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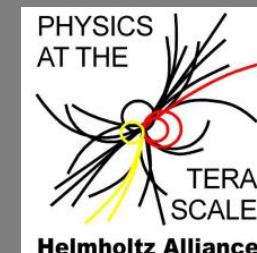
# Impact of proton irradiations with different particle-energies on the electrical properties of Si-diodes

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Thomas Pöhlsen<sup>1</sup>

<sup>1</sup>Hamburg University

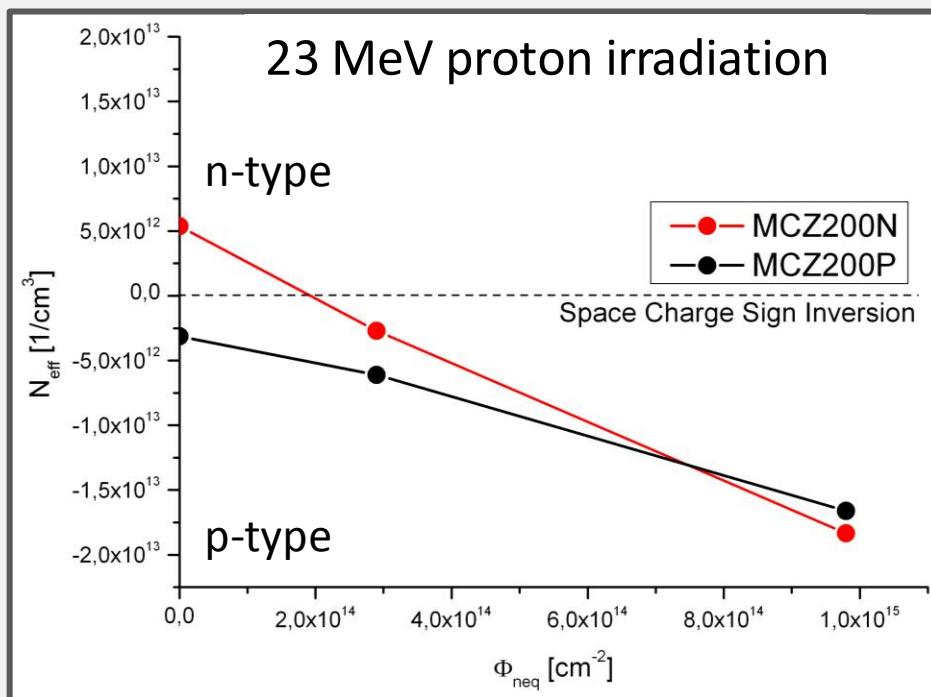
<sup>2</sup>Brown University

<sup>3</sup>DESY

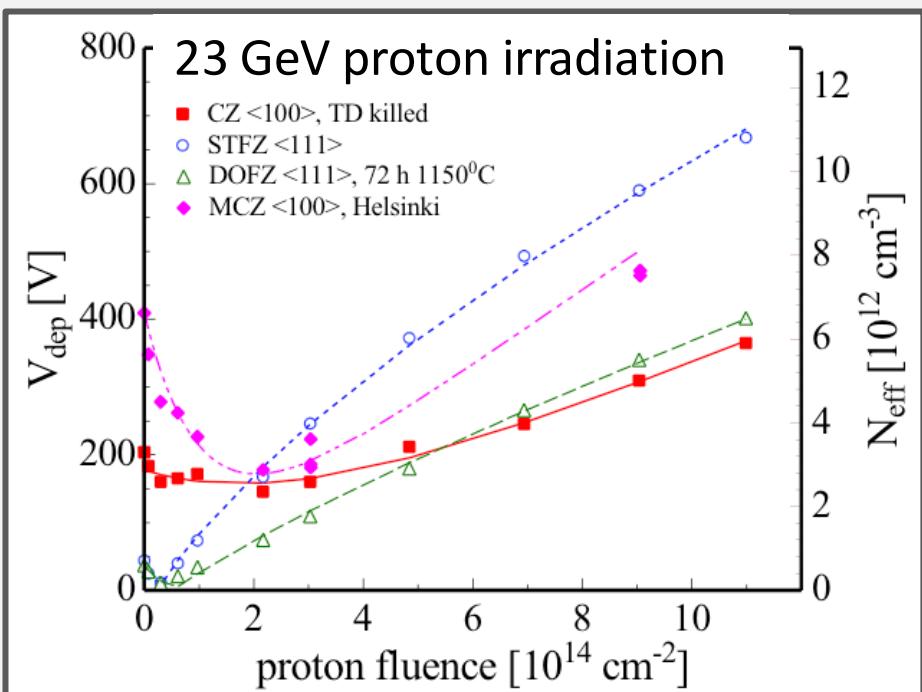


# $N_{\text{eff}}$ for irradiated HPK & RD50 Diodes

## Hamamatsu diodes



## RD50 diodes

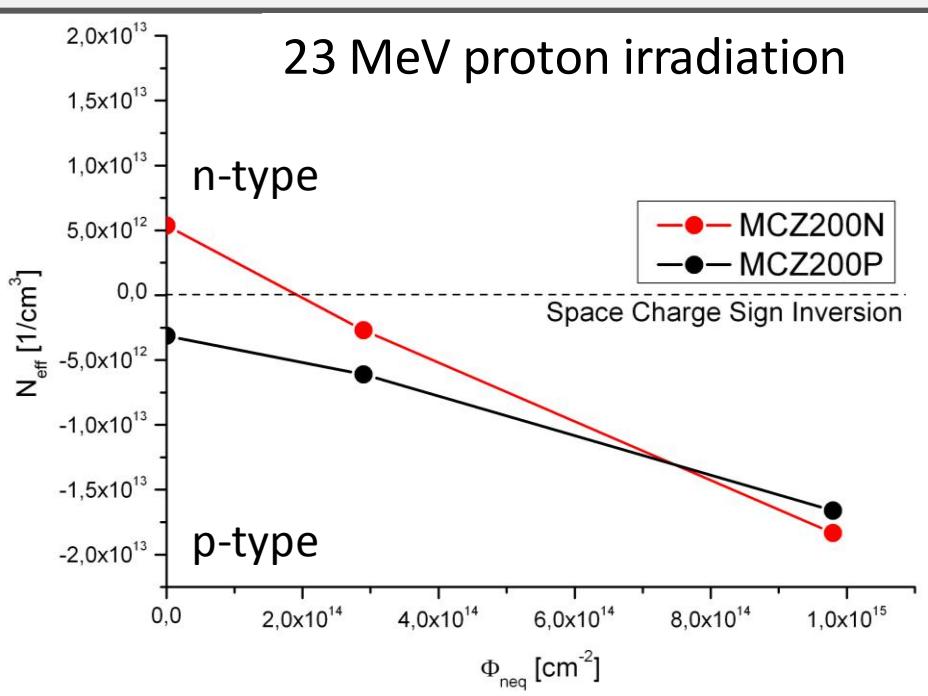


E. Fretwurst, RD50 Workshop CERN, 2003

Type inversion for 200  $\mu\text{m}$  MCz n-type

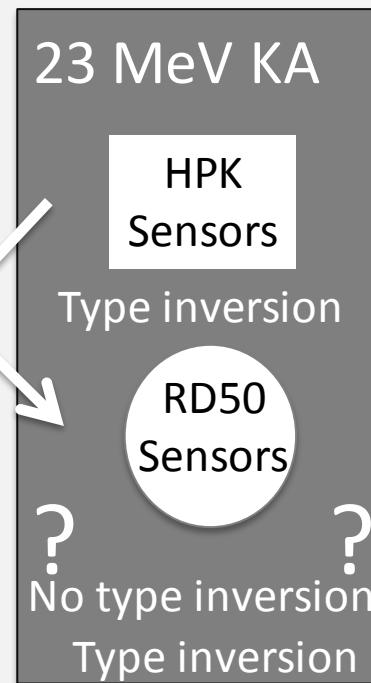
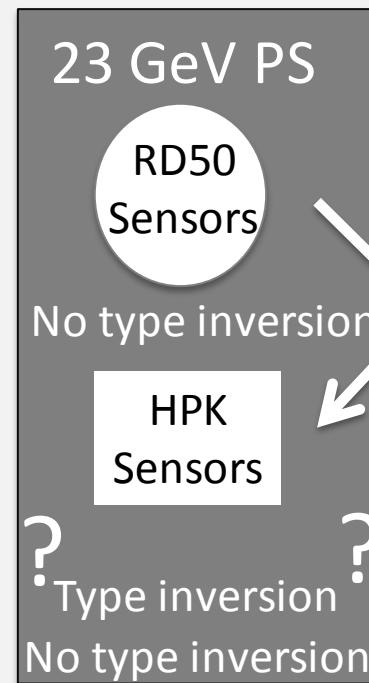
No type inversion for 300  $\mu\text{m}$  MCz

# Unexpected type inversion of HPK MCZ n-type



Type inversion for 200 µm MCz n-type

→ Cross check!

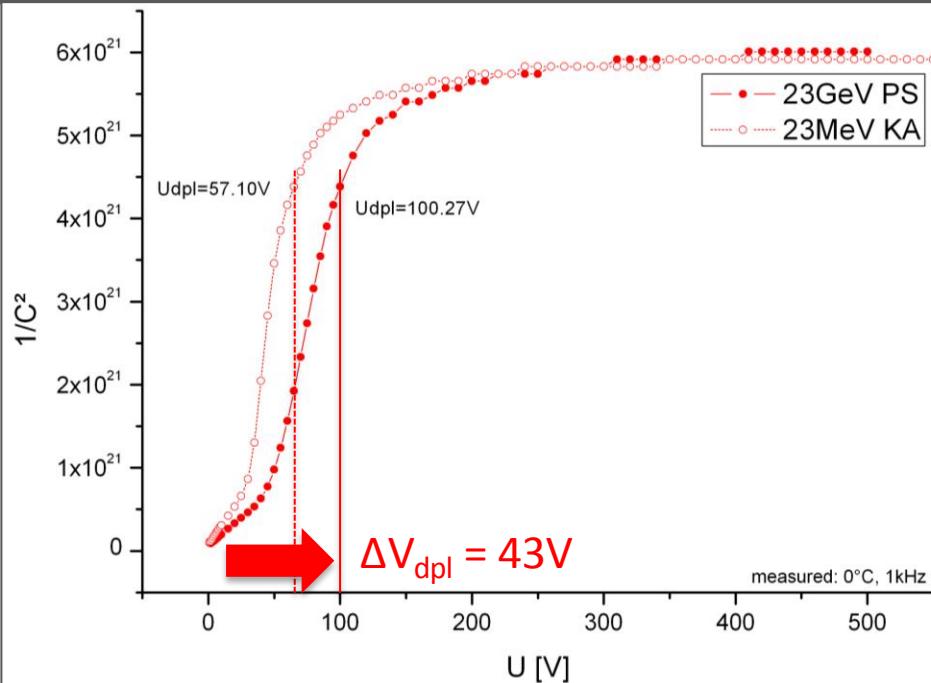


1. Radiation induced defects depend on the MCz material or
2. 23 MeV protons create different defects than 23 GeV protons

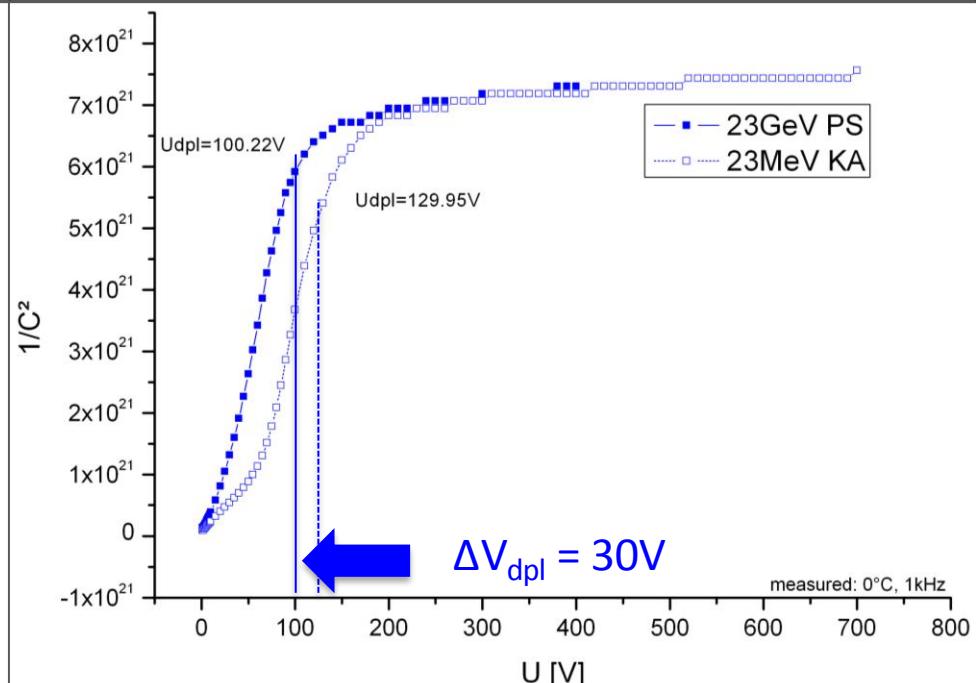
# Comparison between 23GeV and 23MeV p

CV curves of irradiated HPK material: measured directly after  
irradiation

MCZ200N (MagneticCzochalski, 200μm, n-type)

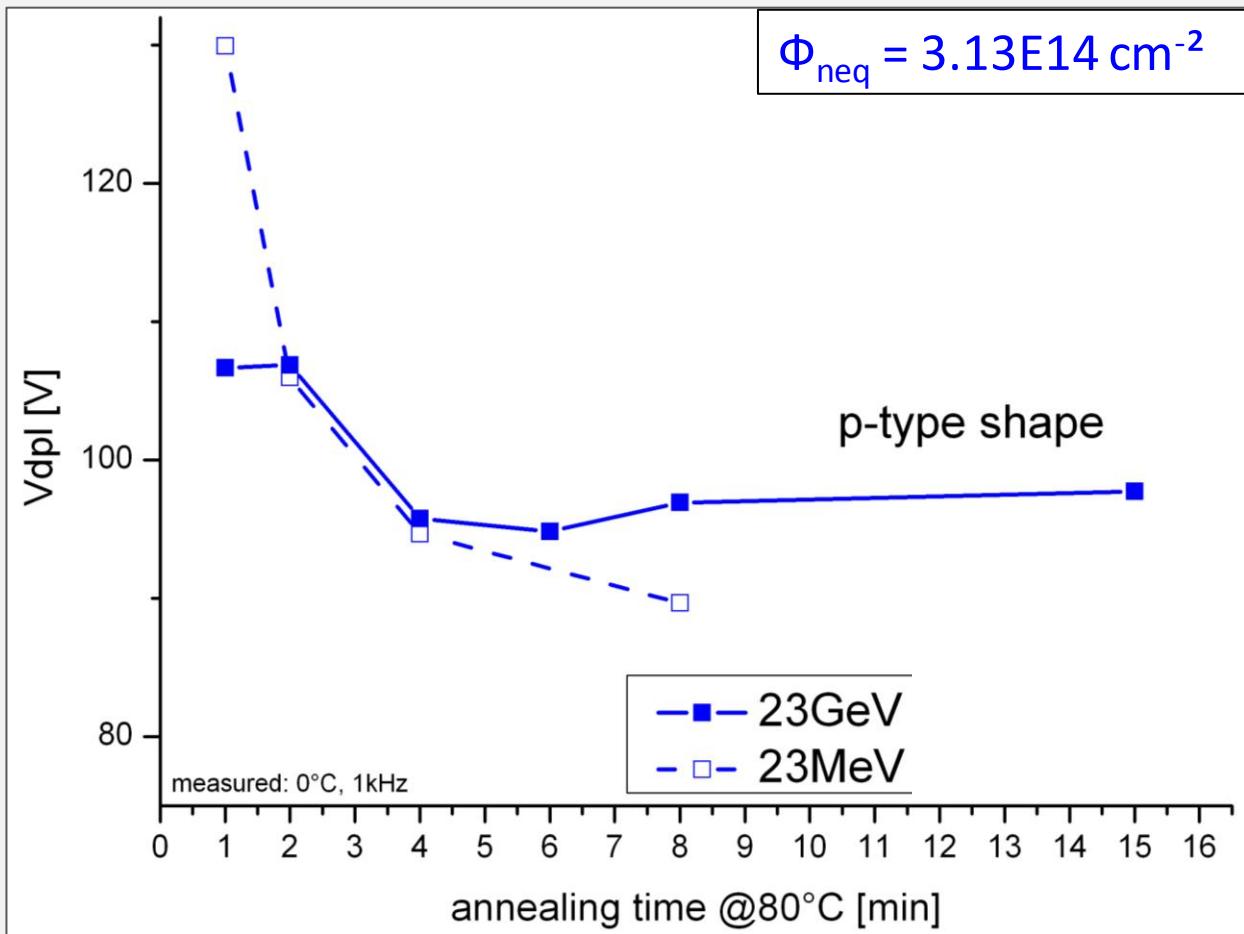


FZ200N (Float Zone, 200μm, n-type)



Big difference in the depletion voltage for both type of material

# Annealing of FZ200N

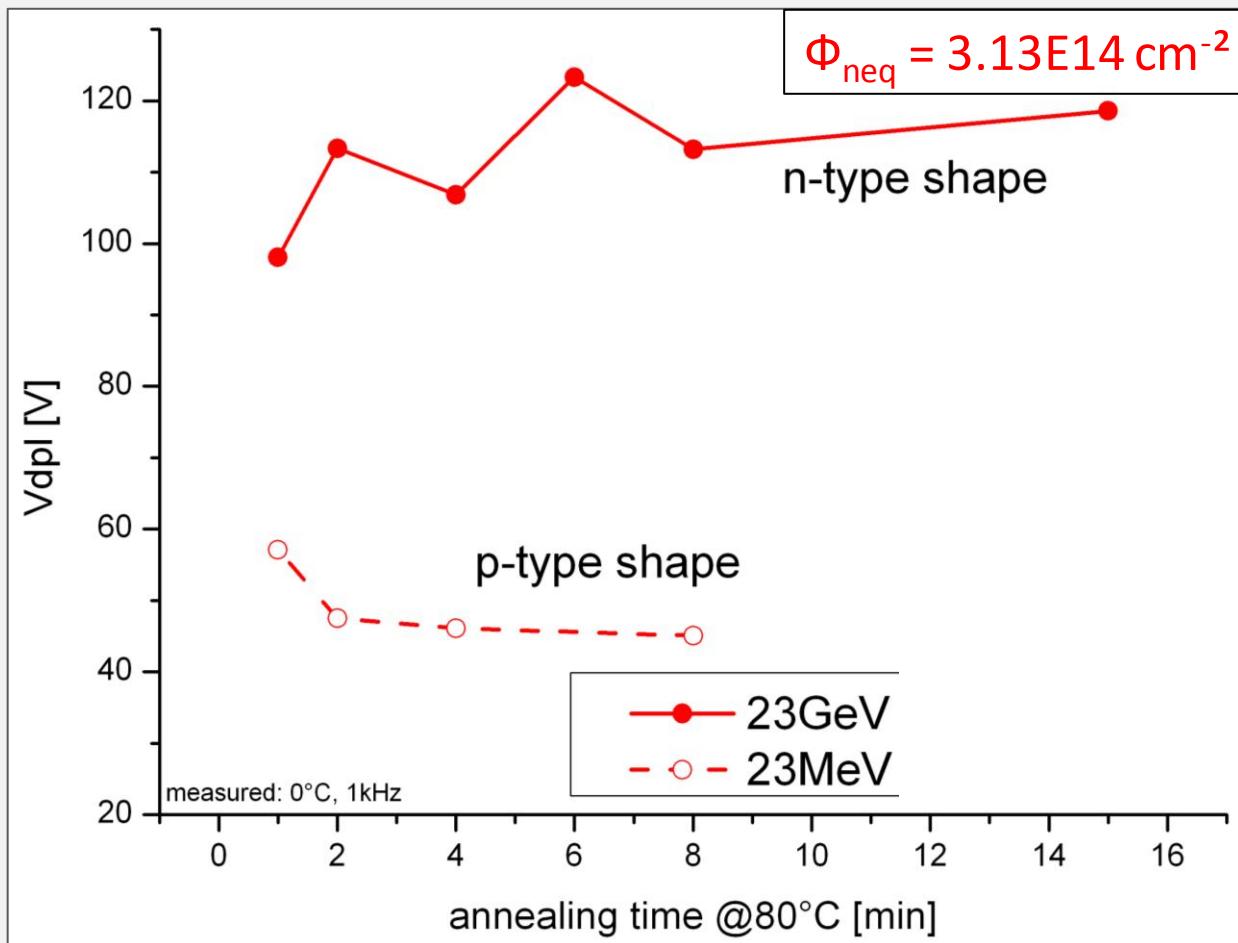


„Short term annealing“:  
create donors or rather  
anneal acceptors

FZ200N:

→ shows p-type  
behaviour after 23GeV  
and 23MeV proton  
irradiation

# Annealing of MCZ200N

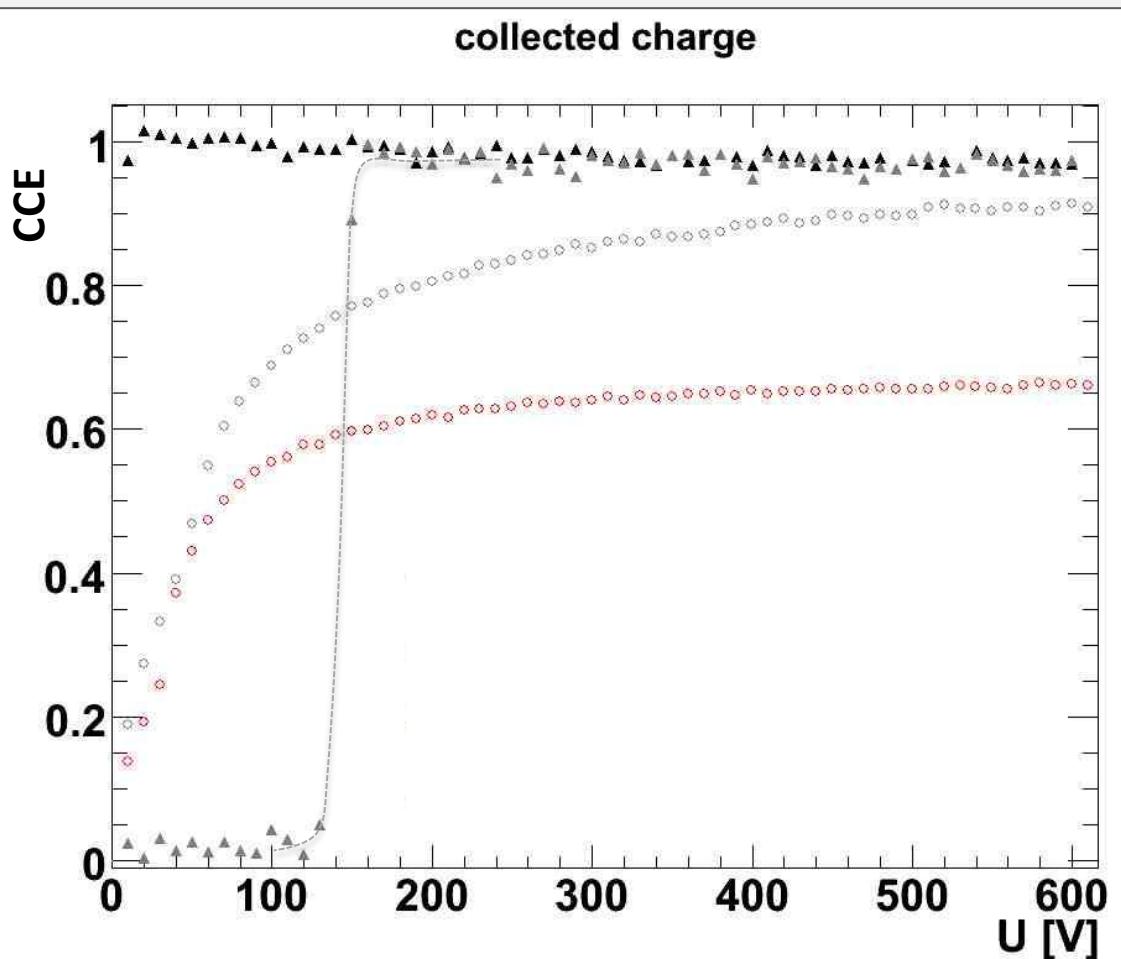


MCZ200N:

Big difference in  
depletion voltage  
→ N<sub>eff</sub>

We were able to  
extract more  
information by means  
of TCT measurements

# CCE for MCZ200N: 23MeV p

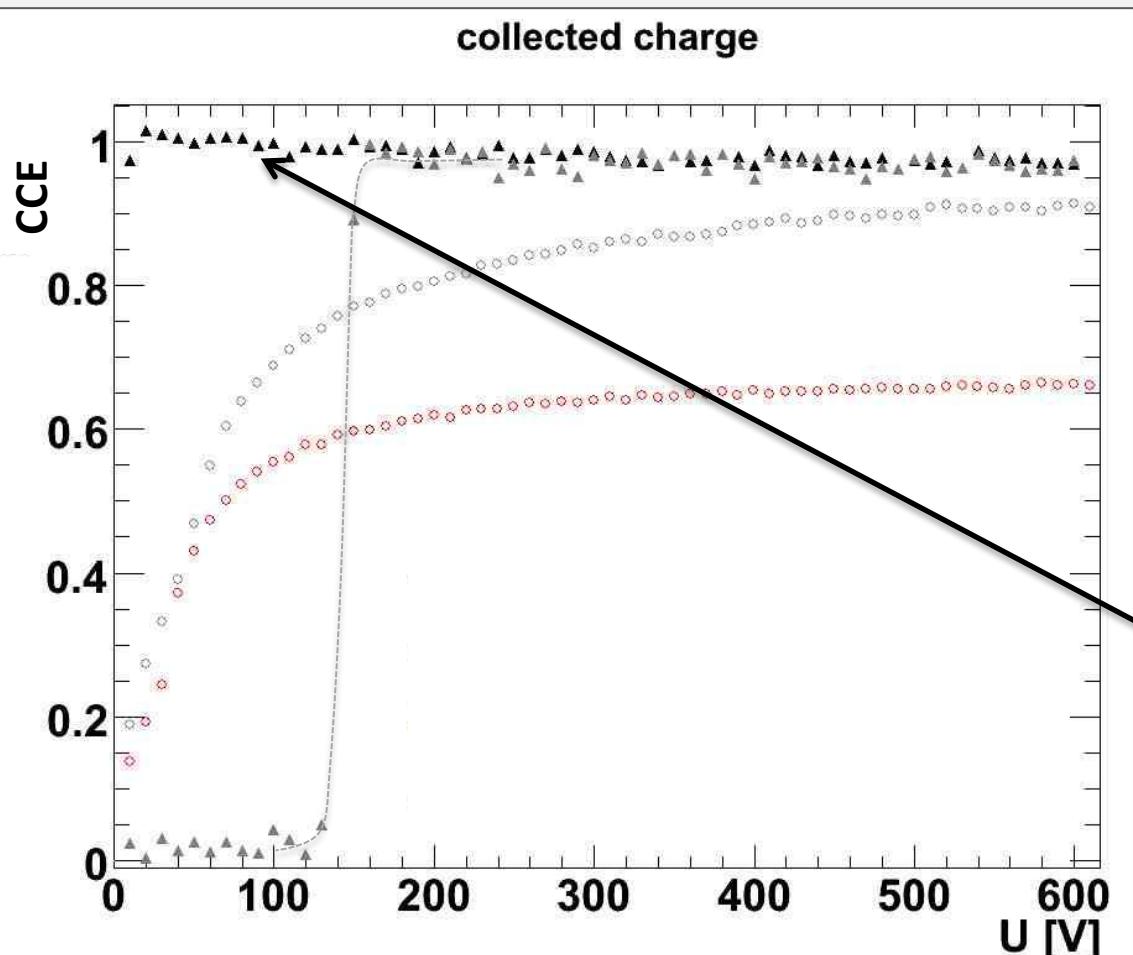


Measurement details:  
Red laser (670 nm), 0°C

▲▲ MCZ200N  
non-irradiated

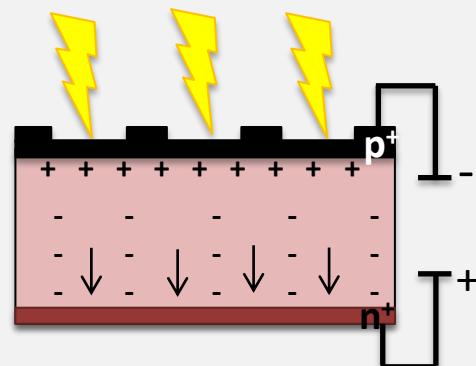
○○ MCZ200N  
irradiated with 23MeV p  
with  $\Phi_{\text{neq}} = 2.93\text{E}14 \text{ cm}^{-2}$   
annealed to 10min@60°C

# CCE for MCZ200N: 23MeV p



Measurement details:  
Red laser (670 nm), 0°C

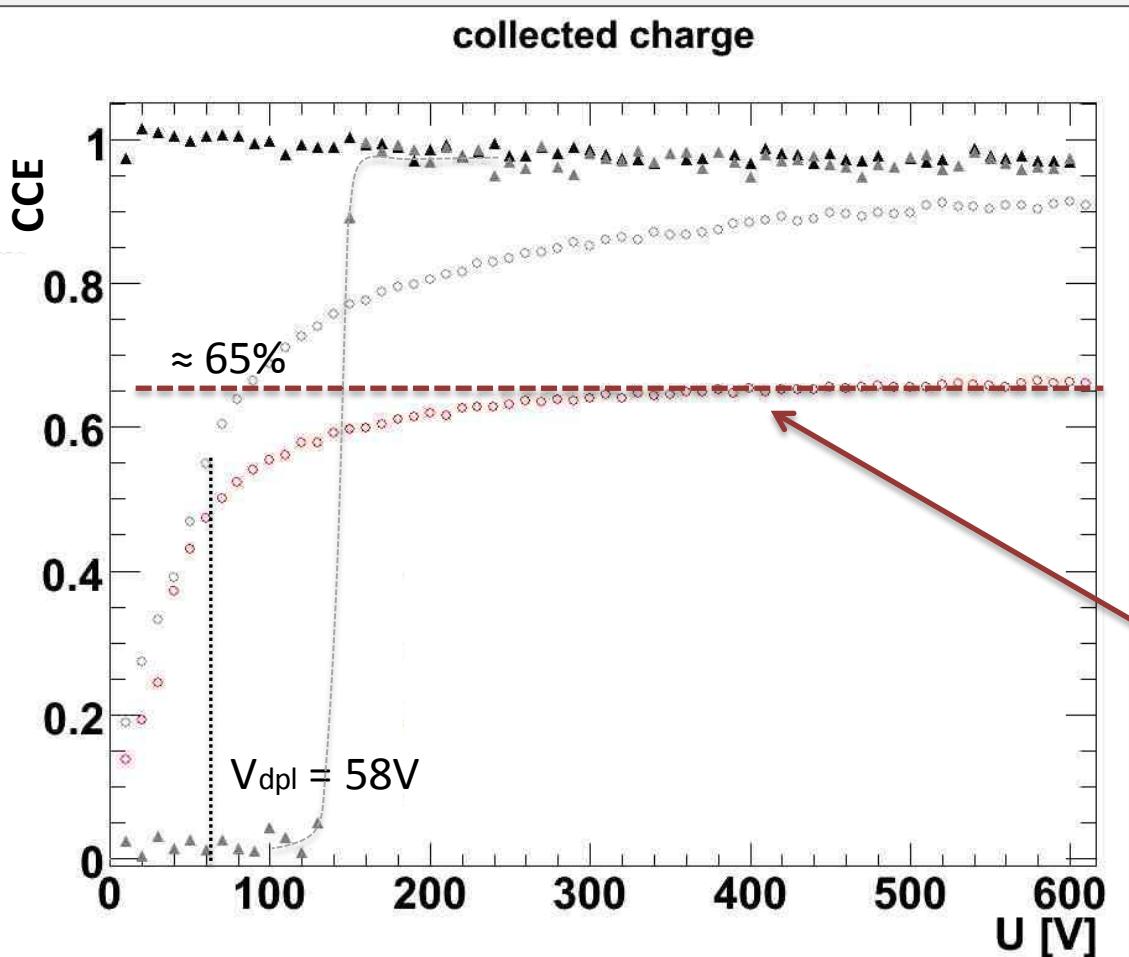
**Front side illumination:**  
**electron drift**



Non-irradiated:  
Front: Charge fully collected  
before  $V_{dep}$  reached

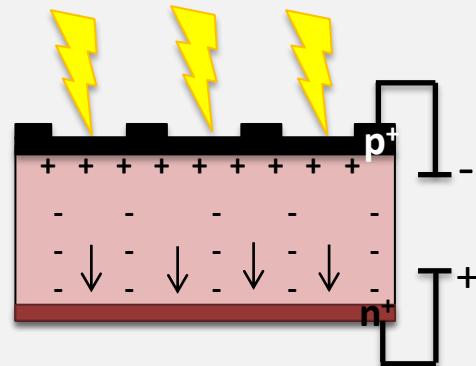
→ Depletion from front

# CCE for MCZ200N: 23MeV p



Measurement details:  
Red laser (670 nm), 0°C

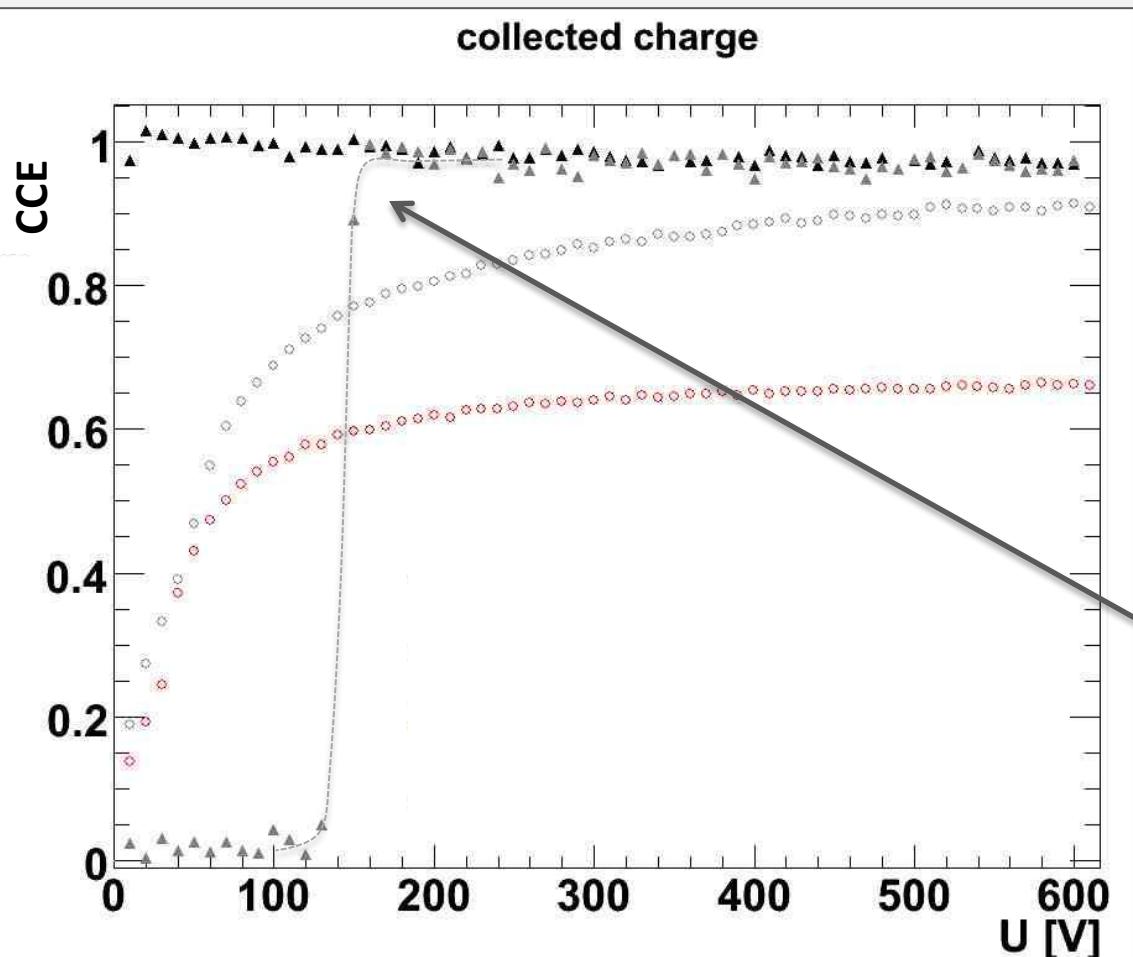
**Front side illumination:  
electron drift**



Irradiated with 23MeV:  
Front:  
charge loss 35%,  
50% of charge collected when  
depletion voltage is reached

$$\Phi_{neq} = 2.93 \times 10^{14} \text{ p/cm}^2$$

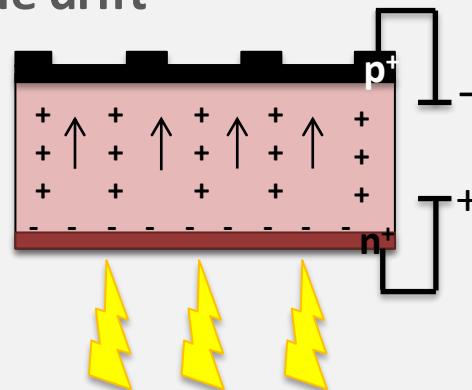
# CCE for MCZ200N: 23MeV p



Measurement details:

Red laser (670 nm), 0°C

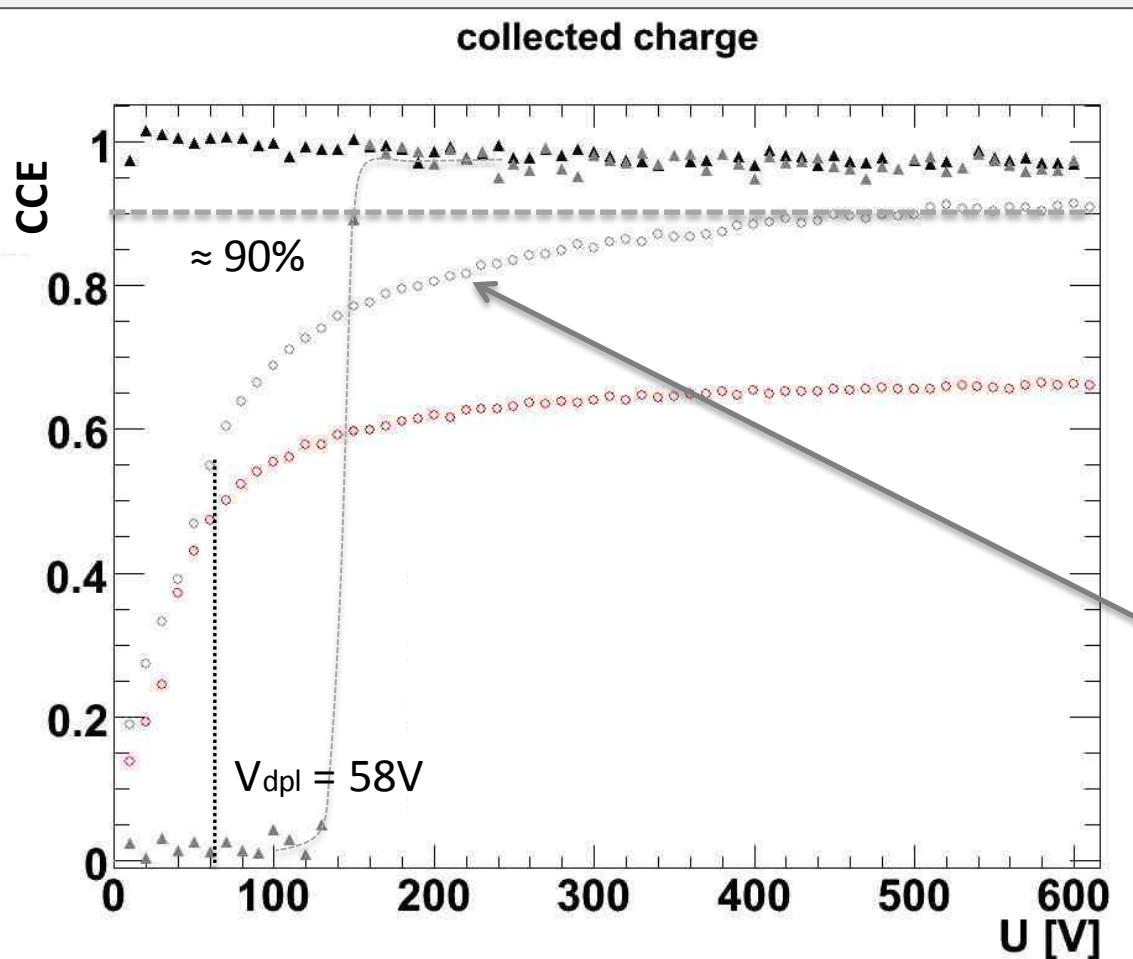
Rear side illumination:  
hole drift



Non-irradiated:  
Rear: Charge collection only  
after full depletion

→ Depletion from front

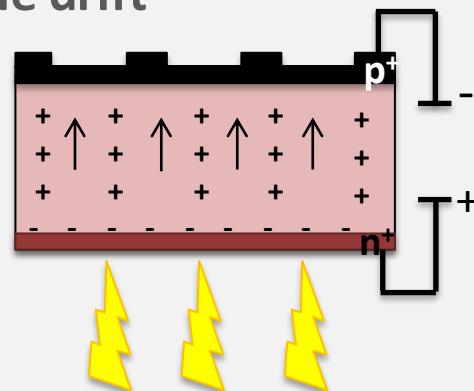
# CCE for MCZ200N: 23MeV p



Measurement details:

Red laser (670 nm), 0°C

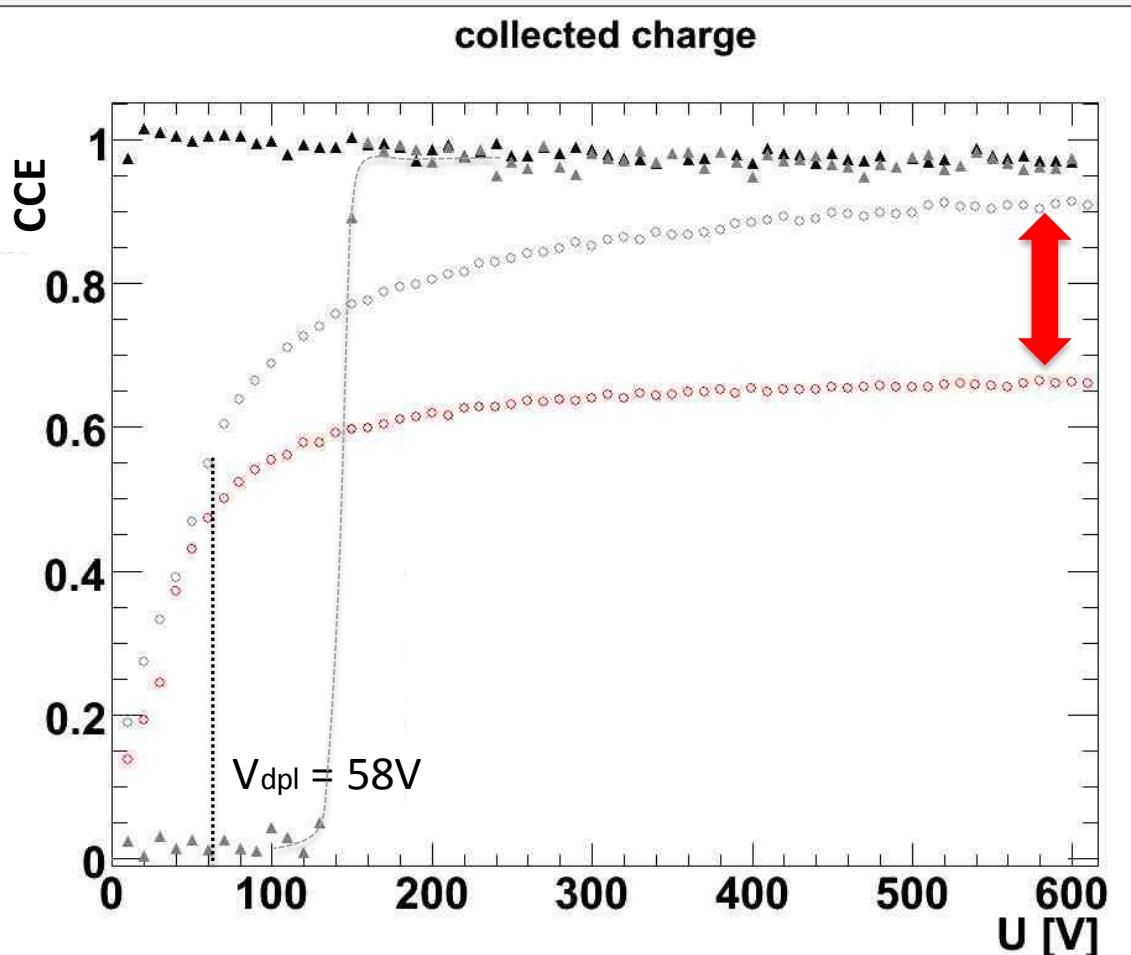
Rear side illumination:  
hole drift



Irradiated with 23MeV:  
Rear:  
charge loss 10%,  
strong increase of CCE also  
before full deletion is reached

$$\Phi_{\text{neq}} = 2.93 \times 10^{14} \text{ p/cm}^2$$

# CCE for MCZ200N: 23MeV p



Measurement details:  
Red laser (670 nm), 0°C

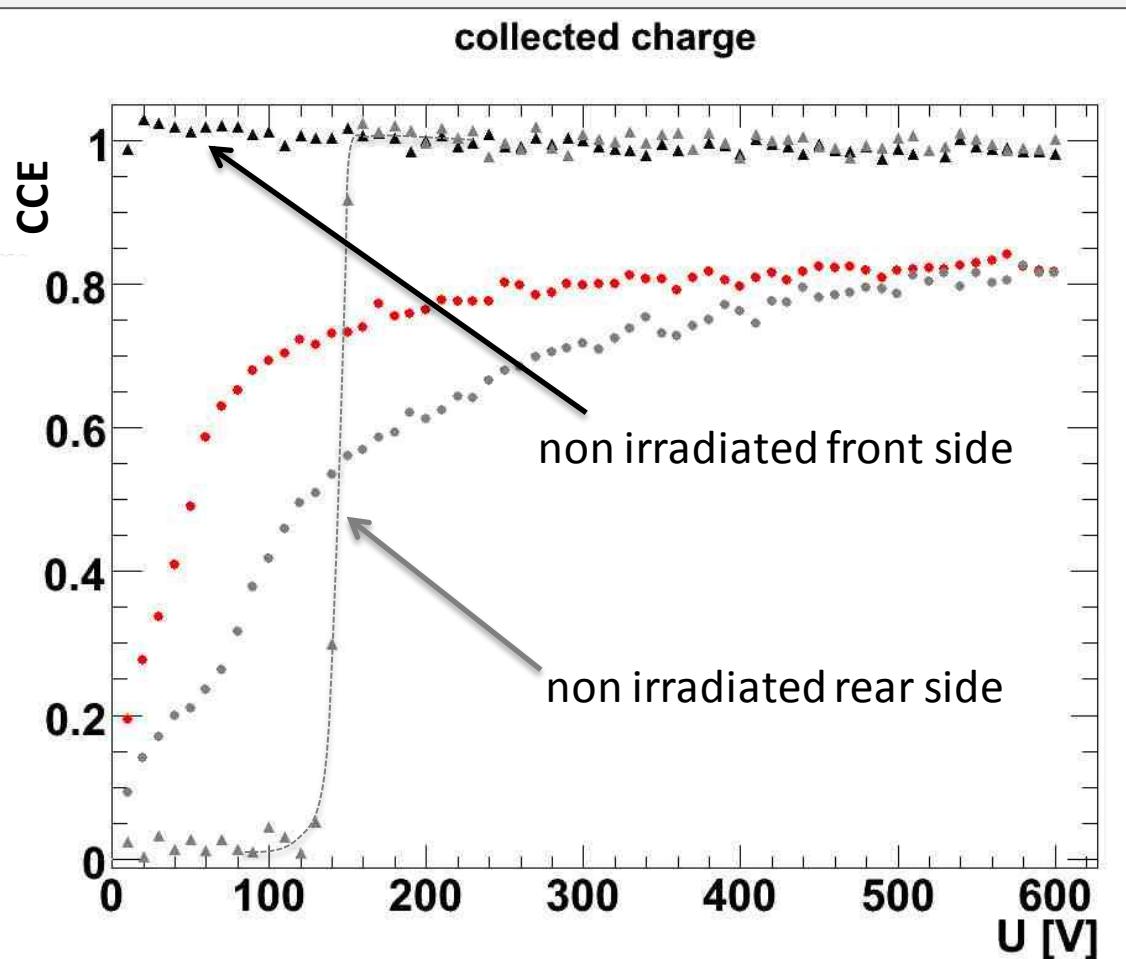
$$\Phi_{neq} = 2.93\text{E}14 \text{ cm}^{-2}$$

Irradiated with 23MeV:  
Charge collection mainly  
from the rear side

→ Higher electric field  
on the back side

→ inversion to p-type

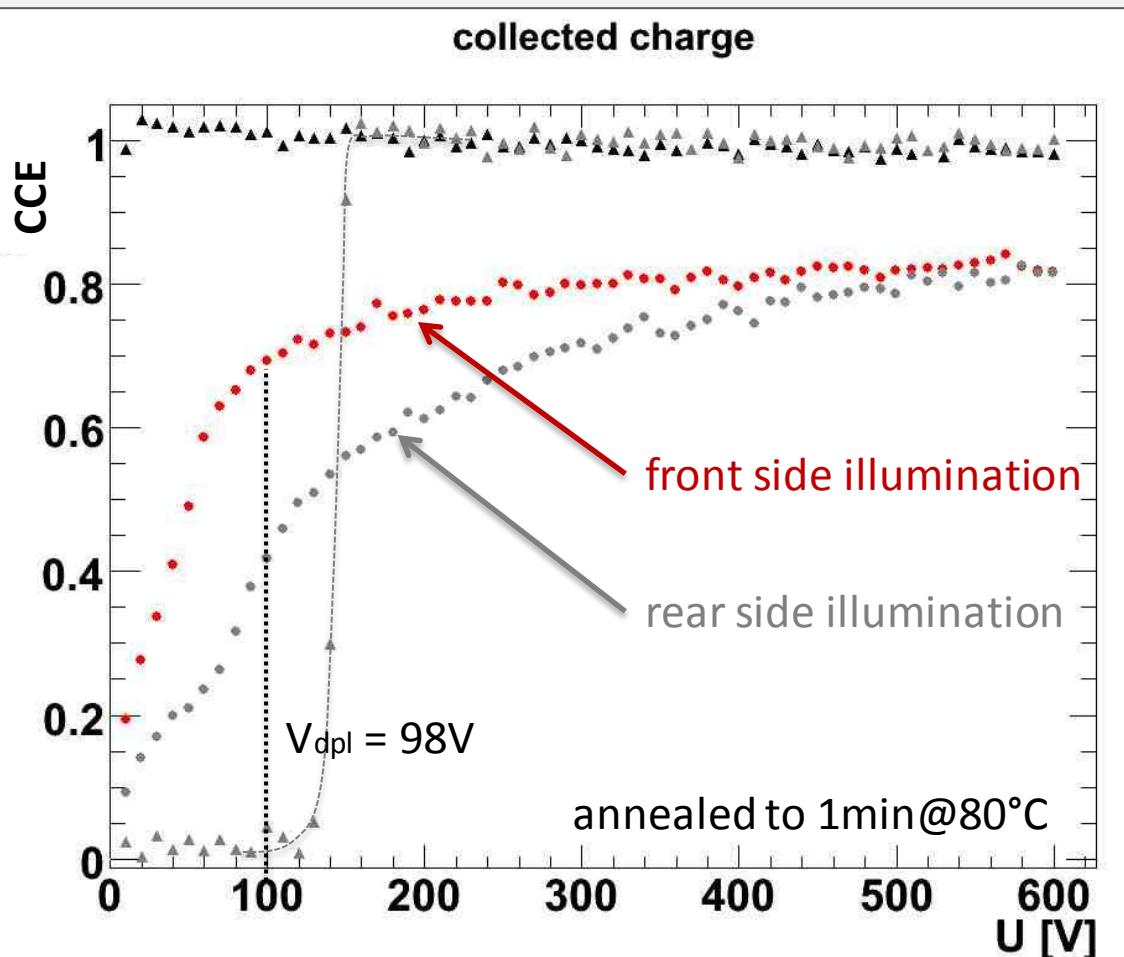
# CCE for MCZ200N: 23GeV p



Measurement details:  
Red laser (670 nm), 0°C

**Non-irradiated:**  
Front: Charge fully collected before  $V_{dep}$  reached  
Rear: Charge collection only after full depletion  
→ Depletion from front

# CCE for MCZ200N: 23GeV p



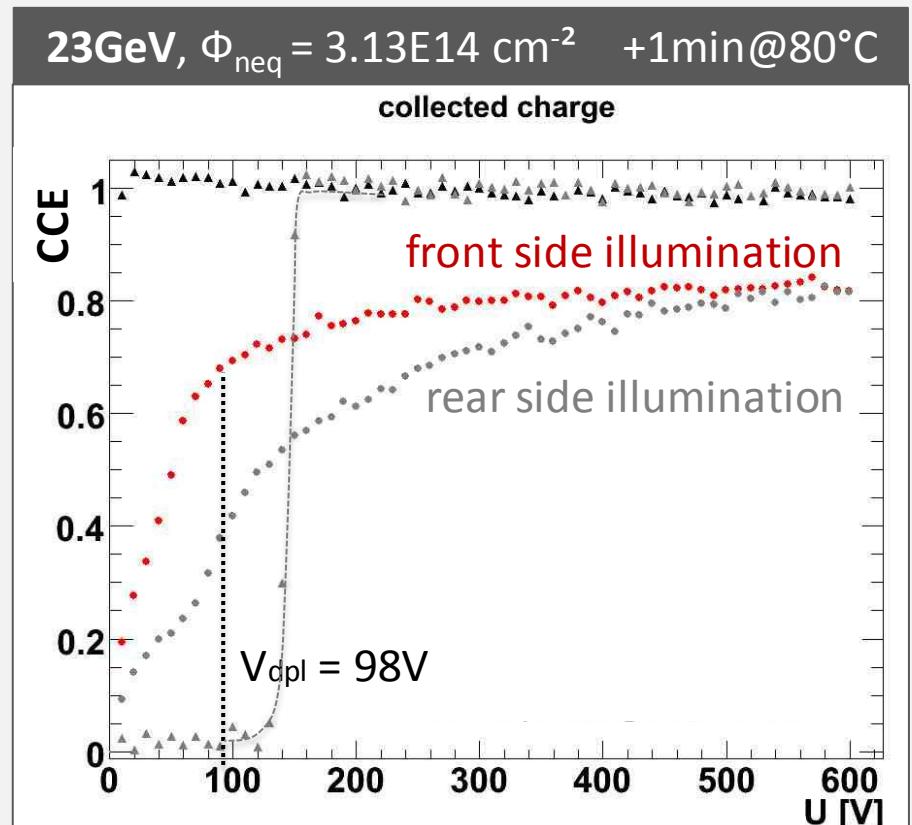
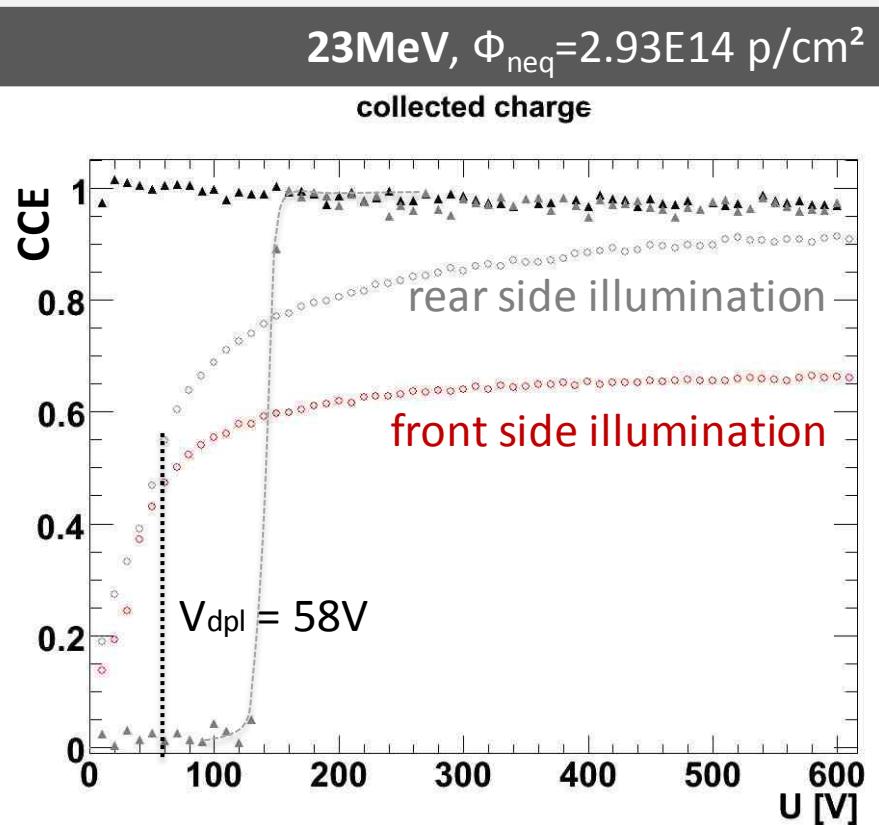
Measurement details:  
Red laser (670 nm), 0°C

$$\Phi_{neq} = 3.13E14 \text{ cm}^{-2}$$

Irradiated with 23GeV:  
Front: Still reasonable  
high signal before  $V_{dpl}$   
Rear: Signal present also  
at low voltages but  
much smaller than front

→ Double junction effect

# CCE for MCZ200N: 23MeV versus 23GeV

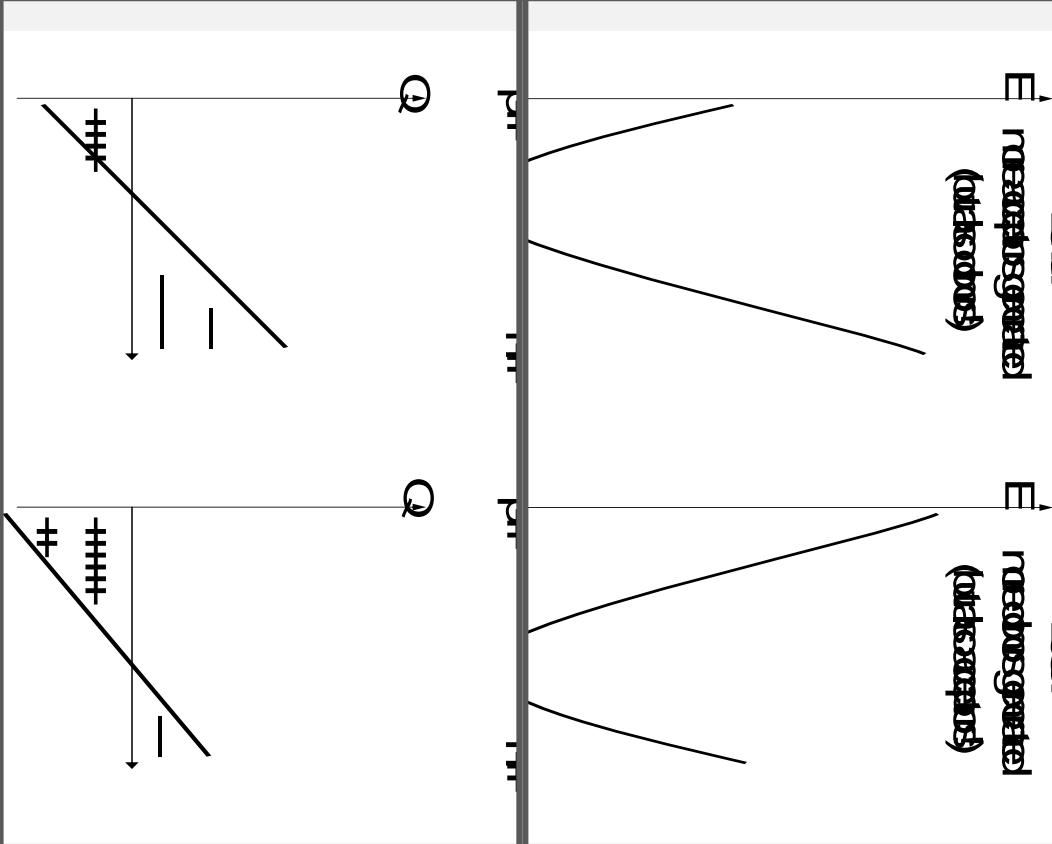


- behave like p-type
- high electric field on the back side

- behave like n-type, but shows a strong double junction effect

# Electric field for MCZ200N

Sketch of the electric field through the sensor



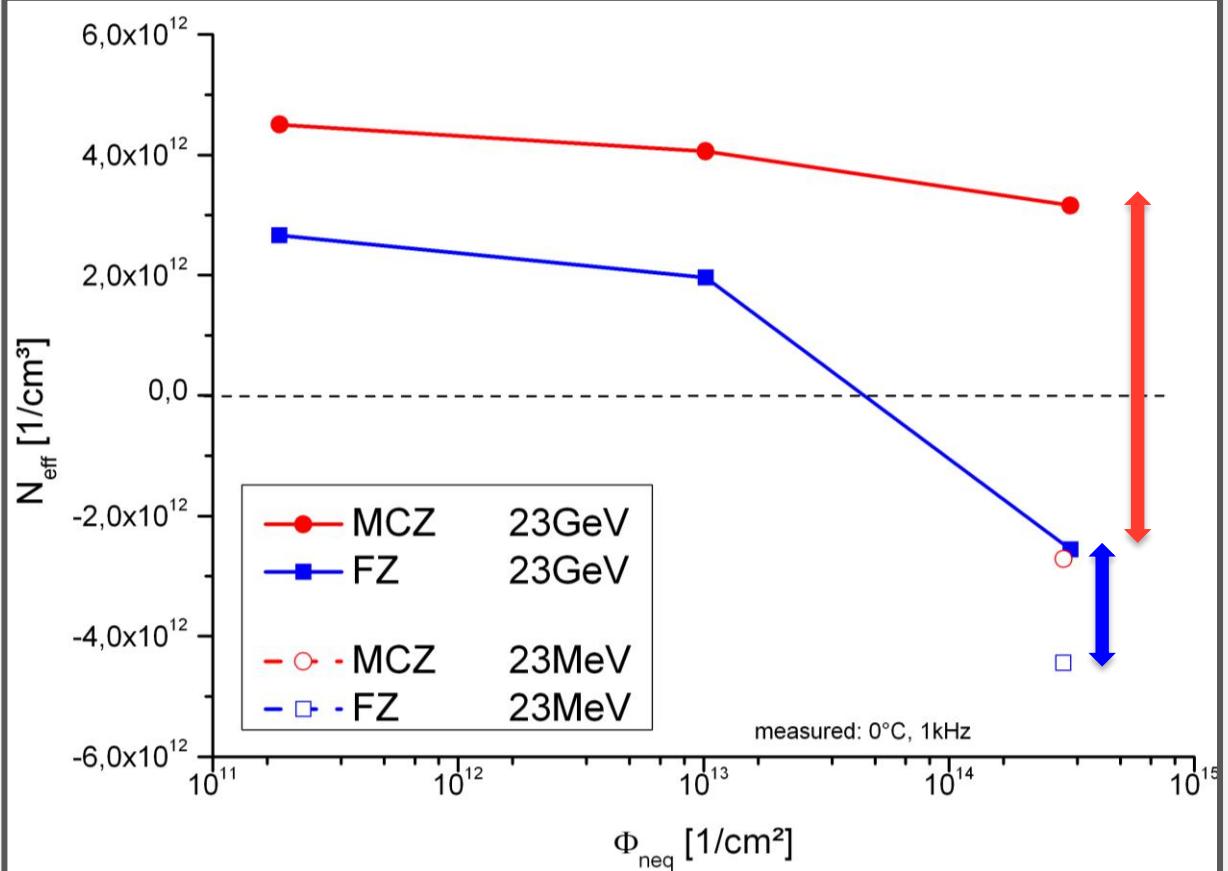
A. Dierlamm

the E-field is not linear through the volume anymore

- for the 23MeV we deplete from both sides
- for 23GeV stronger double junction effect (in the measurements)

# $N_{\text{eff}}$ of MCZ200N & FZ200N

annealed to 10min@60°C/1min@80°C



$$|N_{\text{eff}}| = \frac{2ee_0}{q_0} \frac{(V_{\text{dpl}} + V_{\text{bi}})}{d^2}$$

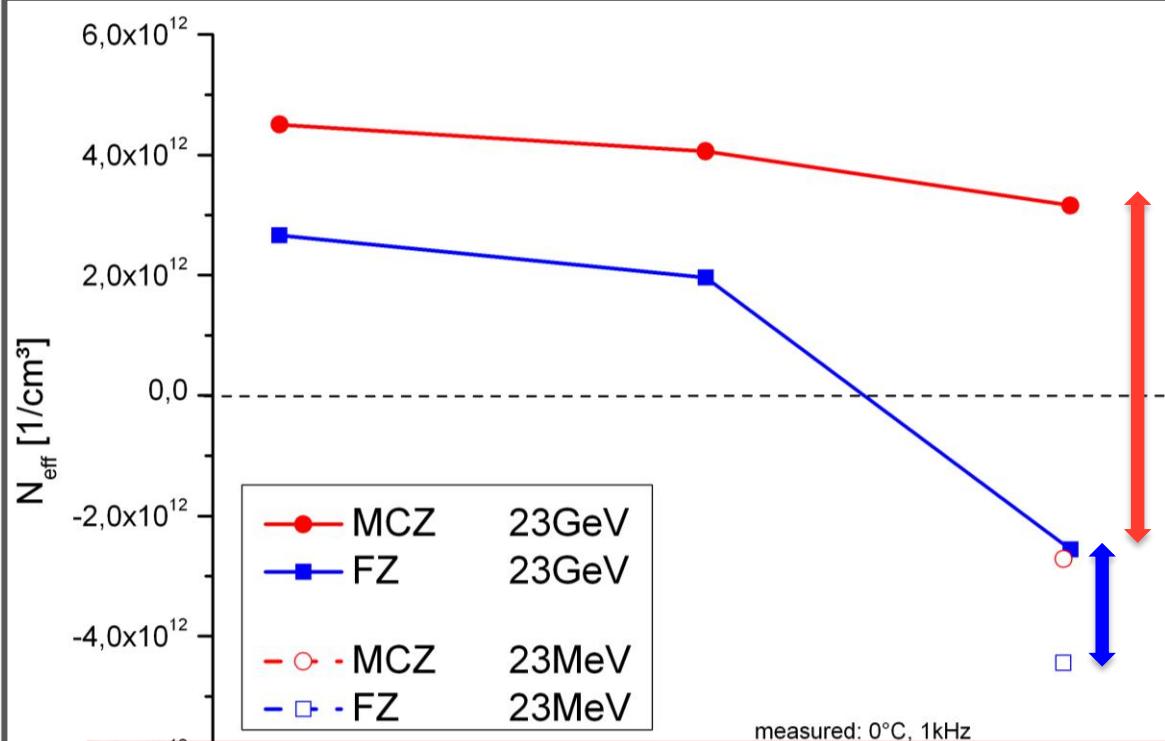
$N_{\text{eff}}$  out of  $V_{\text{dpl}}$  (CV)

Sign for  $N_{\text{eff}}$  out of annealing study and TCT measurements

Big difference in  $N_{\text{eff}}$ !

# $N_{eff}$ of MCZ200N & FZ200N

annealed to 10min@60°C/1min@80°C



Does the HPK material influence radiation induced defects?

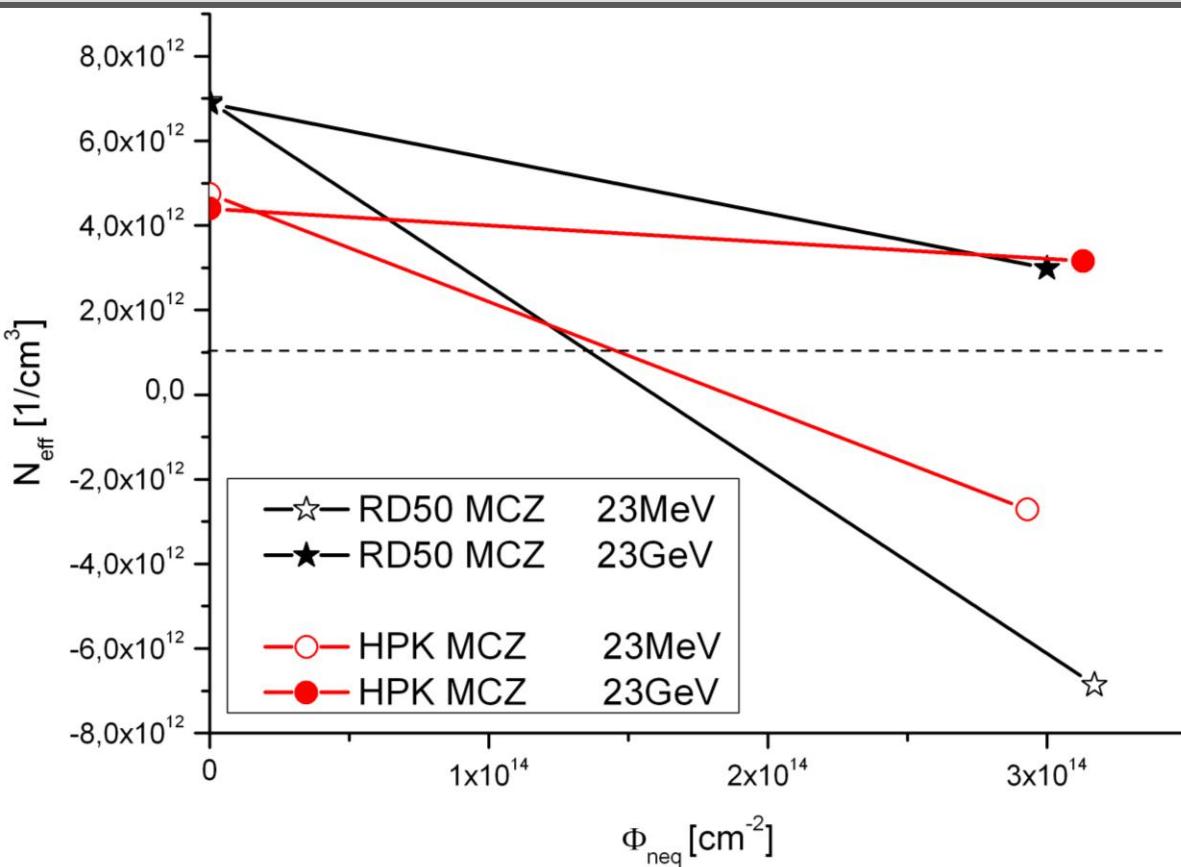
$$|N_{eff}| = \frac{2ee_0}{q_0} \frac{(V_{dpl} + V_{bi})}{d^2}$$

$N_{eff}$  out of  $V_{dpl}$  (CV)

Sign for  $N_{eff}$  out of annealing study and TCT measurements

Big difference in  $N_{eff}$ !

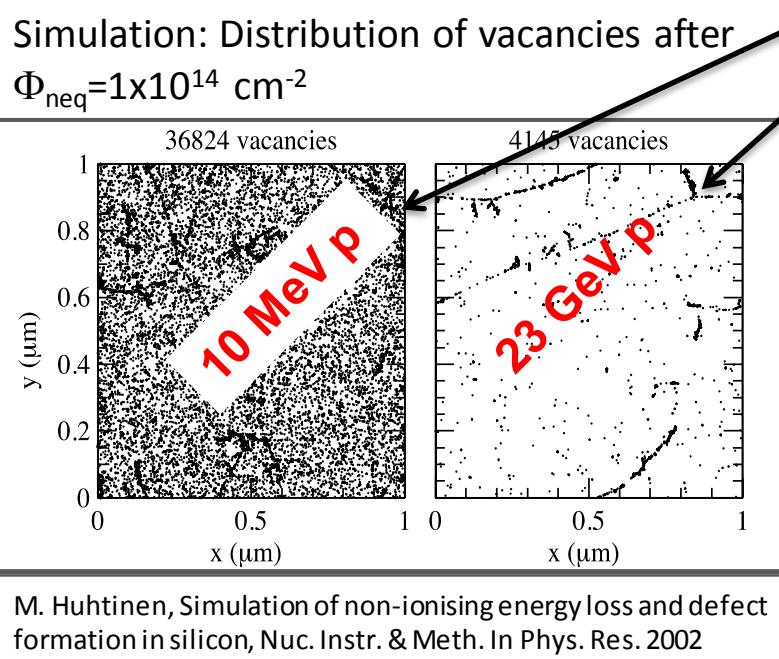
# $N_{\text{eff}}$ for RD50 & HPK MCZ



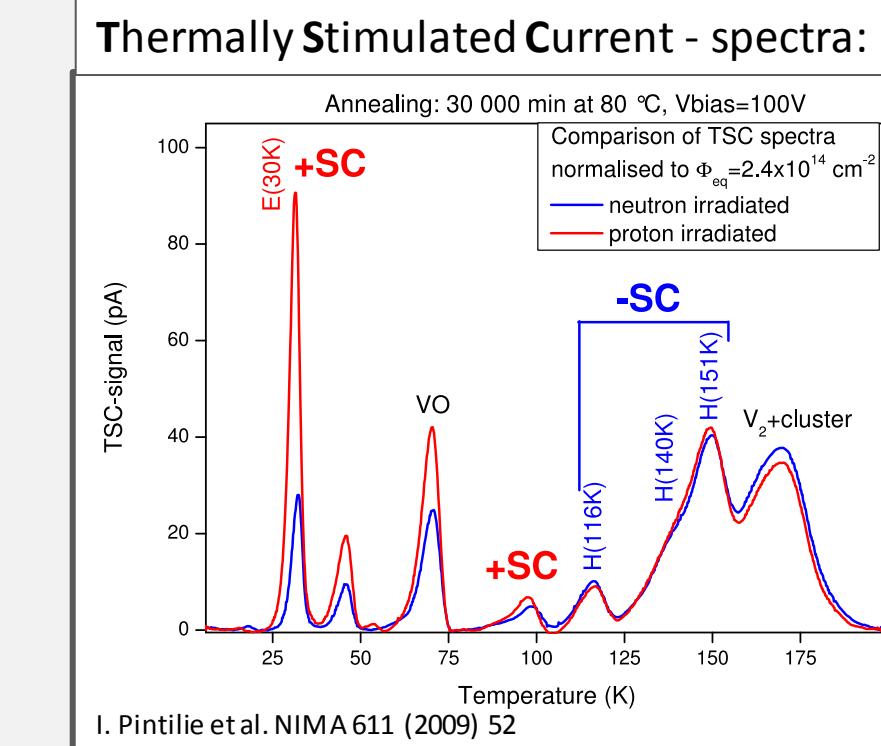
The low energy protons (23MeV) seem to create more acceptor-like defects, or less donor-like ones than the high energy protons (23GeV) do.

→ we conclude that the behaviour of the MCZ200N from Hamamatsu is related to the proton energy

# Explanation: defects with impact on $N_{\text{eff}}$



High number of point defects  
Point and cluster defects

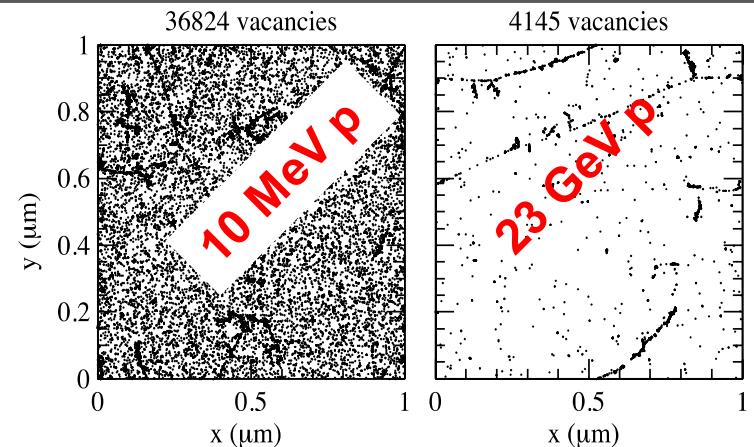


23 GeV protons create much more shallow  
Donors **E30K** than 1 MeV neutrons,  
this overcompensates deep acceptor  
generation of **H-defects** for 23 GeV protons

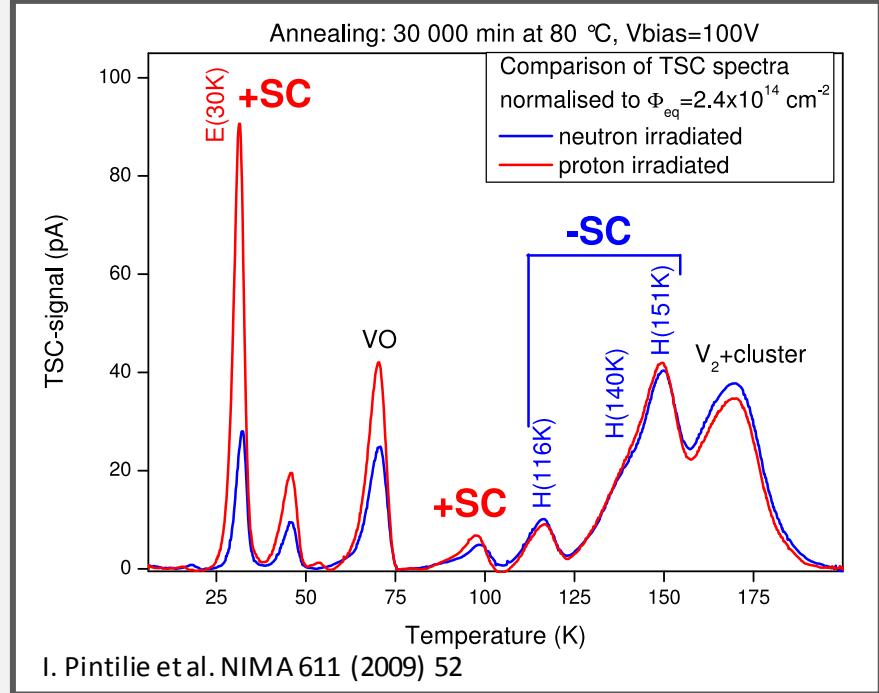
→ no type inversion for 23 GeV protons

# Explanation: defects with impact on $N_{\text{eff}}$

Simulation: Distribution of vacancies after  
 $\Phi_{\text{neq}} = 10^{14} \text{ cm}^{-2}$



M. Huhtinen, Simulation of non-ionising energy loss and defect formation in silicon, Nuc. Instr. & Meth. In Phys. Res. 2002

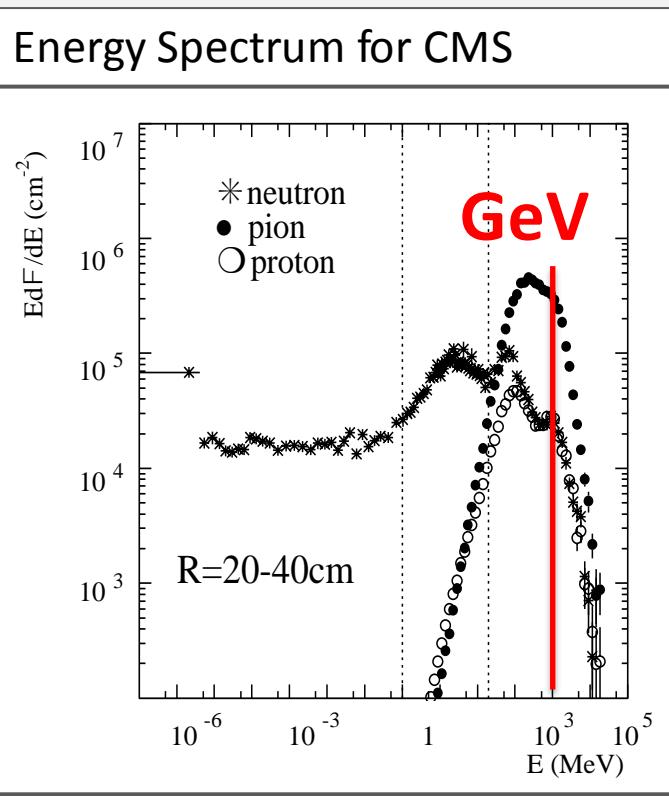


To identify the impact of the proton energy on the defect generation:

- TSC measurements on 23 MeV irradiated samples needed

# Future plans

The HPK campaign will do additional proton irradiations at the PS with 23GeV!



Pion damage dominant in inner region (similar to GeV proton damage)

Pion energies in the range of a few hundred MeV to GeV

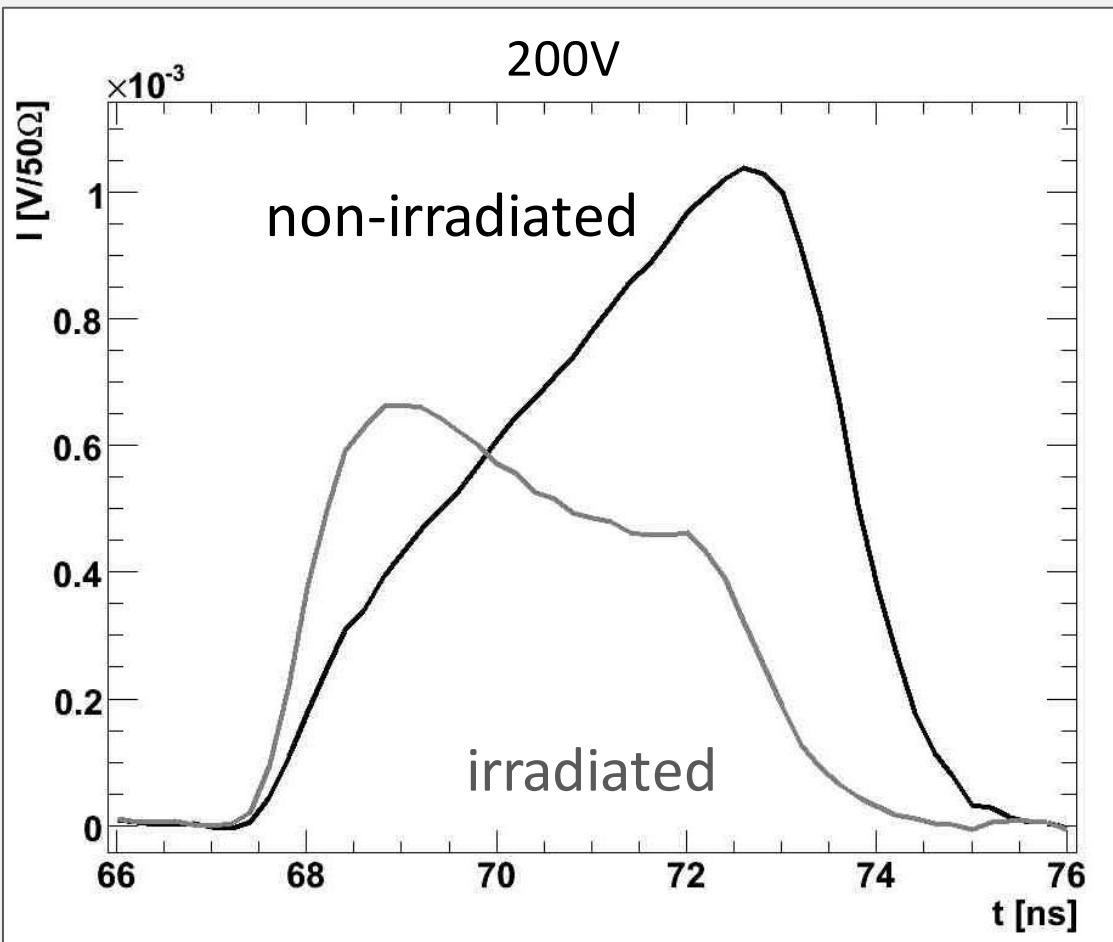
→ we have to investigate other proton sources with comparable energies

# Summary:

- **proton irradiation with different particle energies have an impact on the electrical properties of the detector**  
(shown for MCZ and FZ)
- **Microscopic studies of the defects with impact on the effective doping concentration are necessary**  
(further samples will be irradiated with 23MeV to measure TSC-spectra)
- **Systematic studies of irradiations with protons of different energies would help to gain a better understanding of the defect creation mechanism and the defect properties**

# Back up:

# TCT-pulse MCZ200N: 23GeV p



Measurement details:  
Red laser (670 nm), 0°C

**Rear illumination:**

**Hole drift**

$\Phi_{neq} = 3.13E14 \text{ cm}^{-2}$   
annealed to 1min@80°C

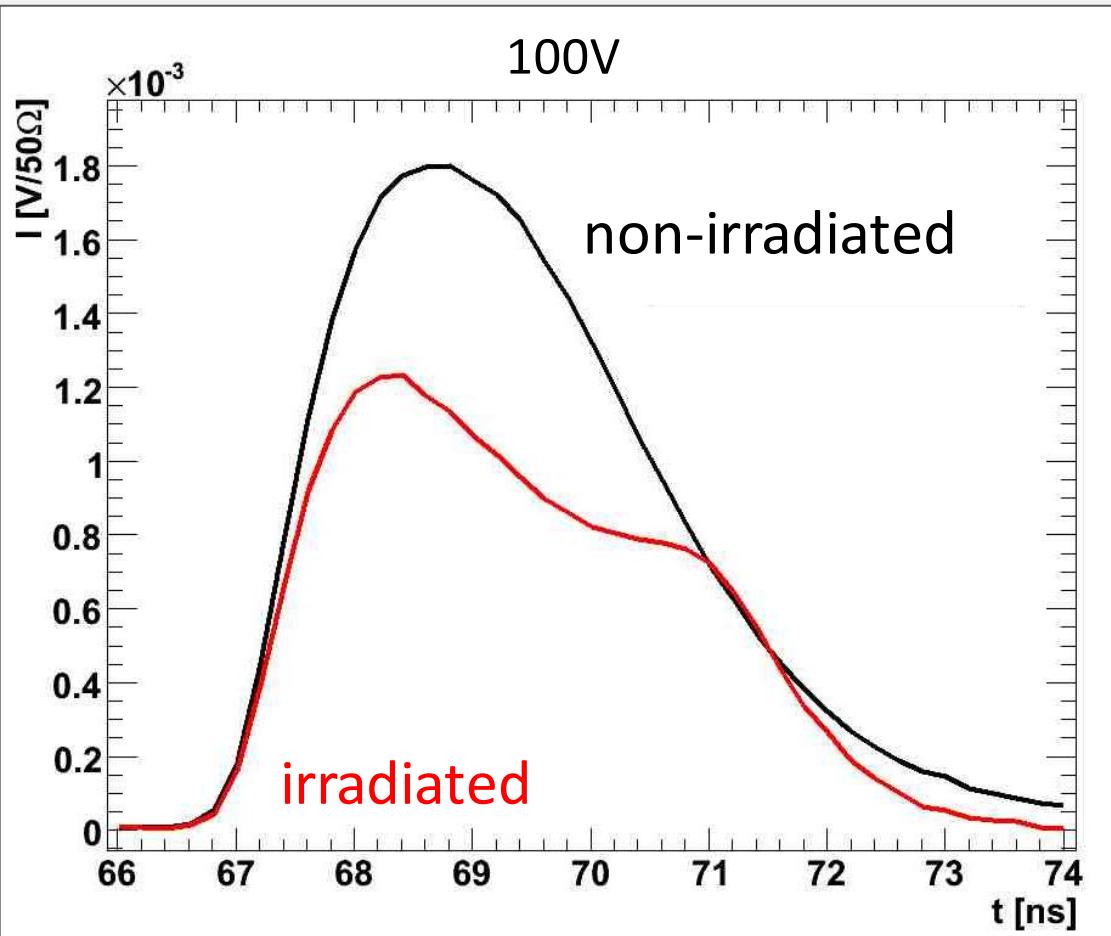
**Irradiated with 23GeV:**

Rear:

Signal present also at  
low voltages but much  
smaller than front

→ Double junction

# TCT-pulse MCZ200N: 23GeV p



Measurement details:  
Red laser (670 nm), 0°C

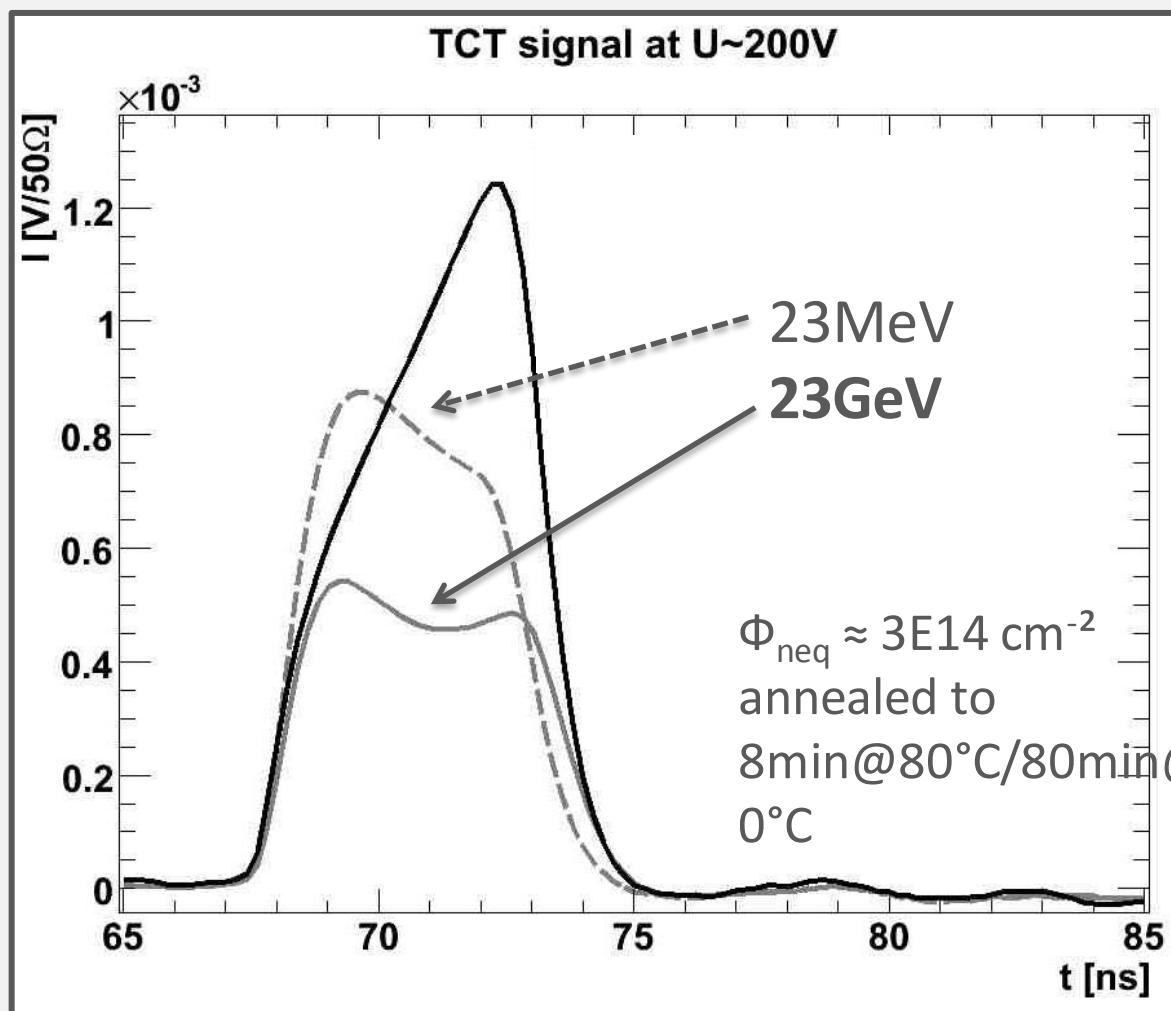
Front illumination:  
Electron drift

$\Phi_{\text{neq}} = 3.13E14 \text{ cm}^{-2}$   
annealed to 1min@80°C

Irradiated with 23GeV:  
Front: Still reasonable  
high signal before  $V_{\text{dpl}}$

→ Double junction

# TCT-pulse MCZ200N: 23GeV & 23MeV p



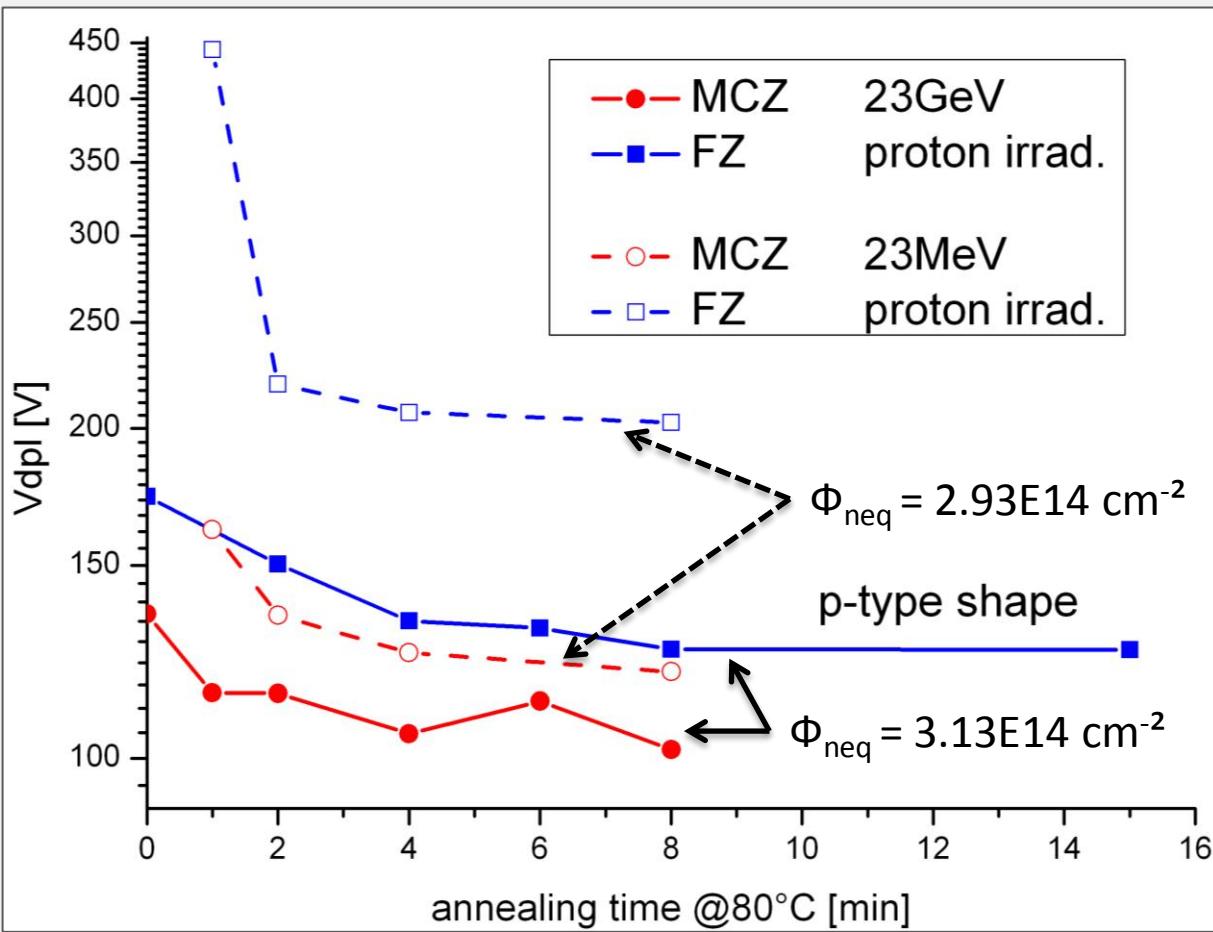
Measurement details:  
Red laser (670 nm), 0°C

Rear illumination:  
Hole drift

23GeV:  
Strong double junction  
effect

23MeV:  
High electric field on the  
back side

# Annealing of p-type: 23GeV vs. 23MeV p

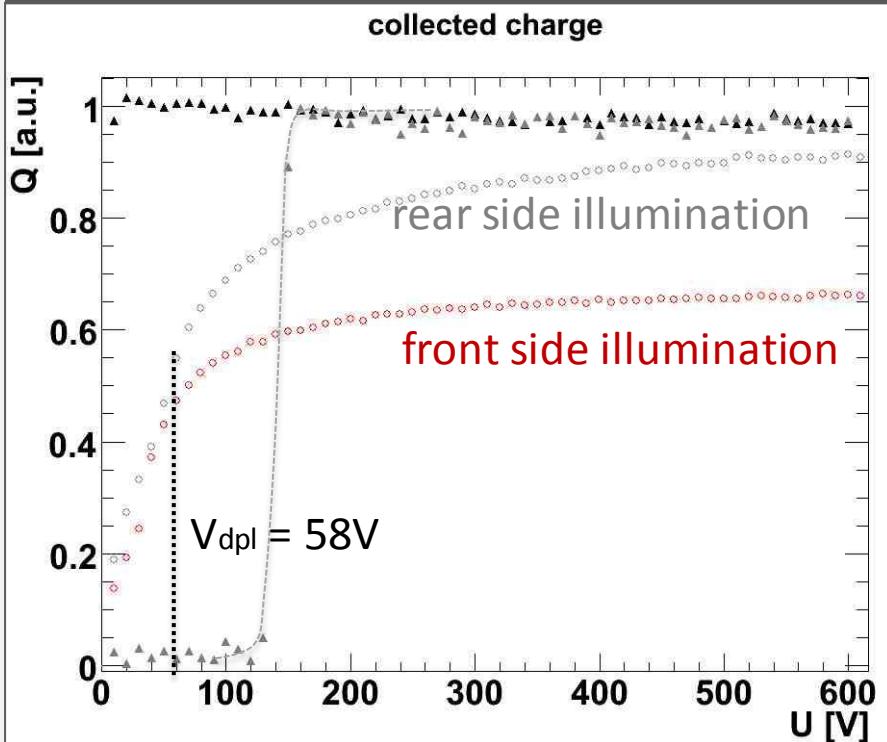


MCZ200Y &  
FZ200Y:

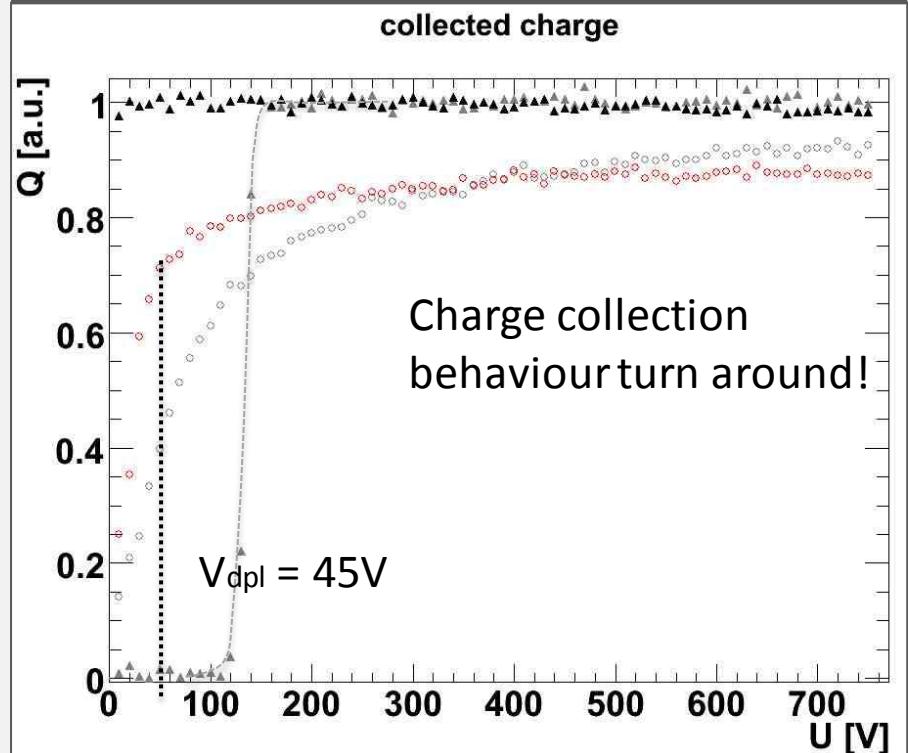
The p-type  
material stays p-  
type after both  
proton irradiations

# CCE for MCZ200N: 25MeV p + 8min@80°C

10min@60°C



80min@60°C

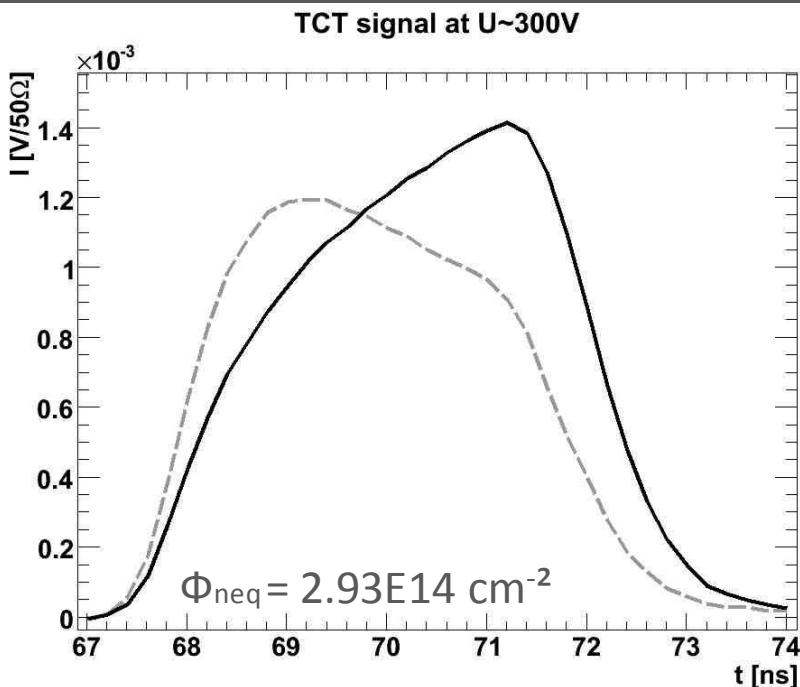


After the annealing to 80min@60°C the charge collection from the front side rises up again!

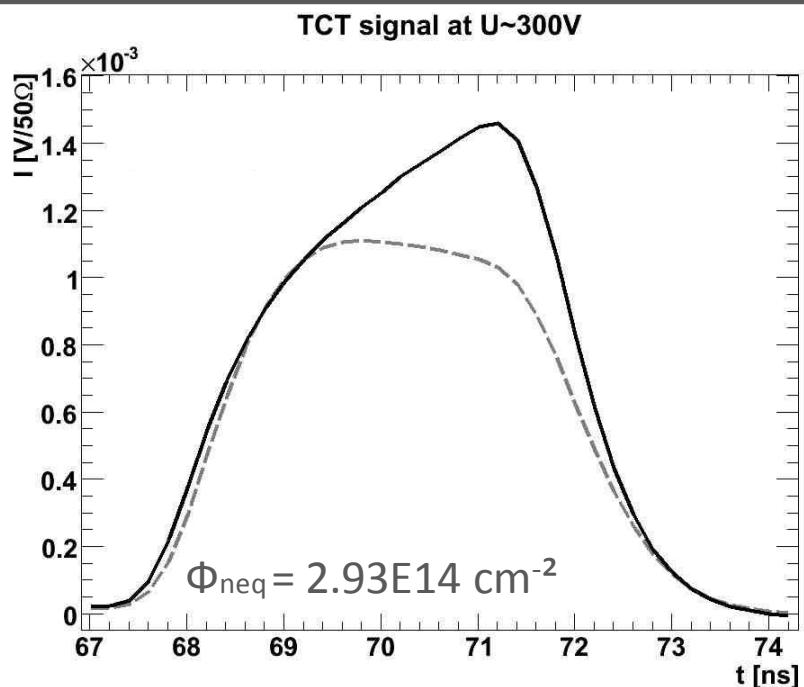
# TCT for MCZ200N: 25MeV p + 8min@80°C

TCT pulse: rear side illumination with red laser at 300V

10min@60°C



80min@60°C

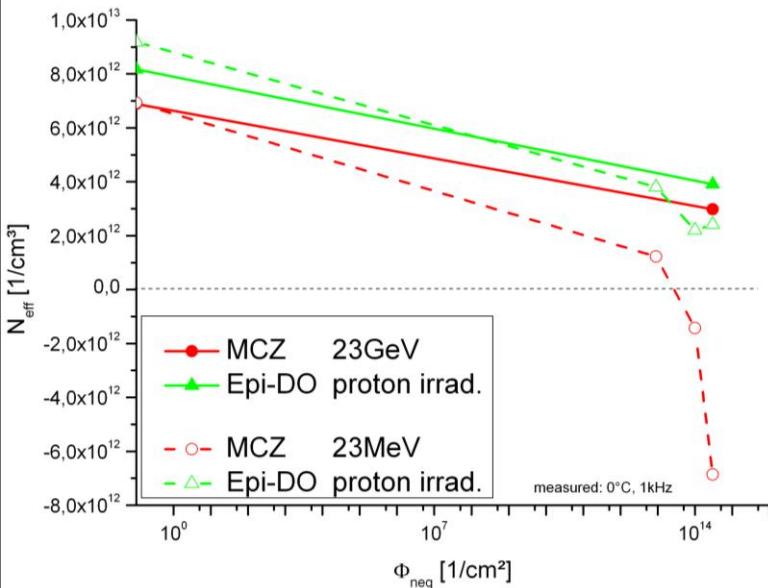


Does the slope of the pulse change the sign?

# $N_{\text{eff}}$ of the RD50 material

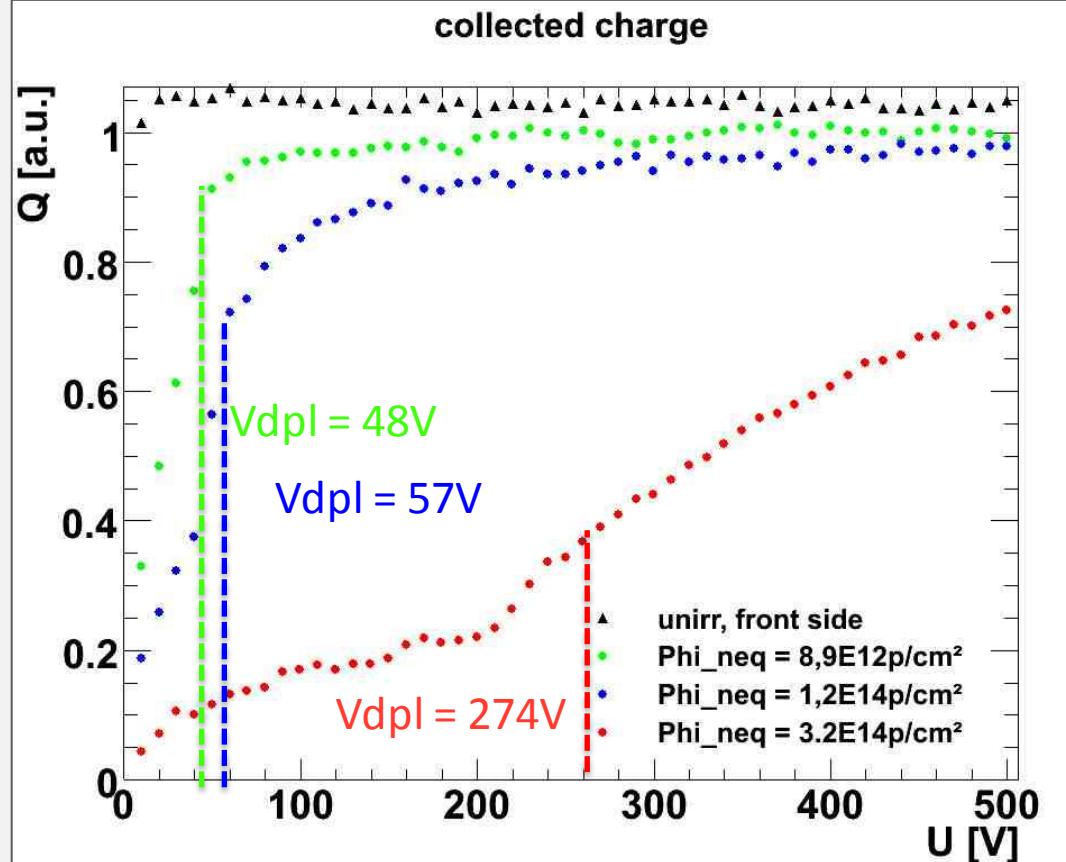
**Front side illumination:**  
electrons are drifting through the bulk

RD50 Si-diodes (as irradiated)



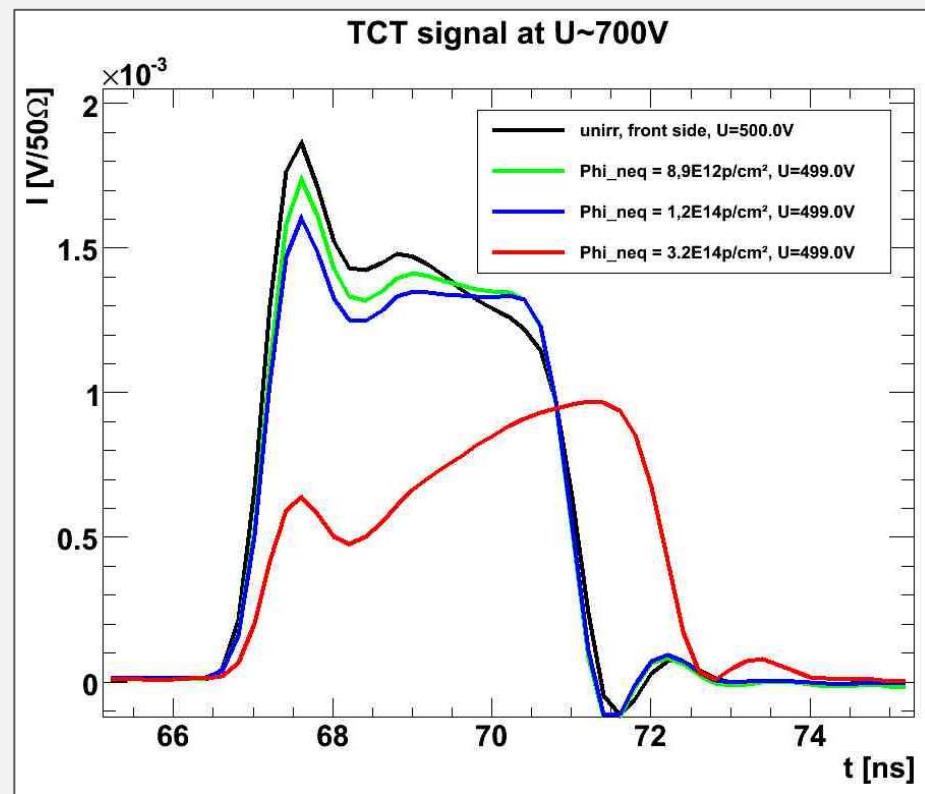
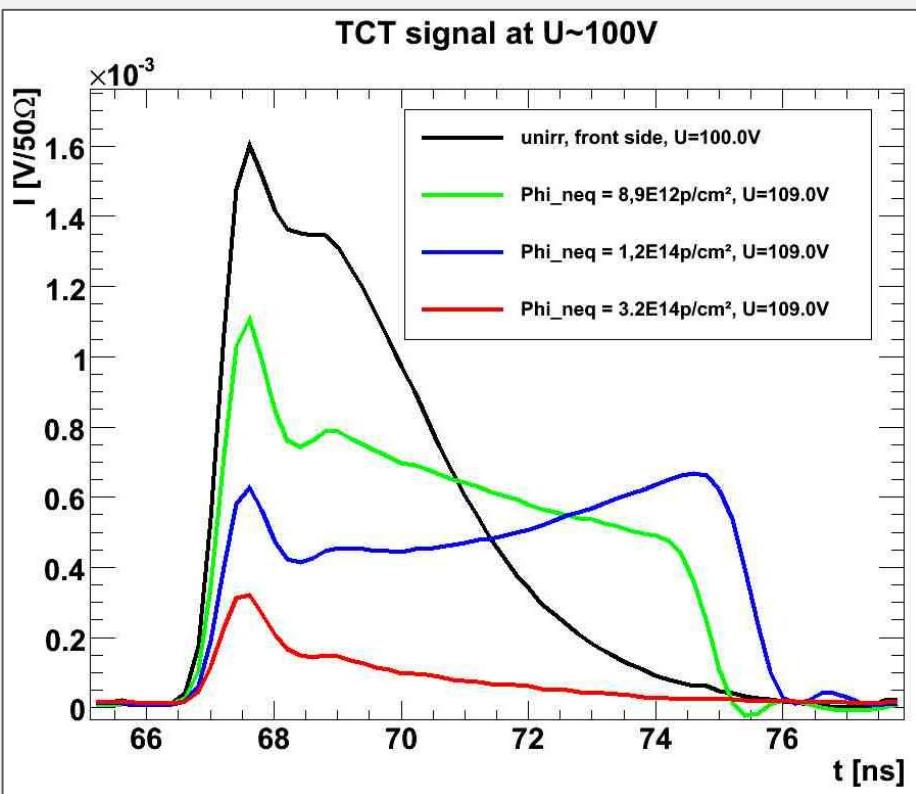
$\Phi_{\text{neq}} = 1.2 \text{E}14 \text{ cm}^{-2}$ :

The charge are mainly getting collected just after depletion



# TCT-pulses of the RD50 material

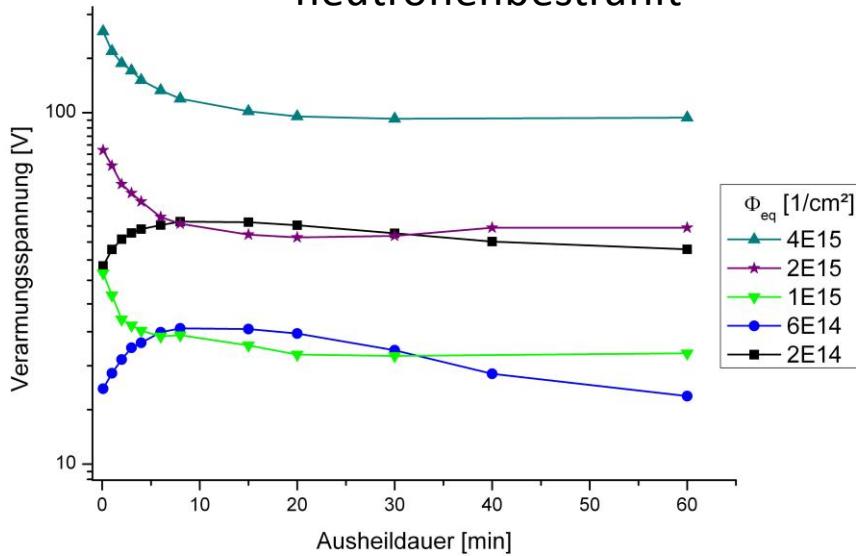
TCT pulses: front side illumination with red laser at 100V and 700V



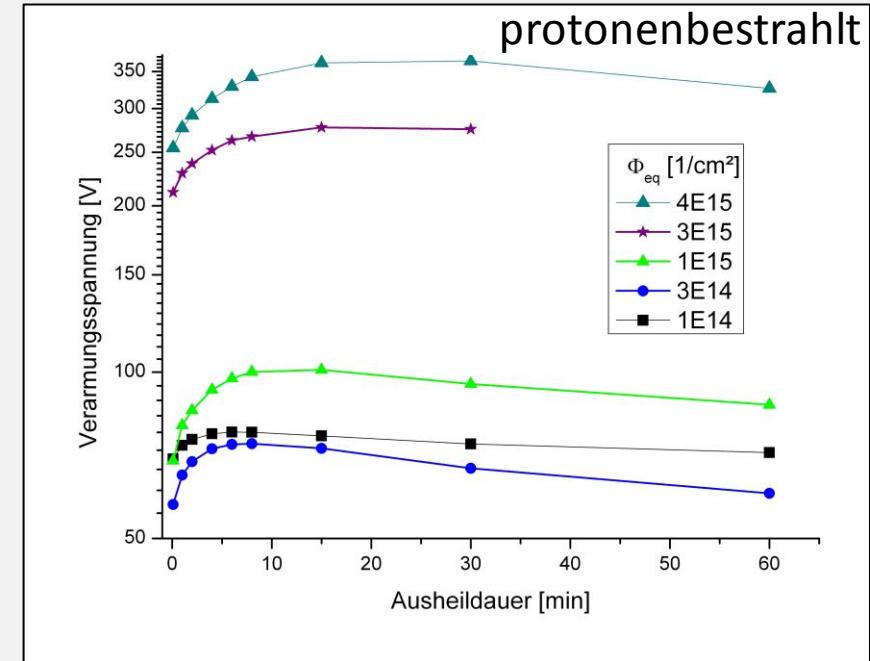
# Messergebnisse n-Typ nach Bestrahlung

## Annealing-Studie (80°C) an 75µm Epi-DO

neutronenbestrahlt

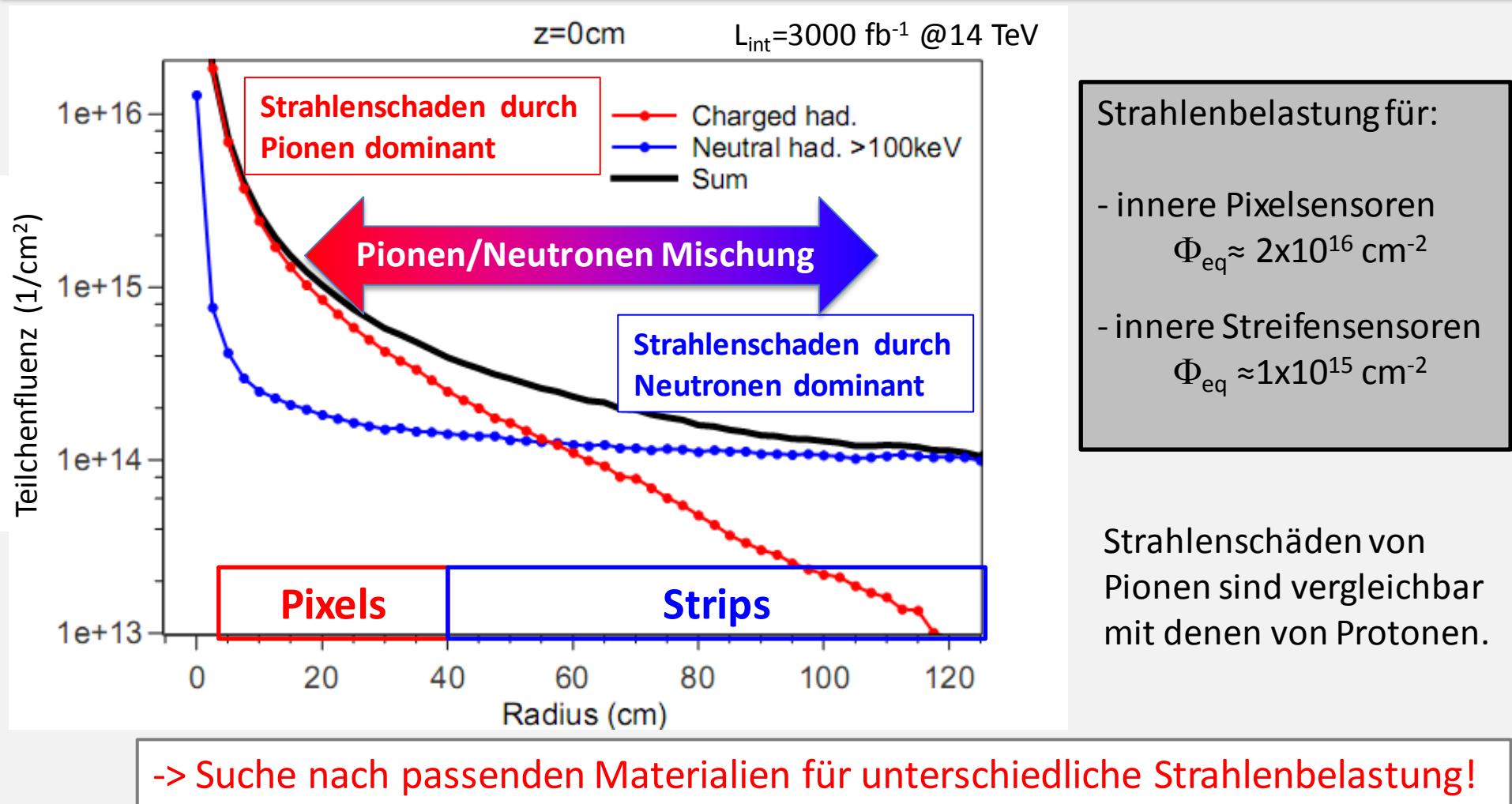


Zwischen den Fluenzen von 6E14 und 1E15 dreht sich das Anfangsverhalten um (siehe p-Typ)  
-> Typeninversion

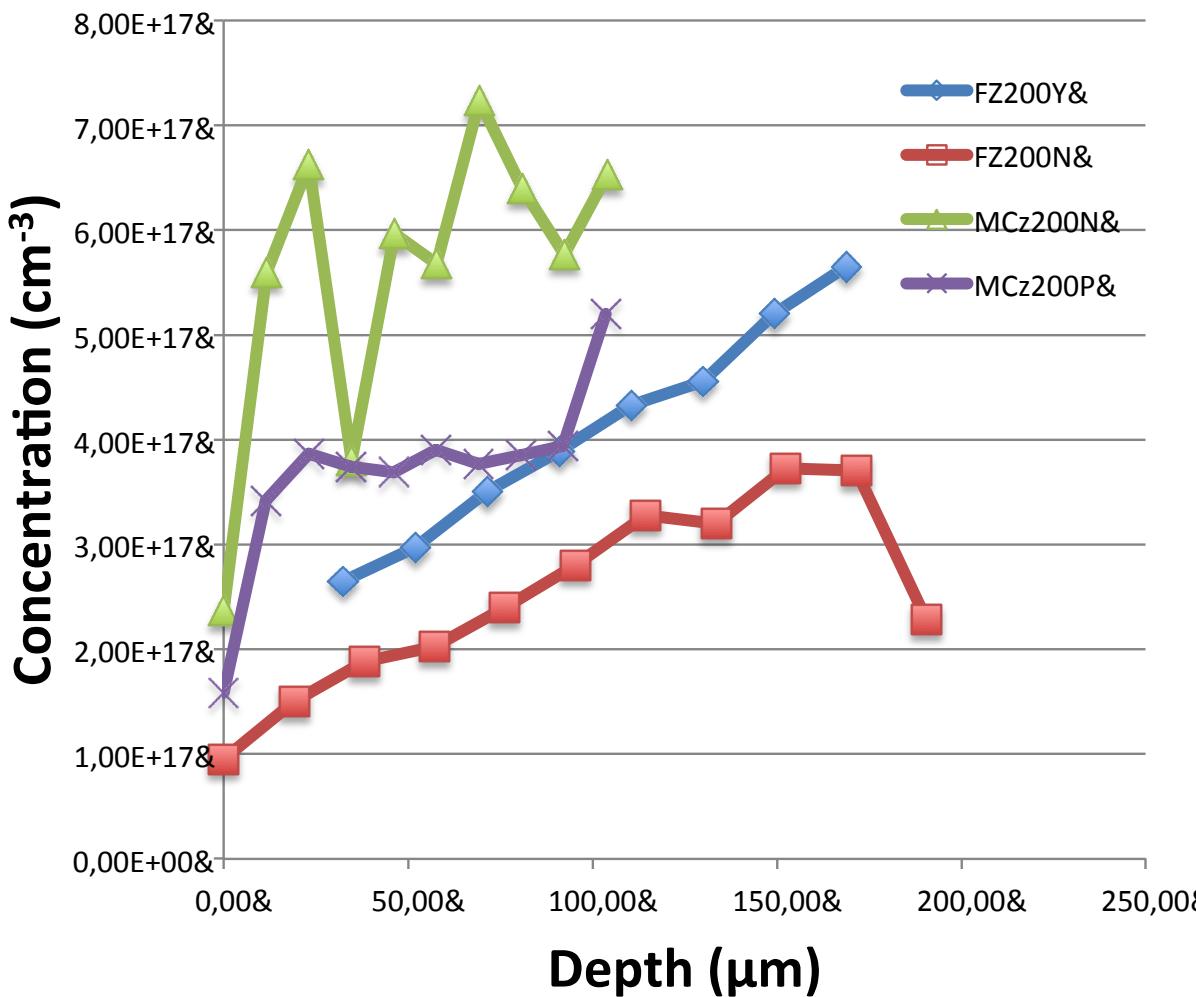


n-Typ zeigt typischen Anstieg der Verarmungsspannung, „*short term annealing*“:  
- Donatoren werden gebildet oder Akzeptoren heilen aus  
-> keine Typeninversion

# Strahlenbelastung am HL-LHC



# Oxygen profiles: SIMS



High O for MCz  
 $[O]=4\text{-}6\text{E}17 \text{ cm}^{-3}$

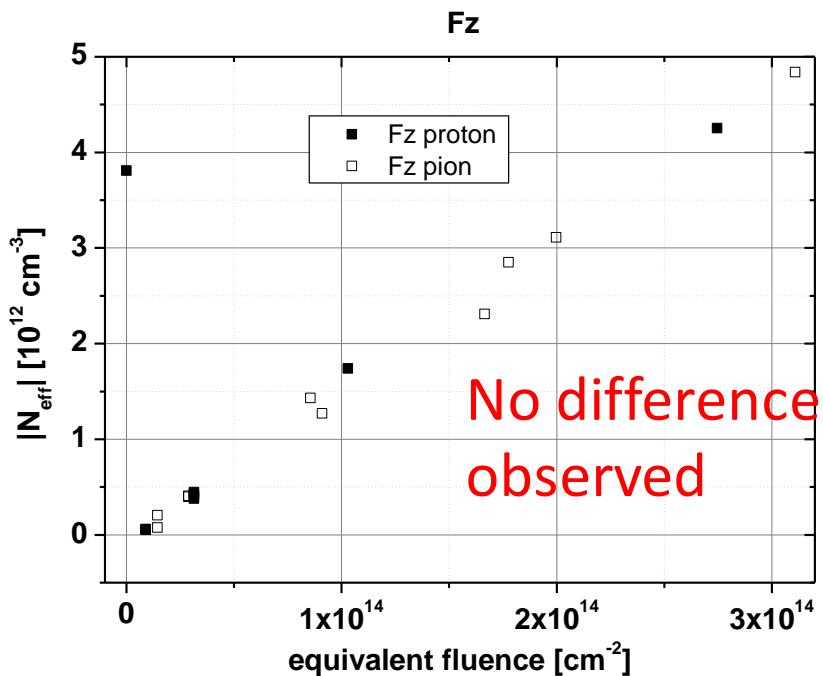
High O for FZ  
 $[O]=2\text{-}4\text{E}17 \text{ cm}^{-3}$

SIMS: ITME



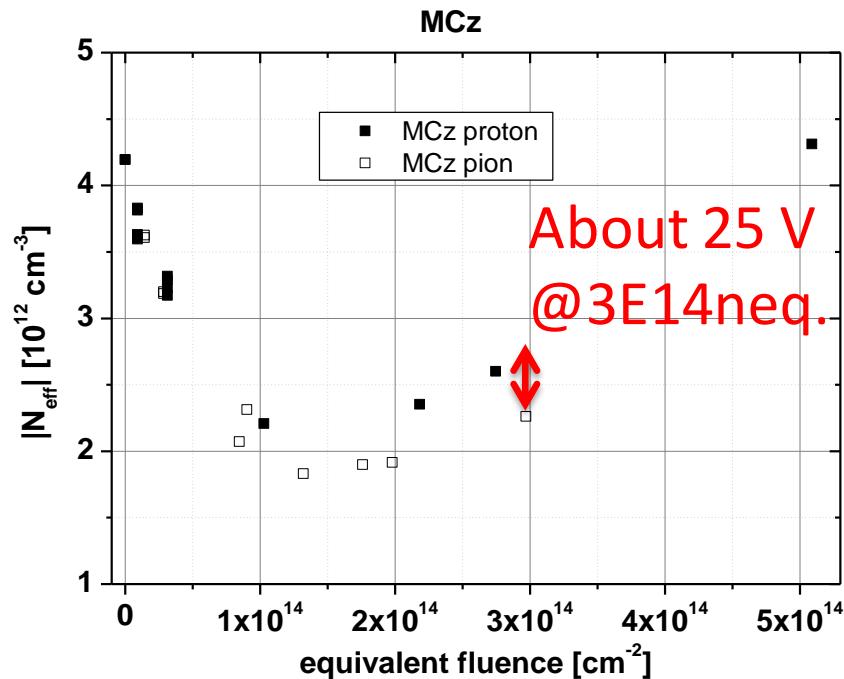
# Do 23 GeV p simulate 300 MeV $\pi$ ?

RD50 FZ



Yes for low O material

RD50 MCz



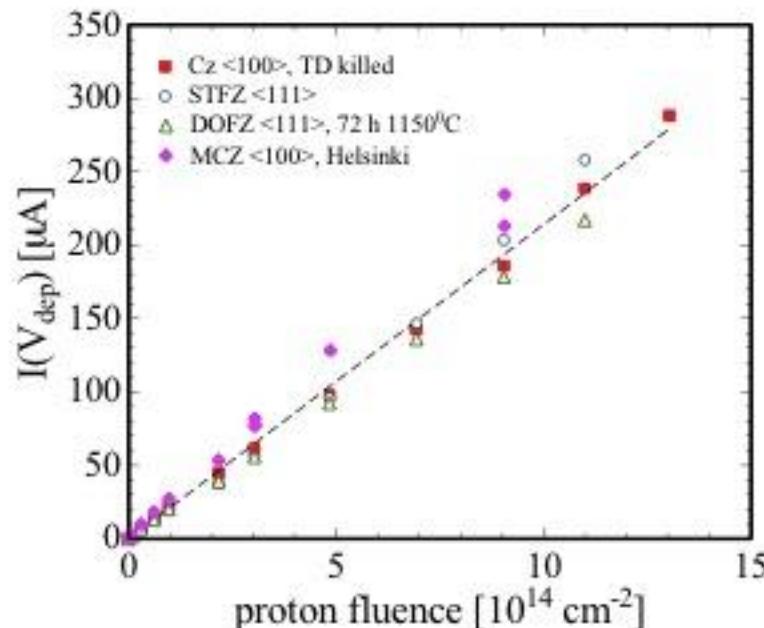
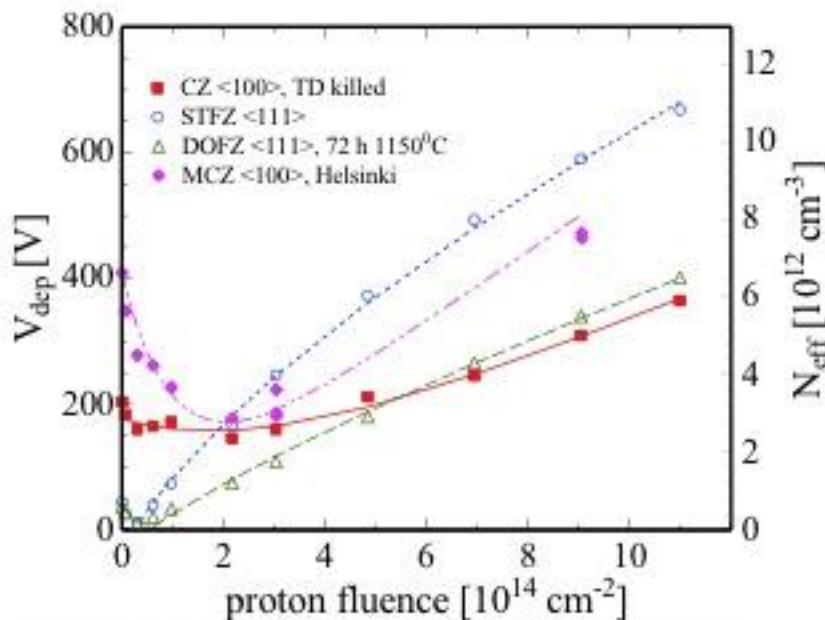
Quite ok for high O

No type inversion for MCz after  $\pi$

# High Resistivity MCz and Cz-Silicon - 24 GeV/c Protons

## CERN-SCENARIO EXPERIMENT

### Comparison with standard FZ-, DOFZ-silicon



- Cz silicon: no inversion in full  $\Phi$  range  
 $\beta_{\text{eff}} = +5.4 \times 10^{-3} \text{ cm}^{-1}$   
 $c = 3.3 \times 10^{-15} \text{ cm}^2$
- MCz silicon: no inversion in full  $\Phi$  range  
 $\beta_{\text{eff}} = +5.5 \times 10^{-3} \text{ cm}^{-1}$   
 $c = 9.5 \times 10^{-15} \text{ cm}^2$

- Same  $I_{\text{rev}}$  increase for all materials
- MCz:  $\langle \alpha_{\text{proton}} \rangle = (3.5 \pm 0.2) \text{ } 10^{-17} \text{ A/cm}$