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Extraction of the effective doping concentration N_{eff} from TCT measurements

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Overview

Introduction / Motivation

Transient current technique (TCT)

- Setup
- Model calculation of TCT pulses

TCT pulse analysis and least χ^2 fit

Results

Conclusion

Motivation

10 x higher radiation damage after LHC high luminosity upgrade

$\Rightarrow$ radiation hard material needed

Radiation damage:

Current generation	-> Increase of leakage current, noise, heat
Trapping centers	-> Charge losses, signal reduction
Change in N_{eff}	-> Increase of full depletion voltage, type inversion
	signal reduction, impact on resolution ?

This talk:

focus on change in effective doping concentration $N_{eff} = N_{donors} - N_{acceptors}$

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

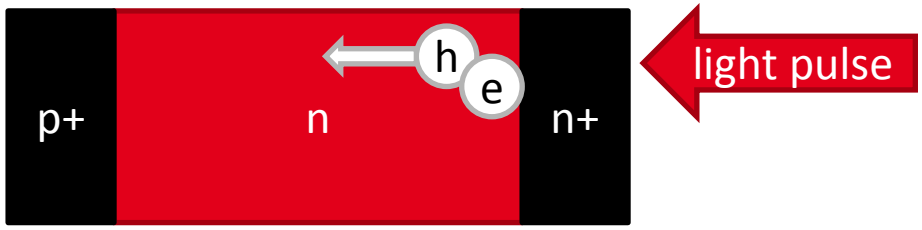
$$V_{fd} = |N_{eff}| \cdot \frac{d^2 q_0}{2\varepsilon\varepsilon_0}$$

- 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)

Transient current technique (TCT)



red laser light pulse:

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

$\Rightarrow$ induced current (pad sensor) : $I(t) = \frac{q_0 N(t)}{d} \mu(E) \cdot E$

readout:

- digital oscilloscope (bandwidth 1 GHz, 512 averages)
- 10 x Phillips current amplifier
- also relevant: diode capacitance of ~14 pF for used diodes with d=200 µm

Model calculation

Electric field

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

Drift velocity

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

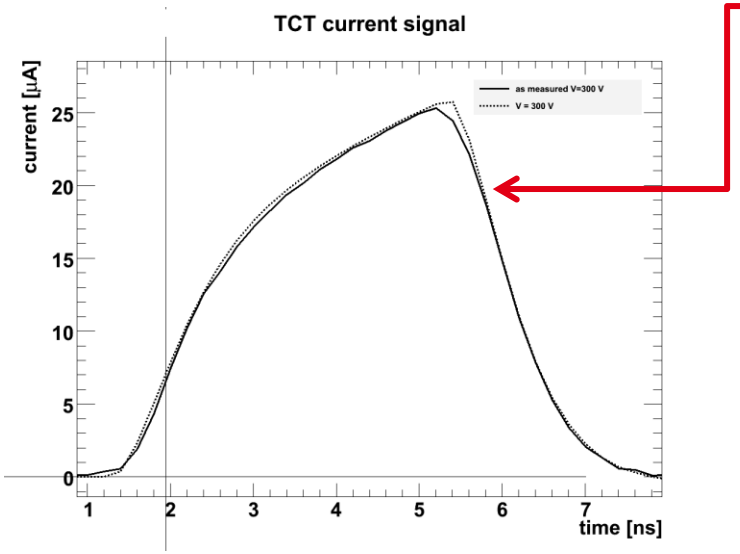
free carriers

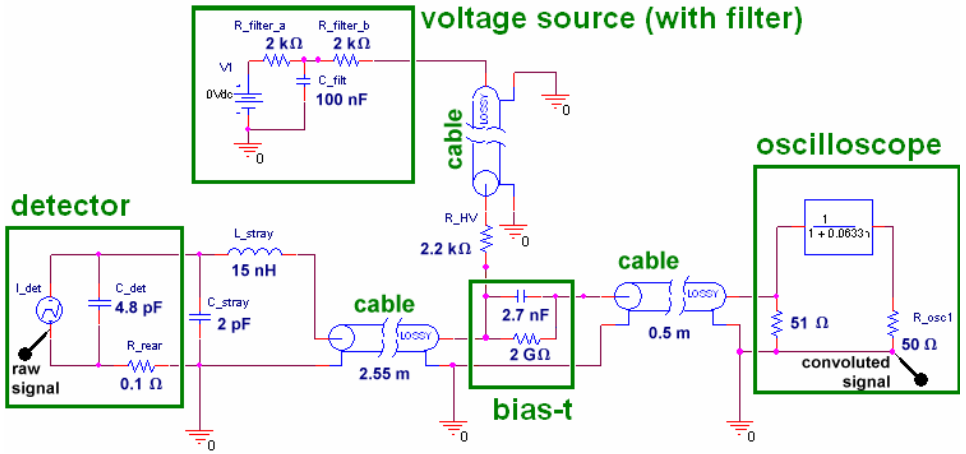
$$N(t) = N_0 \cdot \exp\left(\frac{t_0 - t}{\tau_{eff}}\right)$$

Induced current

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

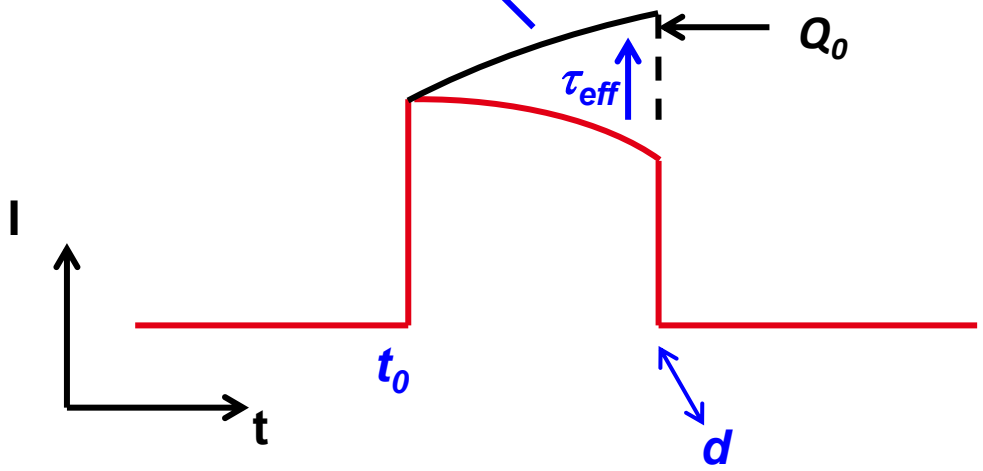
Electronic circuit





Extraction of physical quantities

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



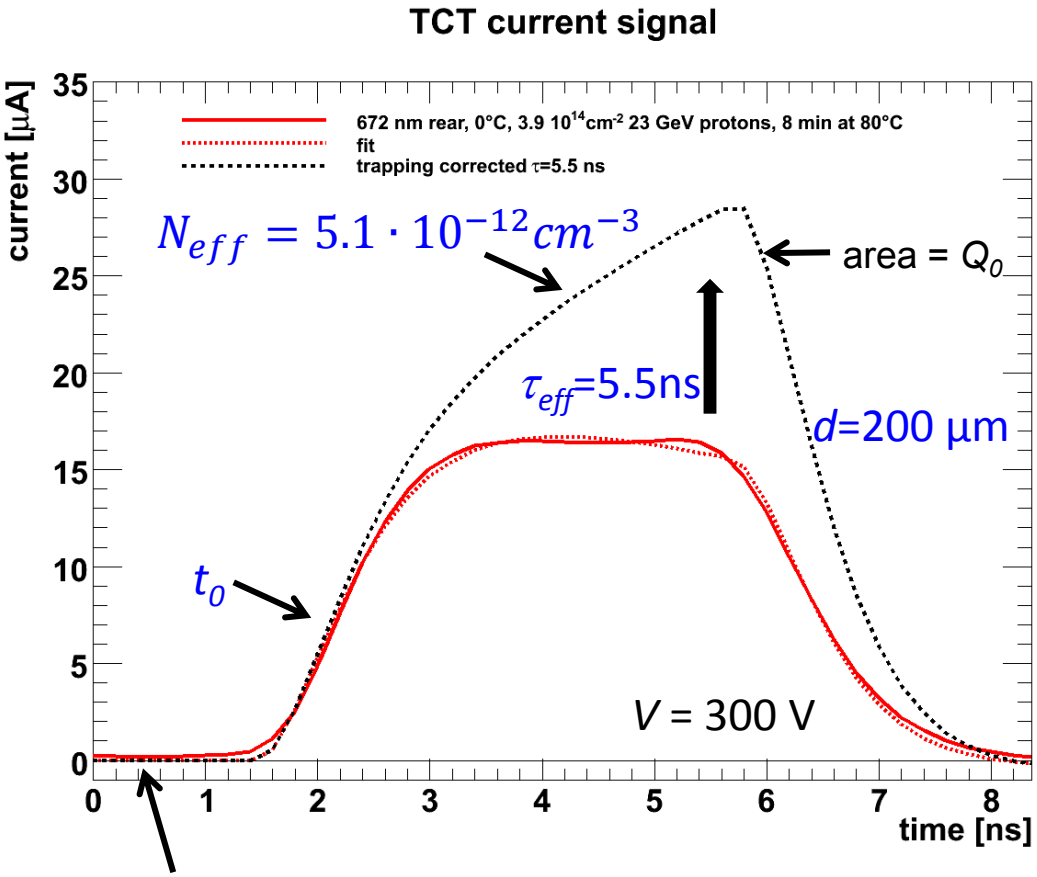
$$N(t) = N_0 \cdot \exp\left(\frac{t_0 - t}{\tau_{eff}}\right)$$

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

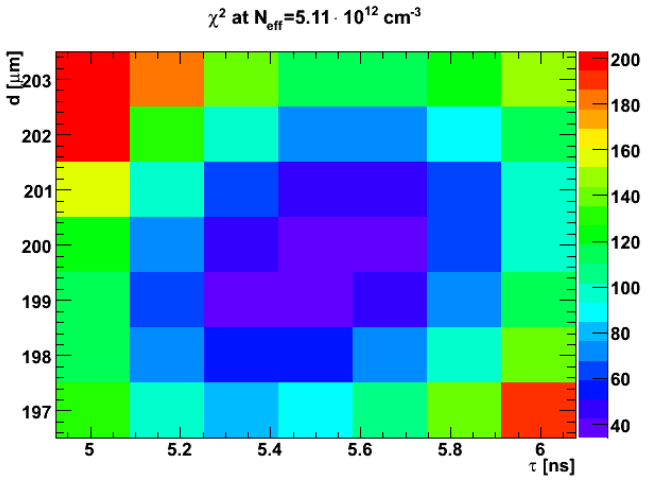
$\Rightarrow$ least χ^2 = 35

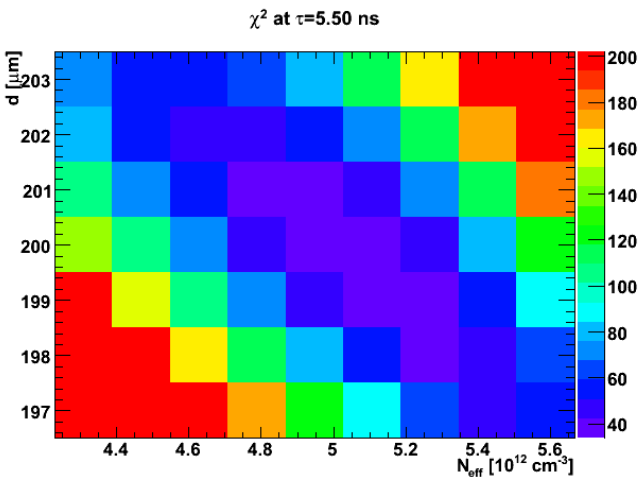
Data points used for least χ^2 fit:
n = 35
4 free fit parameters: τ_{eff}, N_{eff}, t_0, d

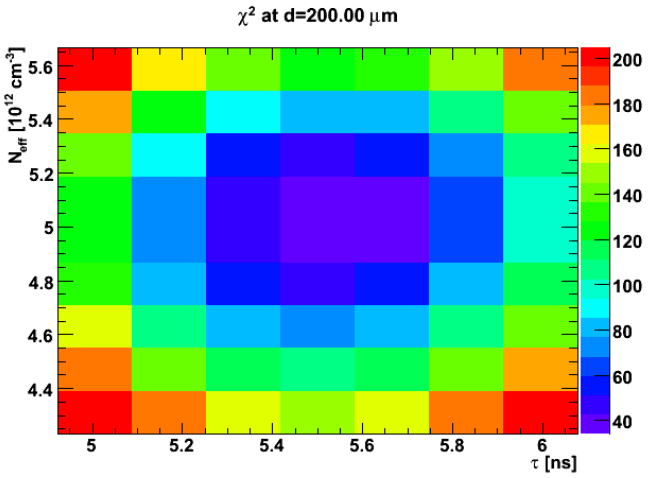
$\Rightarrow$ degrees of freedom: ndf = 31

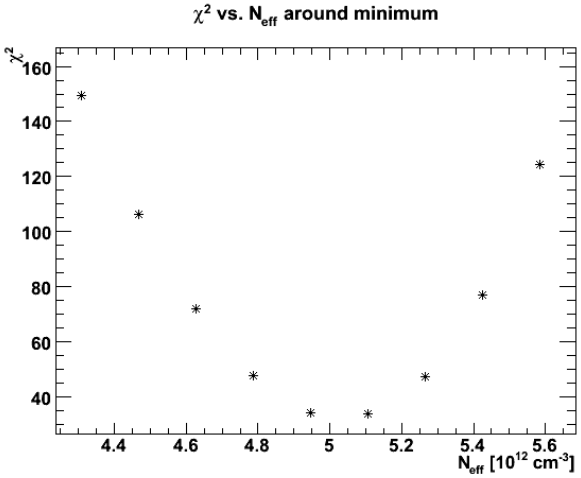
$$V_{fd} = |N_{eff}| \cdot \frac{d^2 q_0}{2\varepsilon\varepsilon_0} = 158\,V\ ?$$

χ^2 matrices for MCz 200 µm after $4 \cdot 10^{14}$ 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]
$= 158 \pm 10_{stat} \pm 10_{Q0}$

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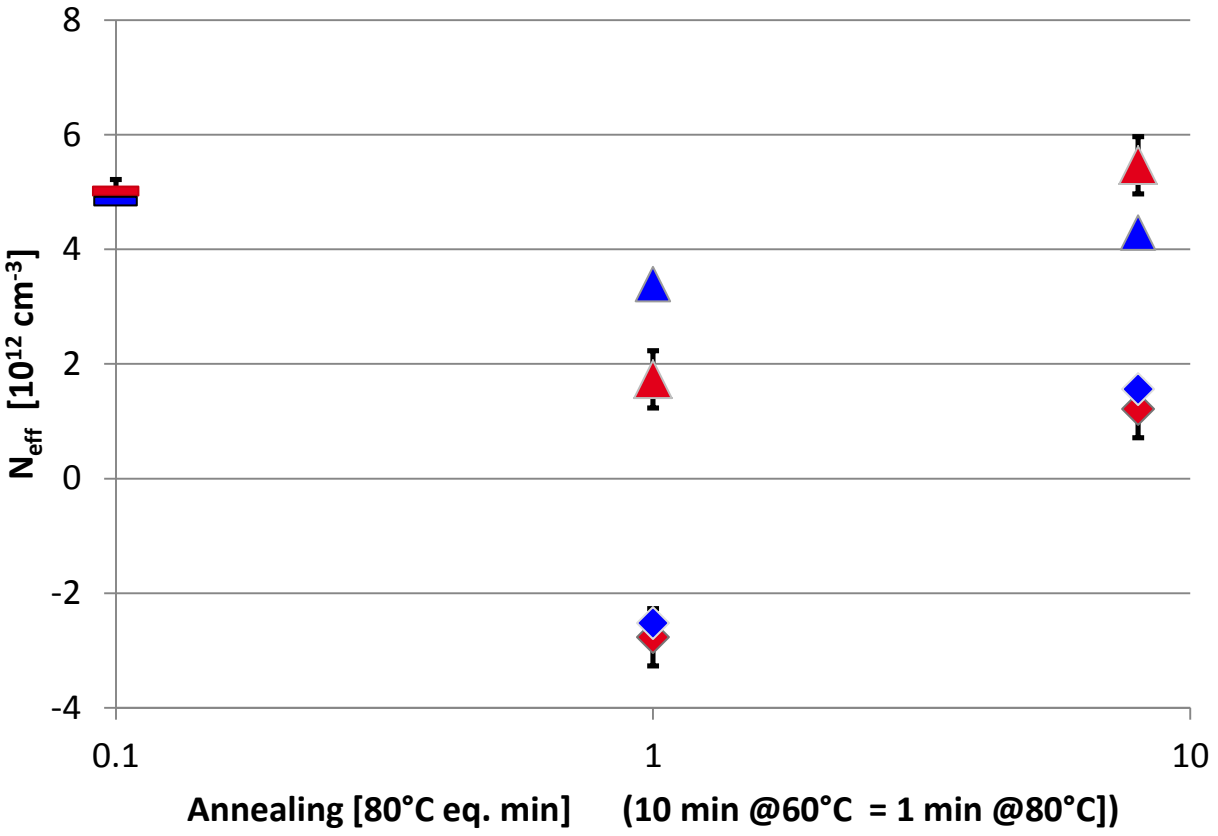
Comparison of N_{eff} for MCz n type



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

- non-irradiated
- 23 MeV, 2.6e14 neq
- 23 GeV, 3.9e14 neq
- CV, non-irradiated
- CV, 23 MeV, 2.6e14 neq
- CV, 23 GeV, 3.9e14 neq

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

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

+ arbitrary sign!

Conclusions

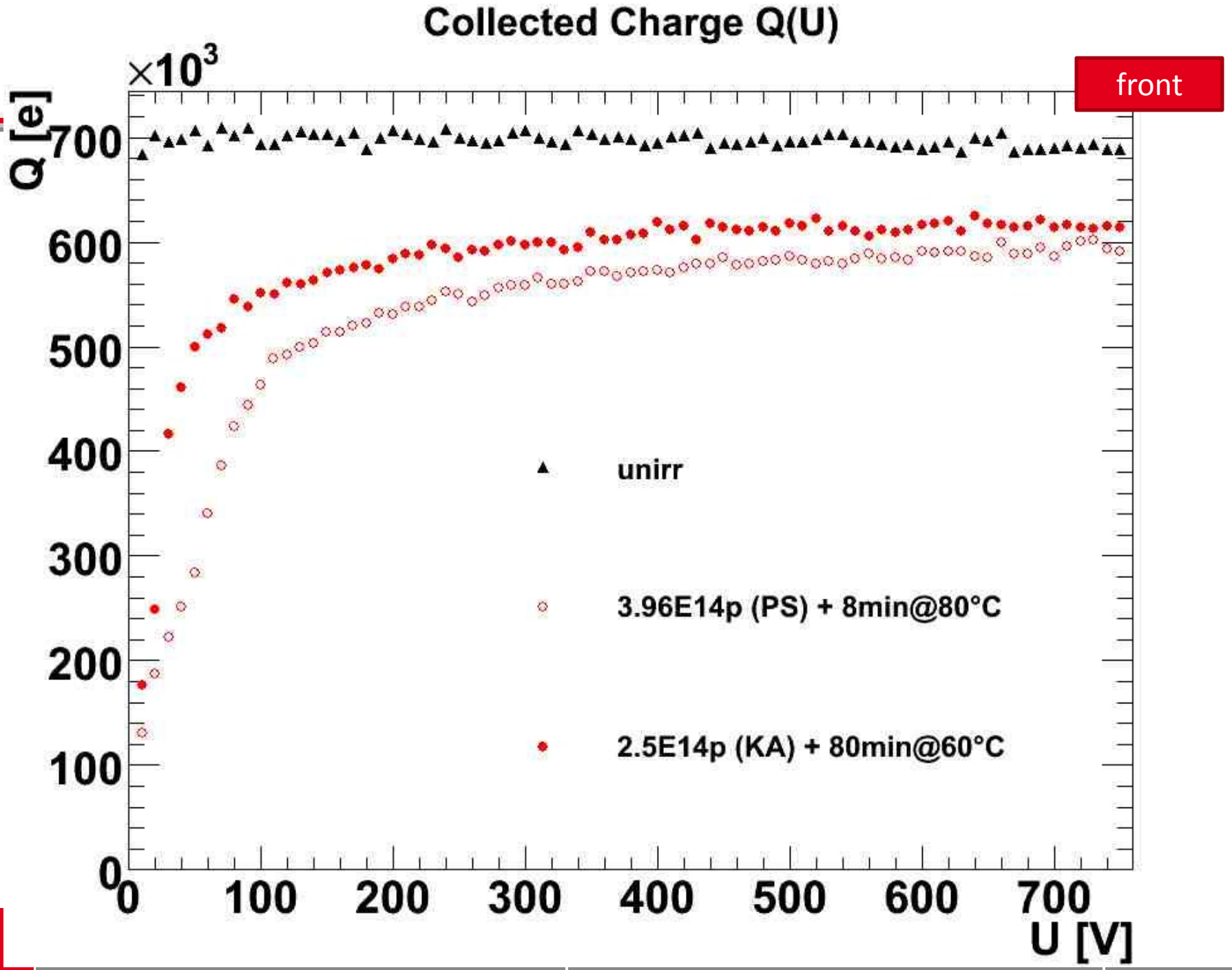
N_{eff} could be extracted from TCT current measurement and is found to strongly depend on:

- 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

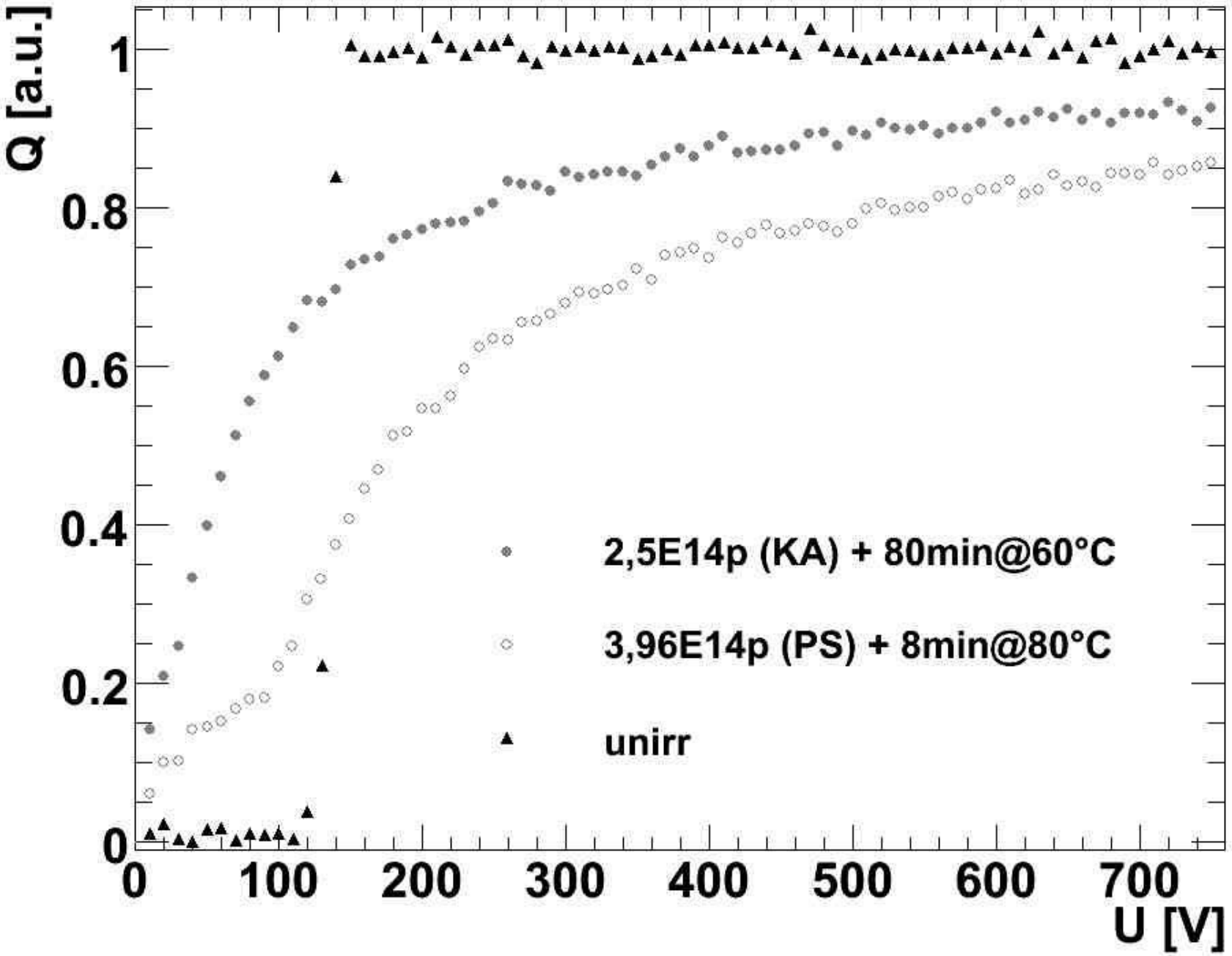
$\Rightarrow$ **open questions:**

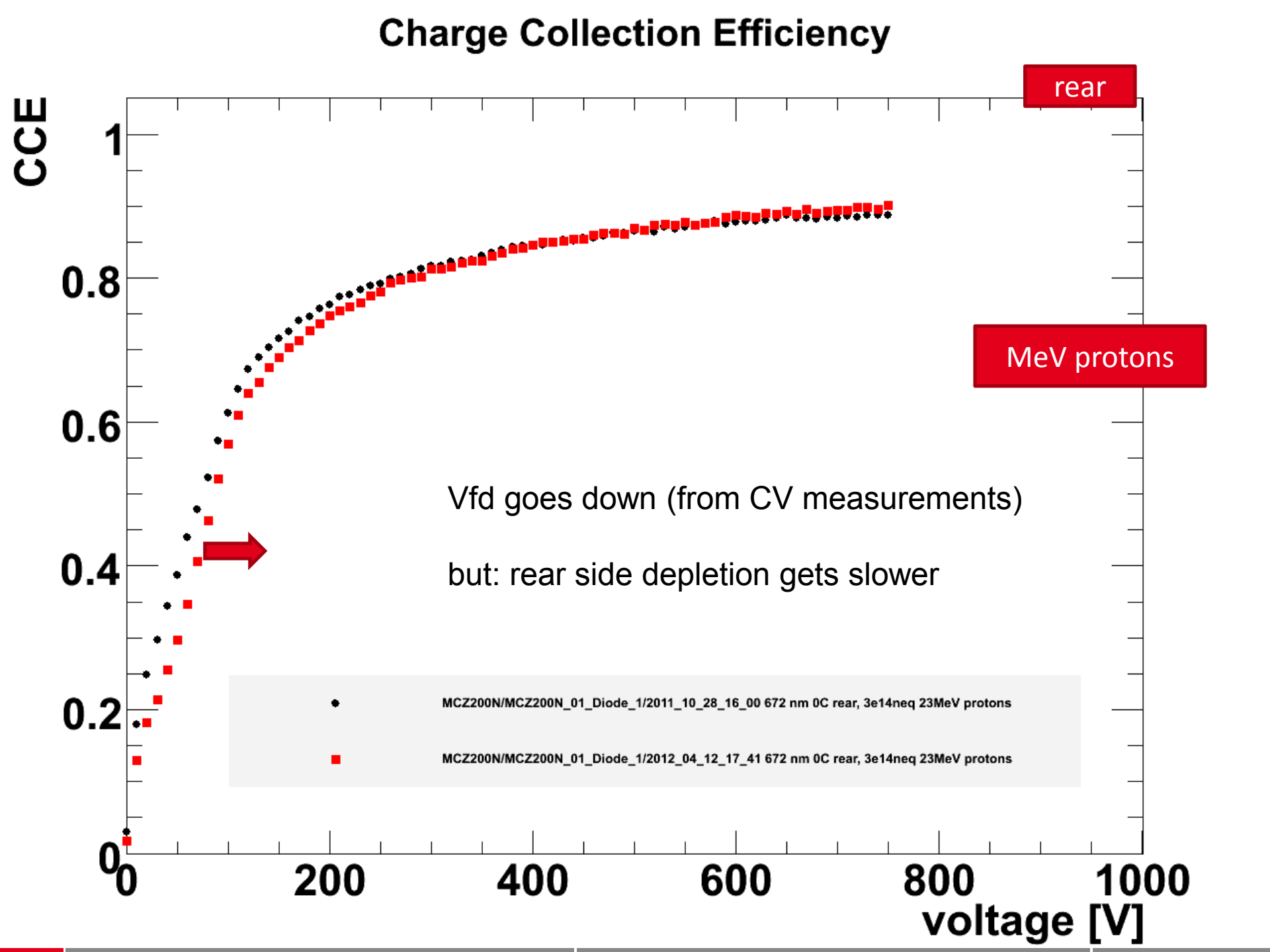
- Impact of a voltage dependent space charge on CV and TCT interpretation? (depletion behaviour unclear, TCAD simulation of double junction and CV?)
- How good is the assumption τ = const for given voltage, i.e. position dependence $\tau(x)$ negligible? (combined edge-TCT / TCT study)
- Systematic impact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

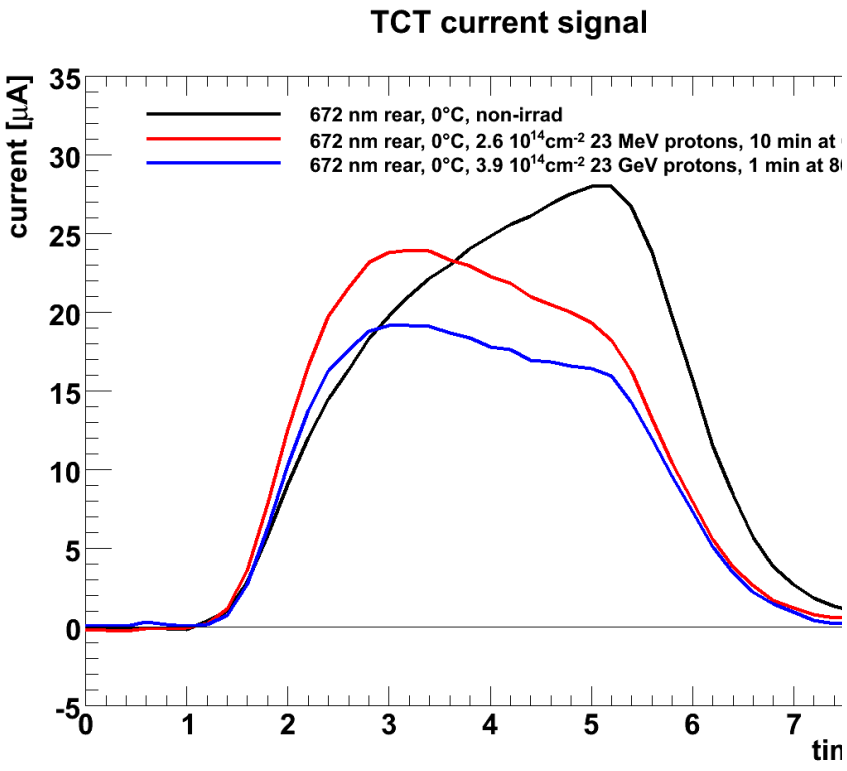

Collected Charge Q(U)
front
×10^3
Q [e]
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
U [V]
unirr
3.96E14p (PS) + 8min@80°C
2.5E14p (KA) + 80min@60°C

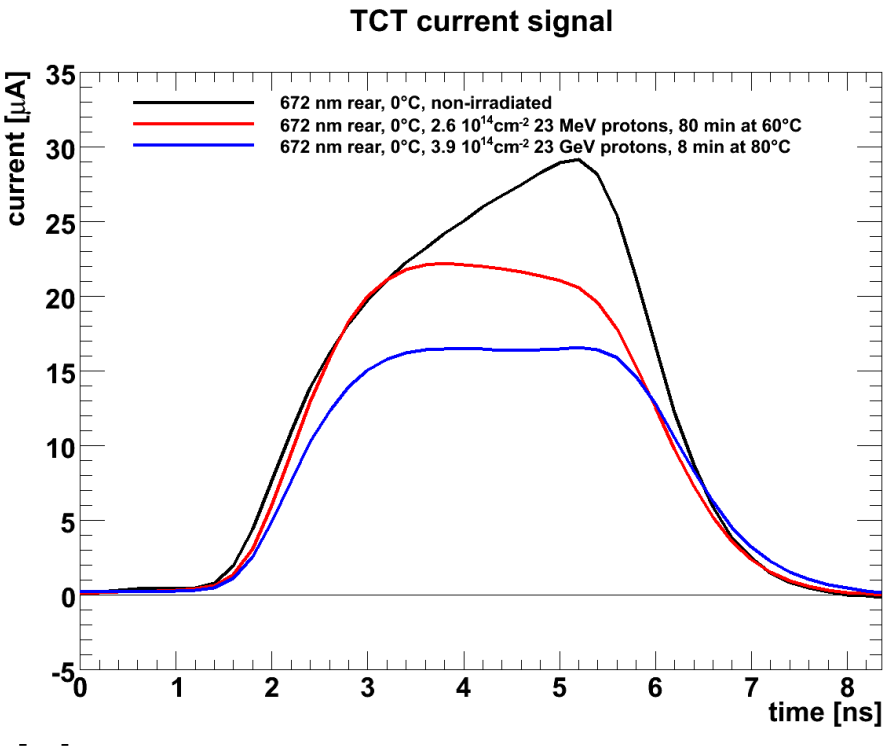
collected charge

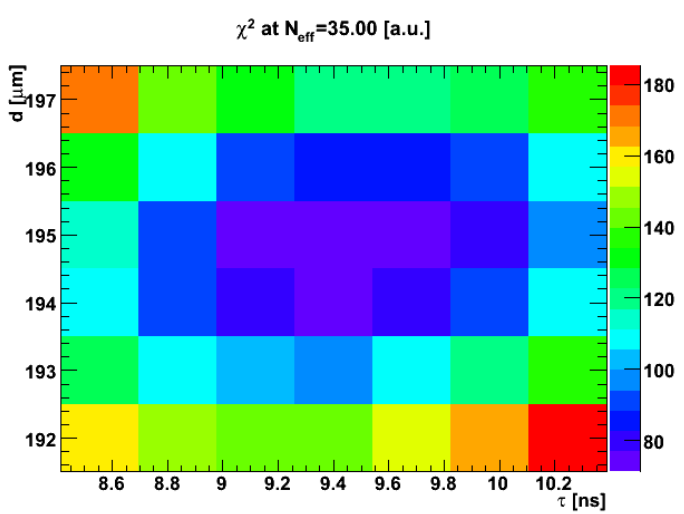
rear

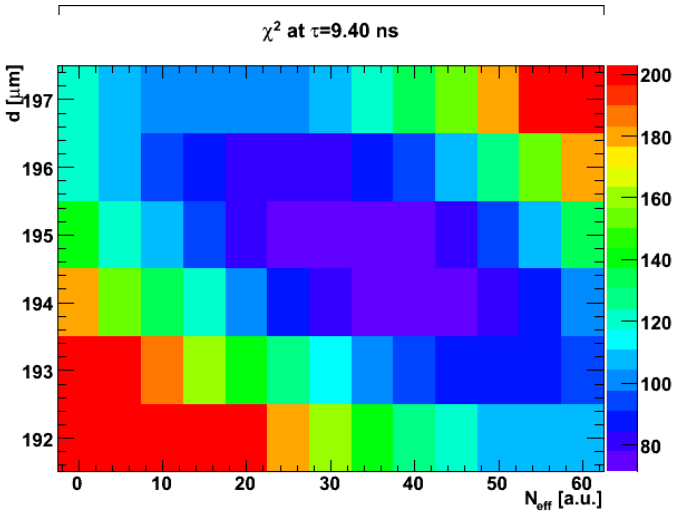


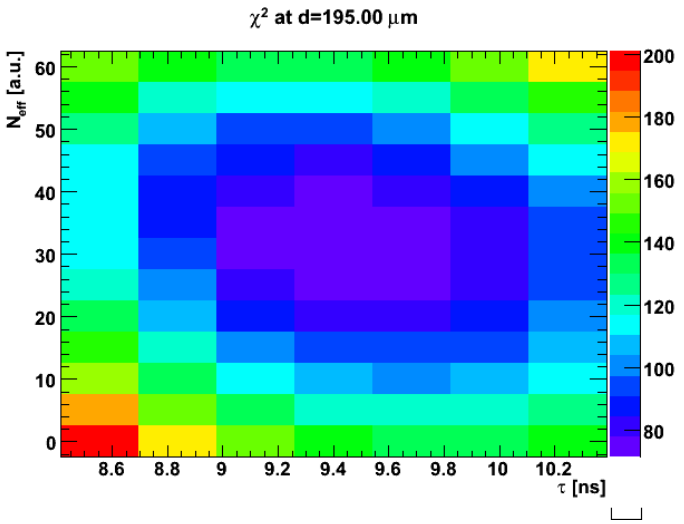

Charge Collection Efficiency
rear
MeV protons
CCE
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
voltage [V]
Vfd goes down (from CV measurements)
but: rear side depletion gets slower
MCZ200N/MCZ200N_01_Diode_1/2011_10_28_16_00 672 nm 0C rear, 3e14neq 23MeV protons
MCZ200N/MCZ200N_01_Diode_1/2012_04_12_17_41 672 nm 0C rear, 3e14neq 23MeV protons

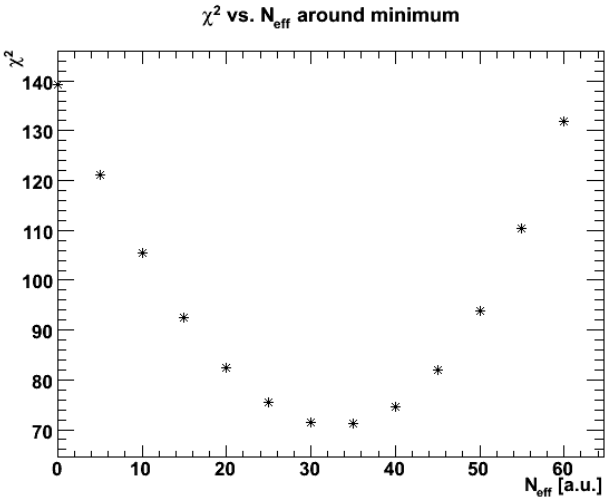

TCT current signal
current [μA]
672 nm rear, 0°C, non-irrad
672 nm rear, 0°C, 2.6 10^14cm^-2 23 MeV protons, 10 min at
672 nm rear, 0°C, 3.9 10^14cm^-2 23 GeV protons, 1 min at 8
tin

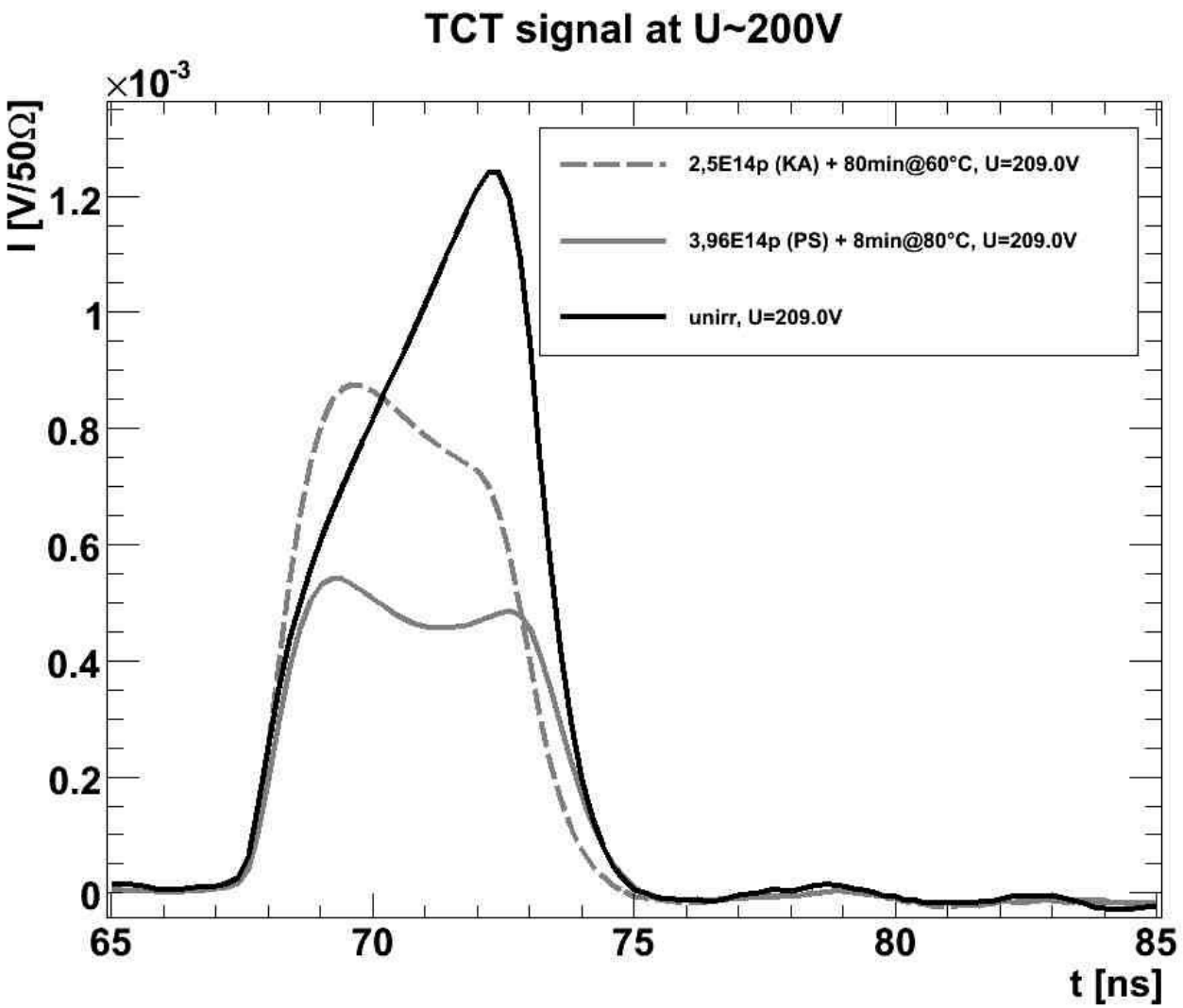

TCT current signal
current [μA]
672 nm rear, 0°C, non-irradiated
672 nm rear, 0°C, 2.6 10^14cm^-2 23 MeV protons, 80 min at 60°C
672 nm rear, 0°C, 3.9 10^14cm^-2 23 GeV protons, 8 min at 80°C
time [ns]

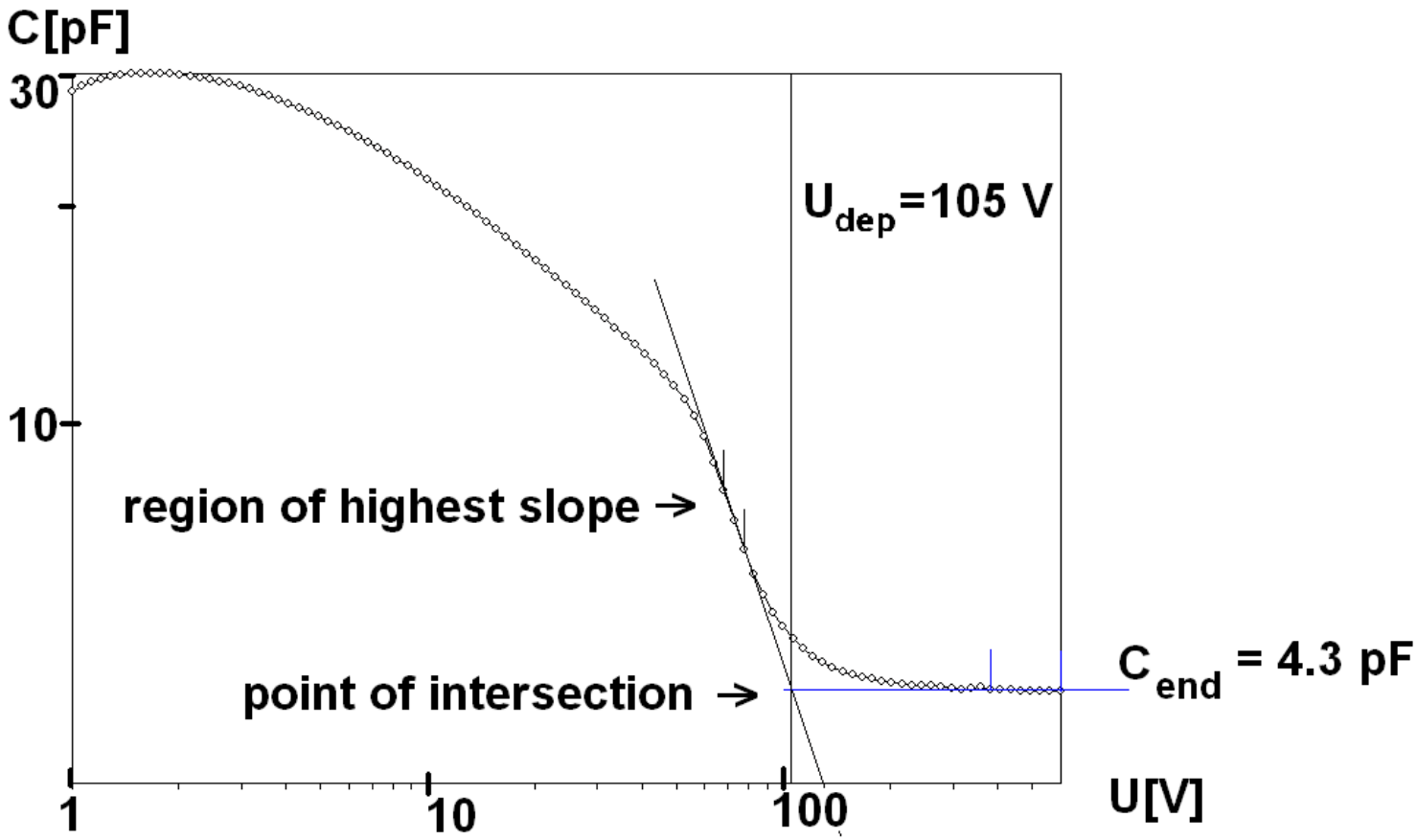

χ^2 at N_{eff}=35.00 [a.u.]
d [μm]
197
196
195
194
193
192
8.6
8.8
9
9.2
9.4
9.6
9.8
10
10.2
τ [ns]
180
160
140
120
100
80


χ^2 at τ=9.40 ns
d [μm]
197
196
195
194
193
192
0
10
20
30
40
50
60
N_{eff} [a.u.]
200
180
160
140
120
100
80


χ^2 at d=195.00 μm
N_{eff} [a.u.]
60
50
40
30
20
10
0
8.6
8.8
9
9.2
9.4
9.6
9.8
10
10.2
τ [ns]
200
180
160
140
120
100
80


χ^2 vs. N_{eff} around minimum
χ^2
140
130
120
110
100
90
80
70
0
10
20
30
40
50
60
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
1
10
100
U[V]
U_{dep}=105 V
region of highest slope →
point of intersection →
C_{end} = 4.3 pF

Voltage dependence

8@80°C

200 V N_{eff} [10^{12} cm^{-3}] = 4

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