# Radiation tolerant epitaxial silicon detectors of different thickness

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- **Motivation**
- **Material parameter**
- **Typical annealing curves**
- **Results for proton and neutron irradiated devices**
- **S-LHC scenario: simulation and experimental data**
- **Outlook**

# Motivation

- **LHC upgrade to Super-LHC**

  **Luminostity LHC: $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$ → S-LHC: $L \sim 10^{35}$ cm$^{-2}$s$^{-1}$**

  **Expected radiation at inner pixel layer (4 cm) under S-LHC conditions:**

  **Fluence for fast hadrons: $1.6\times10^{16}$ cm$^{-2}$ Dose: 420 Mrad**

- **Needed data for prediction of S-LHC operational scenario:**

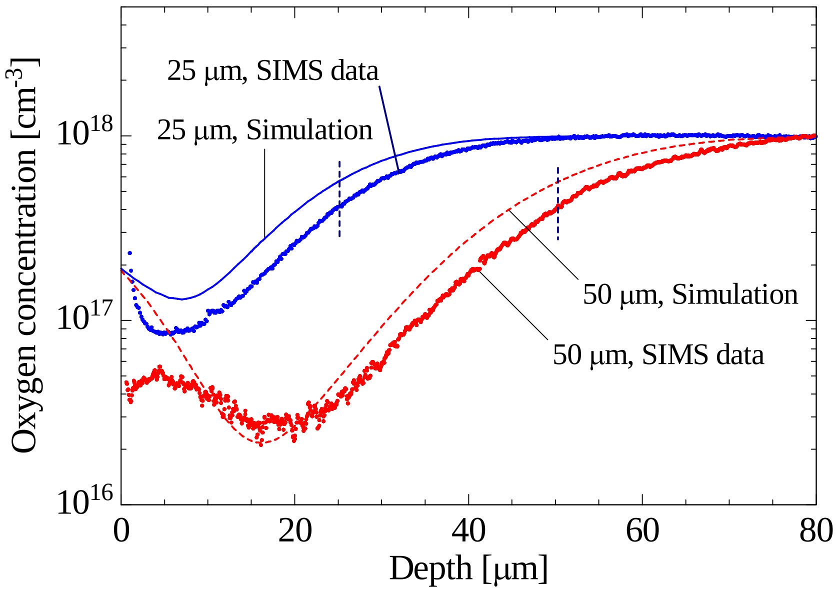
  - **Full set of damage parameters for $N_{eff}$ resp. $V_{fd}$**
  - **Full annealing cycles at elevated temperatures (minimal 2 temperatures)**
  - **Charge collection efficiency at very high fluences**

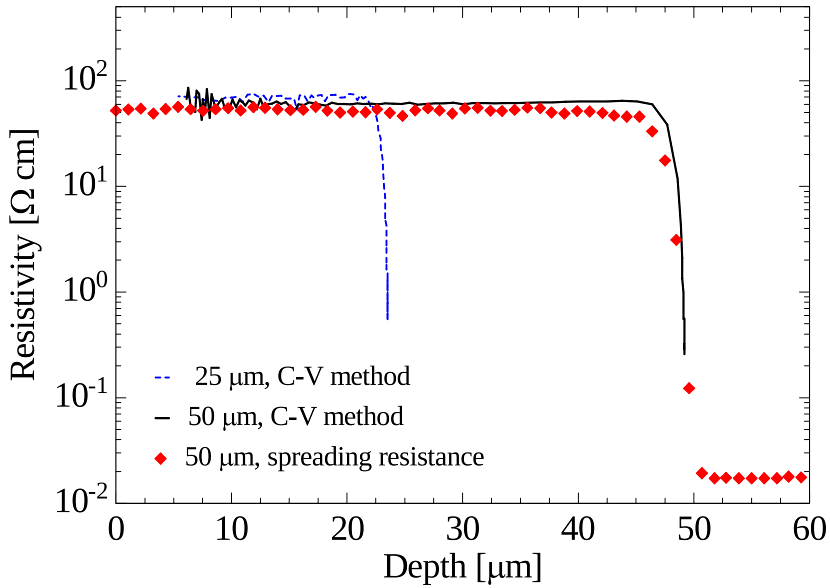
    **CCE is limited by carrier trapping**

    **Extrapolated mean free drift length (*G. Kramberger*) at $10^{16}$ cm$^{-2}$**

$$\lambda_e \approx 20\ \mu m \text{ and } \lambda_h \approx 10\ \mu m$$

# Material Parameter




- **Oxygen depth profiles**

  **SIMS-measurements performed after diode process**

  **O diffusion from substrate into epi-layer**

  **[O] 25 µm > [O] 50 µm**

  (SIMS-measurements: A. Barcz/ITME, Simulations: L. Long/CiS)

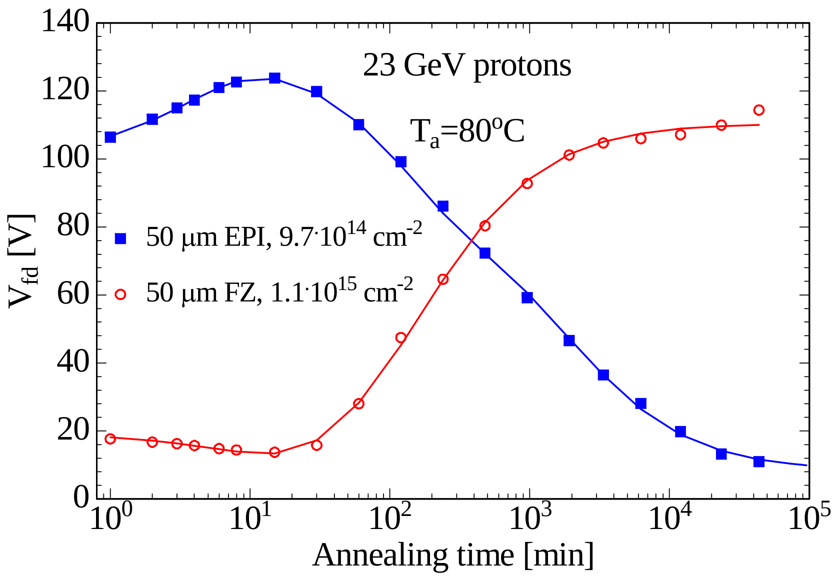
- **Resistivity profiles**

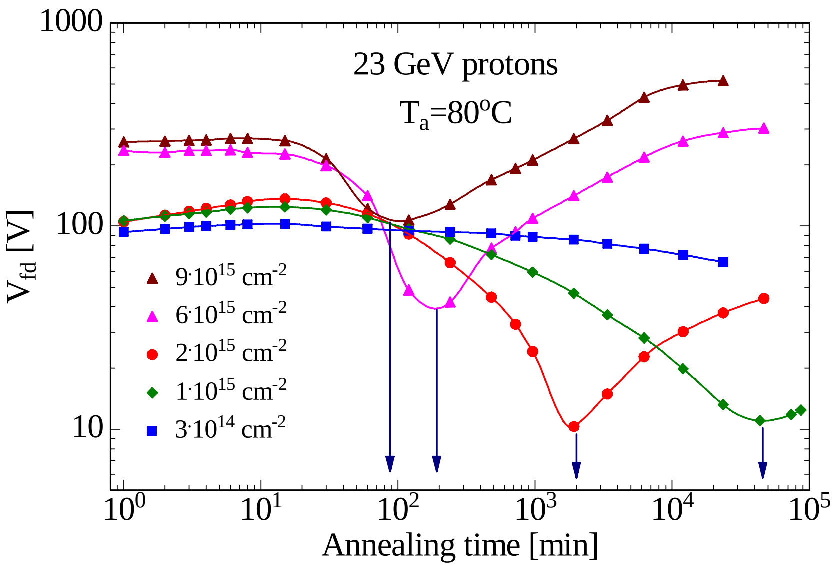
  **ρ measurement before diode process, C-V on diodes**

  **Spreading resistance method coincides well with C-V method**

  **Excellent homogeneity of doping in epi-layers**

# Typical Annealing Curves




**Comparison EPI- with FZ-device:**

**$V_{fd}$ development:**

**short term: EPI increasing, FZ decreasing**
**long term: EPI decreasing, FZ increasing**

**→ EPI not inverted, FZ inverted**

**Typical annealing behavior of EPI-devices:**

**Inversion during annealing (↓)**

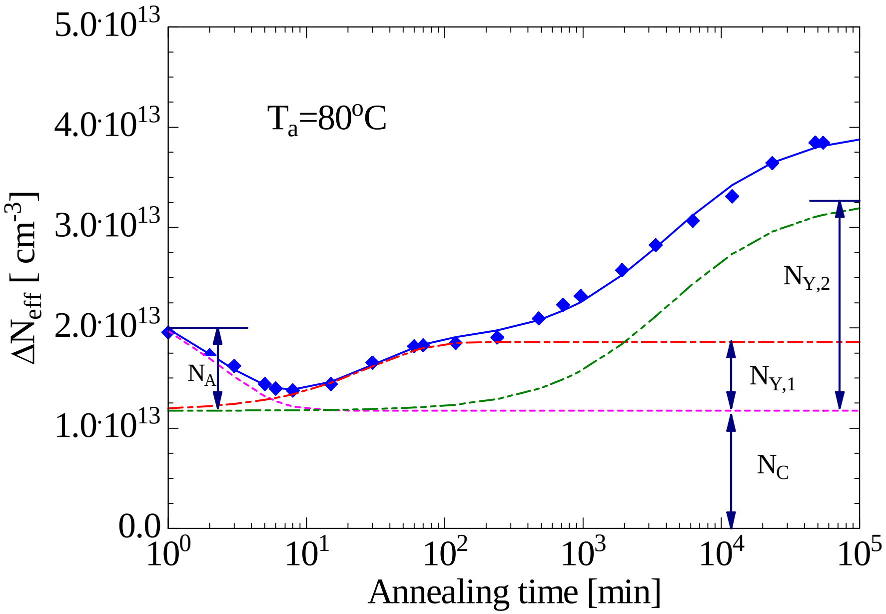
**Annealing time at which inversion appears decreases with increasing fluence**

*E. Fretwurst, Univ. Hamburg, RD50 workshop, Helsinki, June 2005*

# Parameterization of Annealing Results

**Change of effective "doping" concentration: $\Delta N_{eff} = N_{eff,0} - N_{eff}(\Phi,t(T))$**

**Standard parameterization: $\Delta N_{eff} = N_A(\Phi,t(T)) + N_C(\Phi) + N_Y(\Phi,t(T))$**




- **Annealing components:**

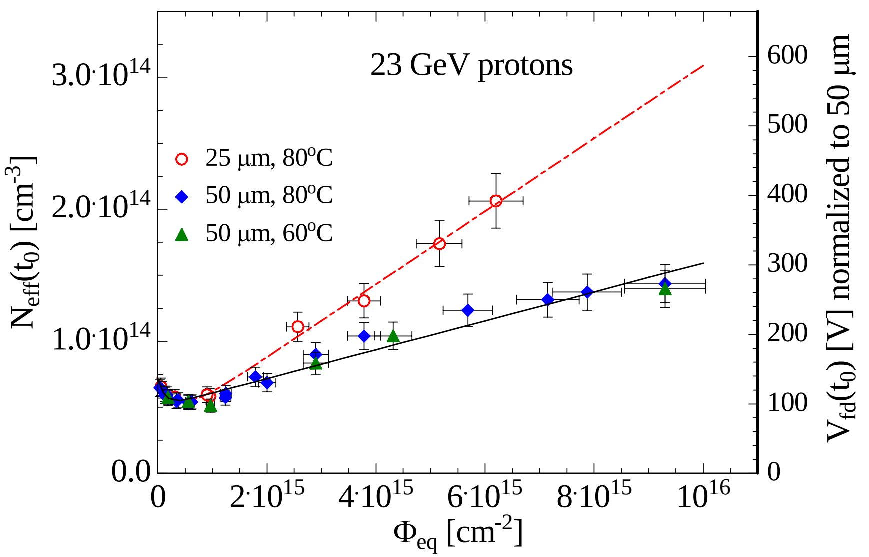
  **Short term annealing → $N_A(\Phi,t(T))$**

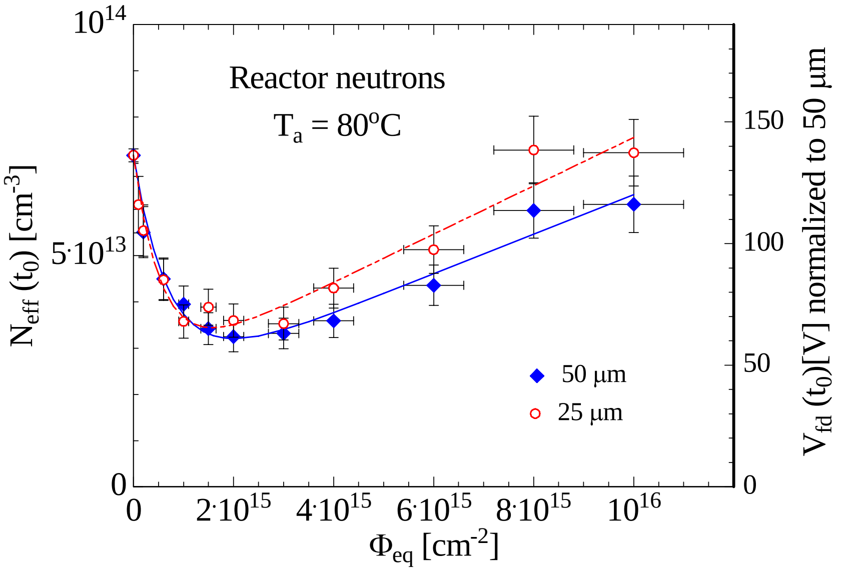
  **Stable damage → $N_C(\Phi)$**

  **Long term (reverse) annealing:**
  **Two components:**

  **→ $N_{Y,1}(\Phi,t(T))$, first order process**
  **→ $N_{Y,2}(\Phi,t(T))$ ,second order process**

# Quasi-Stable Damage Component

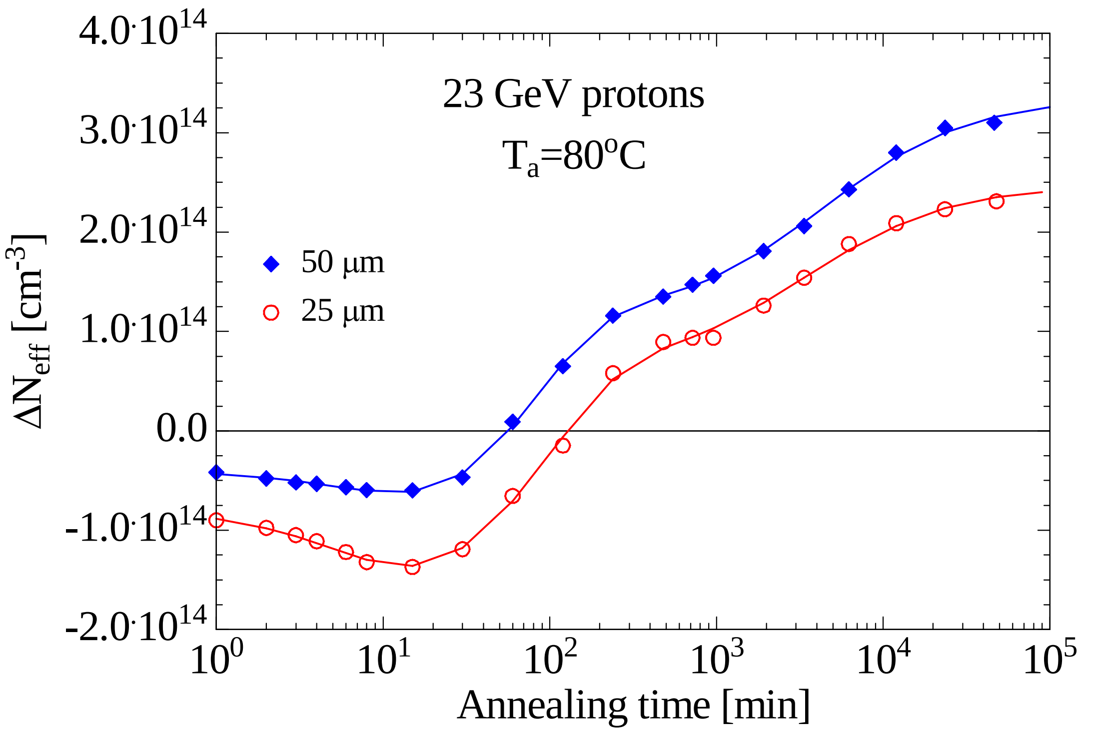



## $N_{eff}(t_0)$: Value taken at annealing time $t_0$ at which $V_{fd}$ maximal

- **No space charge sign inversion after proton and neutron irradiation**
  **Introduction of shallow donors overcompensates creation of acceptors**
- **Protons: Stronger increase for 25 µm compared to 50 µm**
  **→ higher [O] and possibly [$O_2$] in 25 µm (see SIMS profiles)**
- **Neutrons: Similar effect but not as pronounced**
  **most probably due to dominance of cluster-generation**

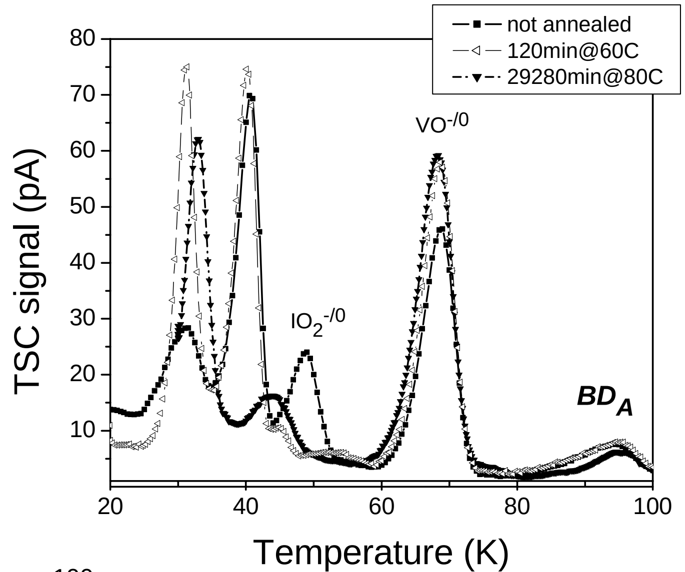
# Annealing Curves for 25 µm and 50 µm

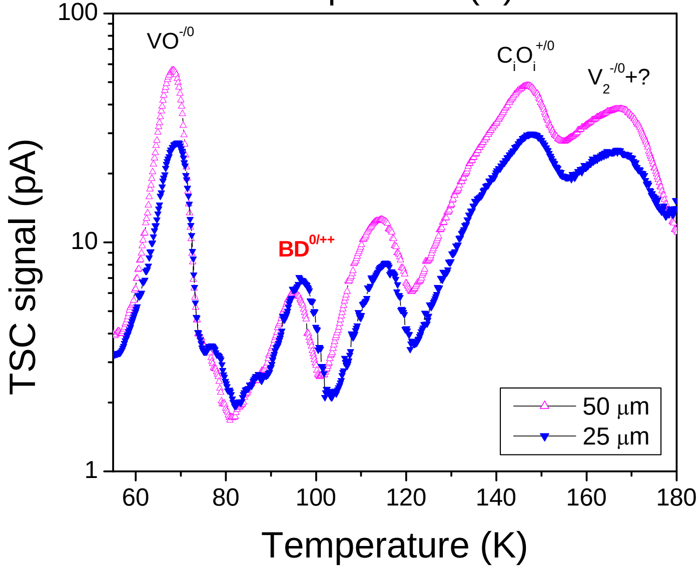



- **Nearly identical time dependence, shift between both curves constant**
- **Shift due to higher introduction of shallow donors in 25 µm epi-Si**
- **Concentration of donors not affected by long term annealing**

→ **Radiation induced donors are stable at 80°C** (*verified by I. Pintilie*)

# TSC Results



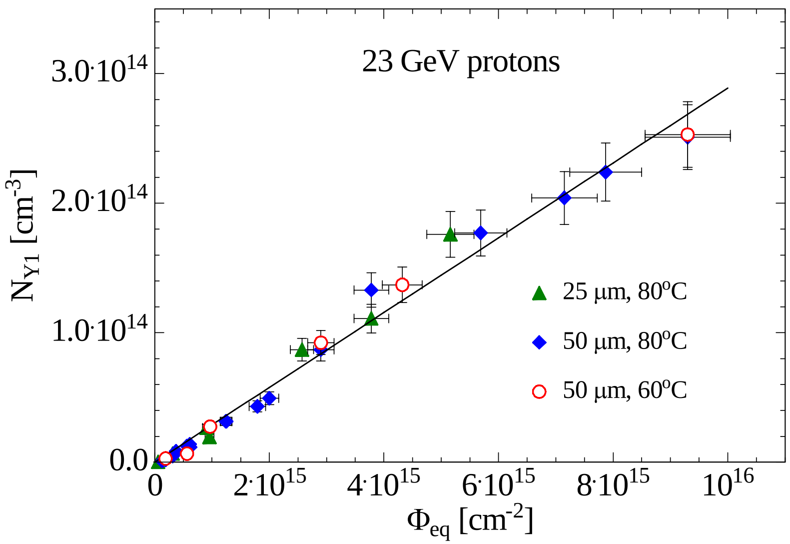

**Defects in EPI-silicon after 23GeV proton irradiation:**

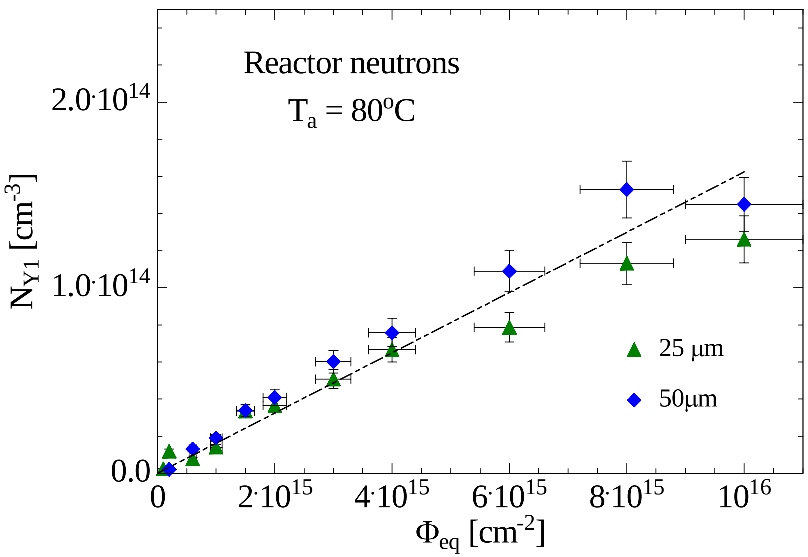
- **Shallow donors:**
  **Introduction of positive space charge**
  bistable donor BD(0/++)
  stable at 80°C up to 20 days
  introduction rate g(25 μm)/g(50 μm) ≈ 2

- **Deep acceptors:**
  **Introduction of negative space charge**
  I-defect I(0/+)
  $V_2$ + $V_2$ clusters
  VP (E-center), in EPI high P concentration

- **$IO_2$ defect:**
  observed in Cz and EPI
  indicates presence of $O_2$ in both materials

# Fluence Dependence of $N_{Y1}$




- **Introduction rate for protons:**

**Independent of epi-layer thickness and annealing temperature**

**$g_{Y1} = 2.9\times10^{-2}$ cm$^{-1}$**

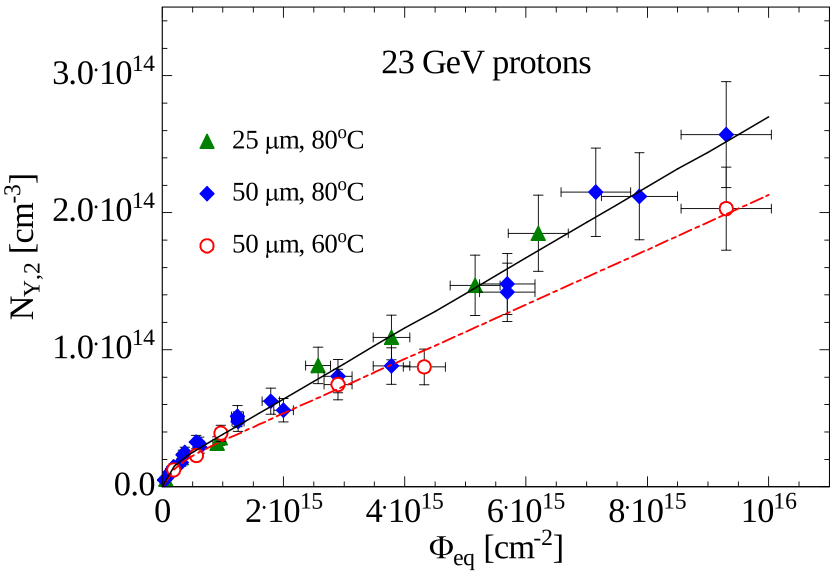
- **Introduction rate for neutrons:**

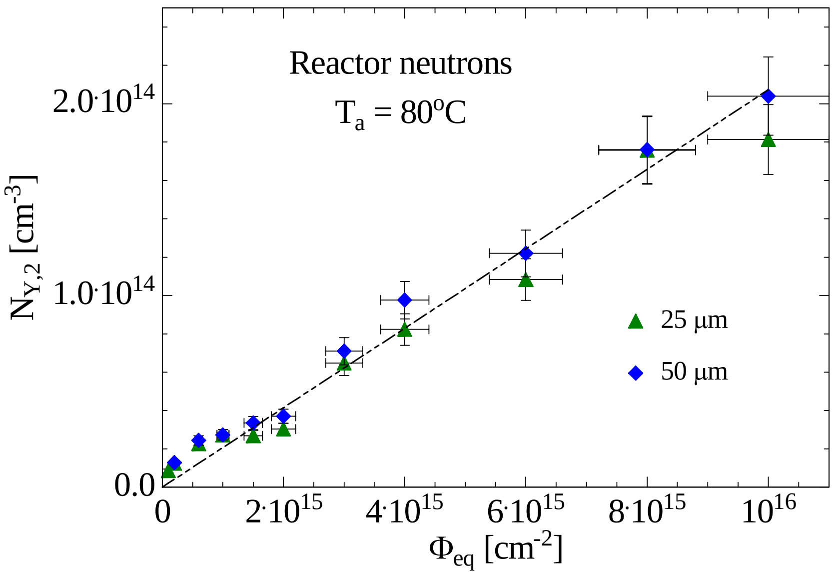
**Value for 25 µm slightly lower compared to 50 µm**
**average value:**

**$g_{Y1} = 1.6\times10^{-2}$ cm$^{-1}$**

**substantially smaller compared to proton damage**

# Fluence Dependence of $N_{Y2}$




- **Introduction rate for protons:**

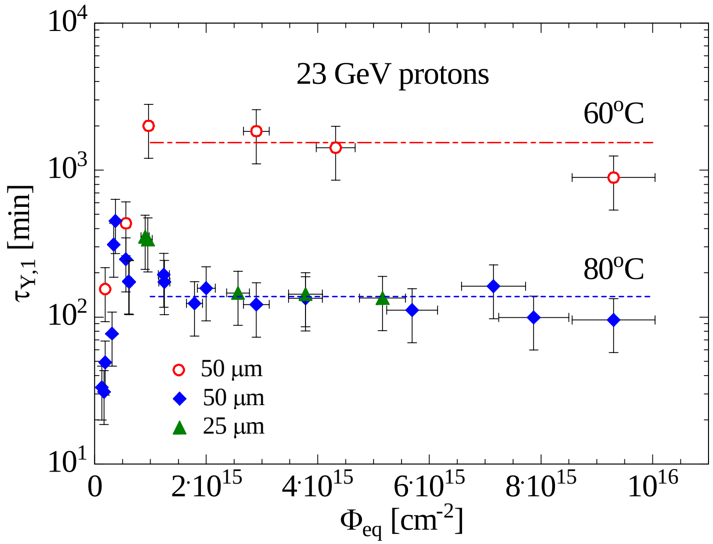
**80°C: $g_{Y2} = 2.6\times10^{-2}$ cm$^{-1}$, 25 and 50 μm**

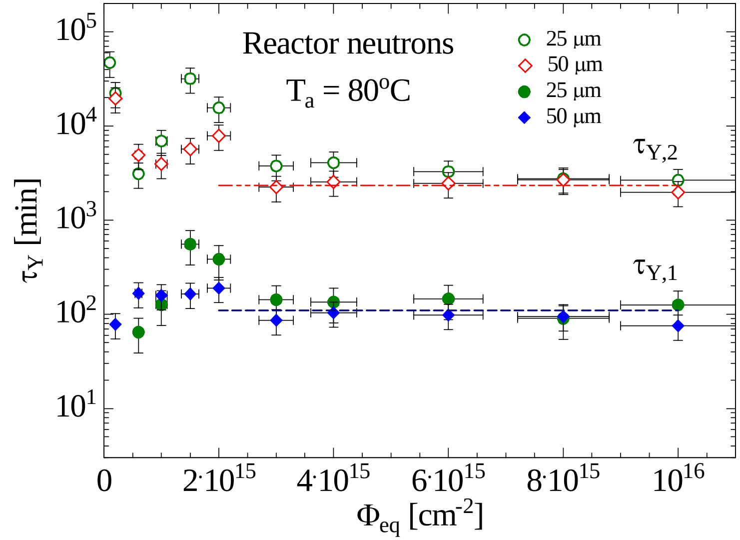
**60°C: $g_{Y2} = 2.0\times10^{-2}$ cm$^{-1}$, 50 μm**

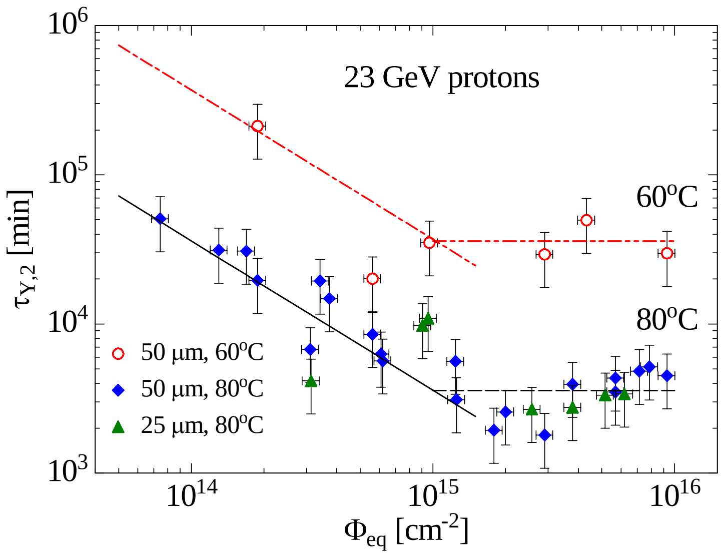
- **Introduction rate for neutrons:**

**80°C: $g_{Y2} = 2.1\times10^{-2}$ cm$^{-1}$, 25 and 50 μm**

# Reverse Annealing Time Constants

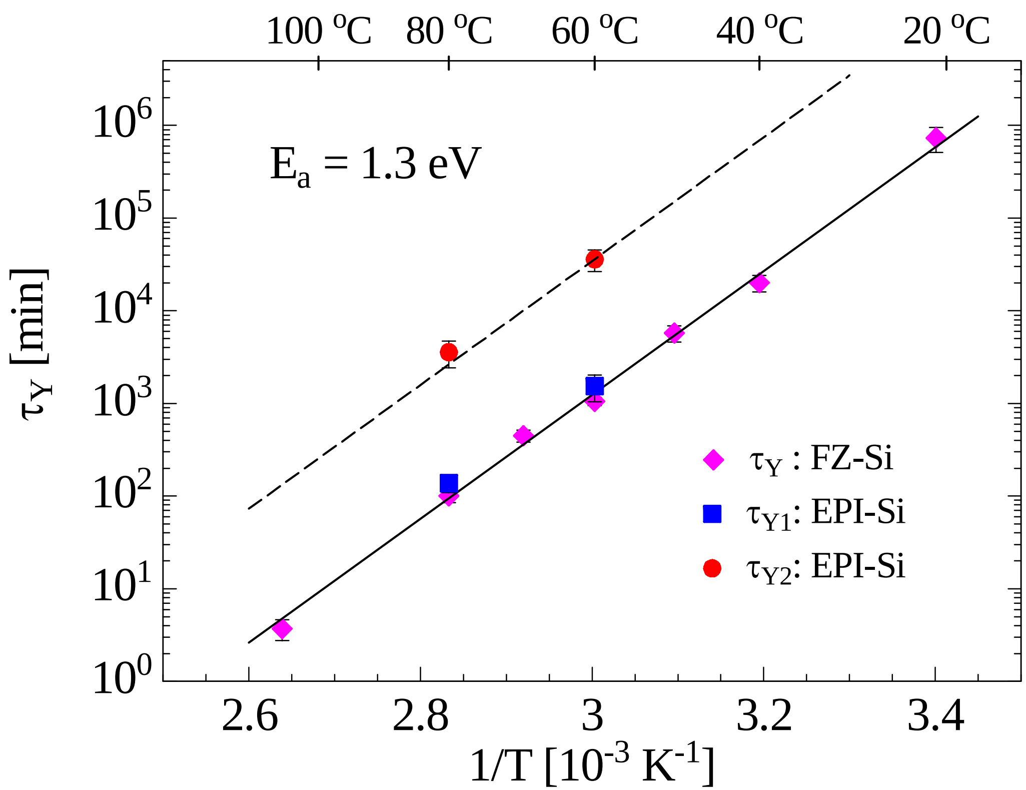



- **Protons:**
  **above $10^{15}$ cm$^{-2}$ $\tau_{Y1}$ and $\tau_{Y2}$ ≈ constant**
  **Ratio $\tau_{Y1}$(60°C)/ $\tau_{Y1}$(80°C) = 11**
  **Ratio $\tau_{Y2}$(60°C)/ $\tau_{Y2}$(80°C) = 10**
  **below $10^{15}$ cm$^{-2}$ $\tau_{Y2} \propto 1/\Phi_{eq}$ ..**
- **Neutrons:**
  **above $2\times10^{15}$ cm$^{-2}$ $\tau_{Y1}$ and $\tau_{Y2}$ ≈ constant**
  **$\tau_{Y1}(n)/\tau_{Y1}(p) = 0.80$**
  **$\tau_{Y2}(n)/\tau_{Y2}(p) = 0.67$**

# Temperature Dependence of $\tau_{Y1}$ and $\tau_{Y2}$
# 23 GeV protons



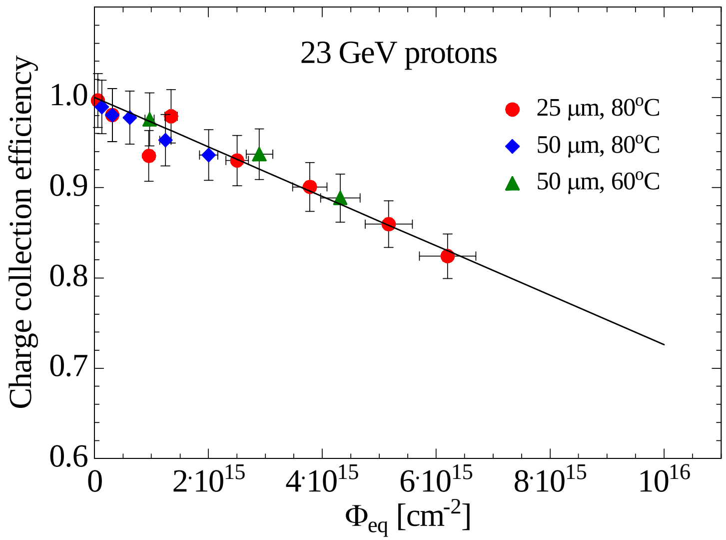

*High resistivity FZ Si:*
*M. Moll, PhD thesis*

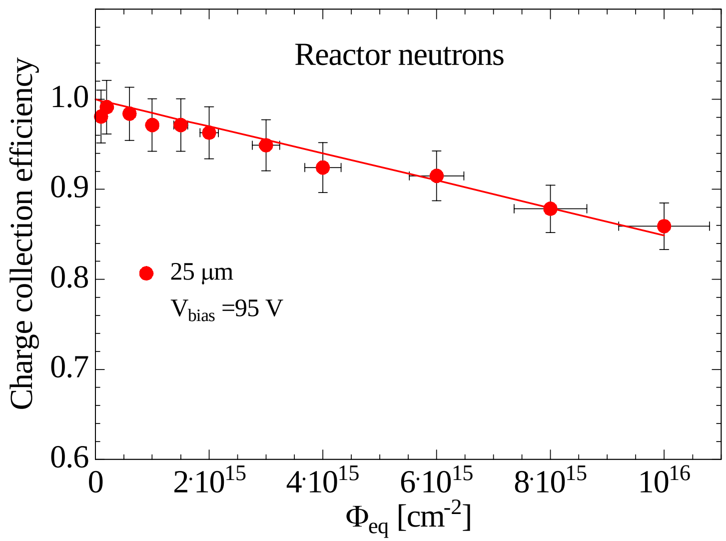
- **Arrhenius relation: $1/\tau_Y = k_0 \times \exp(-E_a/k_B T)$**

  **Y1 component: $E_a$ = 1.3 eV, $k_0 = 1.5 \times 10^{15}\ s^{-1}$**

  **Y2 component: $E_a$ = 1.3 eV, $k_0 = 5.4 \times 10^{13}\ s^{-1}$**

# Charge Collection Efficiency




- **Charge collection efficiency measured with α-particles**
- **$^{244}$Cm α-source, $E_\alpha$ = 5.8 MeV, R≈30 µm**
  **TCT setup used**
  **Integration time window 20 ns**

➢ **CCE degradation linear with fluence if the devices are fully depleted**
**$CCE = 1 - \beta_\alpha \times \Phi$**

➢ **Protons:**
**Bias voltages: 190 V for 50 µm, 130 V for 25 µm**
**$\beta_\alpha = 2.7\times10^{-17}$ cm$^2$**

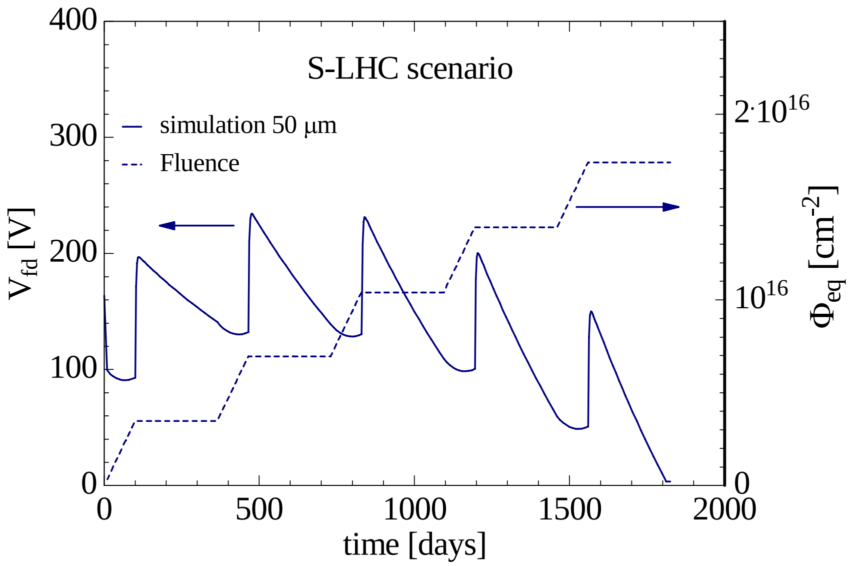
**→ CCE($10^{16}$ cm$^{-2}$) = 72 %**

➢ **Neutrons:**
**Bias voltage: 95 V**
**$\beta_{\alpha,eq} = 1.5\times10^{-17}$ cm$^2$**

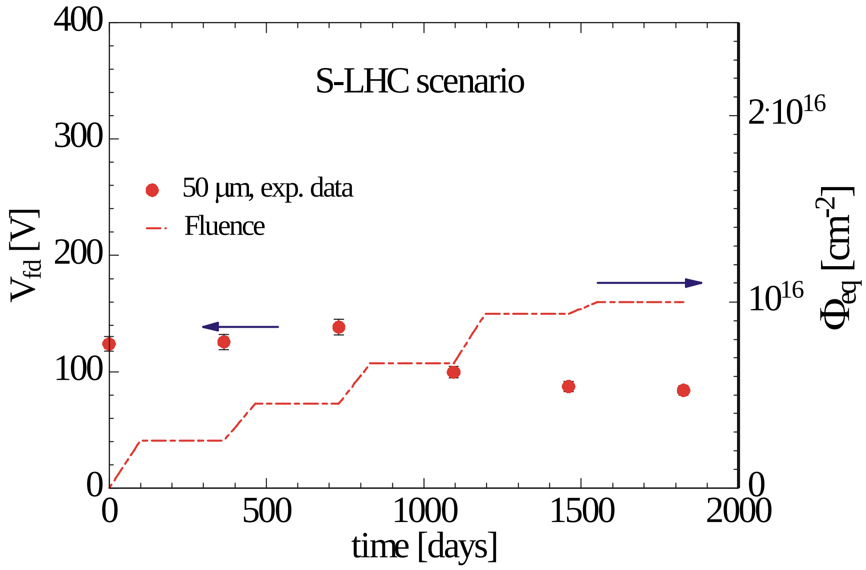
**→ CCE($10^{16}$ cm$^{-2}$) = 86 %**

# S-LHC Scenario

## Simulation




## Experimental Data

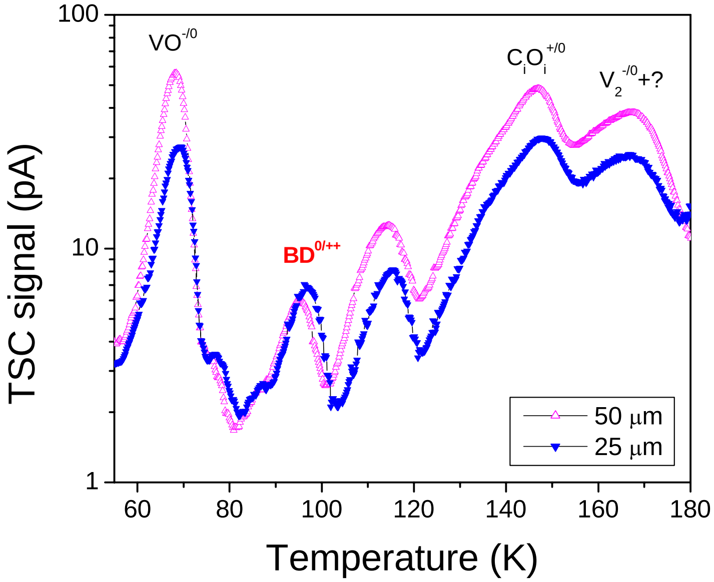



- **Simulation parameter:**
  **Luminosity $10^{35}$ cm$^{-2}$s$^{-1}$**
- **Beam periods 100 days**
  **fluence $3.48\times10^{15}$ cm$^{-2}$**
  **detector temperature –7 °C**
- **Beam off periods 265 days**
  **detector temperature 20°C**

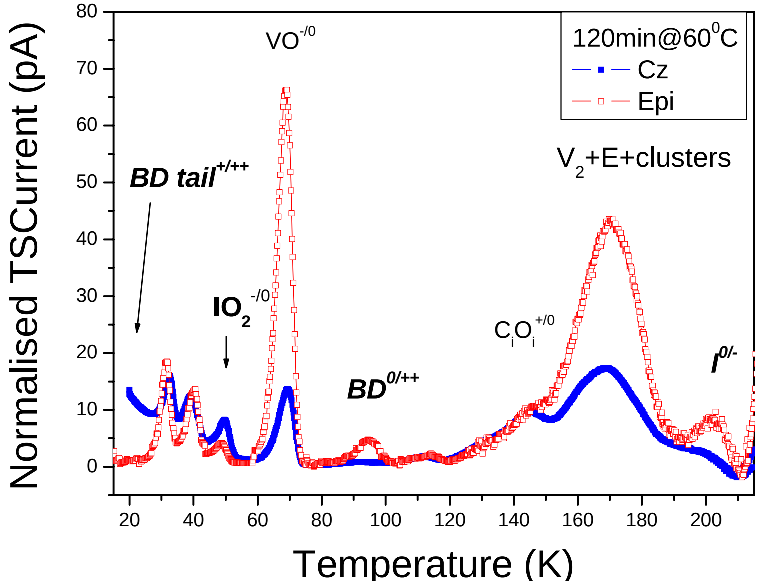
- **Experimental parameter:**
- **Irradiation:**
  **fluence steps ≈ $2.24\times10^{15}$ cm$^{-2}$**
  **irradiation temperature ≈ 25°C**
- **After each irradiation step annealing at 80°C for 50 min, corresponding 265 days at 20°C**

# Outlook

- **Study of different EPI-Material**
  Processing of p-type layers with different thickness
  Processing of n-type layers with larger thickness and lower doping
  Search for getting a more homogeneously distributed oxygen concentration by prolonged heat treatment
- **Systematic CCE studies**
  $\beta$-source at Ljubljana
  $\alpha$-source at Hamburg
  Trapping time constants at extremely high fluences?
- **Extended microscopic studies**
  Fluence dependence of the introduction rate for shallow donors?
  Is the introduction rate of donors $\propto$ [O] or $[O]^2$ resp. $[O_2]$?
  Wich acceptors are mainly reponsible for the macroscopic properties, clusters and point defects ($V_nO_m$, VP, $V_2$, ..)?



VO-/0
BD0/++
CiOi+/0
V2-/0+?
50 µm
25 µm
TSC signal (pA)
Temperature (K)

120min@60⁰C
Cz
Epi
VO-/0
V2+E+clusters
BD tail+/++
IO2-/0
BD0/++
CiOi+/0
I0/-
Normalised TSCurrent (pA)
Temperature (K)