# On MCz SCSI after 24 GeV/c proton irradiation

**D. Creanza**

**On behalf of the Bari and Pisa RD50 groups**

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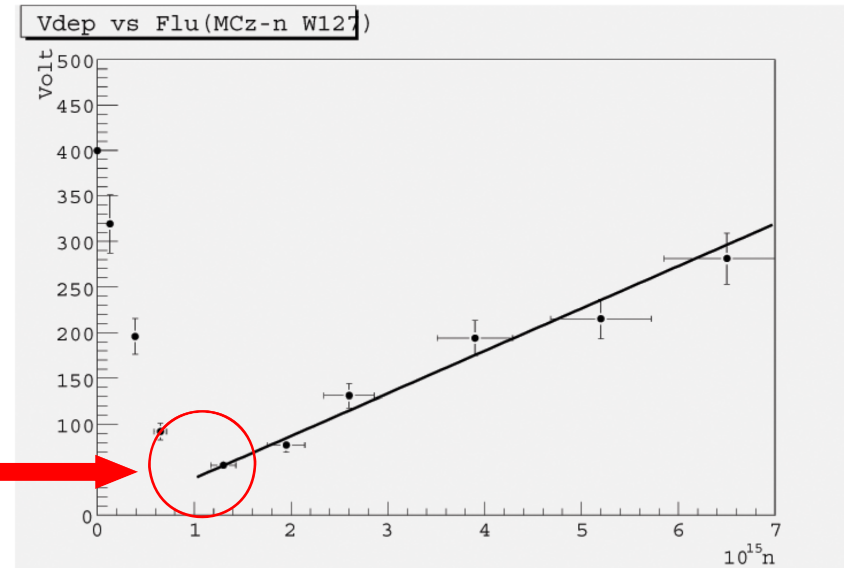
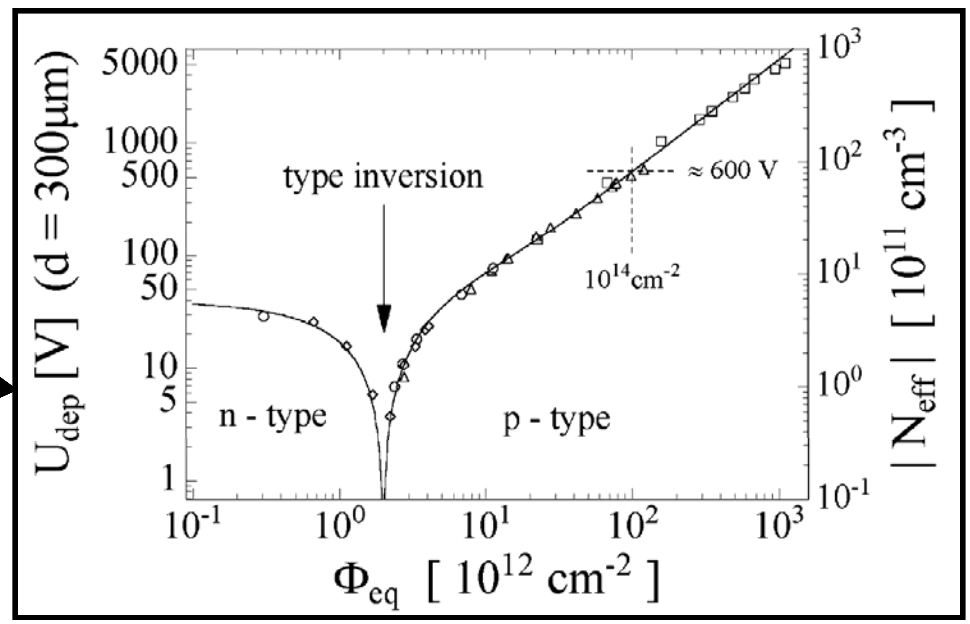
# The inversion puzzle on MCz devices – Overview-1

- Irradiation with 26 MeV protons and reactor neutrons causes MCz-n silicon to “invert” to p-type
  From TCT: the junction on the back becomes dominant
- The inversion takes place at a Vdep > 0 V: first sign of double junction (DJ) effects
- The behaviour is similar to that observed in FZ-n silicon, though in this case the fluence at which inversion takes place is much lower (~$10^{12} n_{eq}/cm^2$)
  No DJ (that comes into play at higher fluences), bulk effect.



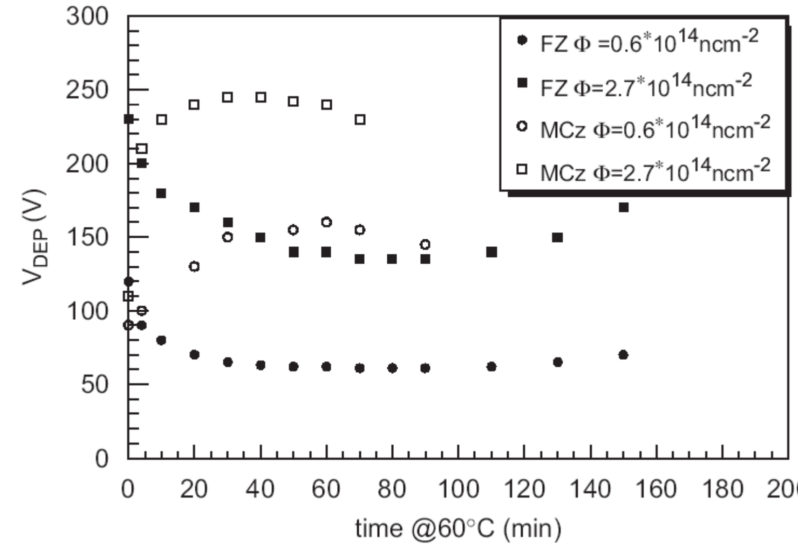
# Overview-2

## Irradiation of MCz silicon with 24 GeV/c protons

Previous annealing studies shew no type inversion in MCz-n silicon irradiated with 24 GeV/c protons.

Confirmed by only few (somewhat questioned) TCT measurements

If this is due to donor introduction, shouldn't MCz-p "invert"?

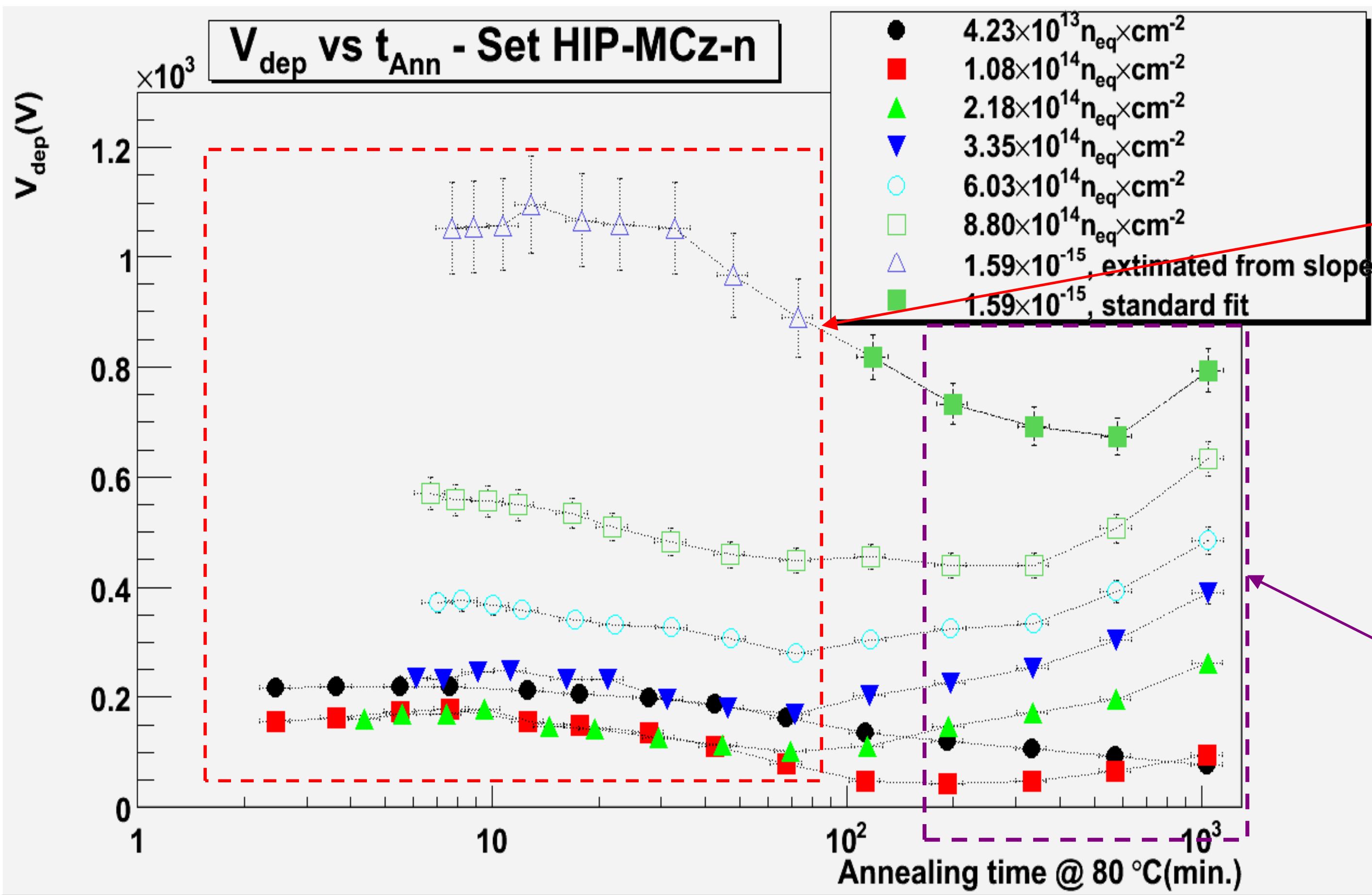



We have irradiated MCz-n and MCz-p diodes with 24 GeV/c protons up to an equivalent fluence of $1.59 \cdot 10^{15}$ n/cm$^2$.

The samples have been electrically characterized (IV/CV) during annealing. Twin diodes were studied with TCT, using the JSI (Ljubljana) setup

| Producer | Subst. | Studies performed |
|---|---|---|
| SMART | MCz-n (300 μm) | Annealing (CV/IV), TCT |
| | MCz-p (300 μm) | |
| HIP | MCz-n (300 μm) | Annealing (CV/IV) |

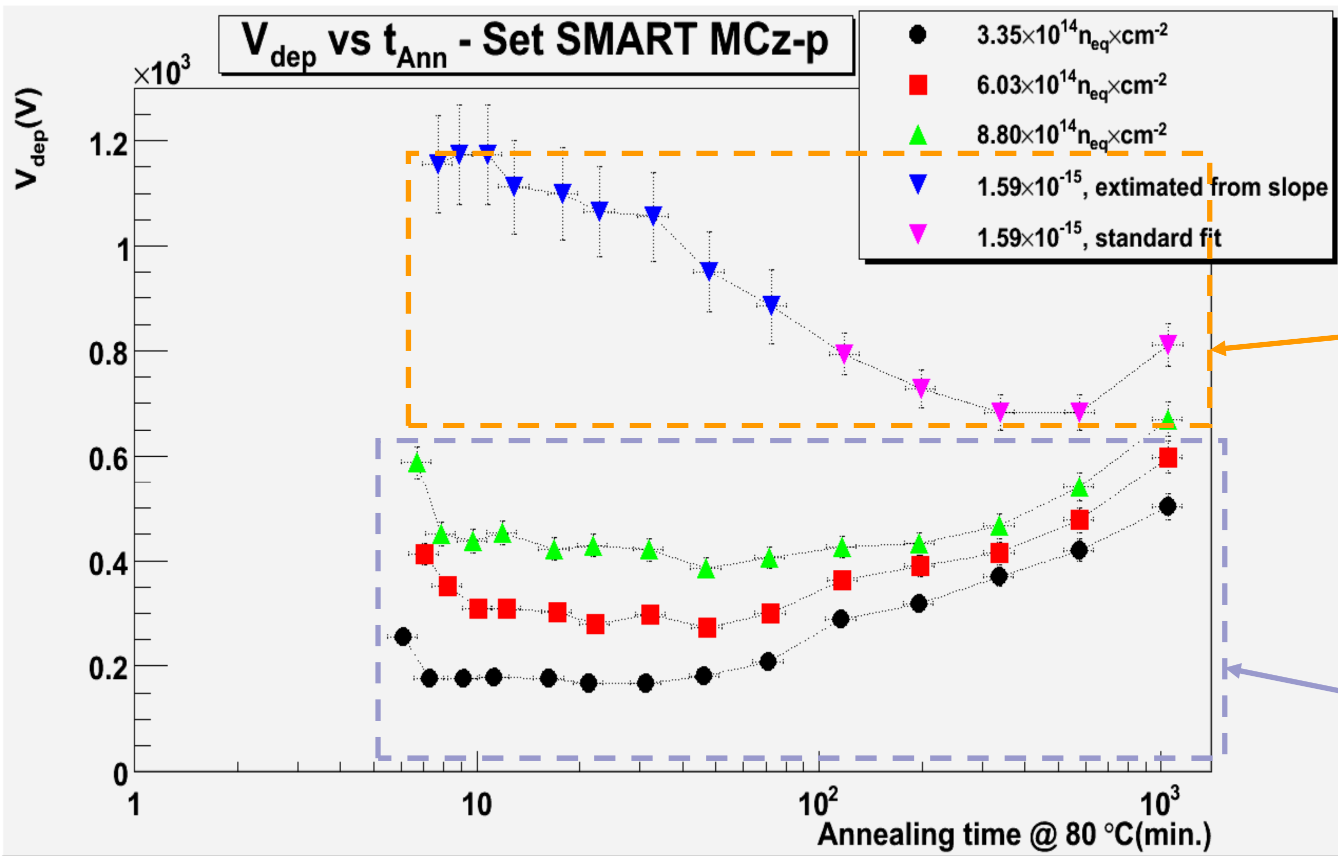
# Annealing study on MCz-n devices




All devices show an n-type annealing behaviour (Vdep rising with beneficial annealing and falling in reverse annealing)

Annealing brings all devices (with the only exception of the least irradiated) to type inversion

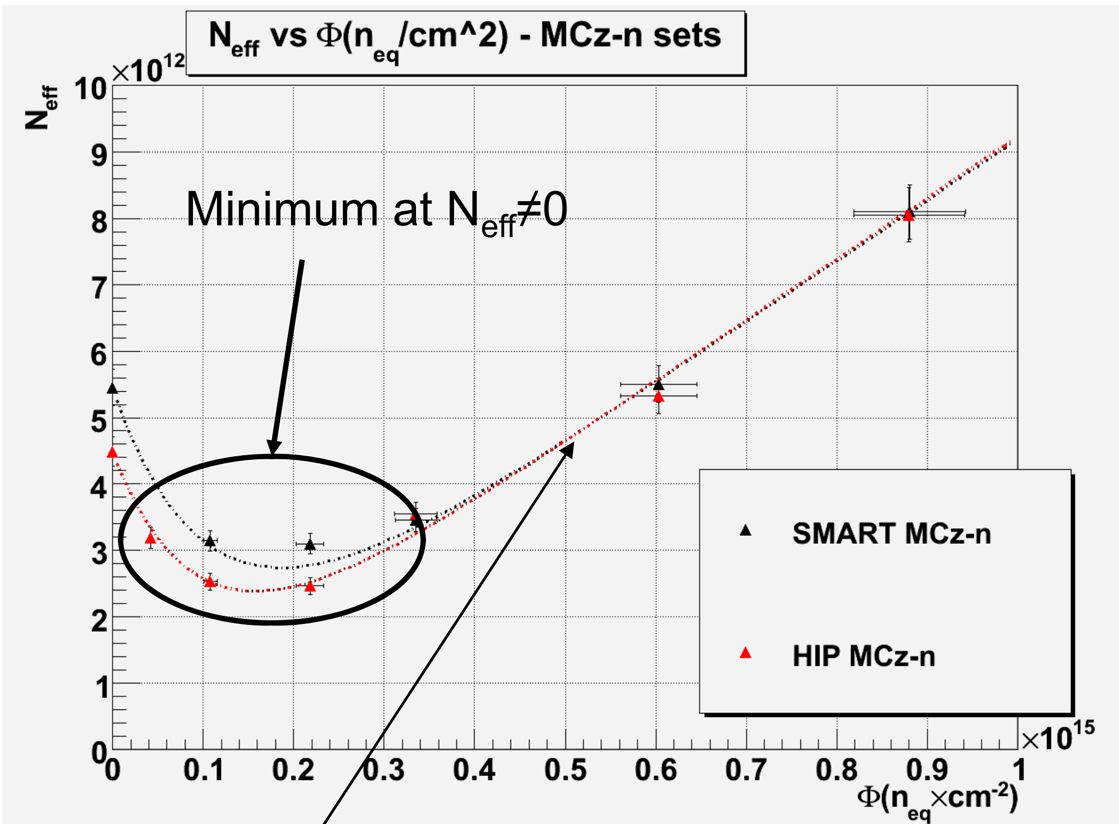
# Annealing study on MCz-p devices




*The most irradiated diode shows an n-like annealing behaviour*

“p-like” annealing behaviour

# $V_{dep}$ vs. flu. for MCz-n silicon diodes



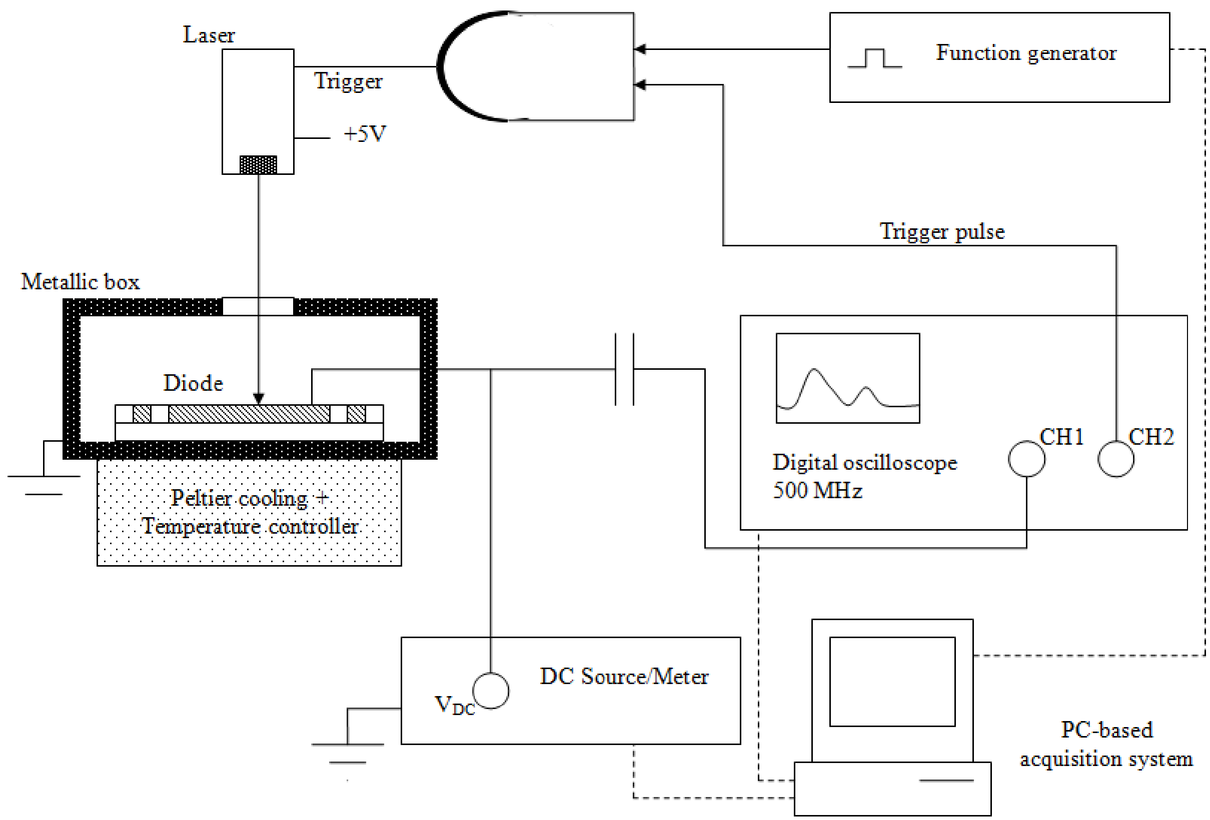

Total removal of original donors (indipendence from initial concentration at high fluencies)

The observed minimum is not necessarily correlated to type inversion. It can instead be explained in terms of double junction effect.

→ **TCT measurements**

# TCT (*T*ransient *C*urrent *T*echnique)

The TCT technique is used to investigate the electric field profile within the polarized detector bulk. In this way we can study the junctions present within the detector.




Laser-induced carriers drift within the diode, inducing on the electrodes a current signal read by an oscilloscope.

$$j = nev = \mu E$$

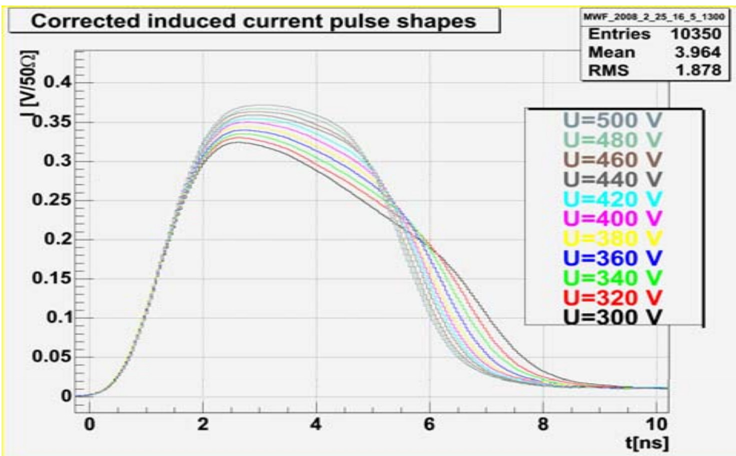
$$\Rightarrow j \propto E$$

# TCT measurements - details

- TCTs were performed using a 670 nm laser (generation of carriers within the first μm)
- SMART diodes allowed only front illumination (signal generated by electrons in MCz-n and holes in MCz-p)
- Trapping times were determined with Charge Correction Method (i.e. finding the trapping time constant for which the collected charge is independent from $V_{bias}$>$V_{dep}$)

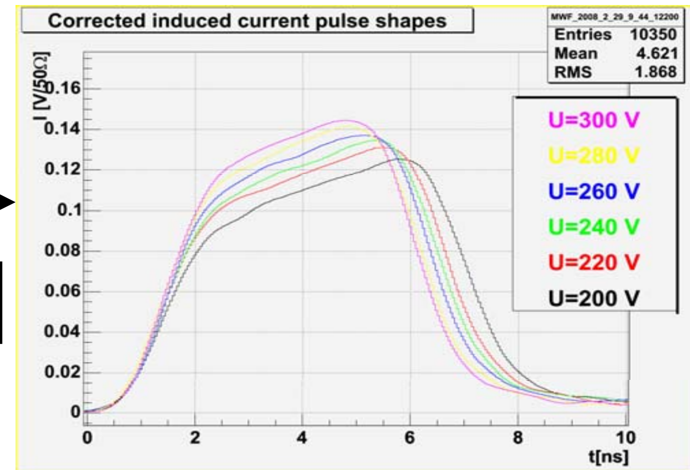
# TCT measurements on MCz-n diodes - results

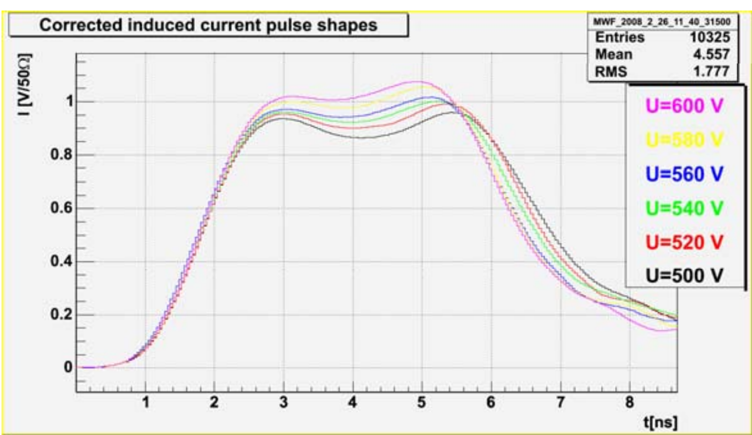
- The least irradiated MCz-n diode is not type-inverted, though there is evidence of the formation of a second junction on the back of the device
- With higher fluencies (up to $8.80 \cdot 10^{14} n_{eq}/cm^2$) the junction on the back is always almost equivalent in height with the one on the front.




1000 min. annaling 80°C

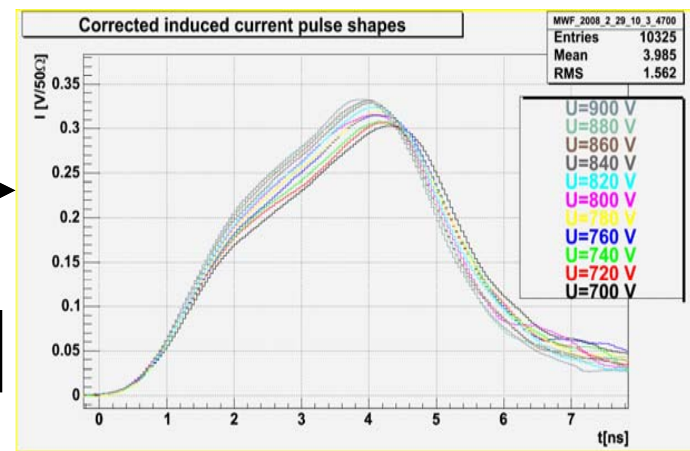
$1.08 \cdot 10^{14} n_{eq}/cm^2$



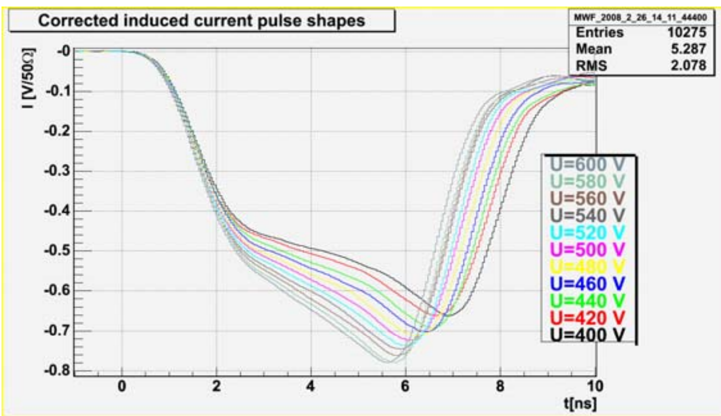

1000 min. annaling 80°C

$8.80 \cdot 10^{14} n_{eq}/cm^2$



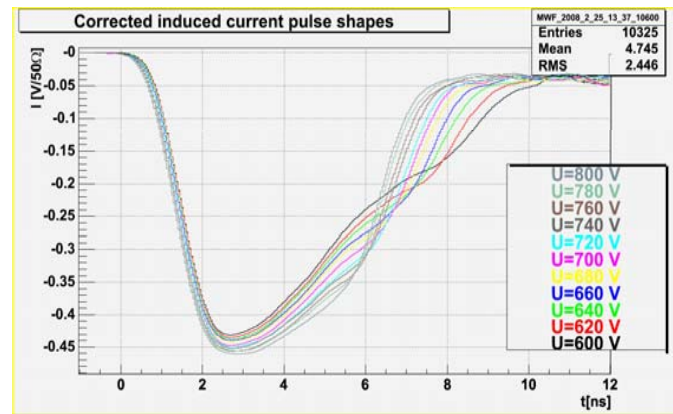
# TCT measurements on MCz-p diodes - results

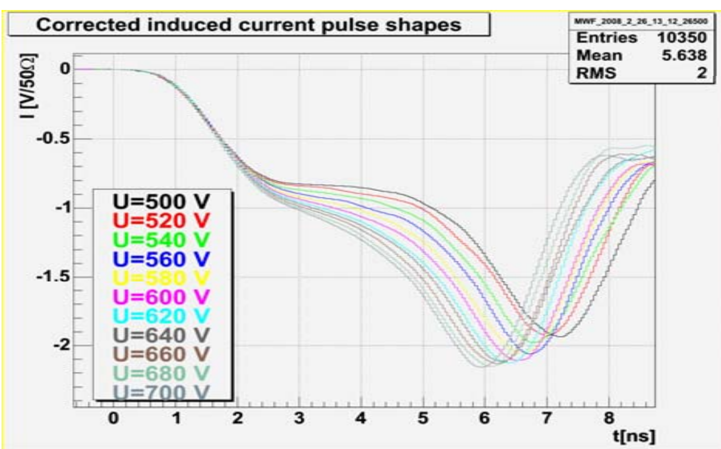
- MCz-p diodes show an important junction on the back even at the lowest fluence studied here ($3.18\cdot10^{14} n_{eq}/cm^2$).
- At the highest fluence the diode has undergone type inversion.
- Annealing brings the junction back on the front (acceptor introduction)




1000 min. annaling 80°C

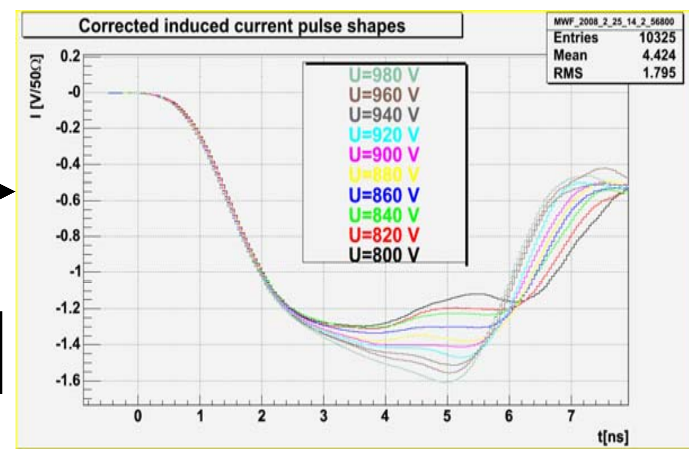
$3.35\cdot10^{14} n_{eq}/cm^2$




1000 min. annaling 80°C

$8.80\cdot10^{14} n_{eq}/cm^2$



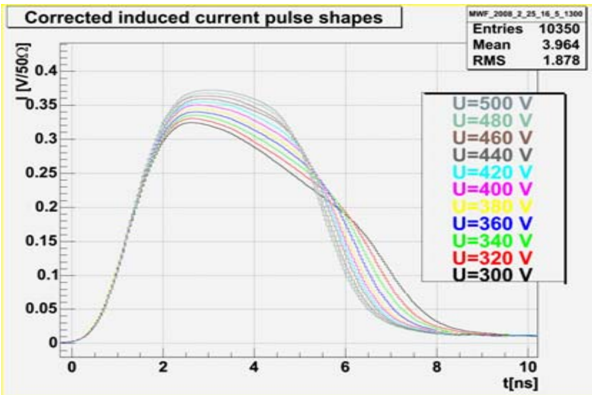
# Summary

- Type inversion was observed for the first time in MCz-p substrates irradiated with 24 GeV/c protons. The annealing behaviour of the most irradiated MCz-p diode is n-like. TCT measurements, corrected for trapping, shows a junction on the back that is clearly dominant at a fluence of $6.03 \cdot 10^{14}\ n_{eq}/cm^2$
- 80°C annealing introduces negative space charge in the detector bulk. Inverted p-type detectors will return to behave as p-type while non-inverted n-type detectors will undergo inversion with annealing.
- $V_{dep}$ vs. fluence for MCz-n shows a total removal of the intial dopants.
- For both MCz-p and MCz-n diodes irradiation bring to the creation of a junction on the back of the device.

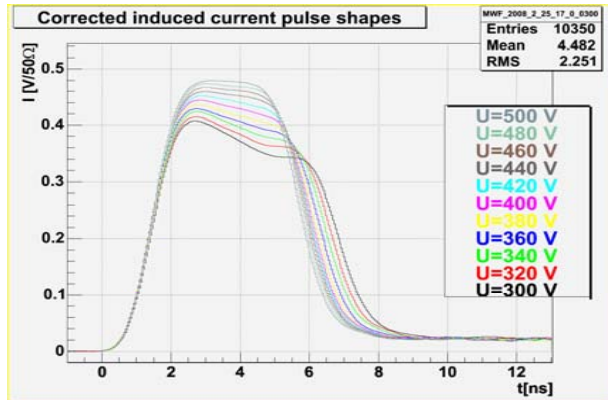
# Future developments

- Further studies will be conducted on neutron irradiated samples, focusing in particular at the high fluencies behaviour.
- The single-junction model (Hamburg Model) needs to be corrected with the effects caused by the presence of a second junction with different space charge
- Studies are necessary towards a better comprehension of how the double junction can affect the working parameters of a ‘real’ detector (microstrip and pixel), such as the SNR and CCE.

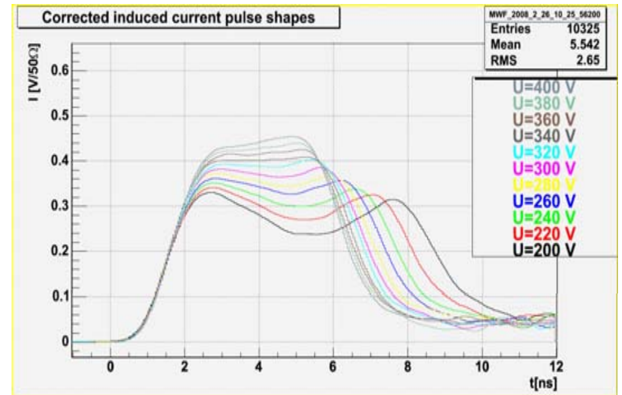
# MCz-n ‘as irradiated’ TCT profiles



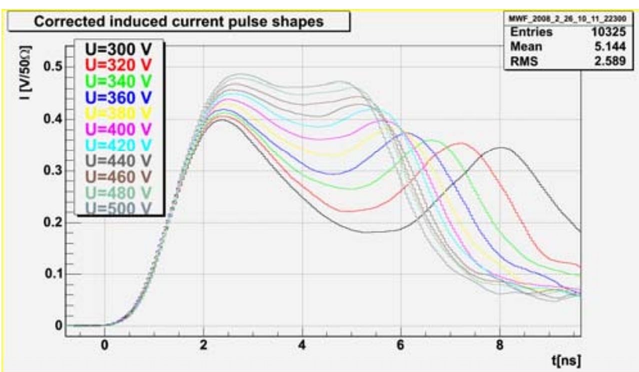

Φ=1.08e14
(tau=18 ns)



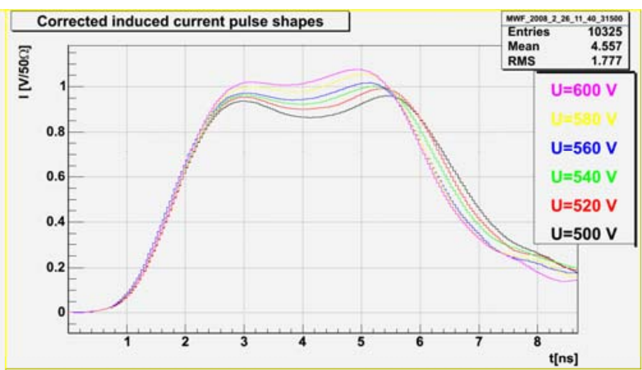

Φ=2.18e14
(tau=8 ns)




Φ=3.35e14
(tau=4.6 ns)

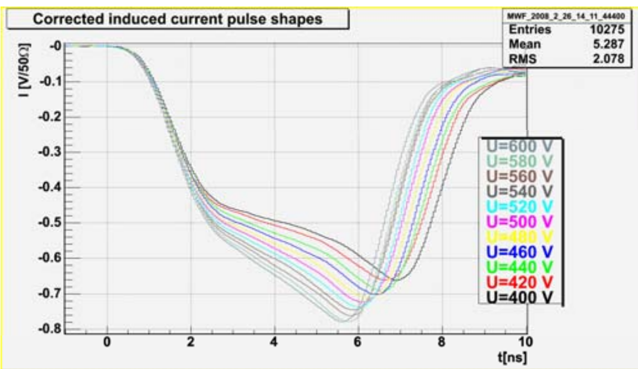



Φ=6.03e14
(tau=3.9 ns)

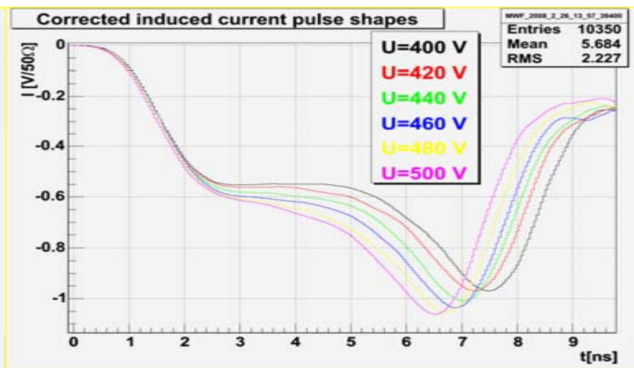



Φ=8.80e14
(tau=3.0 ns)

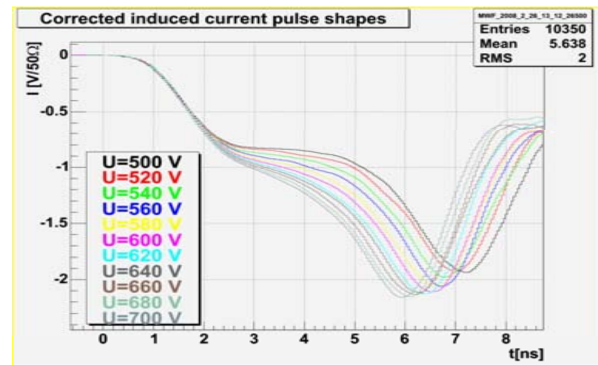
# MCz-p ‘as irradiated’ TCT profiles




Φ=3.35e14
(tau=4.5ns)

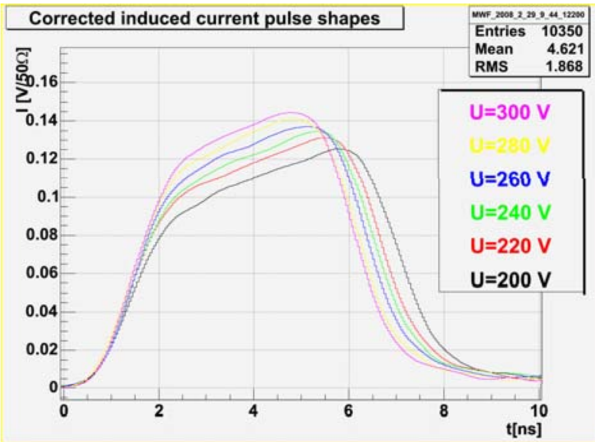


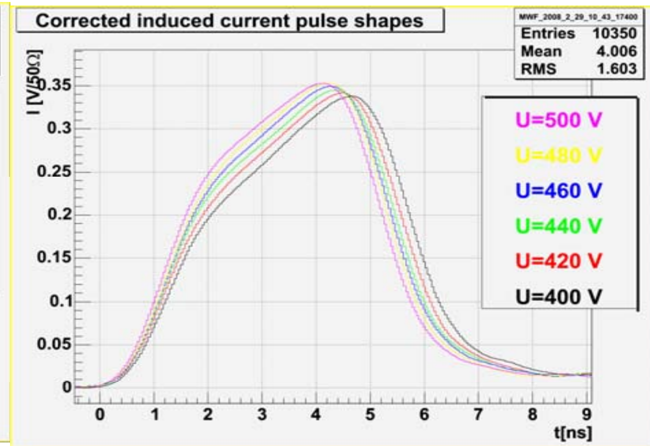

Φ=6.03e14
(tau=3ns)

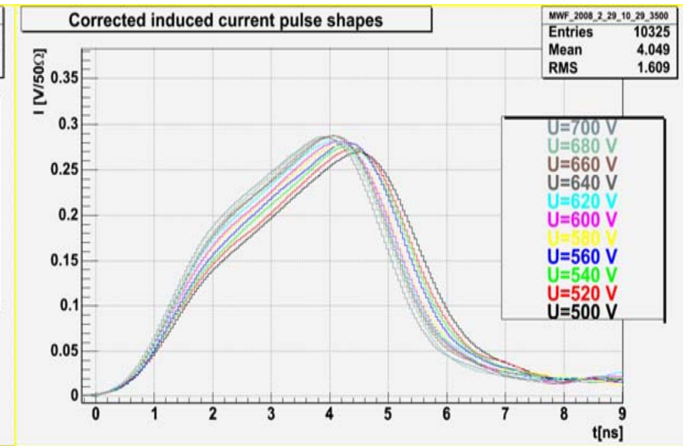



Φ=8.80e14
(tau=2.2 ns)

# MCz-n TCT profiles after annealing



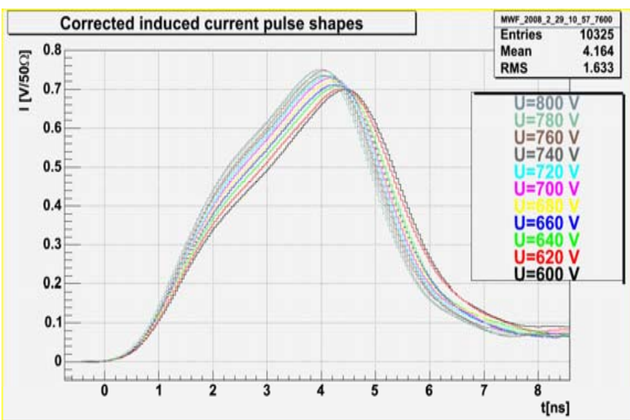



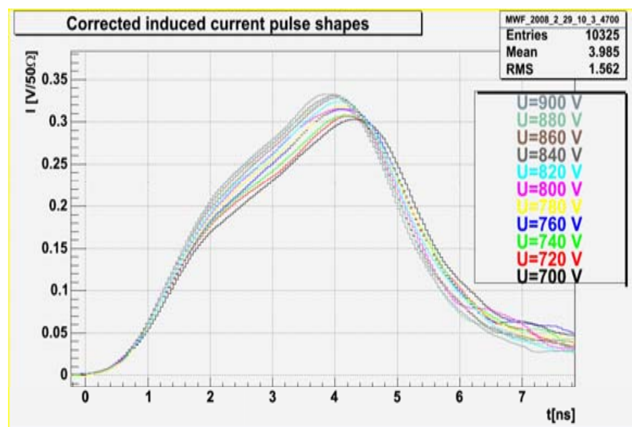

Φ=1.08e14
(tau=22 ns)

Φ=2.18e14
(tau=10 ns)

Φ=3.35e14
(tau=5.5 ns)

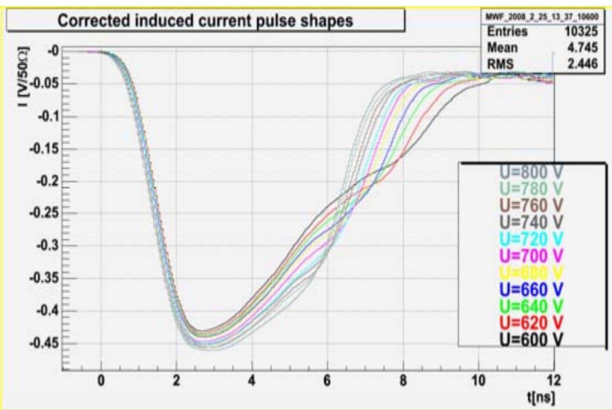



Φ=6.03e14
(tau=4 ns)

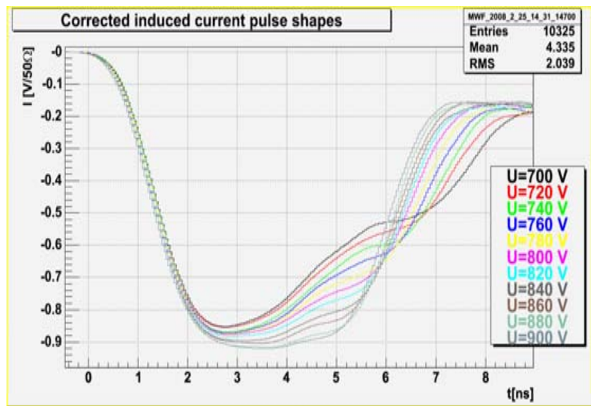



Φ=8.80e14
(tau=3.5)

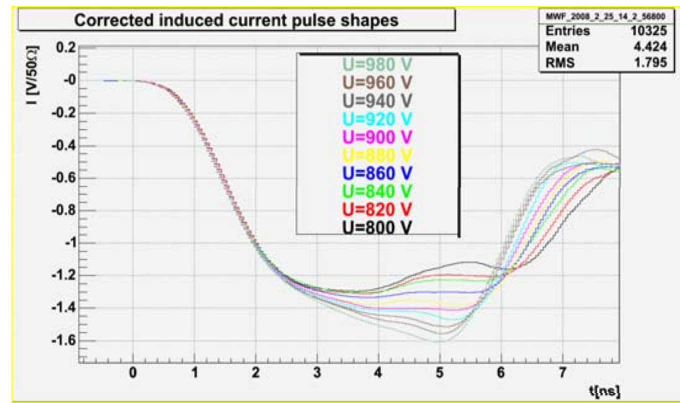
# MCz-p TCT profiles after annealing



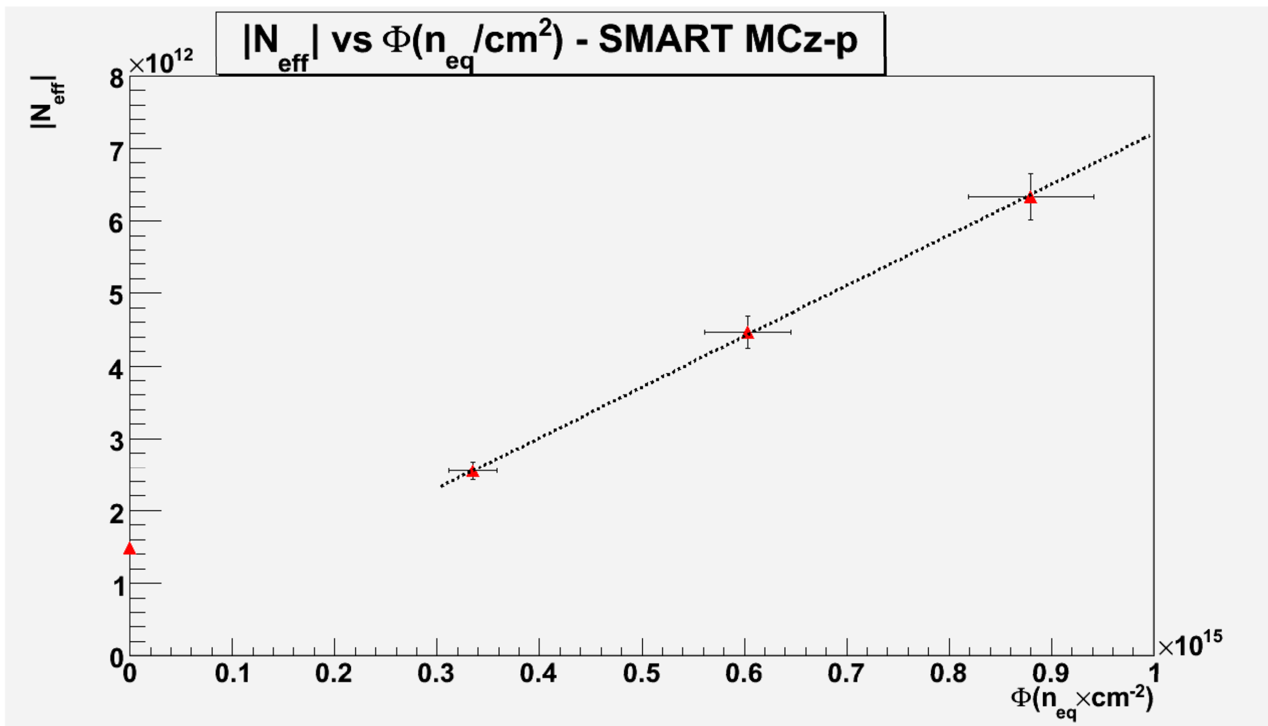

Φ=3.35e14
(tau=5 ns)




Φ=6.03e14
(tau=3ns)




Φ=8.80e14
(tau=2ns)



|N_eff| vs Φ(n_eq/cm²) - SMART MCz-p
|N_eff|
×10^12
8
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
×10^15
Φ(n_eq×cm^-2)