Charge collection and trapping effects in n- and p-type epitaxial silicon diodes after proton irradiation

Jörn Lange, Julian Becker, Eckhart Fretwurst, Gunnar Lindström

Hamburg University

GEFÖRDERT VOM

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UHH

In the framework of the CERN RD50 Collaboration

Introduction

- Trapping: most limiting factor at S-LHC fluences
  - Usually described by an effective trapping time constant τ_{eff}:
  - Previous measurements* for FZ/Cz material at low fluences:

    *cf. G.Kramberger's PhD thesis

$$N(t) = N_0 \exp(-\frac{t}{\tau_{eff}})$$

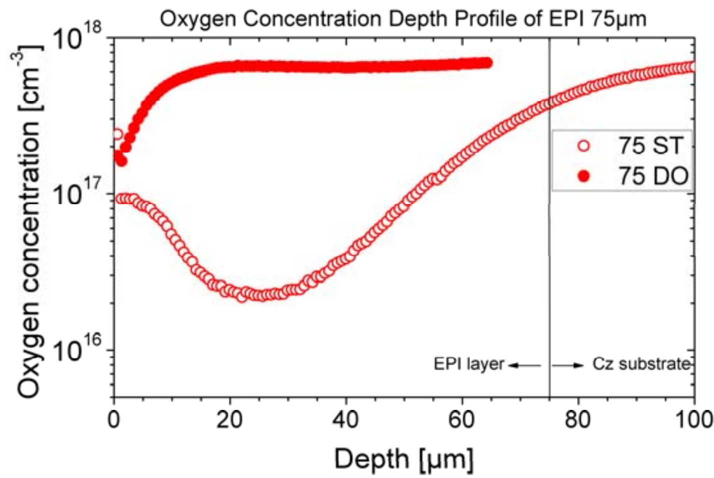
$$\frac{1}{\tau_{eff}} = \beta\, \Phi_{eq}$$

  - What happens in epitaxial material, at high fluences and high voltages?
- Last RD50 workshop (Nov 08): Results for n-type EPI diodes presented
  - Time-resolved TCT signals (670nm laser) for 150µm EPI
  - CCM $\rightarrow$ β_e in EPI similar to FZ/Cz material
  - CCE (α) >1 $\rightarrow$ avalanche effects
  - CCE simulation underestimates measurements $\rightarrow$ modified trapping description needed
- Here:
  - Update for further fluence points
  - p-type investigated (τ_{eff}, CCE (α))
  - Comparison of CCE for different charge injection distributions (670nm, 1060nm, α)

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
- n-type: 75 µm, 100 µm and 150 µm thickness; Standard (ST) and oxygen enriched (DO, diffusion for 24h at 1100°C) material
- p-type: only 75 µm ST material
- 24 GeV/c-proton-irradiation (CERN PS), $\Phi_{eq} = 1 \times 10^{14} - 1 \times 10^{16}$ cm^{-2}

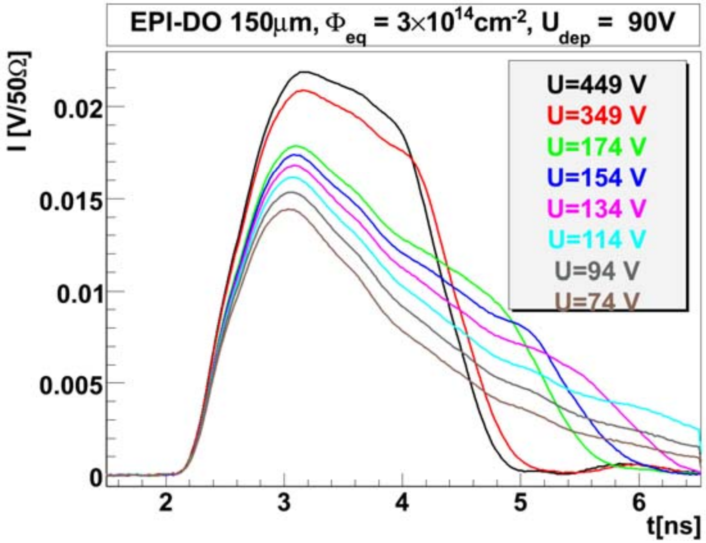
Material	d [µ m]	Wafer	Orientation	$N_{eff,0}$ [10^{12} cm^{-3}]	[O] [10^{16} cm^{-3}]
n-EPI ST 75	74	8364-03	<111>	26	9.3
n-EPI DO 75	72	8364-07	<111>	26	60.0
n-EPI ST 100	102	261636-05	<100>	15	5.4
n-EPI DO 100	99	261636-01	<100>	15	28.0
n-EPI ST 150	147	261636-13	<100>	8.8	4.5
n-EPI DO 150	152	261636-09	<100>	8	14.0
p-EPI ST 150	149	271713-26	<100>	13	

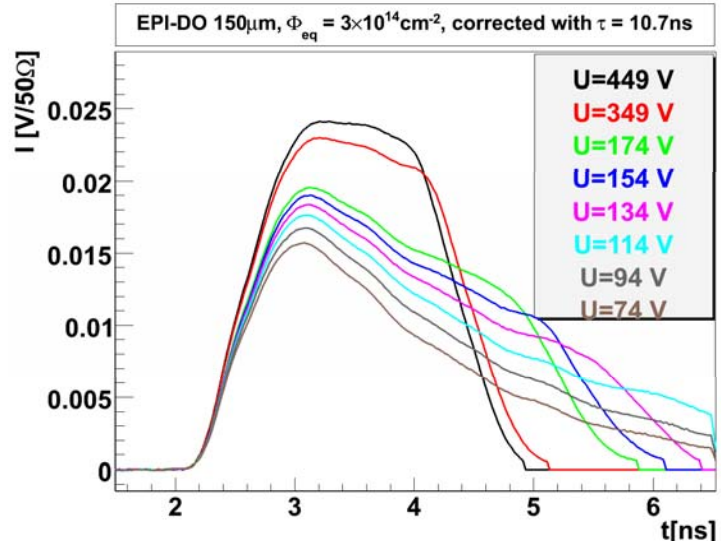


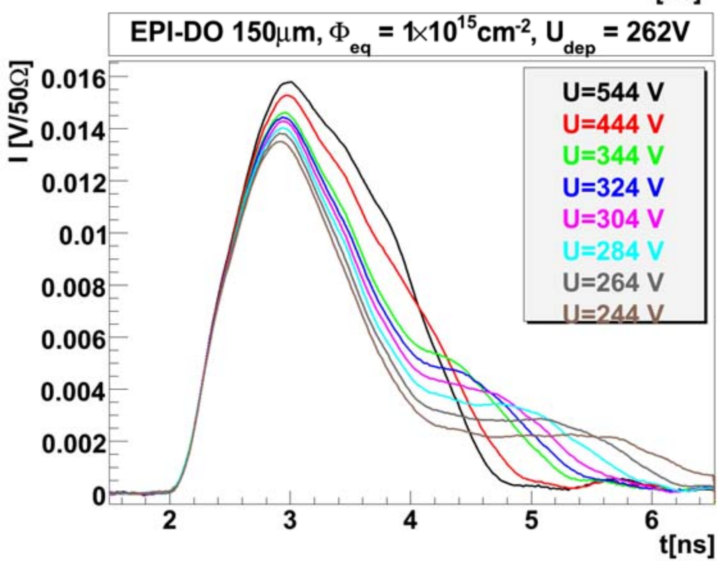
TCT electron signals (n-type)

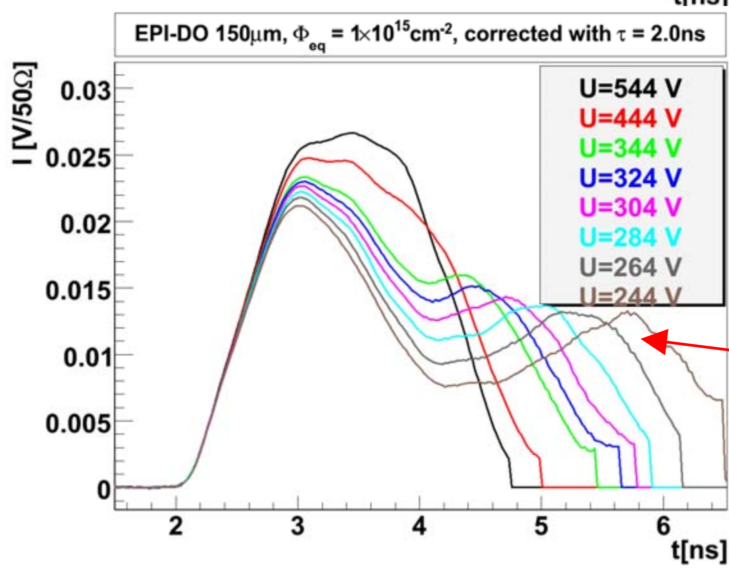
a) measured I_{meas}

b) trapping-corrected $I_{corr} = I_{meas} \cdot \exp((t-t_0)/\tau_{eff})$









Measurements:

- 30min at 80°C anneal.
- performed at 20°C
- 670nm laser (front) → e-signal in n-type

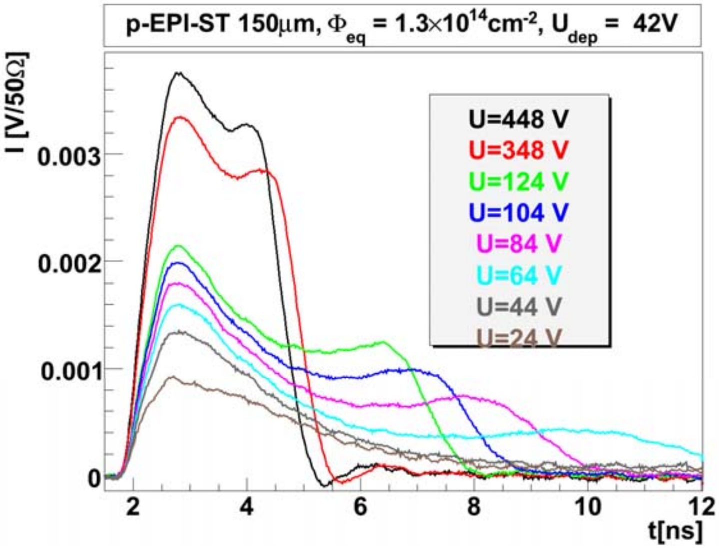
No type inversion

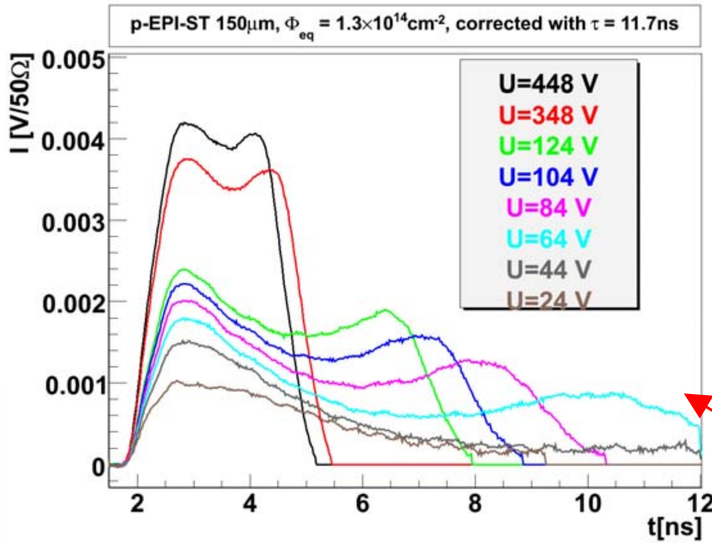
(confirms conclusions from annealing curve)

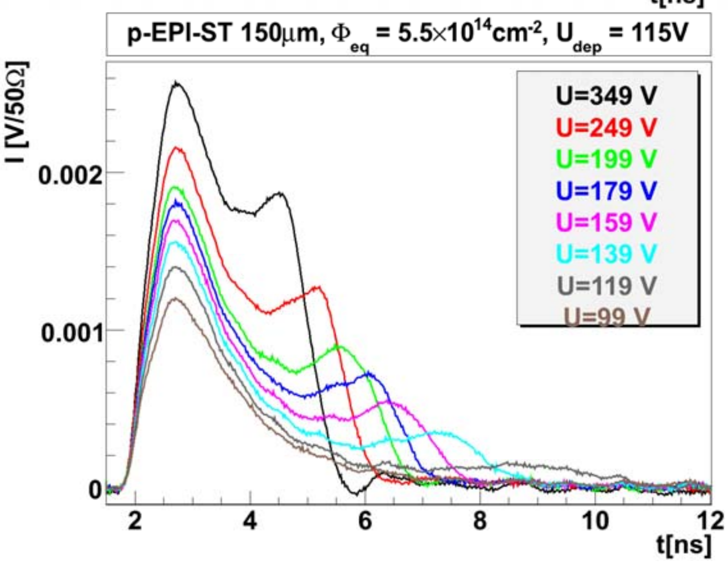
Double Junction!

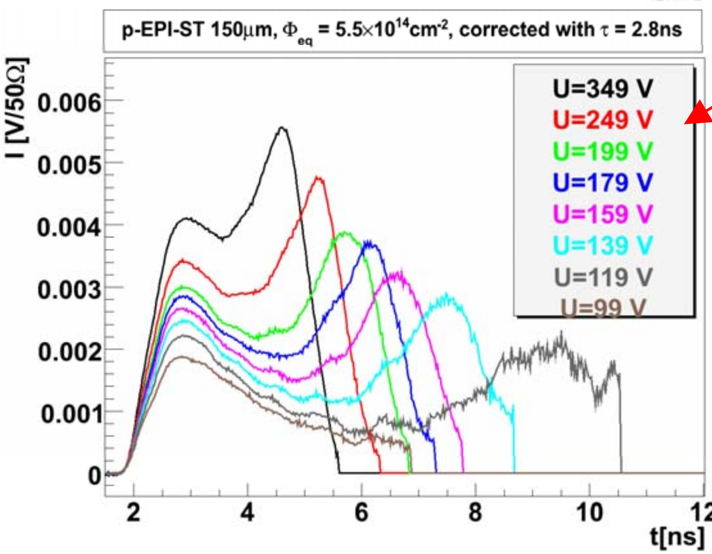
TCT hole signals (p-type)

a) measured I_{meas} **b) trapping-corrected $I_{corr}=I_{meas}\cdot\exp((t-t_0)/\tau_{eff})$**









Measurements:

- 30min at 80°C anneal.
- performed at 20°C
- 670nm laser (front) → h-signal in p-type

No type inversion

for $\Phi_{eq} \leq 1.3\text{x}10^{14}$ cm^{-2}

Type inversion

for $\Phi_{eq} \geq 3.7\text{x}10^{14}$ cm^{-2}

Double Junction

already at low fluences

Determination of τ_{eff}

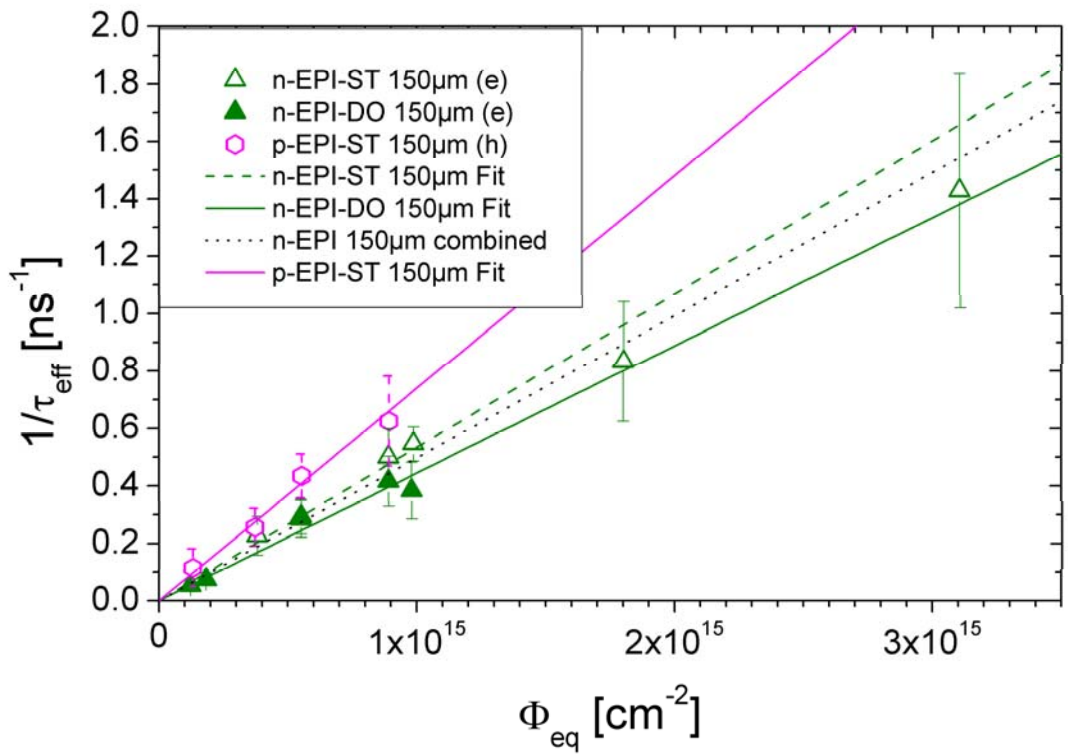
Results from
Charge Correction Method:

- Also in Epi:
  If assumed to be constant at each fluence, trapping probability found to be fluence-proportional

$$\frac{1}{\tau_{eff,e/h}} = \beta_{e/h}\Phi_{eq}$$

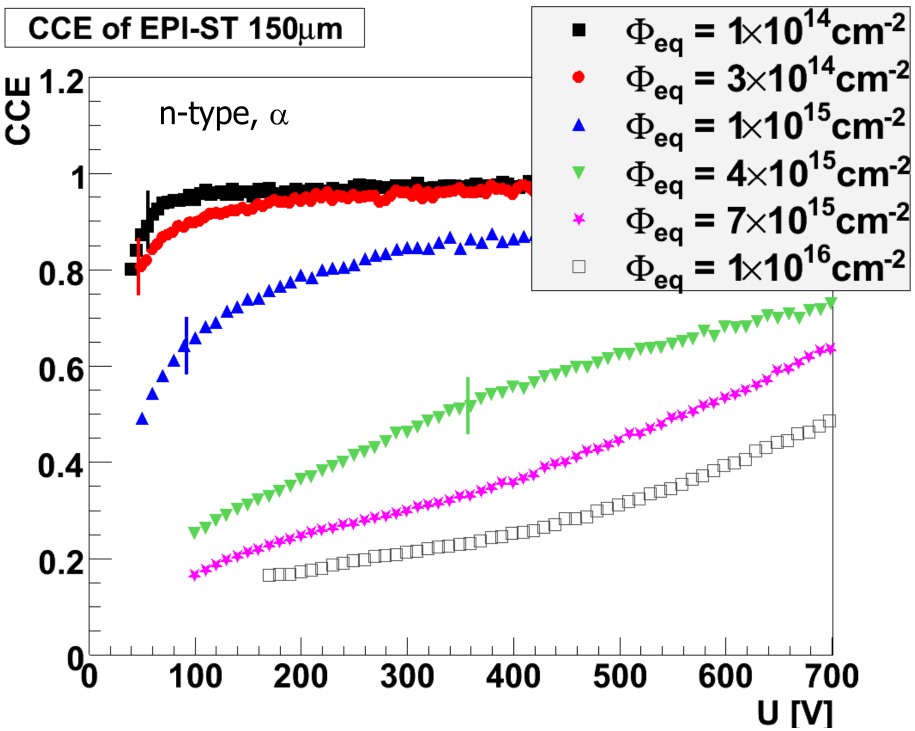
- Damage parameter β:
  similar values as in FZ*

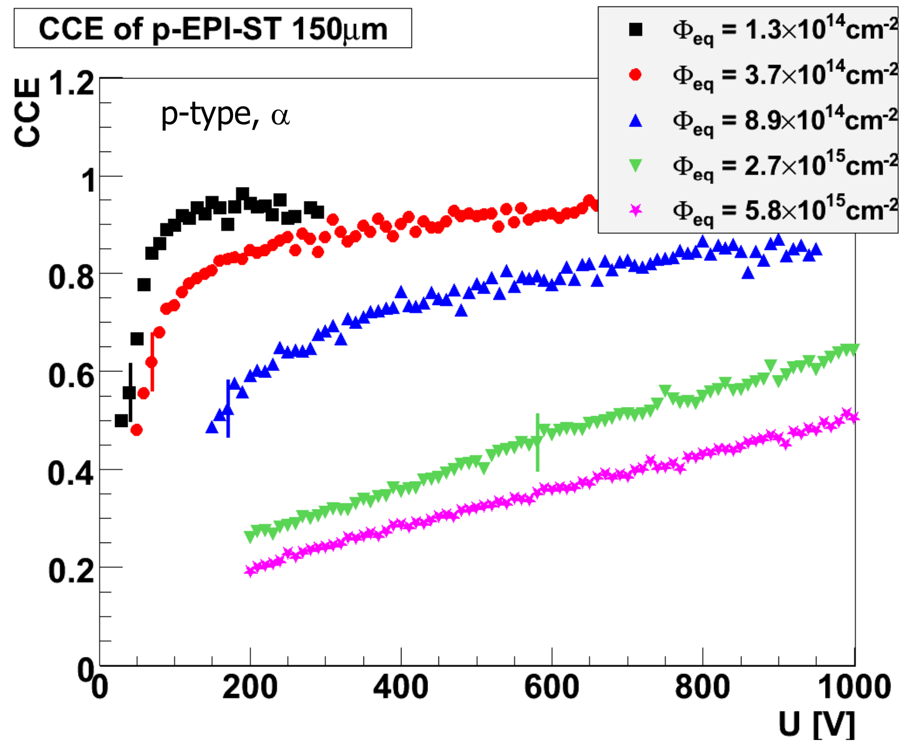
*cf. G.Kramberger's PhD thesis



	n-type β_e [10^{-16} cm^2ns^{-1}]	p-type β_h [10^{-16} cm^2ns^{-1}]
EPI-ST	5.3 ± 0.4	7.4 ± 0.9
EPI-DO	4.5 ± 0.5	
EPI comb.	5.0 ± 0.3	7.4 ± 0.9
cf. FZ*	5.1	6.5

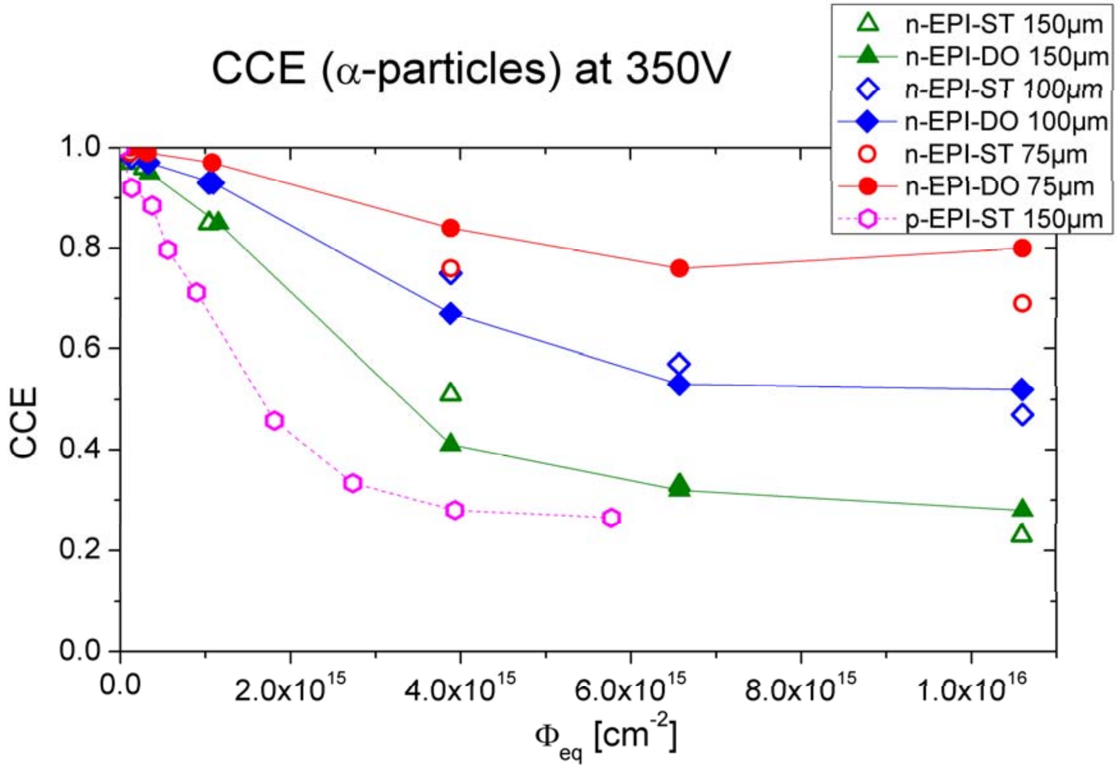
CCE as a function of bias voltage





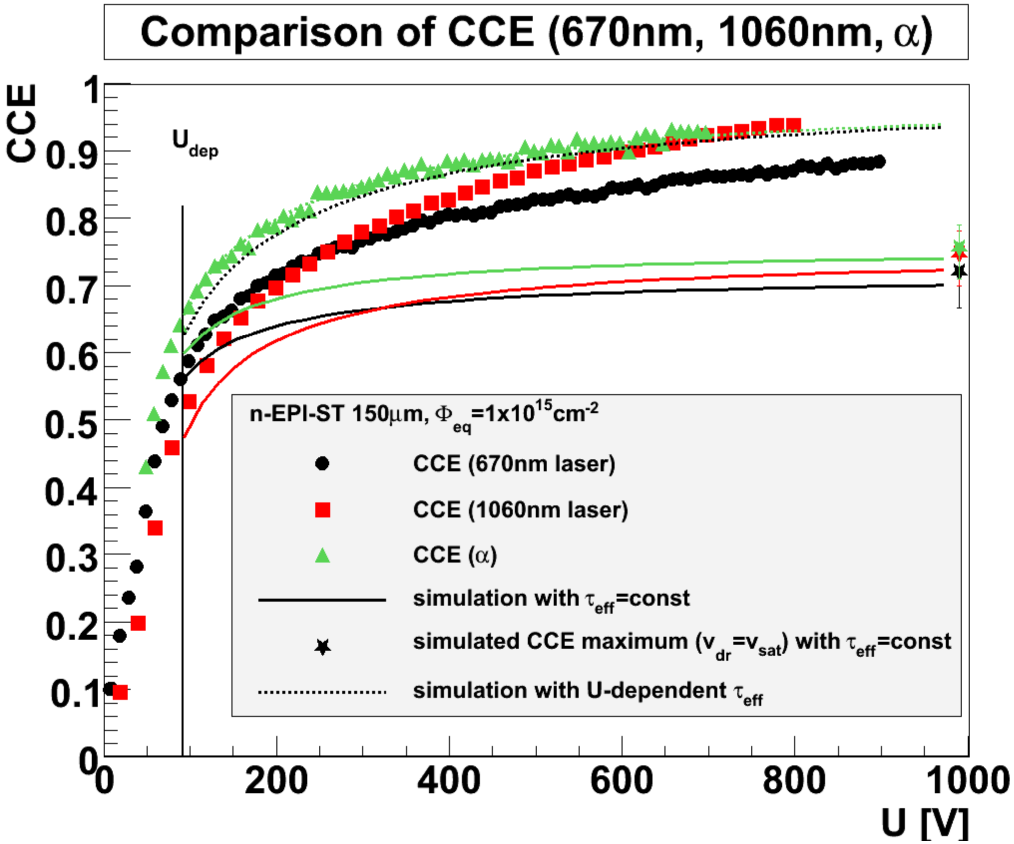
- Almost saturation for low fluences at high voltages
- n-type: Stronger increase for high fluences (avalanche effects)
  p-type: approximately linear increase for $\Phi_{eq} \geq 2.7 \times 10^{15}$ cm^{-2}

CCE as a function of fluence



- CCE degrades with fluence,
  but deceleration at high fluences (due to avalanche effects?)
- CCE improves for decreasing thickness as t_C decreases
  (smaller distance, higher field)
- No significant difference between ST and DO material
- CCE of p-type lower than CCE of n-type (v_{dr} and τ_{eff} smaller for holes)

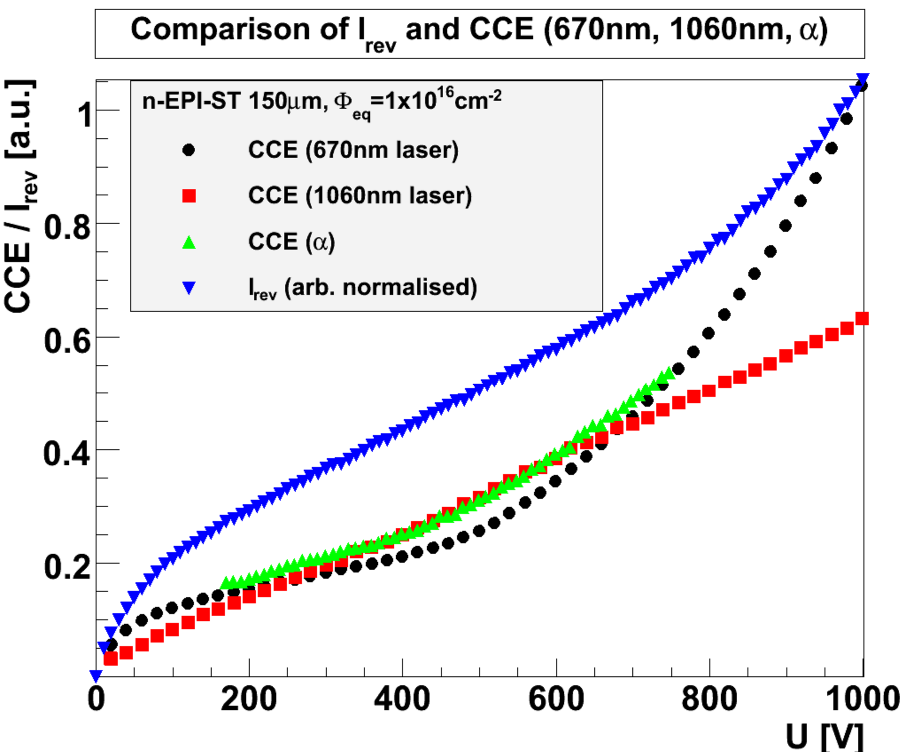
Comparison CCE (670nm, 1060nm laser, α)

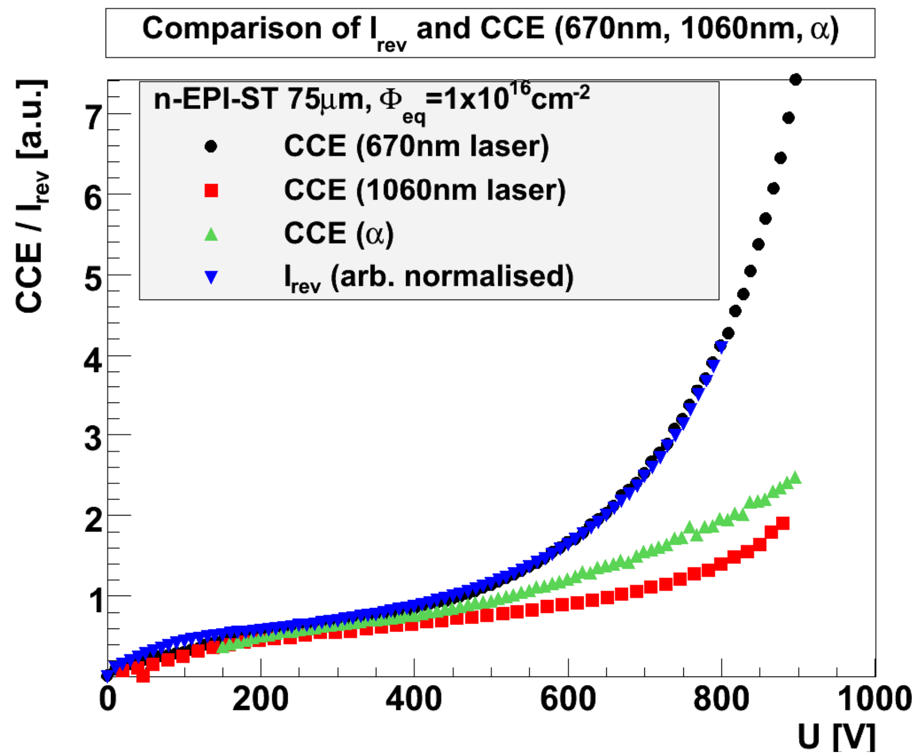


- Different charge injection distributions:
  - 5.8MeV α: range 26μm; well-defined charge deposition → small normalisation error (~3%)
  - 670nm: λ_{abs}=3μm; laser intensity variations → larger normalisation error (up to 10%)
  - 1060nm : λ_{abs}=1mm; laser intensity variations → larger normalisation error (up to 10%)
- Simulation with τ_{eff}=const underestimates measured data in all cases; voltage-dependent behaviour not well reproduced
- But relative position between CCE of different distributions well reproduced
- U-dependent τ_{eff} fits better:

$$\tau_{eff,e} = \tau_0(U_{dep}) + \tau_1 \frac{(U - U_{dep})}{100V}$$

Comparison CCE (670nm, 1060nm laser, α)





- Smaller penetration depth → stronger charge multiplication (more charge deposited in high-field region; more e instead of h)
- CCE(670nm)- and IV-curves almost identical at high voltages (for 75μm, $10^{16}cm^{-2}$)

Summary

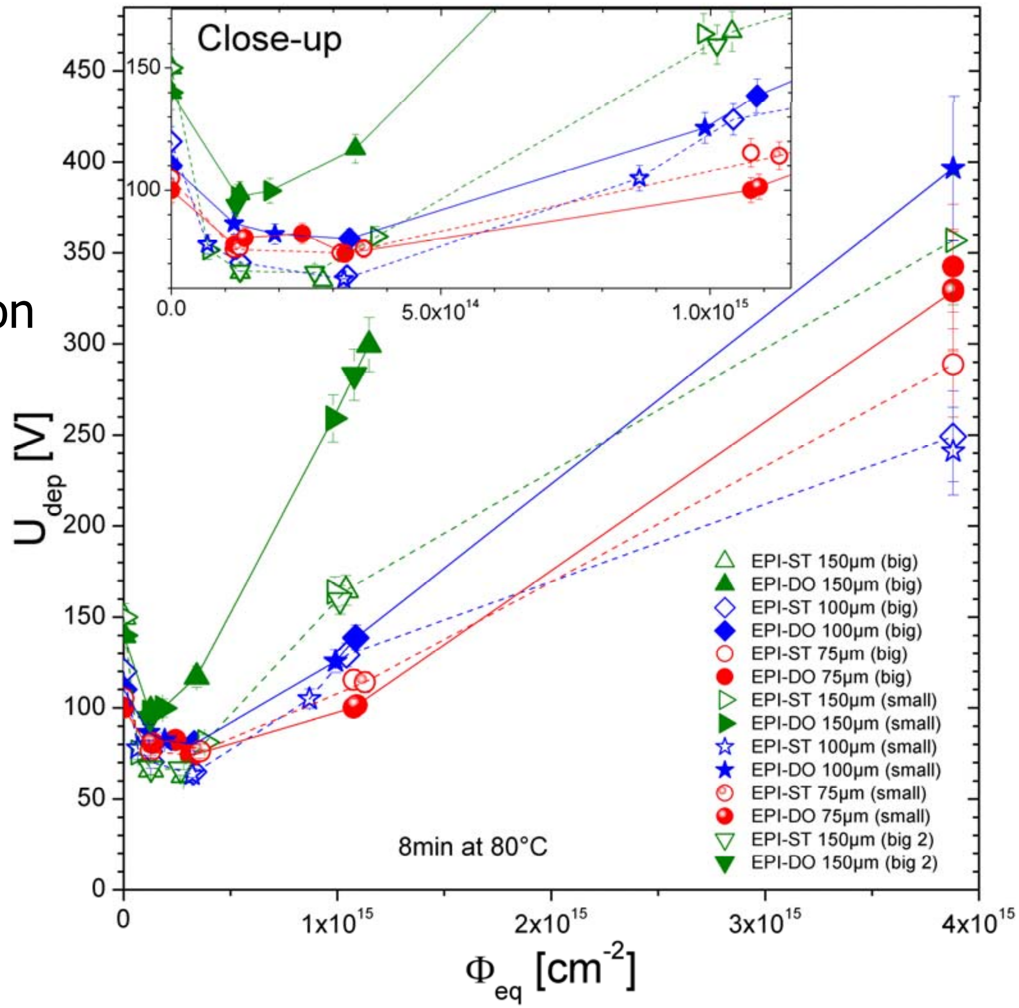
- 670nm laser: time-resolved TCT signals in Epi 150µm
  - n-type: no type inversion; p-type: type inversion for $\Phi_{eq} \geq 3.7 \times 10^{14}$ cm^{-2}
  - Double Junction already at low fluences in p-type
  - CCM -> trapping probability similar to FZ
- CCE determination:
  - $CCE_{e,n\text{-}type} > CCE_{h,p\text{-}type}$
  - Avalanche effect strongest for small penetration depth (CCE>7 for 75µm!)
- Comparison CCE measurements - simulation
  - Simulation underestimates measurements for all charge injection distributions
  - Relative position between different charge injection distributions well reproduced
  - Better agreement if U-dependent τ_{eff} assumed

BACKUP SLIDES

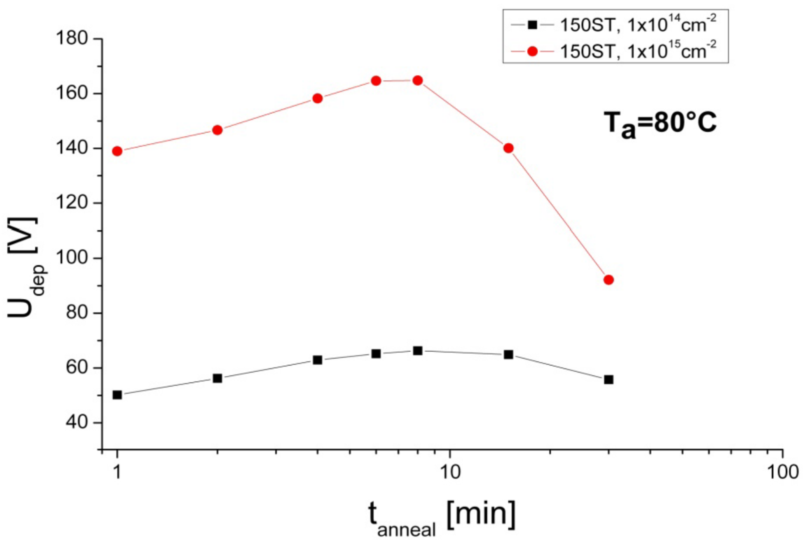
Depletion Voltage (from CV at 10 kHz)

- CV/IV measurable up to 4×10^{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)

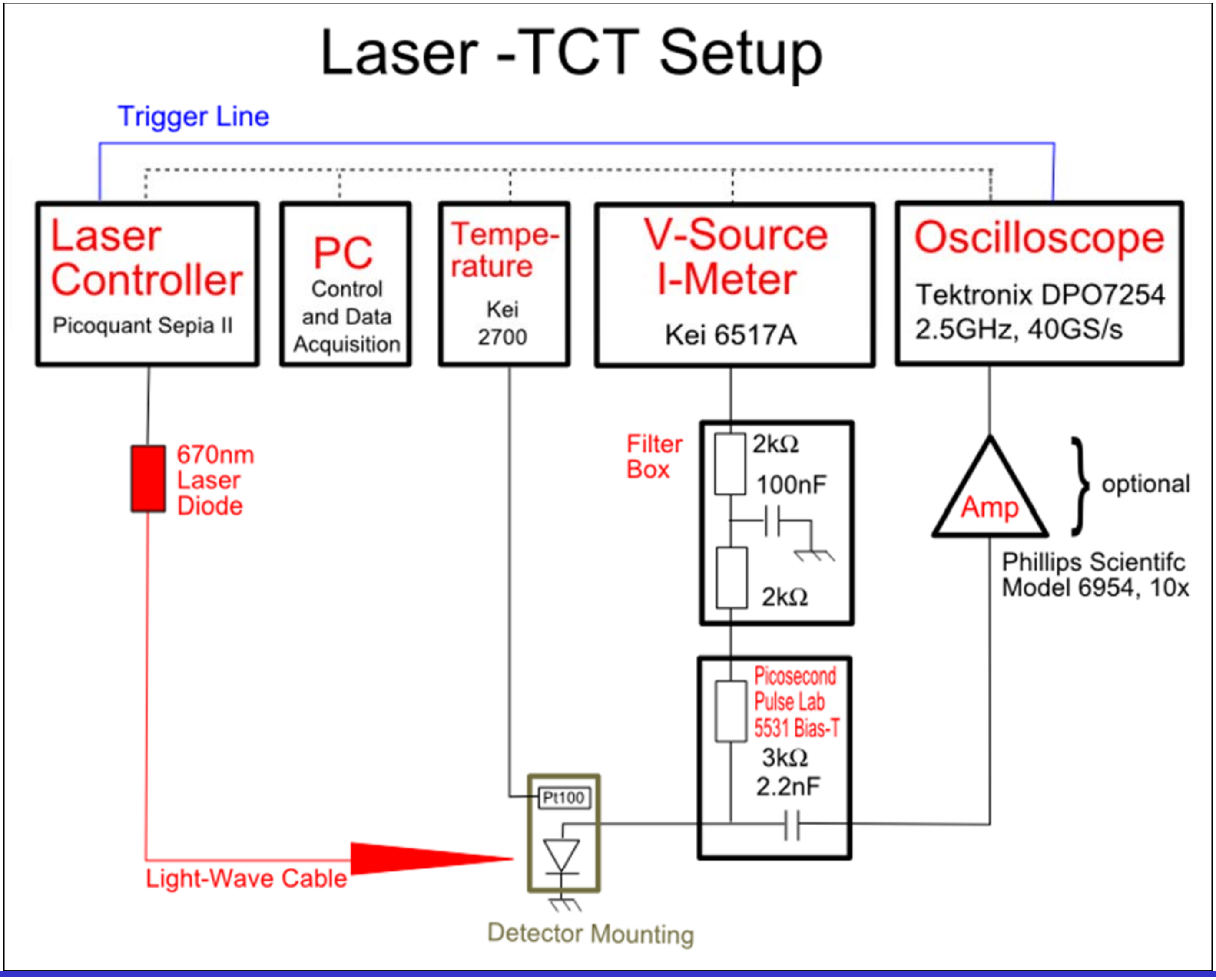
Stable Damage:



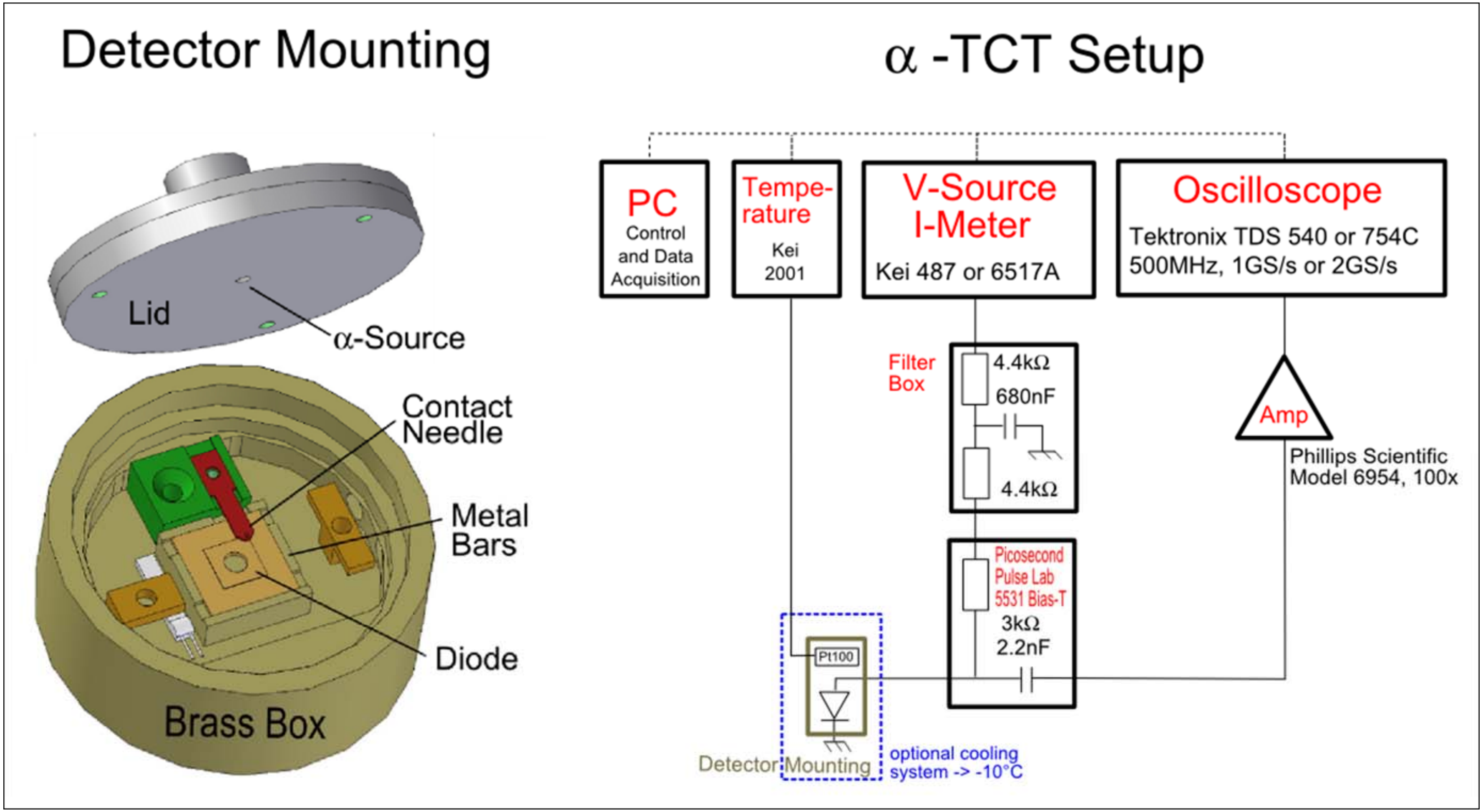
Annealing curve:



New Laser-TCT Setup



Alpha-TCT Setup



Simulation details

Integrated induced charge for e-h pair deposited at x_0 (e + h contribution):

$$Q_{x_0} = \frac{Q_{0,x_0}}{d}\left[\int_{x_0}^{d} \exp\left(-\frac{t(x)}{\tau_{eff,e}}\right) dx - \int_{x_0}^{0} \exp\left(-\frac{t(x)}{\tau_{eff,h}}\right) dx\right] \quad \text{with} \quad t(x) = \int_{x_0}^{x} \frac{1}{v_{dr}\left(E\left(x'\right)\right)} dx'$$

Drift velocity parameterisation (C.Jacobini, Sol.State El., Vol. 20, 1977):

$$v_{dr} = \frac{\mu_0 E}{\left(1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right)^{1/\beta}} \quad \text{with}$$

$$\begin{aligned}
\mu_{0,e} &= 1.51 \times 10^9 \cdot T^{-2.42} \tfrac{cm^2}{Vs} &\Rightarrow\quad & 1605.4 \tfrac{cm^2}{Vs} \quad \text{at } 294K \\
v_{sat,e} &= 1.53 \times 10^9 \cdot T^{-0.87} \tfrac{cm}{s} &\Rightarrow\quad & 1.09 \times 10^7 \tfrac{cm}{s} \\
\beta_e &= 2.57 \times 10^{-2} \cdot T^{0.66} &\Rightarrow\quad & 1.09
\end{aligned}$$

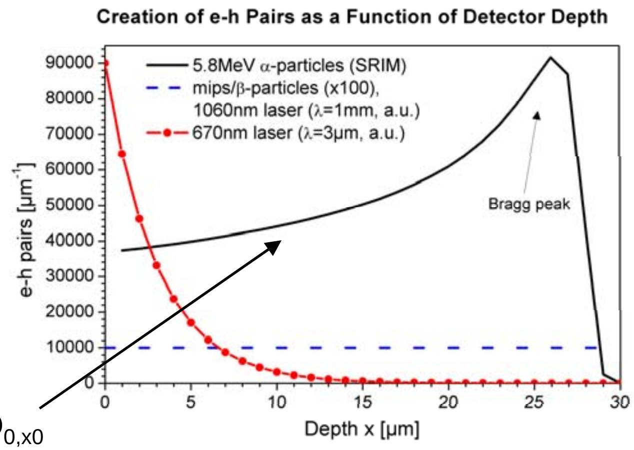
$$\begin{aligned}
\mu_{0,h} &= 1.31 \times 10^8 \cdot T^{-2.2} \tfrac{cm^2}{Vs} &\Rightarrow\quad & 486.3 \tfrac{cm^2}{Vs} \\
v_{sat,h} &= 1.62 \times 10^8 \cdot T^{-0.52} \tfrac{cm}{s} &\Rightarrow\quad & 0.84 \times 10^7 \tfrac{cm}{s} \\
\beta_h &= 0.46 \cdot T^{0.17} &\Rightarrow\quad & 1.21
\end{aligned}$$

Linear electric-field approximation:

$$E(x) = \frac{1}{d}\left[U_{dep}\left(\frac{2x}{d} - 1\right) - U\right], \qquad U \geq U_{dep}$$

Integration over all positions where e-h pairs were created:

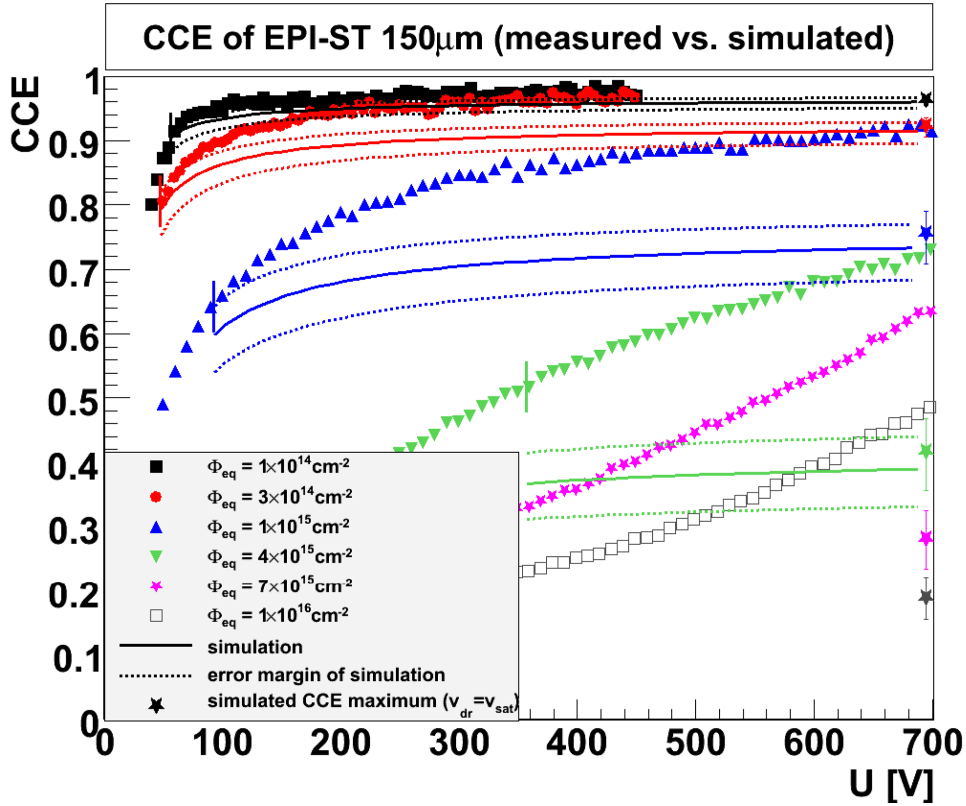
$$Q_{total} = \int_0^d Q_{x_0} dx_0$$

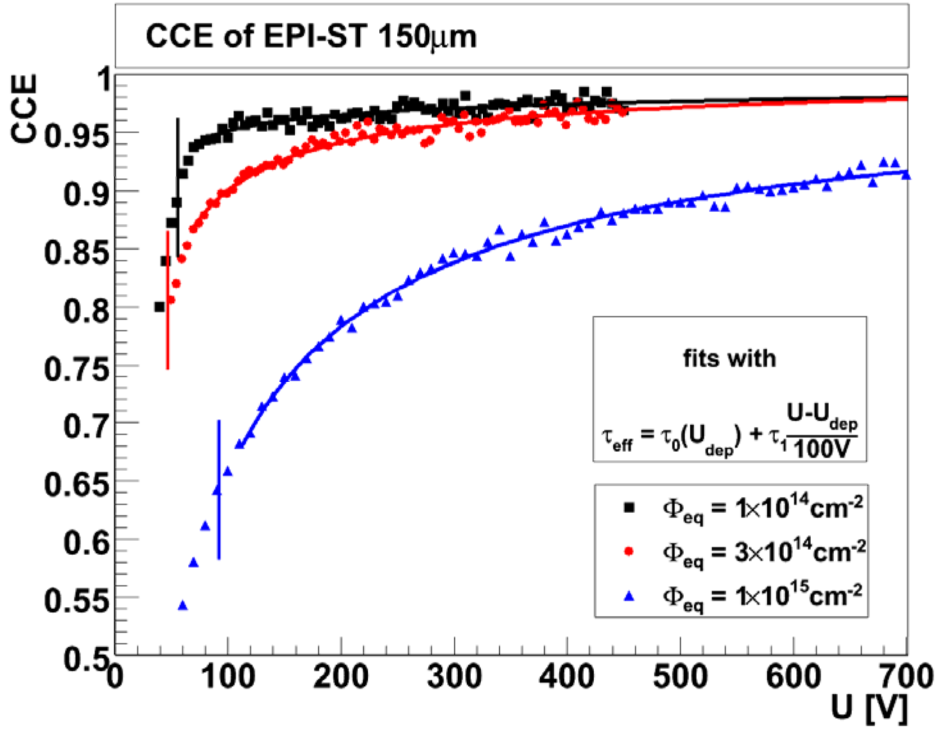


Charge deposition as a function of detector depth $Q_{0,x0}$ calculated by SRIM for 5.8 MeV α-particles

Comparison: Simulation ↔ Measured data

n-type, α





- Simulation with const. τ_{eff} underestimates measured data (even if $v_{dr}=v_{sat}$ assumed everywhere $\Rightarrow$ $v_{dr}(E)$- and $E(x)$ model uncertainties are not the reason)
- Possible Reasons: avalanche effects (only at high U, Φ), detrapping, non-const. τ_{eff} (variable cross section? non-const. occupation, e.g. due to trap filling at high I_{rev}?)
- First try: voltage-dependent τ_{eff}* $\Rightarrow$ good fits possible

* cf. L.Beattie NIM A 421 (1999), 502

Results from U-dependent τ_{eff} fit of CCE(U)

$$\tau_{eff,e} = \tau_0(U_{dep}) + \tau_1 \frac{(U - U_{dep})}{100V}$$

$$\begin{array}{llll} \tau_0(U_{dep}) = 22.5ns, & \tau_1 = 2.0ns & \text{for } 1 \times 10^{14} cm^{-2} \\ \tau_0(U_{dep}) = 8.9ns, & \tau_1 = 4.0ns & \text{for } 3 \times 10^{14} cm^{-2} \\ \tau_0(U_{dep}) = 2.4ns, & \tau_1 = 1.0ns & \text{for } 1 \times 10^{15} cm^{-2} \end{array}$$