Charge Multiplication in Highly-Irradiated Epitaxial Silicon Diodes

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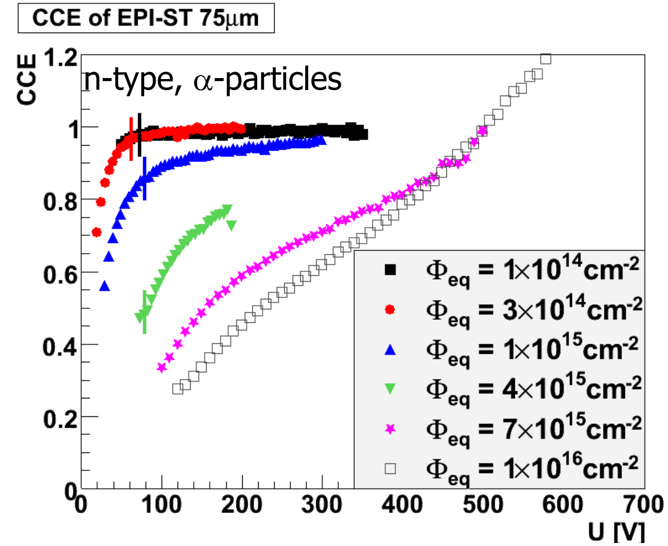
In the framework of the CERN RD50 Collaboration

Introduction

- Charge multiplication observed in highly-irradiated diodes
  $\Rightarrow$ option to overcome trapping at SLHC fluences?

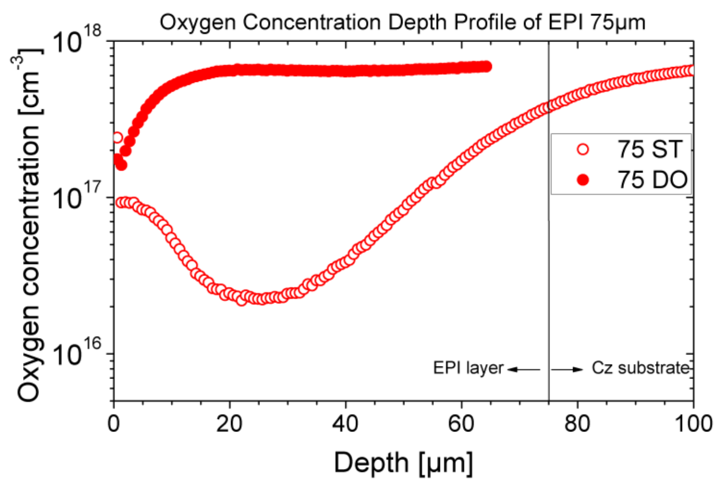


- Knowledge so far:
  - EPI diodes: thin CM region at the front side (p^+-implantation) after p irradiation
  - CM: spatially uniform, stable in time, proportional mode
  - No effect of statistical fluctutations in CM process on charge spectra measured with laser light $\Rightarrow$ no excess noise
- This talk:
  - Dependence of CM on material, thickness
  - Measurements with ^{90}Sr β-setup: signal, noise, SNR, spectrum width

Overview on Investigated Diodes

- Epitaxial Si pad-detectors on Cz-substrate produced by ITME/CiS
- Size: 5 x 5 mm^2 and 2.5 x 2.5 mm^2
- Thickness: 75 μm, 100 μm and 150 μm (n-type)
- Standard (ST) and oxygen enriched (DO, diffusion for 24h at 1100 C) material
- 24 GeV/c proton-irradiation (CERN PS), $\Phi_{eq} = 10^{14} - 10^{16}$ cm^{-2}, no SCSI
- 30 min at 80 C annealing

Material	d [μ m]	Wafer	Orientation	$N_{eff,0}$ [10^{12} cm^{-3}]	[O] [10^{16} cm^{-3}]
n-EPI ST 75	74	8364-03	<111>	26	9.3
n-EPI DO 75	72	8364-07	<111>	26	60.0
n-EPI ST 100	102	261636-05	<100>	15	5.4
n-EPI DO 100	99	261636-01	<100>	15	28.0
n-EPI ST 150	147	261636-13	<100>	8.8	4.5
n-EPI DO 150	152	261636-09	<100>	8	14.0



Experimental Methods

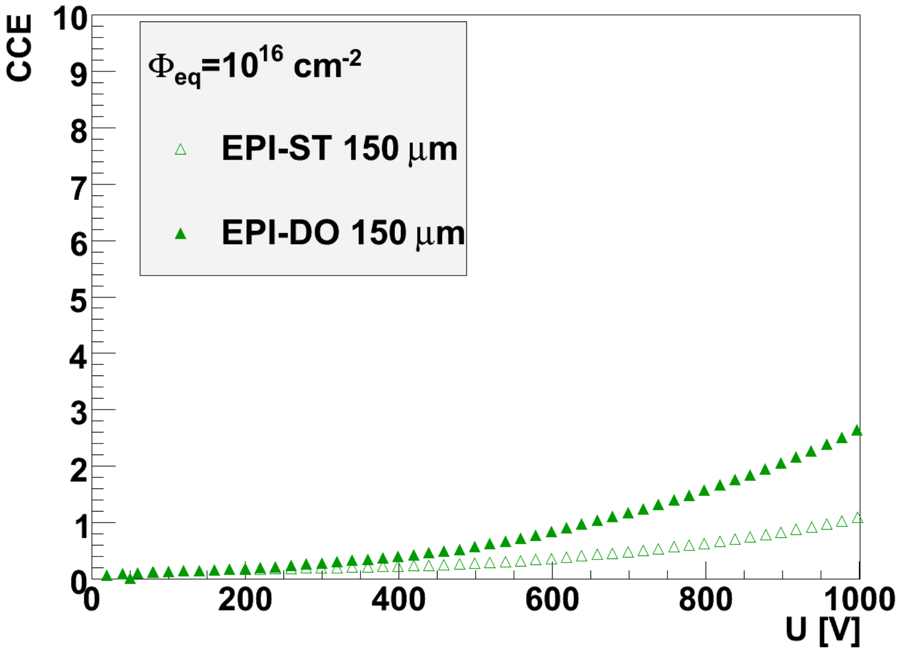
Charge collection investigated with:

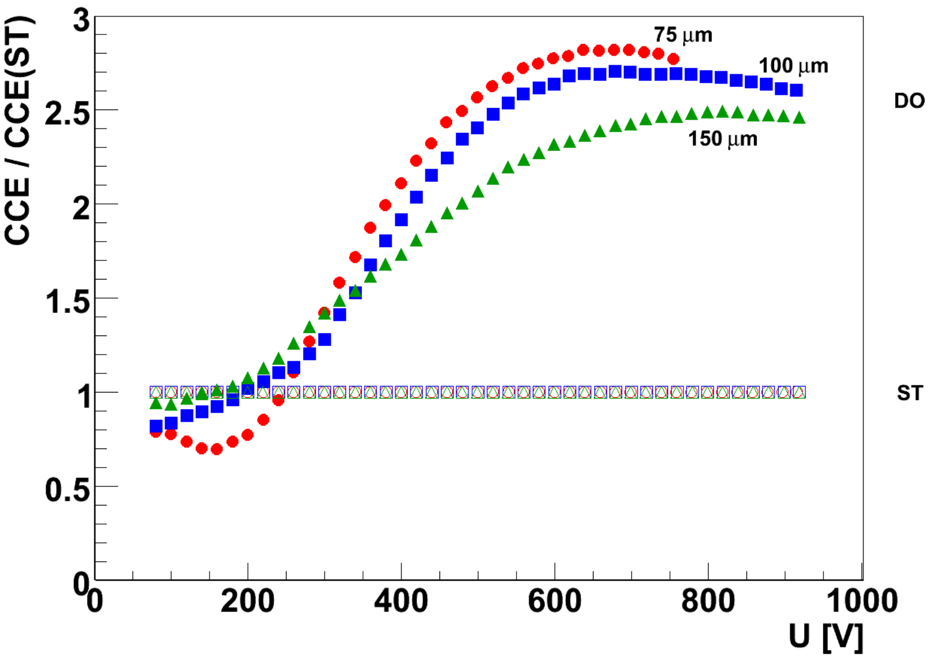
- Transient Current Technique , TCT (Hamburg)
  - 670, 830, 1060 nm laser light, 5.8 MeV α-particles
  - Front illumination
  - Current-sensitive amplifier
  - Integral of current pulse = collected charge Q
  - Charge collection efficiency obtained by normalising Q wrt. unirradiated diode: $CCE = \frac{Q}{Q_0}$
  - Measured at -10 C

- ^{90}Sr-beta setup (Ljubljana)
  - Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
  - Scintillator $\rightarrow$ high purity trigger
    $\Rightarrow$ signals with SNR<1 measurable
  - Measured at -29 C

CCE for Different Materials

670 nm laser

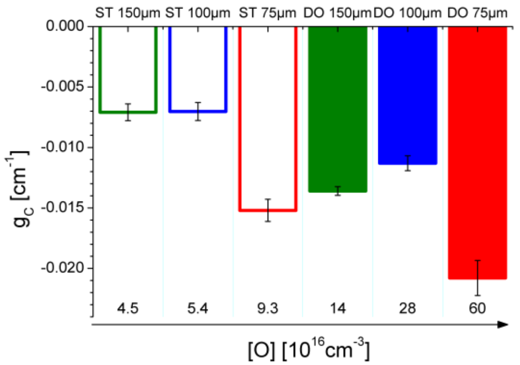




In the CM regime:

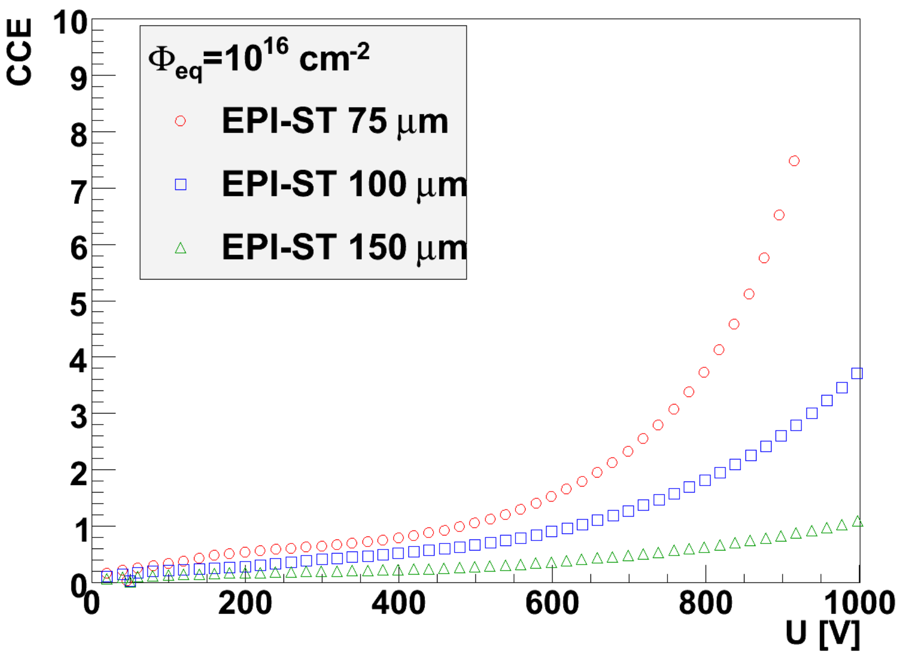
- CCE(DO)>CCE(ST)

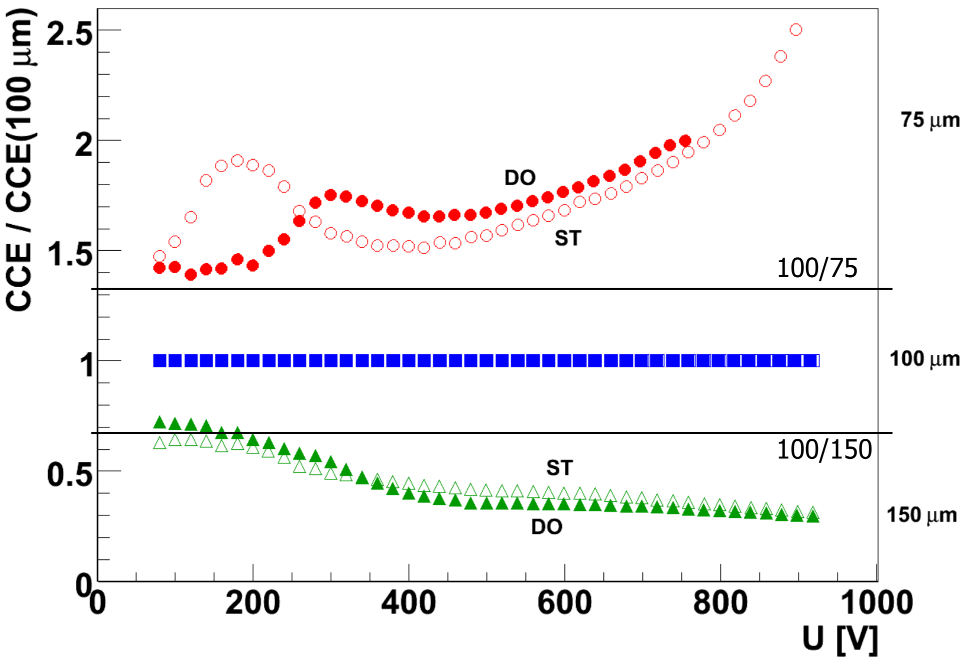
  → higher CM in DO due to larger donor introduction g_C



CCE for Different Thicknesses

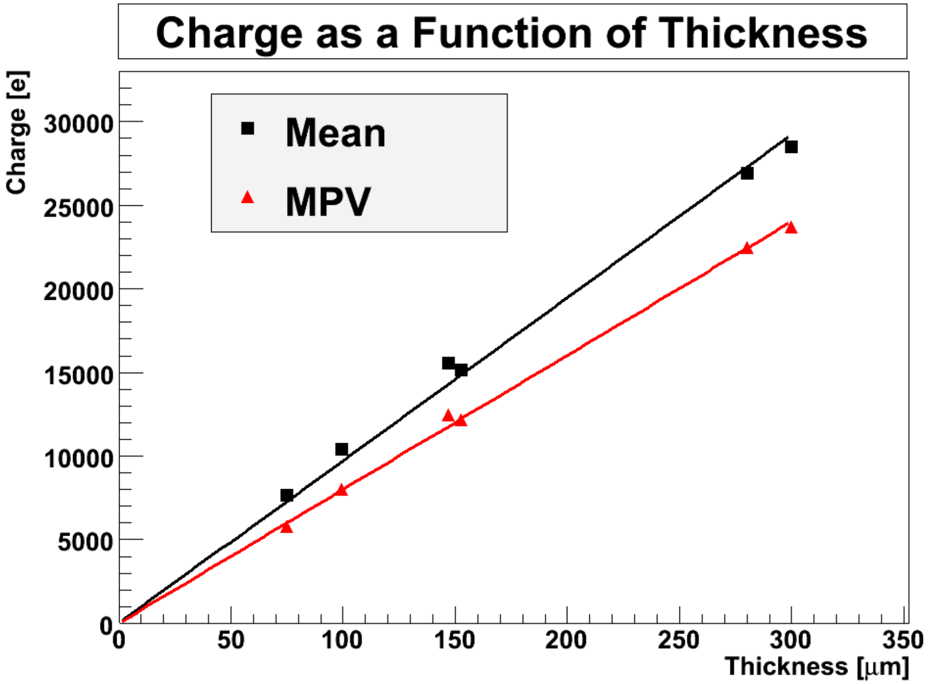
670 nm laser





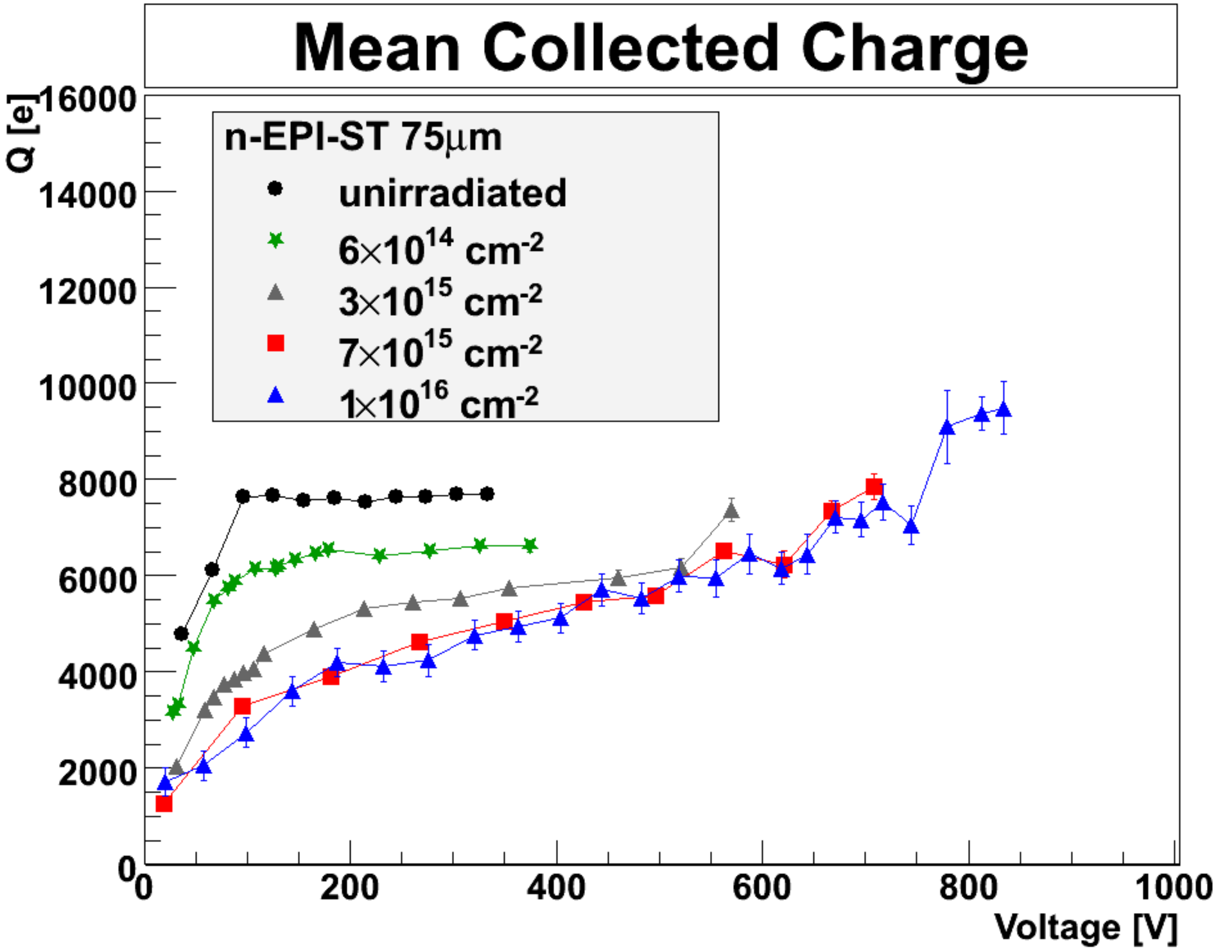
- Increasing CCE for decreasing thickness
  - Less influence of trapping on CCE in thin samples (different weighting fields)
    extreme case: all charge trapped after $l_{eff}<d \Rightarrow CCE_{d1}/CCE_{d2}=d_2/d_1$
  - Higher CM in thin diodes due to higher field?
    But attention: in linear model d-dependence of E for $U<U_{dep}$; Extrapolation: all $U_{dep}>600V$
    But modifications (double junction, voltage drop over neutral bulk region) could lead to d-dependence
  - Higher CM in 75 μm diodes due to larger g_C as [O] is higher in thin samples

Collected Charge with ^{90}Sr β-Setup



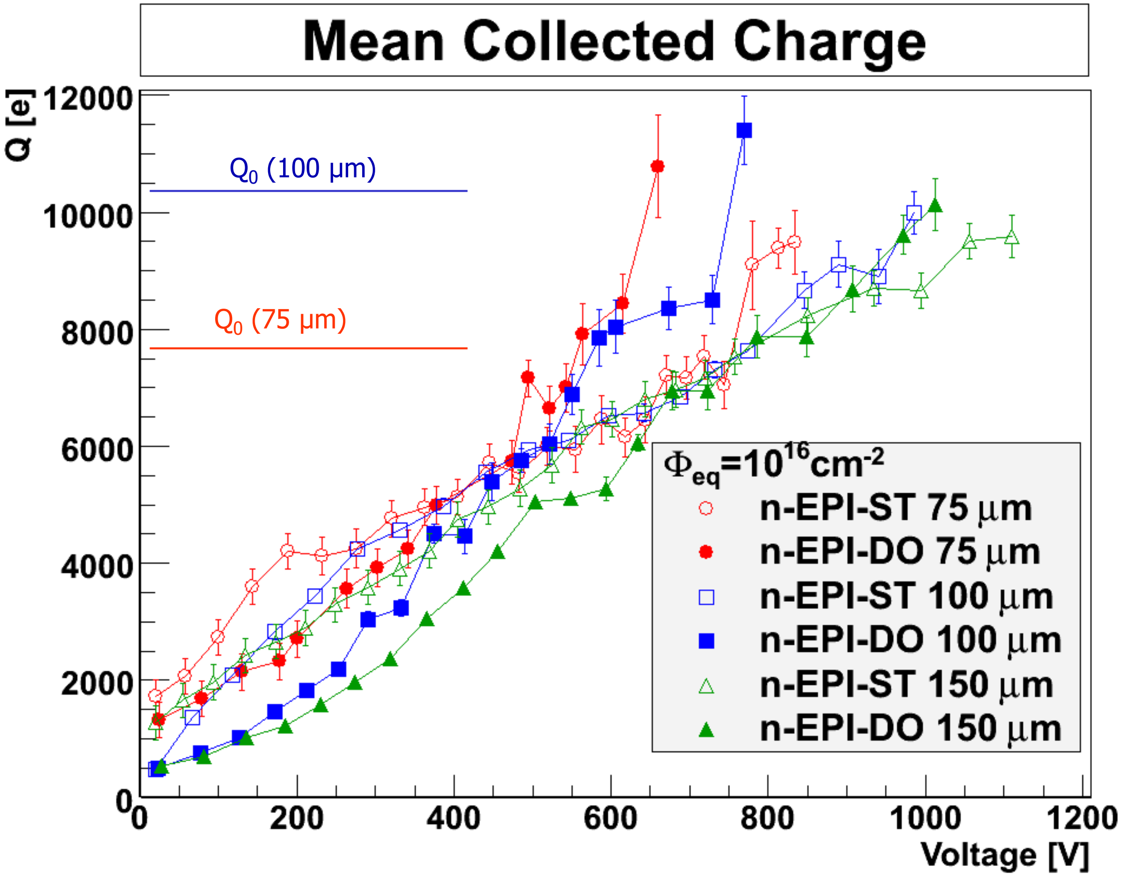
- At least 2500 single waveforms taken
  - Most Probable Value (MPV) determined by Landau-Gauss fit to spectrum: not possible for highly-irradiated diodes due to noise
  - Mean determined by averaging waveforms: also for low Signal-to-Noise Ratio (SNR) possible
- Unirradiated diodes:
  - Collected charge proportional to thickness
    - MPV: 80 e-h/μm
    - Mean: 97 e-h/μm
  - MPV/Mean ≈ 0.75 – 0.85
  - Noise ≈ 2000-3300 e (pad diodes!) depending on size, thickness

Collected Charge for Different Fluences



- Higher charge collection than before irradiation at high fluences and voltages due to CM

Charge for Different Materials and Thicknesses at Highest Fluence



- Q(75µm)>Q(100µm)>Q(150µm) even for absolute collected charge!
- Q(DO)<Q(ST) below the CM regime
  Q(DO)>Q(ST) in the CM regime

⇒ Same material and thickness dependence as for 670 nm laser

- For all materials/thicknesses:
  - More than 9000 e possible at high voltages
  - More than 5000 e at 500 V

  (mean values)

Current and Noise

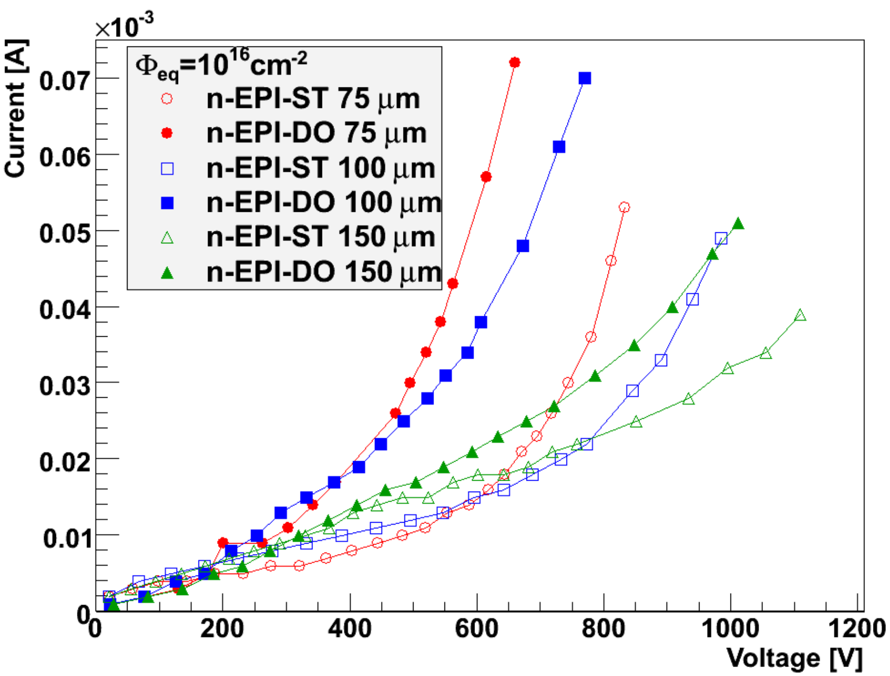
- CM expected to increase signal, current and noise
- Current and noise increase strongly
- Same material and thickness dependence as signal
  - Larger for thinner diodes
  - Larger for DO

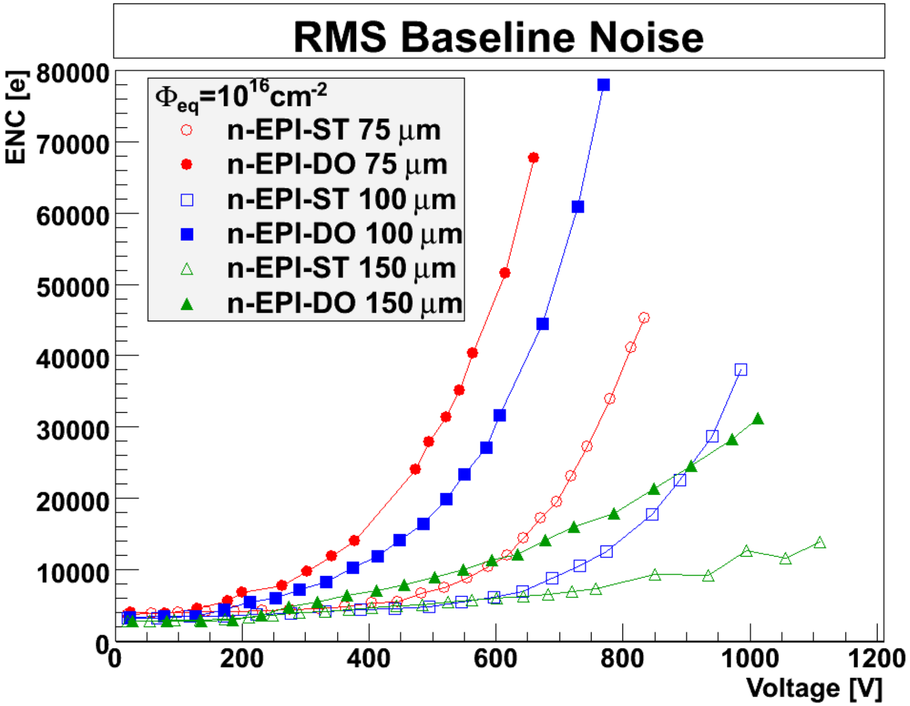
$$Q = MQ_{M=1}$$

$$I = M' I_{M'=1}$$

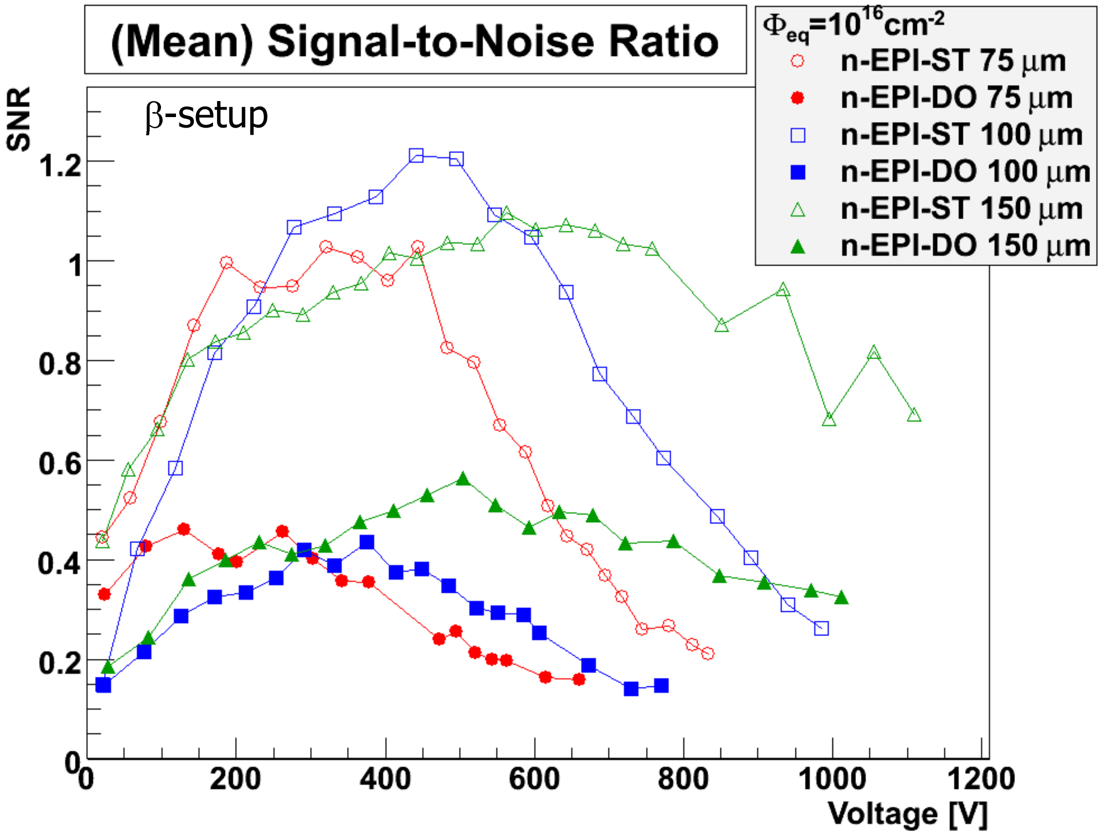
$$\sigma_{shot} = M'\sqrt{F'}\sigma_{shot,M'=1}$$

$$\sigma_{noise} = \sqrt{\sigma_{shot}^2(M') + \sigma'^2_{noise}}$$





Signal-to-Noise Ratio

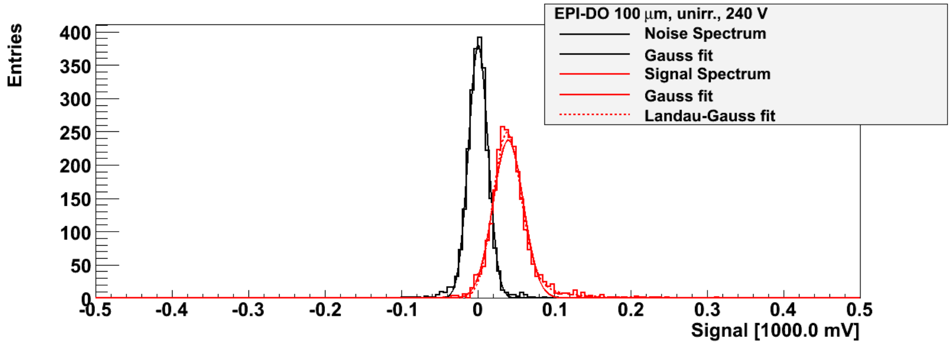


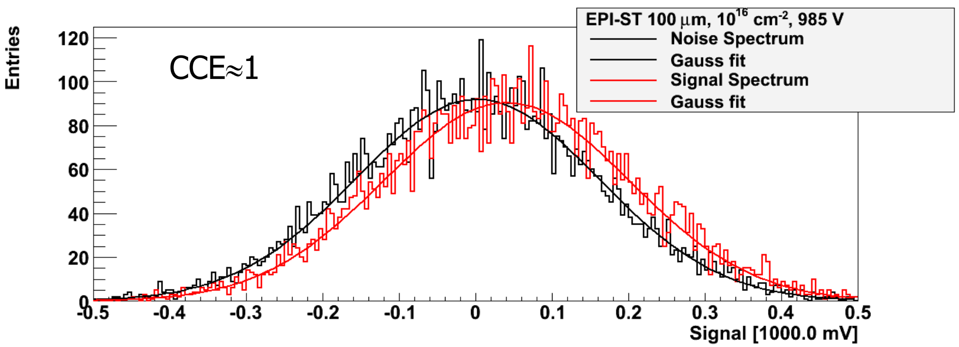
- $$SNR = \frac{Q}{\sigma_{noise}} = \frac{MQ_{M=1}}{\sqrt{M'^2 F' \sigma^2_{shot,M'=1} + \sigma'^2_{noise}}}$$

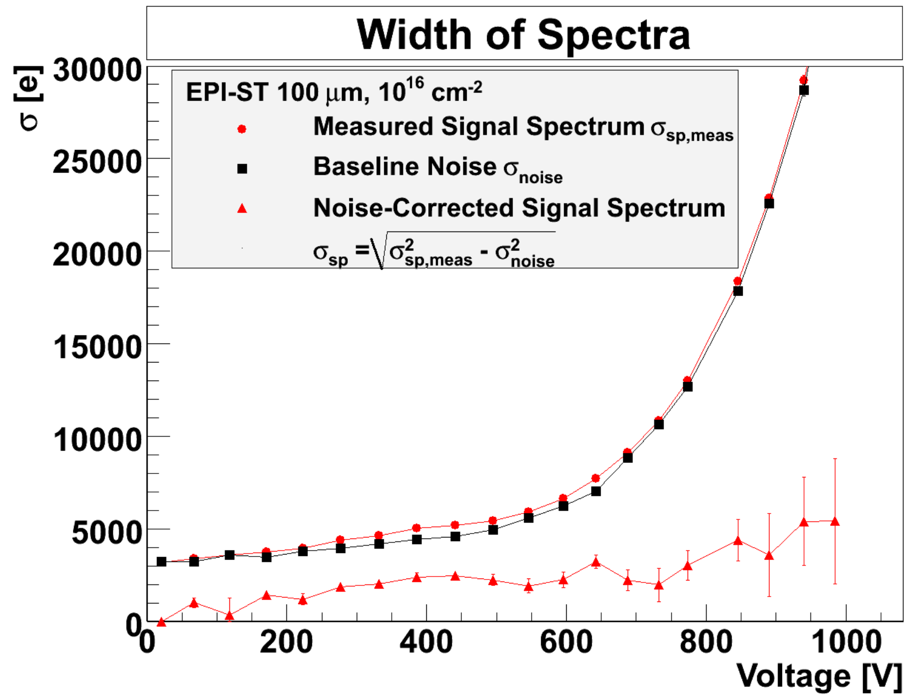
⇒ Depends on relative size of different terms whether CM can improve SNR

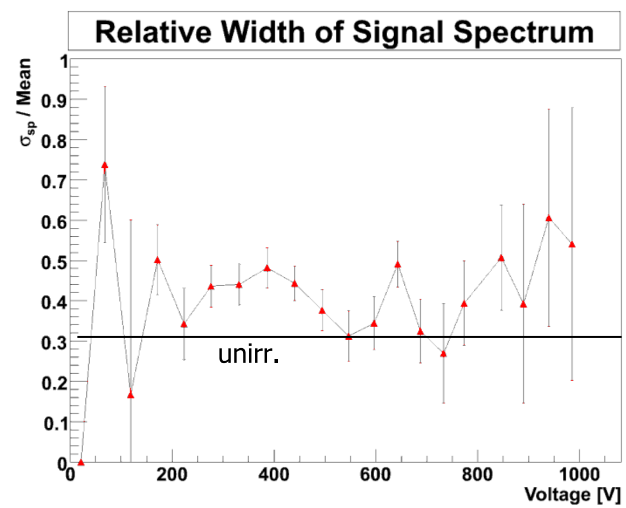
- TCT setup:
  σ'_{noise} large
  ⇒ SNR improves up to 900 V
- β-setup:
  σ'_{noise} smaller
  ⇒ $\sigma_{shot}(M')$ dominates early and increases faster than signal
  ⇒ SNR decreases after maximum at 300 – 500 V
- What about pixels?
  - Lower I
  - Threshold >> noise (unirr.)
    ⇒ noise increase tolerable?

Width of Charge Spectrum









- Fluctuations due to CM might increase spectrum width
- No significant increase of noise-corrected relative width with voltage

⇒ no significant impact of CM fluctuations

Summary

- Properties of charge multiplication investigated with
  - TCT (laser light, α-particles)
  - ^{90}Sr beta setup with charge-sensitive amplifier, 25 ns shaper
- CM is higher for
  - DO material
  - Thinner diodes
- Higher signal than before irradiation due to CM also for β-particles
- Strong noise increase $\Rightarrow$ SNR decreases at high voltages
- No significant increase of noise-corrected relative width
  $\Rightarrow$ no impact of CM fluctuations

High signals possible at S-LHC fluences!

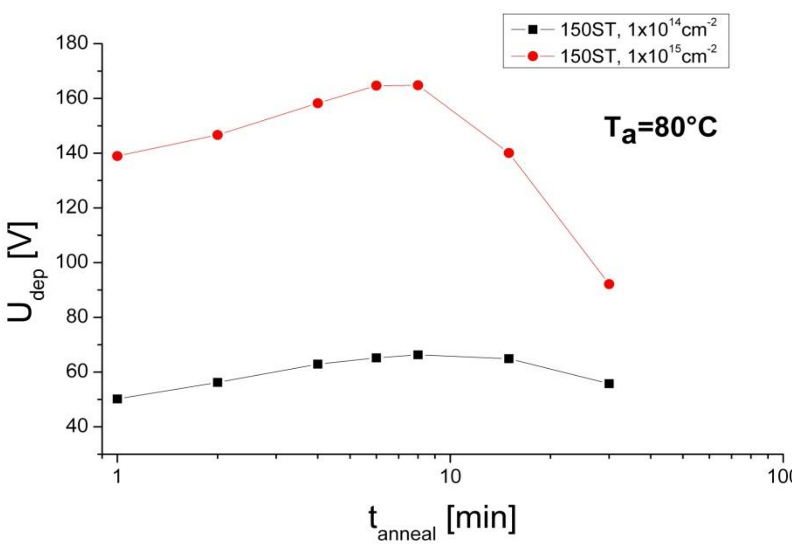
Can noise increase be controlled or tolerated in segmented detectors?

BACKUP SLIDES

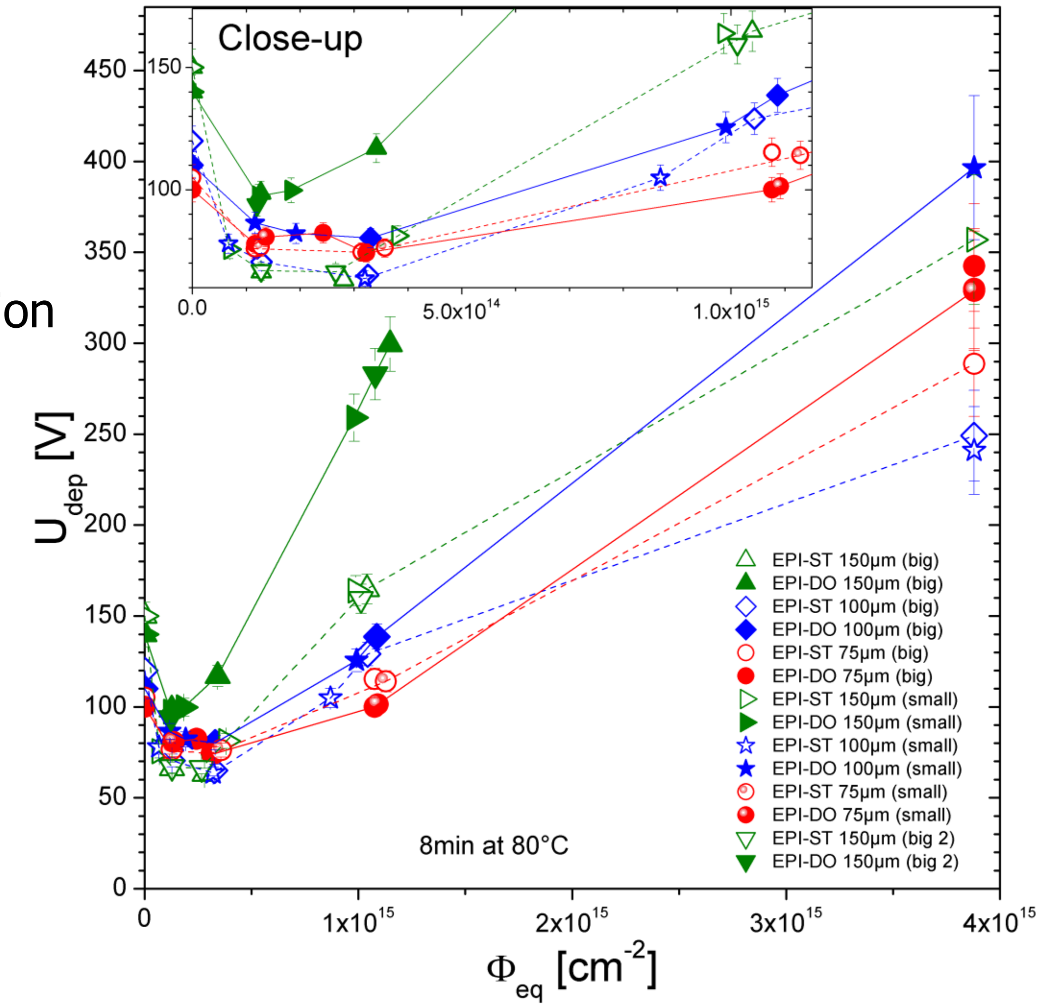
Depletion Voltage (from CV at 10 kHz)

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

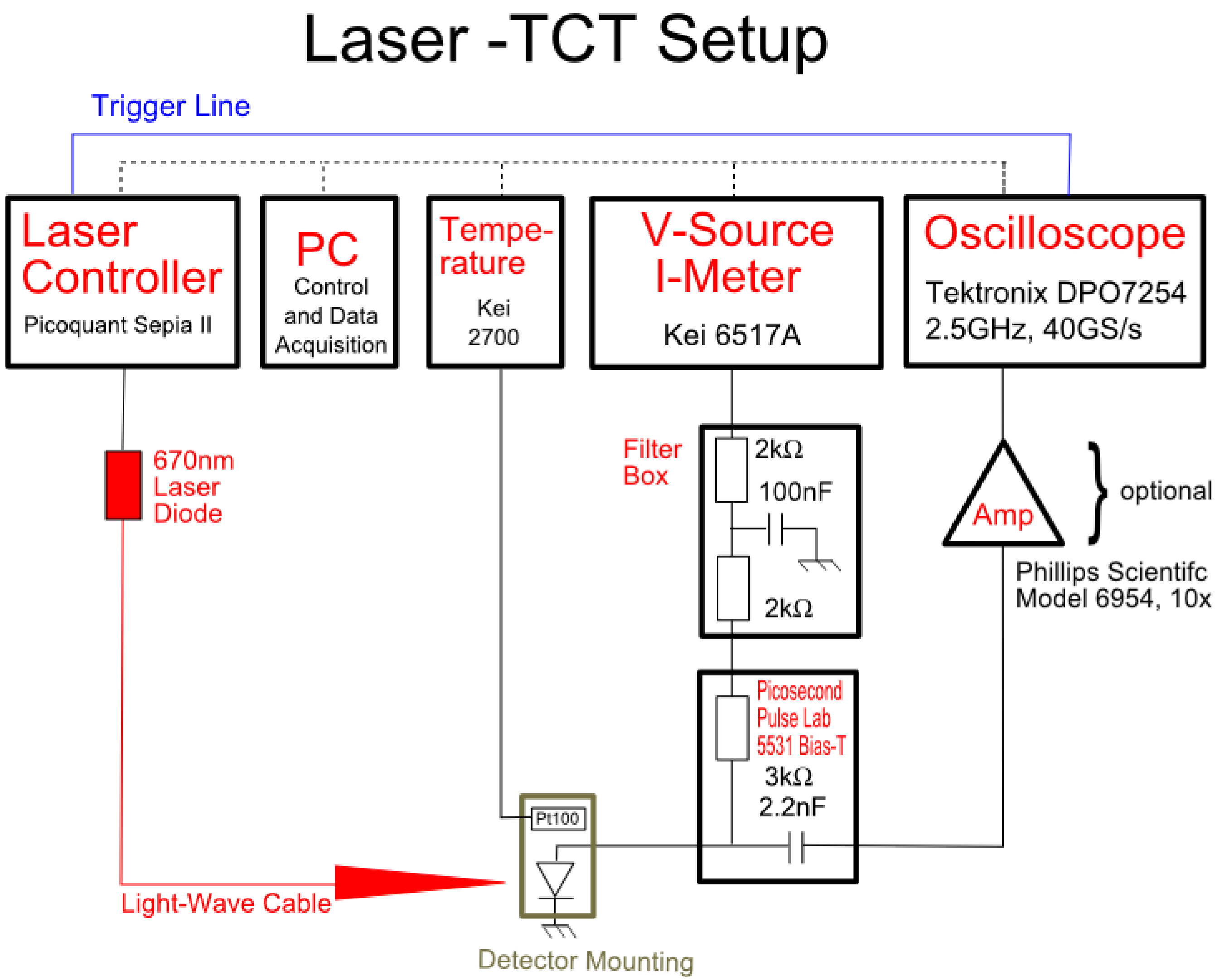
Annealing curve:



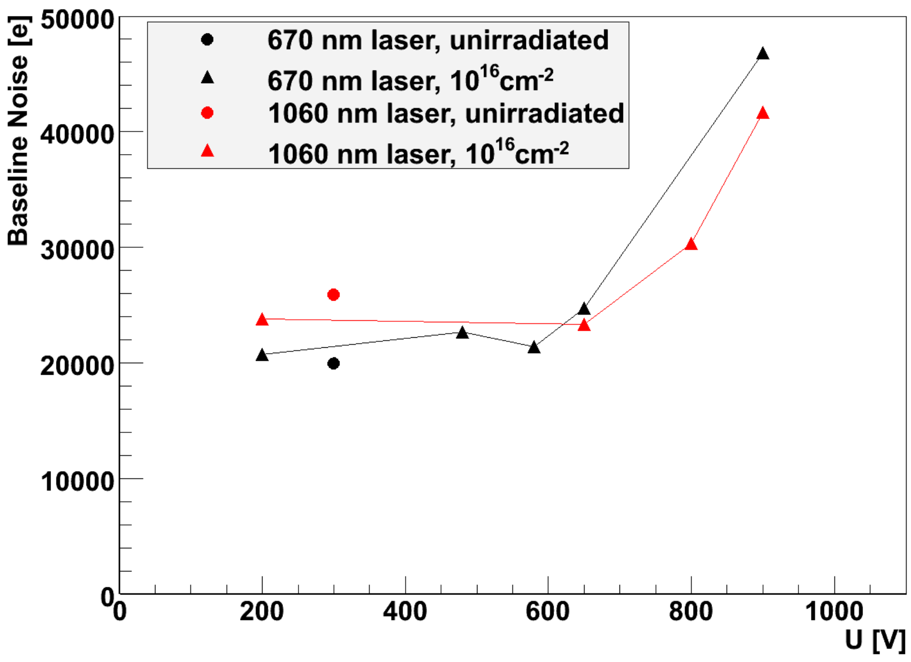
Stable Damage:

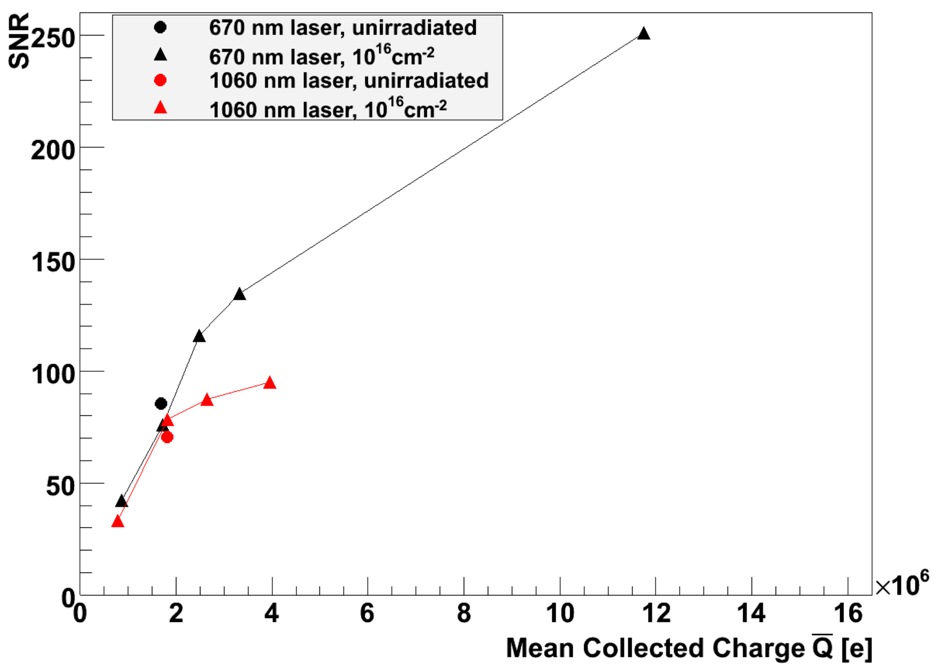


MTCT Laser-TCT Setup



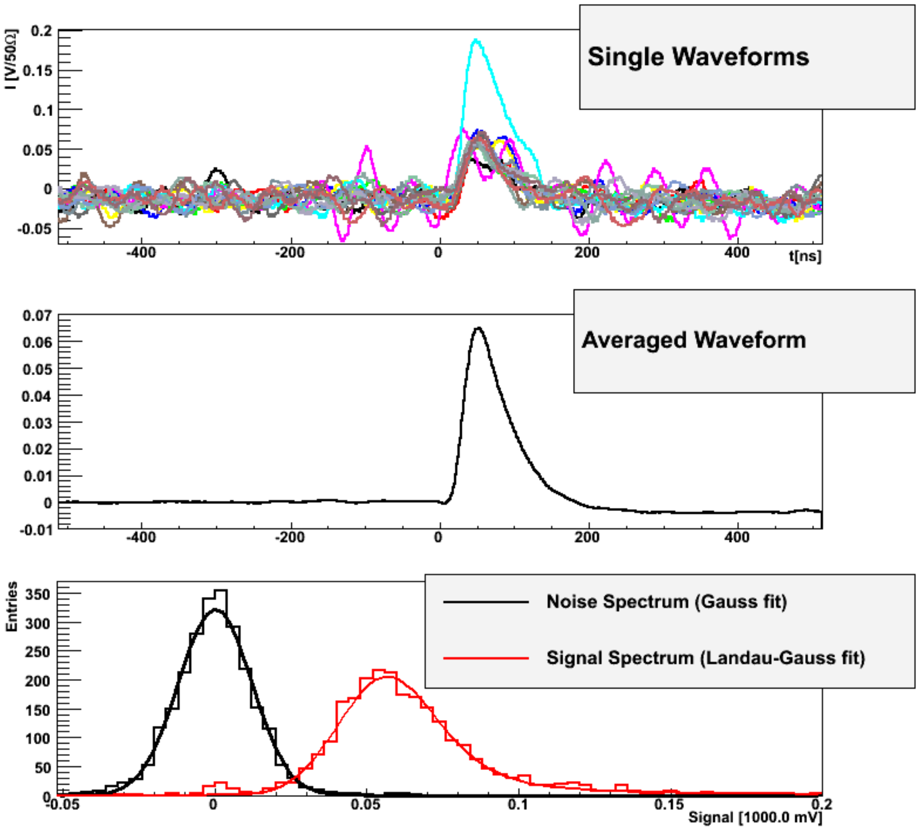
Noise and SNR (TCT with Laser)





^{90}Sr Beta Setup

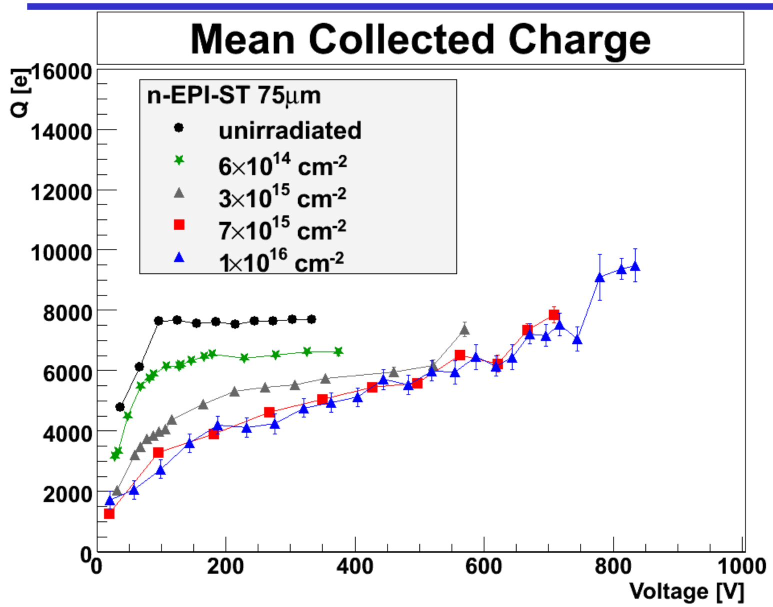
n-EPI-ST 150 µm, unirr., 333 V

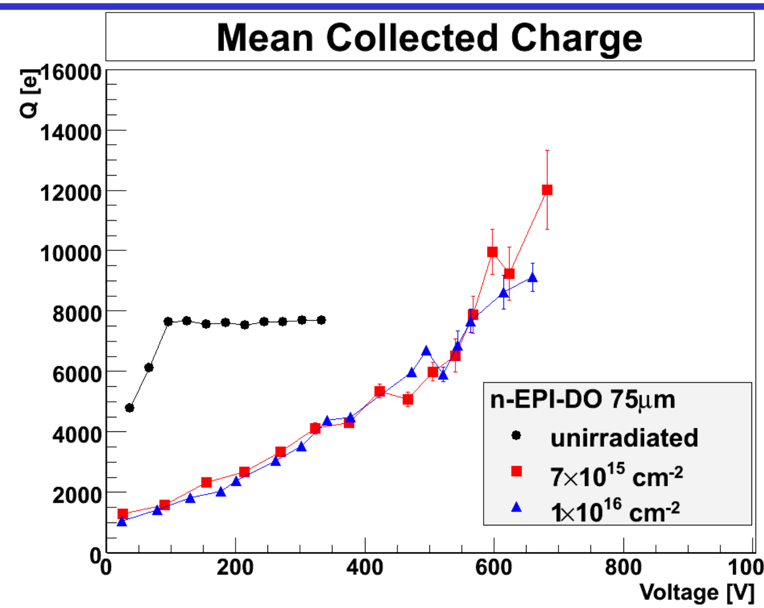


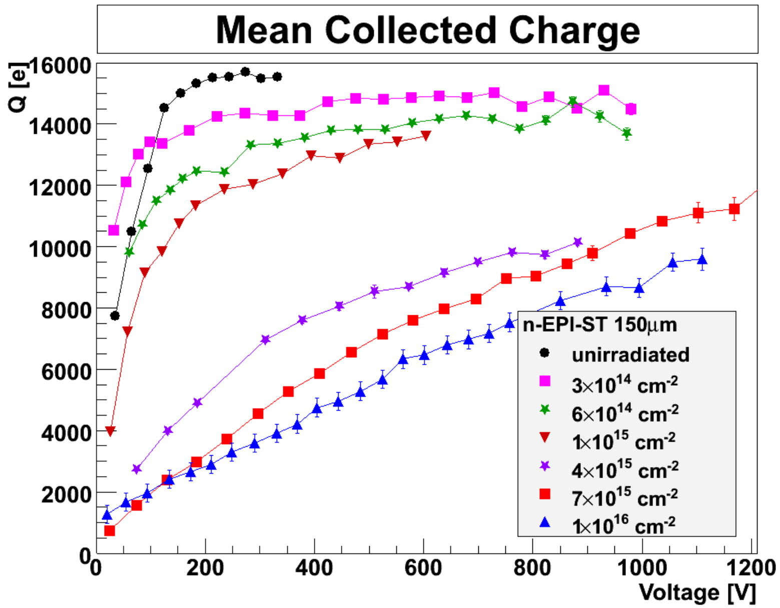
Ljubljana setup for pad diodes:

- Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
- Scintillator → high purity trigger
  ⇒ signals with SNR<1 measurable
- Measured at -29°C
- Calibrated with ^{241}Am, cross-checked with 300 µm diode
- Single waveforms taken with oscilloscope
- Averaged waveform:
  Peak determination possible even for low SNR
  ⇒ for highly-irradiated diodes mean is considered instead of most probable value (MPV)
- Micro discharges in certain samples at high voltages (independent of fluence)

Collected Charge for Different Fluences

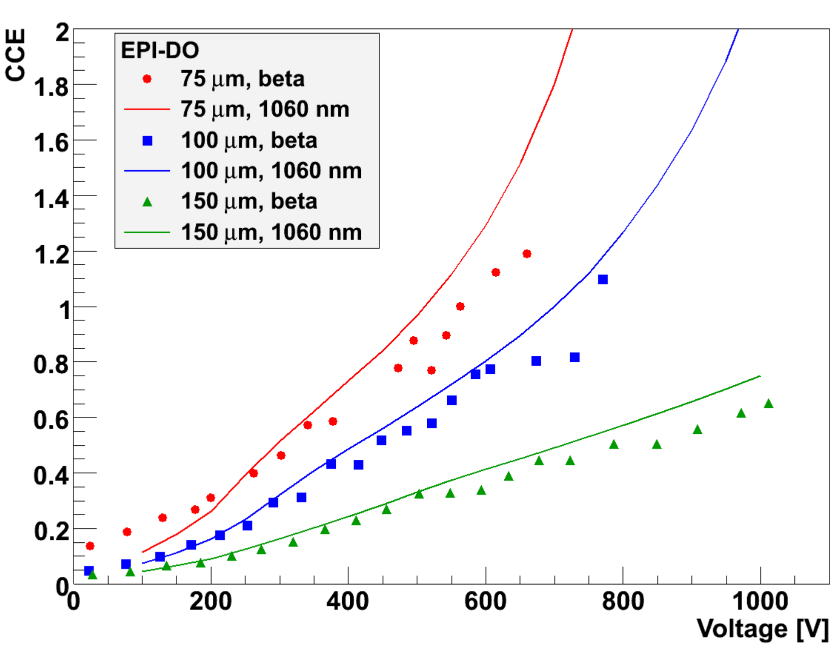


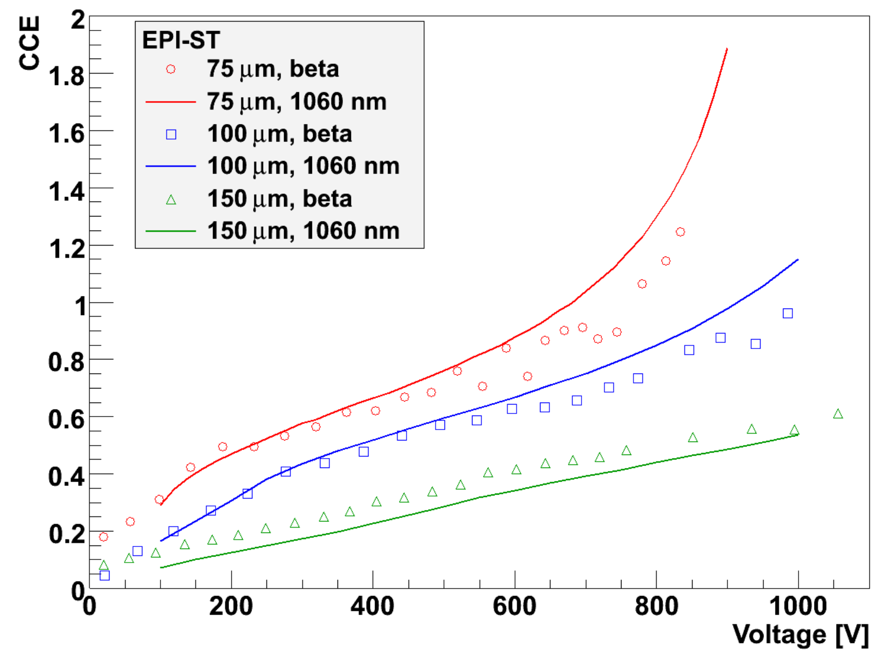




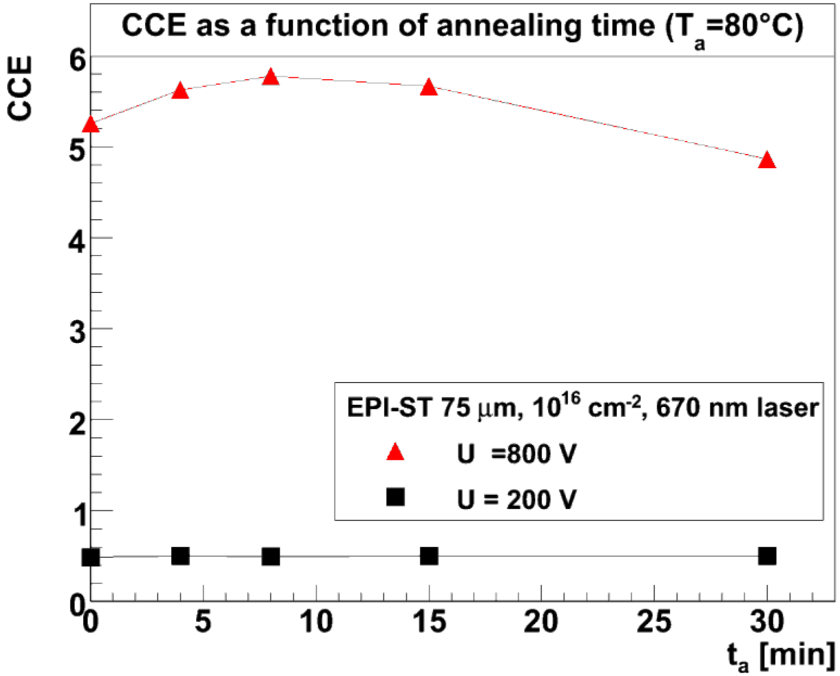
- Charge multiplication at high fluences and voltages

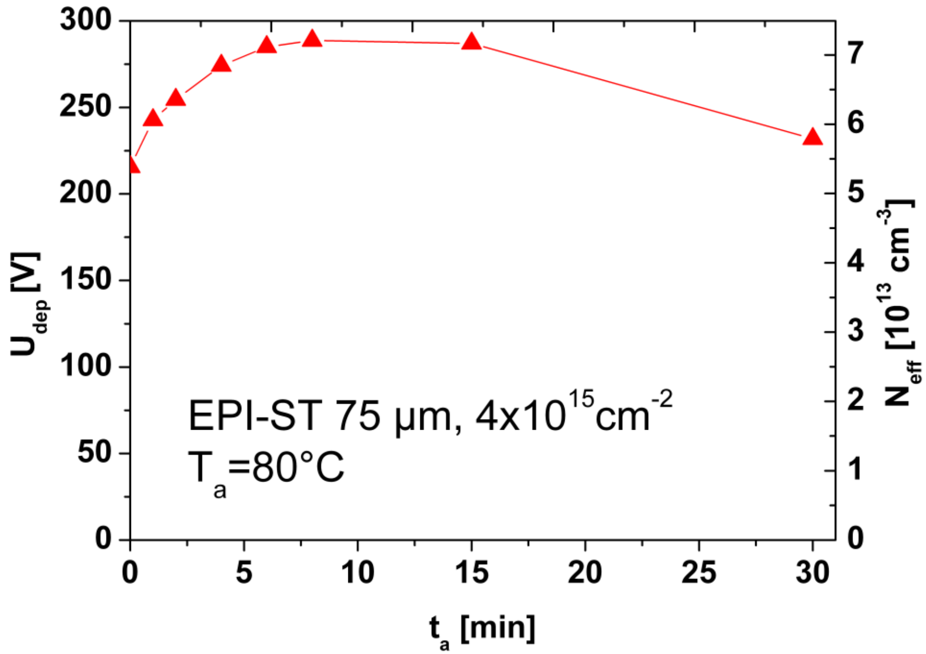
Comparison CCE: 1060nm laser and β-particles





CCE Dependence on Annealing



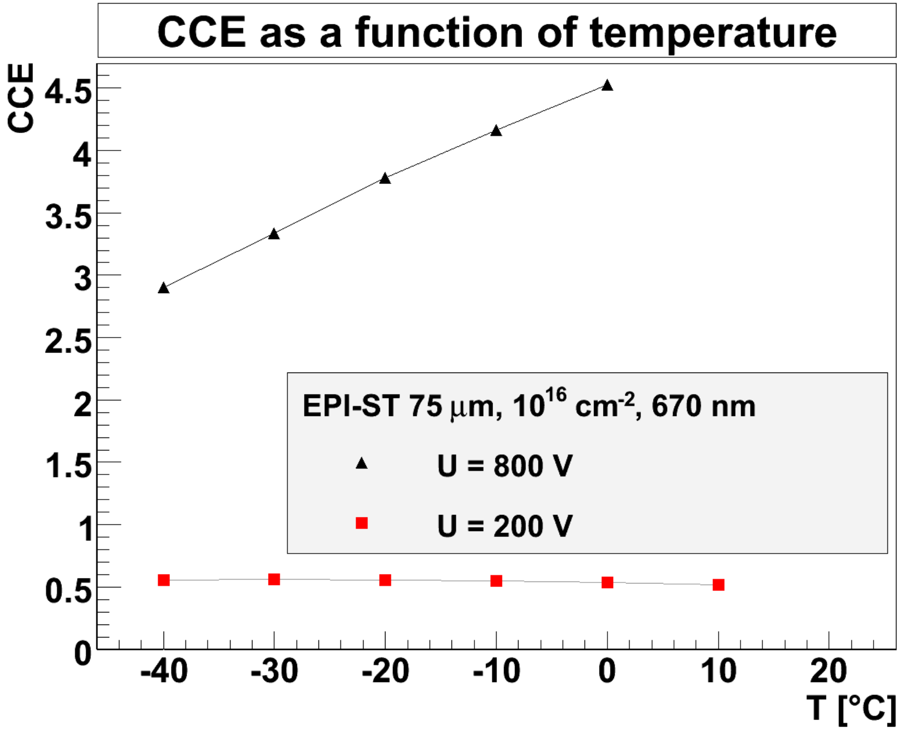


In the CM regime:

- Maximum of CCE at 8 min
- CCE annealing curve shows the same behaviour as the one of U_{dep}, N_{eff}

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

CCE Dependence on Temperature



In the CM regime:

- CCE decreasing for decreasing T
- Contrary to expectations as ionisation coefficients α increase for decreasing T
- Absorption length λ increases for decreasing T; 670 nm: 3.1 µm(0 C) $\rightarrow$ 3.6µm(-40 C)
  But: calculation $\Rightarrow$ effect not large enough; effect tendentially the same for 1060 nm, α

$\Rightarrow$ Change of el. field with T (e.g. due to change in current)?