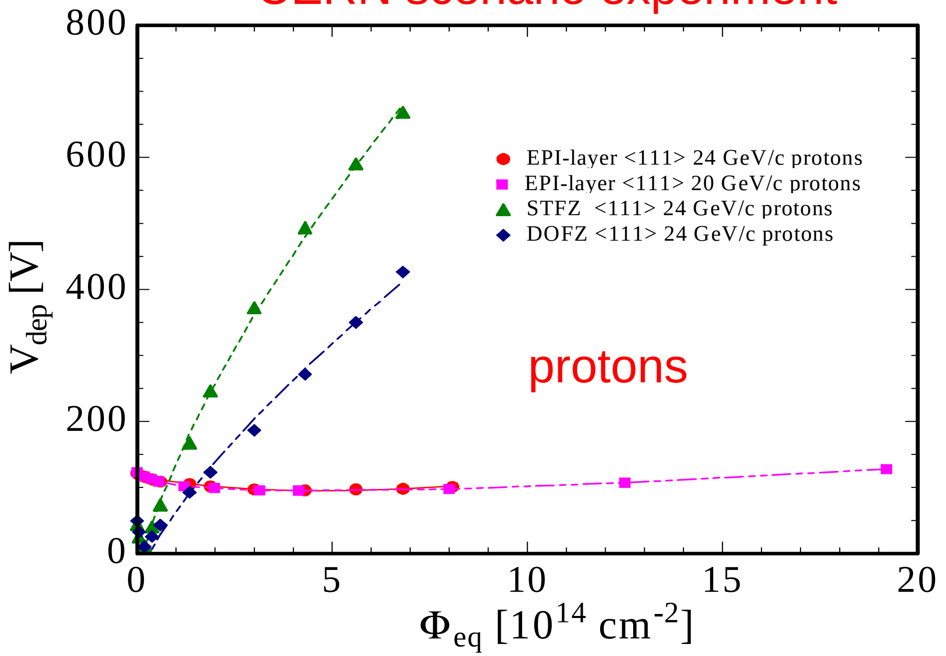
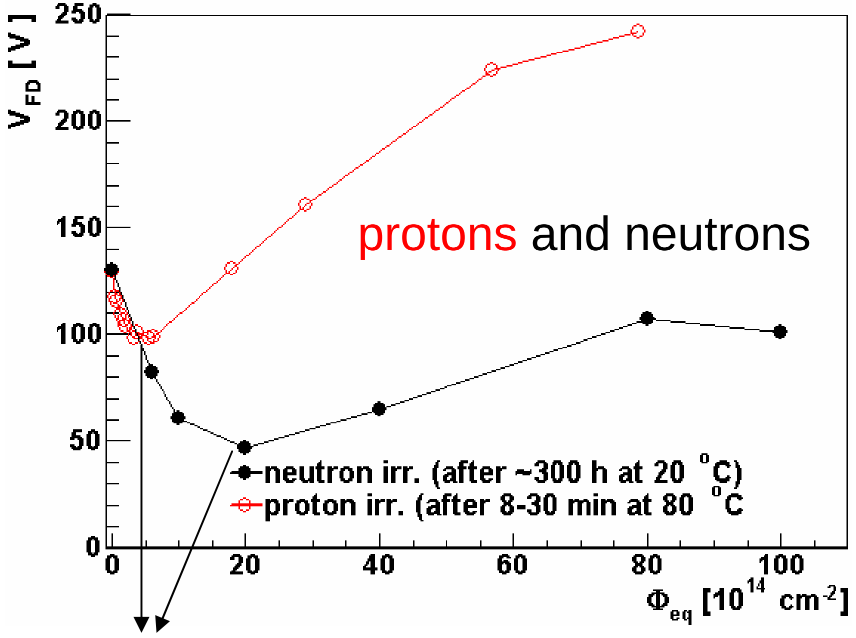
Type inversion of Epi-Si and Cz irradiated devices

50 µm thick epi-Si sensors, 50 Ωcm

CERN scenario experiment



Fixed fluence



Points correspond to MAXIMUM of *V_{fd}* *and not to the minimum like in DOFZ devices*

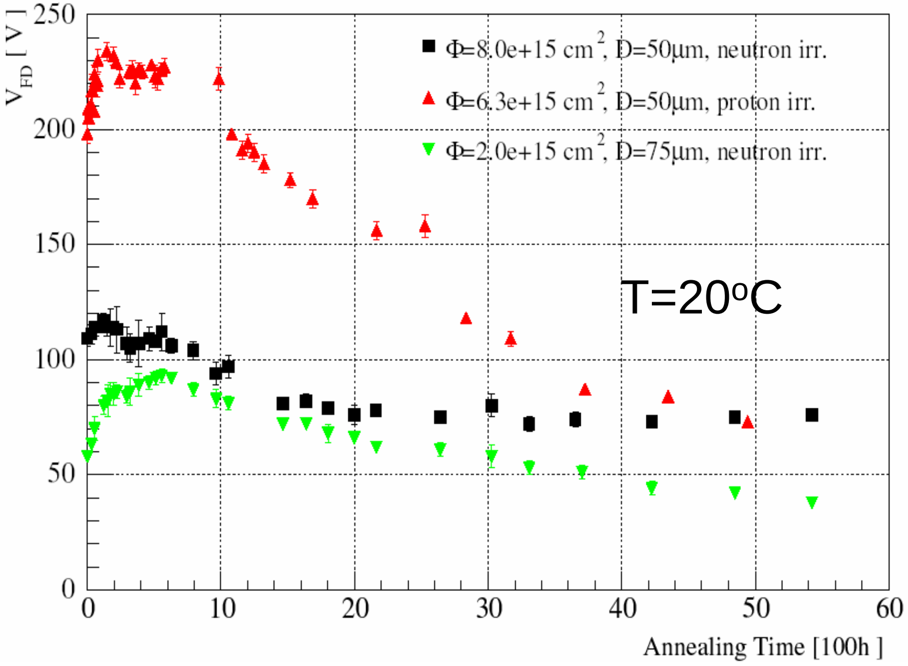
Both CERN scenario and fixed fluence experiments point to **NO** type inversion ☺ for both **neutron** and **proton** irradiated epi-Si samples! But …, this can not be confirmed by TCT – too short pulses!

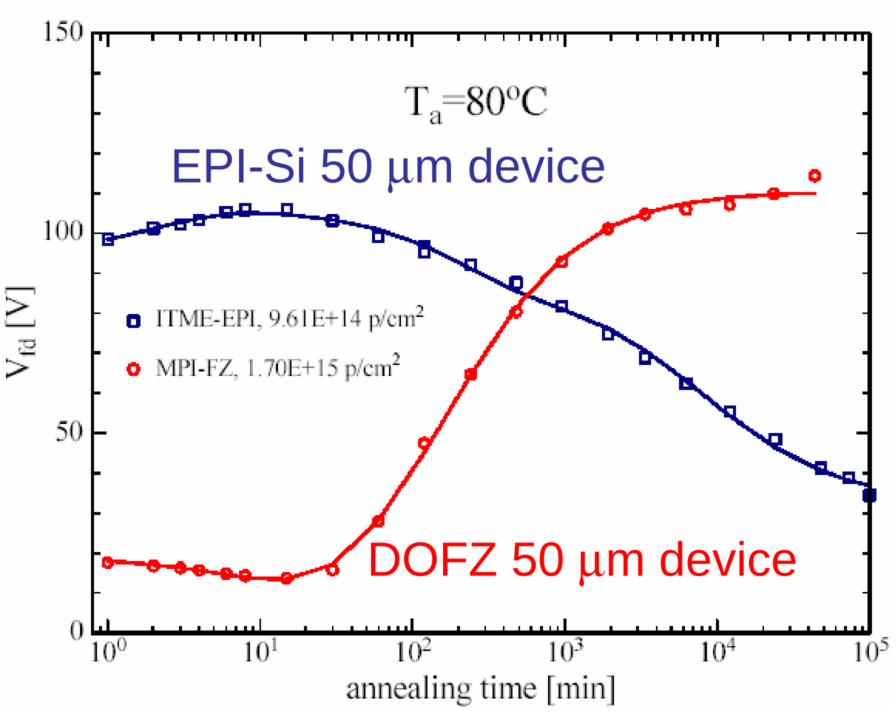
Does this remain true also for thicker/thinner devices? (non-homogenous distribution of oxygen)

Note that for proton irradiated devices the increase of |Neff| with fluence is larger than for DOFZ – as will be shown long term annealing is very beneficial!

Annealing of epi-Si devices

Devices are not inverted – reduction of V_{fd} at late stage annealing





Similar annealing behavior is obtained for standard DOFZ detectors irradiated below inversion point!

- V_{fd} after ~1 year at 20°C is much lower than initial V_{fd} (~125V) for all fluences

↓

The long term annealing at RT reduces the V_{fd} of the detector!

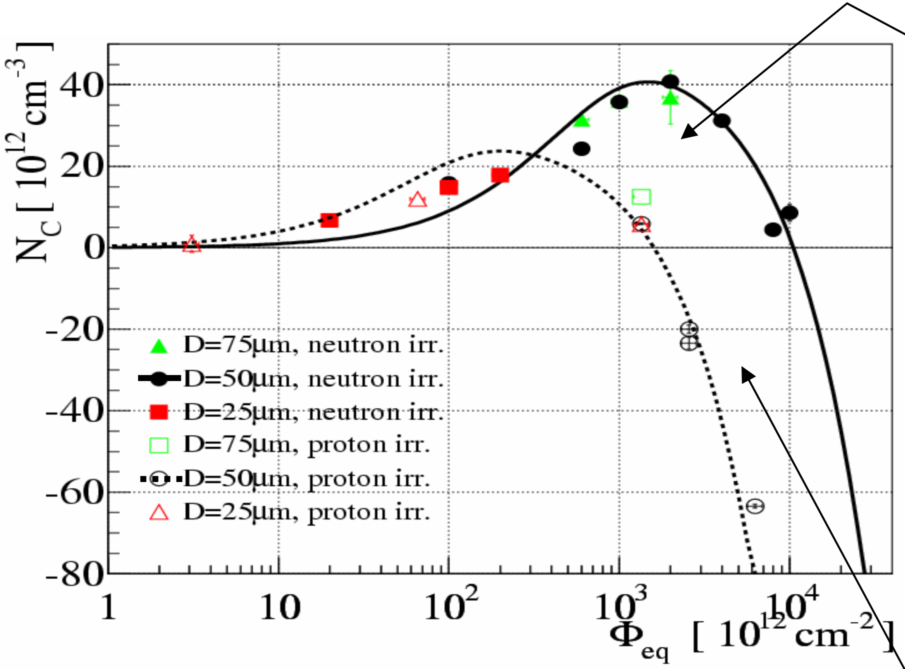
Stable damage of Epi-Si sensors

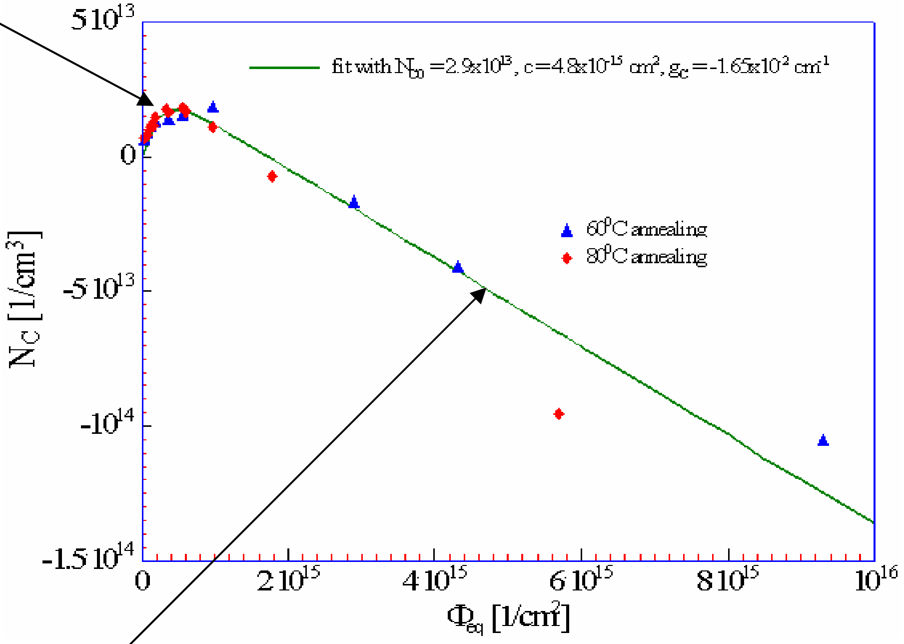
$$\Delta N_{eff} = \boxed{STA(t)} + \boxed{N_C} + \boxed{LTA(t)}$$

generation of acceptors during Long Term Annealing

generation of donors – stable damage

donor removal

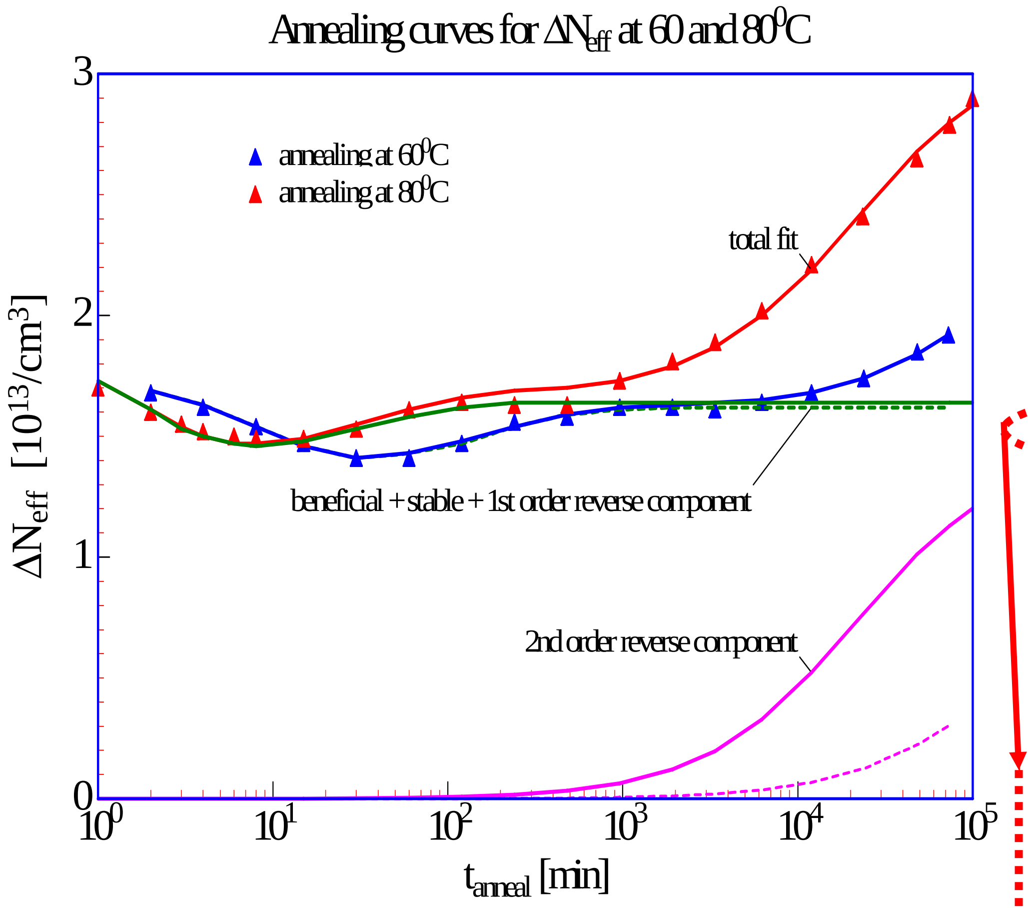




***N_c<0*: Generation of positive space charge**: $N_c = g_c \cdot \Phi$, $g_c = -1.7 \cdot 10^{-2}\,\mathrm{cm}^{-1}$

Good agreement for samples of different thicknesses
Larger donor removal for neutron irradiated samples
The positive stable damage can be compensated by annealing (STA and LTA)!

Short term and long term annealing



<u>Short term annealing</u> similar to DOFZ

<u>Long term (reverse) annealing</u> has two components:

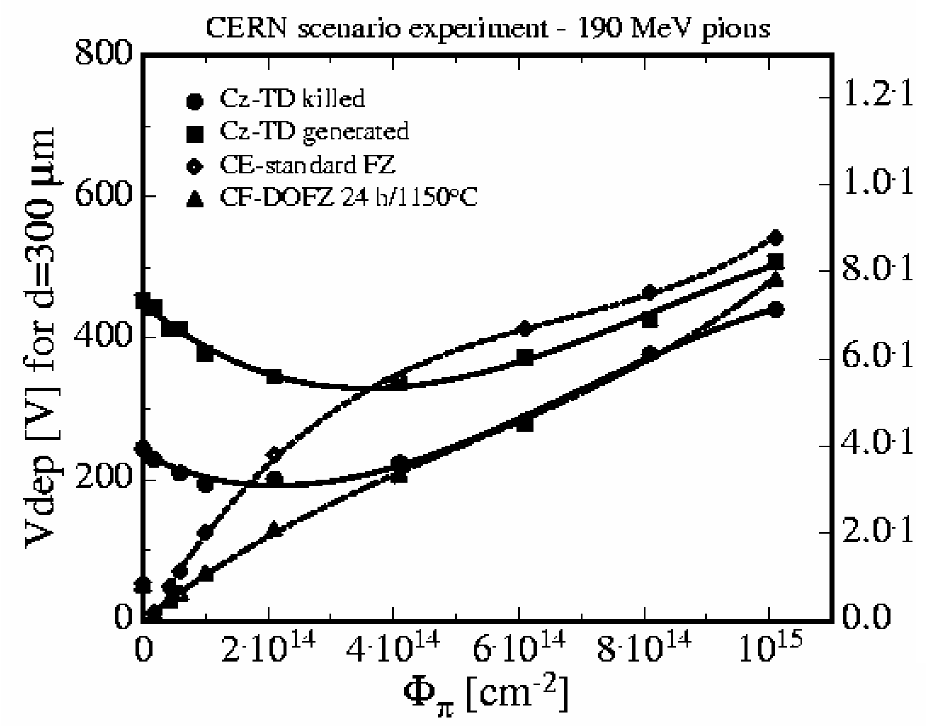
- 1st order component
  $g_{Y1}=2.6\times10^{-2}$ cm^{-1}, τ_{Y1}~ 1000min@ 60^{o}C
- 2nd order component
  ~10 y at 20^{o}C (depending on fluence)

$g_{Y1}>gc$ acceptors formed during annealing can compensate stable donors

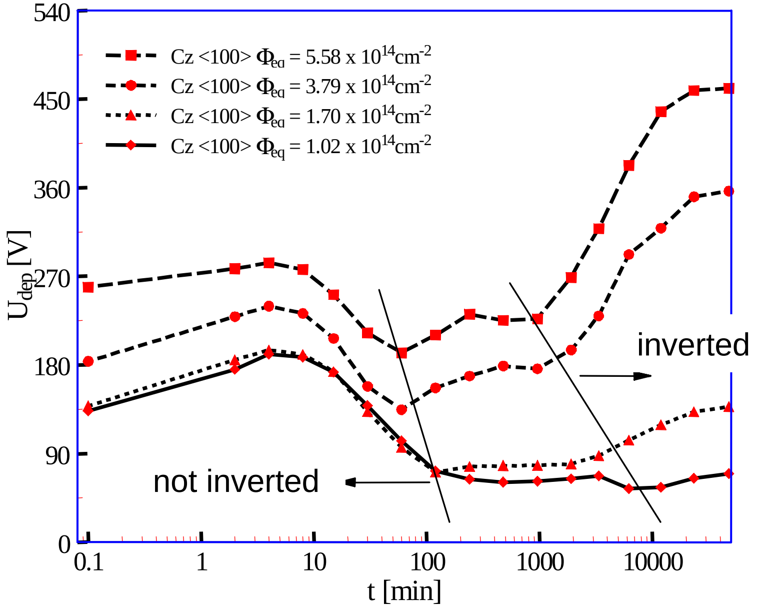
At high fluences detectors can have N_{eff}~0 after annealing!

The lifetime of epi-Si detectors at SLHC is not determined by N_{eff} increase with fluence!

Type inversion of irradiated Cz devices



from F. Hönniger's thesis, Hamburg



Sumitomo p^+n Cz-Diodes: 1.2 kΩ cm, d= 280 µm, $[O_i]$=8.1e17 cm^{-3}

- According to evolution of V_{fd} there is no change in SC sign in CERN scenario experiment ☺
- **Complicated (no simple model) annealing** varying for different samples from the same wafer!

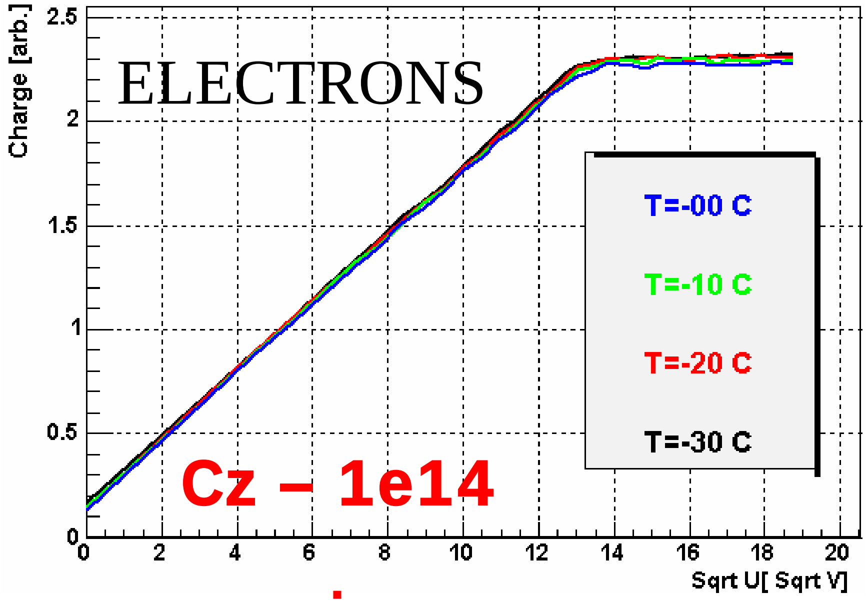
Inversion during annealing investigated with TCT – there is a region for which it is difficult to determine the sign of SC.

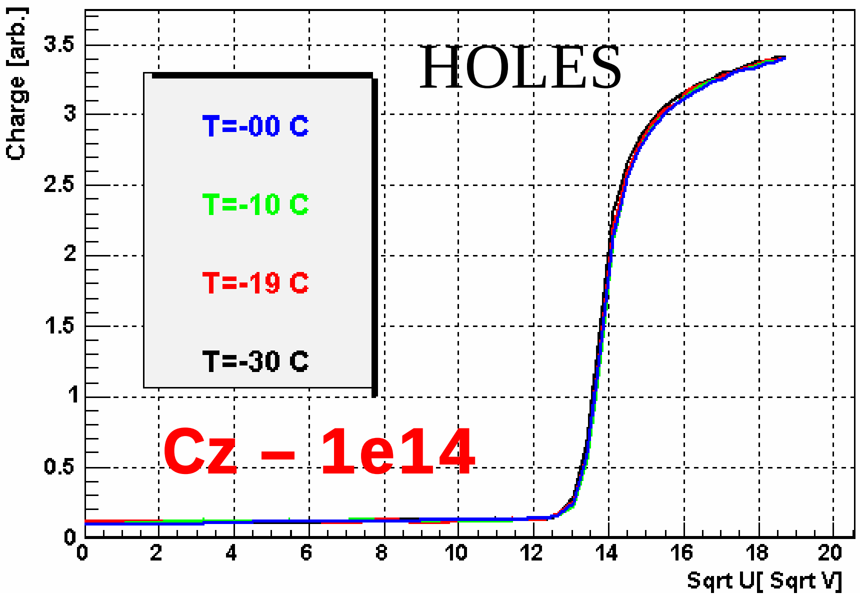
↓

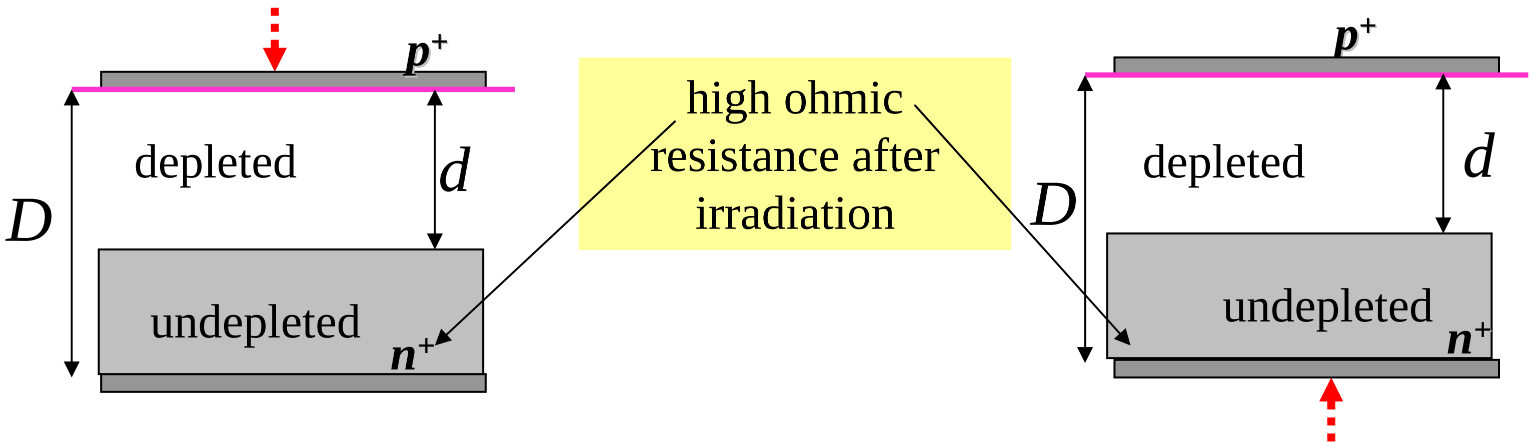
How do we define the sign of the space charge for non-homogenous N_{eff}?

(examples will be shown for proton irradiated Ocmetic (magnetic) Cz from Helsinki – 1.1 kΩcm , 300 µm thick)

In case of low fluence the assumption of constant N_{eff} is valid!







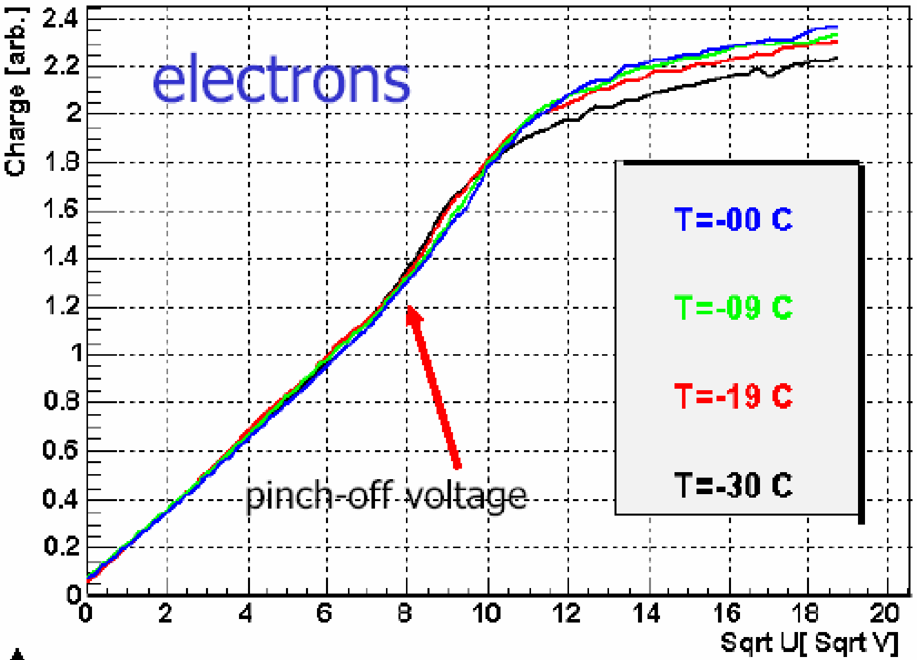
high ohmic resistance after irradiation

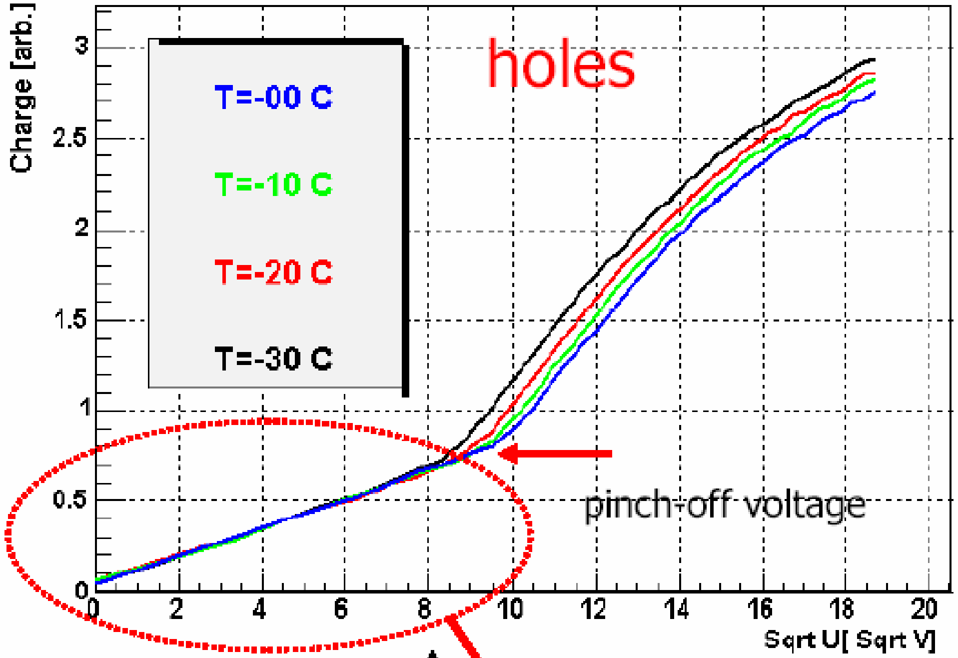
Steep transition at $U \sim V_{FD}$

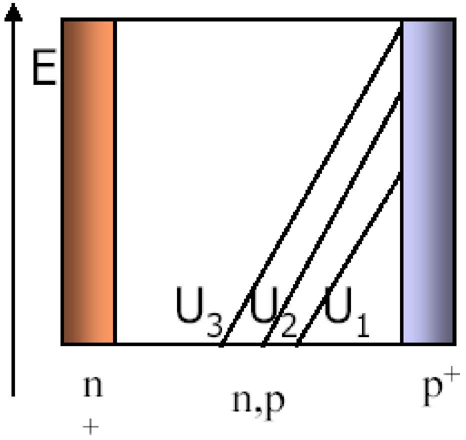
$$Q \propto \frac{d}{D} \Rightarrow Q \propto \sqrt{\frac{U}{V_{FD}}} \rightarrow N_{eff} = const.$$

If the diode is inverted the picture is reversed!

Cz – Irradiated to 5e14

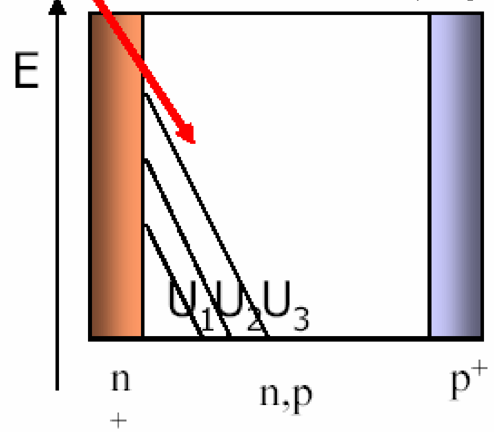






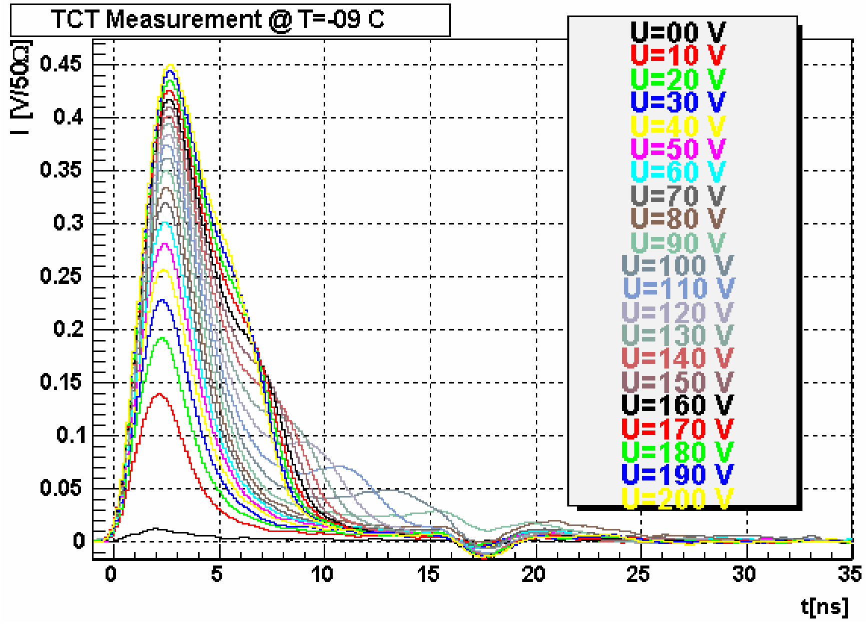
rough estimation:

$$x_{pinch-off} \approx D \cdot \frac{Q_{pinch-off}}{Q_{V_{FD}}}$$

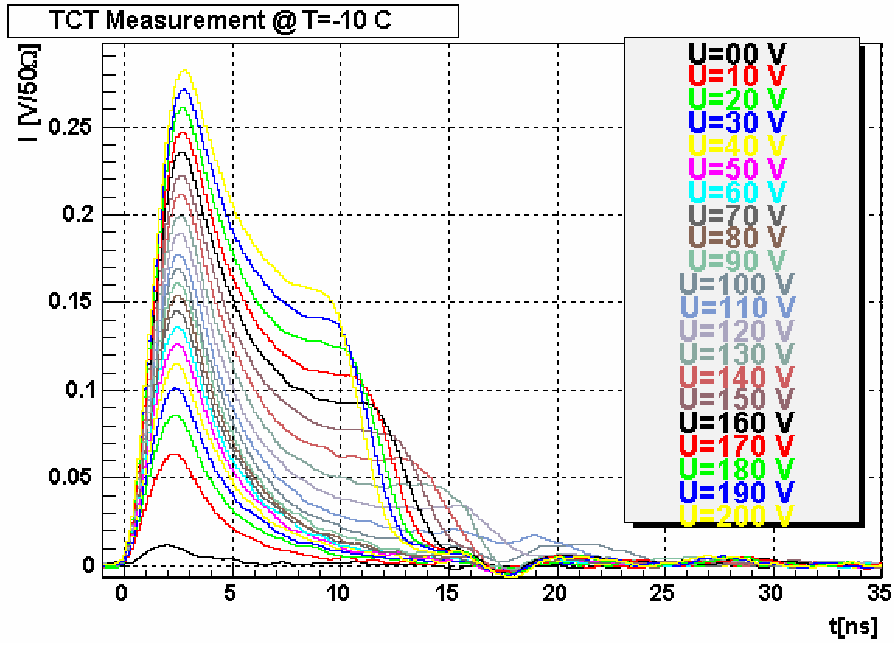


- Charge plots for electron and hole signals show that N_{eff} is not constant!
- Large hole signal (charge) already at low voltages – injection in electric field region

ELECTRONS



HOLES

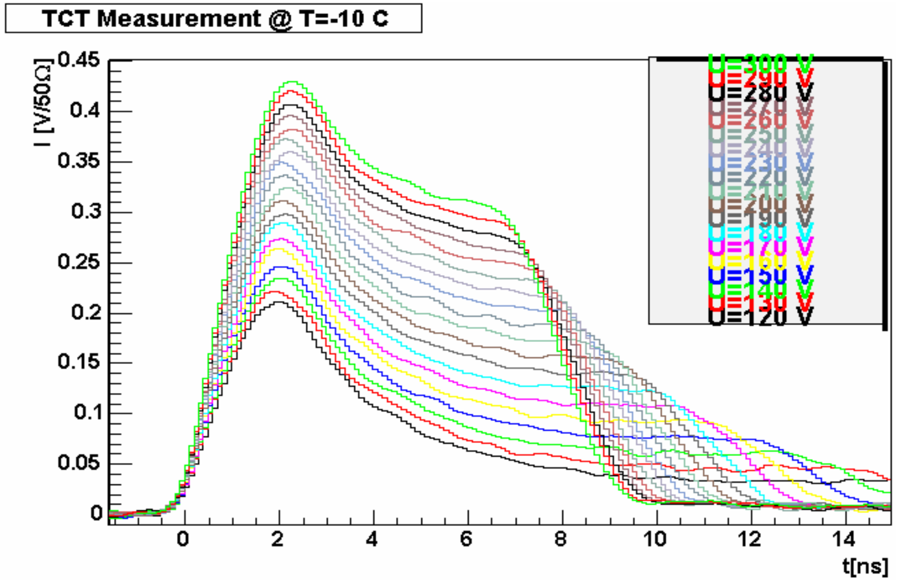


Both electron and hole seems to be injected in high field region, but…
what we measure/see is damped by trapping of the drifting charge

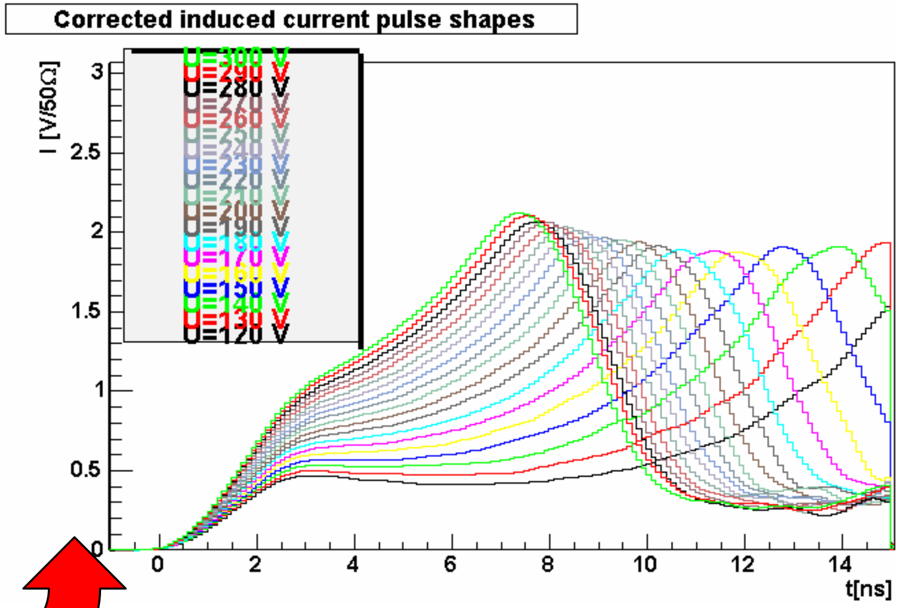
$$I_{e,h}(t) = N_0 \boxed{\exp(\frac{-t}{\tau_{eff_{e,h}}})} \frac{1}{D} \; v_{e,h}(t)$$

To derive the electric field profile/space charge sign you must take trapping into account!

HOLE SIGNALS



TCT Measurement @ T=-10 C



Corrected induced current pulse shapes

τ=4.2 ns

trapping correction

After full depletion the slope of *I(t)* does not change sign

N_{eff} is of the same sign – not inverted !

larger U –> larger slope -> change in Neff

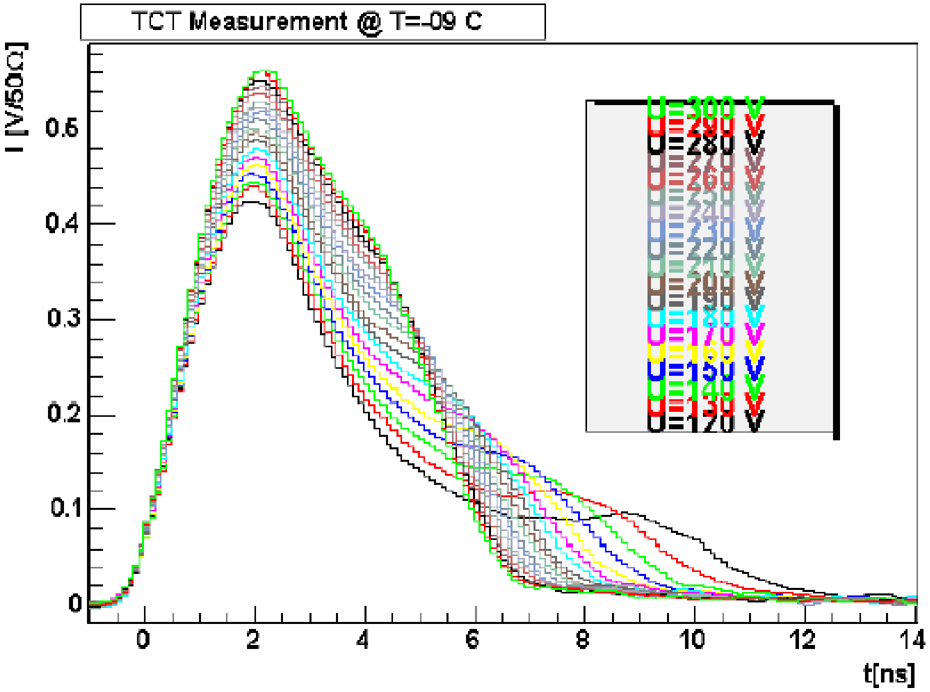
rough explanation:

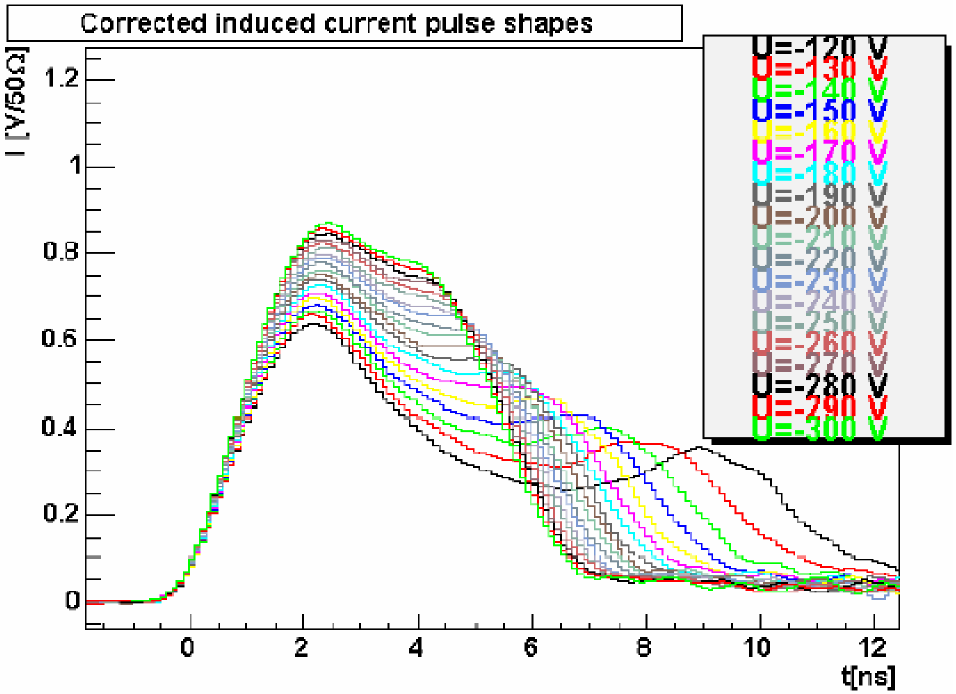
trapping of the free carriers (leakage current) is responsible for change in N_{eff}

$$\left.\begin{aligned} I_e &= -e_0 \cdot n \cdot v_e \\ I_h &= e_0 \cdot p \cdot v_h \end{aligned}\right\} \longrightarrow$$

n,p depend on *U*,
hence occupation probability and N_{eff} as well

ELECTRON SIGNALS – Cz detector





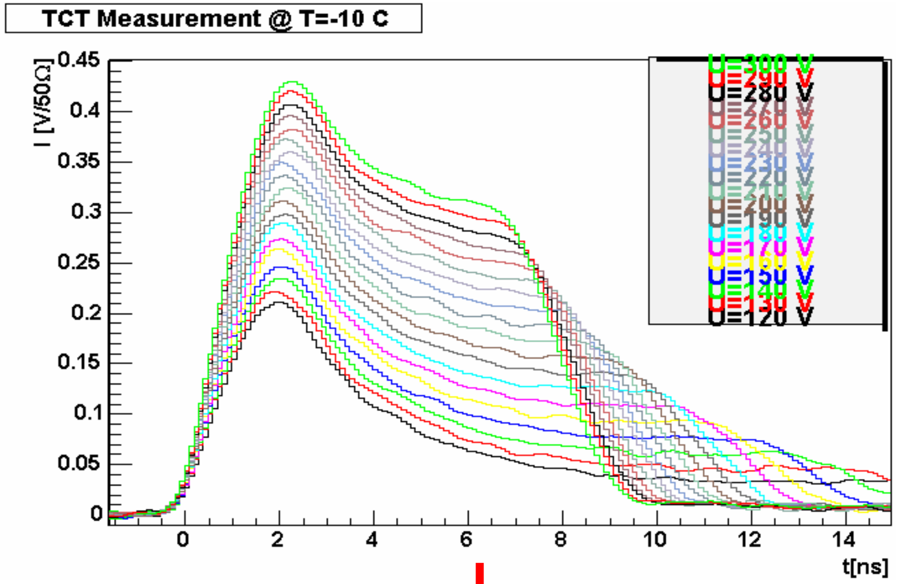
trapping correction τ=7.5 ns

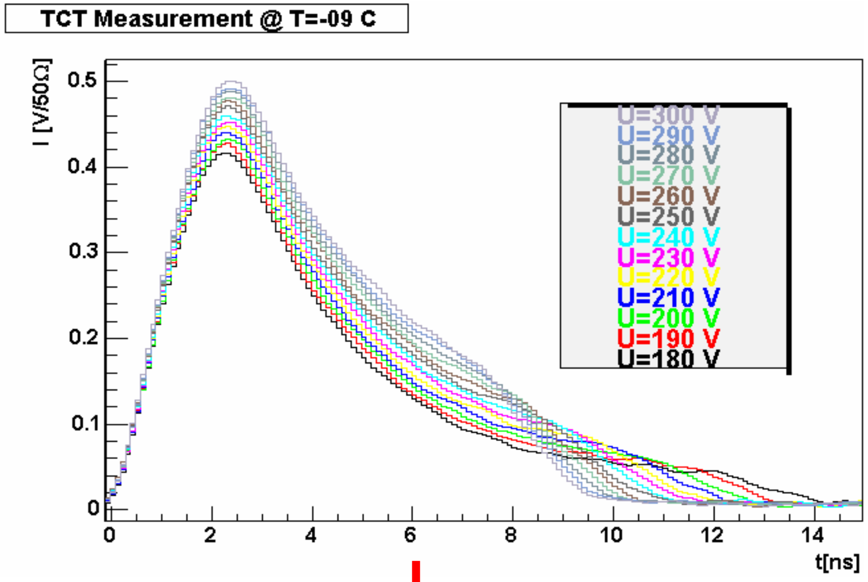
Same conclusions can be drawn as from the hole signal!

How do we define sign of the space charge for non-homogeneous Neff?

The larger of two regions with opposite space charge determines what we call "the sign of the space charge"

Comparison of corrected hole signals for Fz an Cz detector irradiated in parallel to 5e14p


TCT Measurement @ T=-10 C


TCT Measurement @ T=-09 C

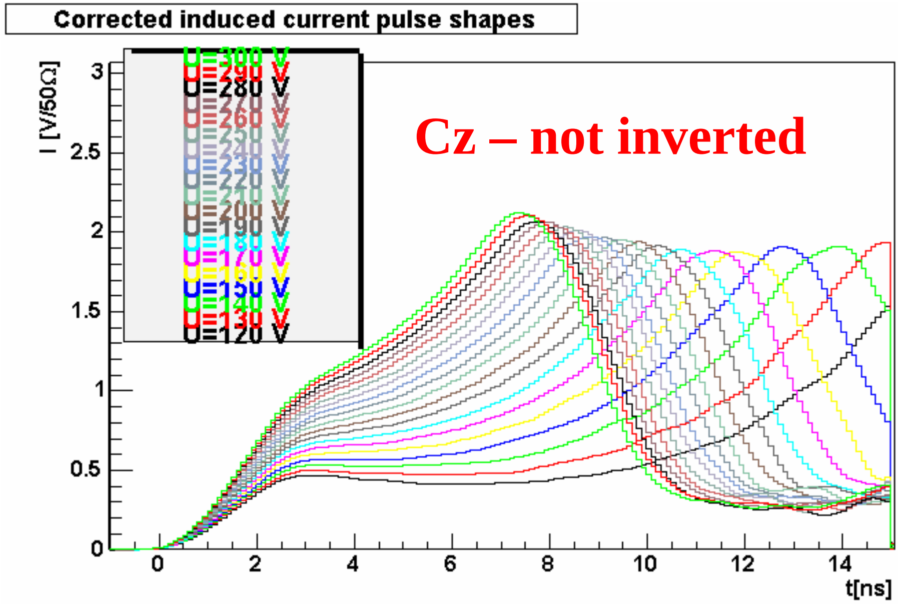
τ=4.2 ns

trapping correction

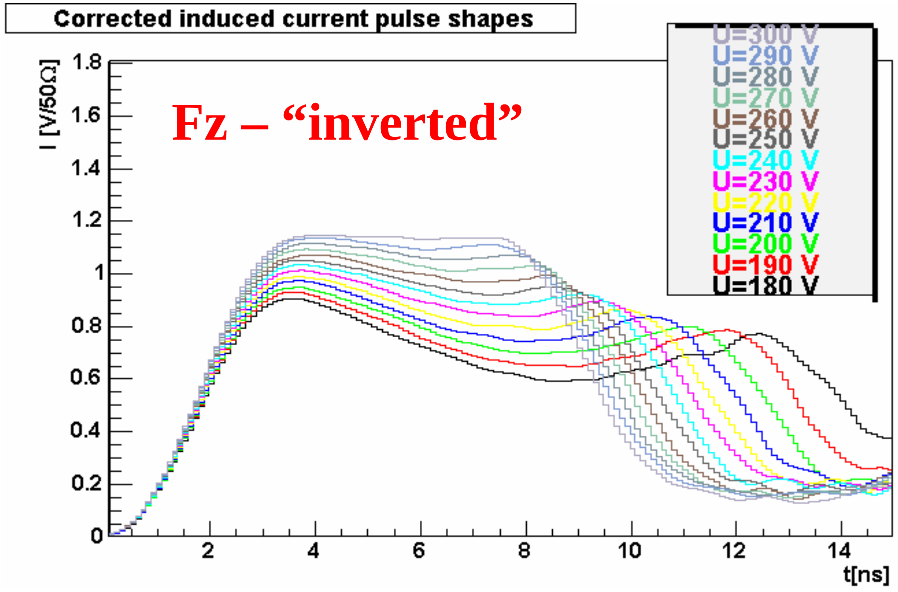
τ=4.6 ns

Main junction in the front

Main junction at the back


Corrected induced current pulse shapes

Cz – not inverted


Corrected induced current pulse shapes

Fz – “inverted”