Irradiation study on diodes of different silicon materials for the CMS tracker upgrade

RD50 Workshop
14-16 November 2012 CERN

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On behalf of the CMS tracker collaboration

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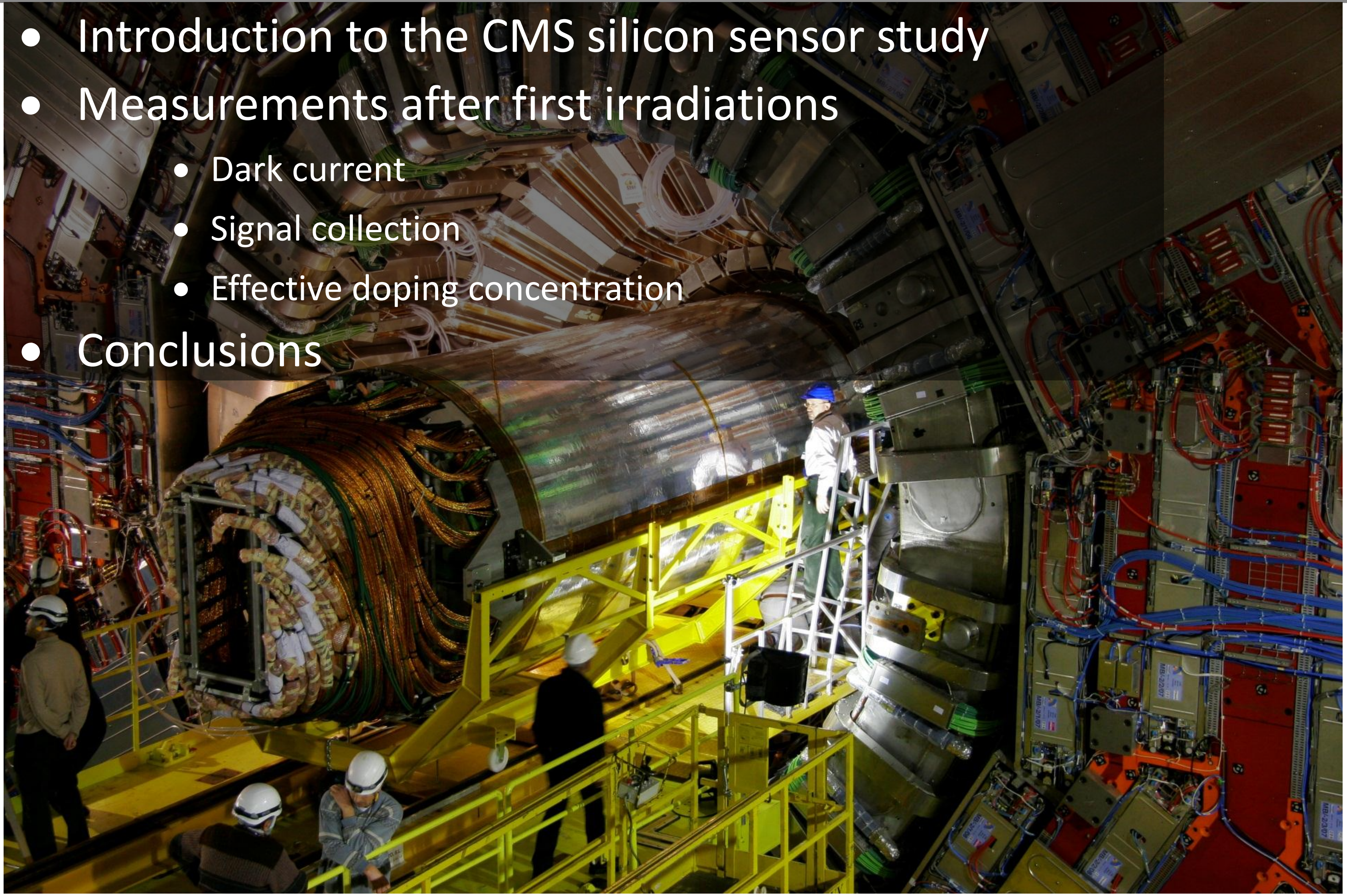
Overview

- Introduction to the CMS silicon sensor study
- Measurements after first irradiations
  - Dark current
  - Signal collection
  - Effective doping concentration
- Conclusions



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Goals of the silicon sensor study

The main goals for the tracker at the HL-LHC will be:

- Cope with higher occupancy
- Add level 1 trigger capability
- **Withstand higher radiation (up to a fluence of $\Phi_{eq} = 10^{16}$ cm^{-2})**

The current tracker would not **withstand the radiation** and also develop occupancy problems

→ Find **best suitable silicon material** a future tracking detector

To achieve that we investigate a large **variety of silicon materials:**

- **Different bulk doping (n and p)**
- **Different fabrication procedures**
- **Different oxygen content**
- **Different thicknesses**

Test sensor geometries and layouts

Irradiations with neutrons or/and protons to simulate HL-LHC radiation dose

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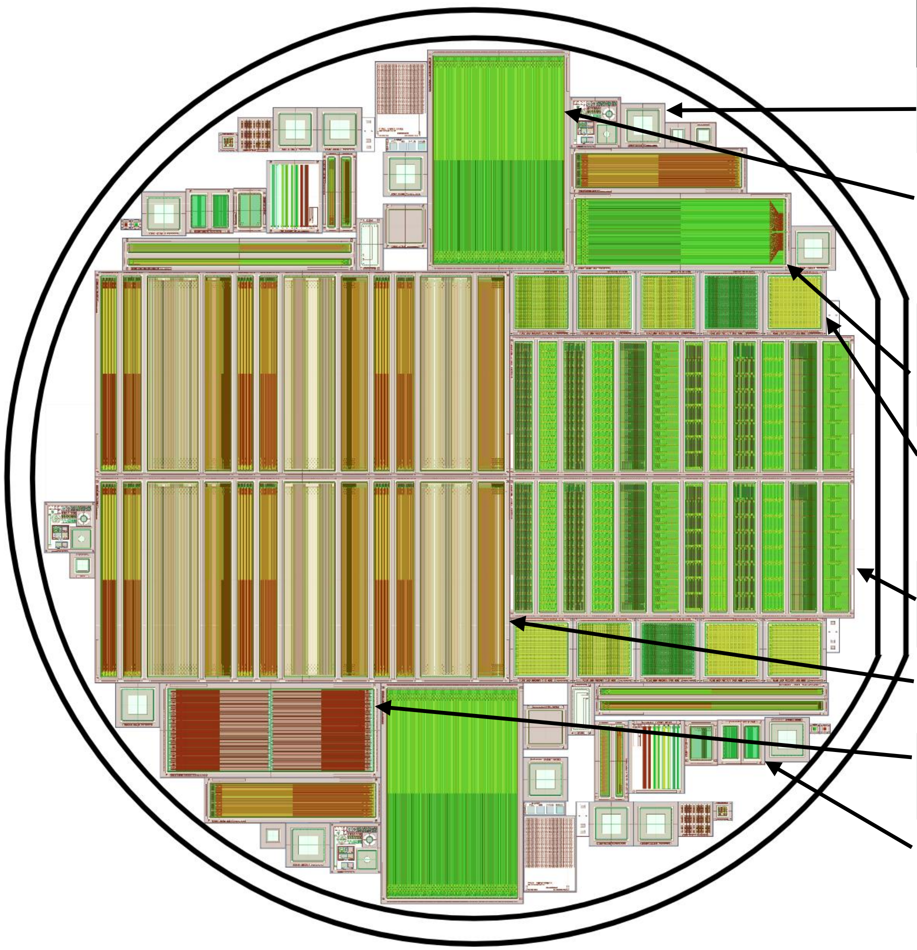
Wafer overview

6“ Wafer



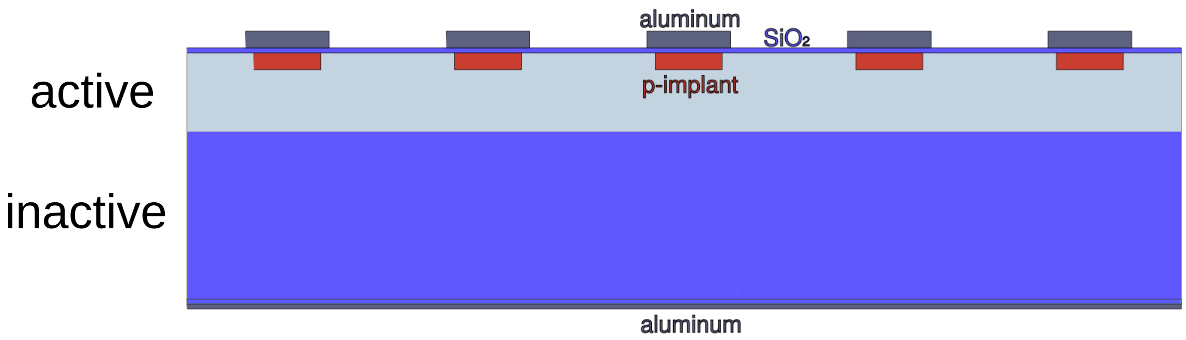
structure	to study
diodes	material
baby strip sensor	reference design / material
baby with integrated pitch adapter	study new design ideas
pixel sensor	reference design / material
multigeometry pixel	layout parameters
multigeometry strips	layout parameters
baby strixel	study new design ideas
teststructures	process parameters

Silicon material

material	thinning method	active thickness [μm]	wafer thickness [μm]	oxygen concentration [10^{17} cm^{-3}]
FZ	deep diffusion	120,**200,300**	320	5,**3,1**
FZ	---	**200**	200	**1**
FZ	handling wafer	120	320	expected small
MCz	---	**200**	200	**4**
Epi	---	50,**100**	320	1,**1**

Of each material there are 2 different types:

- N-type (**N**)
- P-type (**P**)



Irradiations

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radius	protons Φ_{eq} [cm^{-2}]	neutrons Φ_{eq} [cm^{-2}]	total Φ_{eq} [cm^{-2}]	active thickness
40 cm	**$3 \cdot 10^{14}$**	**$4 \cdot 10^{14}$**	$7 \cdot 10^{14}$	≥ 200 µm
20 cm	**$1 \cdot 10^{15}$**	**$5 \cdot 10^{14}$**	$1.5 \cdot 10^{15}$	≥ 200 µm
15 cm	**$1.5 \cdot 10^{15}$**	$6 \cdot 10^{14}$	$2.1 \cdot 10^{15}$	≥ 200 µm
10 cm	**$3 \cdot 10^{15}$**	$7 \cdot 10^{14}$	$3.7 \cdot 10^{15}$	≤ 200 µm
5 cm	$1.3 \cdot 10^{16}$	$1 \cdot 10^{15}$	$1.4 \cdot 10^{16}$	< 200 µm

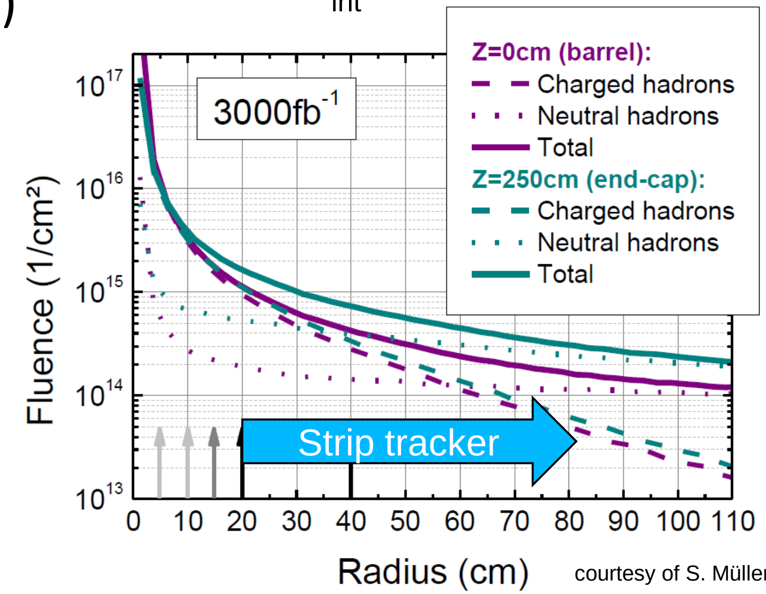
Neutrons: 1 MeV (TRIGA Reactor Ljubljana)

Protons: 23 MeV (Karlsruhe cyclotron)

800 MeV (Los Alamos)

23 GeV (CERN PS)

HL-LHC: L_{int}=3000 fb^{-1}

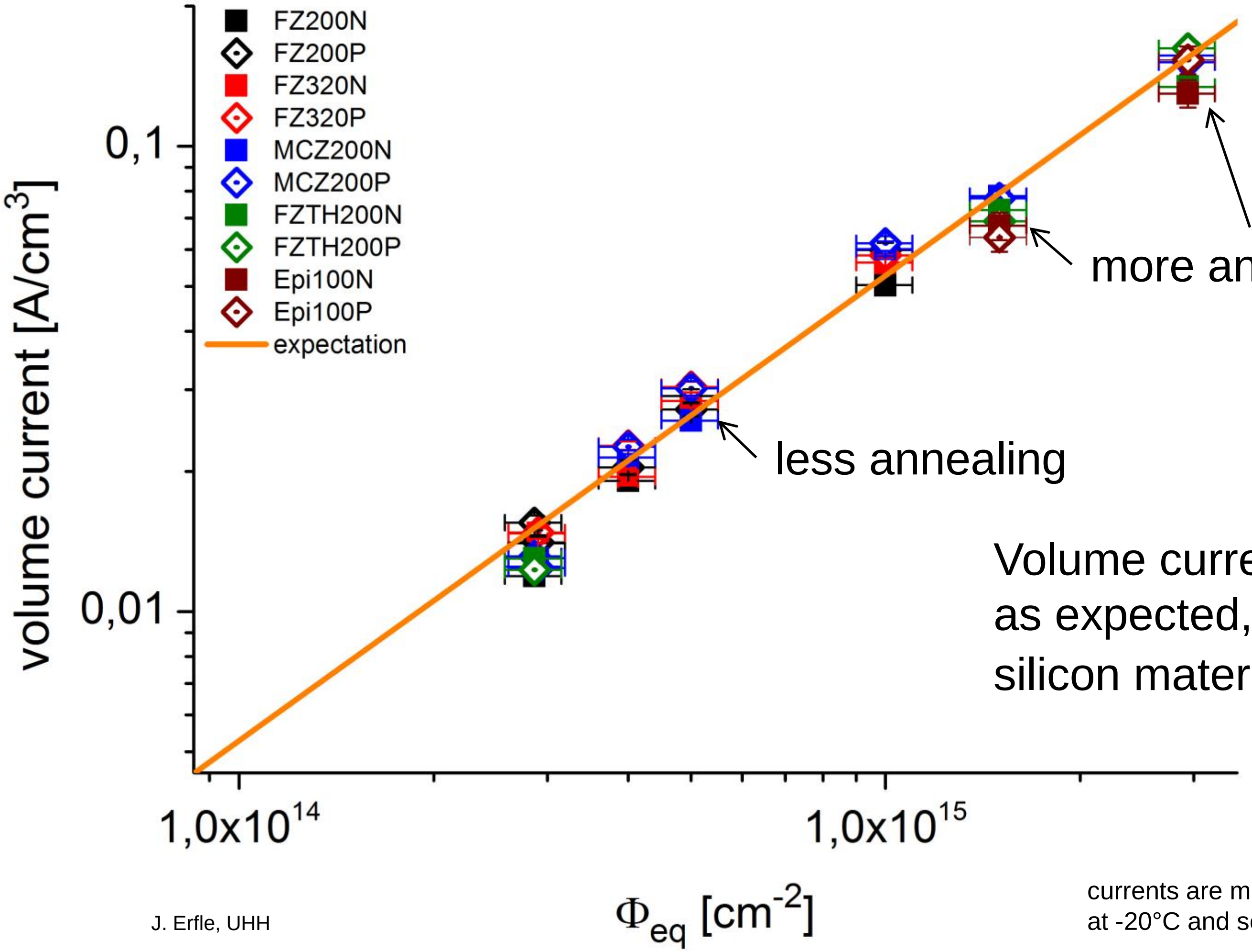


courtesy of S. Müller, KIT

Volume current versus fluence

Measurements scaled to 10 min at 60°C annealing

$$\frac{\Delta I}{V} = \alpha\Phi_{eq}$$



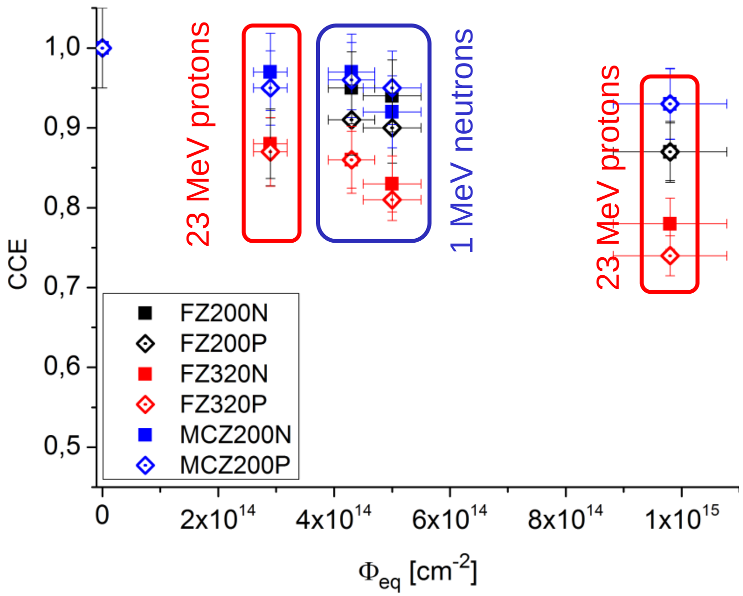
Volume current scales with fluence as expected, **independent** of silicon material (oxygen content).

J. Erfle, UHH

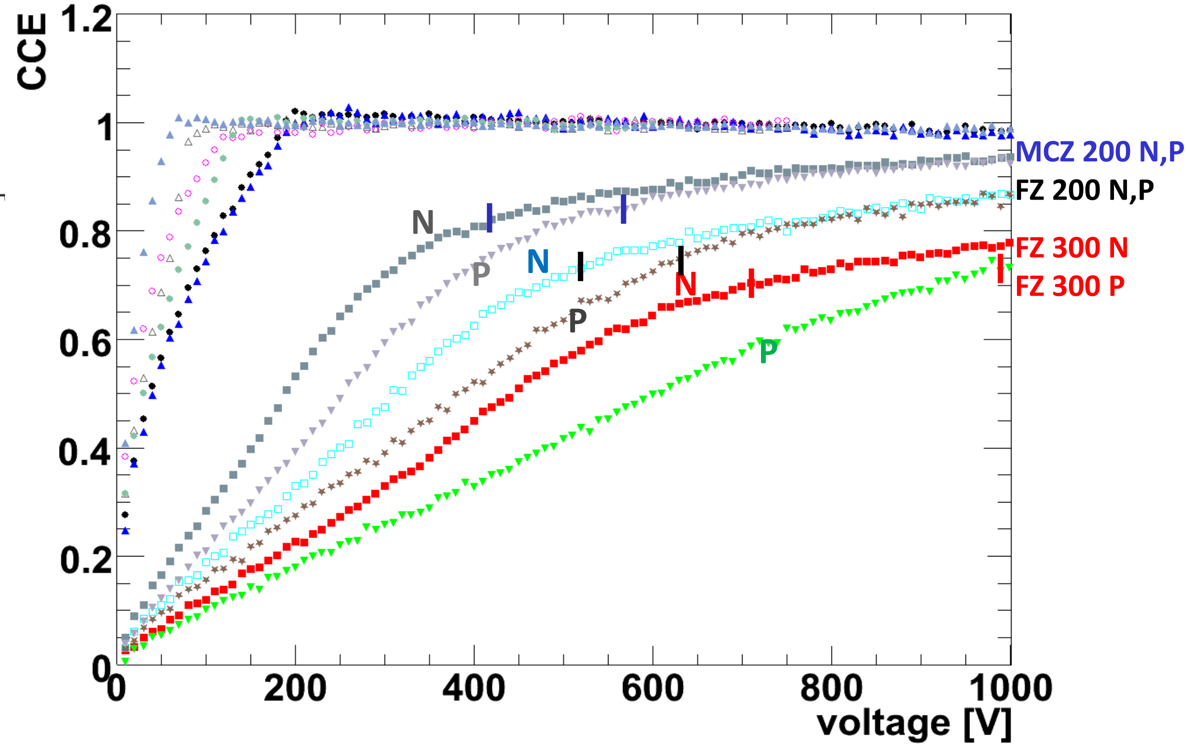
currents are measured after annealing of 10 min@ 60°C at -20°C and scaled to 20°C, guard ring grounded

Charge Collection Efficiency (Signal)

Charge Collection Efficiency at 1000V



→ Thick material is not beneficial anymore: High depletion voltage and more effected by trapping
→ MCz shows highest CCE



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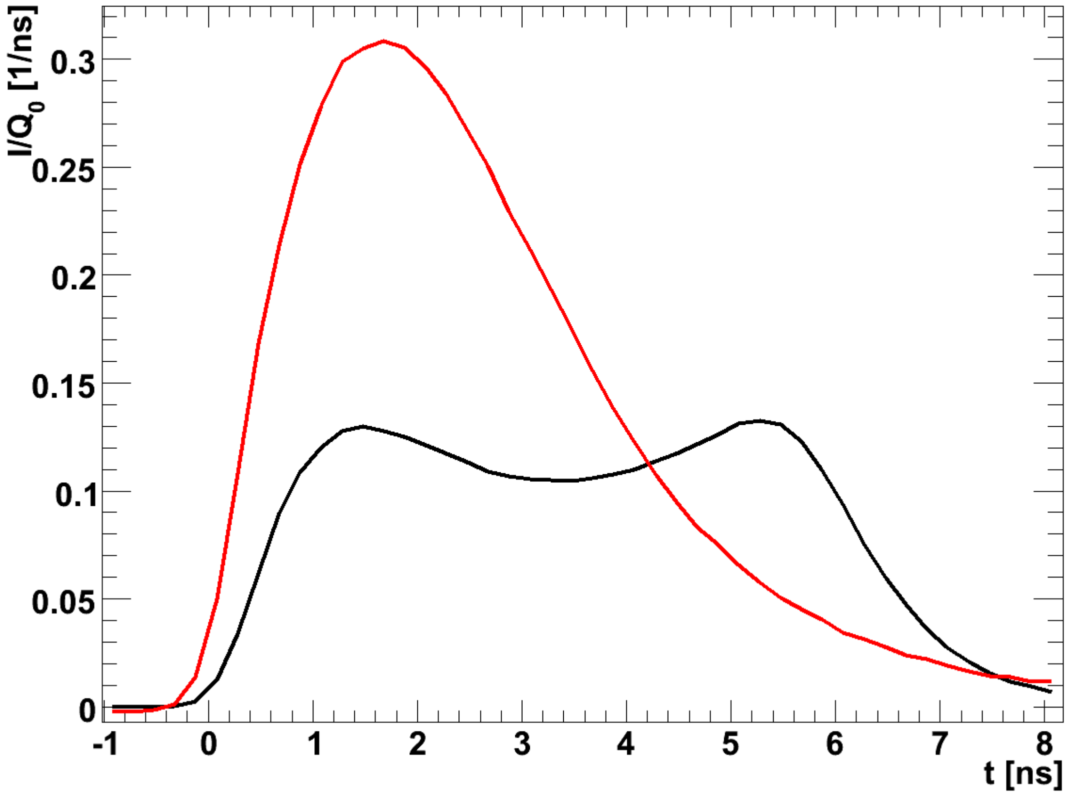
Double junction and $N_{effectiv}$

In the following plots Neff is used with a sign. The sign is deduced from the TCT puls.

If the later peak of a double junction is higher than the earlier peak, we call it „type inverted“.

The Neff itself is deduced from the kink in the $1/C^2$ plot of the C/V curves.

MCZ200N, irradiated with 3E14, 23MeV protons



N_{eff} annealing of irradiated samples

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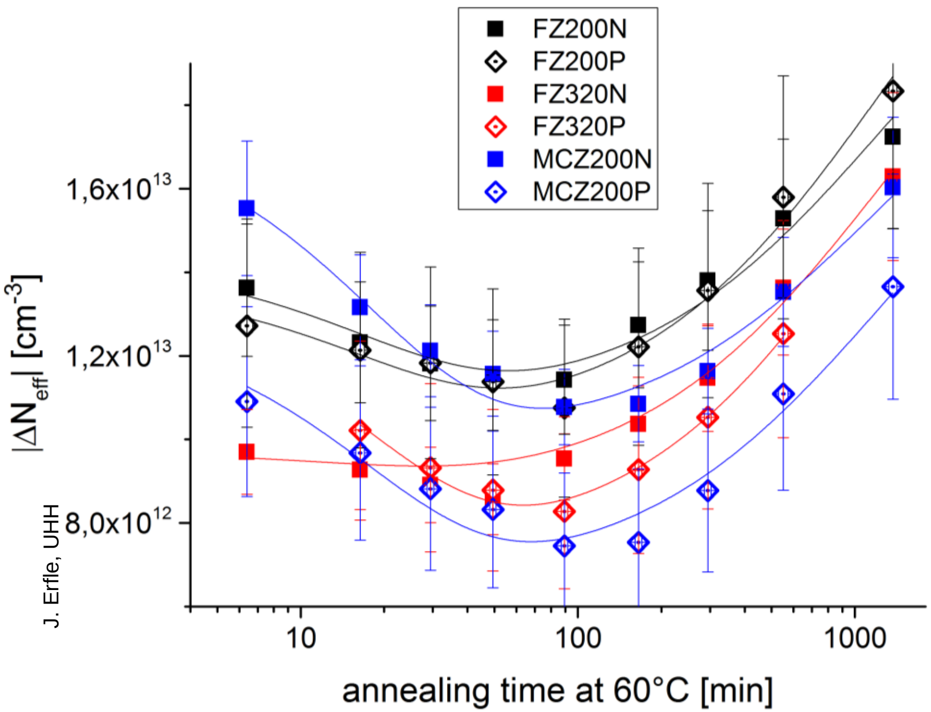
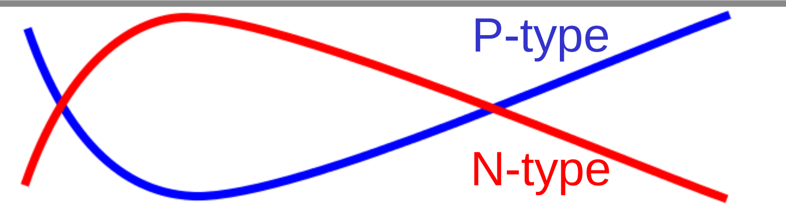
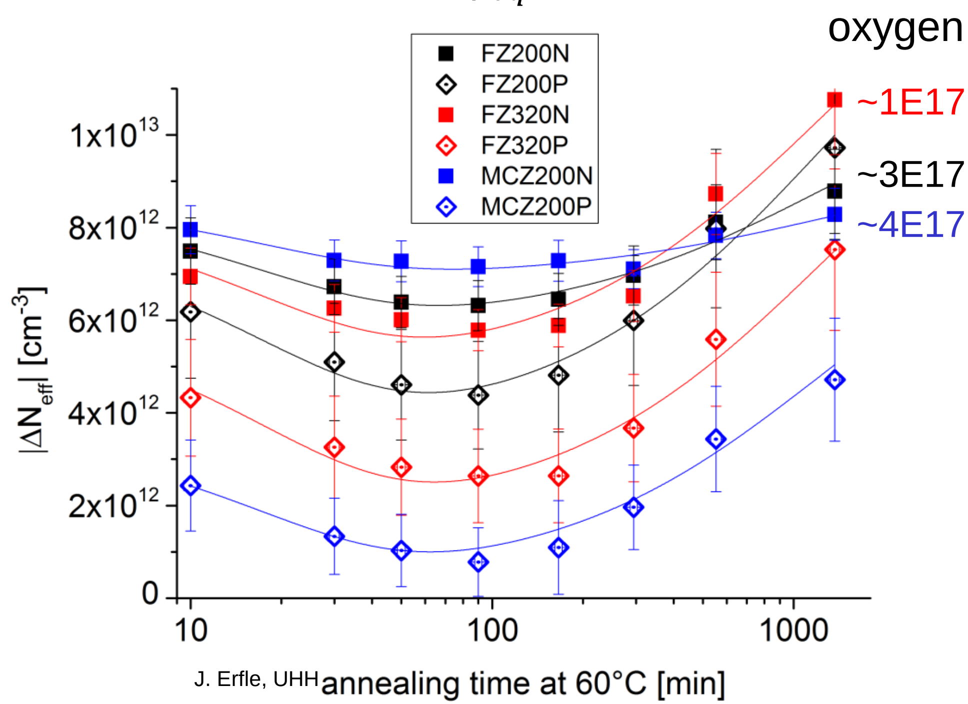
1 MeV neutrons, $\phi_{eq} = 4 \cdot 10^{14}\ cm^{-2}$





Acceptor removal (short term annealing)

23 MeV Protons, $\phi_{eq} = 2.9 \cdot 10^{14}\ cm^{-2}$

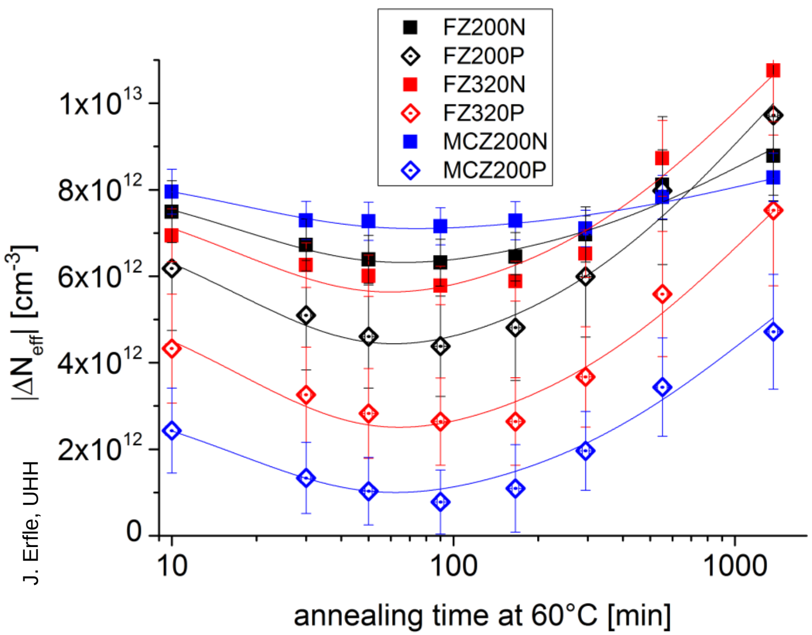


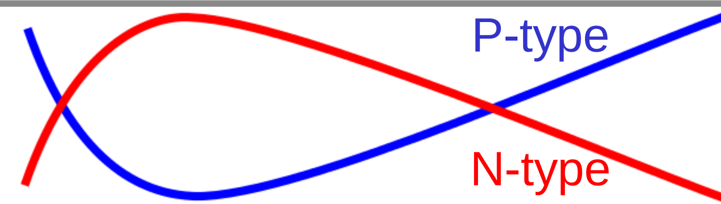
capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded

- Neutrons: **No** real **difference** in the curves of N and P-type material
- Protons: **smaller slope** for **higher oxygen** N-type silicon, no difference of p-type between protons and neutrons

N_{eff} annealing of irradiated samples

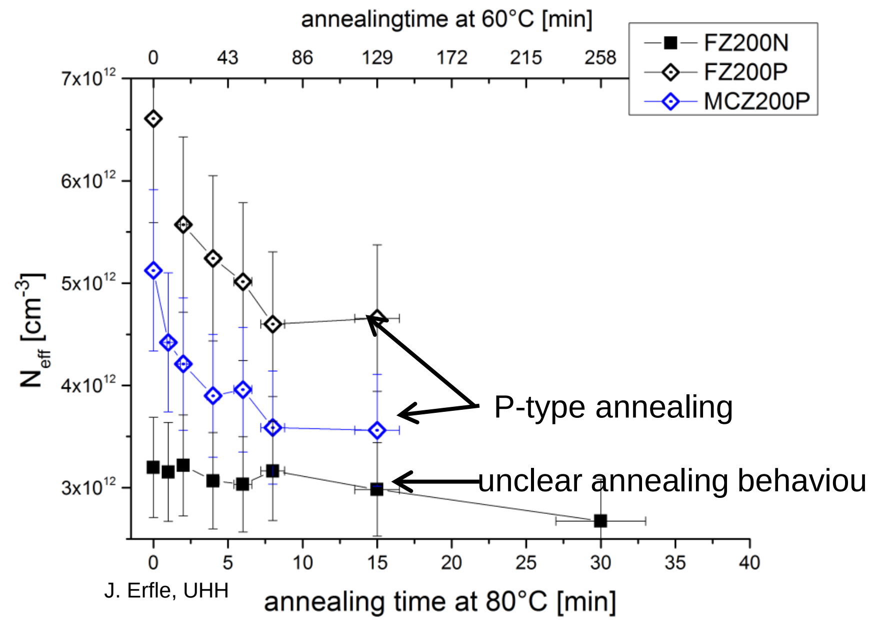
23 MeV protons, $\phi_{eq} = 2.9 \cdot 10^{14}\ cm^{-2}$





acceptor removal (short term annealing)

23 GeV Protons, $\phi_{eq} = 3.1 \cdot 10^{14}\ cm^{-2}$



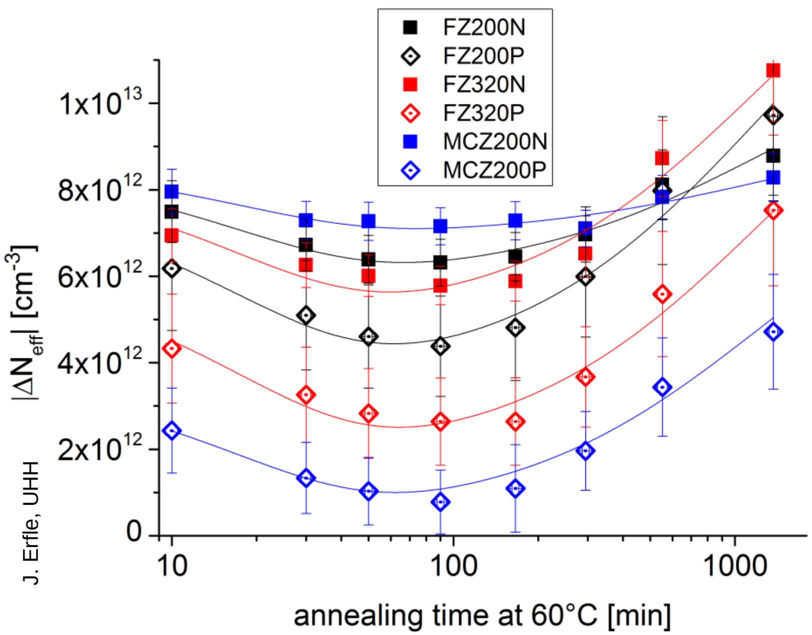
capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded

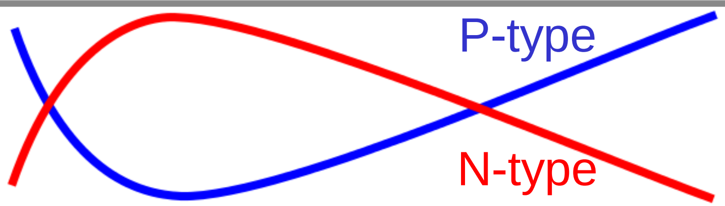
GeV protons:

- FZ200N annealing tends to non type inversion
- TCT tends to type inversion

N_{eff} annealing of irradiated samples

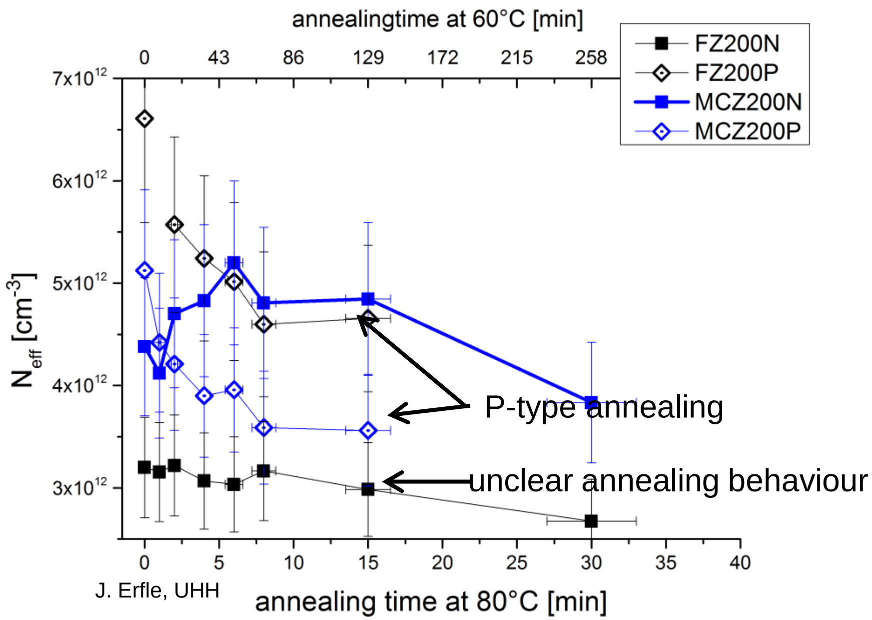
23 MeV protons, $\phi_{eq} = 2.9 \cdot 10^{14}\ cm^{-2}$





acceptor removal (short term annealing)

23 GeV Protons, $\phi_{eq} = 3.1 \cdot 10^{14}\ cm^{-2}$



capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded

GeV protons:

- MCZ200N annealing tends to non type inversion
- TCT tends to non type inversion

Type-inversion threshold of oxygen for 23 GeV protons at 3-4E17

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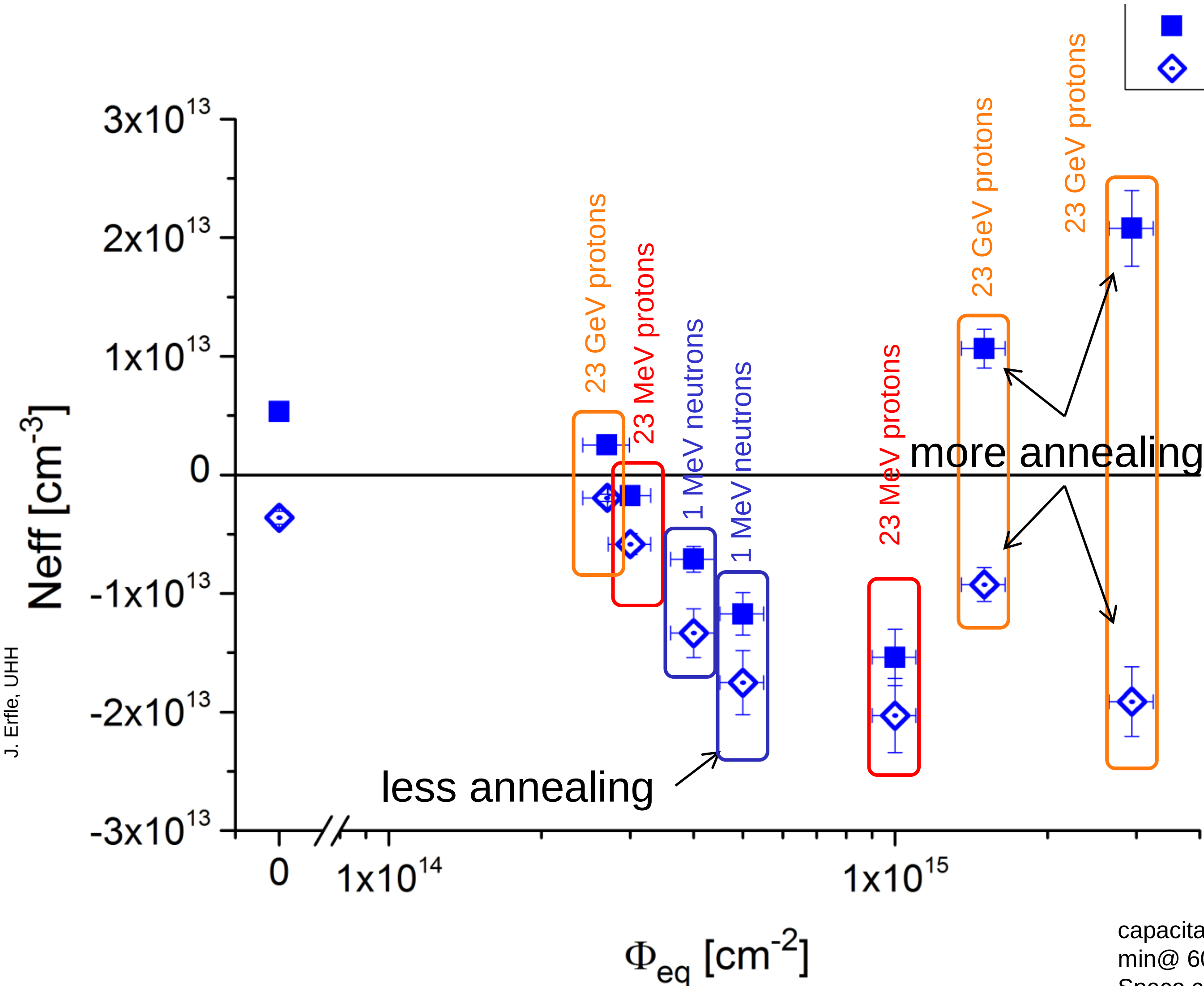
N_{eff} versus fluence

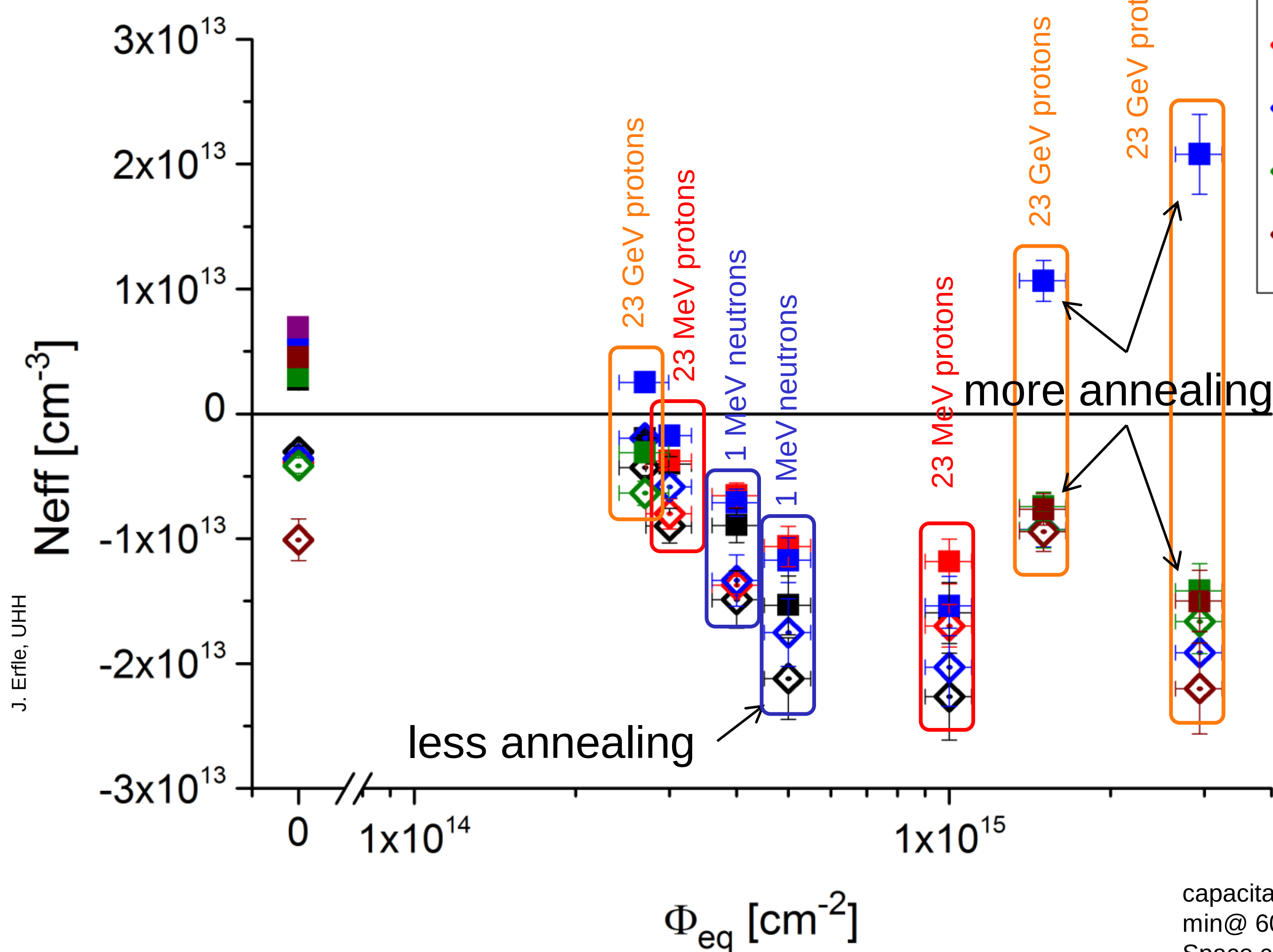


$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

- MCZ N type inverts for low energy protons and neutrons.
- N shows a small advantage over P, if type inverted.

capacitances are measured after (annealing of 10 min@ 60°C) at -20°C, 455Hz, guard ring grounded, Space charge sign determined via TCT.

N_{eff} versus fluence



$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

- No real difference in absolute hight between materials.
- Small advantage for type inverted materials.

capacitances are measured after (annealing of 10 min@ 60°C) at -20°C, 455Hz, guard ring grounded, Space charge sign determined via TCT.

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Conclusions and outlook

- Dark current (→ noise) independent of silicon material (as expected)
- Signal at a proton fluence of 1E15 reduced to 90% for MCz and to 70 % for thick float zone
- Type inversion threshold for 23 GeV protons seems to be at an oxygen concentration of 3-4E17
- Type inversion threshold for 23 MeV protons seems to be at an oxygen concentration above 5E17

- Different proton energy irradiations (PS and Los Alamos) done, measurements running
- Still more irradiations to come
- Further studies ongoing

Backup

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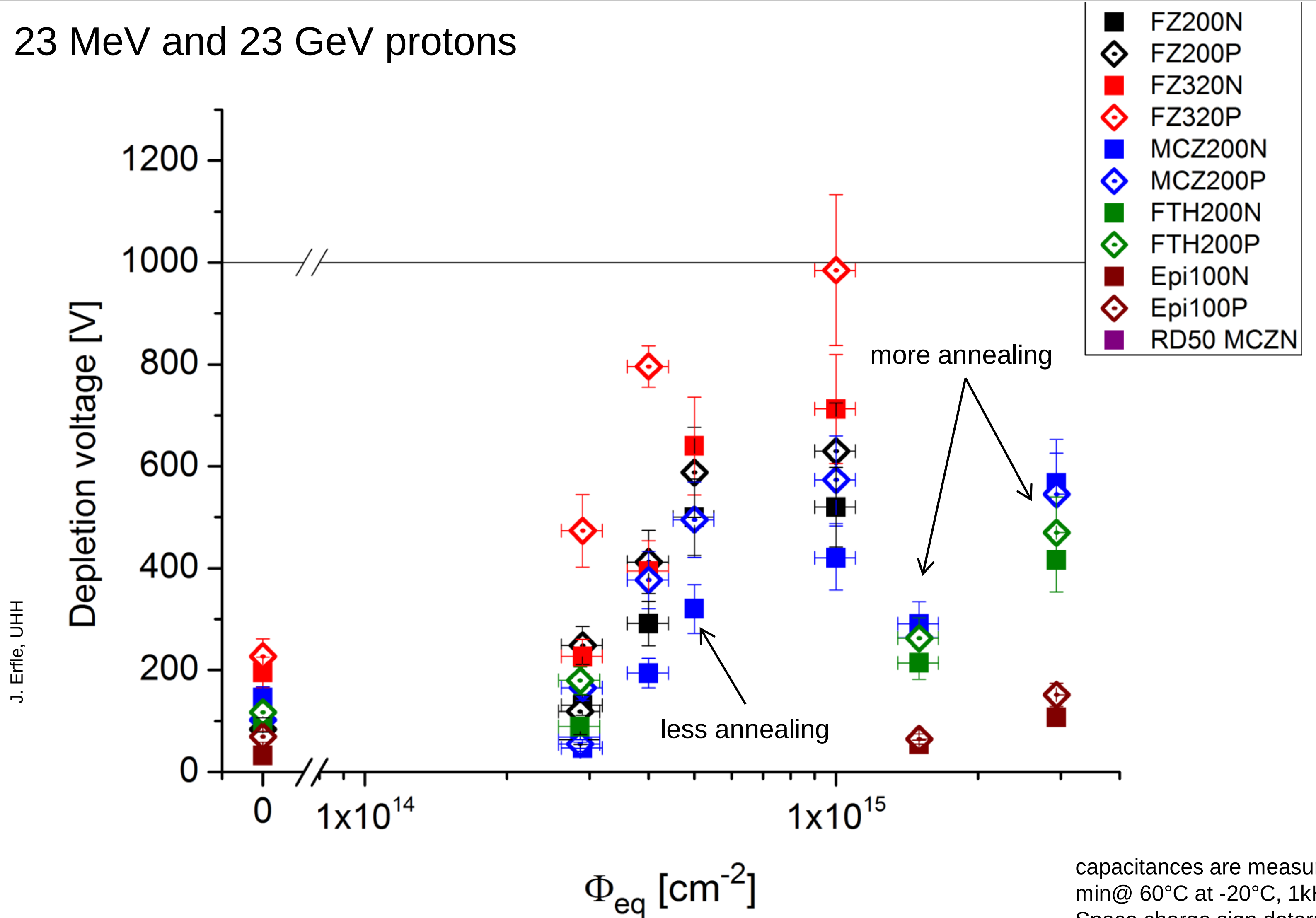
V_{depl} versus fluence

23 MeV and 23 GeV protons



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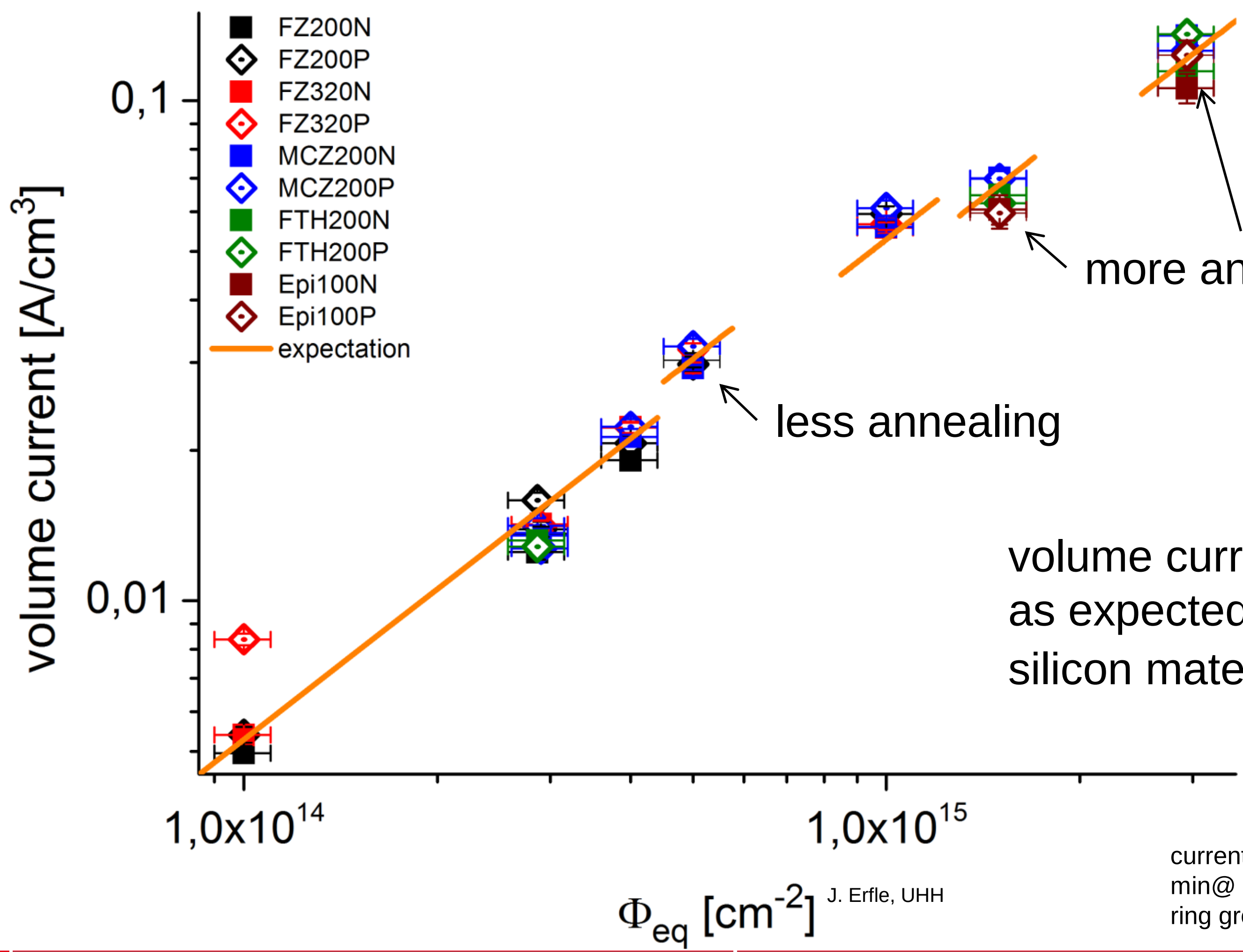
Volume current versus fluence

$$\frac{\Delta I}{V} = \alpha \Phi_{eq}$$

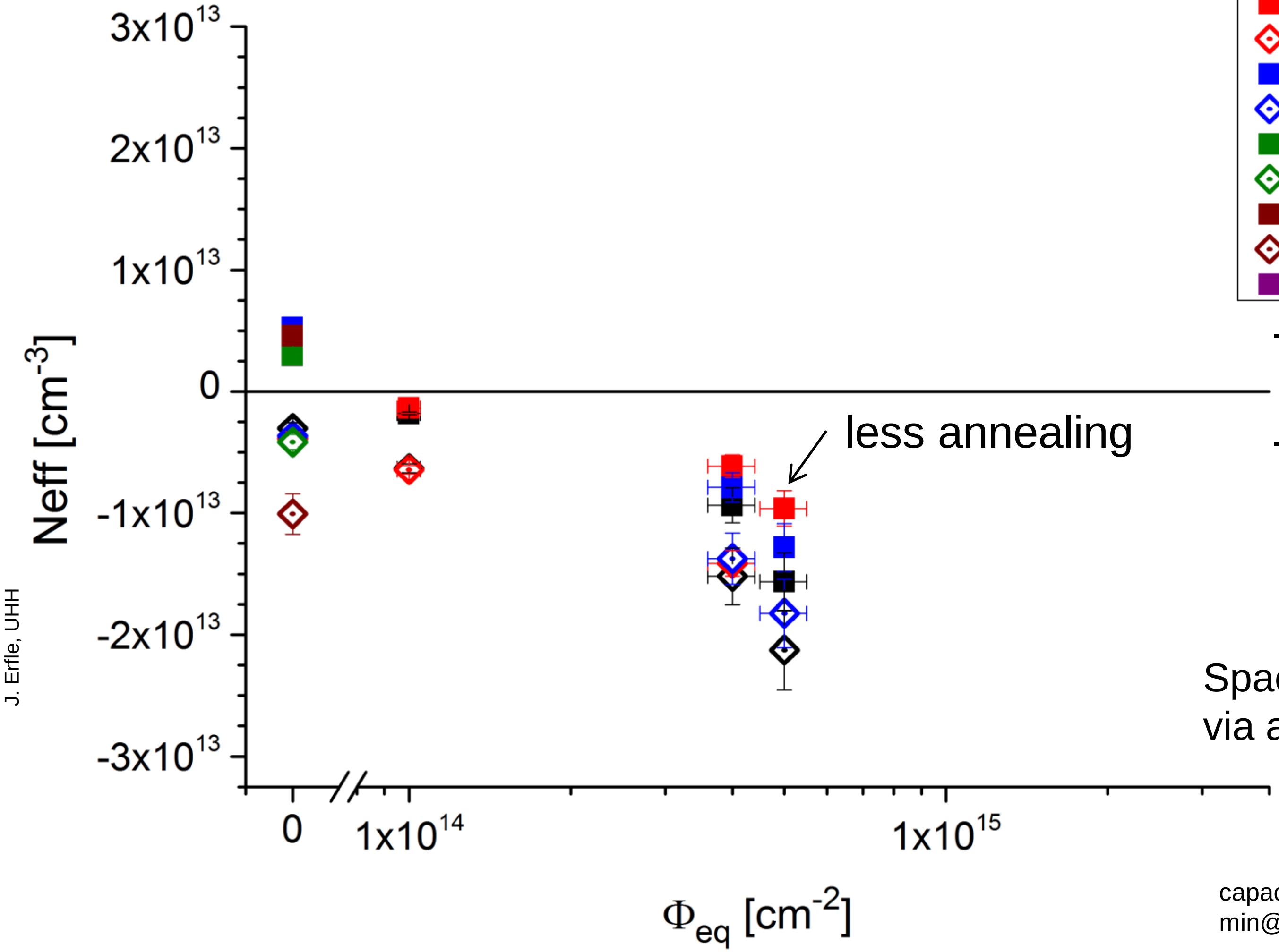


volume current scales with fluence as expected, **independent** of silicon material (oxygen content).

currents are measured after annealing of 10 min@ 60°C at 0°C and scaled to 20°C, guard ring grounded

N_{eff} versus fluence

1 MeV neutrons



$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

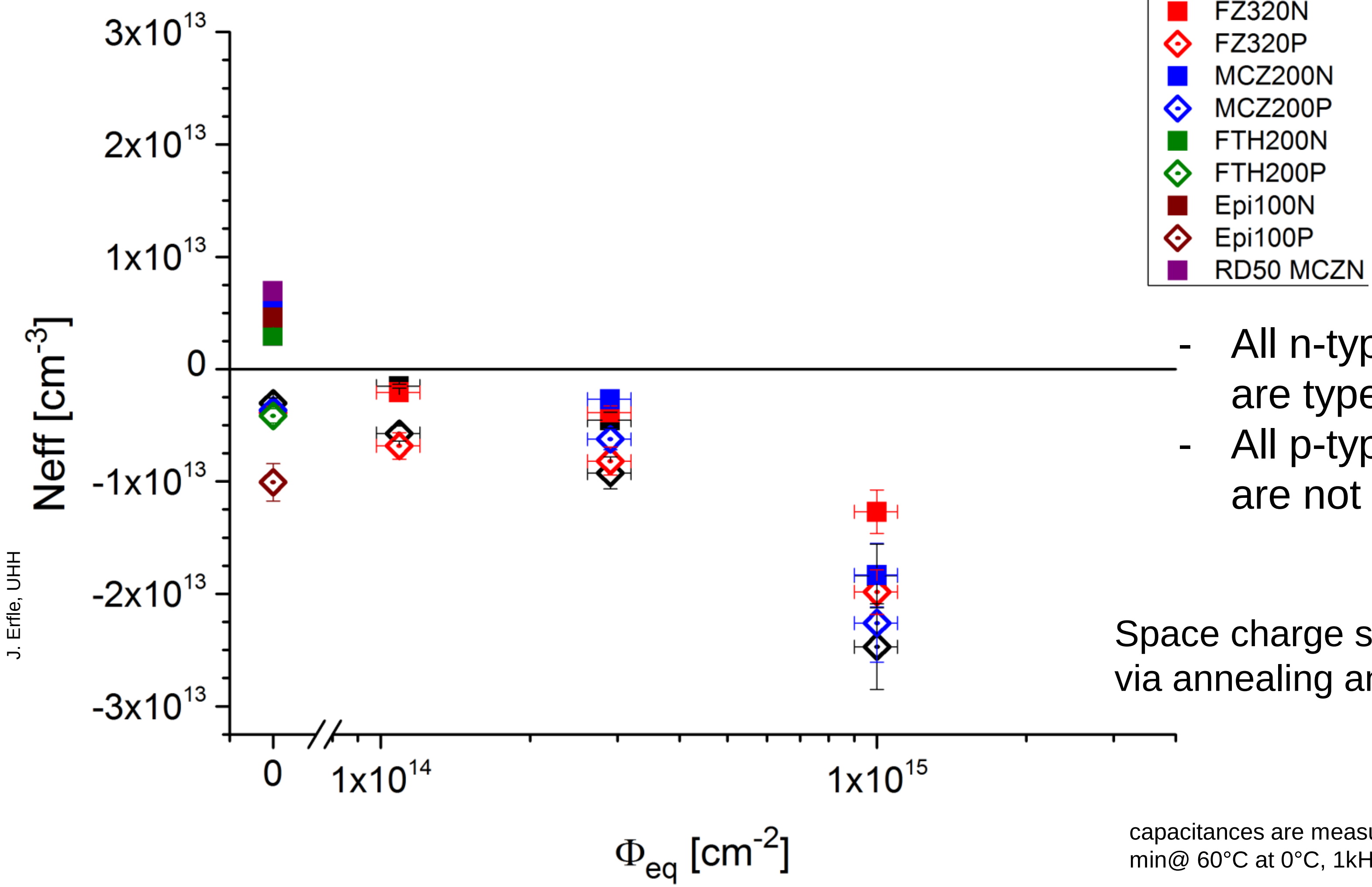
- All n-type materials are type inverted
- All p-type materials are not type inverted

Space charge sign determined via annealing and TCT.

capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded

N_{eff} versus fluence

23 MeV protons



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Space charge sign determined via annealing and TCT.

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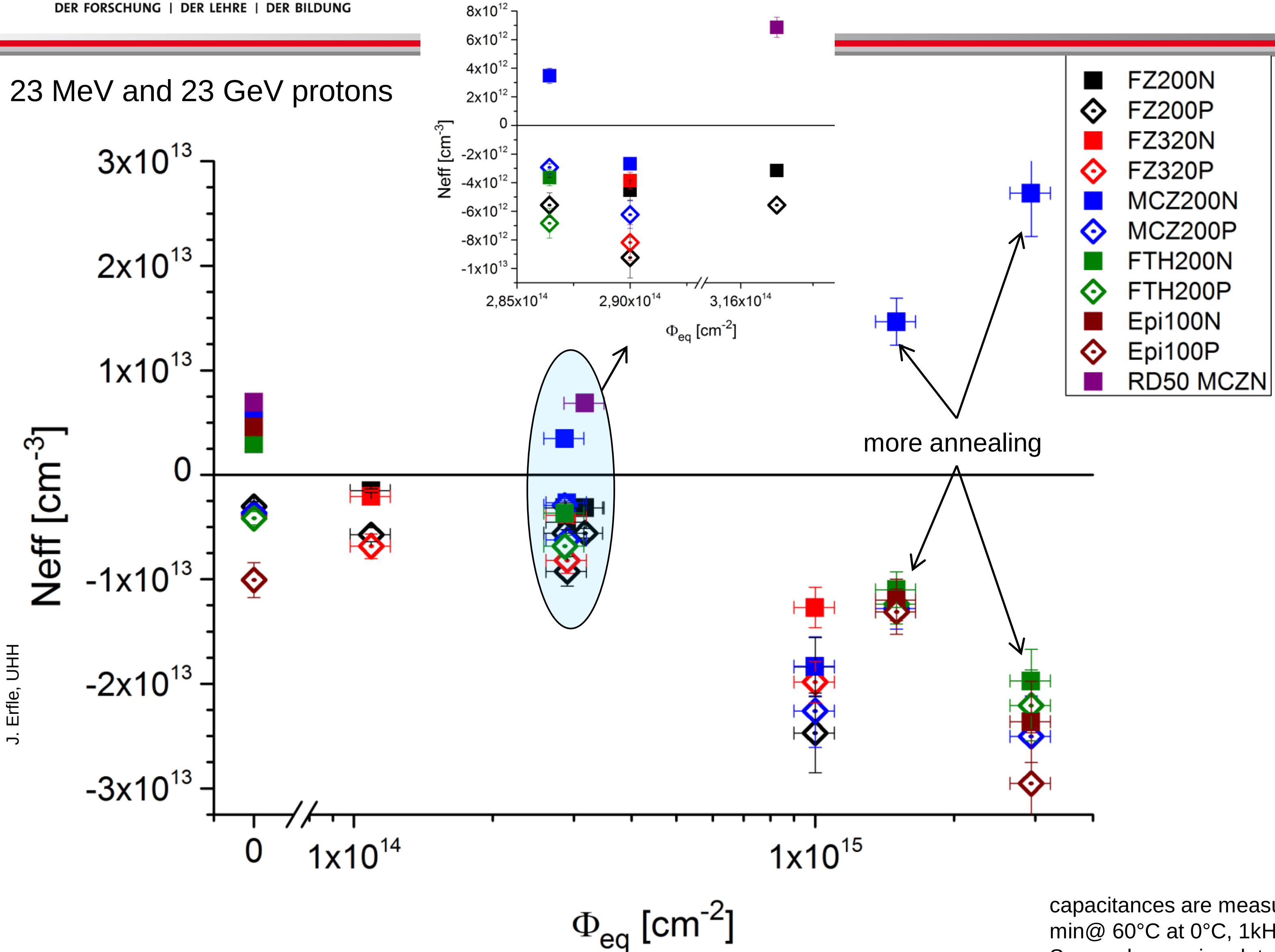
N_{eff} versus fluence

23 MeV and 23 GeV protons

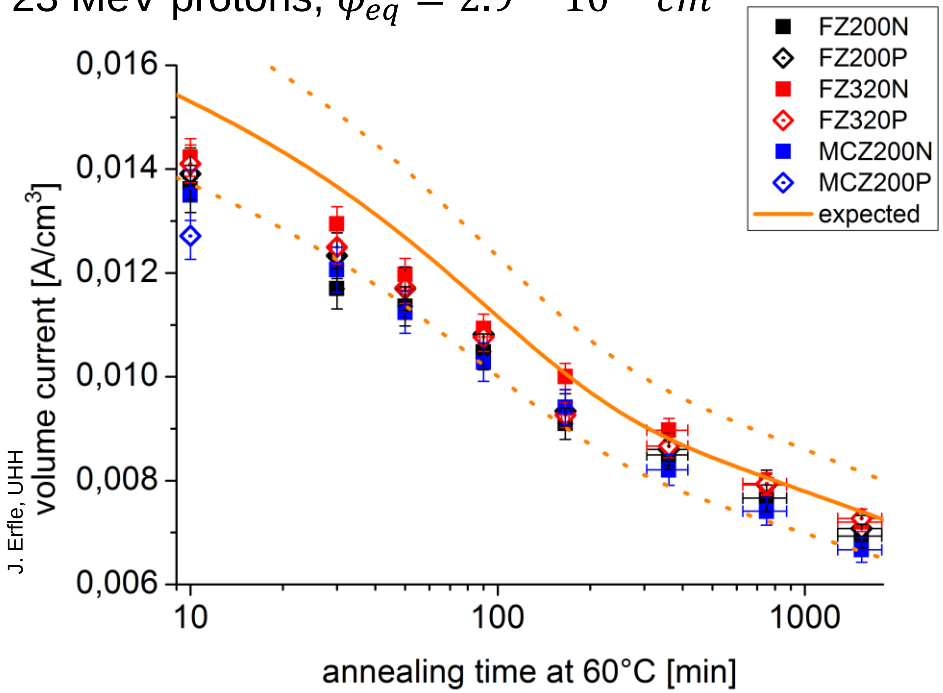
$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$



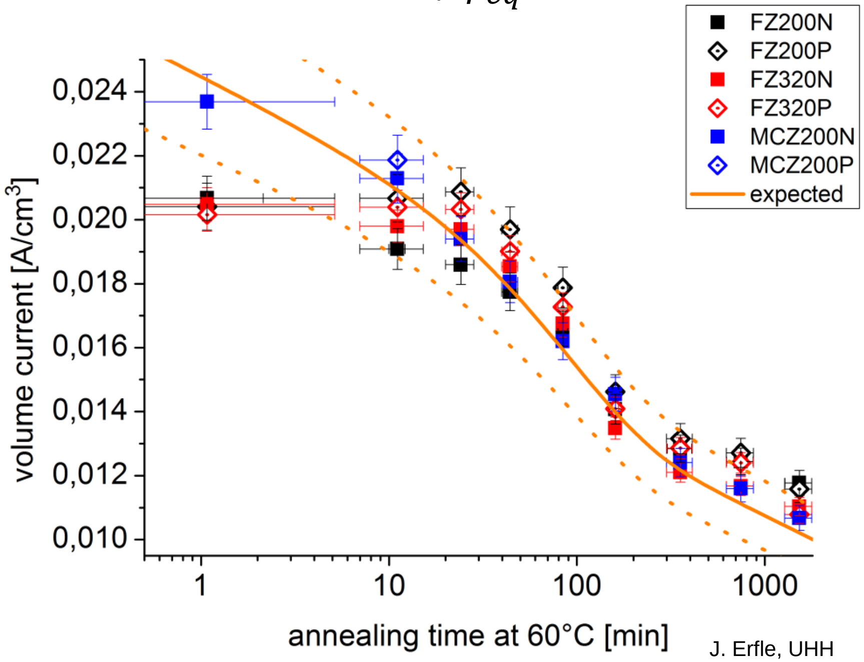
capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded, Space charge sign determined via TCT.

Current annealing of irradiated samples

23 MeV protons, $\phi_{eq} = 2.9 \cdot 10^{14}\ cm^{-2}$



1 MeV neutrons, $\phi_{eq} = 4 \cdot 10^{14}\ cm^{-2}$



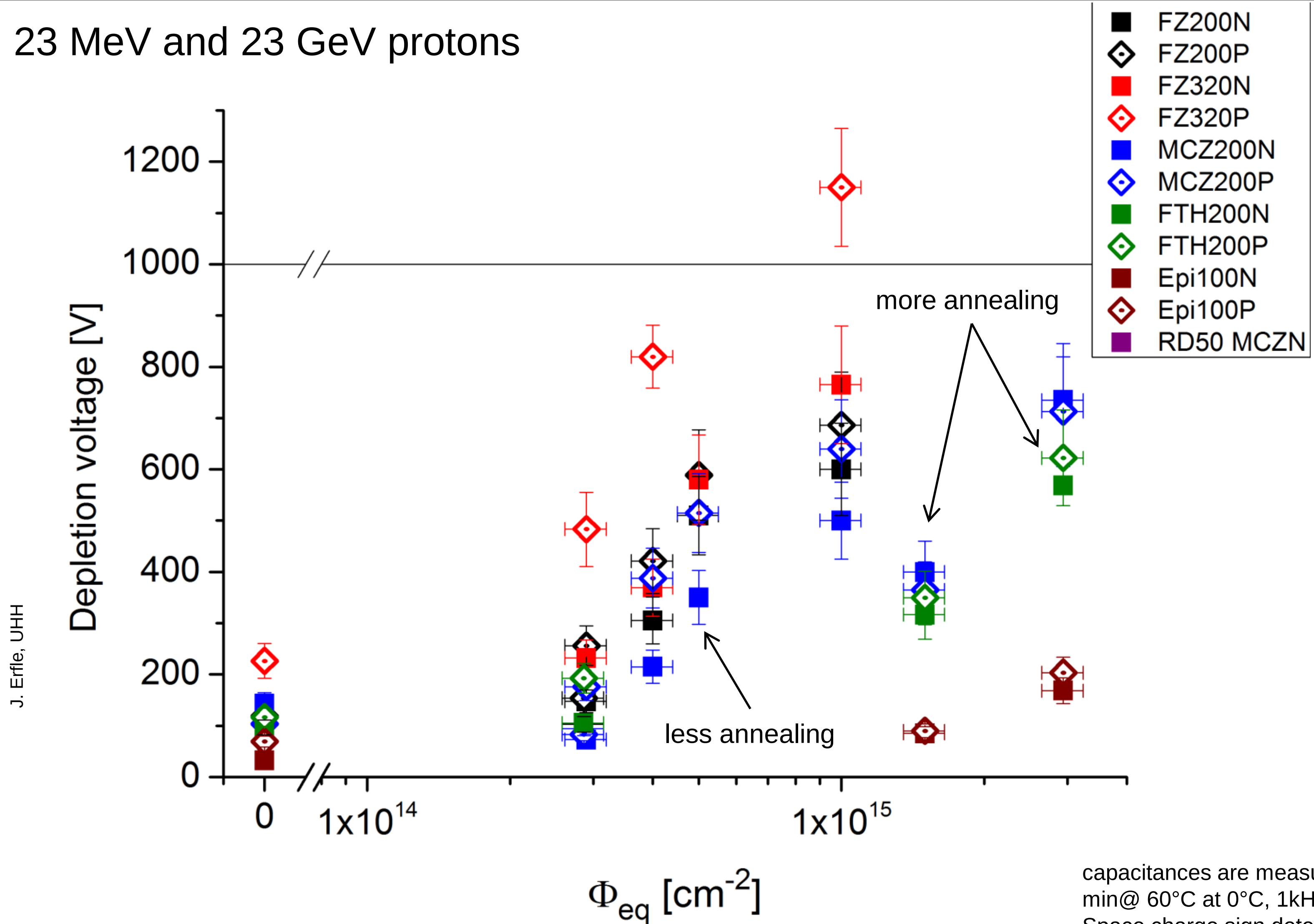
Current annealing matches expectation.

currents are measured at 0°C and scaled to 20°C, guard ring grounded

N_{eff} versus fluence

23 MeV and 23 GeV protons

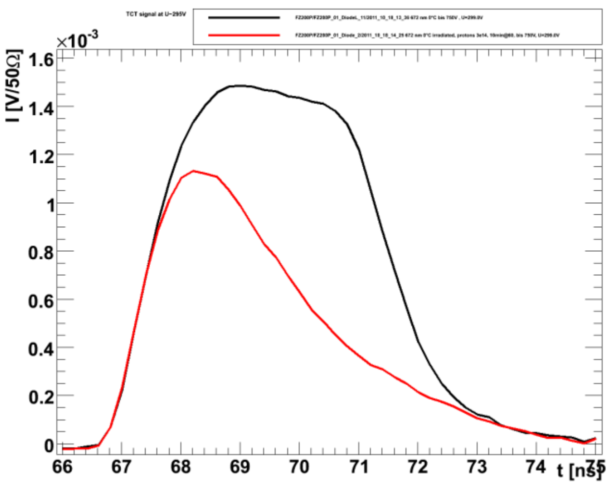
$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$



capacitances are measured after annealing of 10 min@ 60°C at 0°C, 1kHz, guard ring grounded, Space charge sign determined via TCT.

TCT pulses – p-type

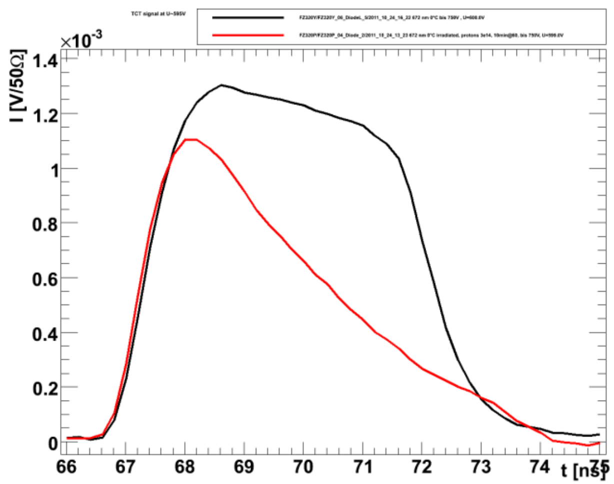
FZ200P



courtesy of T. Pöhlsen

300V

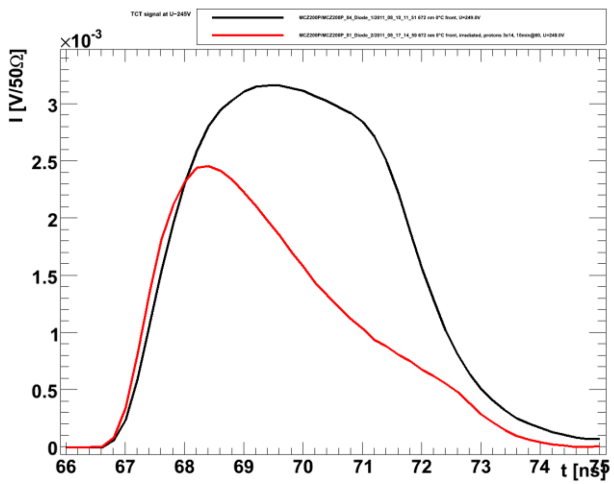
FZ320P



courtesy of T. Pöhlsen

600V

MCZ200P



courtesy of T. Pöhlsen

250V

measurements are performed at 0°C, using a red laser

not type inverted

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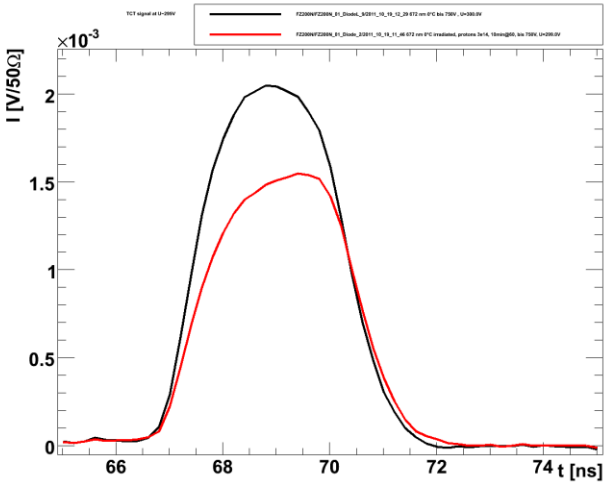
TCT pulses – n-type

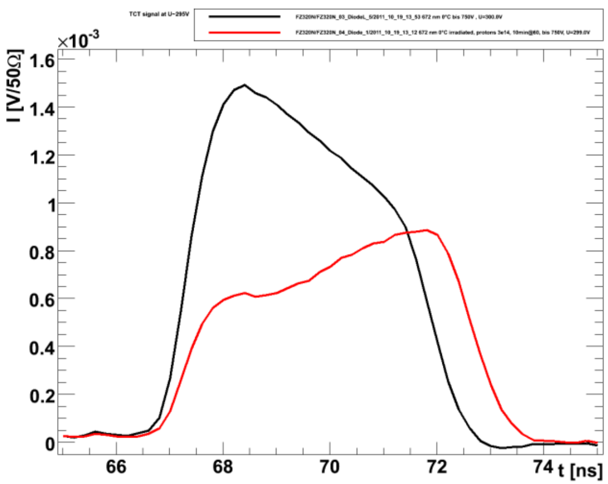
FZ200N



courtesy of T. Pöhlsen

300V

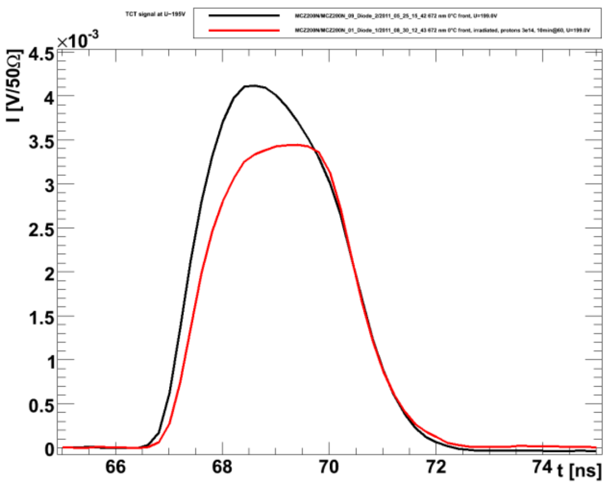
FZ320N



courtesy of T. Pöhlsen

300V

MCZ200N



courtesy of T. Pöhlsen

200V

type inverted

measurements are performed at 0°C, using a red laser

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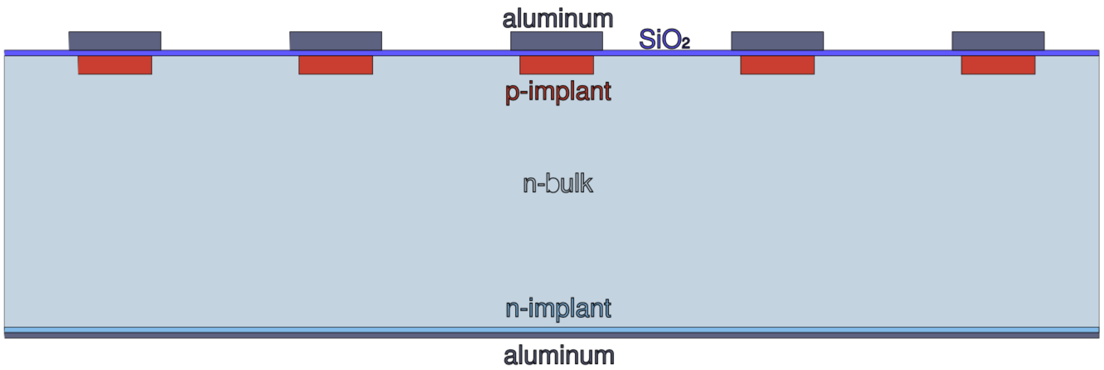
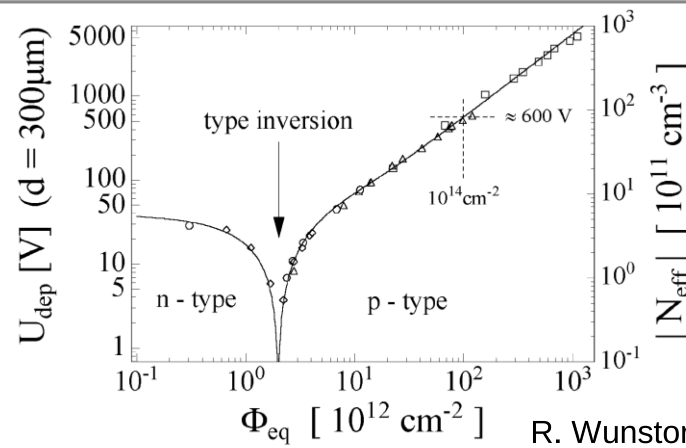
Type inversion of silicon sensors

Basic layout of a strip sensor



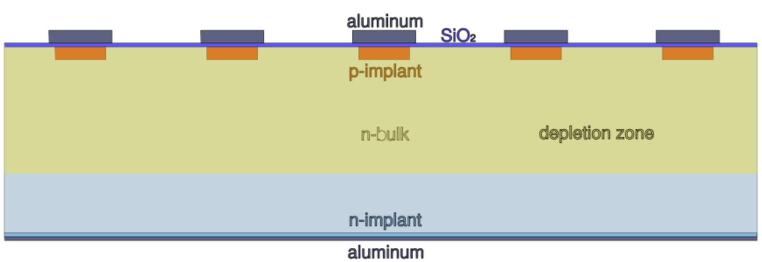


R. Wunstorf

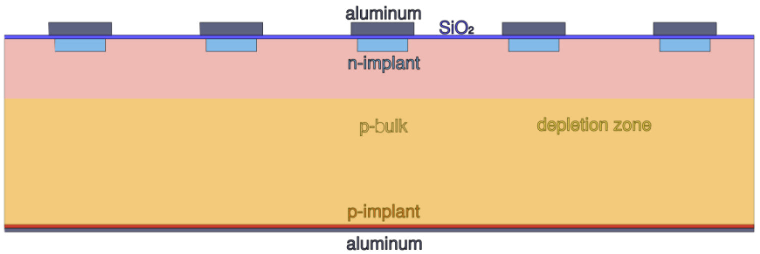
Basically two different types:

- N doped bulk:
  - Hole readout
  - Easier to produce
  - Tends to undergo type inversion
- P doped bulk:
  - Electron readout
  - Harder to produce

Depletion of a standard sensor



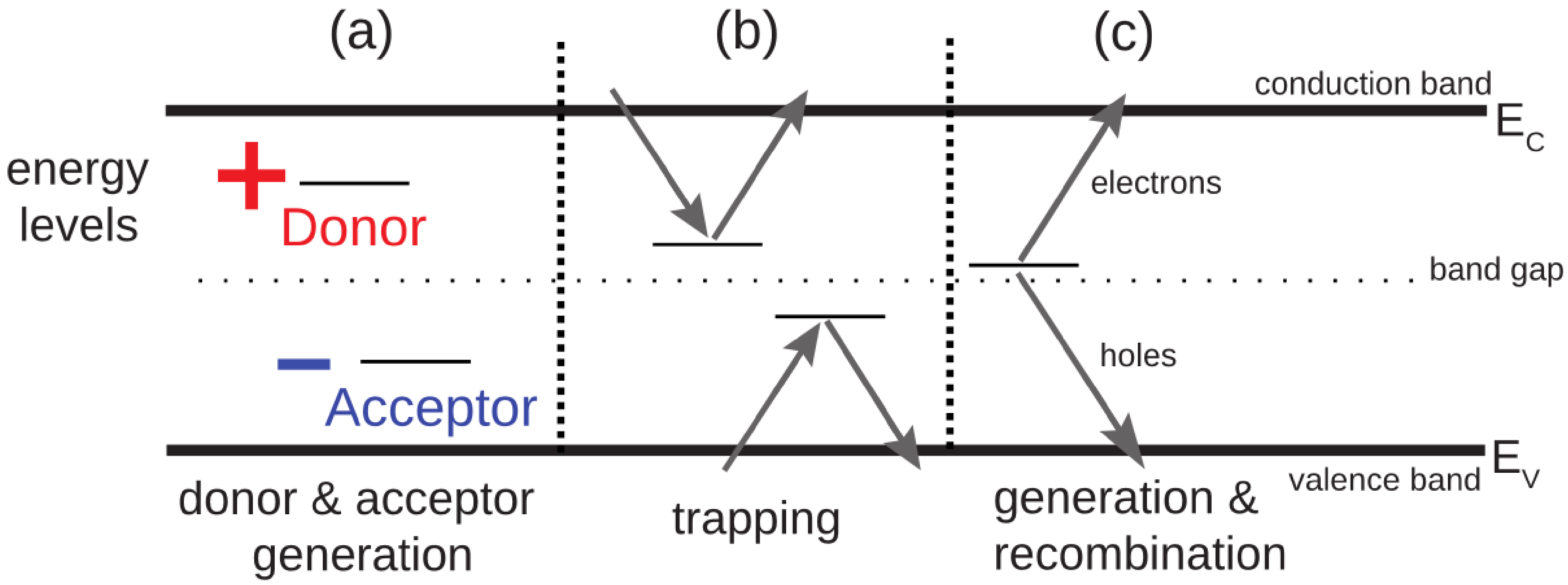
Depletion of a type inverted sensor



Radiation damage in silicon

Two different kinds of radiation damage:

- Surface damage
- Bulk damage → Main damage from hadronic radiation
  - Three different effects on silicon sensors:



Change of effective doping
→ Change of full depletion voltage

Reduction of charge collection
→ Reduction of signal

Increase of dark current
→ Increase of noise