Charge Multiplication Properties in Highly-Irradiated Epitaxial Silicon Detectors

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PHYSICS AT THE TERA SCALE
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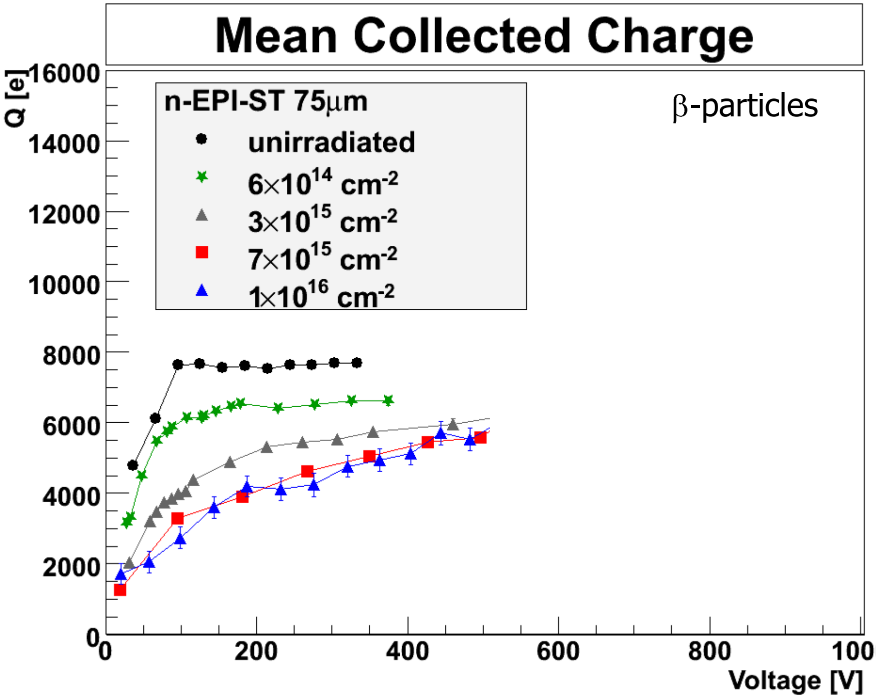
In the framework of the CERN RD50 Collaboration

Introduction

- Trapping: most limiting factor at S-LHC fluences ($\approx 10^{16}$ cm^{-2})
  $\Rightarrow$ 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



Investigated Material

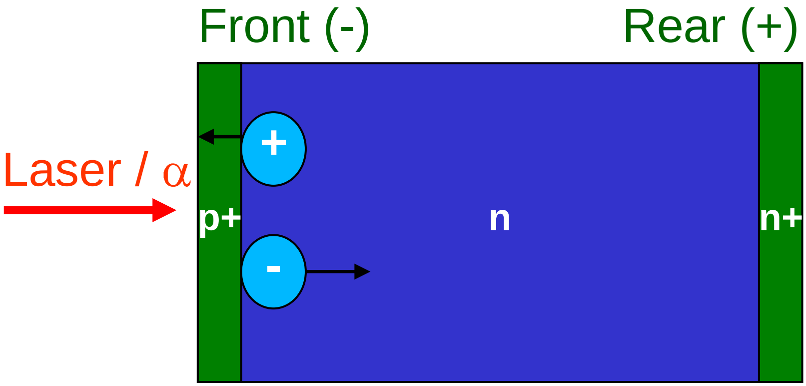
- Epitaxial (Epi) Si on Cz substrate: candidate for superior radiation hardness
  - *Device Engineering:* Thin (25 - 150 µm)
  - *Defect Engineering:*
    - High O concentration in standard material (ST): <[O]>= (4.5 - 9.3) x 10^{16} cm^{-3}
    - Further O enrichment possible (DO): <[O]>= (1.4 - 6.0) x 10^{17} cm^{-3}

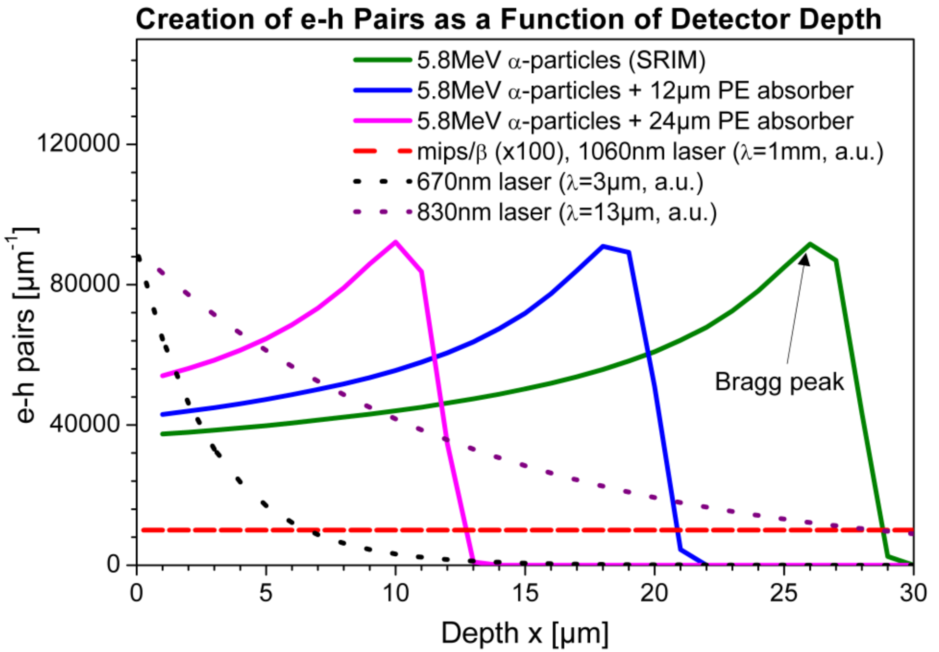
  ⇒ After irradiation with charged hadrons:
    - N_{eff} increase at high fluences due to predominant donor introduction
    - n-type: no space charge sign inversion!

- n-type
- 75 µm, 100 µm, 150 µm thickness
- Pad detectors produced by CiS:
  5 x 5 mm^2 and 2.5 x 2.5 mm^2
- 24 GeV/c proton irradiation (CERN PS)
  up to $\Phi_{eq}=10^{16}$ cm^{-2}
- 30 min at 80 C annealing

Experimental Methods

- Transient Current Technique, TCT (Hamburg)
  - Front illumination (≈10^6 e-h pairs deposited)
  - 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
  - Radiation with different penetration:
    - 5.8 MeV α-particles, optional absorbers
    - 670, 830, 1060 nm laser light
- ^{90}Sr-beta setup (Ljubljana)
  - MIP-like particles
  - Charge-sensitive amplifier, 25 ns shaping time
  - Measured at -29 C

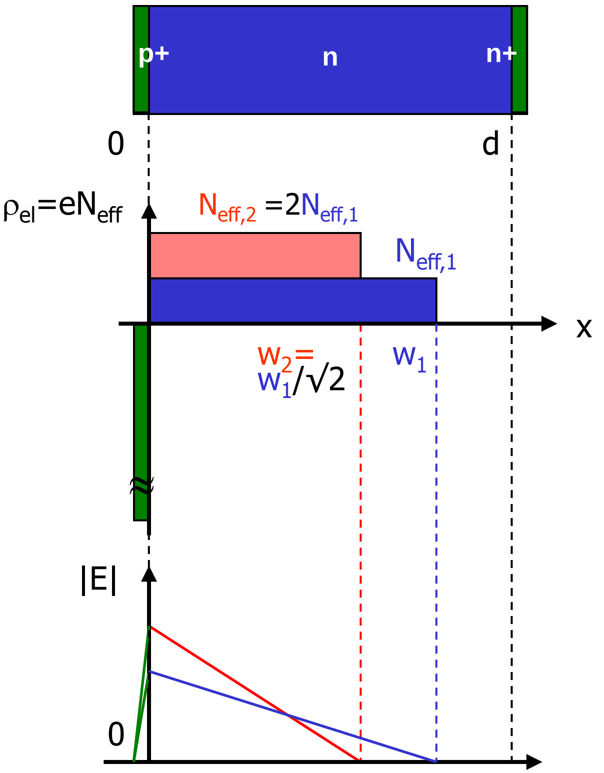




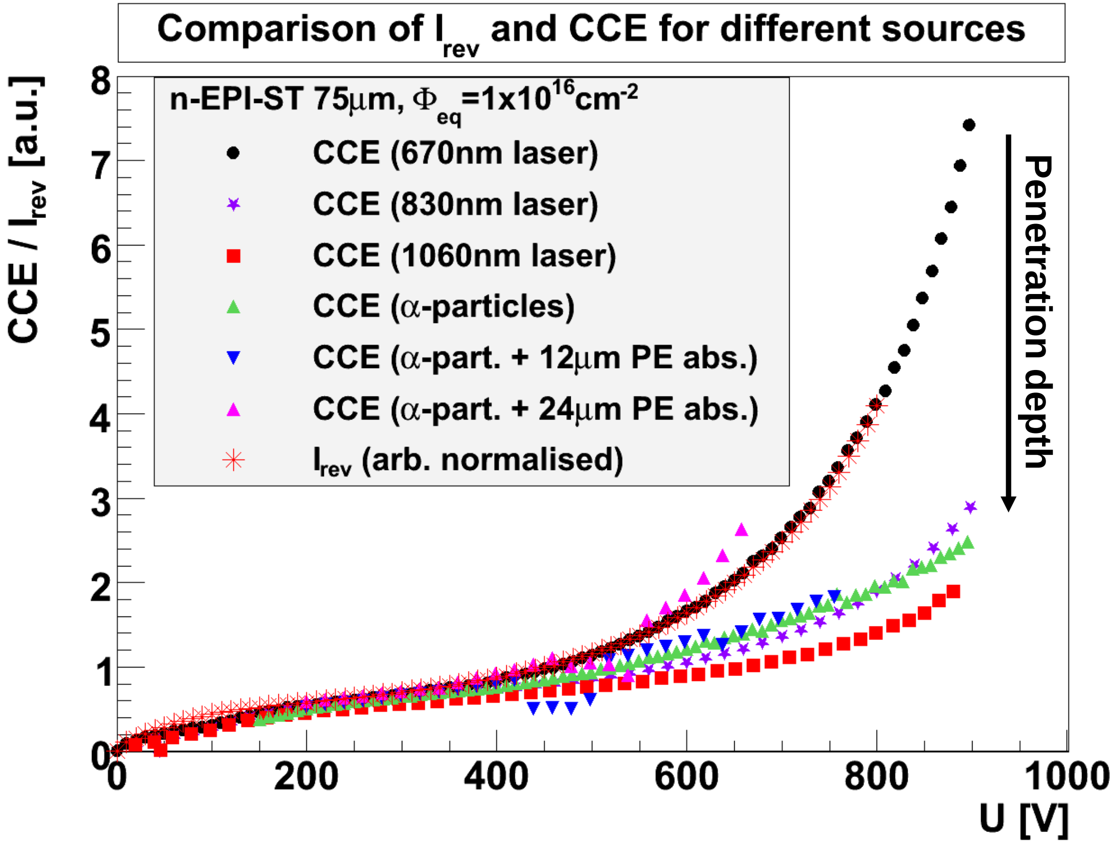
Development and Localisation of the CM Region

Linear field model: N_{eff}=const

(Modifications at high fluences, e.g. double peak)



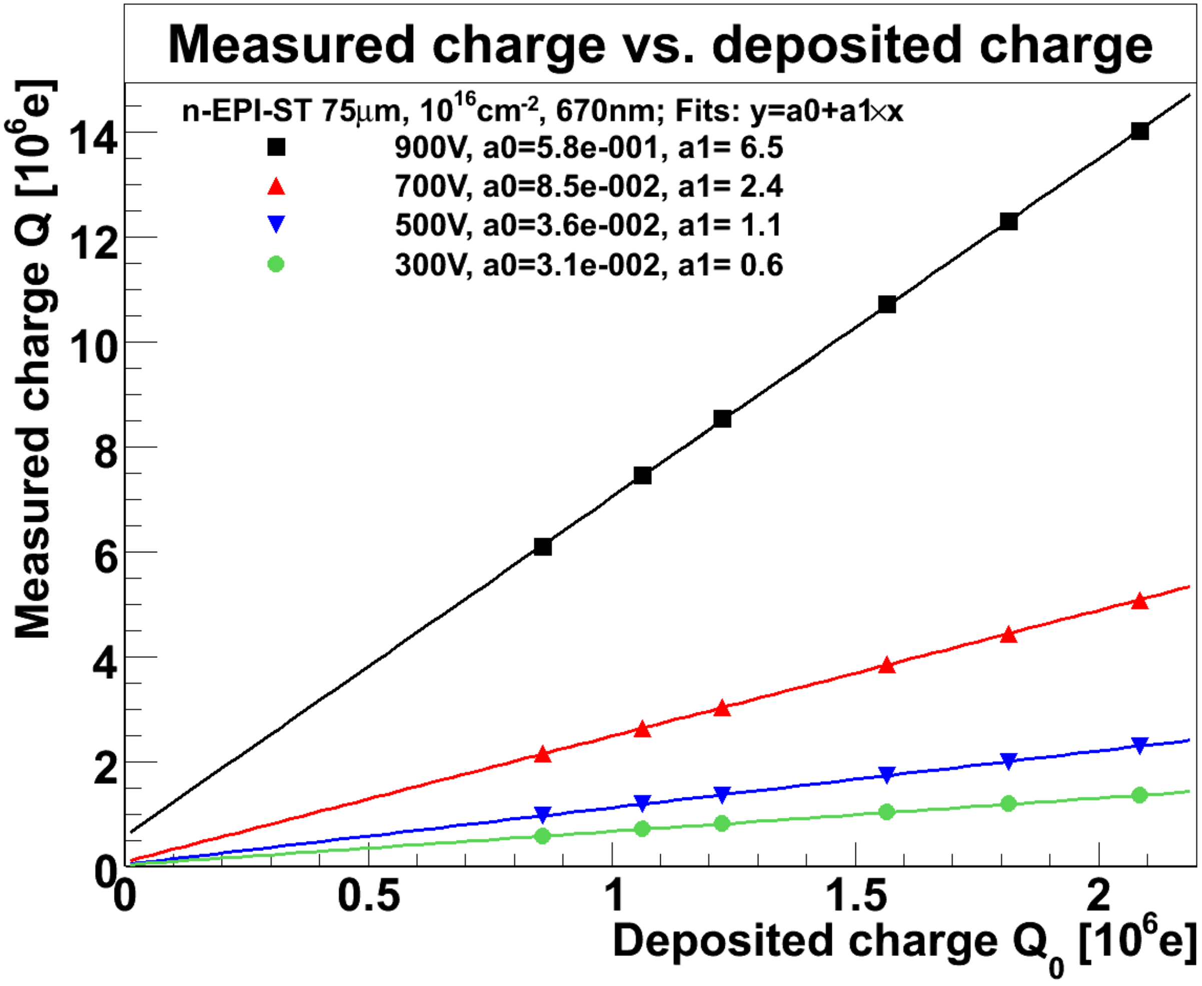
Due to irradiation:
N_{eff} increases → E_{max} at front side increases → CM possible



Smaller penetration depth
→ stronger CM

⇒ Thin CM region located at the front side

Linearity of Measured Charge

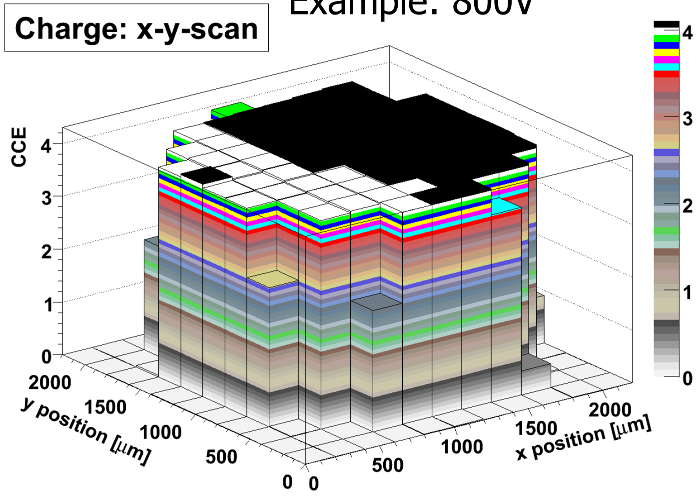


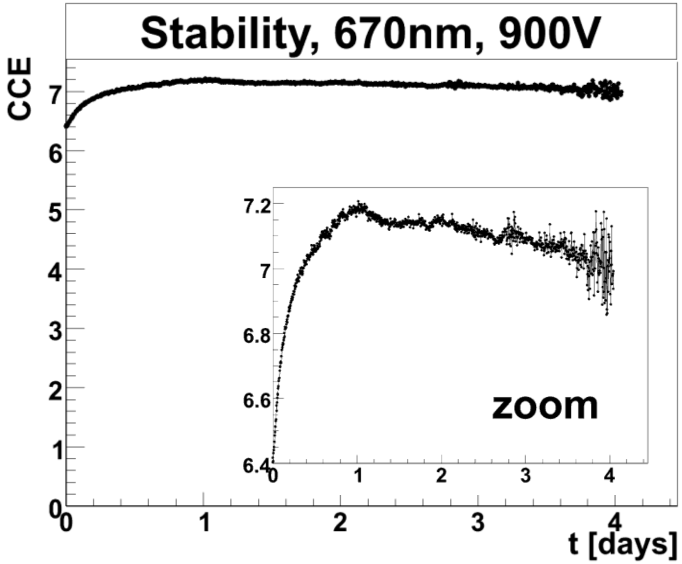
⇒ Proportional mode

not Geiger mode

⇒ E too small for contribution of holes to impact ionisation

Spatial Uniformity and Long-Term Stability

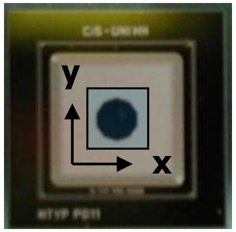

Example: 800V



Uniformity

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

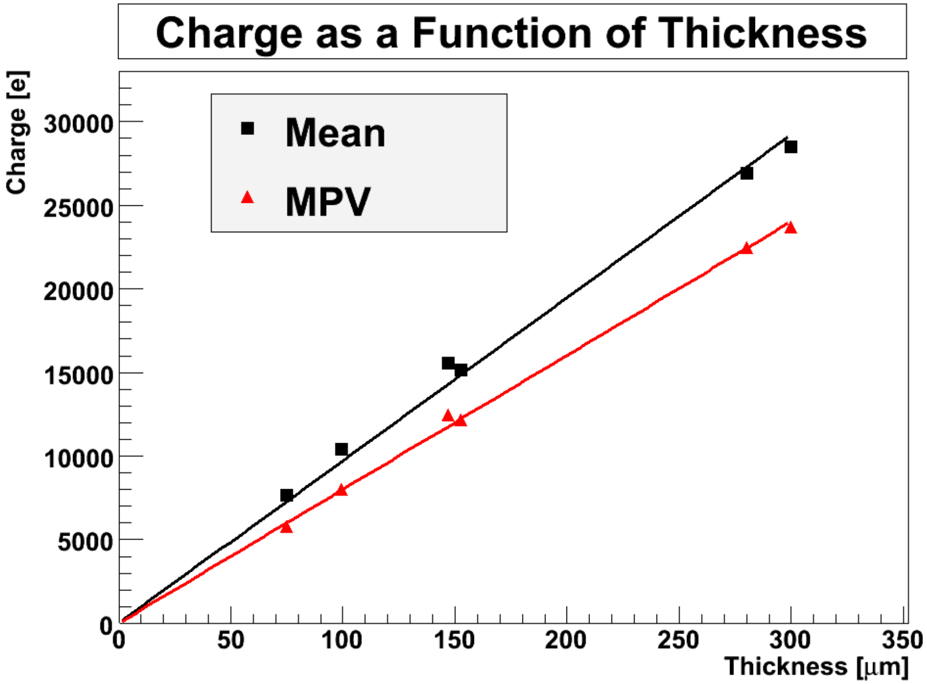
  ⇒ very uniform
  (~0.5 – 1 % standard deviation)



Stability

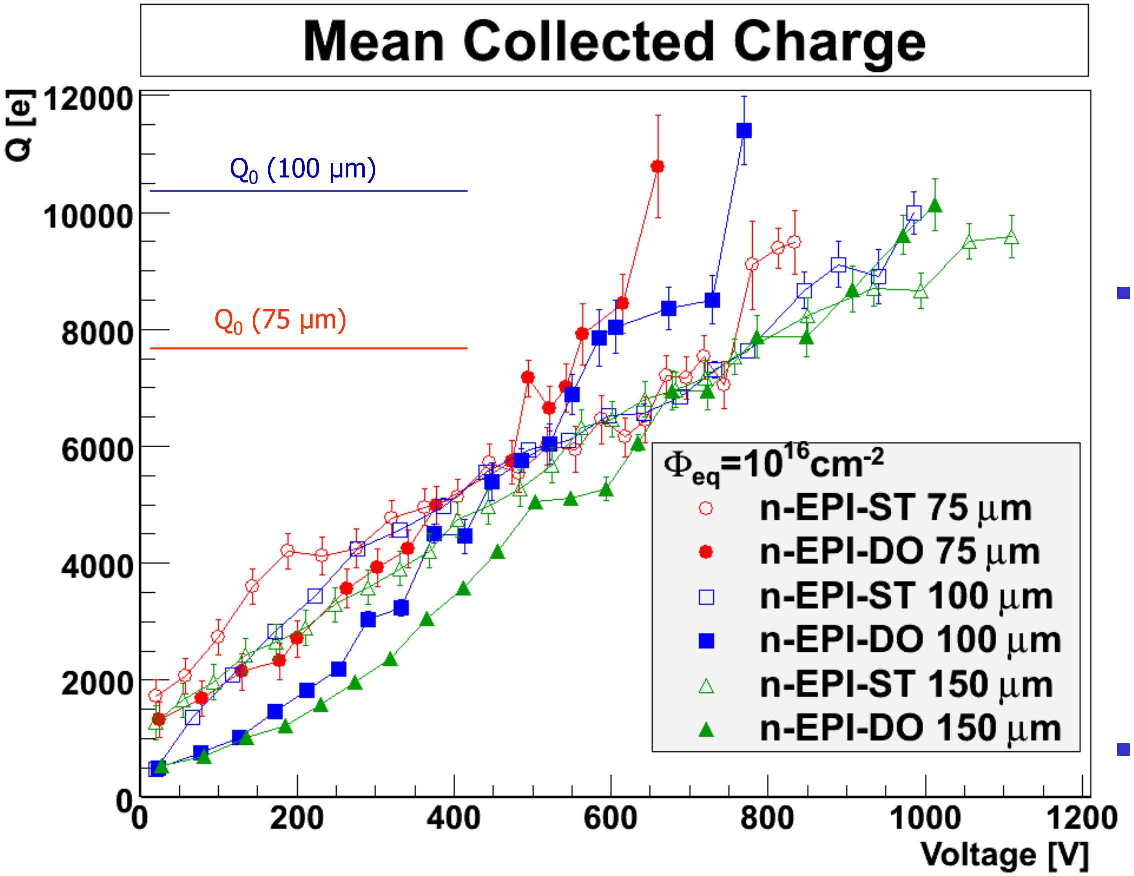
- Repeated measurements at constant voltage, temperature
  ⇒ stable in time
- Limiting factor at high voltages: micro discharges
  ⇒ improvement of device technology desirable

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

Charge for Different Materials and Thicknesses at Highest Fluence



- Q(75μm)>Q(100μm)>Q(150μm)

  due to higher E-field and weighting field in thin diodes
  ⇒ less trapping effects, more CM

- Q(DO)<Q(ST) below the CM regime,
  Q(DO)>Q(ST) in the CM regime

  due to higher donor introduction rate in DO
  ⇒ smaller depleted region at low voltages; higher E_{max}→higher CM

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

    (mean values)

Current and Noise

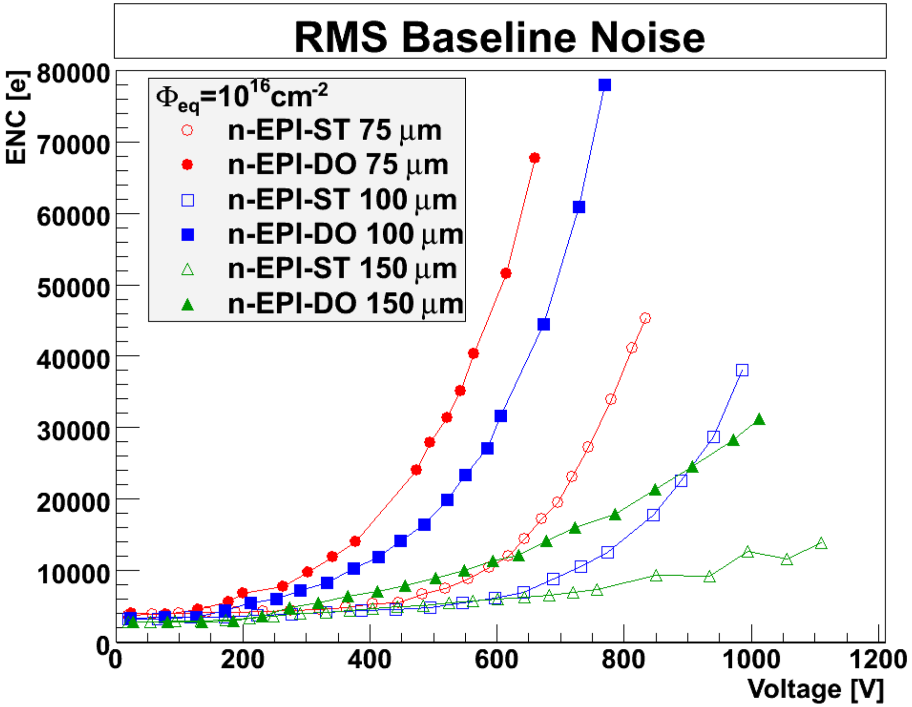
- CM expected to increase signal, current and noise
- Current and noise increase strongly
- Same material and thickness dependence as signal
  - Larger for thinner diodes
  - Larger for DO

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

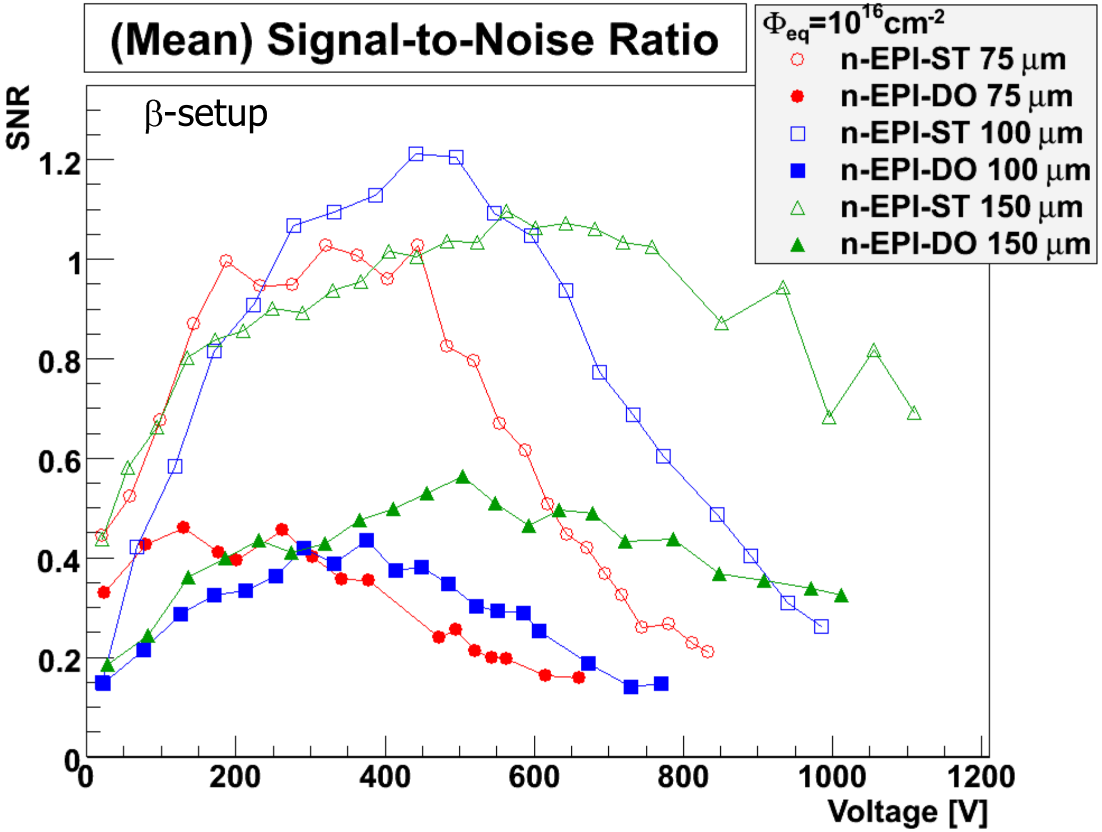
$$I = M'I_{M'=1}$$

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

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



Signal-to-Noise Ratio



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

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

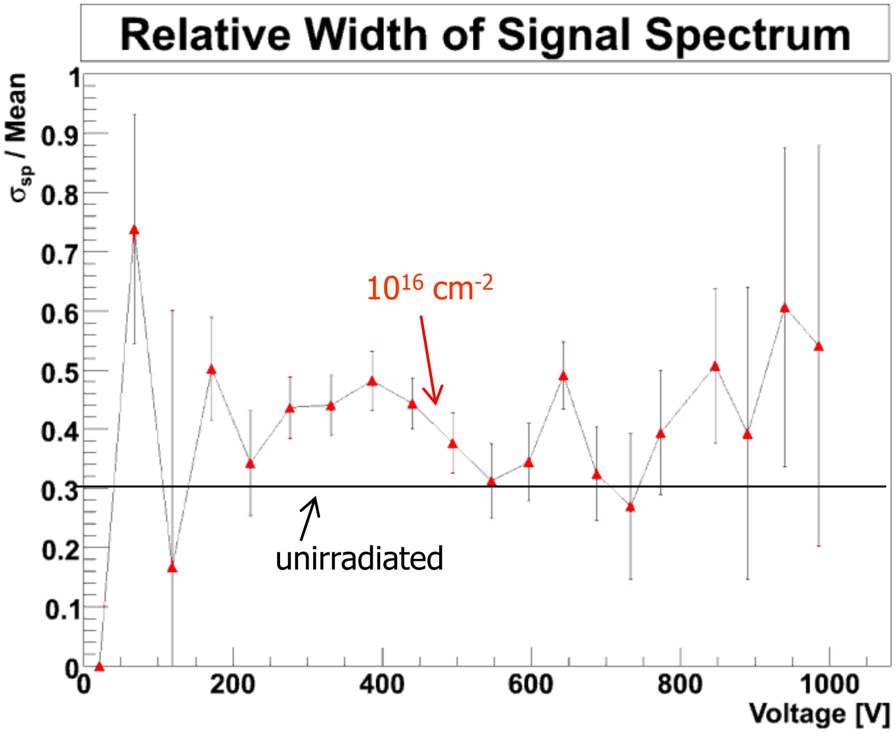
- TCT setup:
  σ'_{noise} large
  ⇒ SNR improves up to 900 V
- β-setup:
  σ'_{noise} smaller
  ⇒ $\sigma_{shot}(M')$ dominates early and increases faster than signal
  ⇒ SNR decreases after maximum at 300 – 500 V
- What about pixels?
  - Lower I
  - Threshold >> noise (unirr.)
    ⇒ noise increase tolerable?

Width of Charge Spectrum

EPI-ST 100 µm

After noise subtraction:

$$\sigma_{sp} = \sqrt{\sigma^2_{sp,meas} - \sigma^2_{noise}}$$



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

$\Rightarrow$ no significant impact of CM fluctuations observed

Summary

- Properties of charge multiplication in proton-irradiated EPI diodes investigated with
  - TCT (laser light, α-particles)
  - ^{90}Sr β-setup with charge-sensitive amplifier, 25 ns shaper
- Thin CM region at the front side
- Proportional mode
- Uniform
- Stable
- β-setup : strong noise increase ⇒ SNR decreases at high voltages
- No significant increase of noise-corrected relative width of charge spectrum
  ⇒ no impact of CM fluctuations

High signals at S-LHC fluences possible!

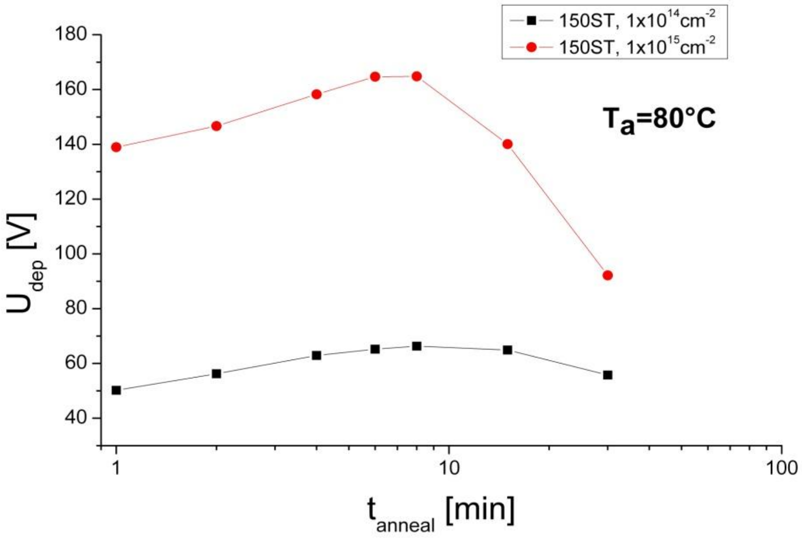
Can noise increase be controlled or tolerated in segmented detectors?

BACKUP SLIDES

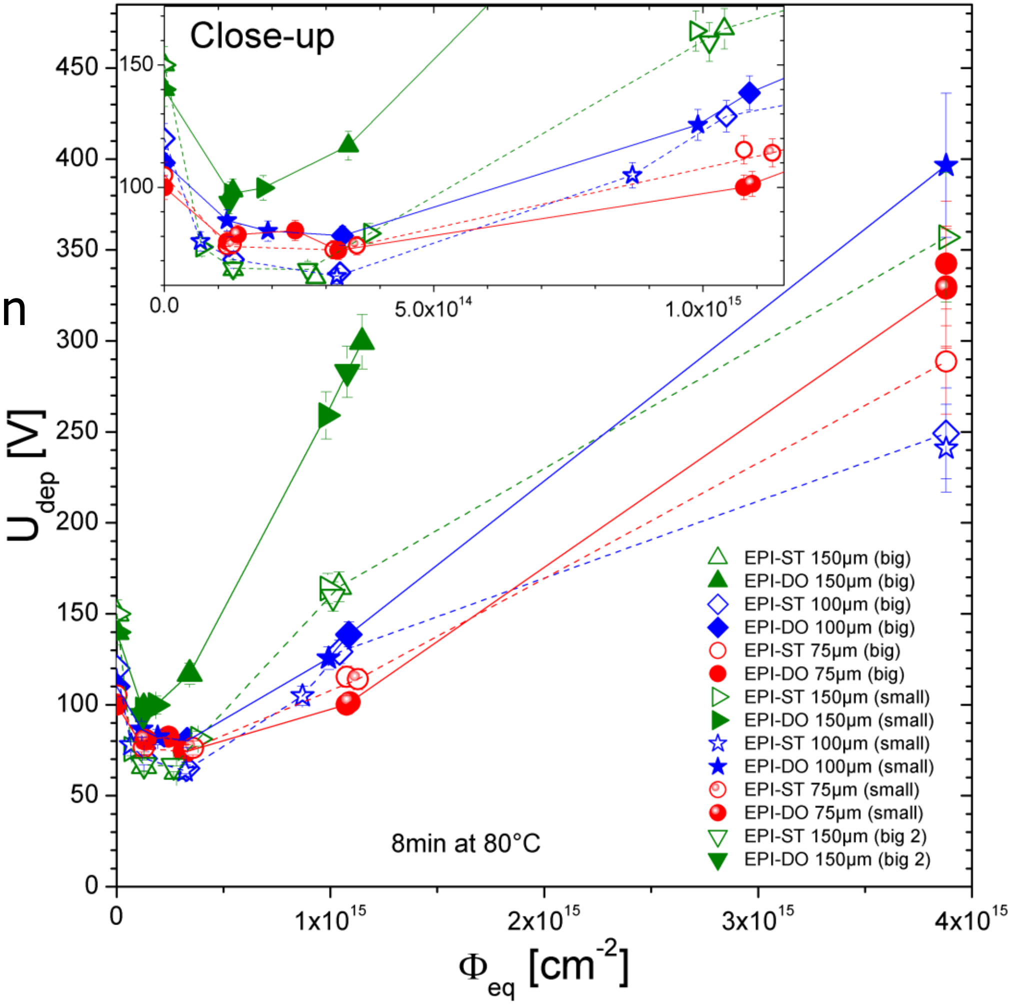
Depletion Voltage (from CV at 10 kHz)

- CV/IV measurable up to $4\times10^{15}\ \mathrm{cm}^{-2}$ 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 $g_C(DO)>g_C(ST)$

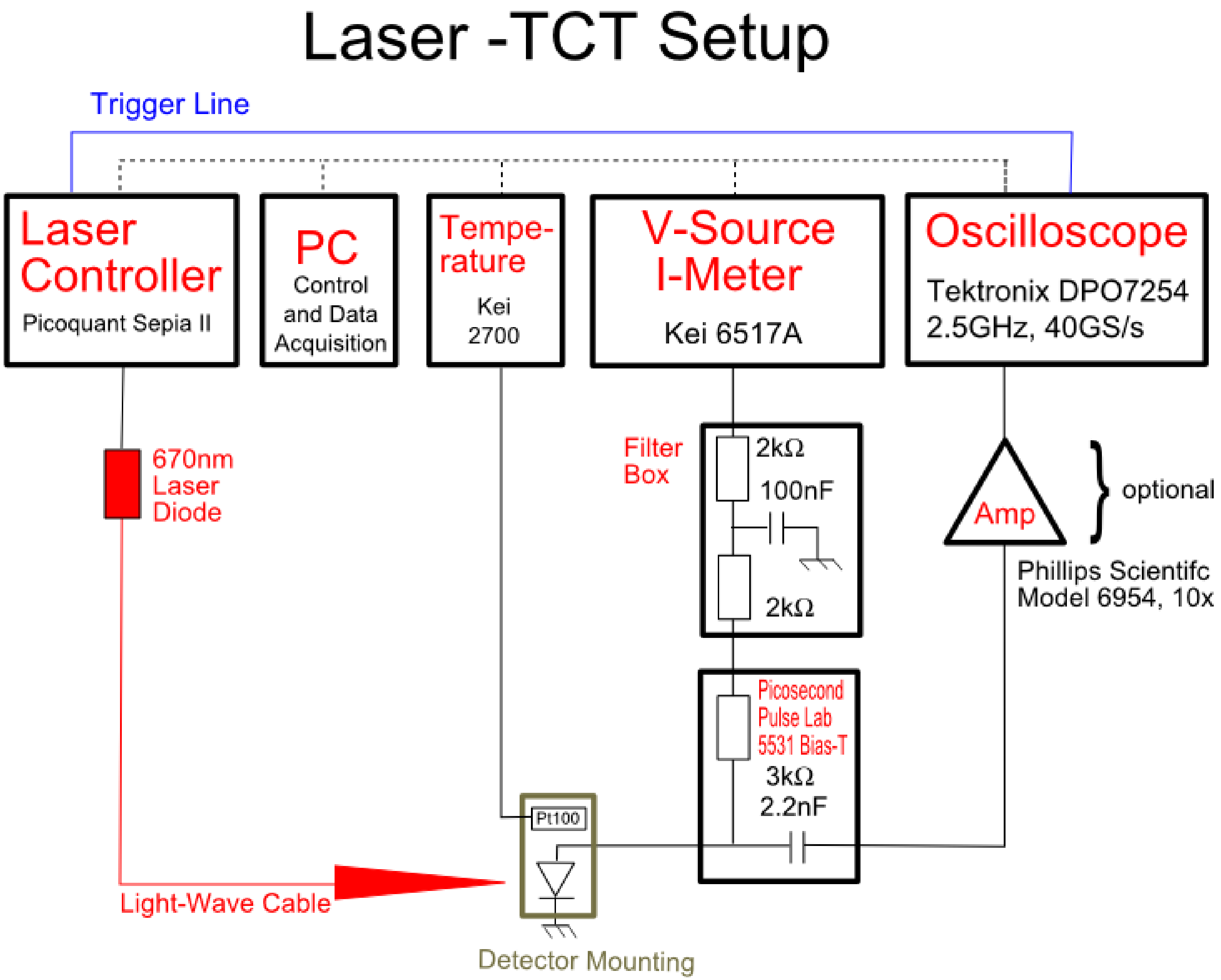
Annealing curve:



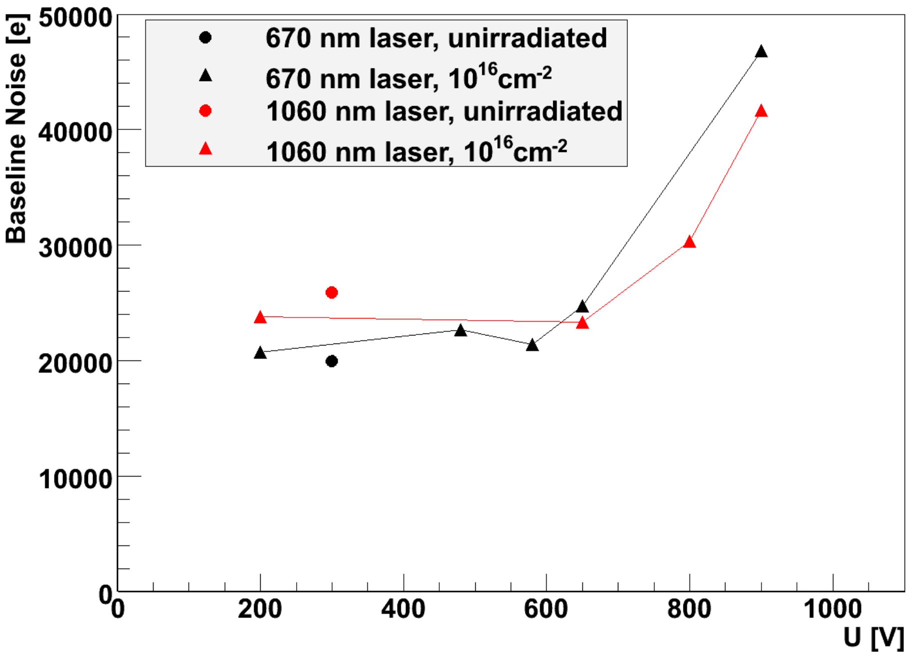
Stable Damage:

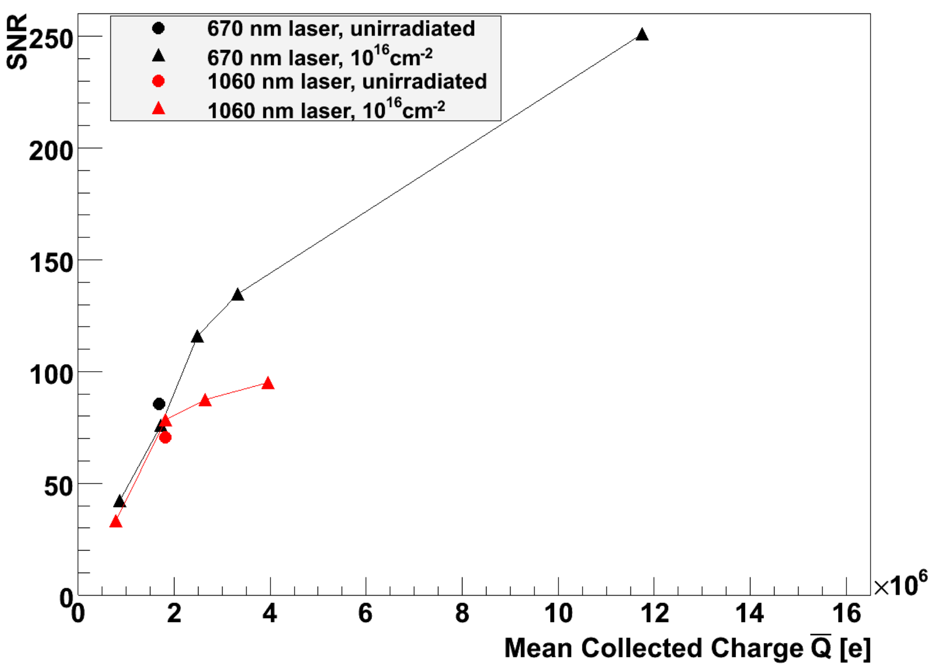


MTCT Laser-TCT Setup



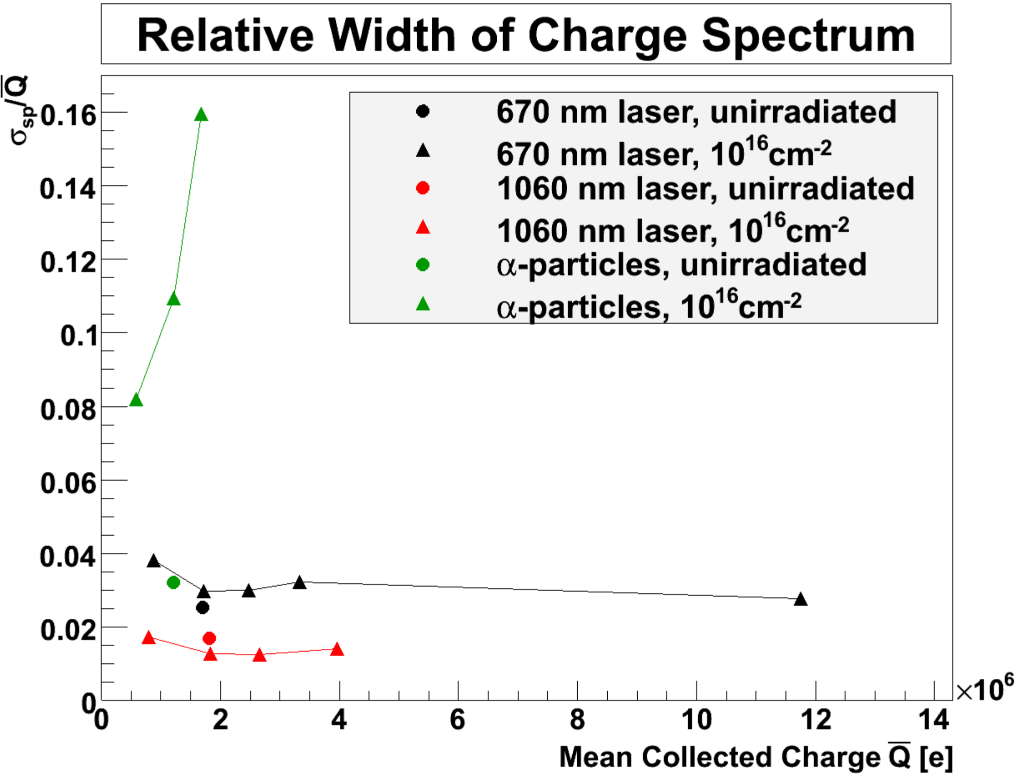
Noise and SNR (TCT with Laser)





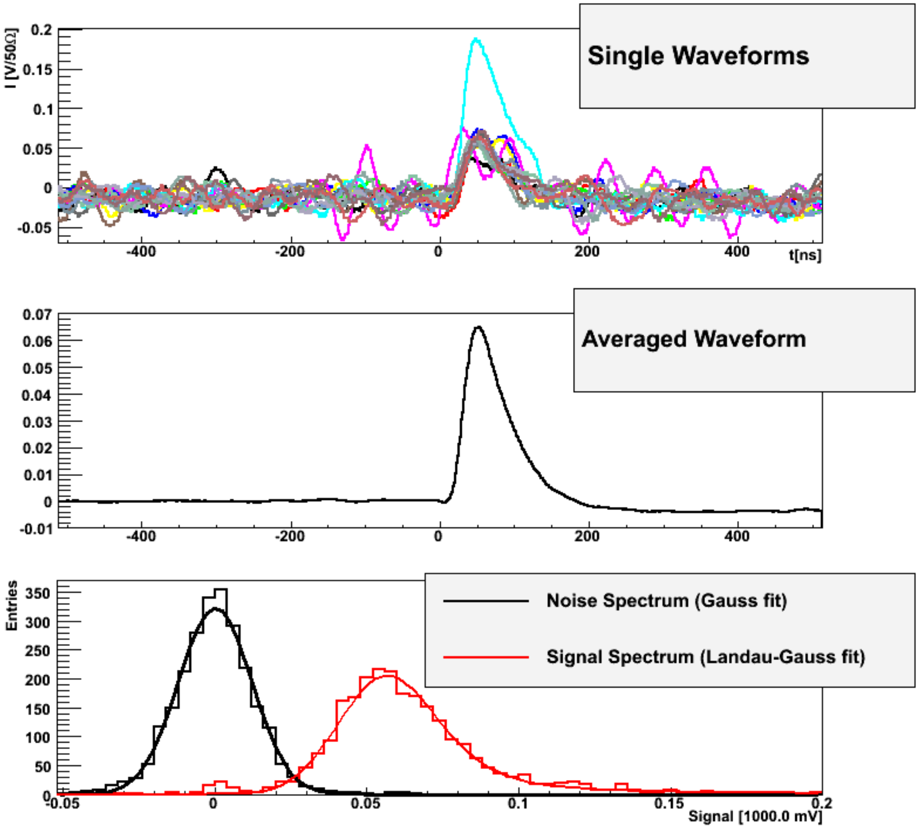
Width of Charge Spectrum

- Fluctuations in the CM process might increase spectrum width: $\sigma_{sp} = M\sqrt{F}\sigma_{sp,M=1}$
- Laser light ($\approx 10^6$ e-h): Relative width of charge spectrum not increasing
  $\Rightarrow$ no fluctuations in CM process
- α-particles: Strong increase of relative width due to fluctuating fraction of charge deposited in the CM region



^{90}Sr Beta Setup

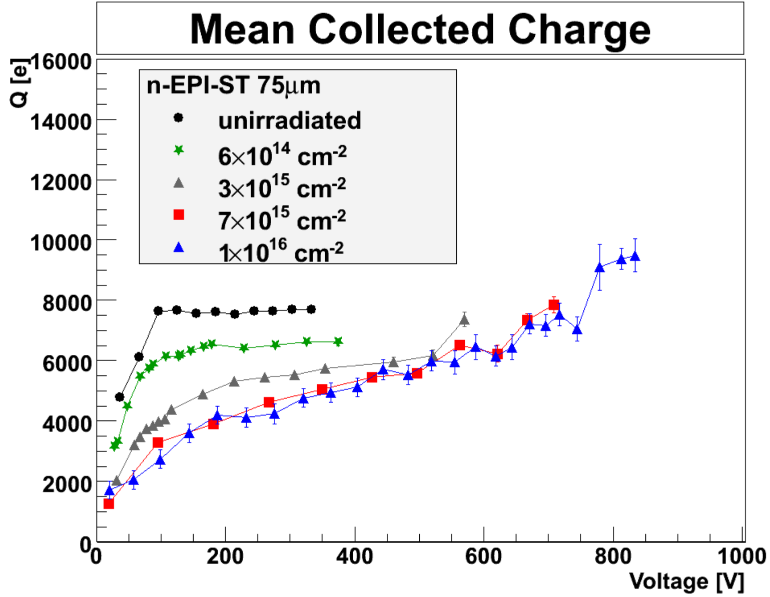
n-EPI-ST 150 µm, unirr., 333 V

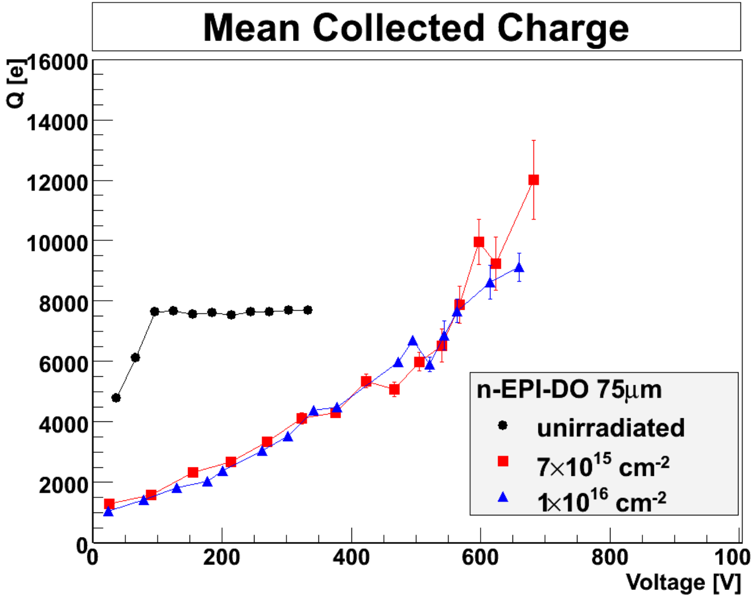


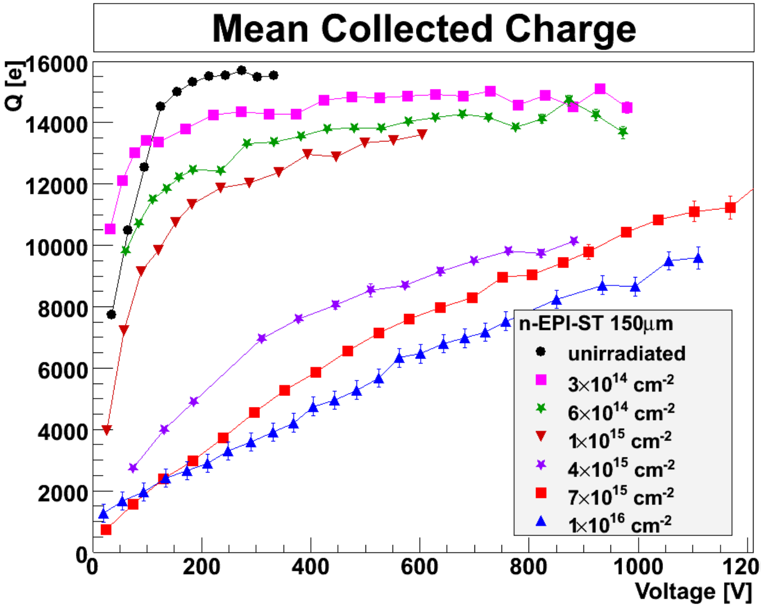
Ljubljana setup for pad diodes:

- Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
- Scintillator → high purity trigger
  ⇒ signals with SNR<1 measurable
- T between -25°C and -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

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

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

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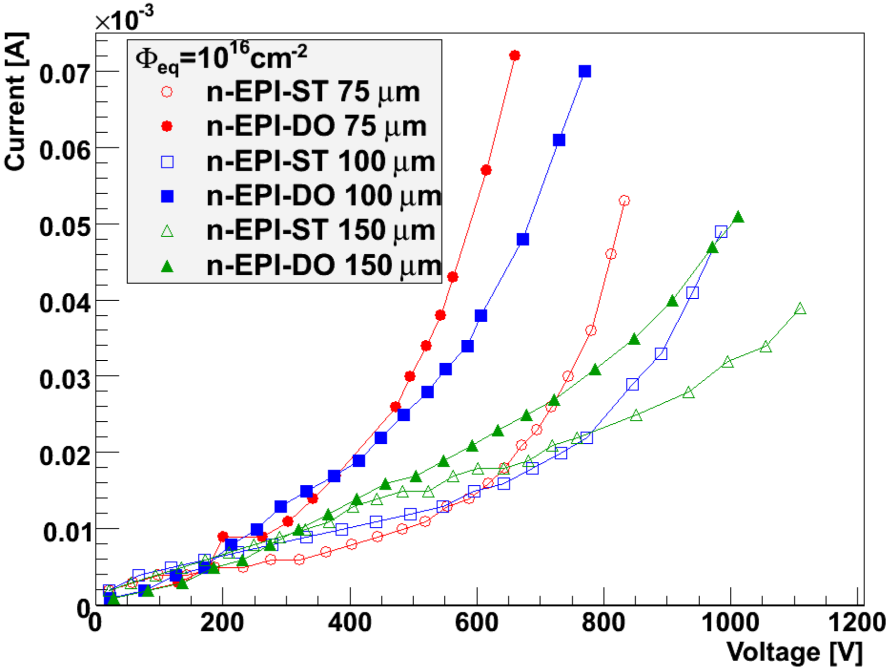
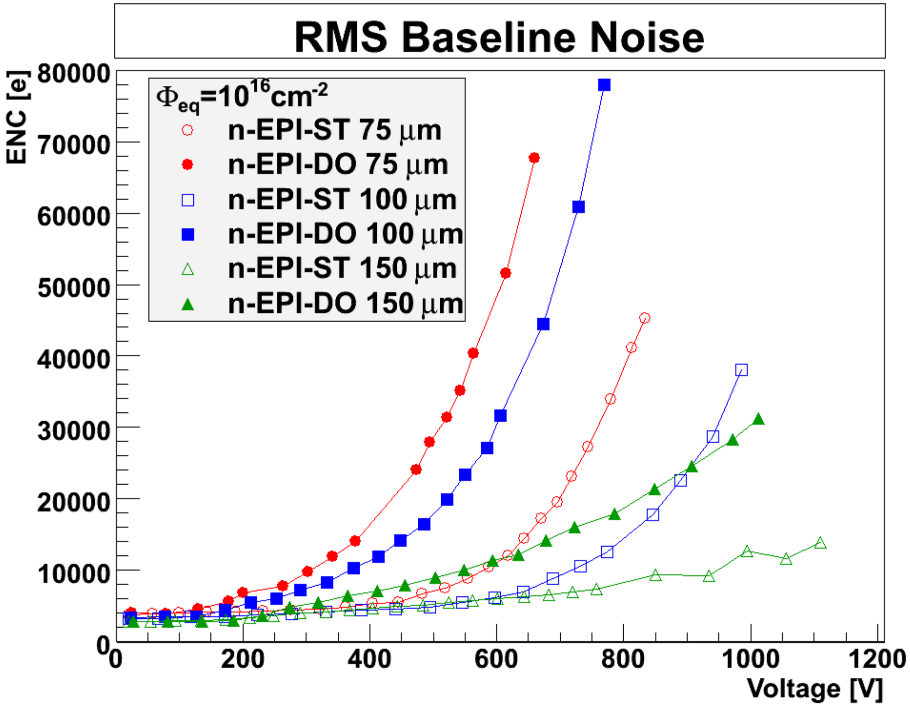
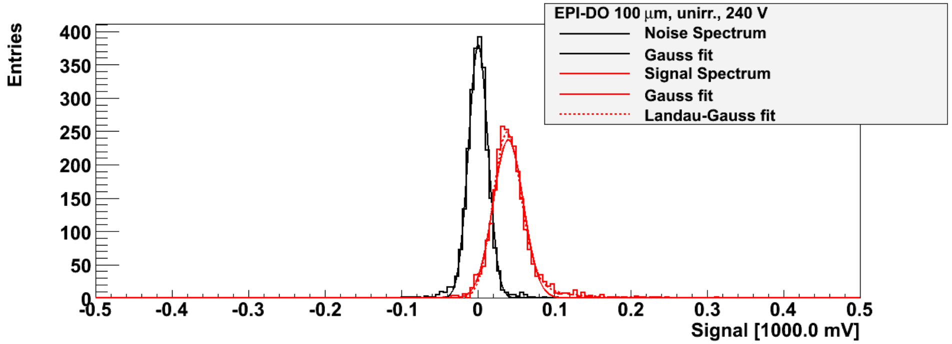
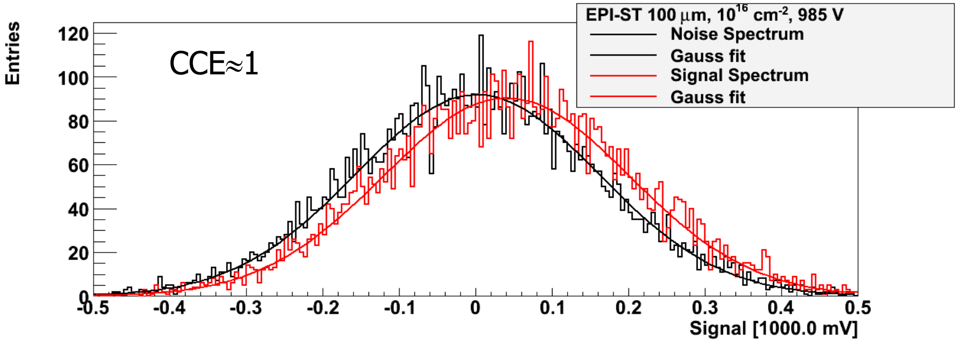
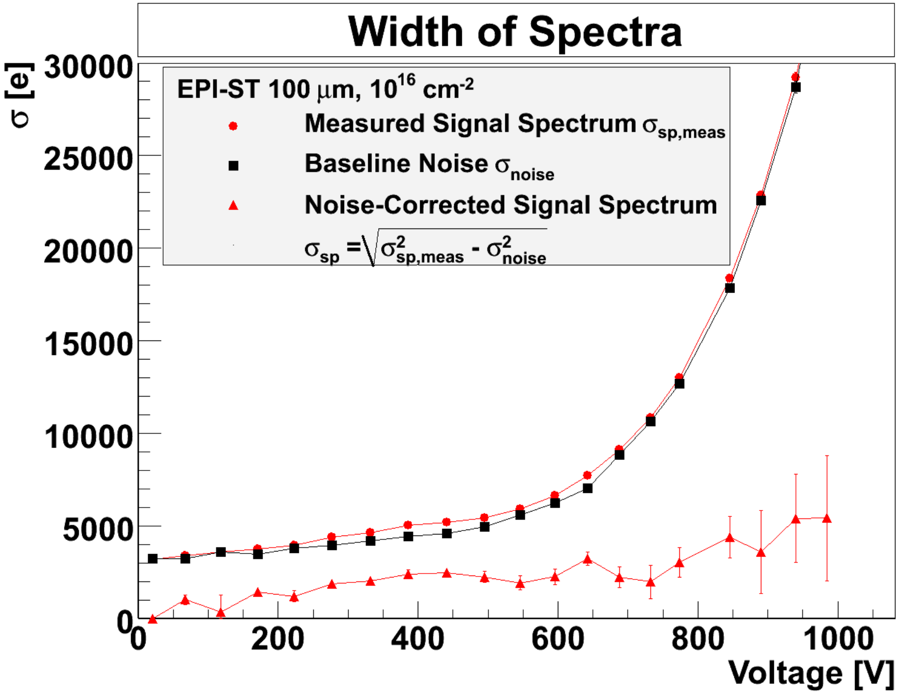


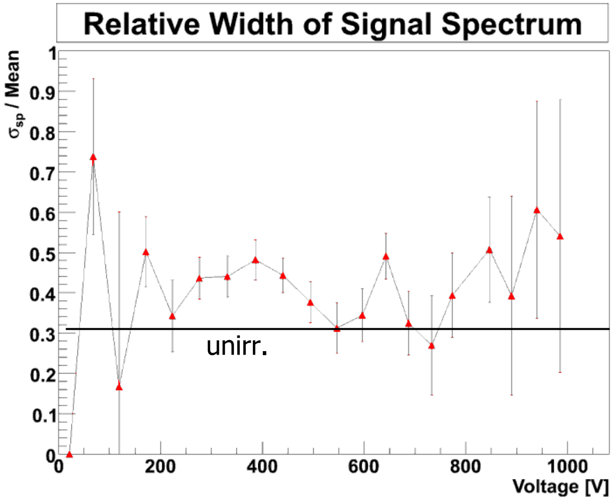


Width of Charge Spectrum





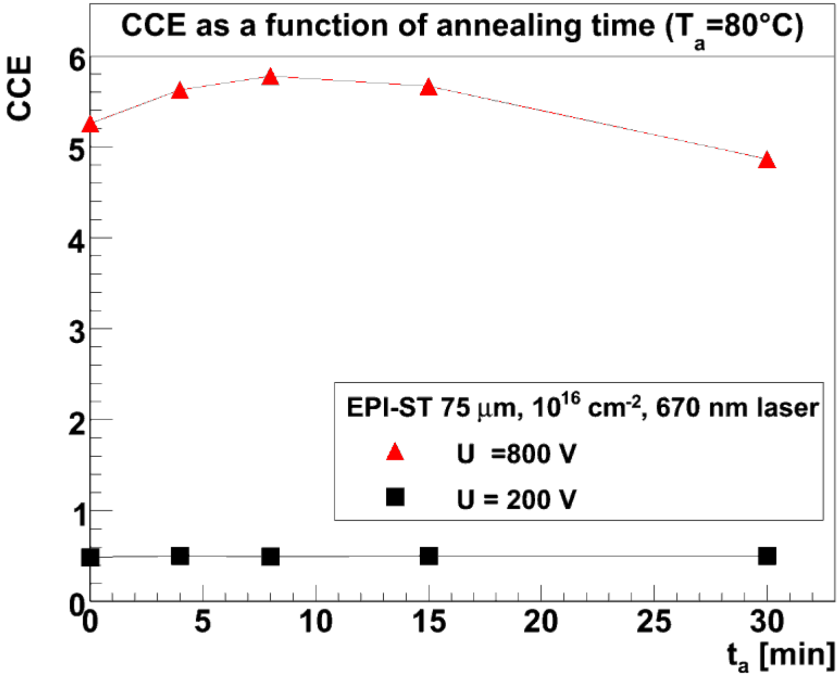


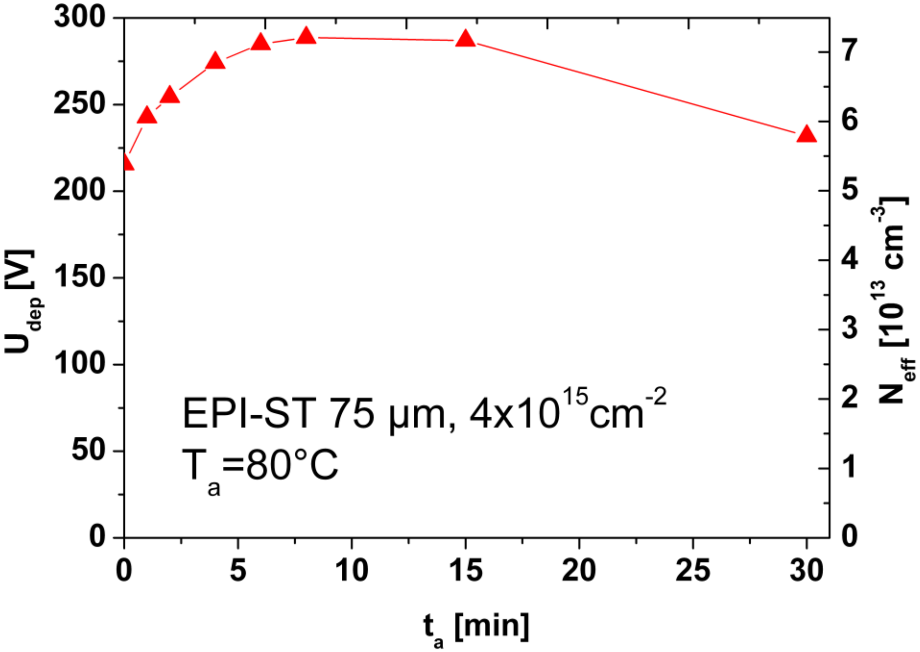


- Fluctuations due to CM might increase spectrum width
- No significant increase of noise-corrected relative width with voltage

⇒ no significant impact of CM fluctuations

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} → higher E_{max} → higher CM