# Charge collection and trapping effects in 75 µm, 100 µm and 150 µm thick n-type epitaxial silicon diodes after proton irradiation

Julian Becker, Eckhart Fretwurst, Jörn Lange, Gunnar Lindström

Hamburg University

GEFÖRDERT VOM
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und Forschung

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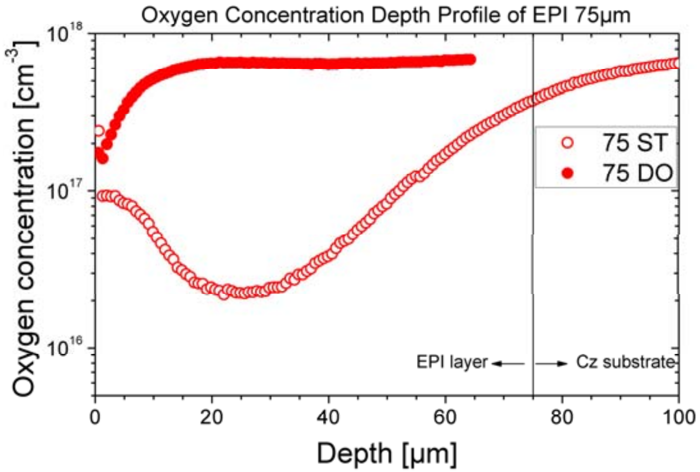
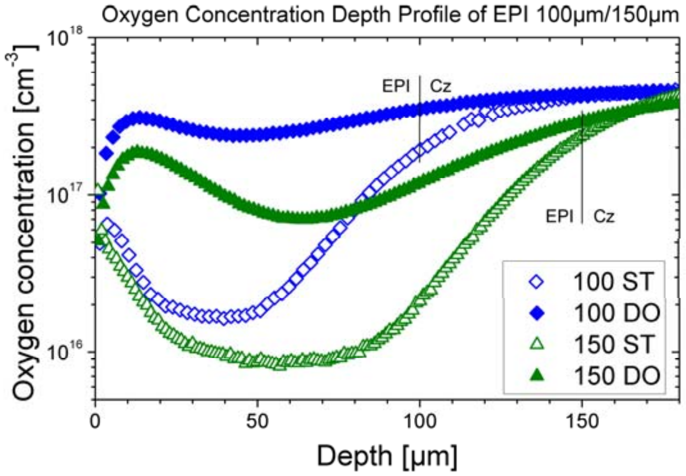
# Overview on investigated diodes

- Epitaxial n-Si pad-detectors on Cz-substrate produced by ITME/CiS
- Thickness: 75 µm, 100 µm and 150 µm, Size: 5 x 5 mm$^2$ and 2.5 x 2.5 mm$^2$
- Standard (ST) and oxygen enriched (DO, diffusion for 24h at 1100°C) material
- 24 GeV/c-proton-irradiation (CERN PS), $\Phi_{eq} = 1 \times 10^{14} - 1 \times 10^{16}$ cm$^{-2}$

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



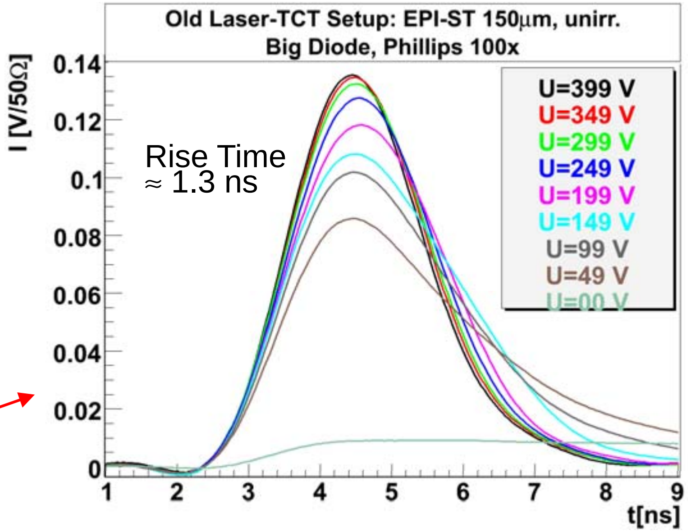


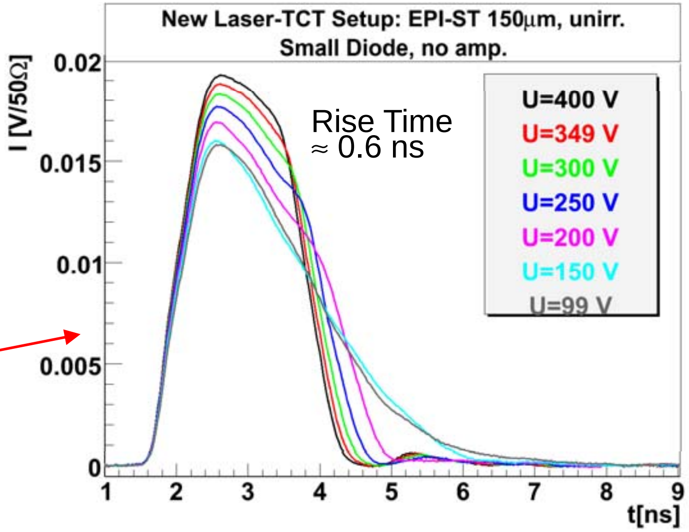
# TCT with 670 nm laser light

- Problem so far: determination of $\tau_{eff}$ via Charge Correction Method requires time-resolved signal
  BUT: $t_C \approx$ rise time of the signal (few ns)
- Example: OLD SETUP
  - laser pulse ≈ 1 ns
  - 500 MHz oscilloscope → 680 ps rise time
  - only 5 x 5 mm$^2$ diodes mountable
    → $\tau_{RC} \approx$ 880 ps for 150 µm

  ⇒ no time-resolved signal
- Solution: NEW SETUP
  - 70 ps laser pulse
  - 2.5 x 2.5 mm$^2$ diodes mountable
    → $\tau_{RC} \approx$ 225 ps for 150 µm
  - new 2.5 GHz oscilloscope → 136 ps rise time

  ⇒ time-resolved signal for 150 µm



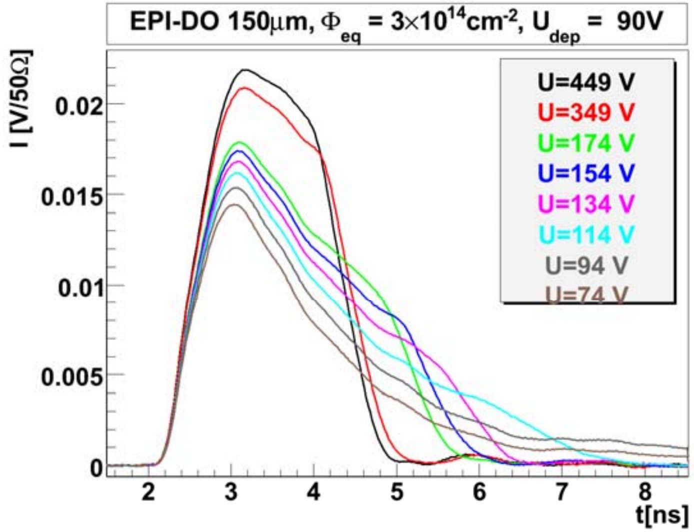


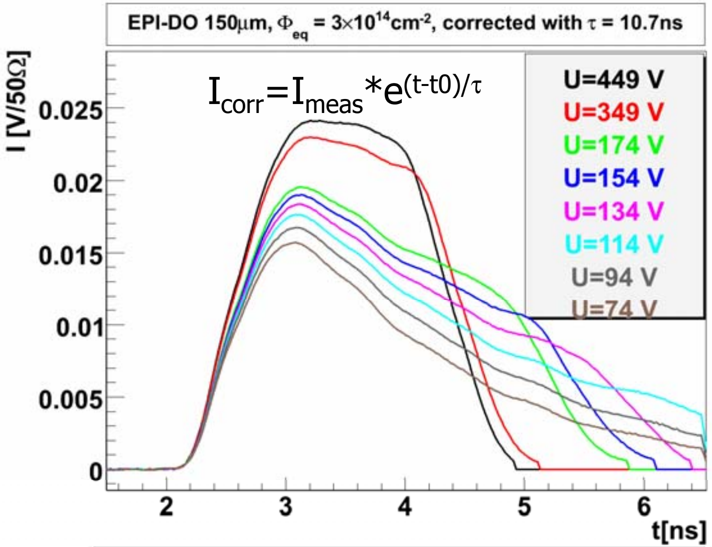
# TCT electron current signal examples

**as measured :** **corrected:**

EPI-DO 150 µm
$\Phi_{eq}=3\times10^{14}\,cm^{-2}$
30 min at 80°C
meas. at room temp.

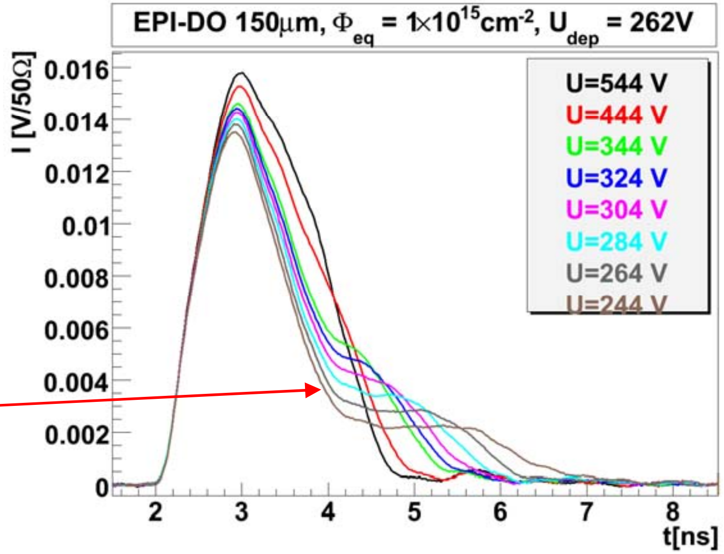
No type inversion
(confirms conclusions from annealing curve)

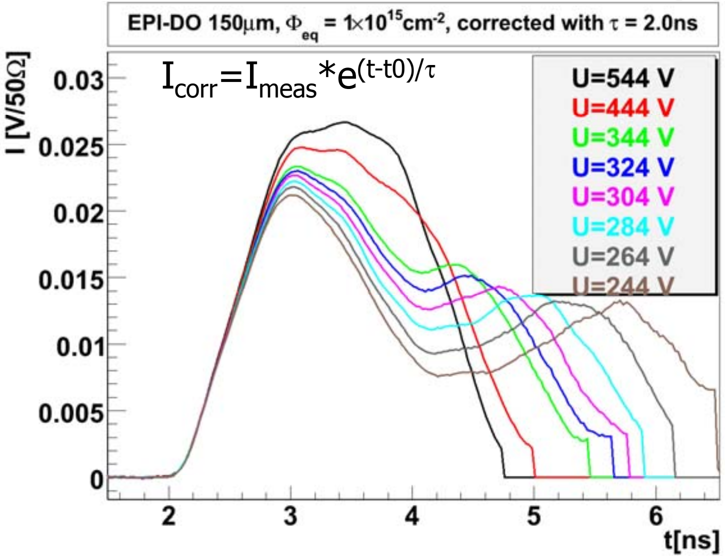




EPI-DO 150 µm
$\Phi_{eq}=1\times10^{15}\,cm^{-2}$
30 min at 80°C
meas. at room temp.

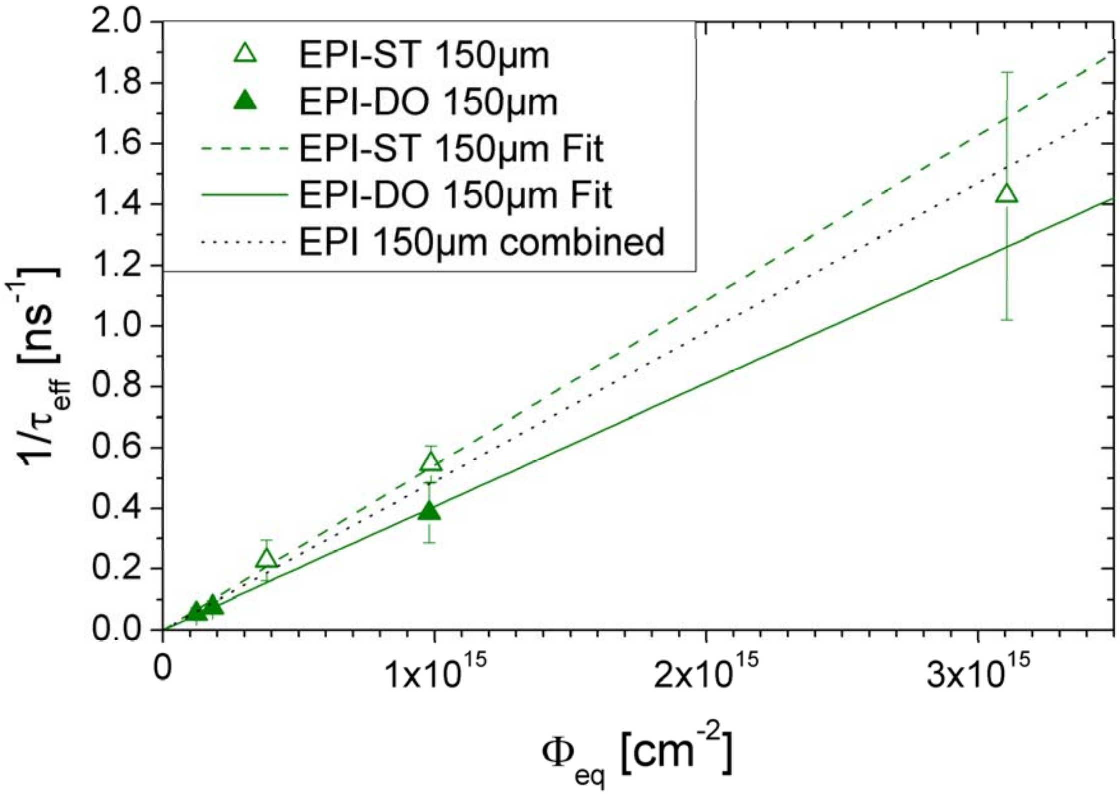
Double Junction!





# Trapping time constant

- Charge Correction Method after deconvolution and cutoff
- Resulting $\tau_{eff}$ sensitive on cutoff level, integration window, fitting range → quite large uncertainty (15 - 40%)
- Result: Trapping probability $1/\tau_{eff}$ fluence-proportional
- Damage parameter $\beta_e$ in the same range as value for FZ*
- 25% difference between ST and DO, but due to large errors not significant

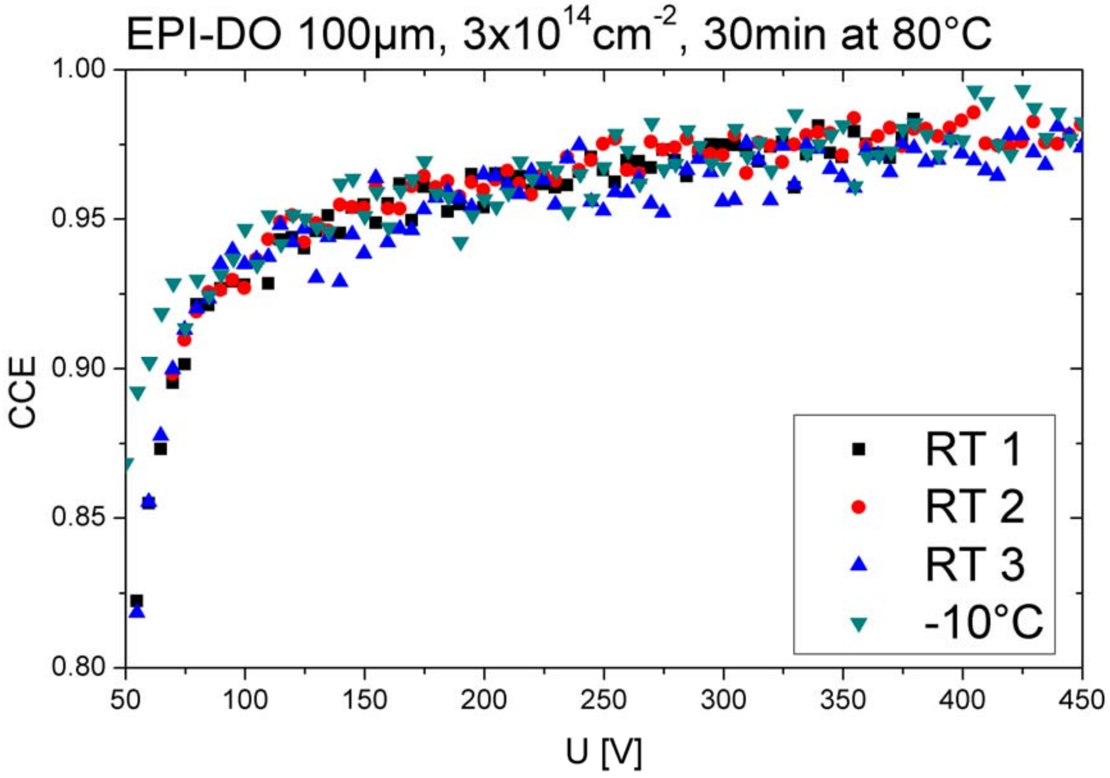


| | $\beta_e$ [$10^{-16}$ cm$^2$ns$^{-1}$] |
|---|---|
| **EPI-ST** | **5.4 ± 0.5** |
| **EPI-DO** | **4.0 ± 0.7** |
| **EPI comb.** | **4.9 ± 0.4** |
| **cf. FZ*** | **5.1** |

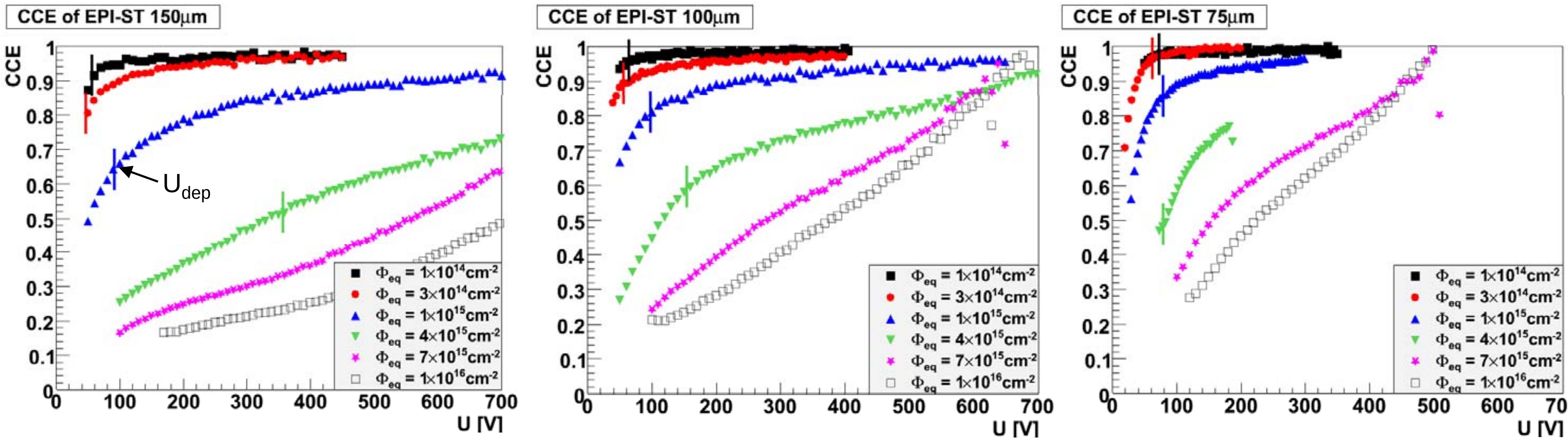
*see G.Kramberger's Doctoral Thesis, for T=294K

# TCT with 5.8 MeV α-particles

- $^{244}$Cm α-source: 5.8 MeV, 26µm penetration depth (SRIM)
- CCE obtained by normalising integrated charge to the one of unirradiated diode
- Measurements usually at RT, but for highly irradiated diodes at -10°C because of high currents
- Good reproducibility, no difference for CCE between RT and -10°C
  → mobility rise and $\tau_{eff}$ decrease at low T obviously compensate

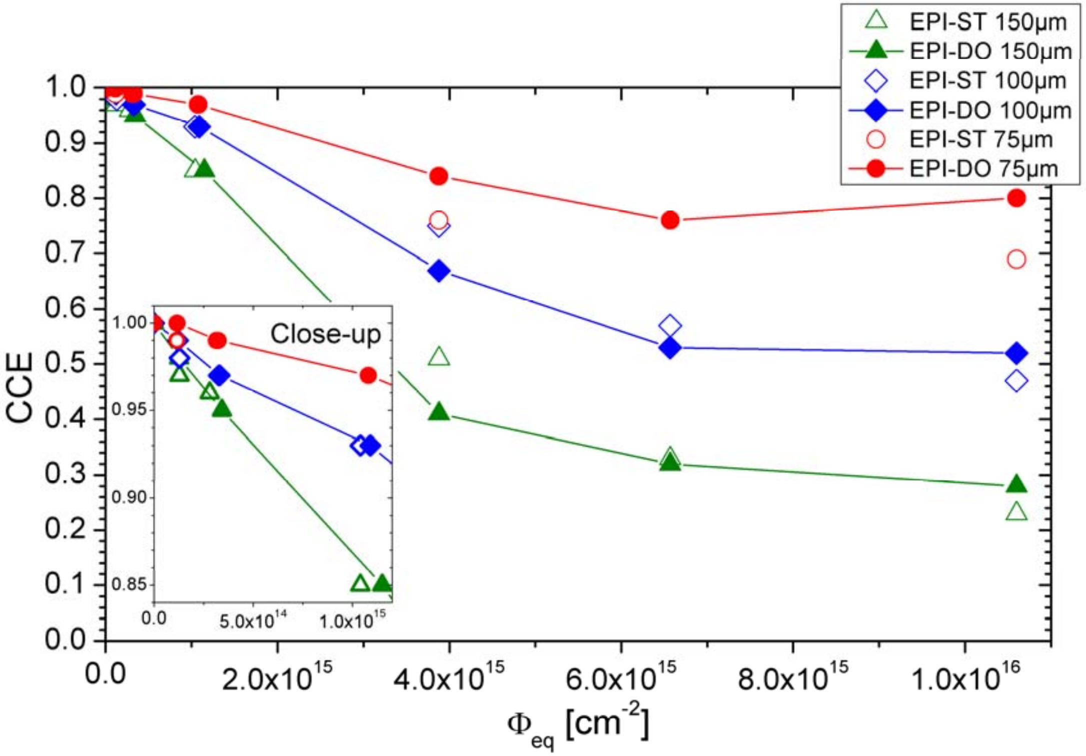


# CCE as a function of bias



- CCE(U) almost saturating for low fluences
- CCE(U) rises strongly for high fluences (exceeds even 1 at high U for thin diodes) → avalanche effects?
- CCE degrades with fluence

# CCE as a function of fluence (at 350V)



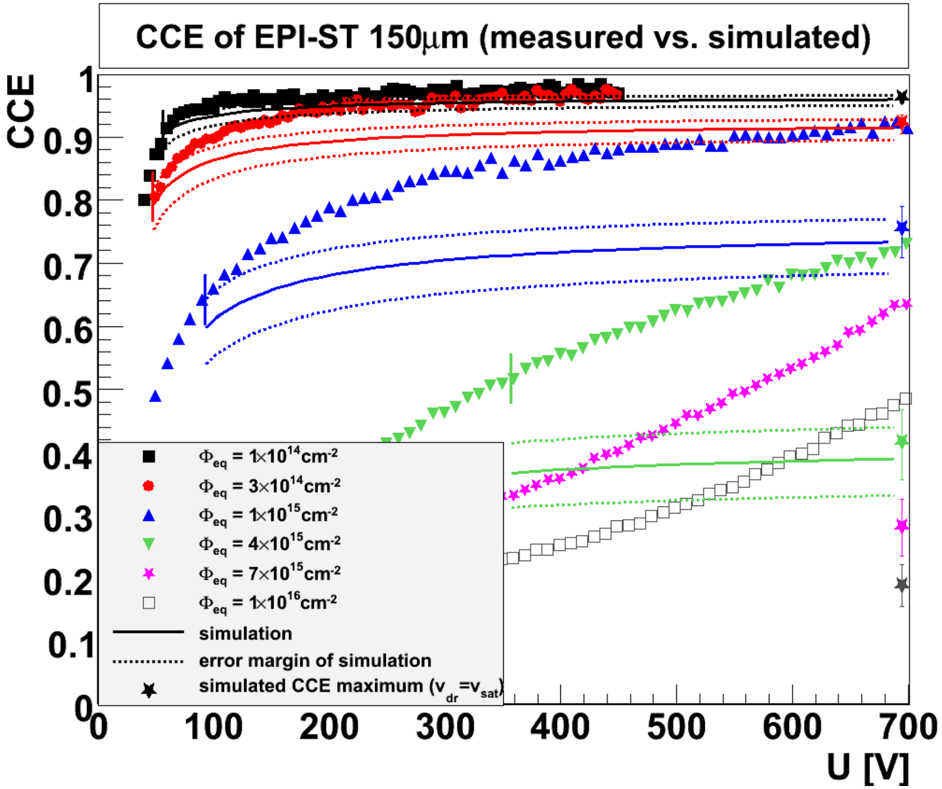
- CCE degrades with fluence, but deceleration at high fluences due to avalance effects?
- CCE improves for decreasing thickness as $t_C$ decreases (smaller distance, higher field)
- No significant difference between ST and DO

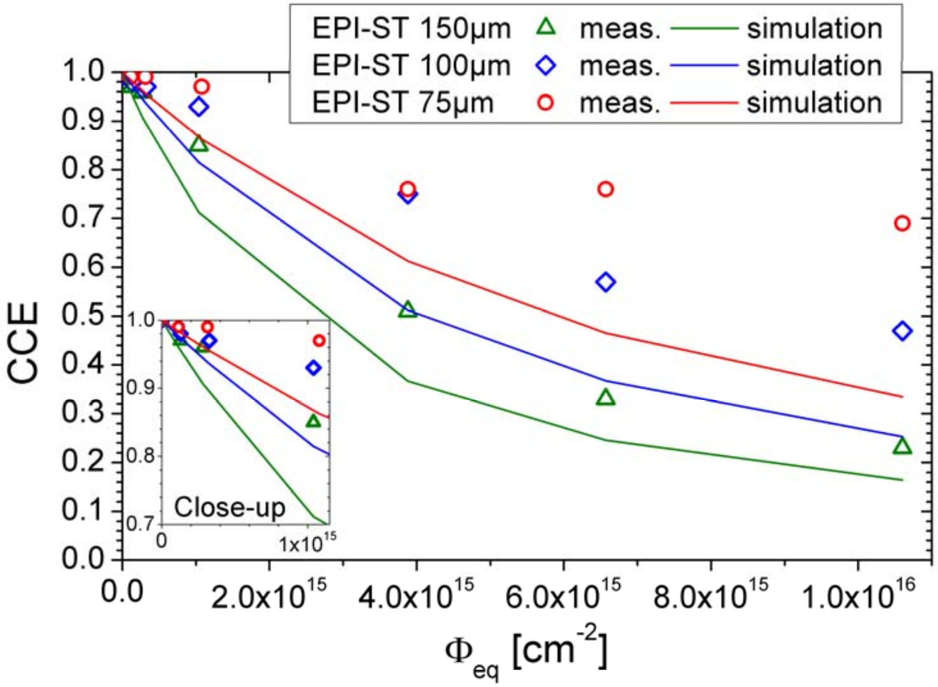
# Simulation of CCE

- $\tau_{eff}$ found to be linear with fluence, same values as in FZ
  → everything as expected and understood?
  → check with simulation!
- Simulation of CCE with $\alpha$-particles taking $\tau_{eff}$ obtained by CCM
- Input:
  - $v_{dr}$ parameterisation including saturation
  - linear electric-field approximation (reasonable for $U >> U_{dep}$)
  - e-h pair distribution after penetration of $\alpha$-particles as calculated by SRIM
  - $\beta_e = 5.1 \times 10^{-16}$ cm$^2$ns$^{-1}$, $\beta_h = 6.5 \times 10^{-16}$ cm$^2$ns$^{-1}$ used for calculating $\tau_{eff}$ (G. Kramberger)

# CCE measured vs. simulated

## CCE(U):                CCE($\Phi_{eq}$) at 350V:





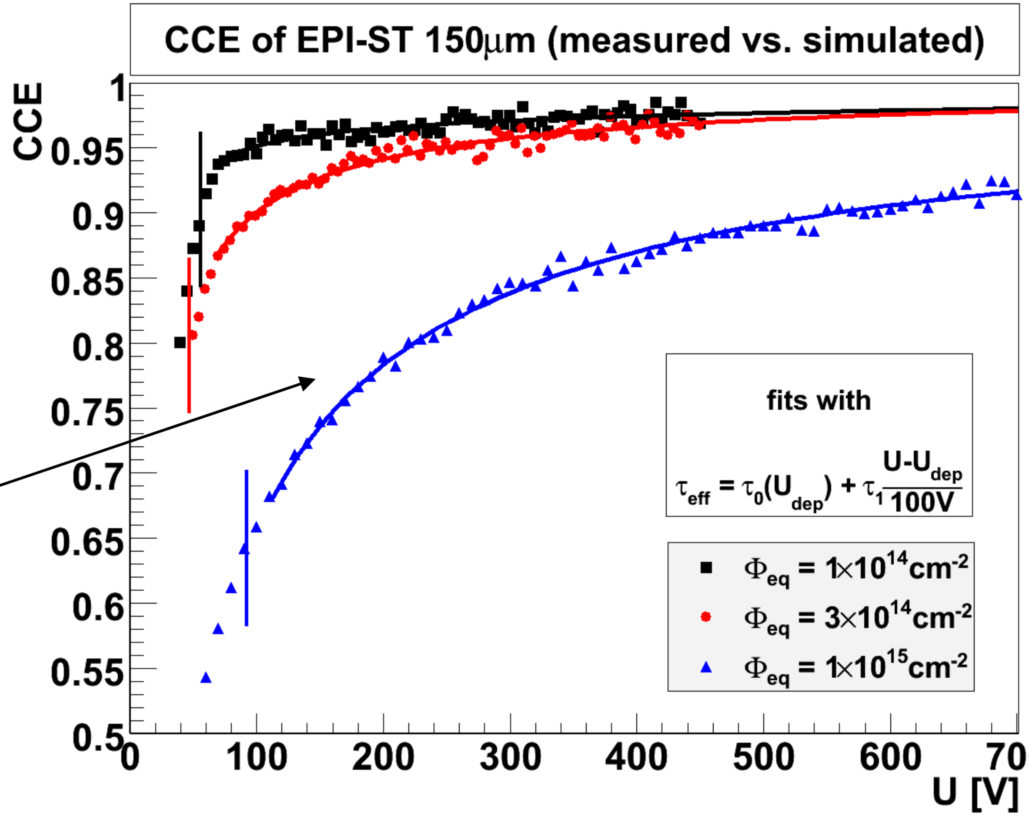
- No good agreement: simulation systematically underestimate measurements
- Avalanche effects? But should not be the case for lowest fluences
- Plasma effect? But same problem seen before for laser- and β-TCT (see e.g. G.Kramberger, 8th RD50 Workshop Prague; L.Beattie NIM A 421 (1999), 502)
- Model assumptions (e.g. $v_{dr}(E)$, $E(x)$) wrong?
  But even calculated maximum CCE in case of assuming $v_{dr} = v_{sat}$ everywhere is too low!

→ Discrepancy must be related to trapping model

# Possible solutions (speculative!)

- Fast detrapping?
- Exponential decay $\exp(-t/\tau_{eff})$ with constant $\tau_{eff}$ does not provide accurate description of trapping?
  - assumption $v_{dr} << v_{th}$ not valid if $v_{dr} \approx v_{sat}$?
  - cross section dependent on $v_{dr}$?
  - inhomogeneous trap density?
  - trap filling at high currents?
- First try:
  voltage-dependent $\tau_{eff}$*
  → fits CCE(U) well!
  → modified CCM can also produce flat slope of Q(U)!

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



# Summary

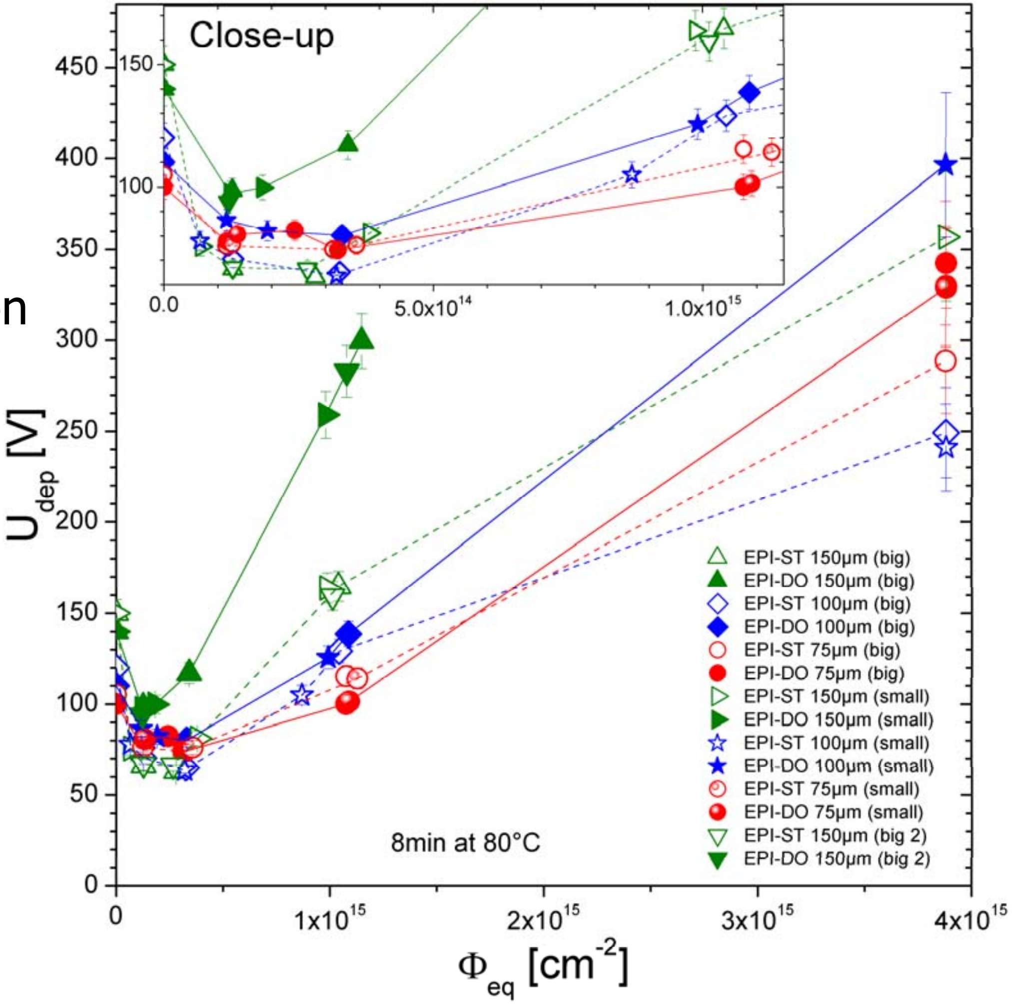
- New Laser-TCT setup with improved rise time
  → Time-resolved signal even for 150 µm EPI diodes
  → No type inversion in p-irradiated n-type EPI diodes
  → Double Junction at high fluences
  → CCM possible: $1/\tau_{eff}$ linear with fluence with $\beta_e$ similar to FZ
- CCE with $\alpha$-particles:
  - CCE increases for decreasing thickness
  - No difference between ST and DO
  - Degradation with fluence decelerated due to avalanche effects
- Simulated CCE underestimates measurements
  - Modified trapping description needed?
  - E.g. voltage-dependent $\tau_{eff}$ fits data well

# BACKUP SLIDES

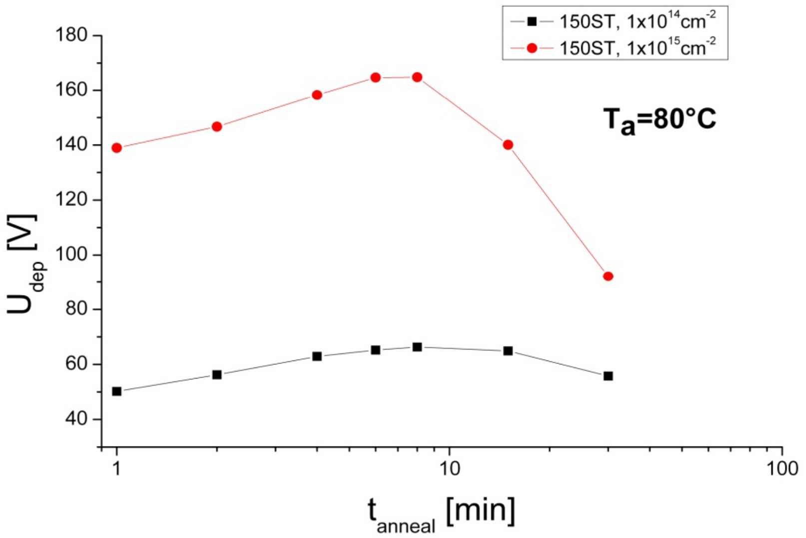
# Depletion Voltage (from CV at 10 kHz)

- CV/IV measurable up to 4x$10^{15}$ $cm^{-2}$ 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)

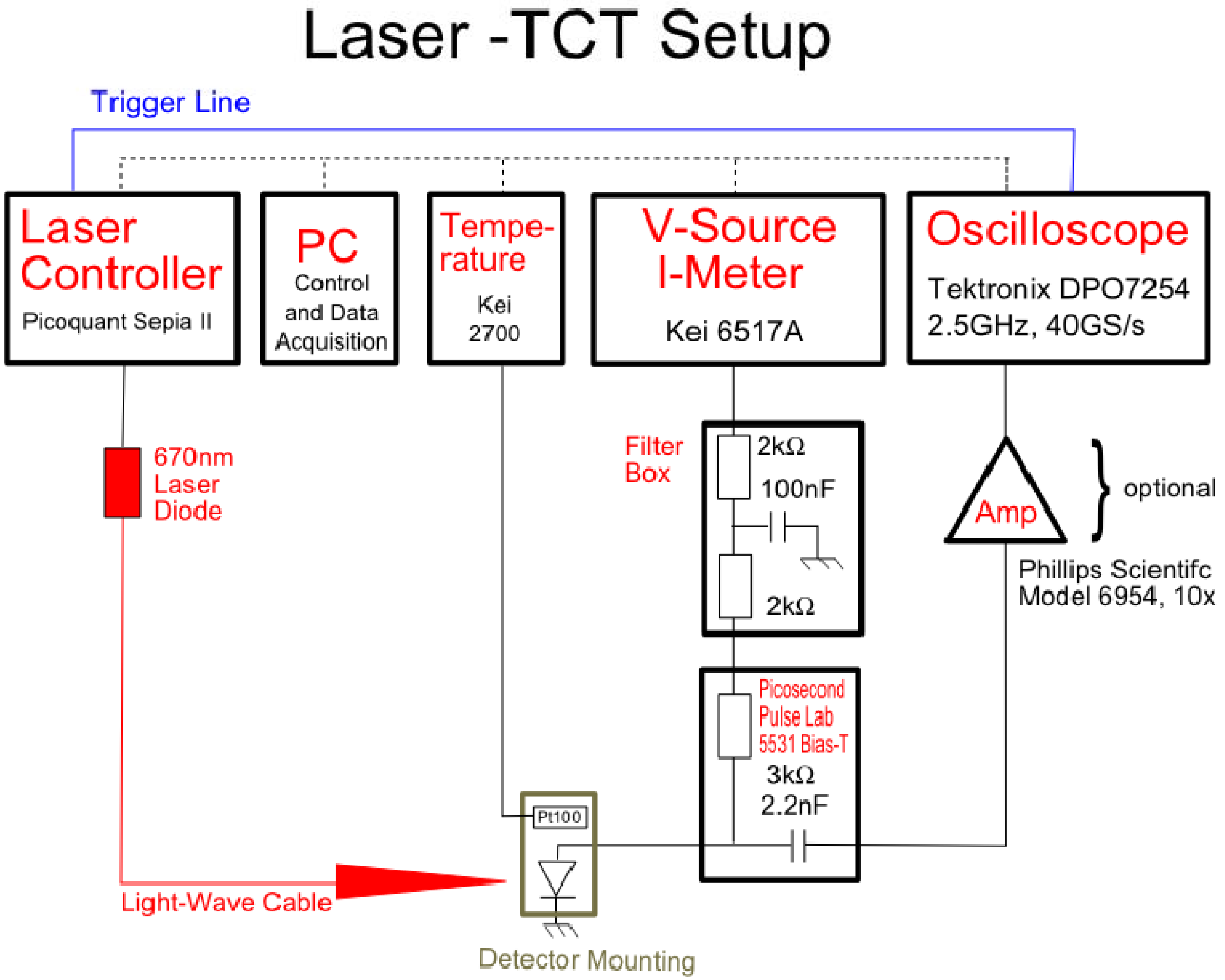
**Stable Damage:**



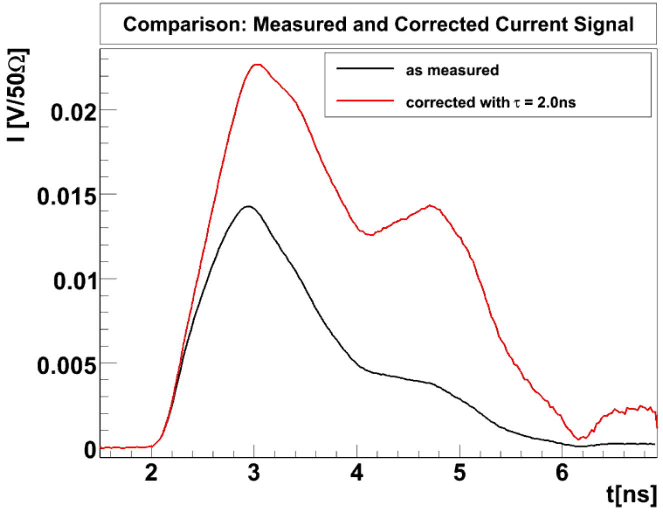
**Annealing curve:**

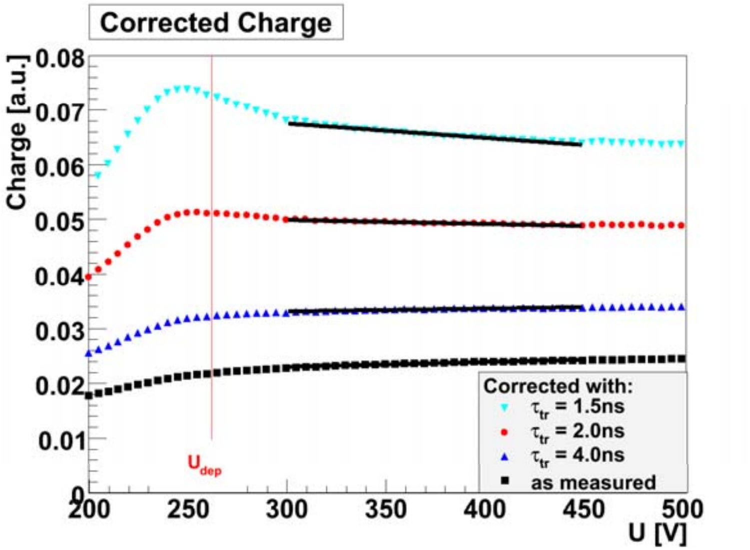


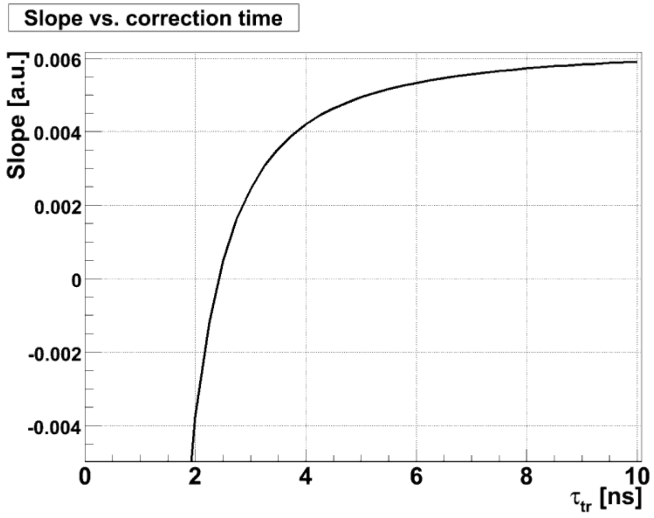
# New Laser-TCT Setup



# CCM

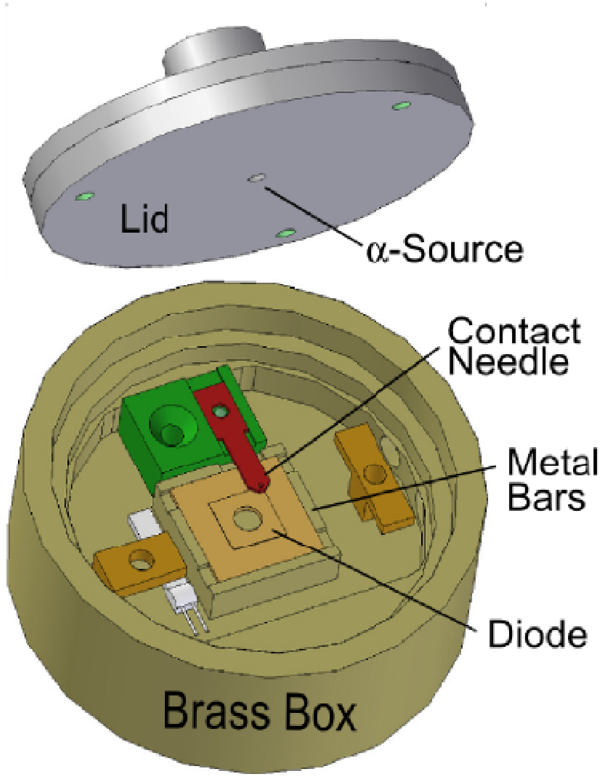

Comparison: Measured and Corrected Current Signal
I [V/50Ω]
0.02
0.015
0.01
0.005
0
2
3
4
5
6
t[ns]
as measured
corrected with τ = 2.0ns


Corrected Charge
Charge [a.u.]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
200
250
300
350
400
450
500
U [V]
U_dep
Corrected with:
τ_tr = 1.5ns
τ_tr = 2.0ns
τ_tr = 4.0ns
as measured

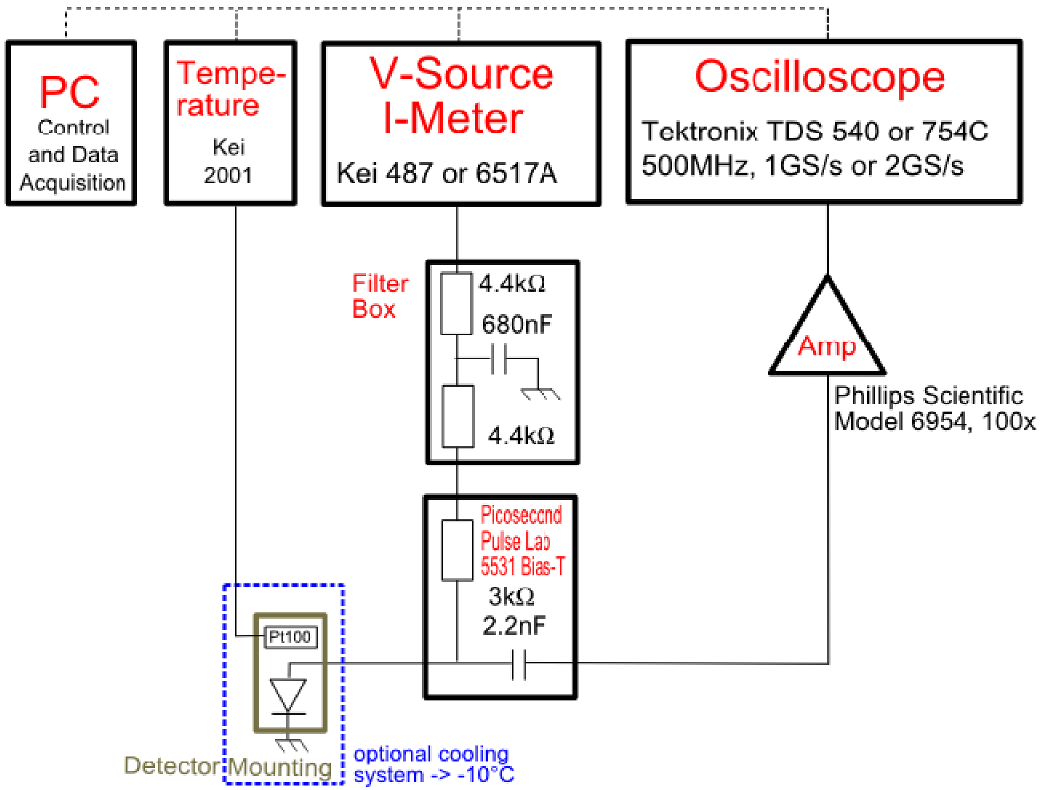

Slope vs. correction time
Slope [a.u.]
0.006
0.004
0.002
0
-0.002
-0.004
0
2
4
6
8
10
τ_tr [ns]

# Alpha-TCT Setup

## Detector Mounting



## α -TCT Setup



# Simulation details

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

$$Q_{x_0} = \frac{Q_{0,x_0}}{d}\left[\int_{x_0}^{d} \exp\left(-\frac{t(x)}{\tau_{eff,e}}\right) dx - \int_{x_0}^{0} \exp\left(-\frac{t(x)}{\tau_{eff,h}}\right) dx\right]$$

with

$$t(x) = \int_{x_0}^{x} \frac{1}{v_{dr}\left(E\left(x'\right)\right)} dx'$$

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

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

with

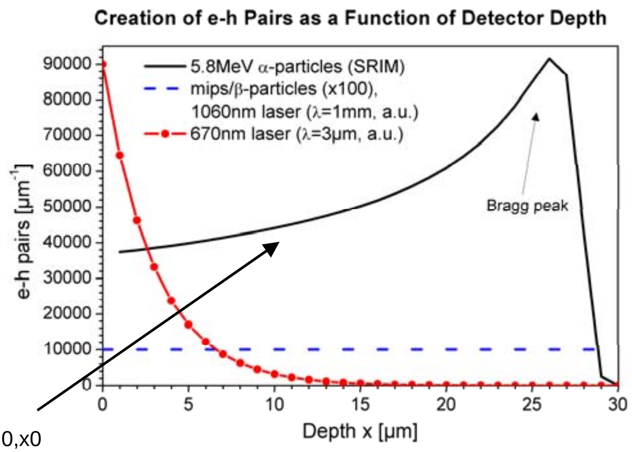
$$\begin{aligned}
\mu_{0,e} &= 1.51 \times 10^9 \cdot T^{-2.42} \tfrac{cm^2}{Vs} & \Rightarrow \quad & 1605.4 \tfrac{cm^2}{Vs} \quad \text{at } 294K \\
v_{sat,e} &= 1.53 \times 10^9 \cdot T^{-0.87} \tfrac{cm}{s} & \Rightarrow \quad & 1.09 \times 10^7 \tfrac{cm}{s} \\
\beta_e &= 2.57 \times 10^{-2} \cdot T^{0.66} & \Rightarrow \quad & 1.09 \\
\\
\mu_{0,h} &= 1.31 \times 10^8 \cdot T^{-2.2} \tfrac{cm^2}{Vs} & \Rightarrow \quad & 486.3 \tfrac{cm^2}{Vs} \\
v_{sat,h} &= 1.62 \times 10^8 \cdot T^{-0.52} \tfrac{cm}{s} & \Rightarrow \quad & 0.84 \times 10^7 \tfrac{cm}{s} \\
\beta_h &= 0.46 \cdot T^{0.17} & \Rightarrow \quad & 1.21
\end{aligned}$$

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

# Results from U-dependent $\tau_{eff}$ fit of CCE(U)

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

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