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PHYSICS AT THE TERA SCALE
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Life time determination of free charge carriers in irradiated silicon sensors

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Hamburg University *DESY

Overview

Motivation

Transient current technique (TCT)

Methods to determine the life time:

- Charge Correction Method (**CCM**)
- modified Charge Correction Method (**mCCM**)

  Comparison of **CCM** and **mCCM** on model calculations and on data

- Model calculations of TCT pulses

Conclusion

Outlook

Motivation

LHC upgrade: 10 x higher radiation damage after high luminosity upgrade

⇒ radiation hard material needed

Radiation induced trapping centers → charge losses, signal reduction

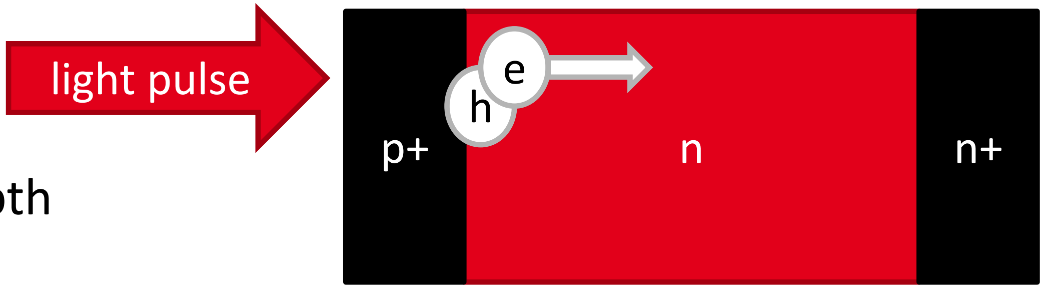
Aim: understand and describe signal reduction in irradiated silicon

(HL-LHC fluences)

Find a standard method to extract life times in irradiated silicon

(e.g. for HPK-campaign)

Transient current technique (TCT)



red laser light pulse:

- 670 nm, 3 µm penetration depth
- FWHM 40 ps
- generates N = ~ 1 million e-h pairs

⇒ induced current (pad sensor) : $I(t) = \frac{q_0 N(t)}{d} \cdot v_{dr}(E), \qquad v_{dr} = \mu(E) \cdot E$

$$Q = \int I(t)\, dt\,, \qquad CCE = \frac{Q_{irradiated}}{Q_{non\ irradiated}} = \frac{Q}{Q_0}$$

readout:

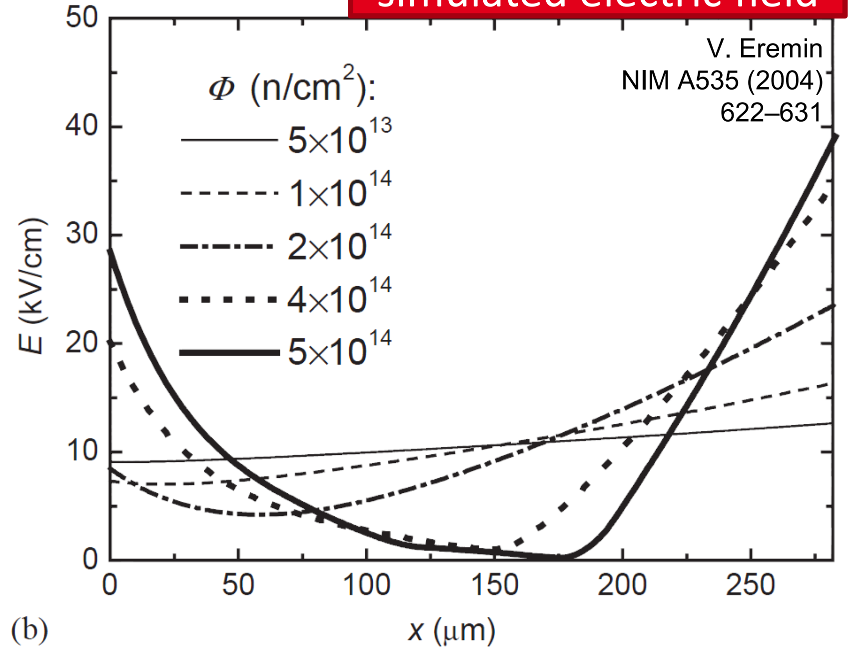
- digital oscilloscope (bandwidth 1 GHz, 512 averages)
- 10 x Phillips current amplifier
- diode capacitance of ~4 pF for used diodes with d=150 µm

Difficulties for Life Time Determination

Trapping probability $1/\tau$ depends on:

- **Density of traps**
- **Occupation probability of traps**
  - Density of free electrons
  - Density of free holes
  - Temperature
  - Electric field
- **Capture cross section σ_{trap}**
  - Velocity of charge carriers
  - Electric field

simulated electric field



Electric field not known

$\Rightarrow$ Model assumptions to estimate an effective trapping time τ

Time constant of the electronics: $\mathcal{O}$(charge collection time)

Charge Correction Method (CCM)

- Number of drifting charge carriers ***N*** reduces due to trapping:

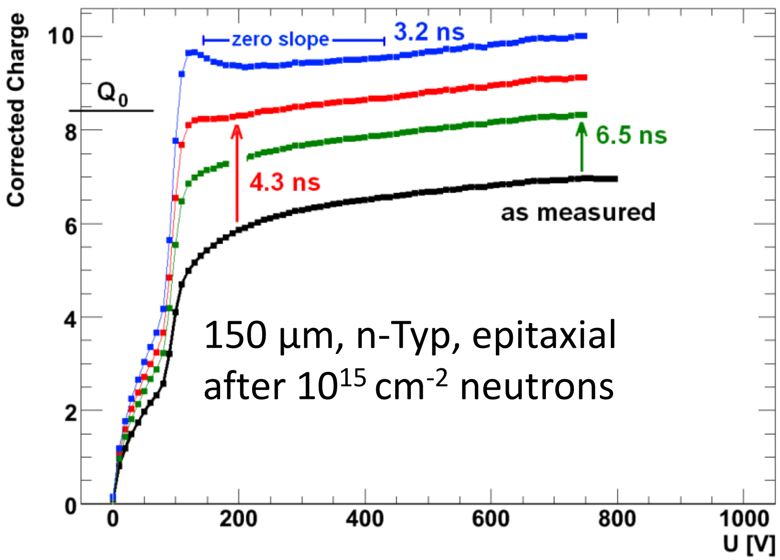
$$\frac{\mathrm{d}N}{N} = -\frac{1}{\tau}\,\mathrm{d}t \Rightarrow N(t) = N_0 \cdot e^{-\frac{t}{\tau}}, \qquad \text{for } \tau = \text{const}$$

- Drift velocity field dependent $\Rightarrow$ charge collection time voltage dependent
  $\Rightarrow \mathrm{Q} = \mathrm{Q(V)}$

- Trapping corrected signal: $I_c(t, \tau_{tr}) = I(t) \cdot e^{t/\tau_{tr}}$
- Trapping fully corrected: $\boldsymbol{Q_c(\tau_{tr}) = Q_0 = \mathrm{const}}$ (full charge collection, CCE=1)
- Correct all voltages with the same τ_{tr} until linear fit of $Q_c(V)$ gives **slope = 0**
- **No reference measurement (Q_0) needed!**
  (i.e. no knowledge on CCE needed)

CCM was used for fluences up to

a few 10^{14} cm^{-2} neq. and voltages close to V_{fd}



CCM by G. Kramberger. Doctoral Thesis, Ljubljana, 2001.

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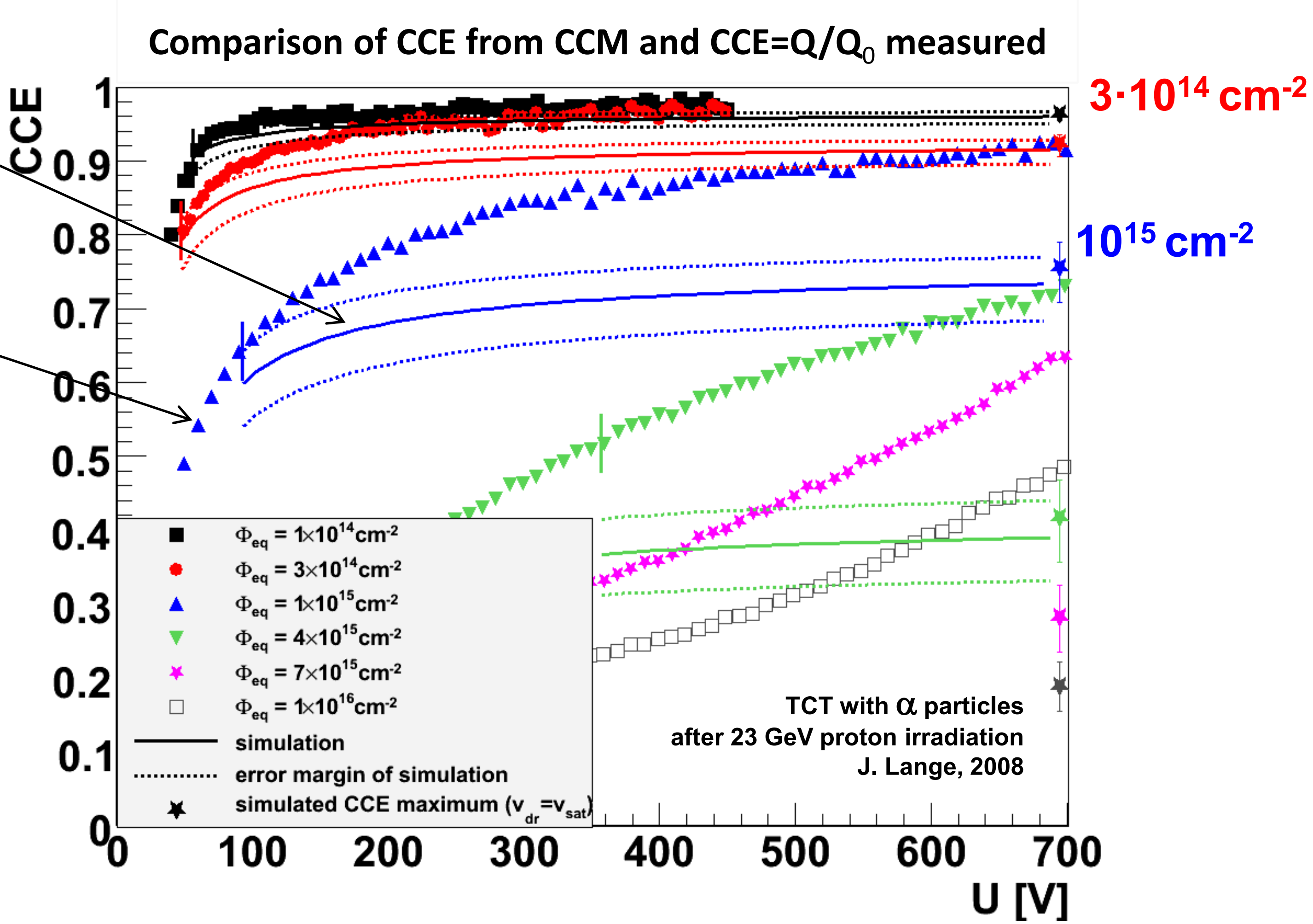
Limitations of the Charge Correction Method

1.) CCE calculated:
with τ from CCM
(lines)

2.) CCE measured:
CCE = Q / Q_0
(Symbols)

Comparison:
using CCM leads to overestimation of charge losses at voltages >> V_{fd}

$\Rightarrow \tau = \tau(V)$?



Modified Charge Correction Method

Collected charge: $Q = \int I(t)\mathrm{d}t$

Use collected charge of non-irradiated diode Q_0

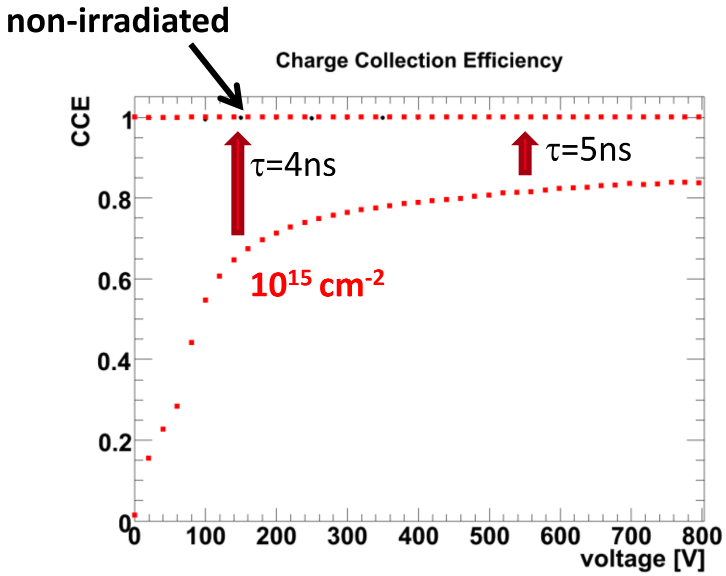
Charge collection efficiency **$CCE = Q / Q_0$**

For each voltage independently:

$$I_c(t) = I(t) \cdot e^{t/\tau_{tr}}$$

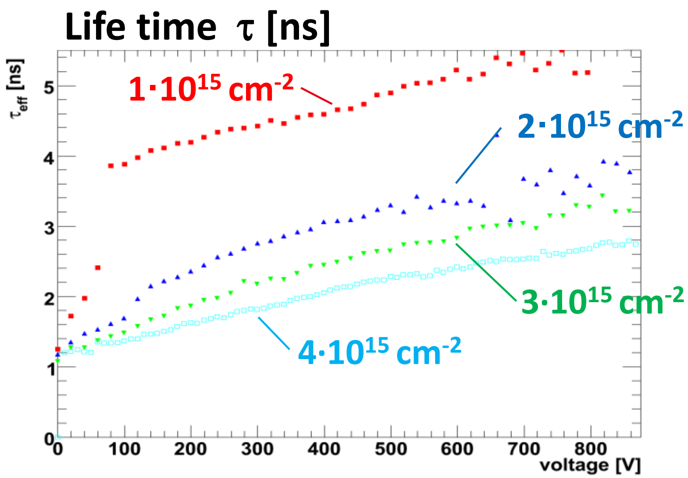
Current $I(t)$ is corrected until $\boldsymbol{Q_c = Q_0}$

(i.e. $CCE_C = 1$)



$\Rightarrow$ Extracted life time depends on voltage:

$$\tau = \tau(V), \quad \tau \sim \text{linear in } V$$



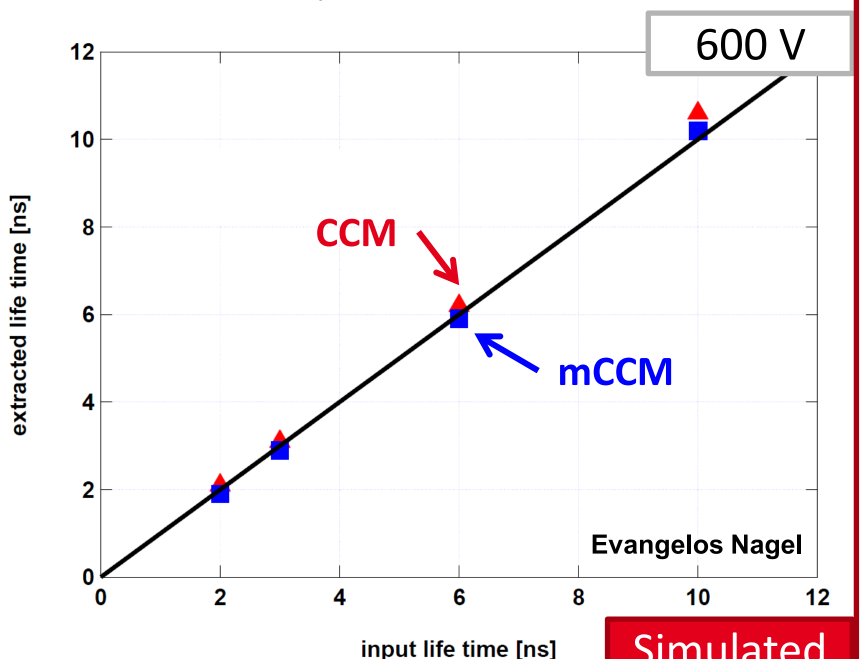
life time field dependent: $\boldsymbol{\tau = \tau(E)}$?

Comparison of CCM and mCCM for model calculated TCT signals

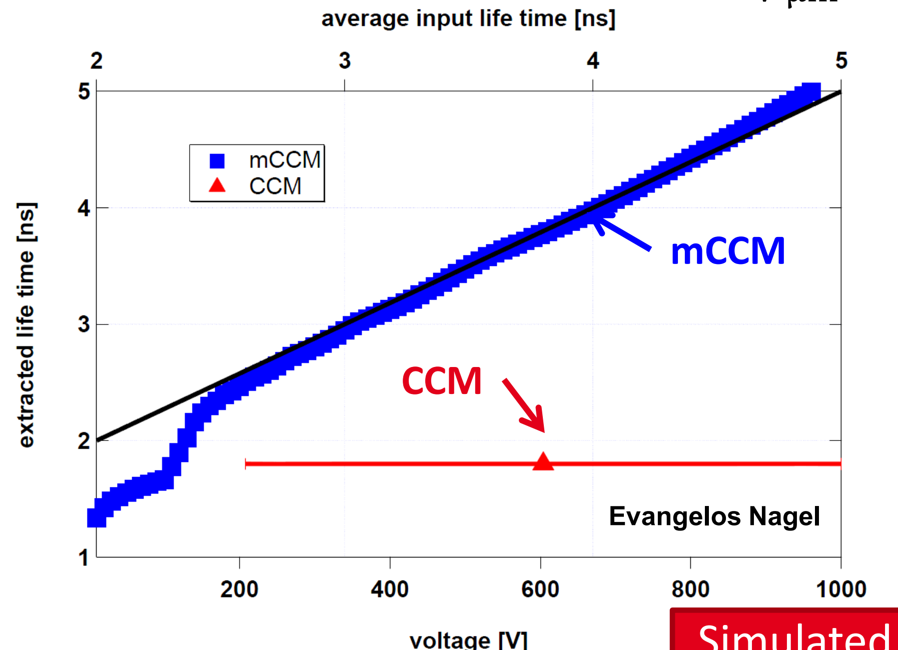
Model calculation:

- $I(t) = \frac{q_0 N(t)}{d} \cdot \mu(E) \cdot E,$ electronic distortions calculated in SPICE
- V_{fd} = 100 V, N_{eff} = const, d = 200 µm

a) $\tau = \text{const}$

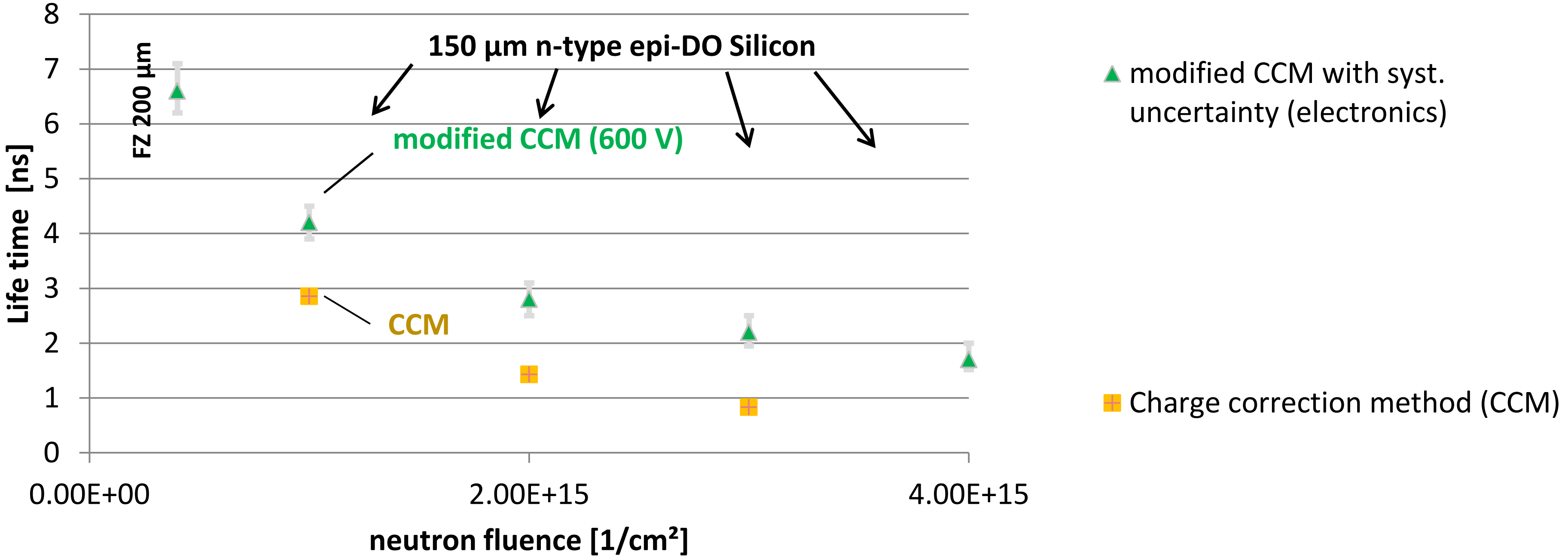


b) $\tau = \tau_0 + \tau_1 \cdot E = 2\text{ ns} + 0.6\text{ ns} \cdot \frac{E}{\text{V}\,\mu\text{m}^{-1}}$



$\Rightarrow$ **CCM underestimates τ for $\tau = \tau(E)$, mCCM give proper results.**

Comparison of CCM and mCCM on data



$\Rightarrow$ **CCM underestimates τ**

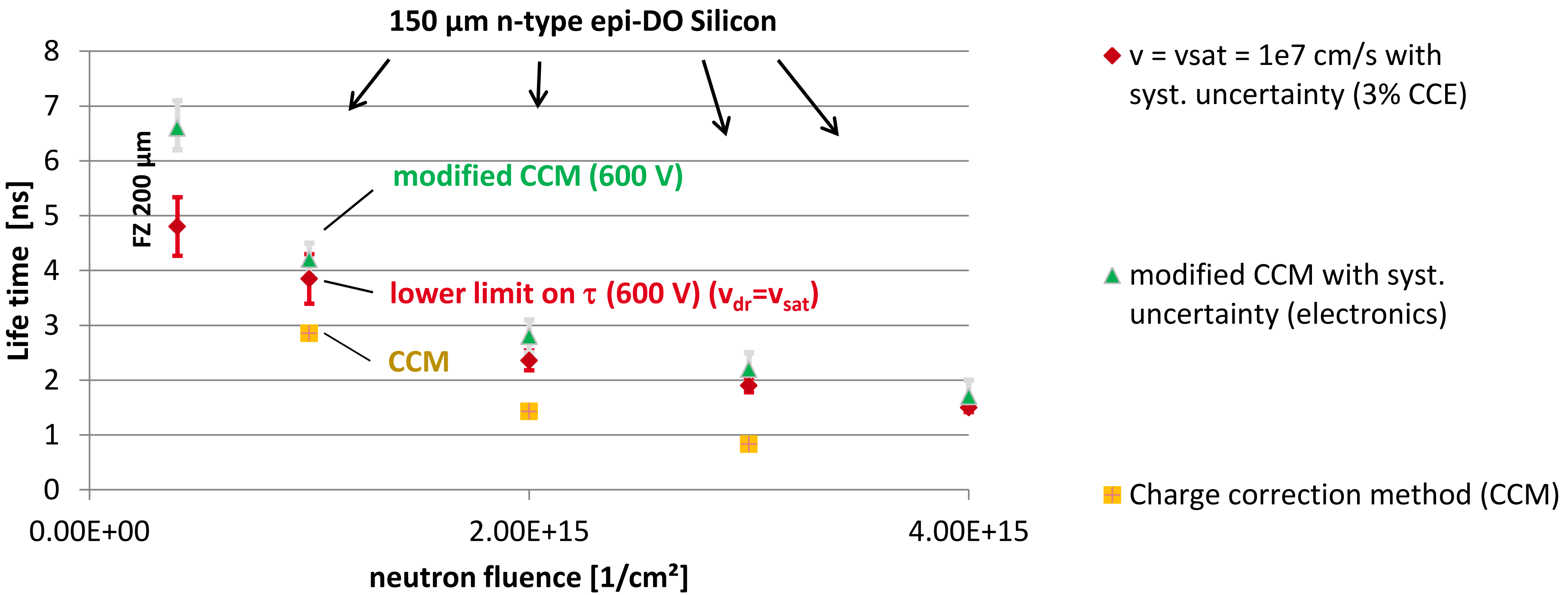
Ansätze for life time determination

	Input data	Assumptions
Charge Correction Method (CCM)	time resolved current I(t)	τ = const
modified CCM	time resolved current I(t) non-irradiated Q_0	$\tau = \tau$ (V)

Ansätze for life time determination

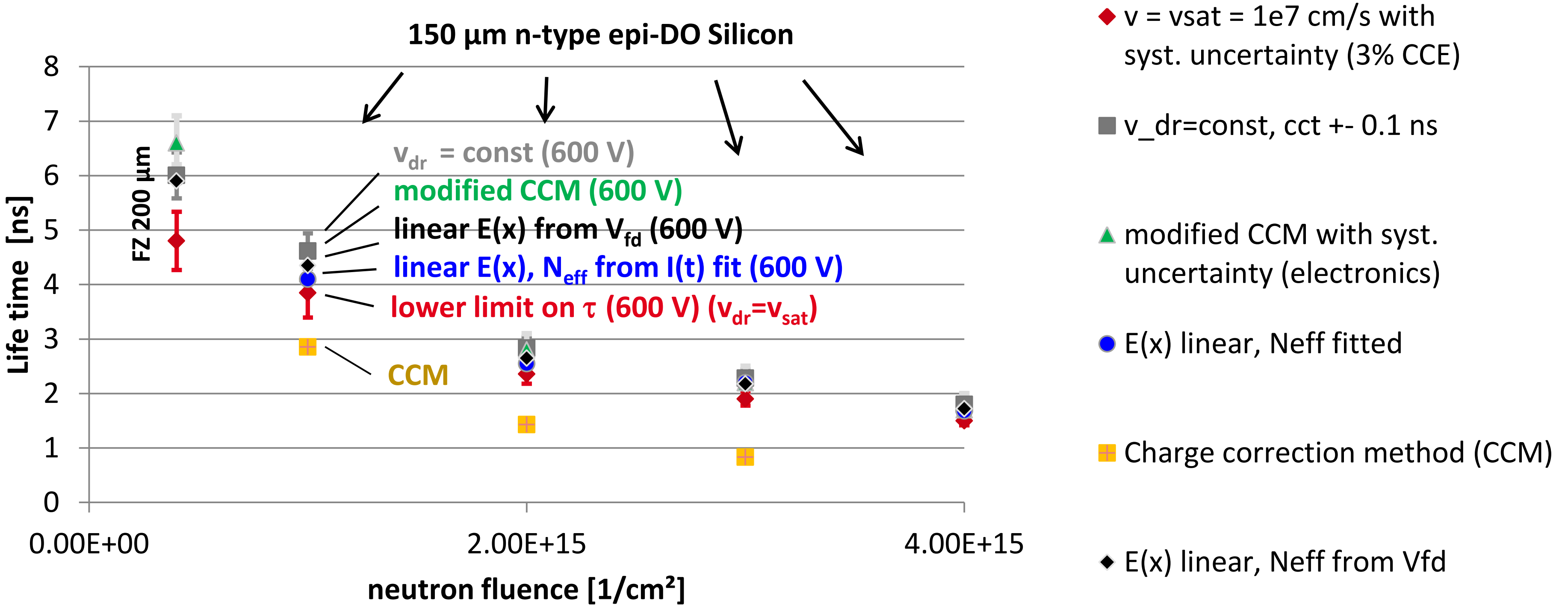
	Input data	Assumptions
Charge Correction Method (CCM)	time resolved current I(t)	$\tau = \text{const}$
modified CCM	time resolved current I(t) non-irradiated Q_0	$\tau = \tau(V)$
Model calculation with measured drift velocity	$CCE = \frac{Q}{Q_0}$ charge collection time *cct* sensor thickness *d*	$\tau = \tau(V)$ $v_{dr} = < v_{dr} > = \frac{d}{cct} = \text{const}$
Model calculation with linear field E(x)	$CCE = \frac{Q}{Q_0}$, sensor thickness d, a) full depletion voltage V_{fd} b) I(t)	$\tau = \tau(V)$, $v_{dr} = v_{dr}(E)$ a) $\nabla E \leftarrow N_{eff} \leftarrow V_{fd} \leftarrow$ CV b) $\nabla E \leftarrow$ free fit par. from I(t)
Model calculation with max. drift velocity v_{sat}	$CCE = \frac{Q}{Q_0}$ sensor thickness d	lower limit on $\tau = \tau_{\min}(V)$ $v_{dr} = v_{sat} = 10^7\ \text{cm s}^{-1}$

Life time comparison for different methods



Classical CCM underestimates τ

Life time comparison for different methods



Classical CCM underestimates τ.

All other methods: max. difference < 20 % in life time τ

$\Rightarrow$ **exact knowledge on electric field not neccessary to extract life time within 20% uncertainty (if CCE known)**

Summary and Conclusion

- **Classical Charge Correction Method** fails at high fluences (> 10^{15} cm^{-2}) for electron collection in studied sampled.
- A **modified Charge Correction Method** was developed **taking into account the charge collection efficiency (CCE).**
- Extracted life times are **compatible with model calculations** within systematic uncertainties of ~ 20%

⇒ even without exact knowledge on E(x): τ can be estimated with $\frac{\Delta\tau|_{\text{model}}}{\tau} \approx 20\%$

- uncertainties of the charge collection efficiency must be taken into account

⇒ $\frac{\Delta\tau|_{\text{CCE}}}{\tau} \approx 20\%$

- Effective life times are voltage dependent: $\boldsymbol{\tau = \tau(V)}$
  (higher life times for higher voltages).

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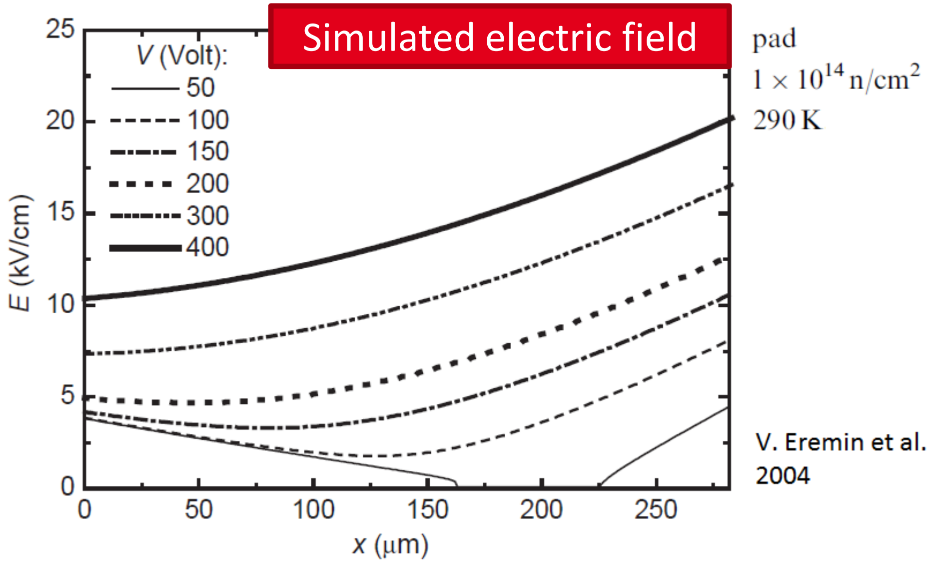
Outlook τ(x)

$\tau\ (V)$ can be extracted without knowledge on $E(x)$.

Can we also extract $\tau\ (V, x)$ if we know $E(x)$?

May we then draw conclusions on field dependence? $\tau = \tau\ (E)$?

Will we see filled electron traps at the n+ side? $\tau \rightarrow \infty$, for $x \rightarrow d$?



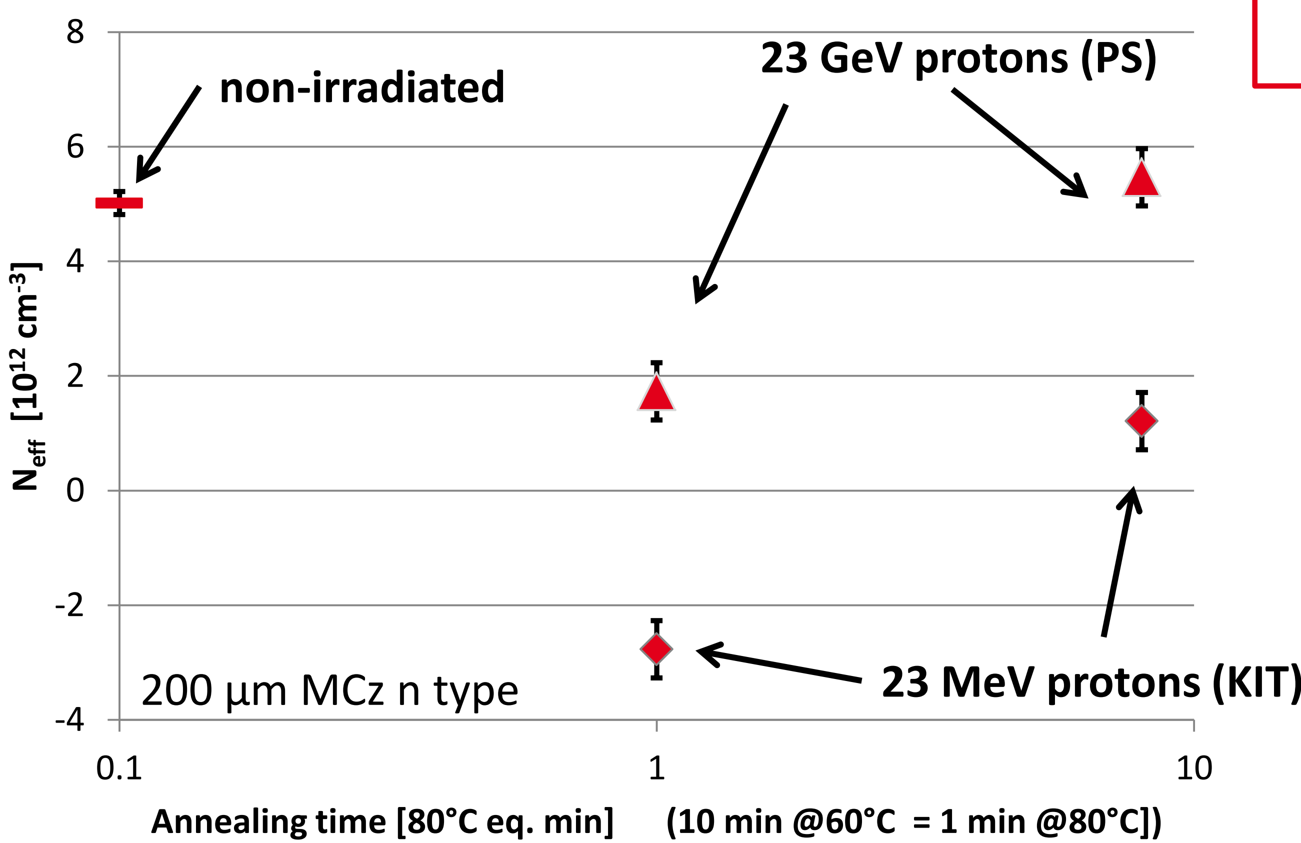
Combined study with both,

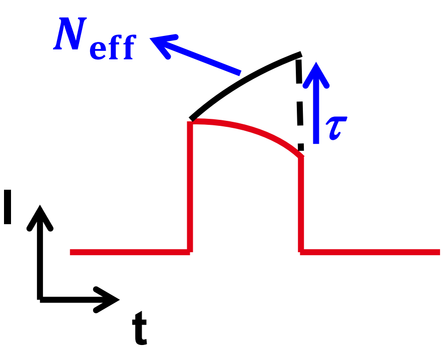
- classical TCT $\rightarrow I(t), CCE$
- and edge TCT $\rightarrow v_{dr}(x), E(x)$

within the frame work of the CMS HPK campaign.

N_{eff} from TCT pulses

N_{eff} at V=300 V extracted from I(t) (TCT, hole signal)





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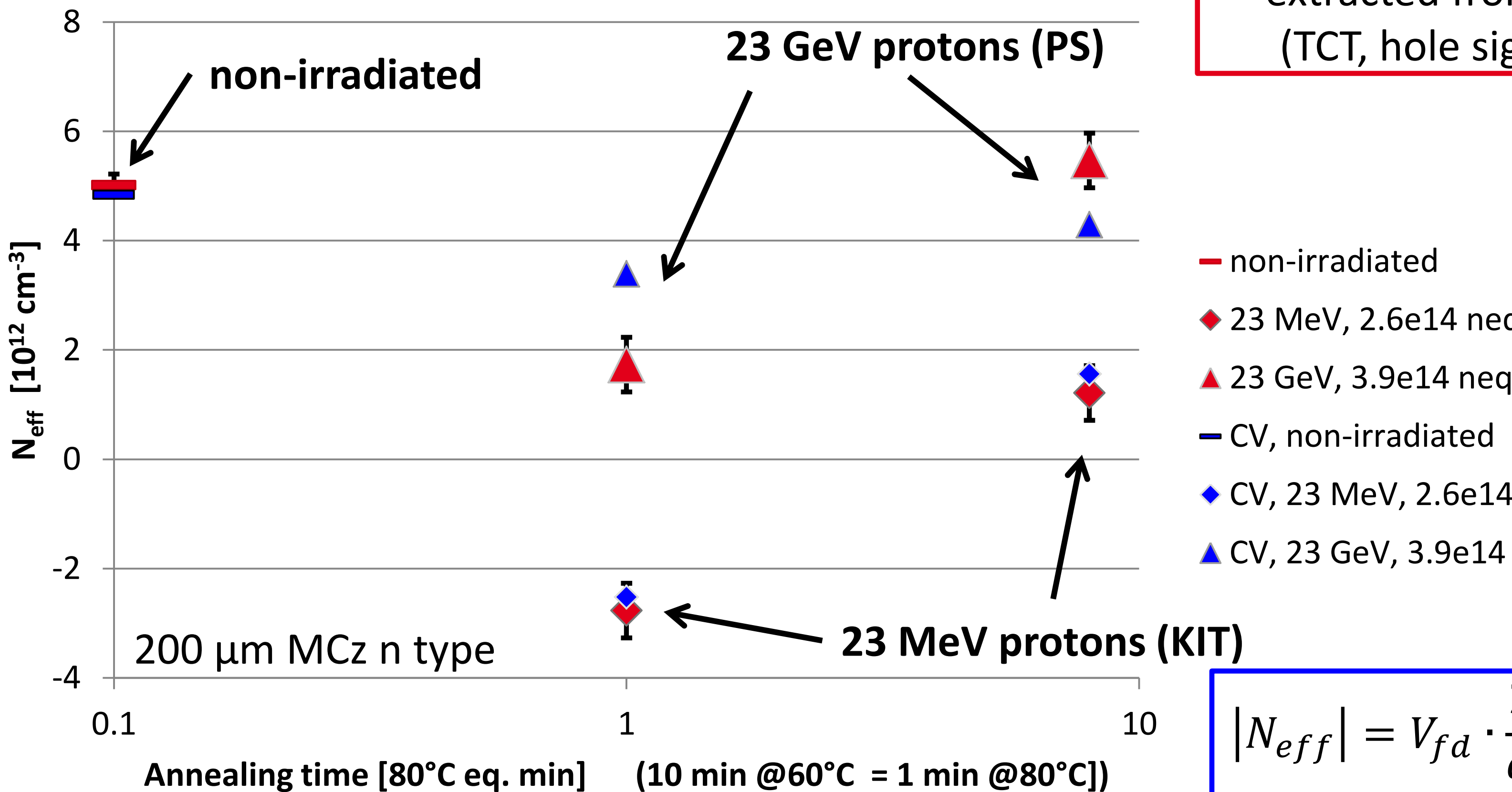
N_{eff} from TCT pulses and from CV



N_{eff} at V=300 V
extracted from I(t)
(TCT, hole signal)

$$|N_{eff}| = V_{fd} \cdot \frac{2\varepsilon\varepsilon_0}{d^2 q_0}$$

V_{fd} from CV (0°C, 1 kHz)
sign according to TCT

Model calculation

Electric field

$$|\nabla E| = \frac{q_0\ N_{eff}}{\varepsilon\ \varepsilon_0}$$

Drift velocity

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

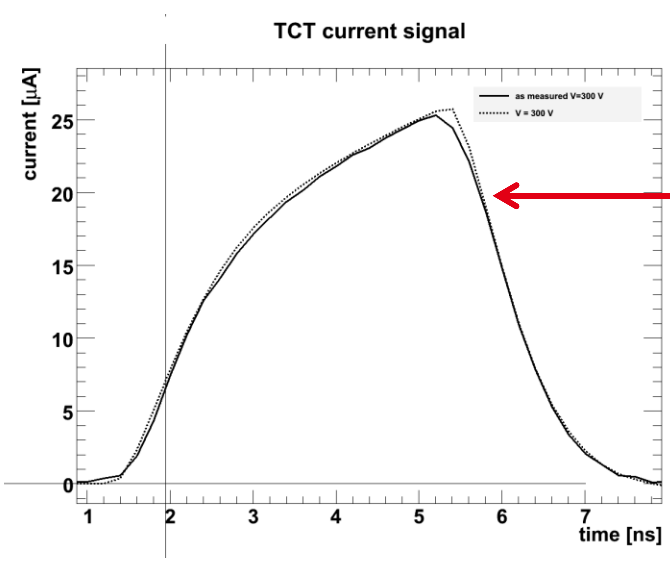
 # free carriers

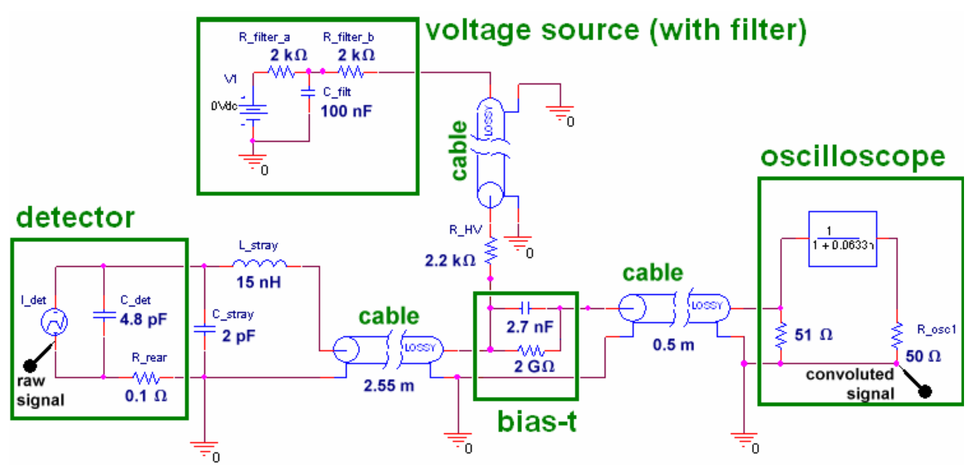
$$N(t) = N_0 \cdot \exp\left(\frac{t_0 - t}{\tau_{eff}}\right)$$

Induced current

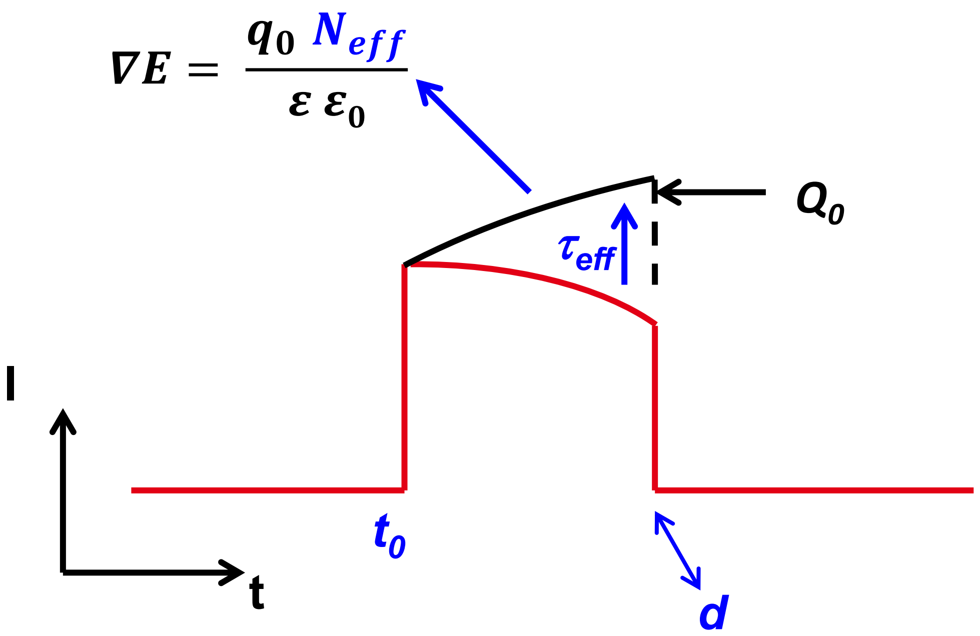
$$I(t) = \frac{q_0 N(t)}{d} v_{dr}(t)$$

Electronic circuit





Extraction of physical quantities



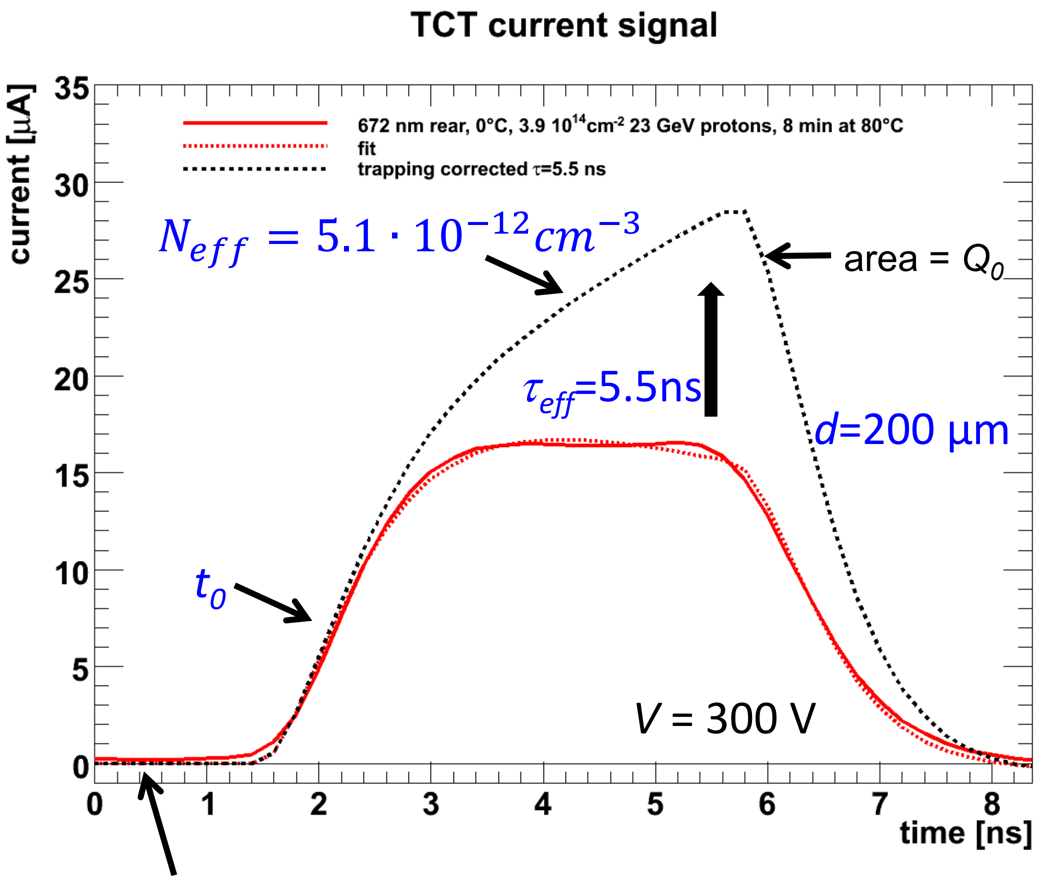
$$N(t) = N_0 \cdot \exp\left(\frac{t_0 - t}{\tau_{eff}}\right)$$

Reference diode with collected charge Q_0 => τ_{eff}

Extraction method: least χ^2 fit of model calculation to measured TCT pulse

model calculation with $N_0 = Q_0 / q_0$ drifting charge carriers at t=0

Least χ^2-fit results for MCz 200 µm, after $3.9 \cdot 10^{14}$ cm^{-2} 23GeV protons and 8 min @80°C



baseline before pulse:

$\sigma_i \approx 0.25$ µA

$$\chi^2 = \sum_{i=1}^{n} \frac{({I^{meas}}_i - {I^{calc}}_i)^2}{{\sigma_i}^2}$$

σ_i := 0.3 µA

$\Rightarrow$ least χ^2 = 35

Data points used for least χ^2 fit:

n = 35

4 free fit parameters: τ_{eff}, N_{eff}, t_0, d

$\Rightarrow$ degrees of freedom: ndf = 31

$$V_{fd} = |N_{eff}| \cdot \frac{d^2 q_0}{2\varepsilon\varepsilon_0} = 158\,V\ ?$$

V_{fd} and N_{eff} in the presense of double junction

TCT:

assuming const. space charge:

slope of the electric field at V > V_{fd} (e.g. 300 V)

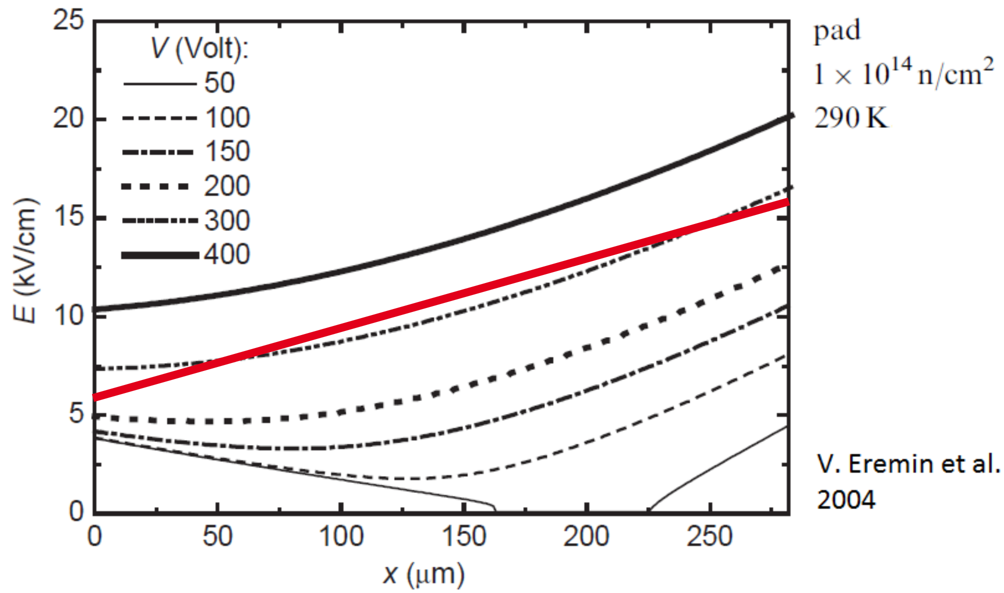
CV:

N_{eff} according to depletion behaviour at V_{fd} (< 150 V)

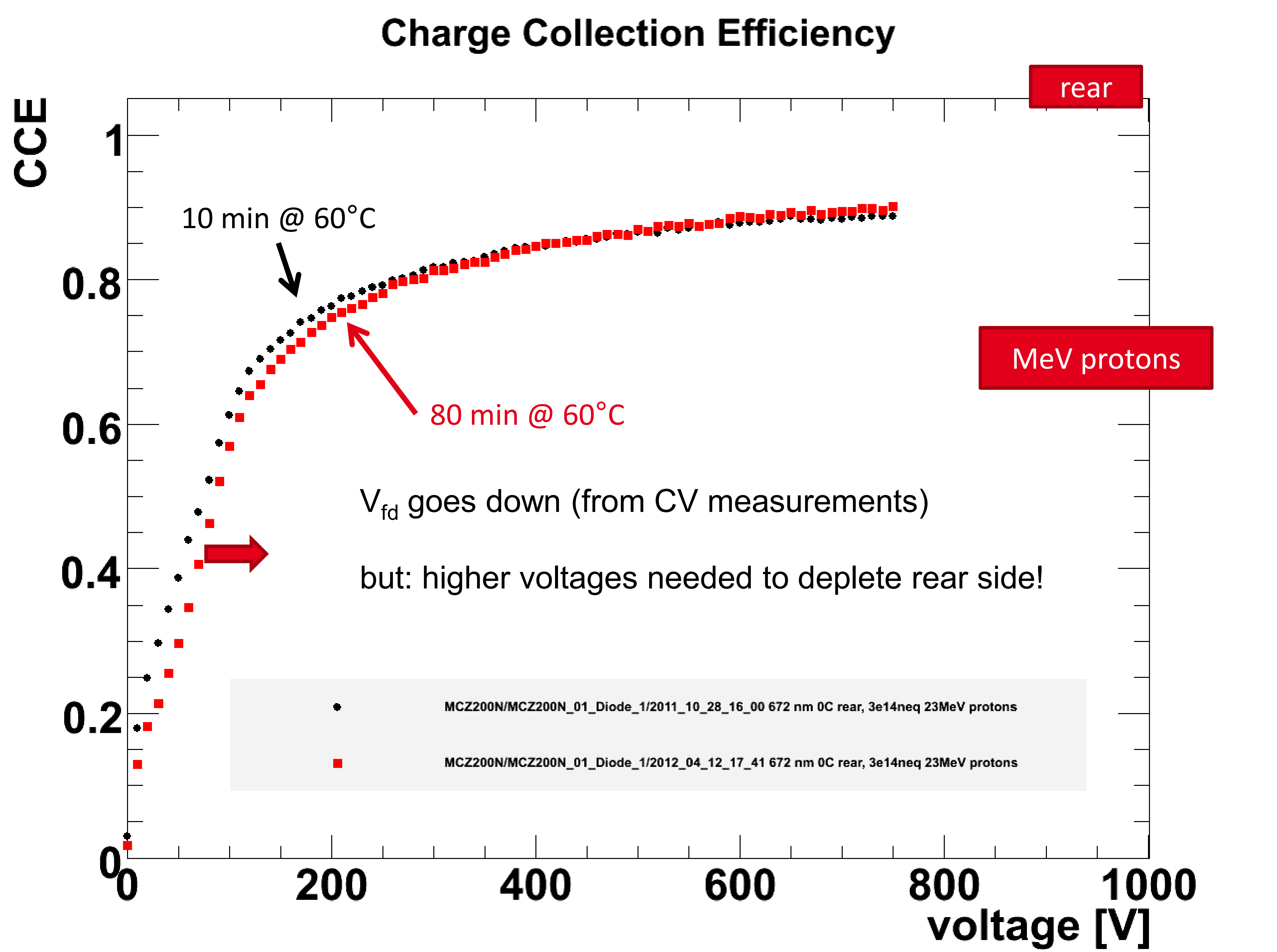
How to extract N_{eff}?

Or: what does N_{eff} mean if extracted via CV?

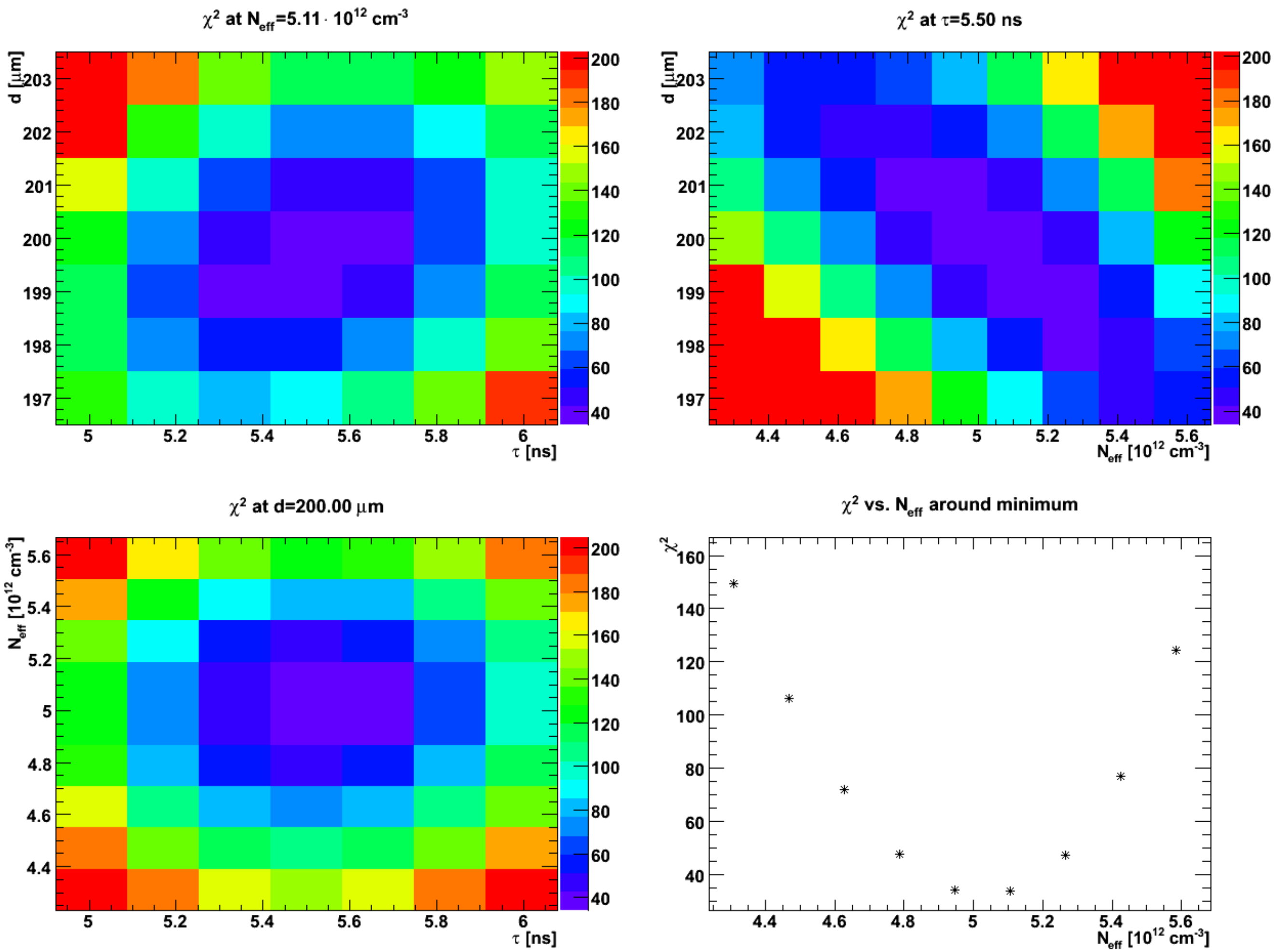
How to define the sign of N_{eff} ?



V_{fd} = 80 V ?
=>


Charge Collection Efficiency
rear
CCE
1
0.8
0.6
0.4
0.2
0
10 min @ 60°C
80 min @ 60°C
MeV protons
V_fd goes down (from CV measurements)
but: higher voltages needed to deplete rear side!
MCZ200N/MCZ200N_01_Diode_1/2011_10_28_16_00 672 nm 0C rear, 3e14neq 23MeV protons
MCZ200N/MCZ200N_01_Diode_1/2012_04_12_17_41 672 nm 0C rear, 3e14neq 23MeV protons
0
200
400
600
800
1000
voltage [V]

χ^2 matrices for MCz 200 µm after $4\cdot10^{14}$ cm^{-2} 23 GeV protons, 8 min @ 80°C



N_{eff} <-> d correlated

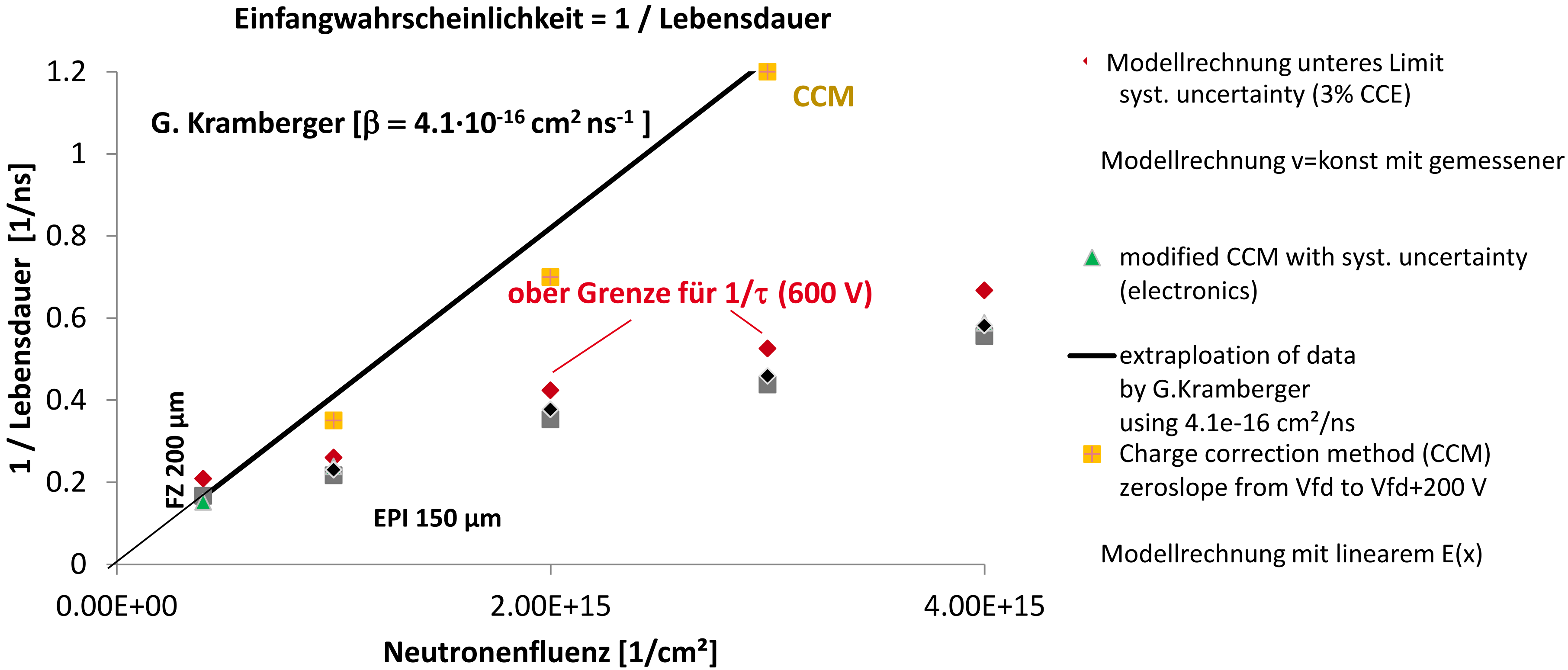
d ≈ 200 µm
(~198 µm from CV)

Additional
uncertainty in Q_0

N_{eff} [10^{12} cm^{-3}]
= $5.1 \pm 0.3_{stat} \pm 0.3_{Q0}$

? V_{fd} [V]
= $158 \pm 10_{stat} \pm 10_{Q0}$

Vergleich von verschiedenen Methoden

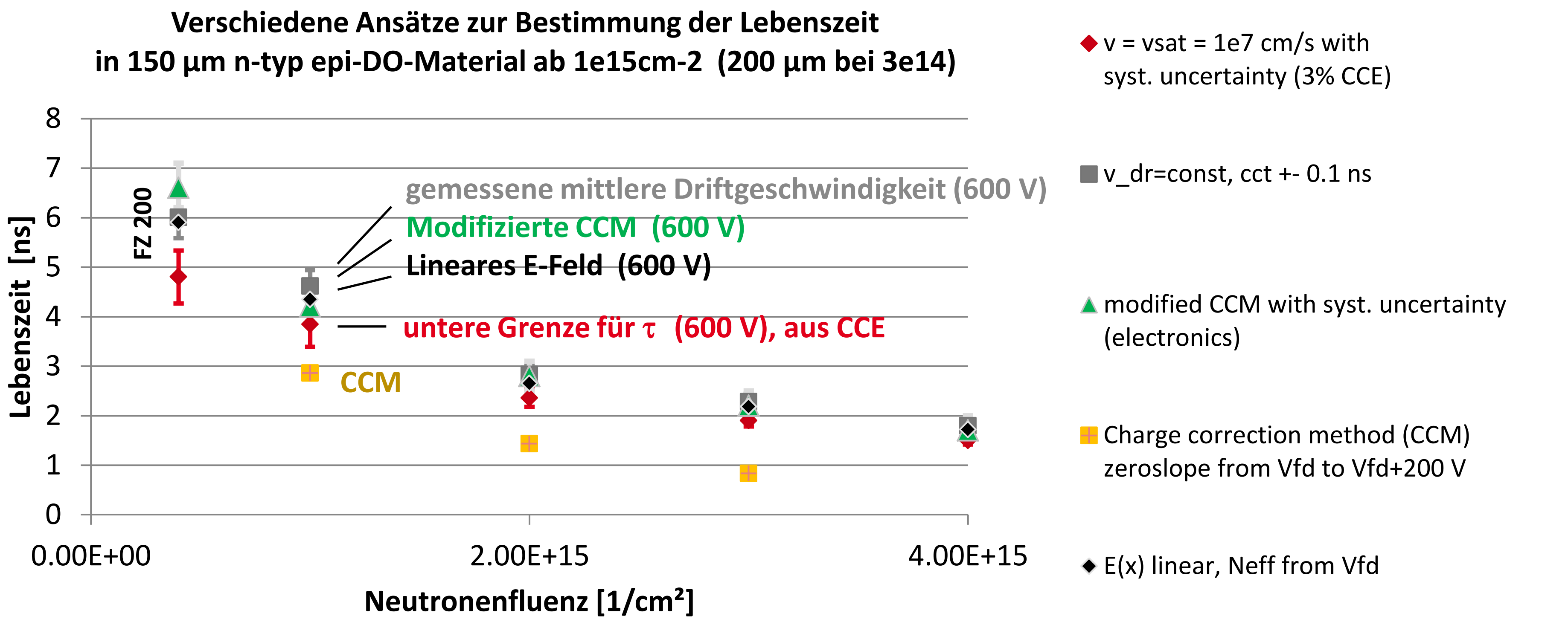


Up to fluences of $2 \cdot 10^{14}$ cm^{-2} according to G. Kramberger*: $1/\tau = \beta \phi$

here: $1/\tau$ at fixed voltage not proportional to fluence!

* G. Kramberger. Doctoral Thesis, Ljubljana, 2001.

Vergleich von verschiedenen Methoden



Classical CCM gives life times incompatible with CCE.

All other methods give consistant results for life time τ, max. difference ~ 15 %.

$\Delta\tau|_{CCE} > \Delta\tau|_{method}$ => **exact knowledge on electric field not neccessary to extract life time**

HPK-campaign, mixed irradiation

HPK-campaign mixed irradiation

with protons and neutrons according to expected ratio between charged and neutral hadrons. So far: 23 MeV protons from Karlsruhe (KIT)

Type inversion in MCz n-type material after 23 MeV proton irradiation observed (not expected). Effect due to the **proton energy**?

$|N_{eff}|$ may be extracted from CV measurements via **full depletion voltage V_{fd}.**

For non-irradiated diodes: well understood

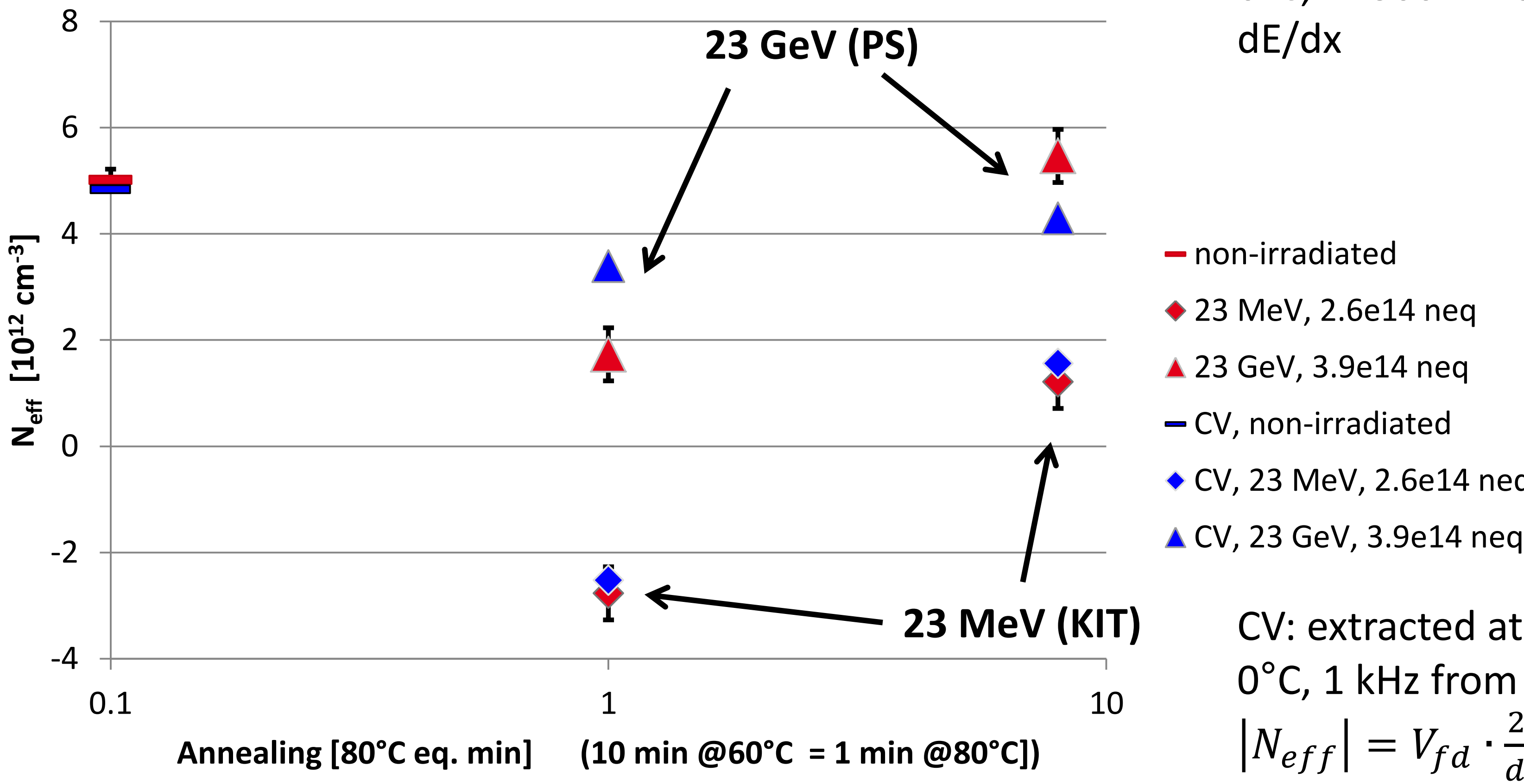
$$V_{fd} = |N_{eff}| \cdot \frac{d^2 q_0}{2\varepsilon\varepsilon_0}$$

- but: only the absolute value $|N_{eff}|$ is accessible

For irradiated diodes **further limitations**:

- depletion behavior unclear (double junction), frequency and temperature dependent
- $\nabla E = \nabla E$ (V) (space charge is voltage dependent)

Comparison of N_{eff} for MCz n type



TCT: extracted at 0°C, V=300 V from dE/dx

CV: extracted at 0°C, 1 kHz from V_{fd}

$$\left|N_{eff}\right| = V_{fd} \cdot \frac{2\varepsilon\varepsilon_0}{d^2 q_0}$$

sign according to TCT fit result!

V_{fd} and N_{eff} in the presense of double junction

TCT:

assuming const. space charge:

slope of the electric field at V > V_{fd} (e.g. 300 V)

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N_{eff} according to depletion behaviour at V_{fd} (< 150 V)

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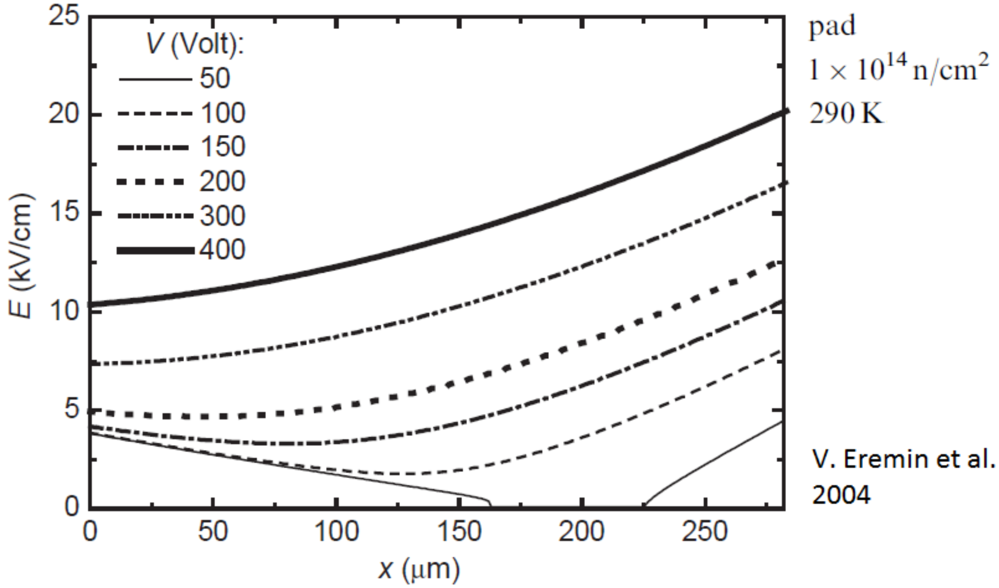


V. Eremin et al. 2004

V_{fd} = 80 V ?
=>

Conclusions

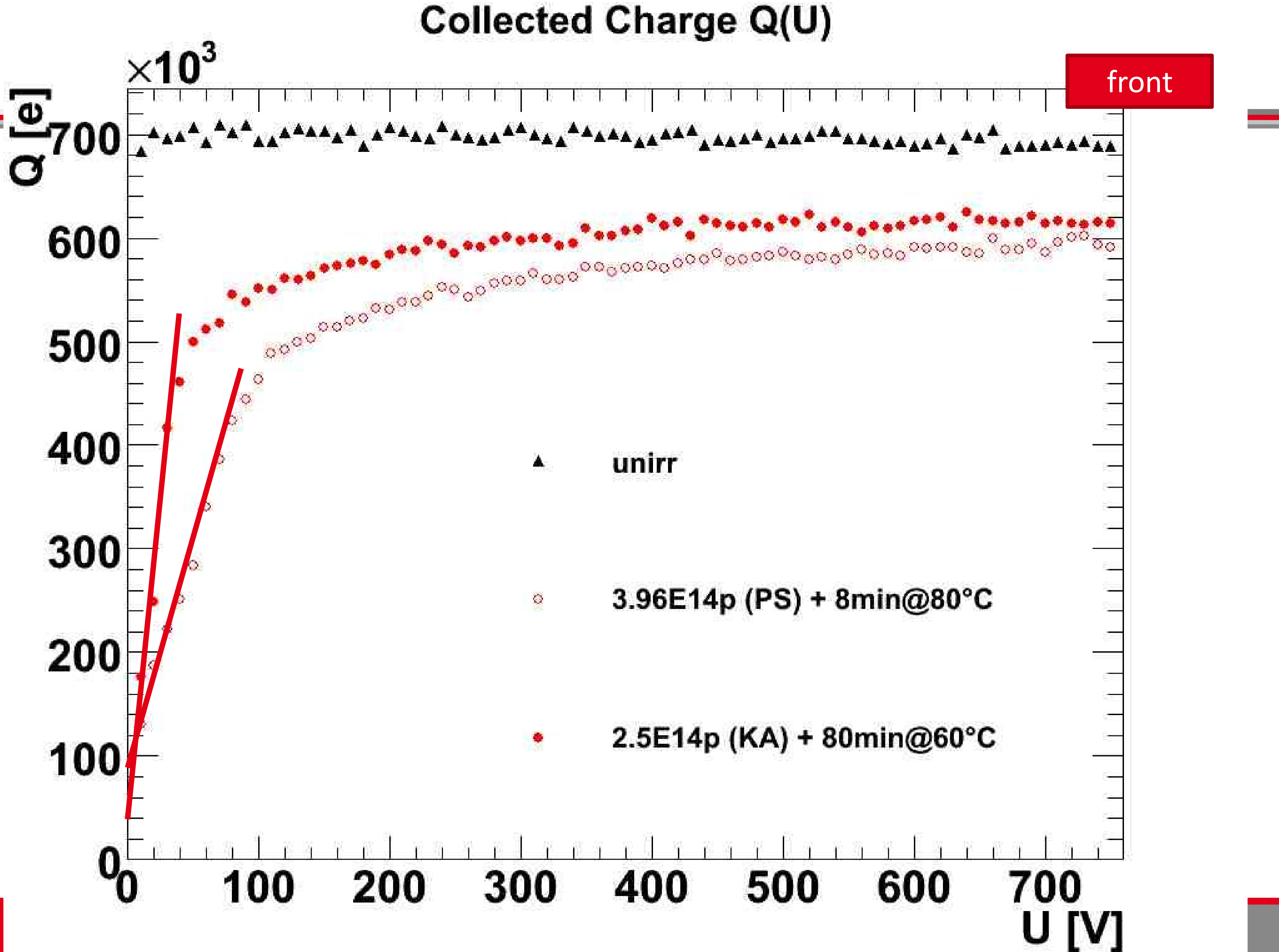
N_{eff} could be extracted from TCT current measurement and is found to strongly depend on:

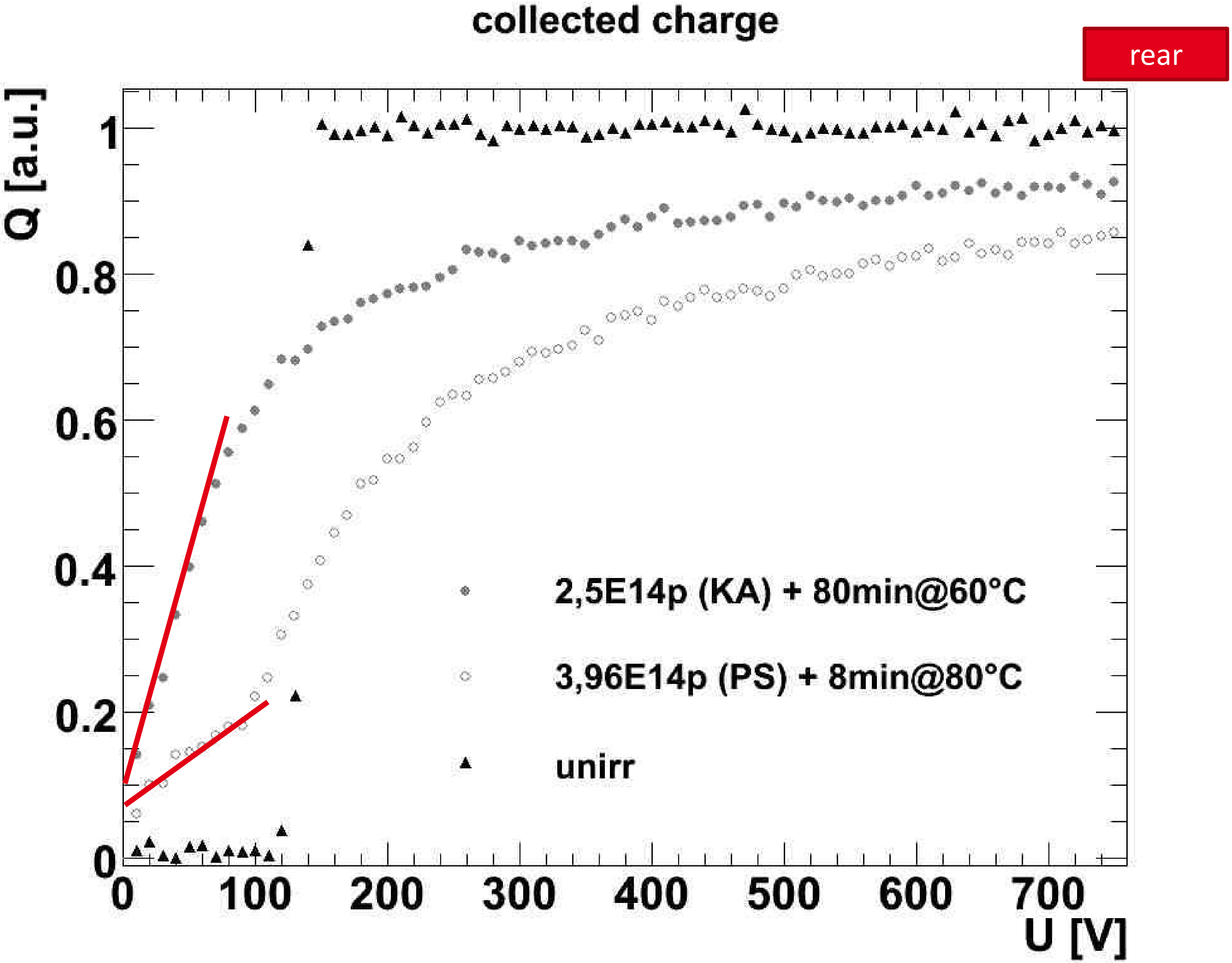
- annealing (1 min to 10 min @ 80 °C -> $\Delta N_{eff} = 3.5 \cdot 10^{12}$ cm^{-3})
- proton energy (23 GeV vs. 23 MeV)

Differences to $|N_{eff}|$ extracted from CV measurements observed

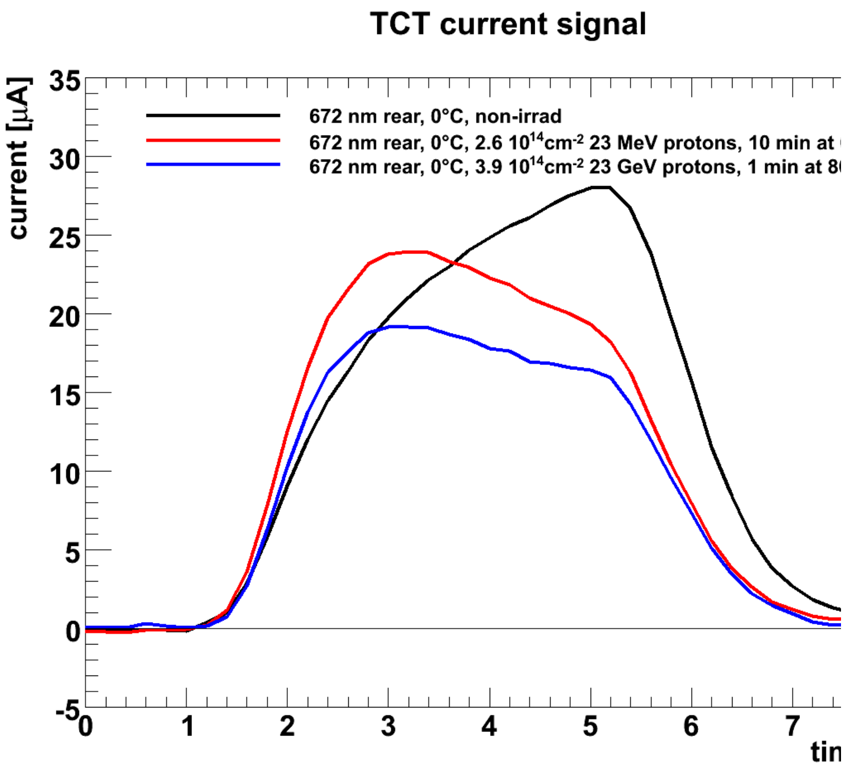
$\Rightarrow$ **open questions:**

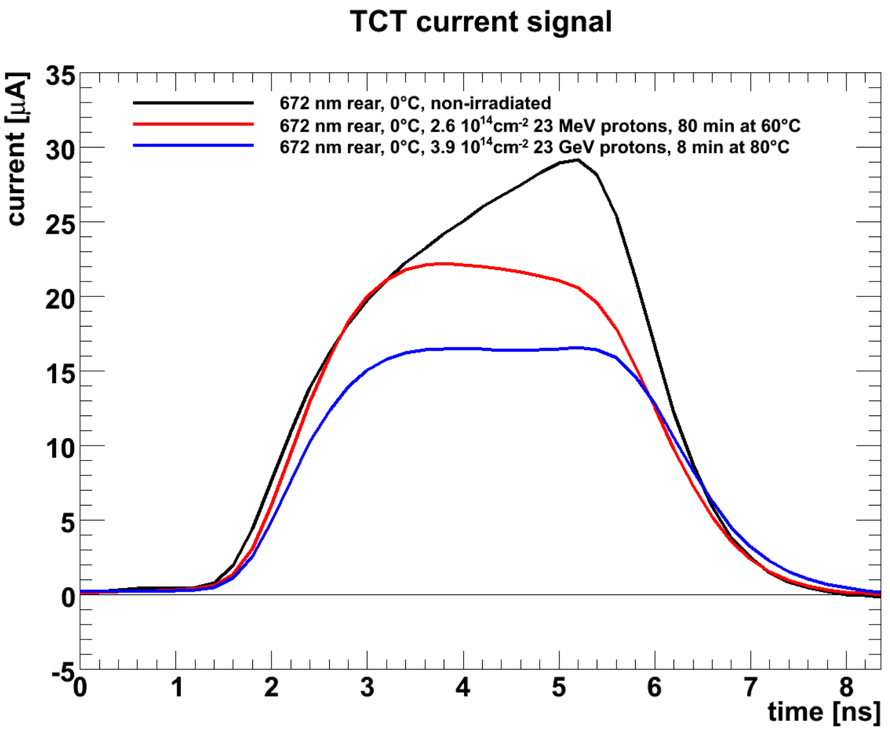
- Impact of a voltage dependent space charge on CV and TCT interpretation? (depletion behaviour unclear, TCAD simulation of double junction and CV?)
- How good is the assumption τ = const for given voltage, i.e. position dependence $\tau(x)$ negligible? (combined edge-TCT / TCT study)
- Systematic impact of electronic circuit? (description improvable?)

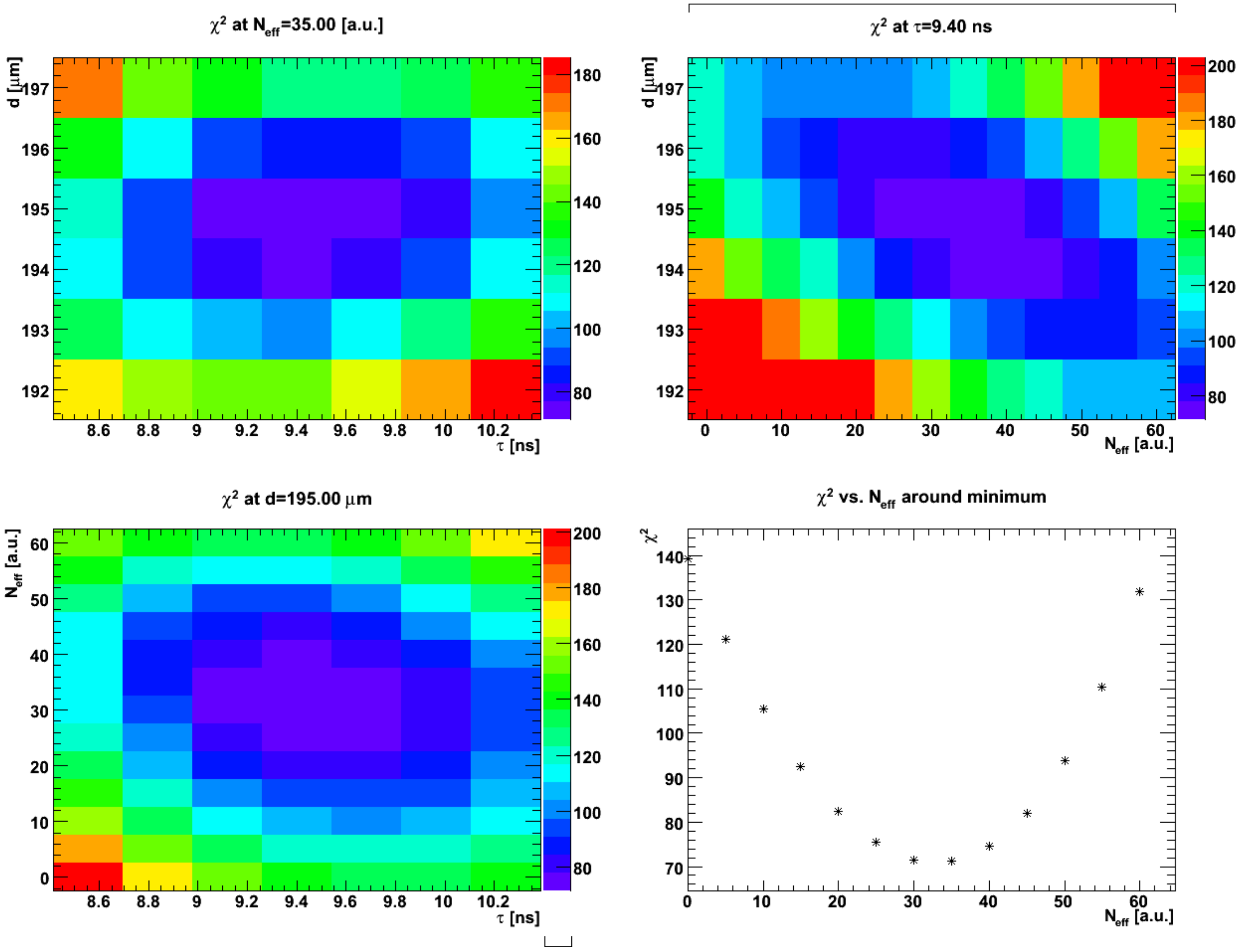

Collected Charge Q(U)
front
×10³
Q [e]
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
U [V]
unirr
3.96E14p (PS) + 8min@80°C
2.5E14p (KA) + 80min@60°C

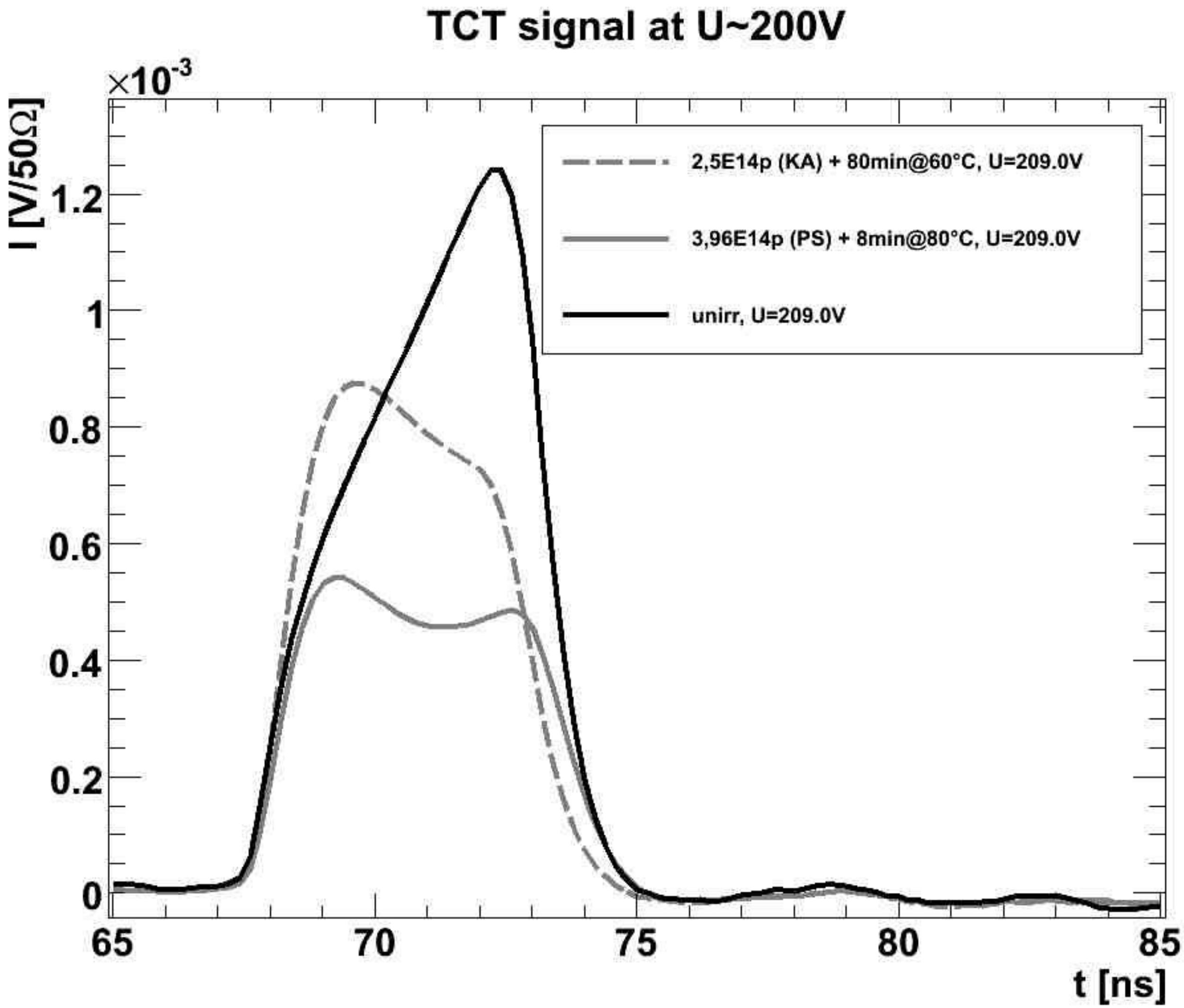


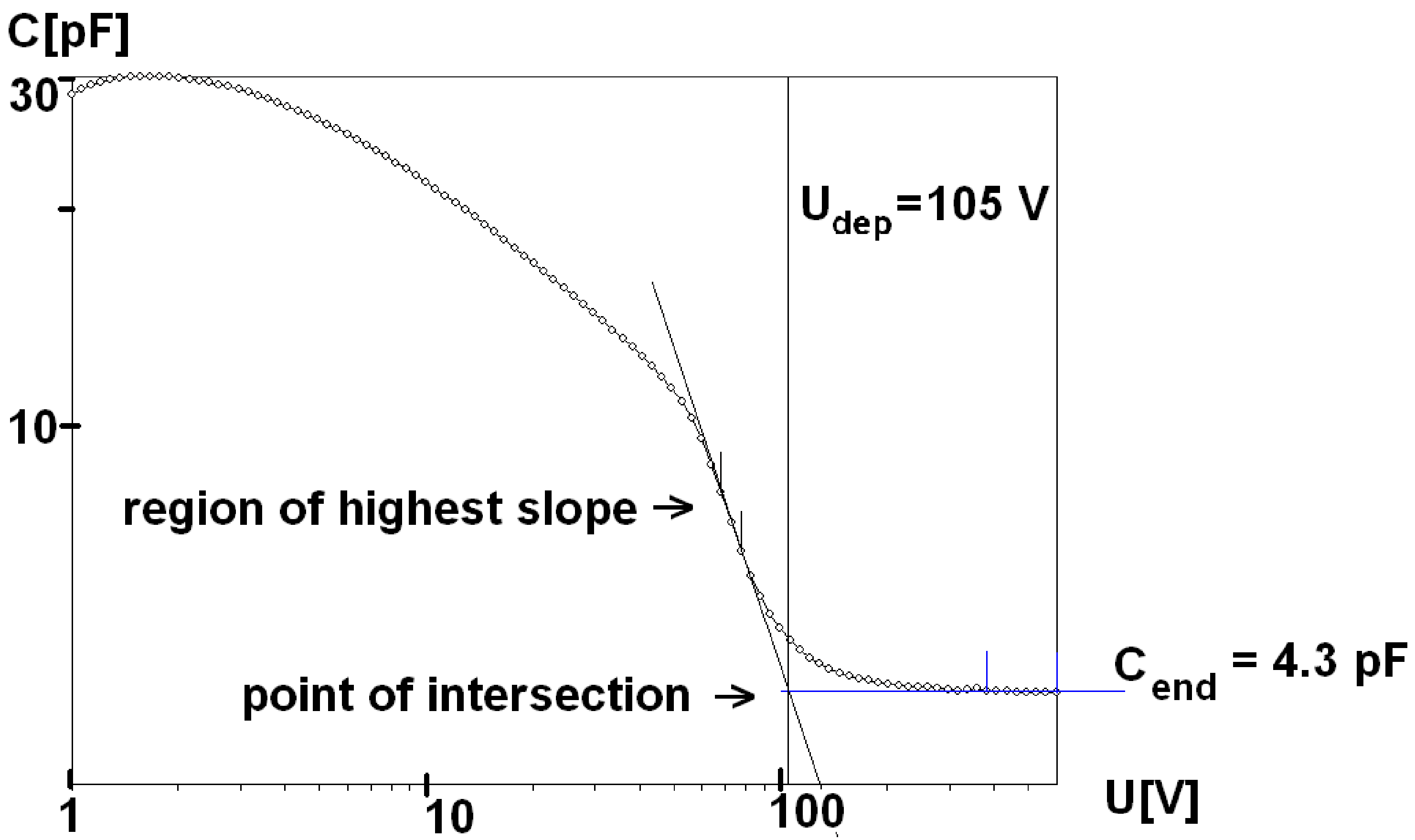
collected charge
rear
Q [a.u.]
U [V]
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
2,5E14p (KA) + 80min@60°C
3,96E14p (PS) + 8min@80°C
unirr


TCT current signal
current [μA]
672 nm rear, 0°C, non-irrad
672 nm rear, 0°C, 2.6 10^14cm^-2 23 MeV protons, 10 min at
672 nm rear, 0°C, 3.9 10^14cm^-2 23 GeV protons, 1 min at 8
tin


TCT current signal
current [μA]
672 nm rear, 0°C, non-irradiated
672 nm rear, 0°C, 2.6 10^14cm^-2 23 MeV protons, 80 min at 60°C
672 nm rear, 0°C, 3.9 10^14cm^-2 23 GeV protons, 8 min at 80°C
time [ns]


χ^2 at N_{eff}=35.00 [a.u.]
d [μm]
τ [ns]
χ^2 at τ=9.40 ns
d [μm]
N_{eff} [a.u.]
χ^2 at d=195.00 μm
N_{eff} [a.u.]
τ [ns]
χ^2 vs. N_{eff} around minimum
χ^2
N_{eff} [a.u.]


TCT signal at U~200V
×10^-3
I [V/50Ω]
1.2
1
0.8
0.6
0.4
0.2
0
65
70
75
80
85
t [ns]
2,5E14p (KA) + 80min@60°C, U=209.0V
3,96E14p (PS) + 8min@80°C, U=209.0V
unirr, U=209.0V


C[pF]
30
10
Udep=105 V
region of highest slope →
point of intersection →
Cend = 4.3 pF
1
10
100
U[V]

Voltage dependence

8@80°C

200 V	N_{eff} [10^{12} cm^{-3}] = 4
300 V	N_{eff} [10^{12} cm^{-3}] = 5.1 ± 0.3_{stat} ± 0.3_{Q0} (d = 200 µm)
400 V	N_{eff} [10^{12} cm^{-3}] = 5.7 for d = 200 µm fixed
	6.5 for d = 196 µm free
700 V	fit not possible with given electronic circuit & drift model
	-> to optimize!