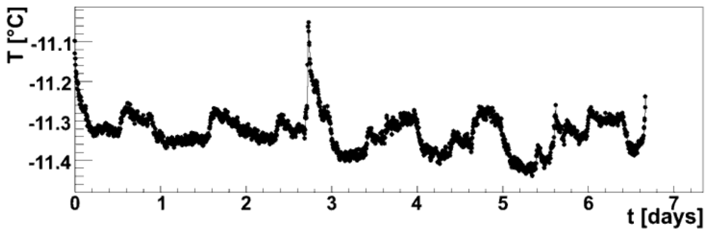
  → systematic linear slope in x-direction
  (0.5-2%/mm, increasing with CCE)
  → possible reason: inhomogeneous irradiation?

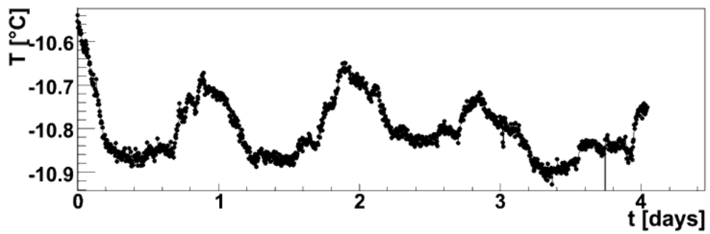
Long-Term Stability

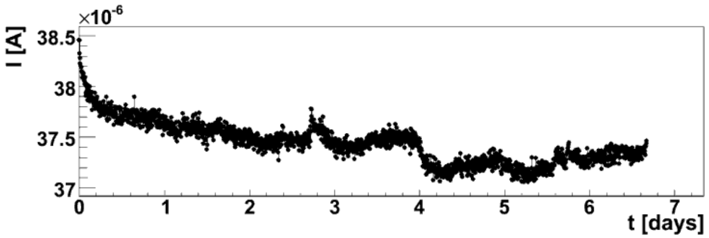


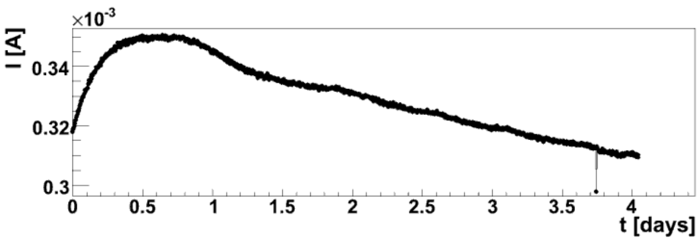


- Uninterrupted long-term measurement
  - constant voltage and temperature
  - 512 averages, every 5min
- CCE (CM) stable for days
- At high voltages limited by micro discharges









Summary and Outlook

- Properties of Charge Multiplication in highly irradiated EPI diodes:
  - Thin CM region at the front side
  - Proportional mode
  - Normalised width of charge spectrum constant (laser)
    $\rightarrow$ no significant fluctuations in CM process
  - Only slight noise increase (TCT)
  - Homogeneous over the detector area
  - Stable in time
- Open issues:
  - Large broadening of charge spectrum in case of α-particles
    $\rightarrow$ what about MIPs?
  - What about noise in case of charge readout?
  - Biggest challenge for diodes used here:
    Can micro discharges at high voltages be reduced and controlled?
  - Possible effects on position resolution $\rightarrow$ segmented sensors

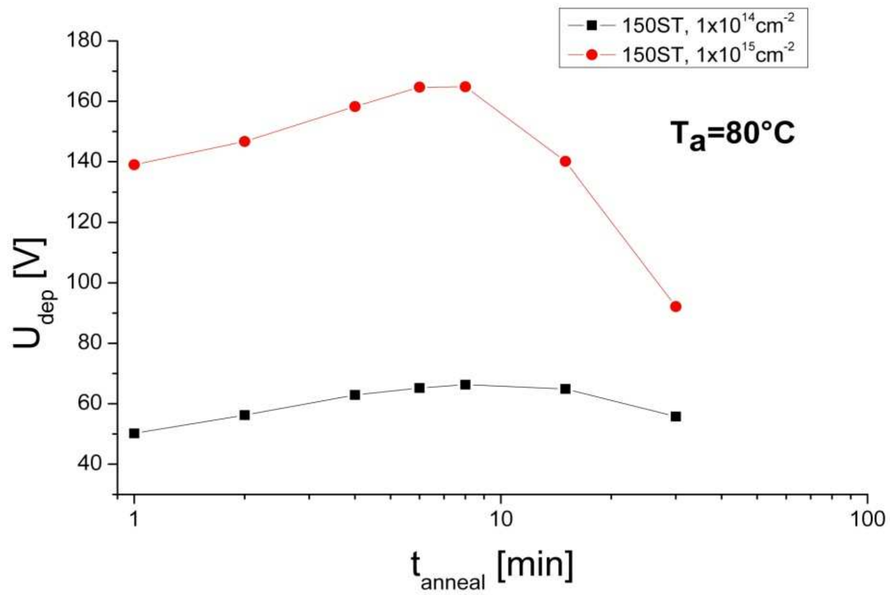
Using charge multiplication to overcome trapping in highly irradiated detectors looks promising

BACKUP SLIDES

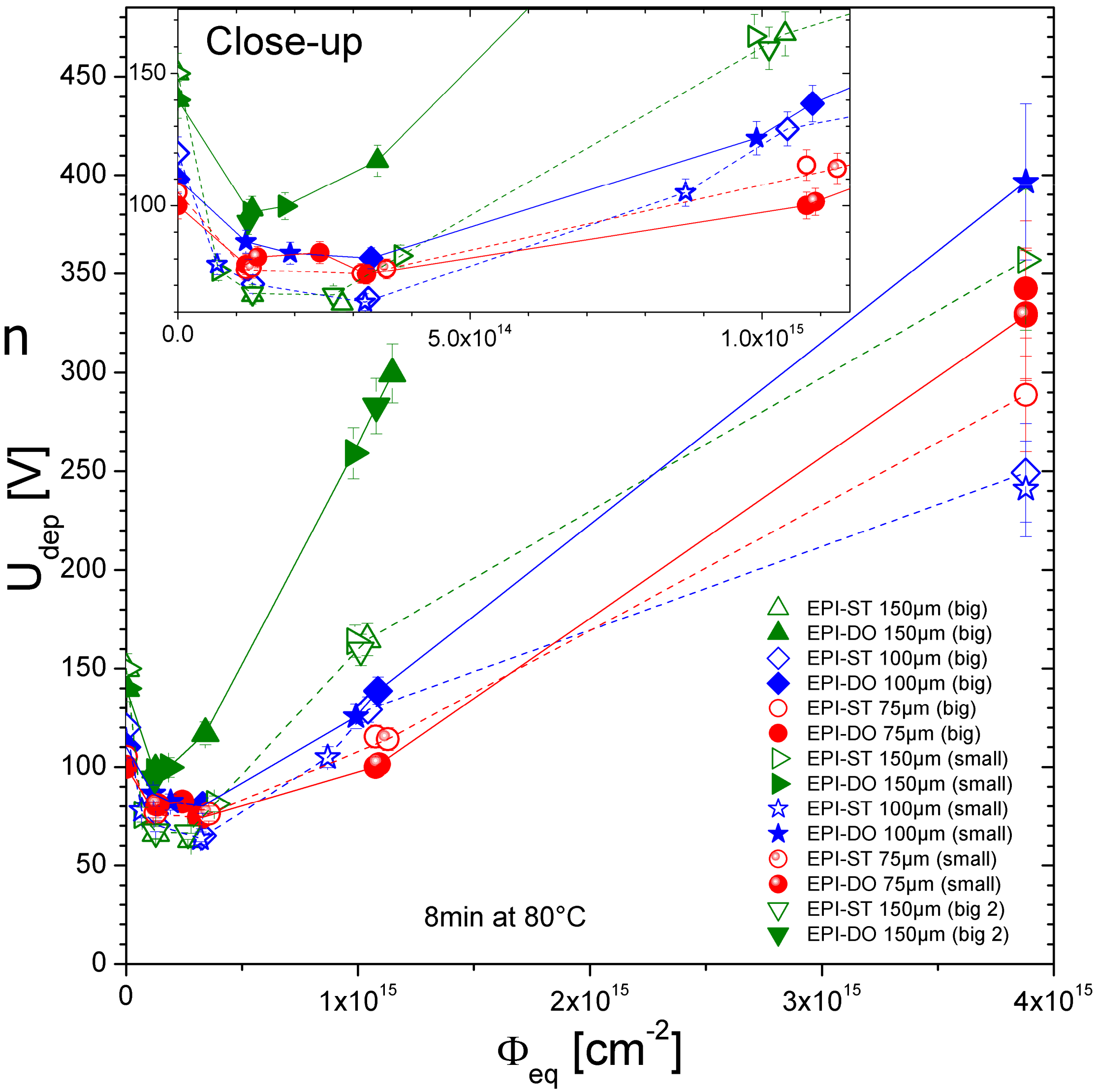
Depletion Voltage (from CV at 10 kHz)

- 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 $g_C(DO)>g_C(ST)$

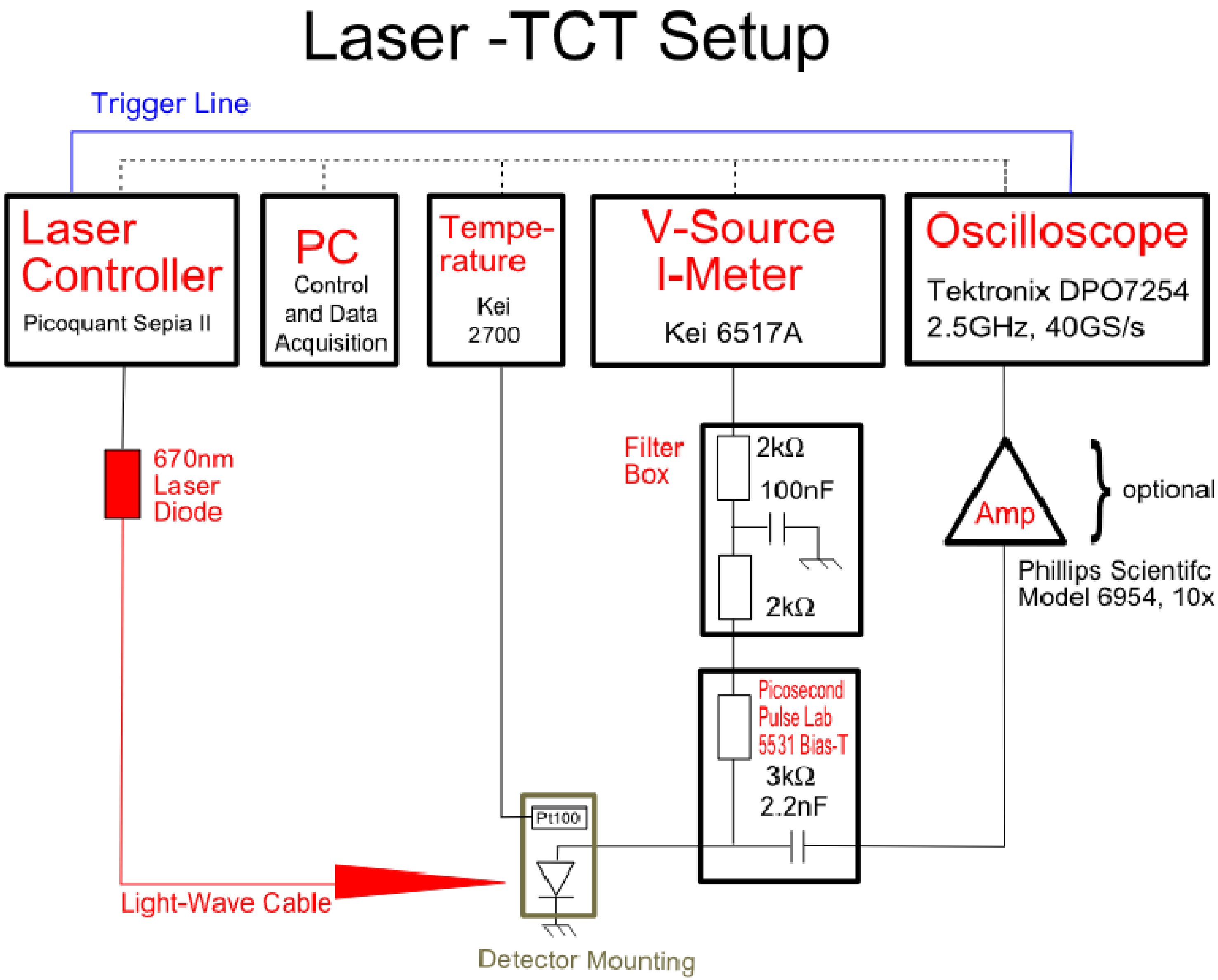
Annealing curve:



Stable Damage:

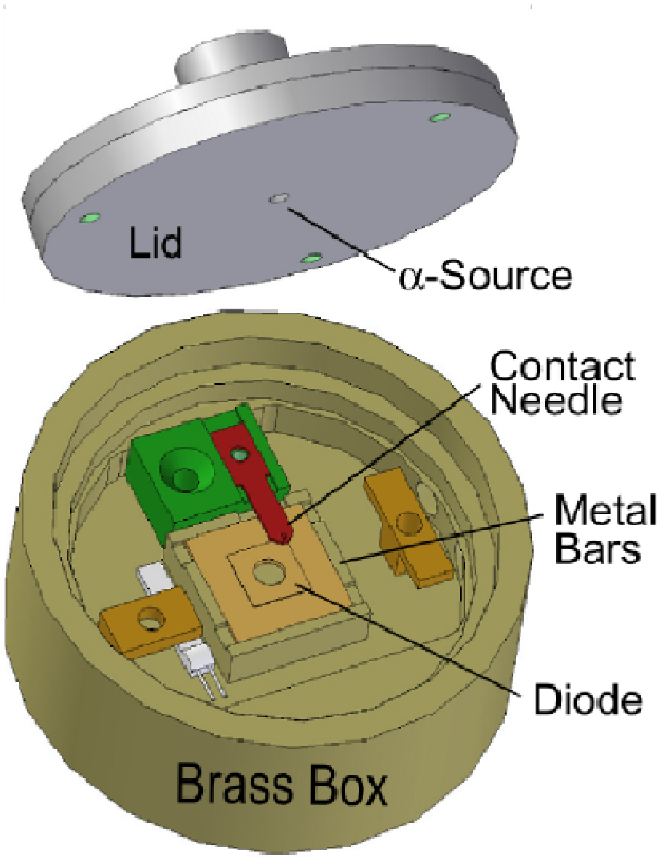


MTCT Laser-TCT Setup

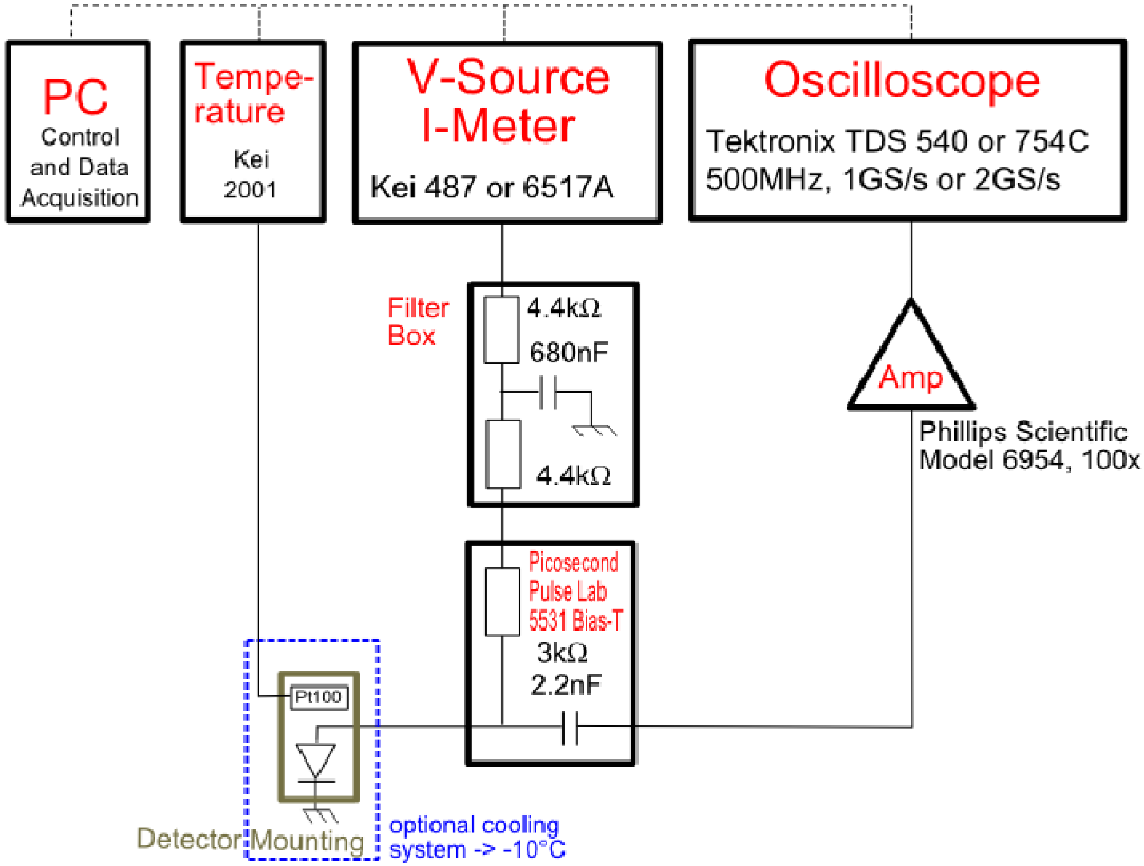


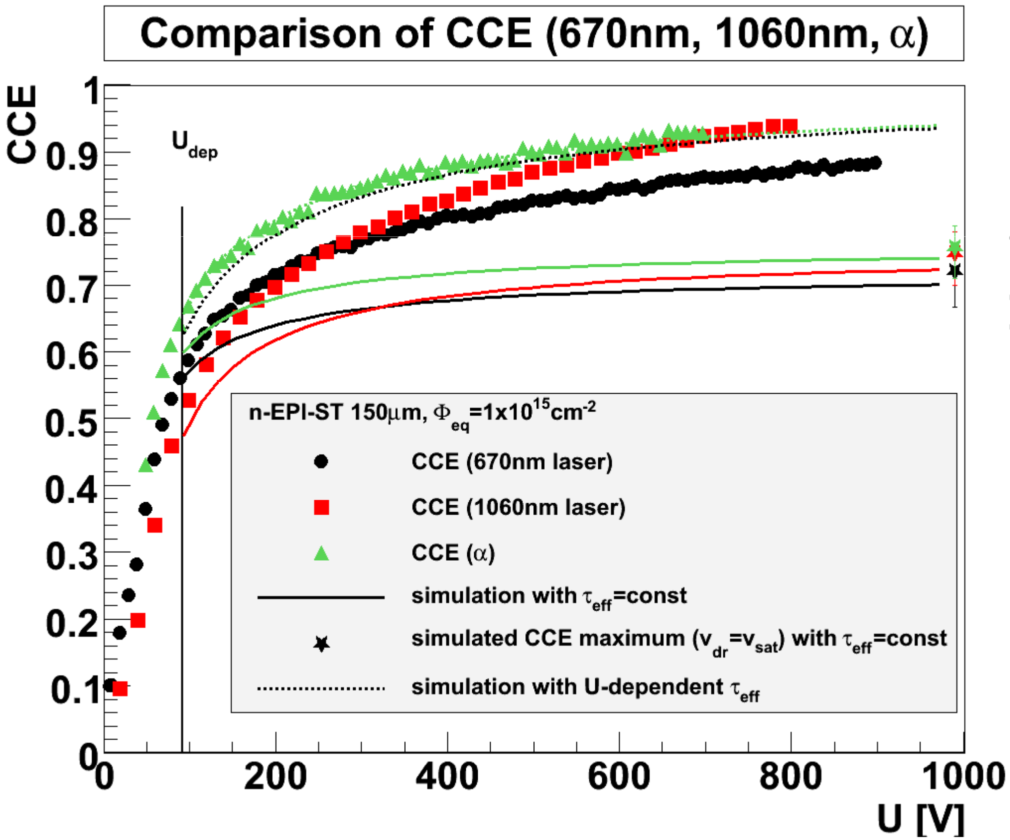
Alpha-TCT Setup

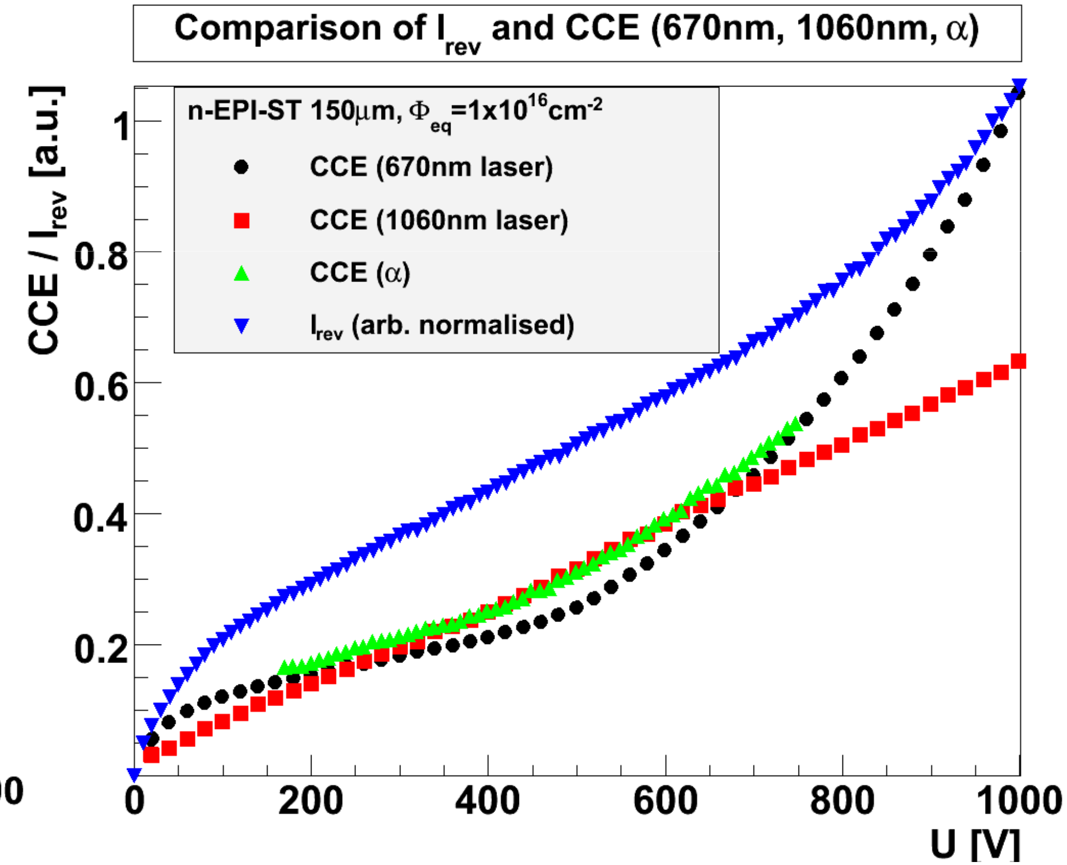
Detector Mounting



α -TCT Setup




Comparison of CCE (670nm, 1060nm, α)
CCE
U [V]
U_dep
n-EPI-ST 150µm, Φ_eq=1x10^15 cm^-2
CCE (670nm laser)
CCE (1060nm laser)
CCE (α)
simulation with τ_eff=const
simulated CCE maximum (v_dr=v_sat) with τ_eff=const
simulation with U-dependent τ_eff


Comparison of I_rev and CCE (670nm, 1060nm, α)
CCE / I_rev [a.u.]
U [V]
n-EPI-ST 150µm, Φ_eq=1x10^16 cm^-2
CCE (670nm laser)
CCE (1060nm laser)
CCE (α)
I_rev (arb. normalised)