Status of TSC Measurements at Hamburg

I. Nitrogen enriched versus standard FZ material
II. Acceptor removal after irradiation with 5.5 MeV electrons

I. E. Fretwurst, J. Schwandt, E. Garutti

Institute for Experimental Physics
University of Hamburg

II. E. Fretwurst, L. F. Makarenko[a], M. Moll[b], I. Pintilie[c]

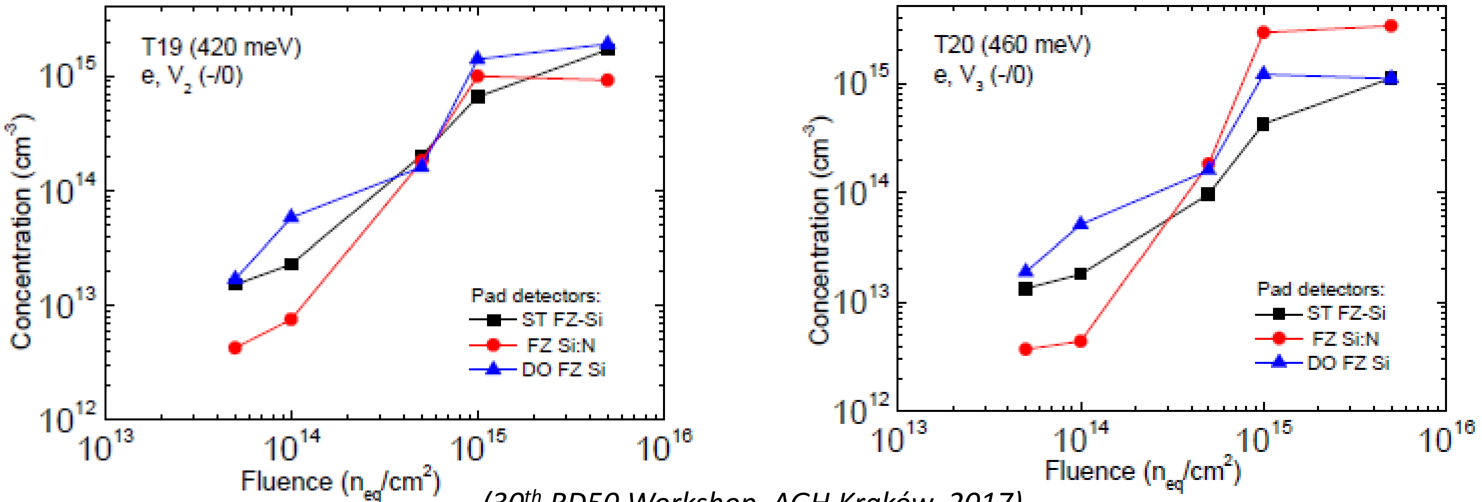
a) Belarusian State University, Minsk, Belarus

b) CERN, Geneva, Switzerland

c) Natinal Institute of Material Physics, Magurele, Romania

Introduction I

- Microscopic studies by Pawel Kaminski:
  Introduction of vacancy related cluster defects reduced in N enriched FZ samples
  Examples: PITS-measurements after 23 MeV proton irradiation



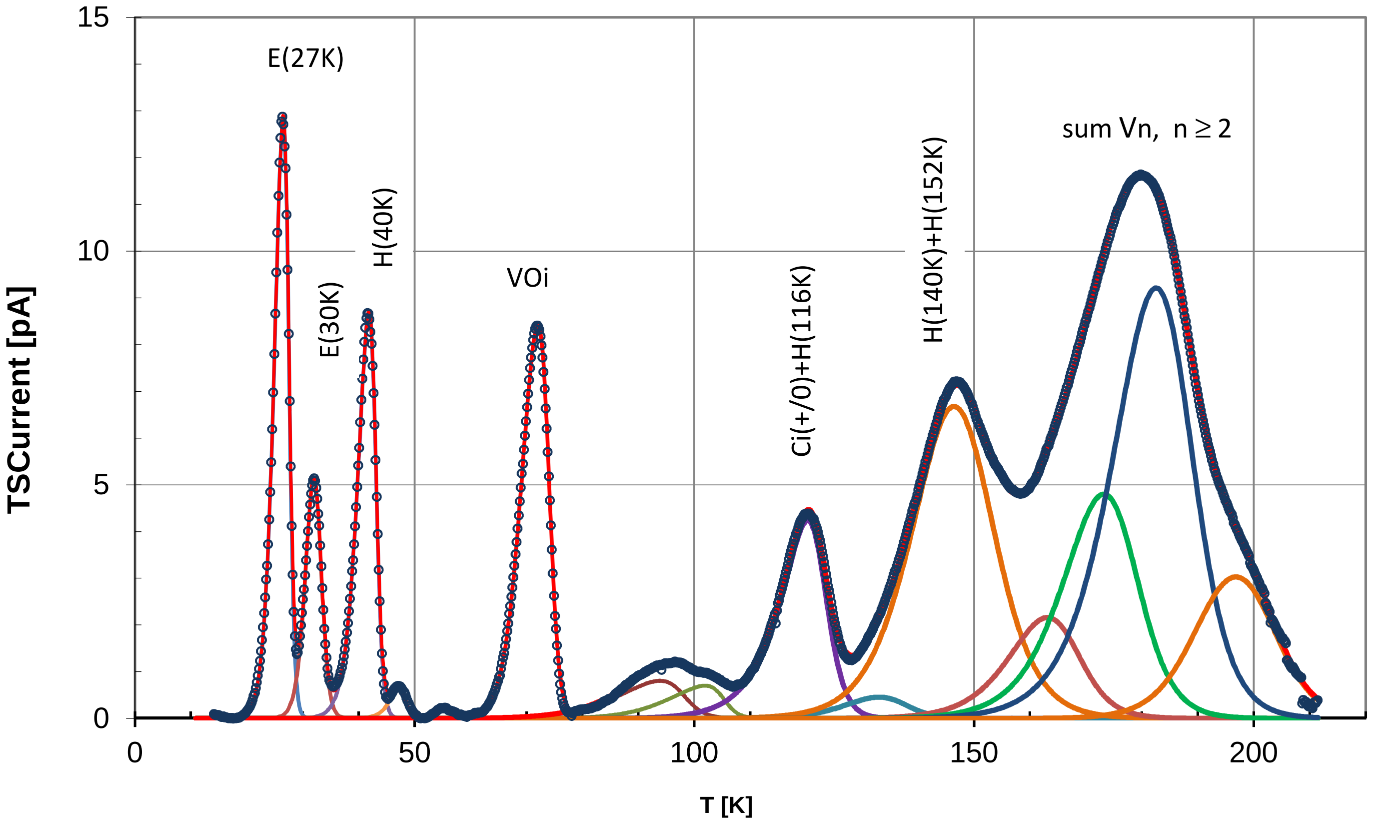
(30th RD50 Workshop, AGH Kraków, 2017)

- Are these results reproducible by the TSC- technique?
  - Such measurements can only performed on diodes
  - Fluence range limited to some 10^{14} n_{eq}/cm^2 , due to
  - needed bias voltage for total depletion

Experimental Details

- Investigated material:
  Nitrogen enriched FZ, [N] ≈ (1.3-1.6)x10^{15} cm^{-3}
  Standard FZ , [N] < 2x10^{14} cm^{-3}
  Oxygen enriched FZ, [N] < 2x10^{14} cm^{-3}
  Resistivity $\rho \approx 2$ kΩcm
- Pad diodes fabricated at CNM:
  Pad area A_{pad} : 0.18801 cm^2
  Optical window A_w: 2.25×10^{-2} cm^2
  Active thickness d: ~ 280 µm
- Irradiation:
  CERN PS protons: fluence range 8×10^{12} – 1.78×10^{14} p/cm^2 (TSC: 1.4x10^{13} n_{eq}/cm^2)
  Reactor neutrons (Ljubljana): fluence range 2×10^{11} – 1×10^{14} cm^{-2} (TSC: 1x10^{13} n_{eq}/cm^2)
  23 MeV protons (KIT): fluence range: 10^{13} – 10^{14} cm^{-2} (TSC: not done so far)
- Macroscopic measurements: I-V, C-V at 20 °C and -20 °C, always guard ring connected to ground
- Microscopic measurements: Thermally Stimulated Current (TSC) method, cooling under 0 bias, trap filling either by forward current (1mA) or by light (520 nm) on p+ electrode (electron injection), heating up under reverse bias with rate β = 0.183 K/s

TSC – Spectrum, 23 GeV protons

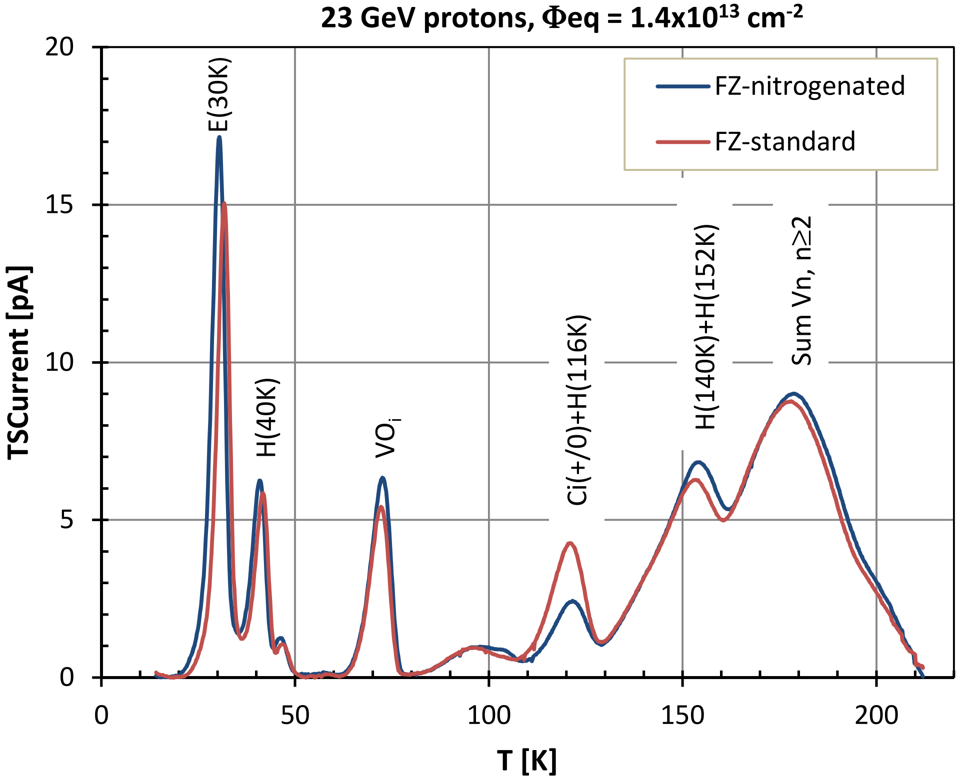


Example of a TSC-spectrum for a nitrogen enriched sample:

Φ_{eq} = 1.4×10^{13} cm^{-2}, as irradiated, trap filling with 1mA forward current

Spectrum fitted assuming 14 defect levels

TSC – Spectra, 23 GeV protons



Annealing: 80 min @ 60 °C

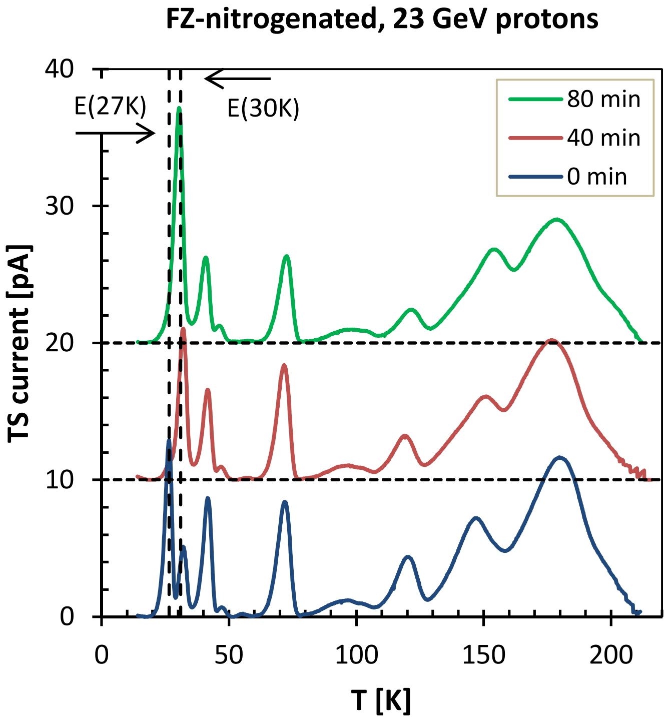
Defect	FZ-NIT	FZ-STD
E(30K)	9.5 $x10^{11}$	$7.7x10^{11}$
H(40K)	$4.0x10^{11}$	$3.4x10^{11}$
VO	$5.2x10^{11}$	$4.2x10^{11}$
Ci+H(116K)	$3.4x10^{11}$	$5.9x10^{11}$
Sum(H)	$1.6x10^{12}$	$1.4x10^{12}$
Sum(Vn)	**$3.7x10^{12}$**	**$3.6x10^{12}$**

Comparison of a nitrogen enriched with a standard FZ sample:

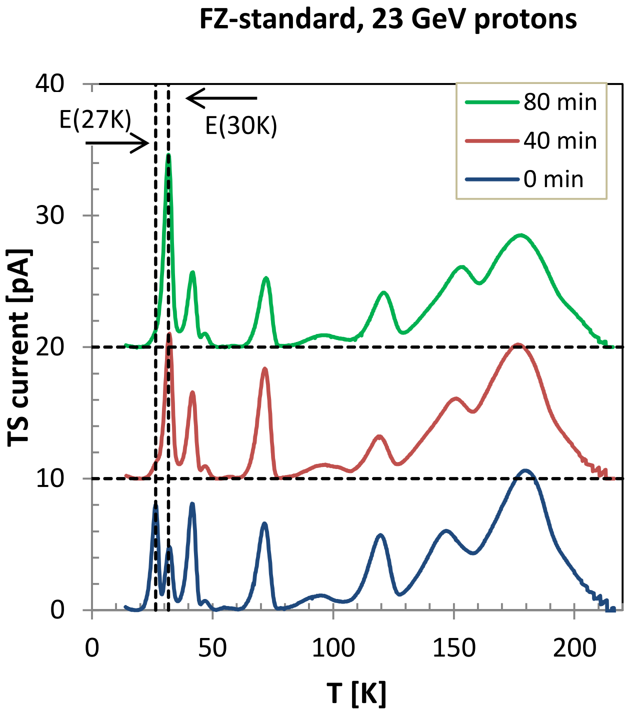
- Sum V_n , n ≥2 (E205a, V_2 , V_3 , H(220K)) cluster peak for both materials nearly identical
- Higher C_i(+/0)+H(116K) for FZ-STD
- E(30K) and VOi higher for FZ-NIT

The last 2 points indicate a larger oxygen concentration in FZ-NIT material

TSC – Spectra, annealing at 60 °C



FZ-nitrogenated, 23 GeV protons



FZ-standard, 23 GeV protons

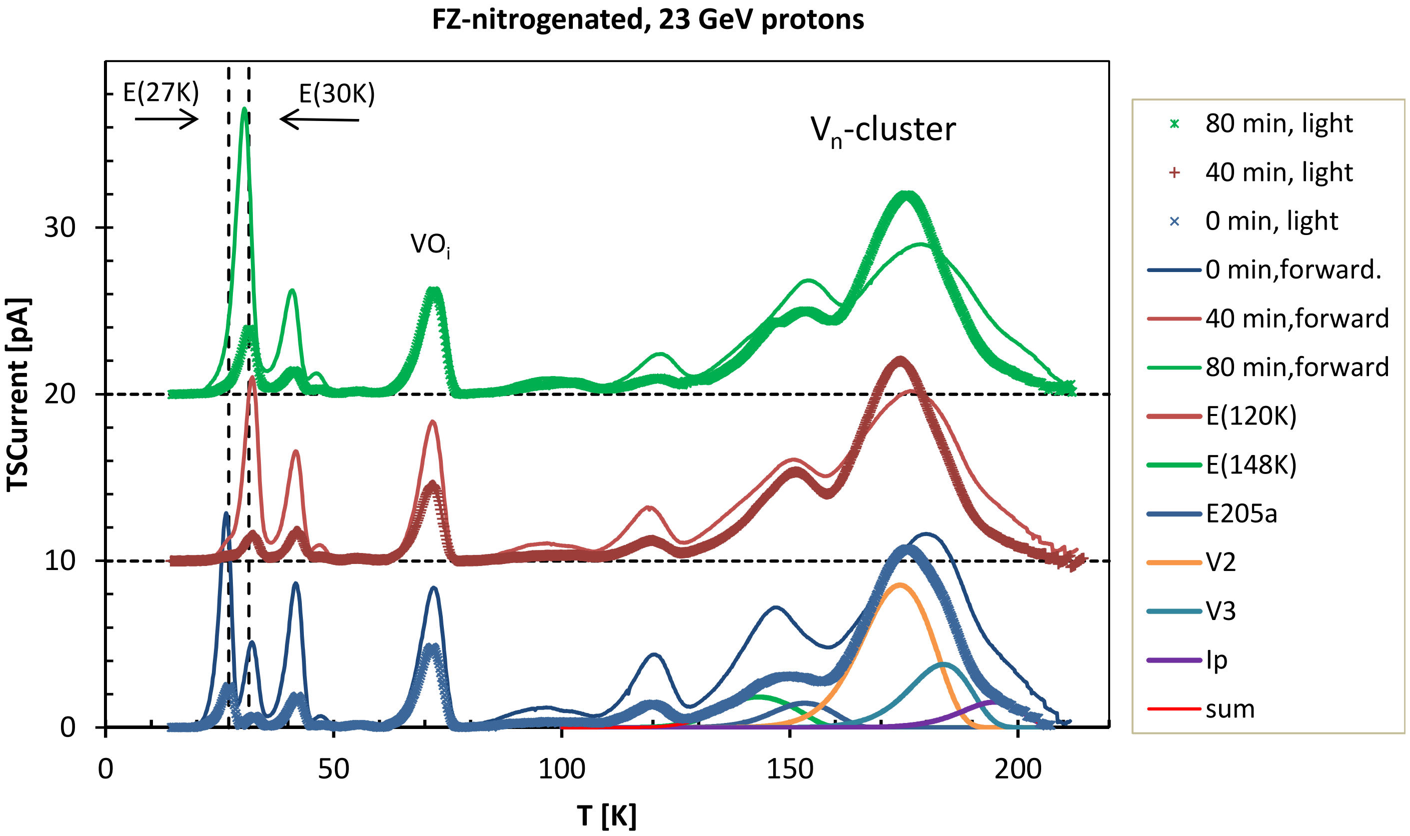
Comparison of the annealing for nitrogen enriched and standard FZ sample:

– fast decrease of E(27K) peak → increase of E(30K) defect in both materials

– E(27K) and E(30K) lager in FZ-NIT material

– similar annealing of sum(V_n) cluster peak

TSC – Spectra, different trap filling

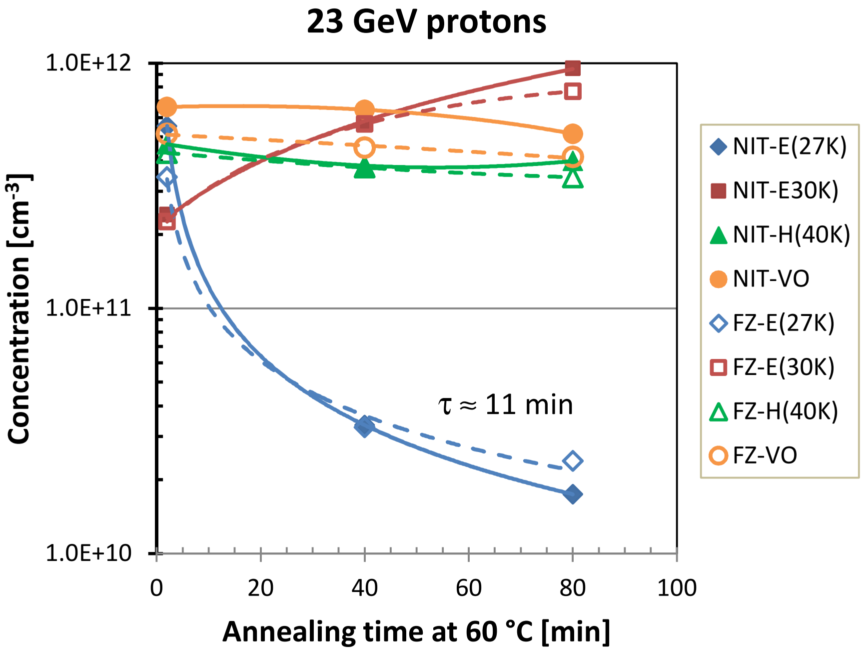


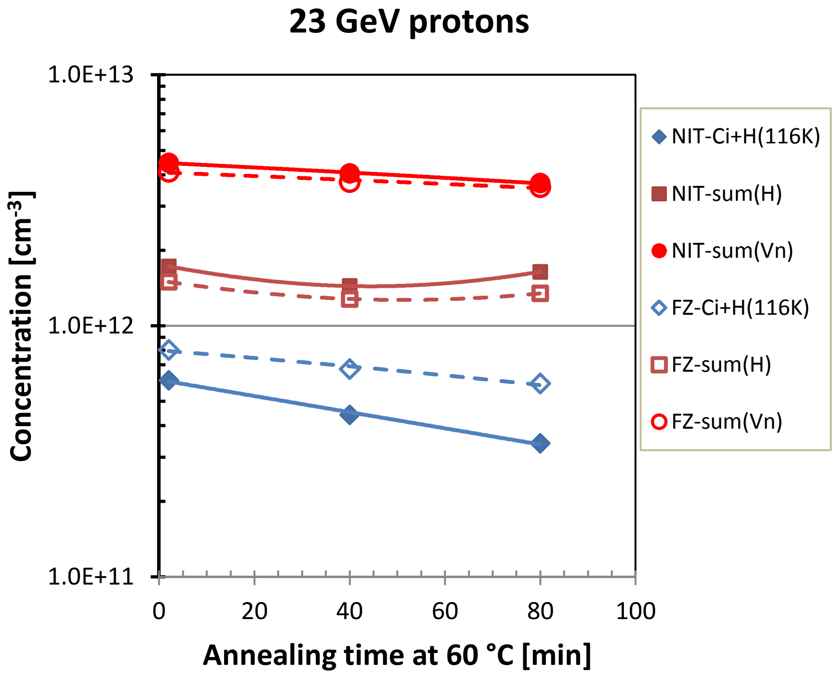
Comparison of spectra for trap filling with light (520 nm) on p$^+$-electrode (symbols) and forward current (solid lines):

– Cluster peak width smaller for light (only e$^-$ traps filled) than for forward current injection (e+h)

– Shallow traps much smaller peak height for light injection

Annealing at 60 °C, 23 GeV protons





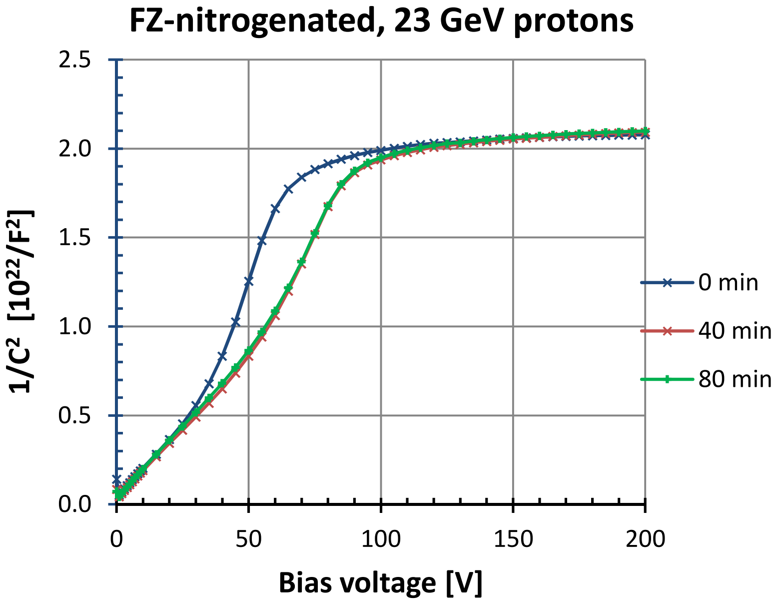
Comparison of ‘shallow’ defects:

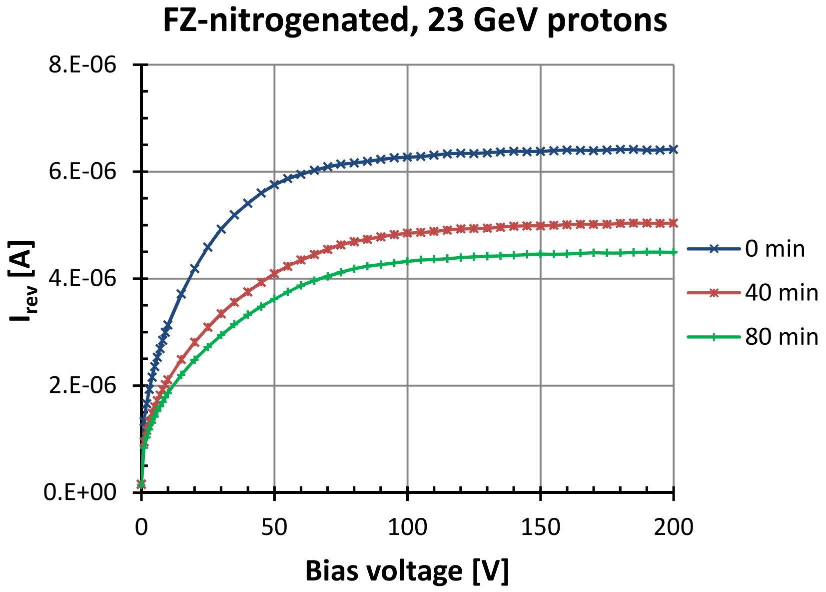
– fast decay of E(27K) for both materials,
– similar increase of E(30K) for both
– H(40K) development the same for both
– VO larger in NIT sample, slight decrease

Comparison of ‘deep’ defects:

– sum(V_n) nearly identical for both materials, very small decrease
– sum(H) defects similar development for both
– C_i(+/0)+H(116K) larger in FZ-STD sample, decrease with time

Macroscopic data, 23 GeV protons



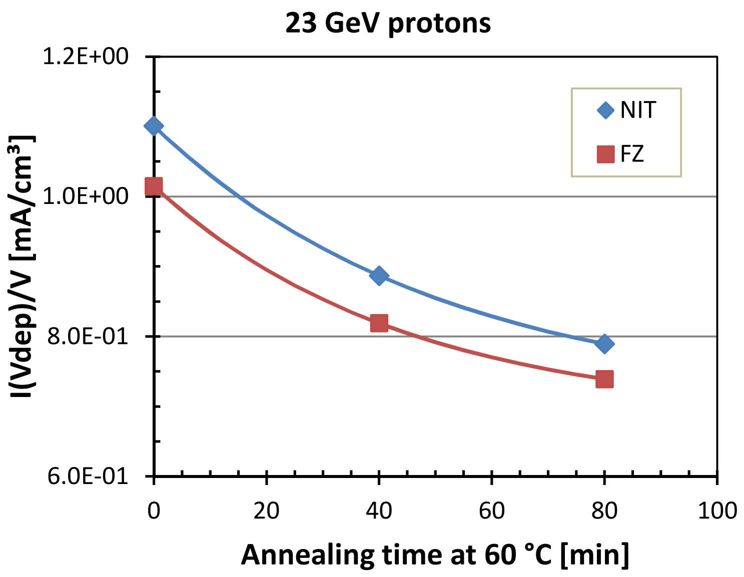


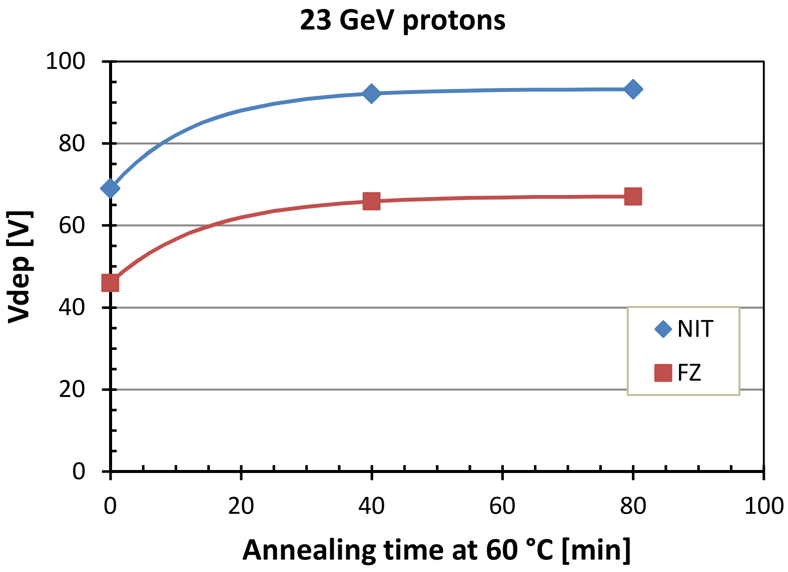
C-V and I-V characteristics for nitrogen enriched FZ sample (annealing at 60 °C):

- Shift of $1/C^2$ curve with annealing → increase of V_{dep} (see next page)
- Shape indicates non-uniform space charge → “double junction” effect
- I-V shape ~ $V^{1/2}$ up to V_{dep}
- Current annealing see next page

- For FZ standard material the same behavior, only V_{dep} smaller

Macroscopic data, 23 GeV protons

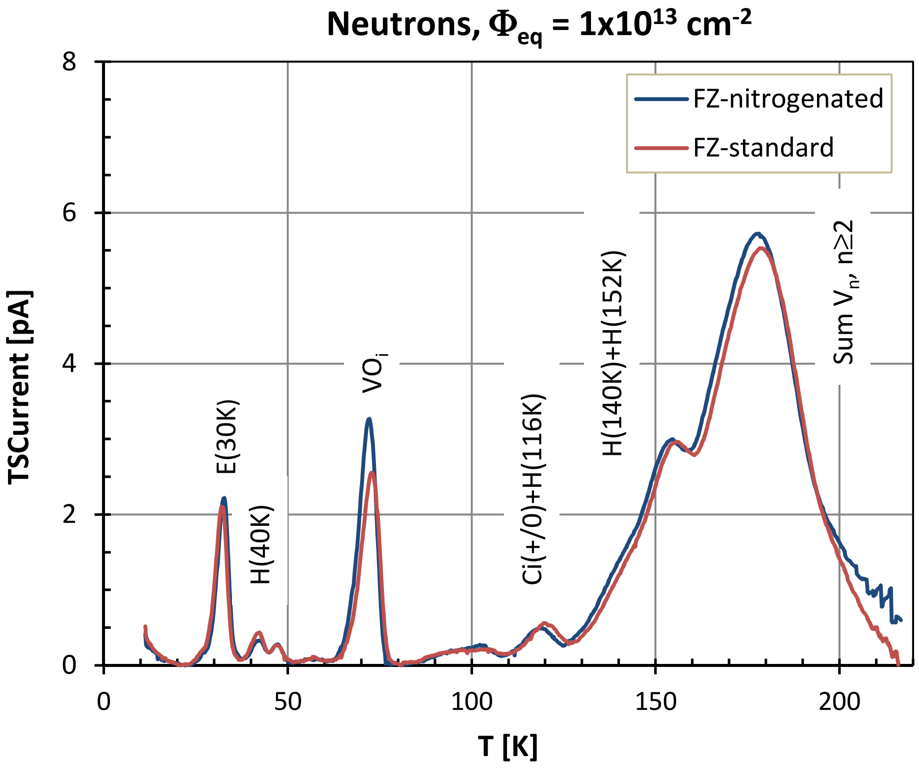




Comparison of dark current and V_{dep} annealing at 60 °C for nitrogen enriched and standard FZ sample:

- Time constant for dark current $\tau \approx (45/50)$ min for FZ-STD/FZ-NIT
- Time constant for V_{dep} $\tau \approx (14/13)$ min for FZ-STD/FZ-NIT

TSC – Spectra, Neutrons



Annealing: 80 min @ 60 °C

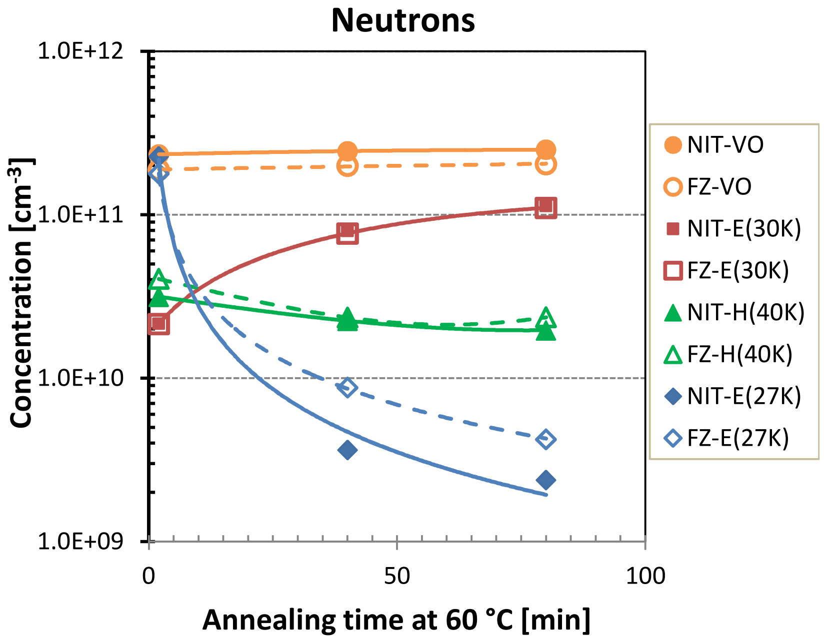
Defect	FZ-NIT	FZ-STD
E(30K)	1.1 x10^{11}	1.1x10^{11}
H(40K)	2.0x10^{10}	2.4x10^{10}
VO	2.5x10^{11}	2.0x10^{11}
Ci+H(116K)	6.5x10^{10}	7.3x10^{10}
Sum(H)	5.7x10^{11}	6.0x10^{11}
Sum(V_n)	**2.3x10^{12}**	**2.2x10^{12}**

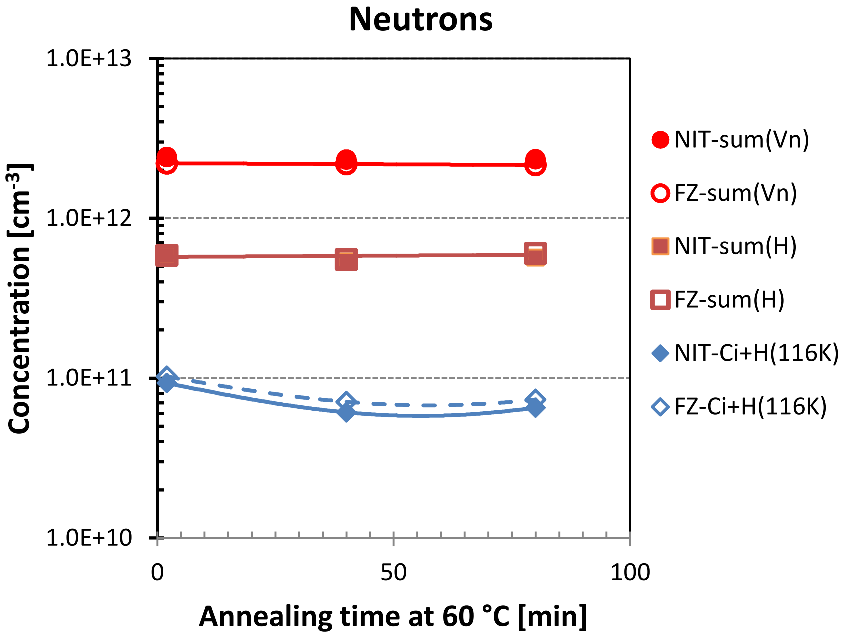
Comparison of a nitrogen enriched with a standard FZ sample:

- Sum V_n , n ≥2 (E205a, V_2 , V_3 , H(220K)) cluster peak for both materials nearly identical
- Higher Ci+H(116K) for FZ-STD, small effect
- VO_i higher for FZ-NIT

Main difference to proton irradiation: introduction of shallow defects much smaller

Annealing at 60 °C, Neutrons





Annealing behavior similar to 23 GeV proton damage

Comparison of 'shallow' defects:

– fast decay of E(27K) for both materials

– similar increase of E(30K) for both

– H(40K) the same development for both

– VO larger in NIT sample

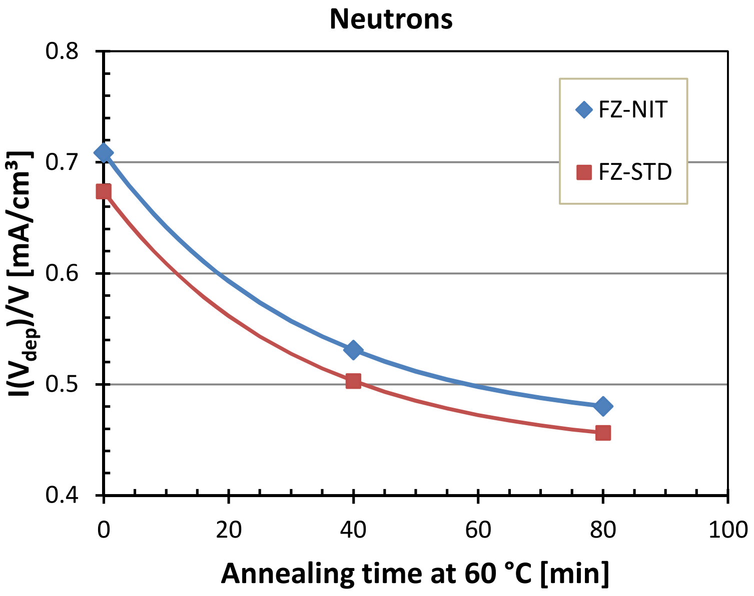
Comparison of 'deep' defects:

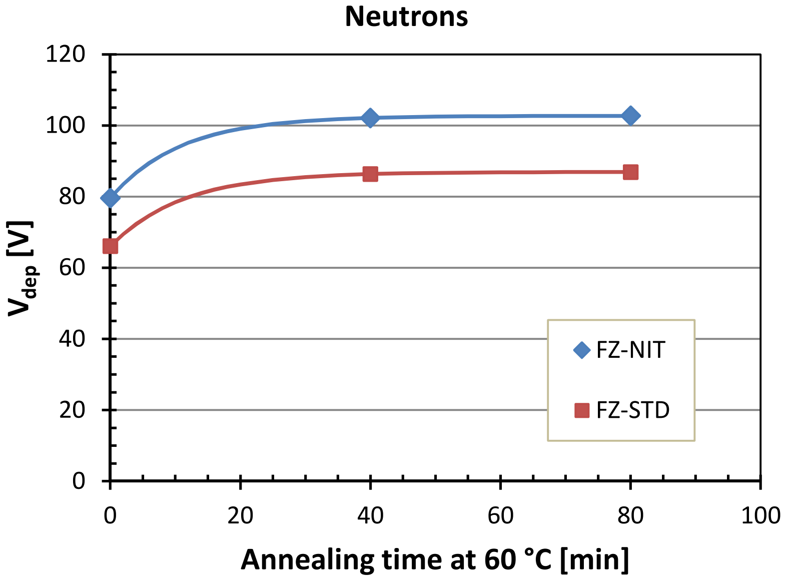
– sum(V_n) nearly identical for both materials,

– sum(H) defects nearly constant, similar development for both

– C_i(+/0)+H(116K) larger in FZ-STD sample

Macroscopic data, Neutrons





Comparison of annealing at 60 °C for nitrogen enriched with standard FZ sample:

- Dark current decay: $\tau \approx$ (31/32) min for FZ-STD/FZ-NIT
- V_{dep} increase: $\tau \approx$ (11/11) min for FZ-STD/FZ-NIT

Conclusions and Outlook I

- No difference between nitrogen enriched and standard n-type FZ devices with respect to the deep cluster defects is observed by TSC measurements.
  This holds for irradiation with 23 GeV protons as well as reactor neutrons.

- Also the annealing show no difference between both materials (for the clusters)

- Only differences are observed in the introduction of shallow defects (E(27K) and E(30K)) which is larger in nitrogen enriched material and the introduction of the C_i(+/0)+H(116K) signal is larger in the standard FZ material

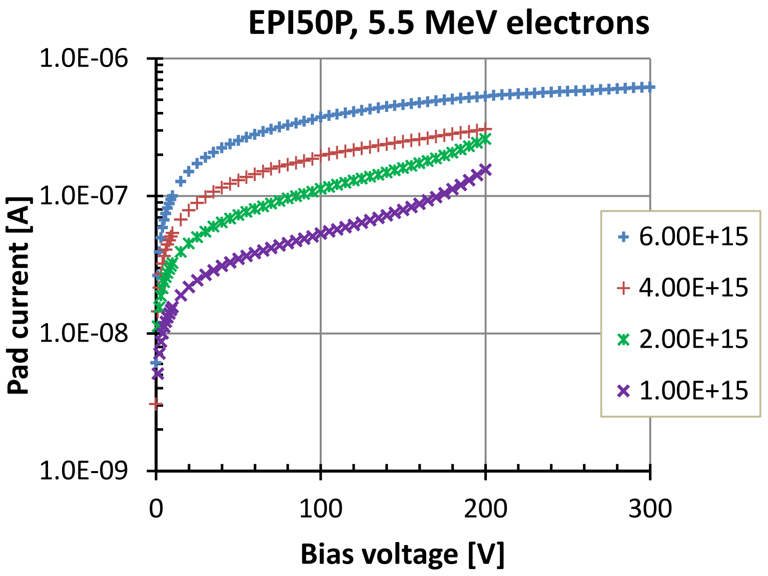
- Outlook:
  - The annealing will be continued
  - Measurements for more fluence values have to be performed
  - Special parameters of the TSC will be changed systematically, i.e. filling temperature, filling time, heating rate β

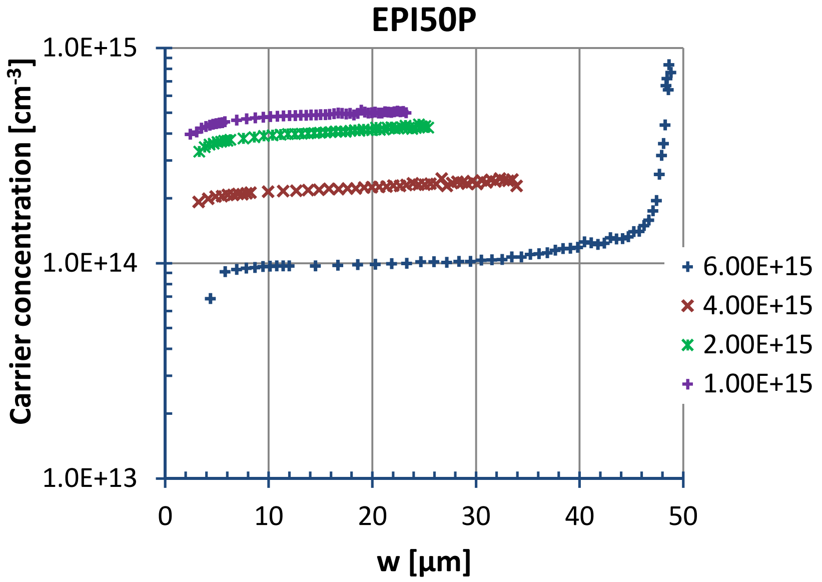
Introduction II

Acceptor removal in highly Boron doped EPI silicon:

- Boron removal is of outmost interest for the radiation hardness of LGAD- and HV-CMOS- sensors for application in HEP-experiments
- Irradiation with 5.5 MeV electrons at Minsk, $\Phi_e = (1\text{-}6)\text{x}10^{15}$ cm^{-2}
- First preliminary results presented on:
  - I-V and C-V characteristics of 10 Ωcm p-type EPI-Material (50 µm thickness) after irradiation
  - TSC measurements:
    Introduction of the B_iO_i defect
    - Fluence values between 1x10^{15} cm^{-2} and 6x10^{15} cm^{-2}
    - Preliminary results on fluence dependence

Macroscopic Results





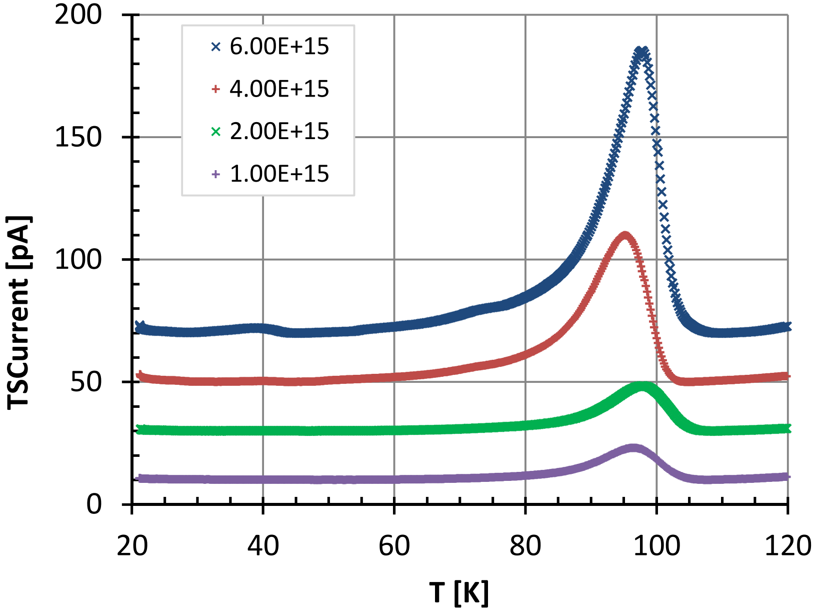
I-V for as irradiated diodes:

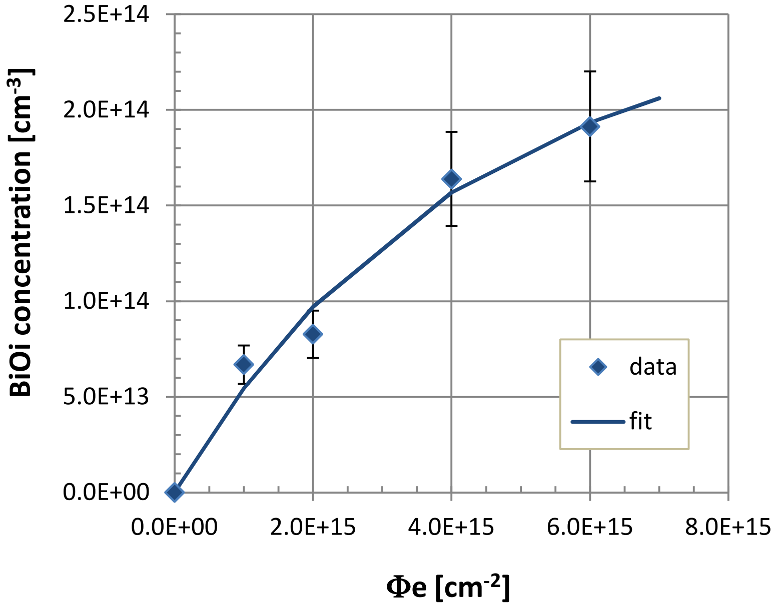
- Soft break down for 1 and 2x10^{15} cm^{-2}
  → limitation of bias voltage in TSC
- Full depletion only for 6x10^{15} cm^{-2}
- Problem: Volume only estimated from C-V data
- C-V measurements down to ~ 60 K difficult (reliable?)

Free charge carrier concentration profiles:

- Concentration decreases with Φ_e
- Depletion width increases with Φ_e
- Total depletion for 6x10^{15} cm^{-2}

TSC Results





TSC spectra for Φ_e = (1, 2, 4, 6)x10^{15} cm^{-2}

- Temperature shift of peak positions due to different bias voltages
  → Poole-Frenkel effect

B_iO_i concentration versus Φ_e

- Boron removal parameter
  $c_e \approx 2.4 \times 10^{-16}$ cm^2 ,
- For a hardness factor of
  κ_{neq}(5.5 MeV, e)=3.98×10^{-2} *
  $c_{neq} \approx 6.1 \times 10^{-15}$ cm^2

* (*I. Jun et al., IEEE TS Nucl. Sci. Vol.56, No.6, 2009*)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Summary and Outlook II

- Boron removal was studied via the introduction of B_iO_i in high doped EPI diodes irradiated with 5.5 MeV electrons using the TSC method
- The analysis of the measured TSC spectra versus electron fluence result in a removal parameter of $c_e \approx 2.4 \times 10^{-16}$ cm^2 for 5.5 MeV electrons
- Taking the NIEL value from Jun et al. a hardness factor of $\kappa_{eq} = 3.98 \times 10^{-2}$ is calculated leading to removal parameter of $c_{eq} \approx 6.1 \times 10^{-15}$ cm^2 which is in the same order as given by G. Kramberger for neutrons ($\sim 4 \times 10^{-15}$ cm^2)
- Outlook:
  - The problem of TSC measurements for non fully depleted devices will be studied
  - TSC data on new p-type devices irradiated with GeV protons will start soon.

Thanks for your attention