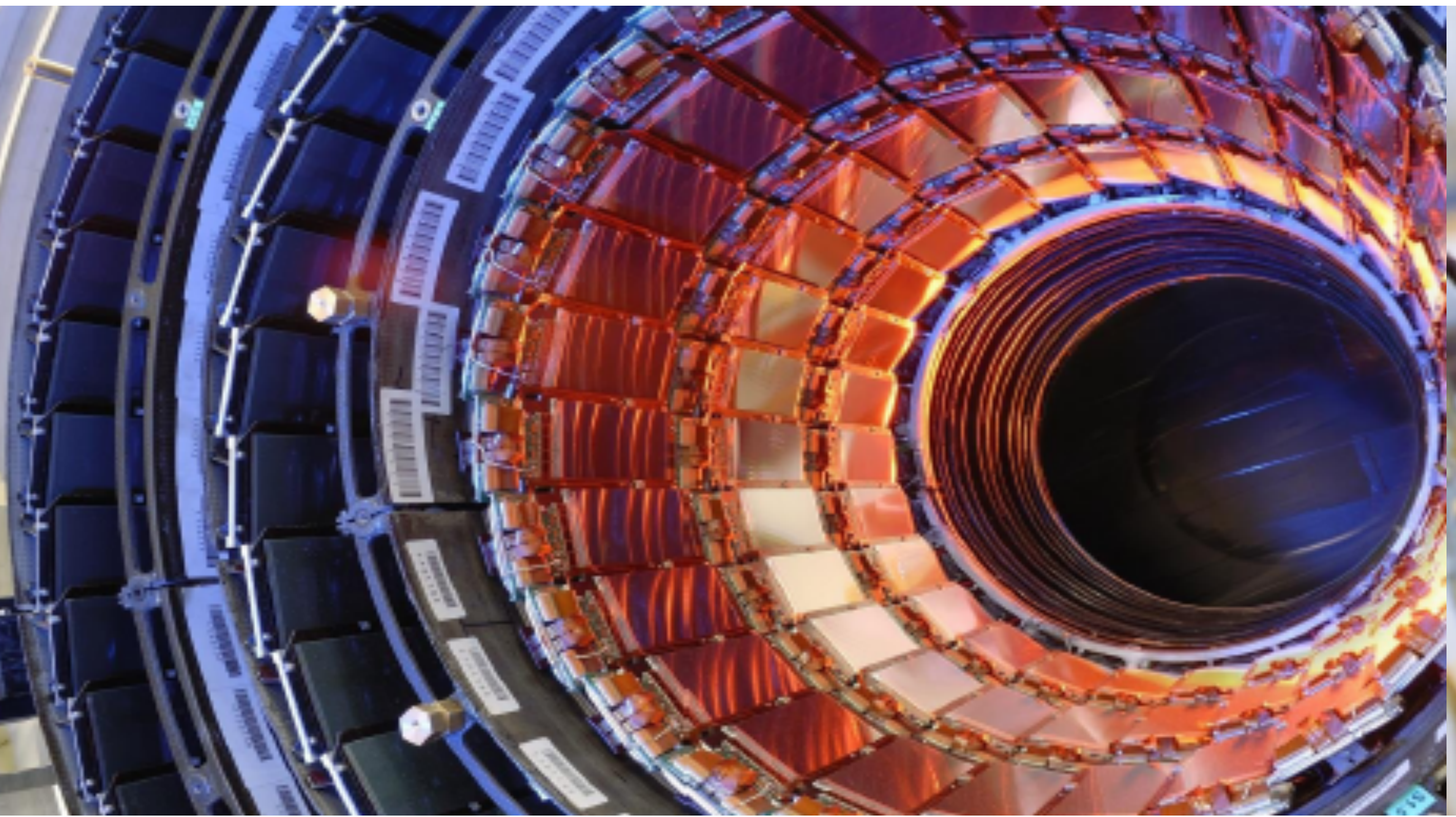
Doris Eckstein (CMS)

8. October 2024



Disclaimer

This is not an up-to-date status of radiation damage status

There are people which to-day work on these topics

My aim is

- to give an introduction to radiation damage applicable to the silicon sensors currently used at the LHC
- to motivate the usage of n-in-p at HL-LHC
- to raise awareness that models are phenomenological descriptions and the defects used therein are not actual defects in silicon
- to raise awareness that acceptor-removal and donor-removal are simplifications of what actually happens in the lattice

Radiation damage: types

- Particles passing through silicon material loose energy through
  - interaction with shell electrons (**I**onizing **E**nergy **L**oss)

    ➔ surface damage

    →local charges accumulate in surface

    (charges cannot recombine in insulating surface

    - amorphous Si, SiO_2-

    thus it causes damage in the surface)

    → damage caused primarily through photons, charged particles

    →this is used for particle detection

    →fast recombination in silicon bulk ➔ no damage in the bulk

  - interaction with atomic core or whole atom (**N**on **I**onizing **E**nergy **L**oss)

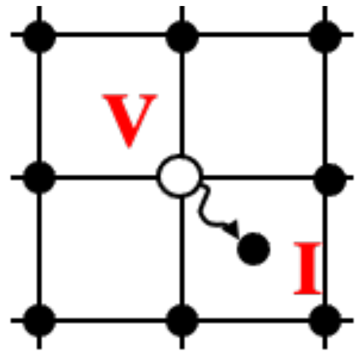
    ➔ bulk damage

    →Displacement of atoms in the lattice

    →Caused by massive particles as protons, pions, neutrons

Microscopic defects

particle → Si_S → E_K>25 eV



Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

E_K > 5 keV *point defects and clusters of defects*

- **^{60}Co-gammas**
  - Compton Electrons with max. $E_\gamma \approx 1$ MeV (no cluster production)
- **Electrons**
  - E_e > 255 keV for displacement
  - E_e > 8 MeV for cluster
- **Neutrons (elastic scattering)**
  - E_n > 185 eV for displacement
  - E_n > 35 keV for cluster

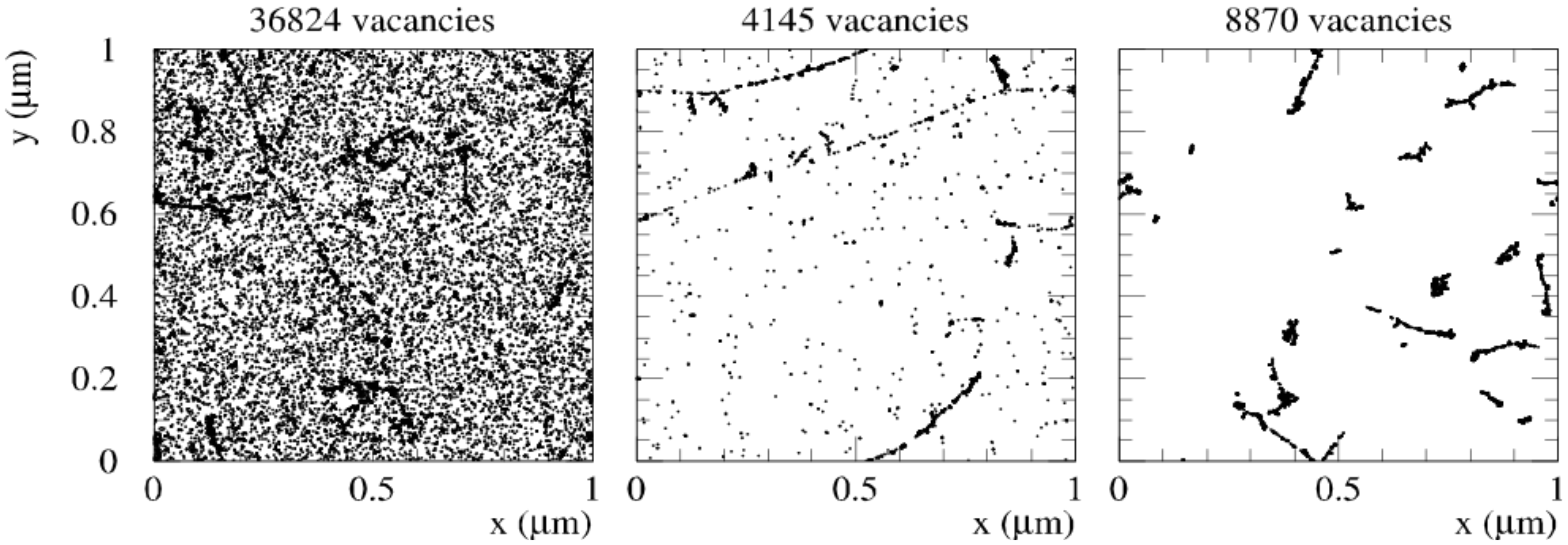
Only point defects ⟷ **point defects & clusters** ⟷ **Mainly clusters**

Simulation:

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]

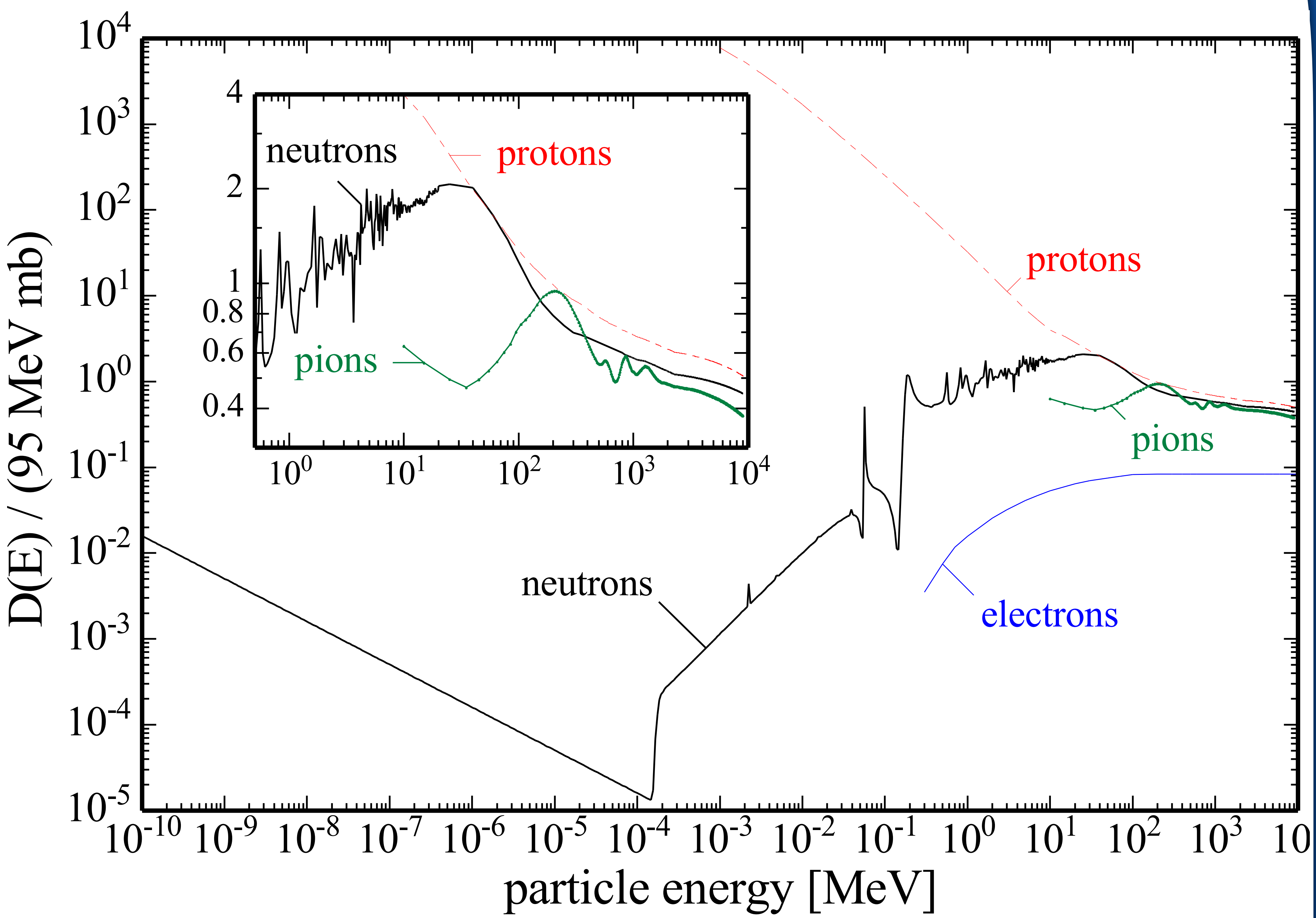
10 MeV protons | **24 GeV/c protons** | **1 MeV neutrons**



NIEL scaling

- **NIEL - Non Ionizing Energy Loss scaling using hardness factors**
  of a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons

$$\kappa = \frac{1}{D(1MeV\ neutrons)} \bullet \frac{\int D(E)\,\phi(E)\,dE}{\int \phi(E)\,dE}$$



- **E** energy of particle
- **D(E)** displacement damage cross section for a certain particle at energy E
  D(1MeV neutrons)=95 MeV·mb
- **Φ(E)** energy spectrum of radiation field

The integrals are evaluated for the interval [E_{MIN},E_{MAX}], being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

- NIEL - Non Ionizing Energy Loss
- NIEL - Hypothesis: Damage parameters scale with the NIEL
  - *Be careful, does not hold for all particles & damage parameters (see later)*

N_{eq} fluence **hardness factors for reactor neutrons: 0.91, for 23GeV protons 0.62**

some equations

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

with $\frac{d}{dx}\phi(x=w)=0$

$\phi(x=w)=0$

$$-\frac{d}{dx}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)$$

$$\phi(x) = \frac{1}{2}\cdot\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)^2$$

depletion voltage

$$V_{dep} = \frac{q_0}{2\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2$$

w = depletion depth
d = detector thickness
U = voltage

N_{eff} = effective doping concentration

$$w(U) = \sqrt{\frac{2\varepsilon\varepsilon_0}{q_0\left|N_{eff}\right|}\cdot U}$$

$$C = \frac{dQ}{dU} = \frac{dQ\cdot dw}{dw\cdot dU}$$

$$C(U) = A\cdot\sqrt{\frac{\varepsilon\varepsilon_0 q_0\left|N_{eff}\right|}{2U}}$$

$$C(w) = \frac{\varepsilon\varepsilon_0 A}{w}$$

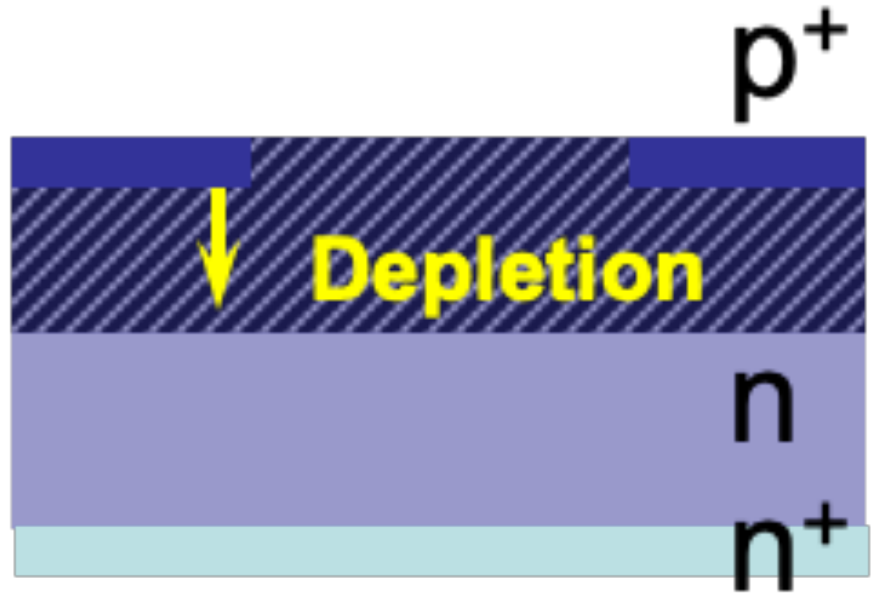
Measurements with diodes

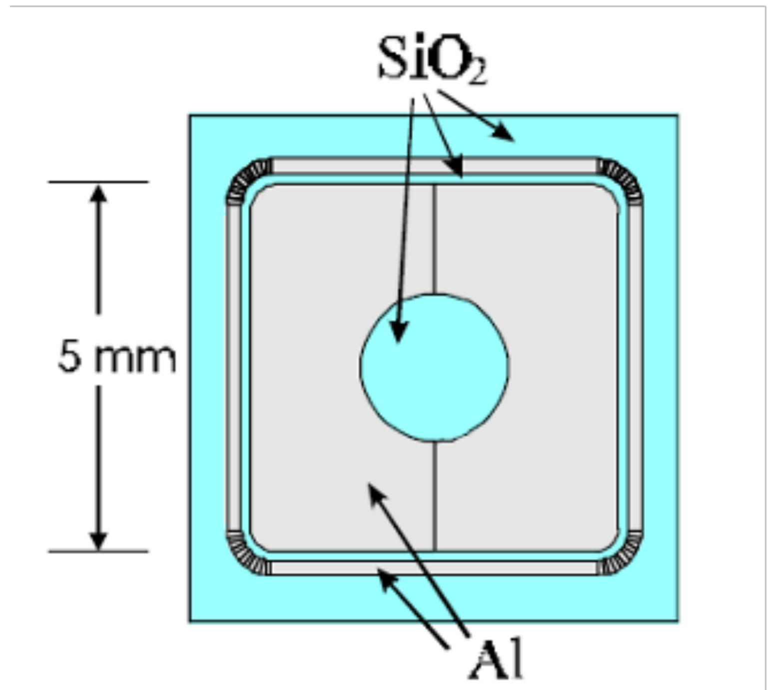
Standard experiments:
- Irradiations with p, n, γ, π

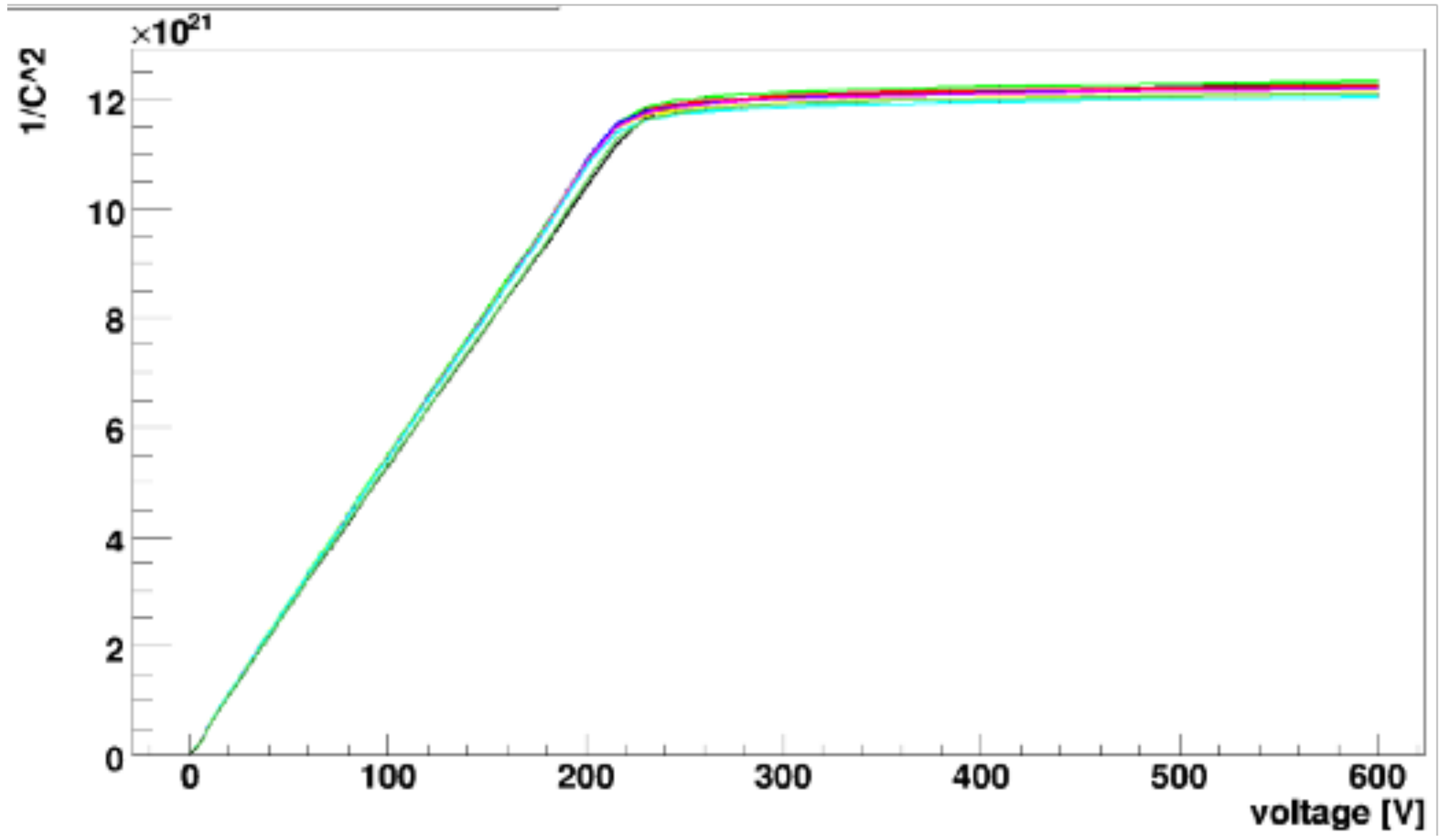
Measurements:
- CV measurements ➔ V_{dep} ~ N_{eff}
- IV measurements ➔ I_{leak} at V_{dep}
- Laser (TCT) measurements ➔ Charge Collection
- DLTS and TSC ➔ microscopic defects

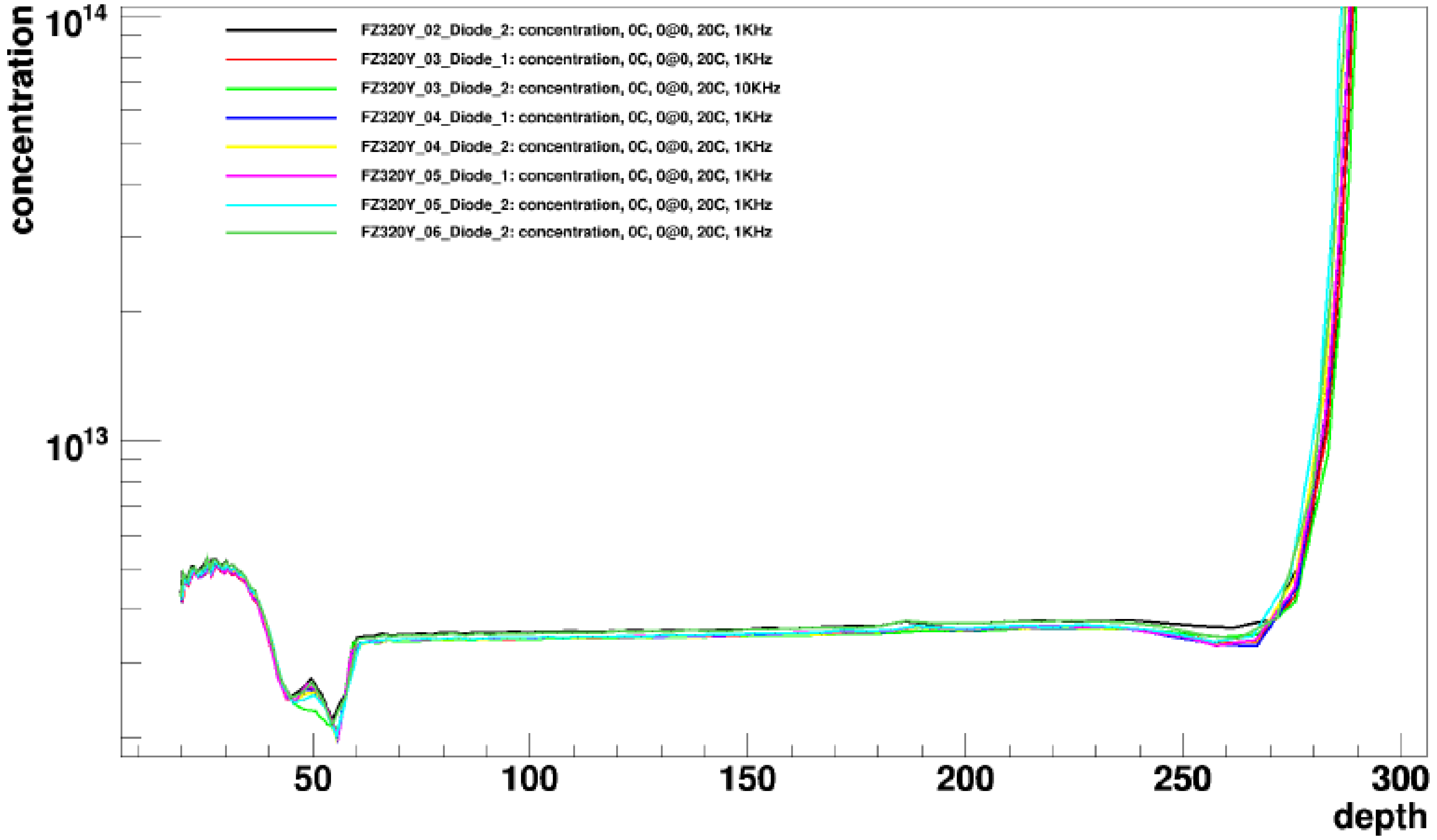
Annealing:

Isochronal and isothermal
➔ learn about defect parameters
➔ damage scenarios for LHC



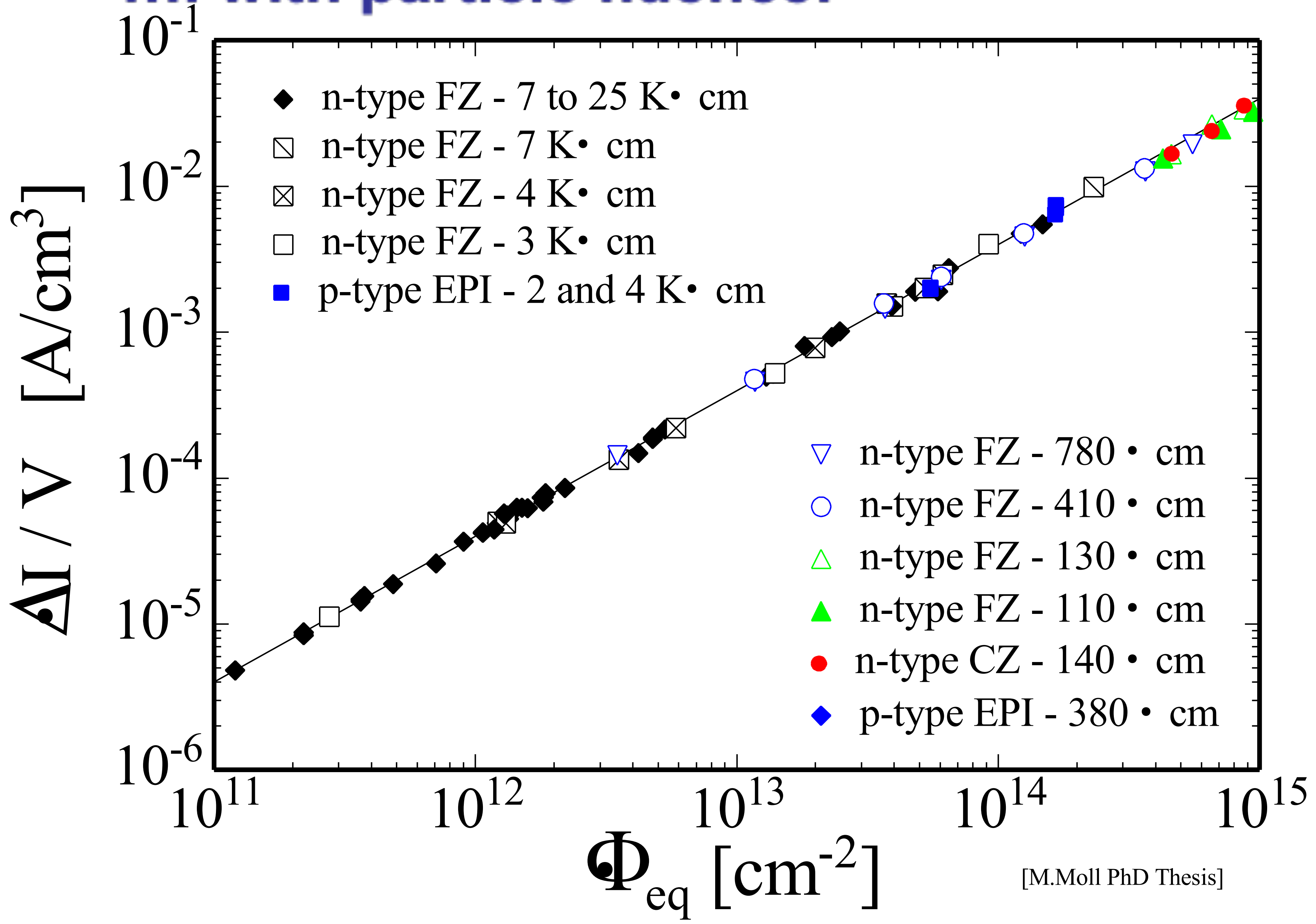






Change of leakage current

…. with particle fluence:



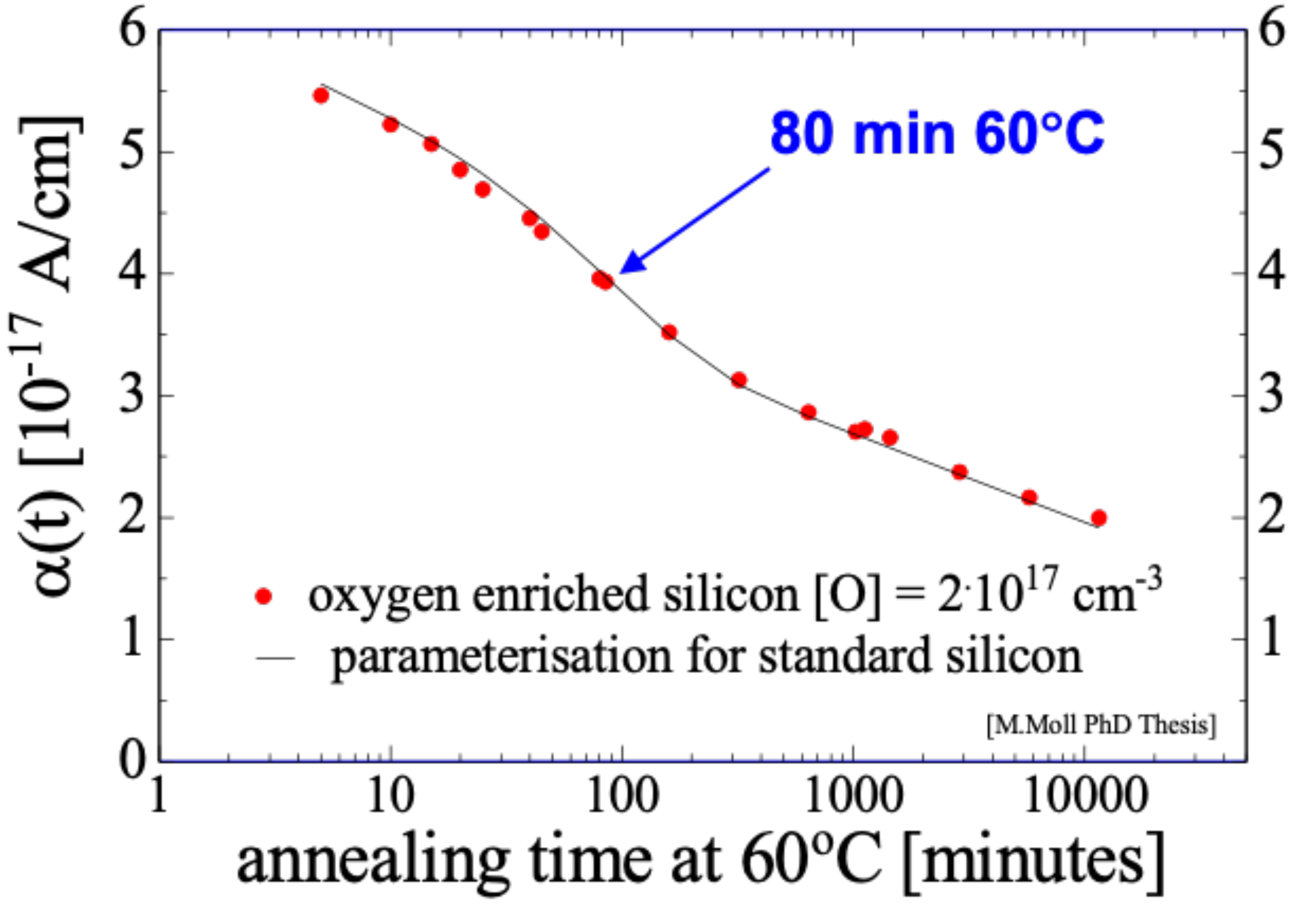
- **Damage parameter α (slope in figure)**

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

Leakage current per unit volume and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
- ➩ **can be used for fluence measurement!**

…. with time (annealing):



- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

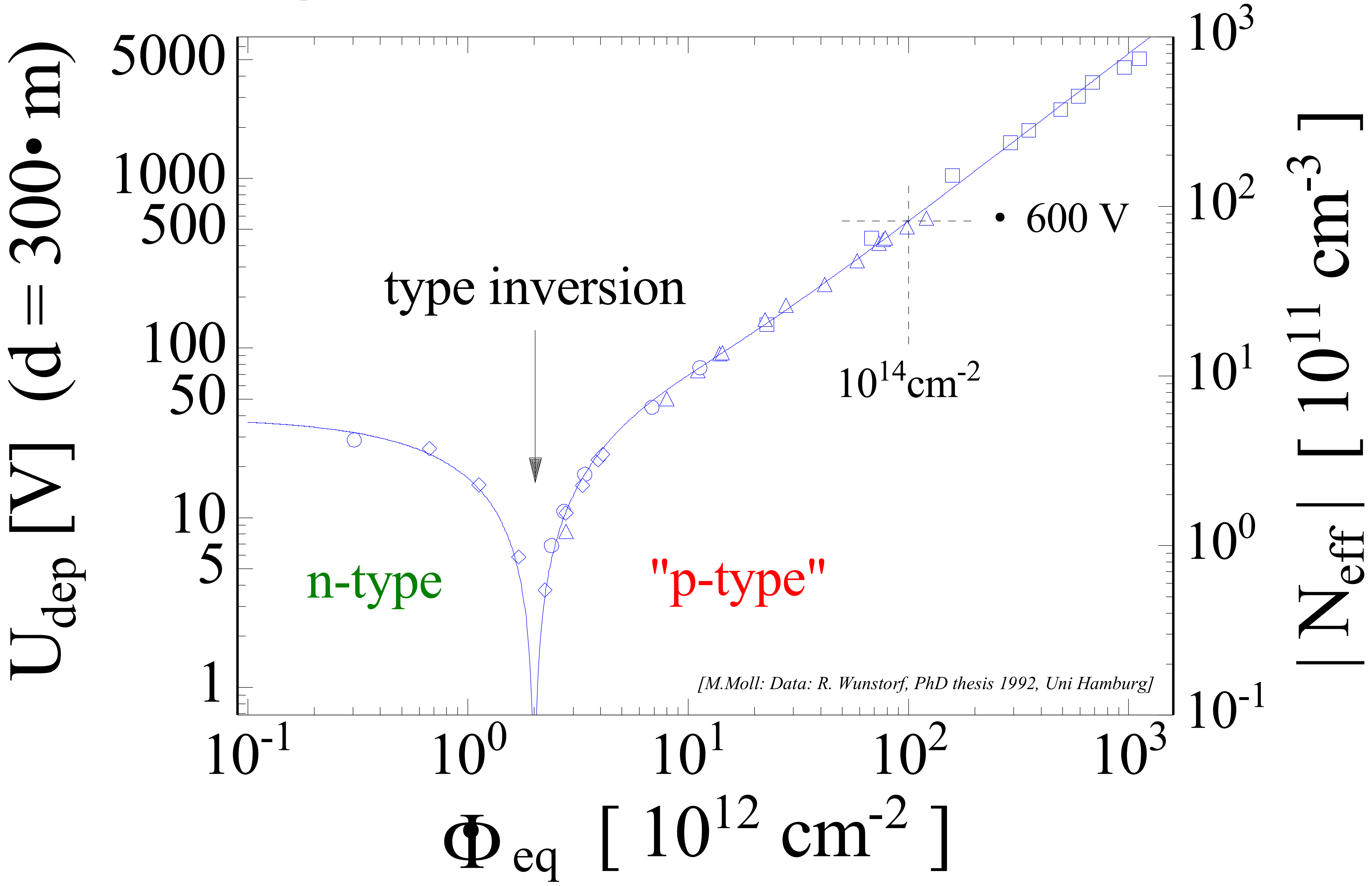
$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

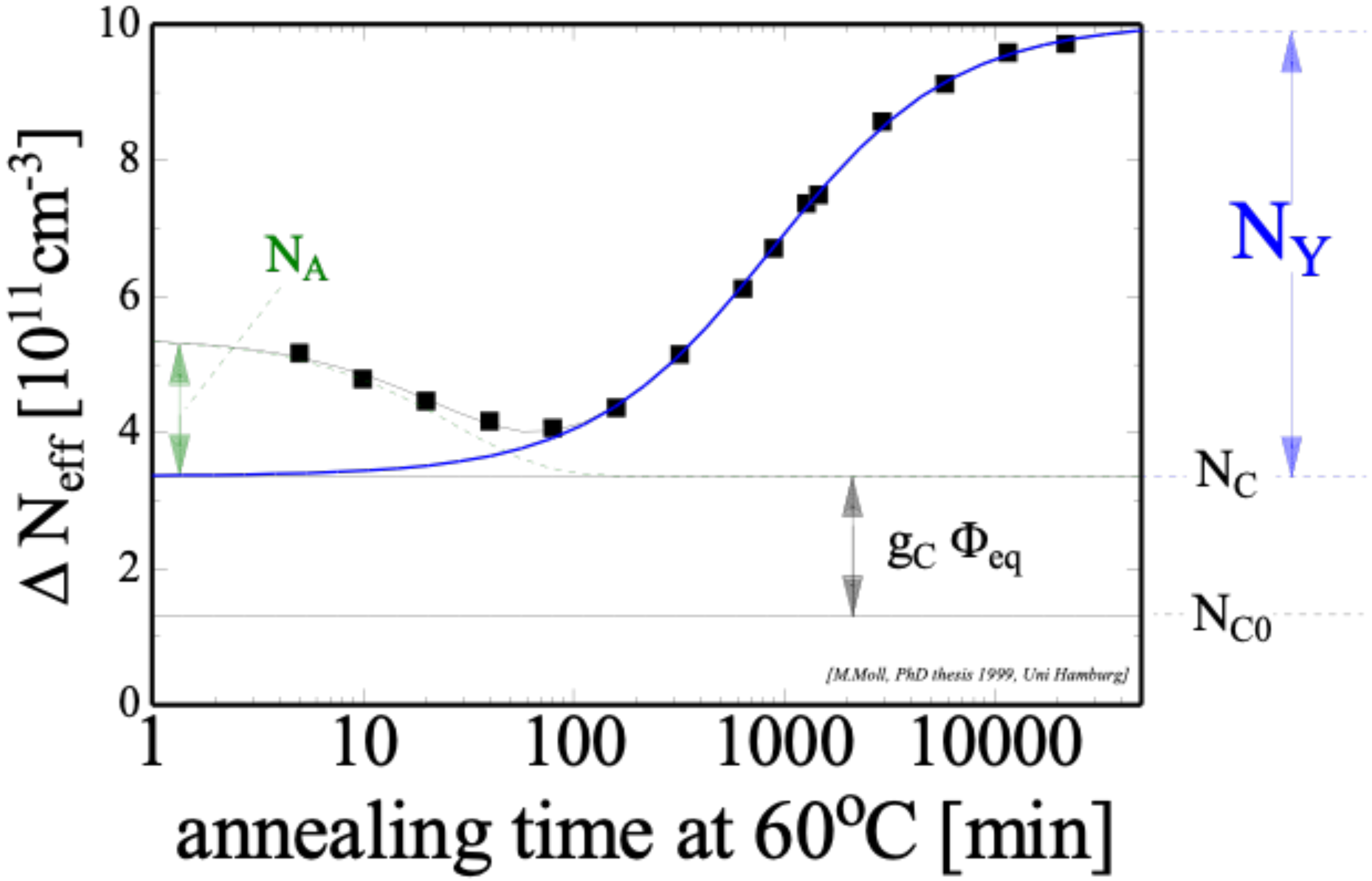
Change of depletion voltage

…. with particle fluence:



- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

…. with time (annealing):



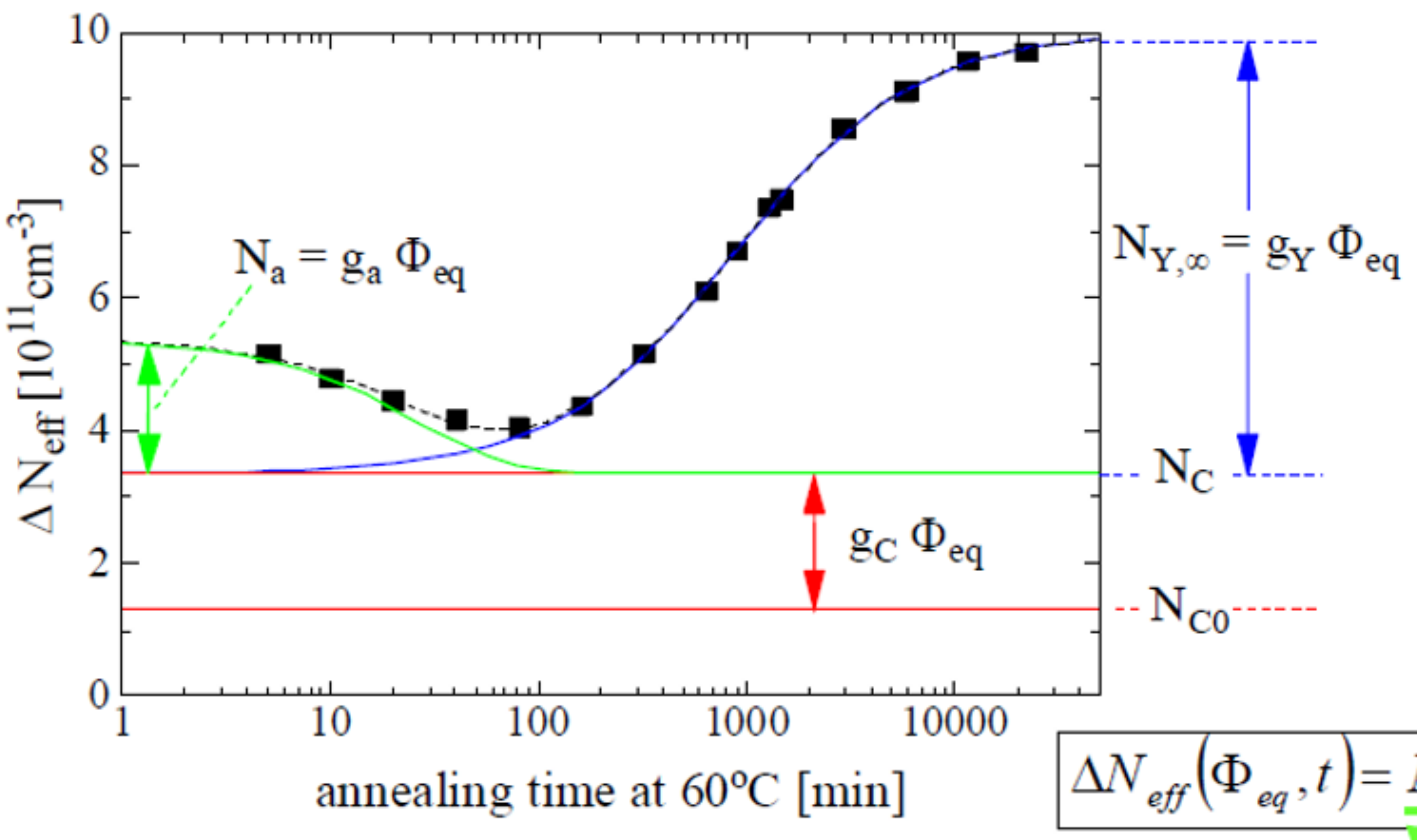
- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"
  - **time constant depends on temperature:**
    - **~ 500 years (-10°C)**
    - **~ 500 days (20°C)**
    - **~ 21 hours (60°C)**
  - Consequence: **Detectors must be cooled even when the experiment is not running!**

Annealing of Neff

Annealing behavior of N_{eff} - Hamburg model -

$$\Delta N_{eff}(\Phi_{eq},t) = N_{eff\,0} - N_{eff}(\Phi_{eq},t)$$

ΔN_{eff} = Change of N_{eff} with respect to $N_{eff\,0}$ (value before irradiation)



long term reverse annealing:

$$N_Y = N_{Y,\infty}\cdot\left(1-\frac{1}{1+t/\tau_y}\right)$$

second order parameterization (with $N_{y,\infty}=g_y\times\Phi_{eq}$).gives best fit

But:

τ_y independent of Φ_{eq}

⇒ underlying defect reaction based on **first order** process!

$$\Delta N_{eff}(\Phi_{eq},t) = N_a(\Phi_{eq},t) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq},t)$$

short term annealing:

$$N_a = \Phi_{eq}\times\sum_i g_{ai}\times\exp\left(-\,t/\tau_i\right)$$

first order decay of acceptors introduced proportional to Φ_{eq} during irradiation

stable damage:

$$N_C = N_{C0}\cdot\left(1-\exp(-c\cdot\Phi_{eq})\right) + g_C\cdot\Phi_{eq}$$

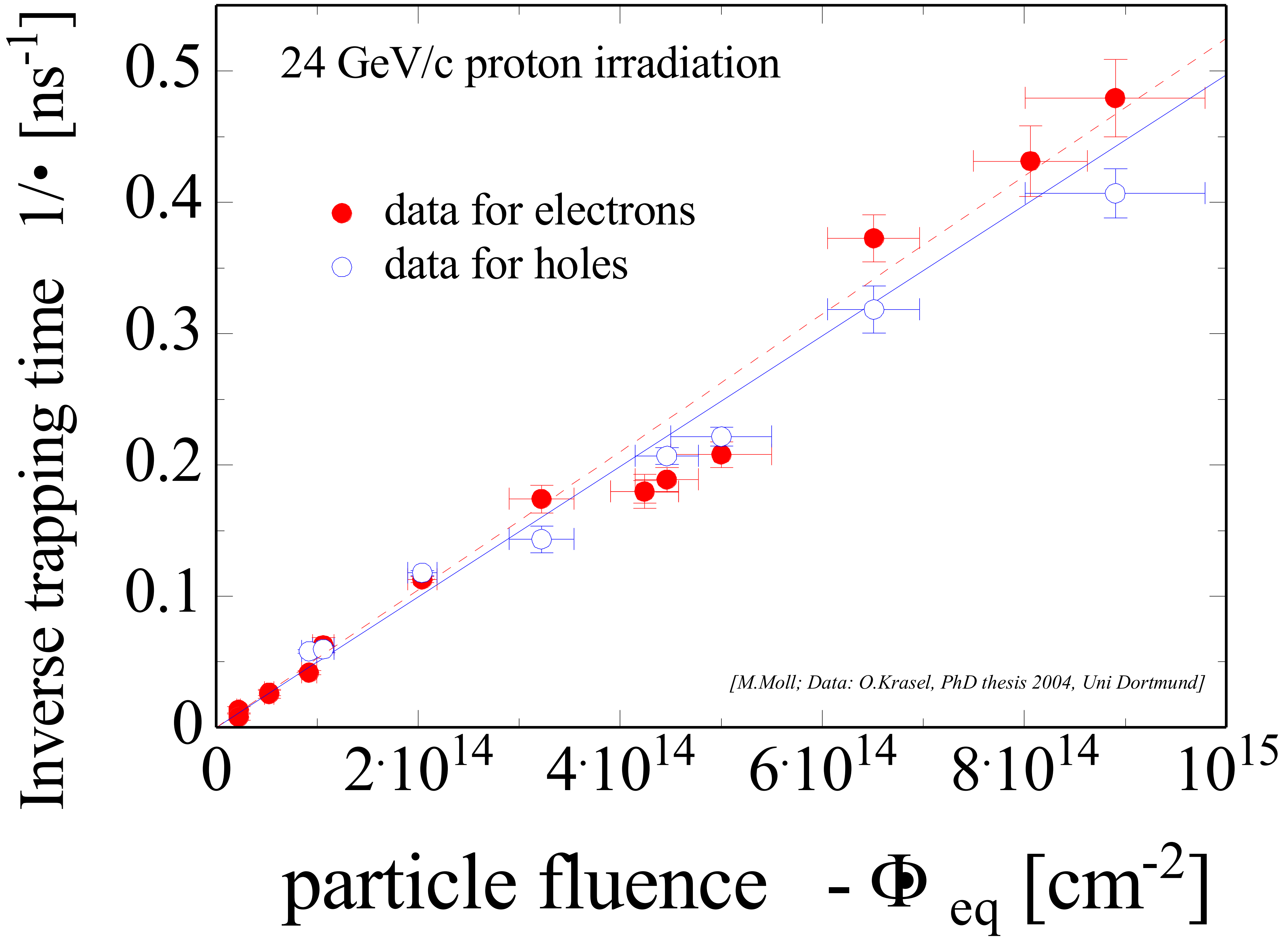
incomplete „donor removal“
+ introduction of stable acceptors

- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \quad \textbf{where} \quad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence



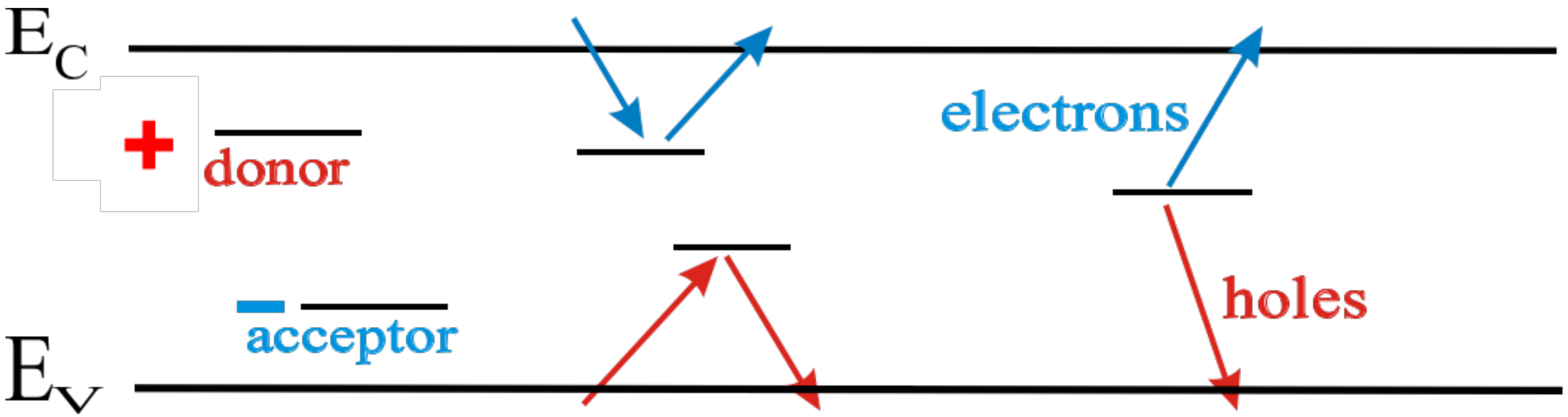
drift velocity of electrons > drift velocity of holes

—> electron collection is beneficial

Change of detector properties

- defects in the crystal
- point defects and "cluster" defects

➔ energy levels in the band gap filled



charged defects	deep traps (e and h), recombination centers	deep traps, generation centers
⇒N_{eff} , V_{dep}	⇒Charge Collection Efficiency	⇒Leakage current
e.g. donors in upper and acceptors in lower half of band gap	shallow defects do not contribute at room temperature due to fast detrapping	Levels close to midgap most effective

Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

Known defects in silicon

- **Calculate/Simulate effect on device properties if all defect parameters are known**

→ **cross section, ionization energy, concentration**

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 1.7 \cdot 10^{-15}$ cm²
  - $\sigma p^{I} = 9 \cdot 10^{-14}$ cm²

Cluster related centers

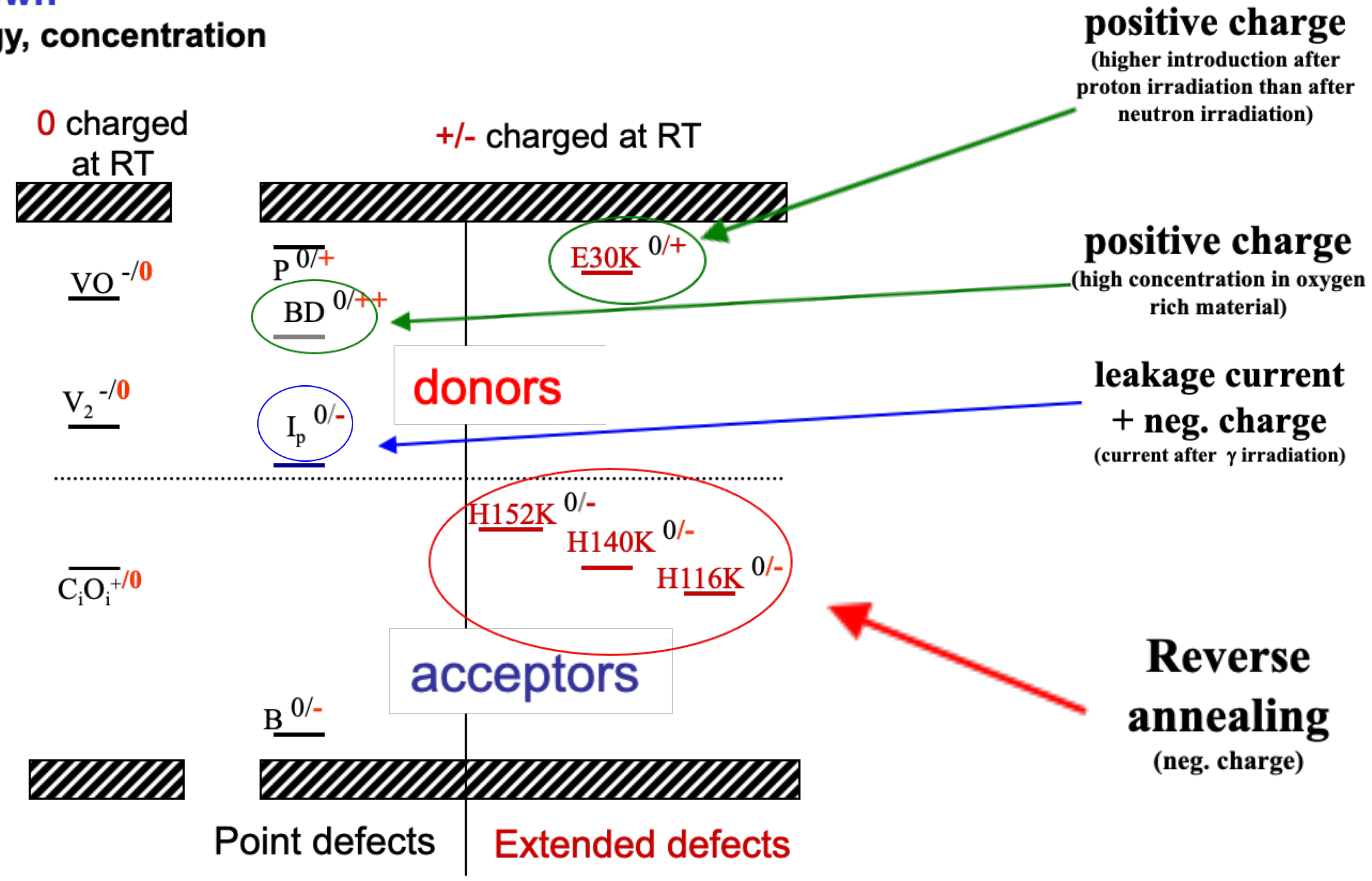
- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm²

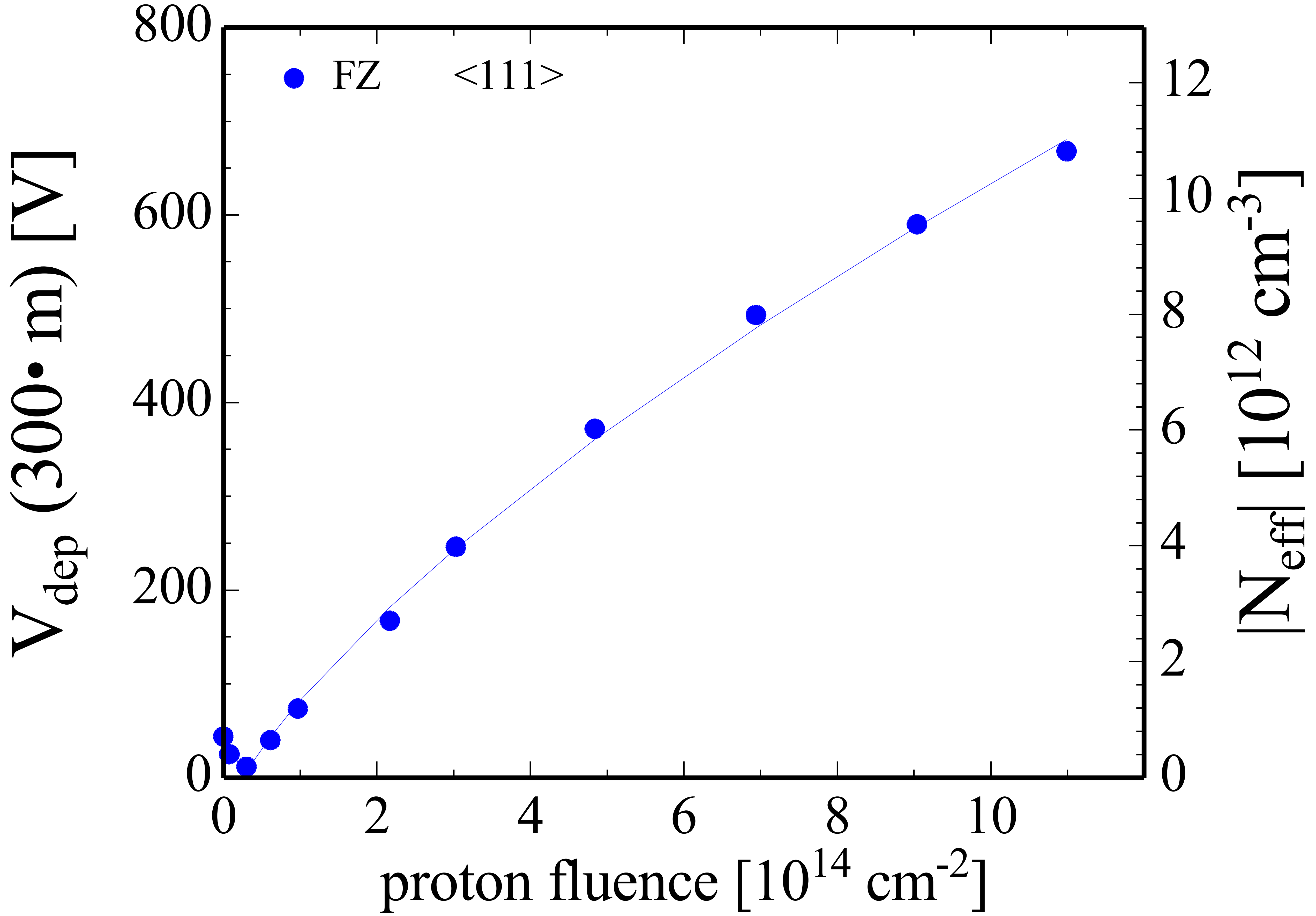
- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm²

[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]

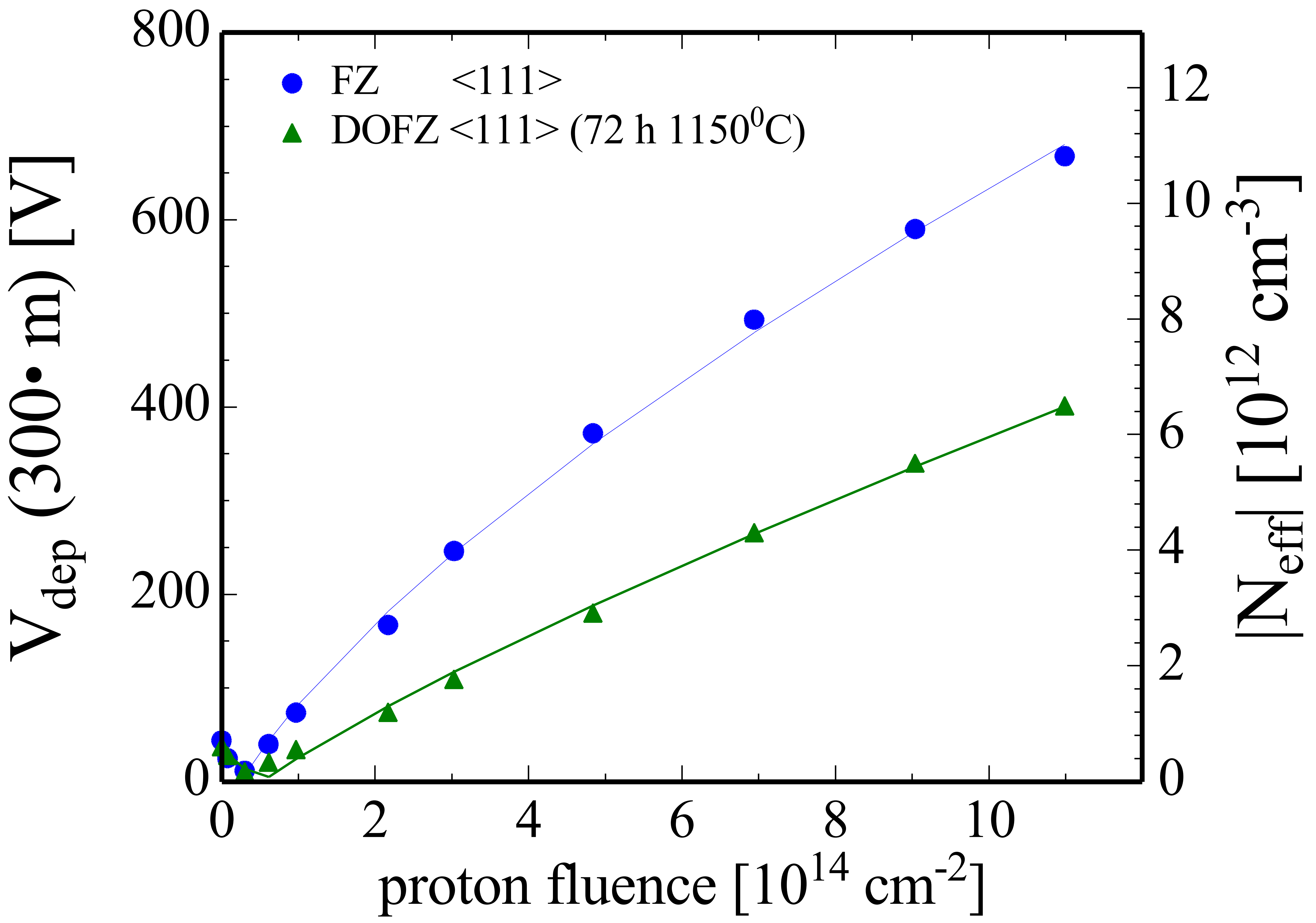


Impurities - oxygen

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence

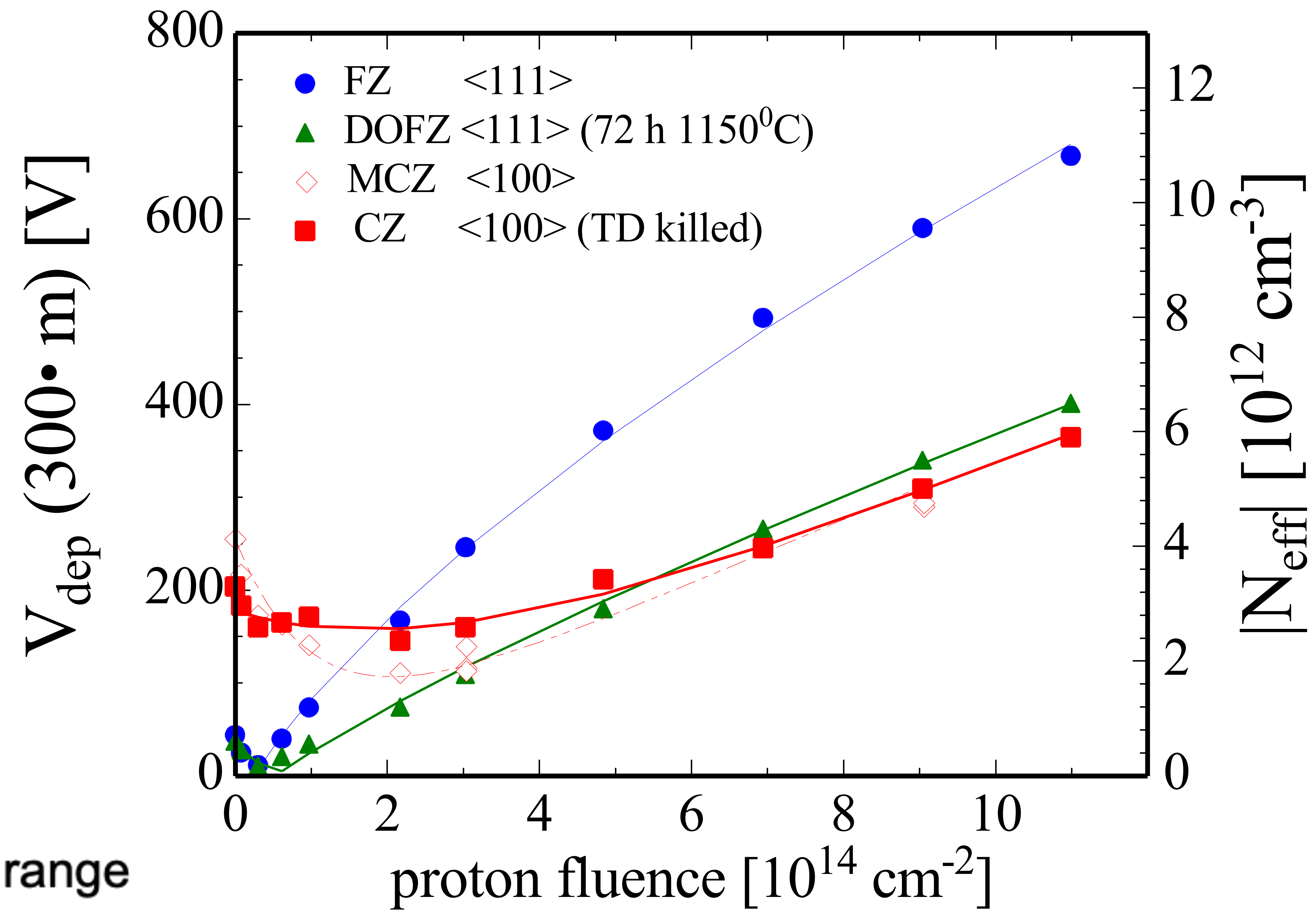


- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence



Impurities - oxygen

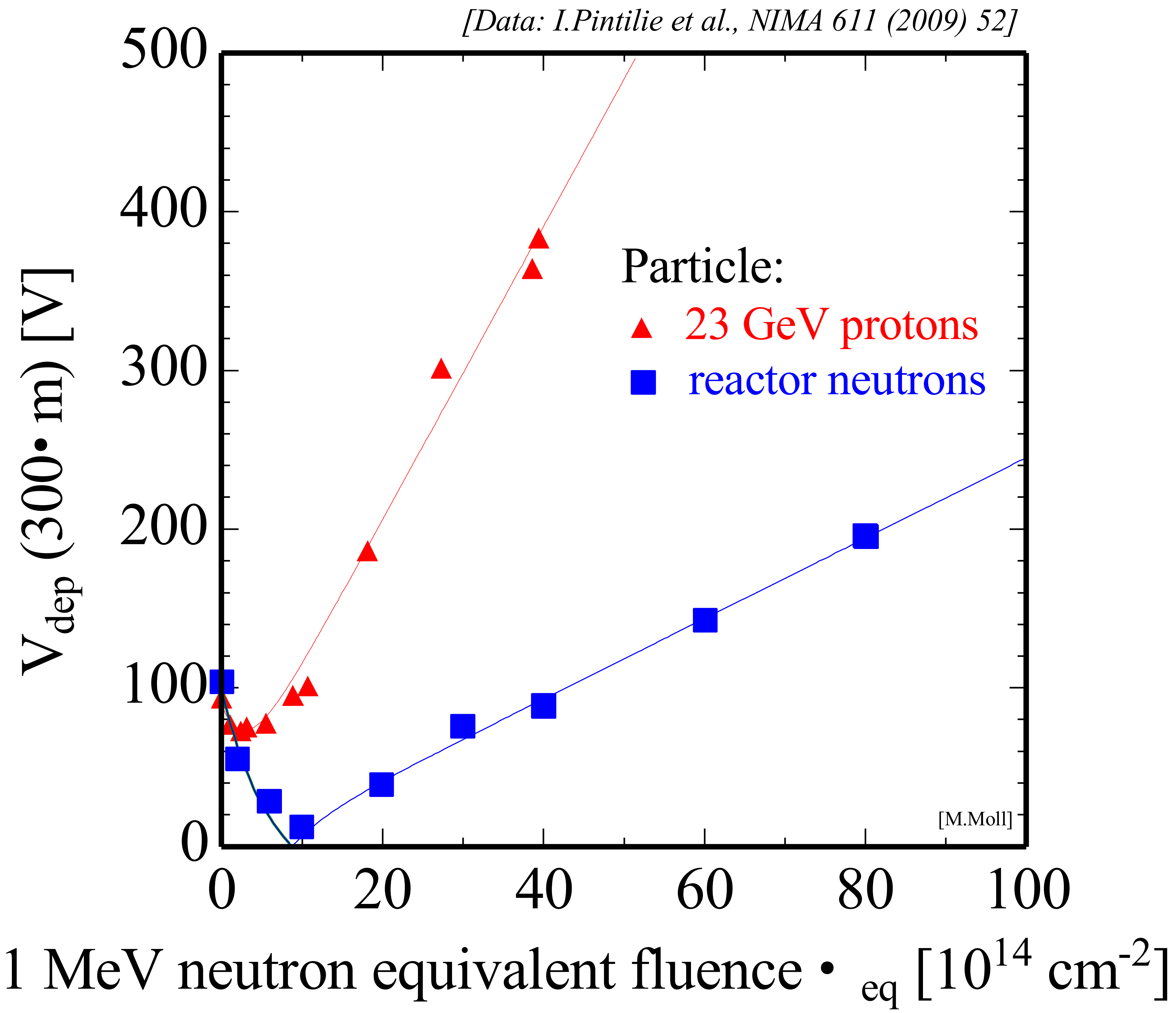
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range

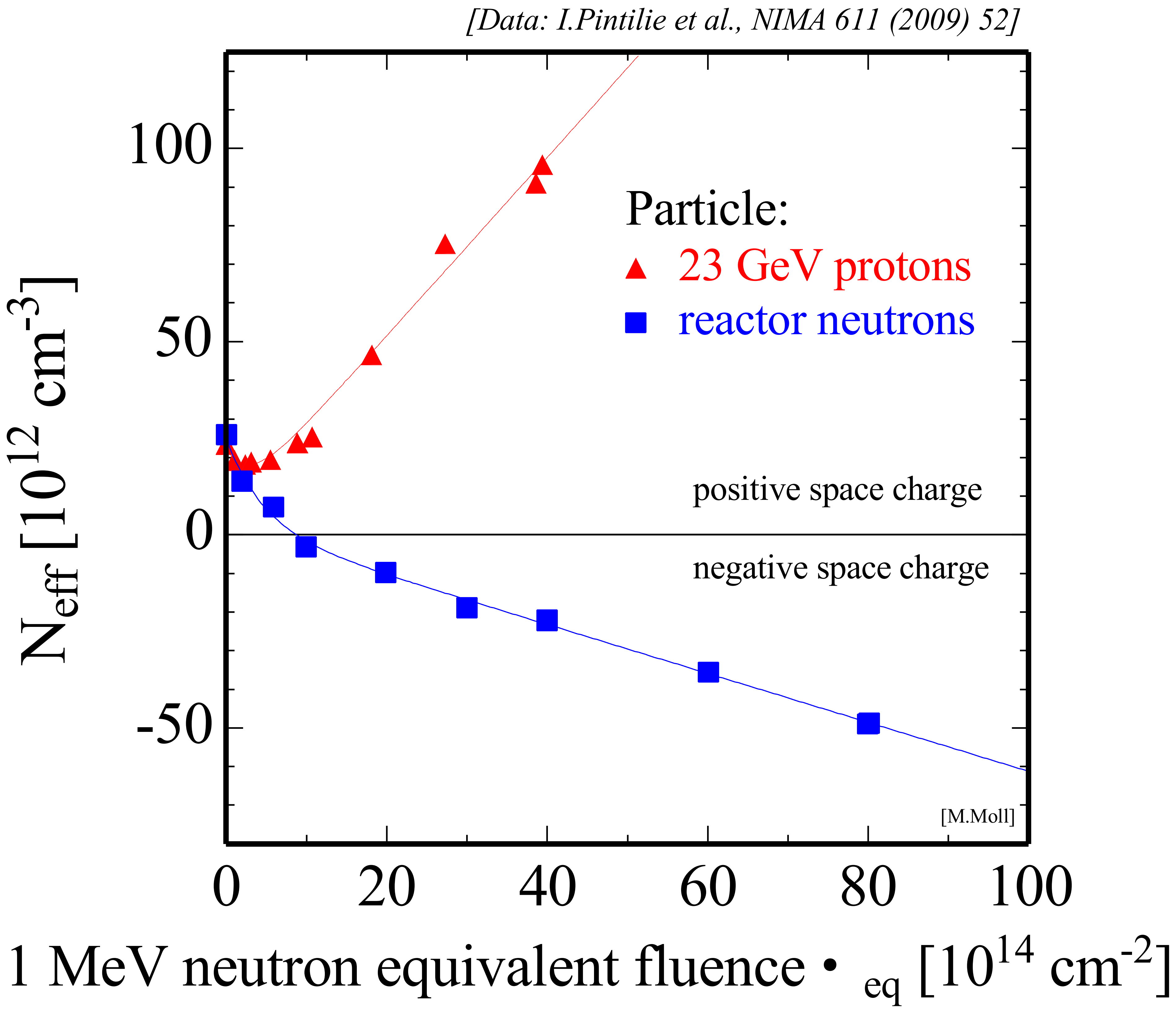


(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

Proton vs. Neutron Irradiation

- Epitaxial silicon ***(EPI-DO, 72μm, 170Ωcm, diodes)***
  irradiated with <u>23 GeV protons</u> or <u>reactor neutrons</u>





depletion voltage → $$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$ ← ***absolute effective space charge density***

Proton vs. Neutron Irradiation

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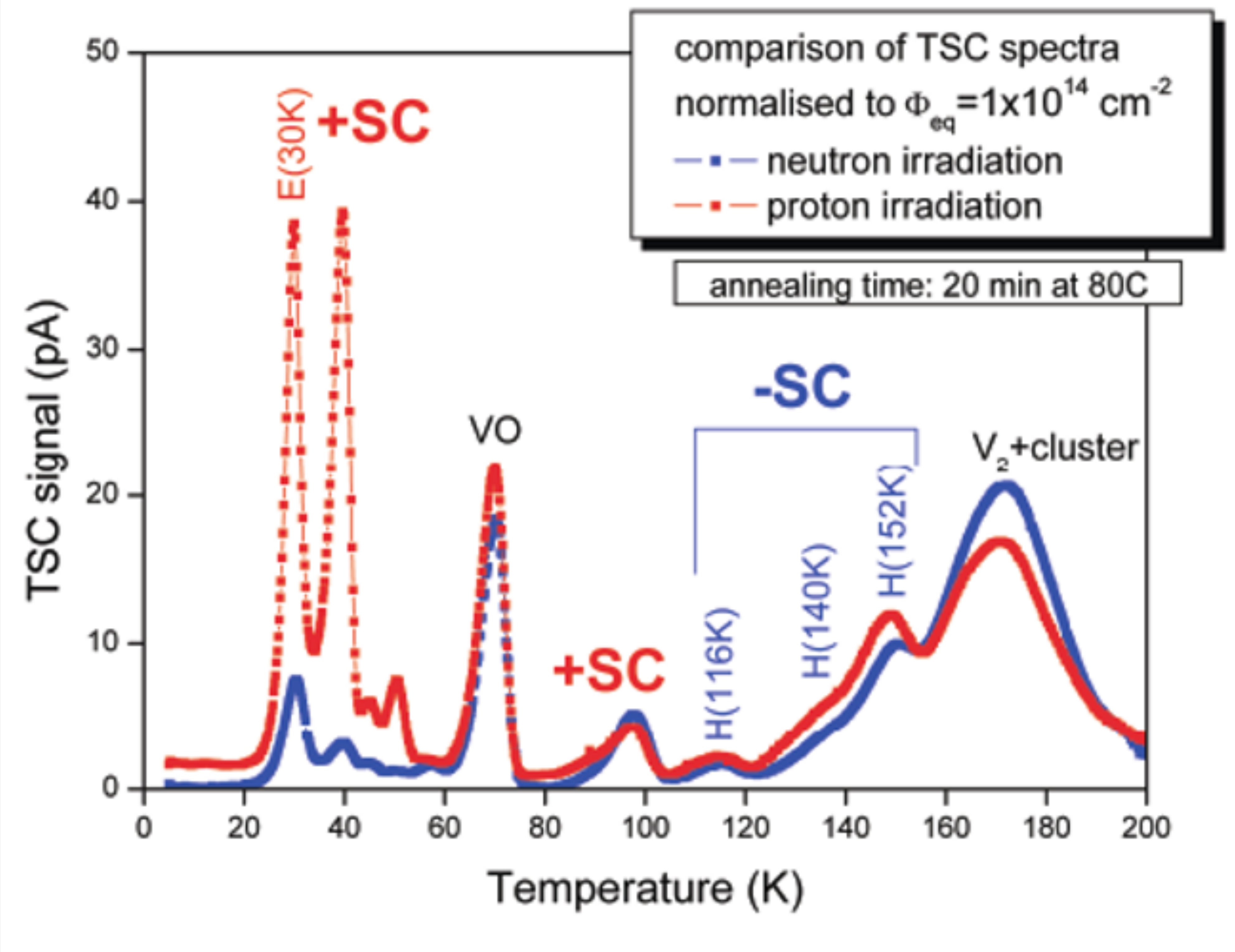
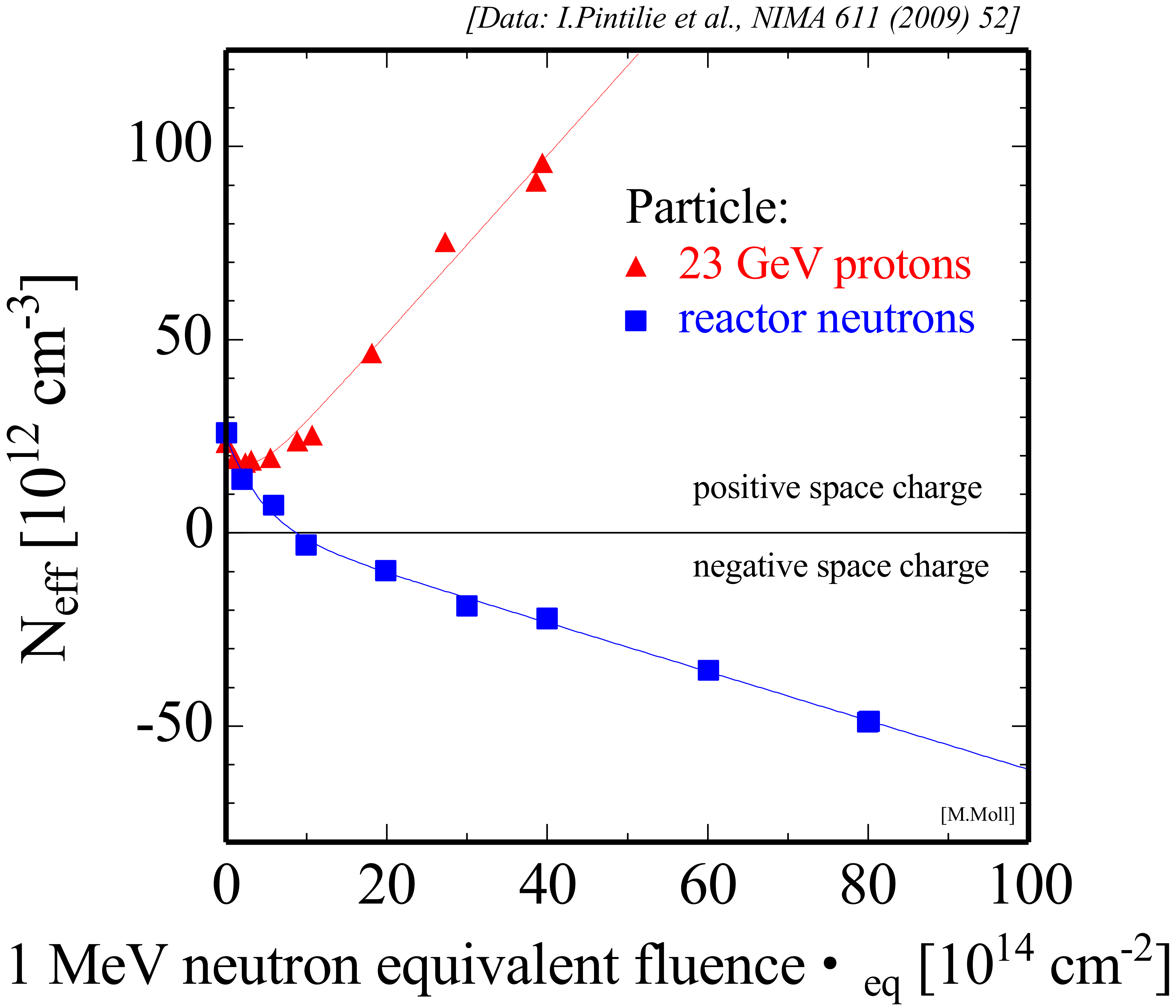


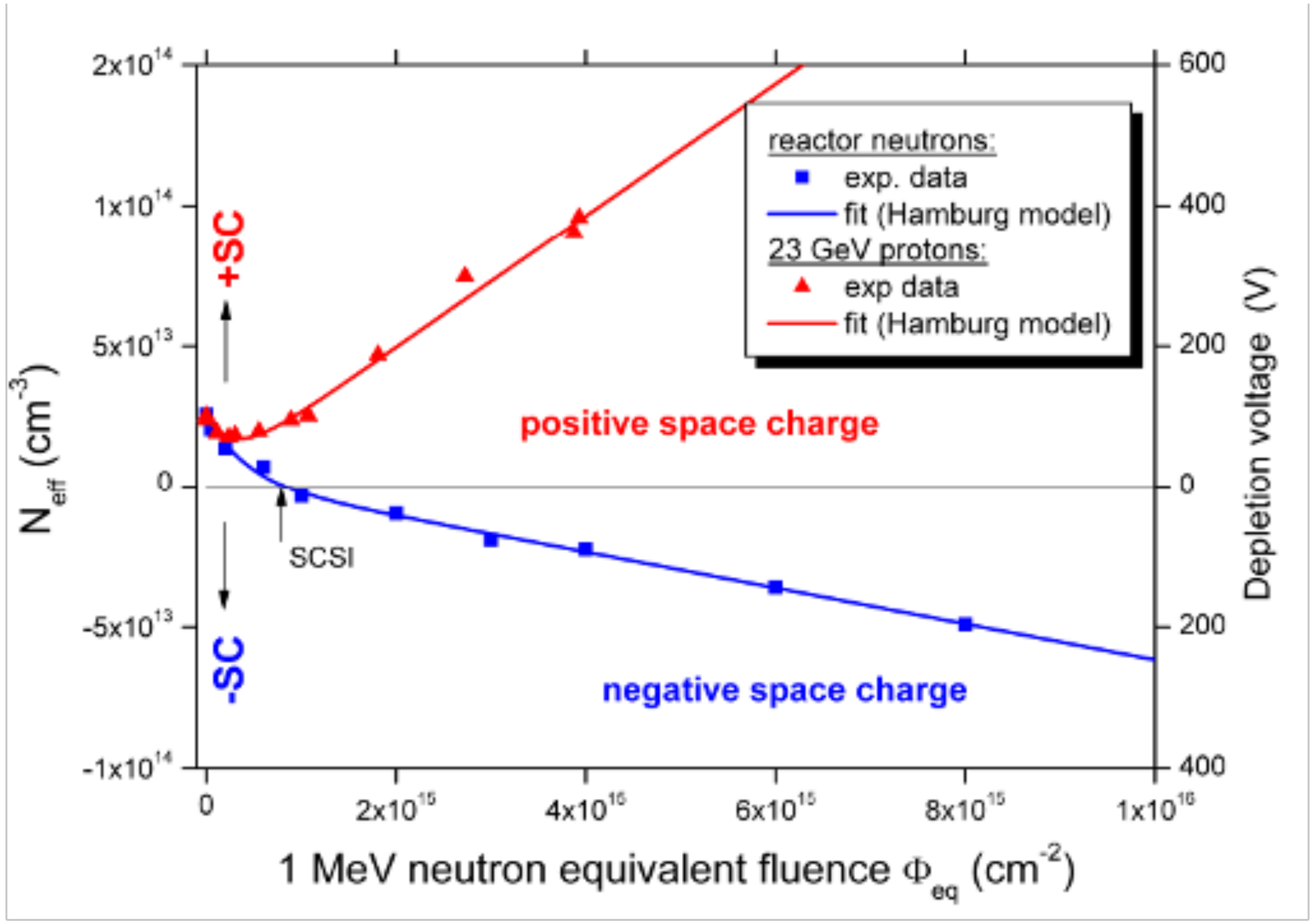


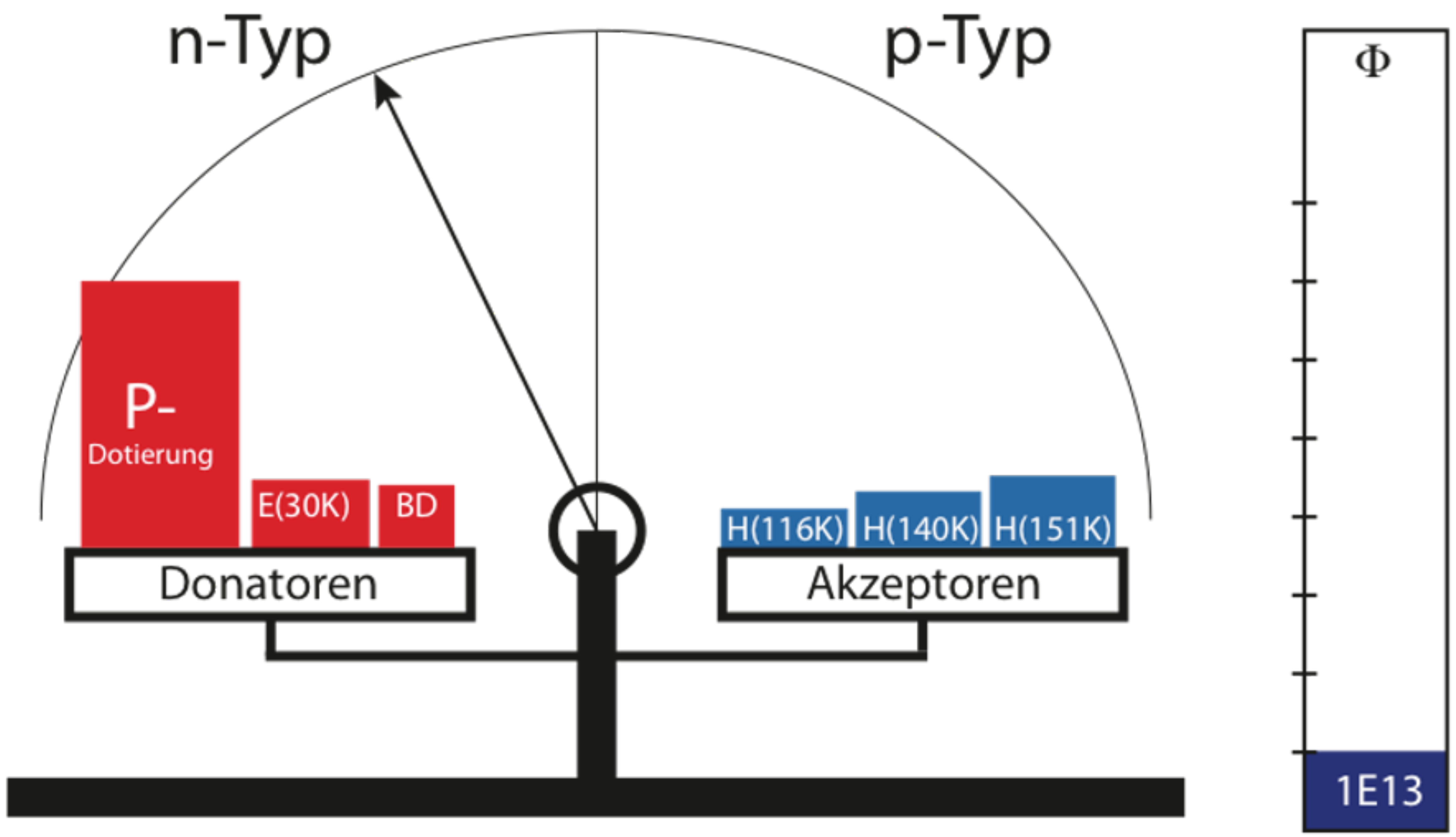
- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low Φ_{eq}

[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

Neutrons

Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)***
irradiated with reactor neutrons





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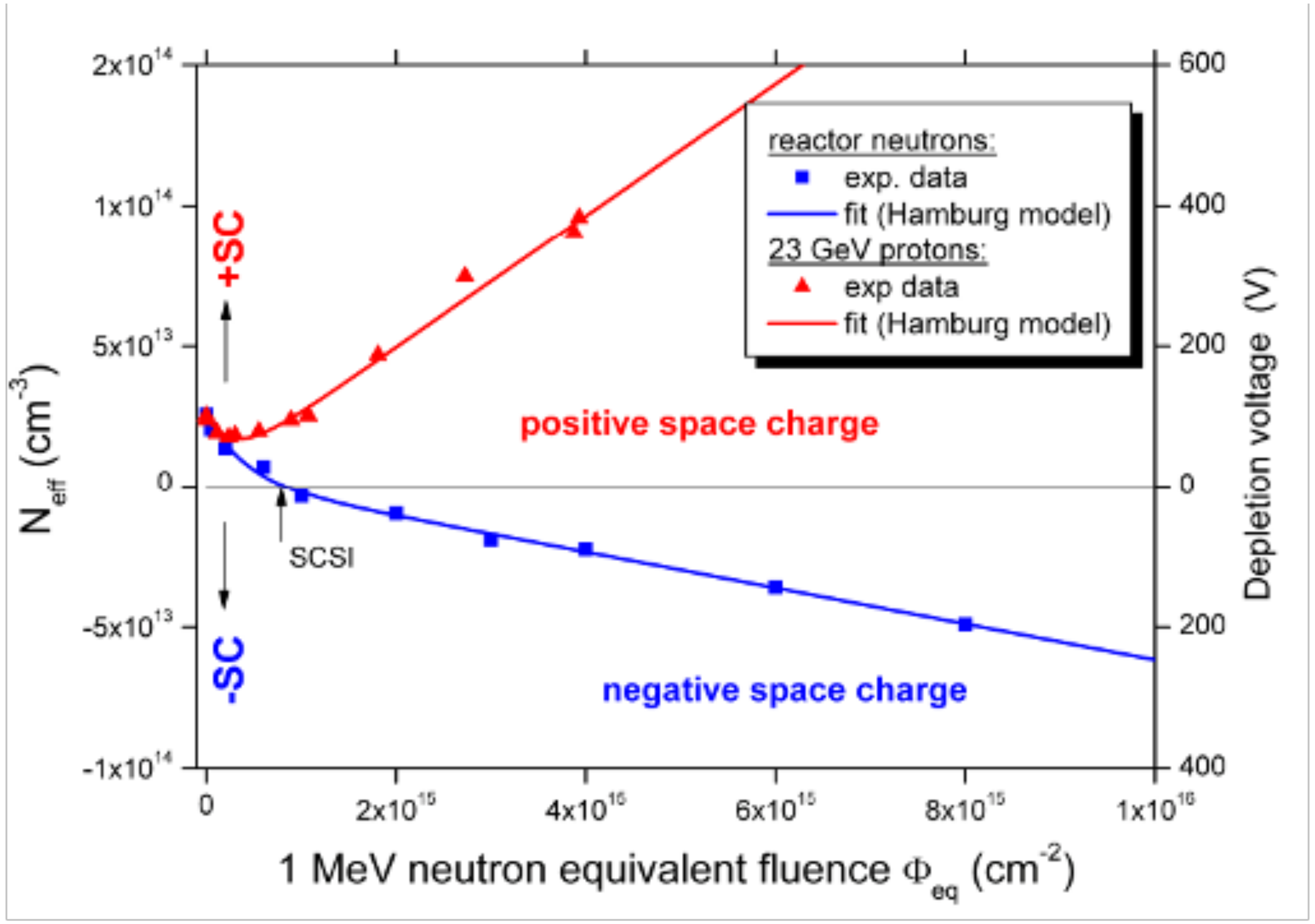
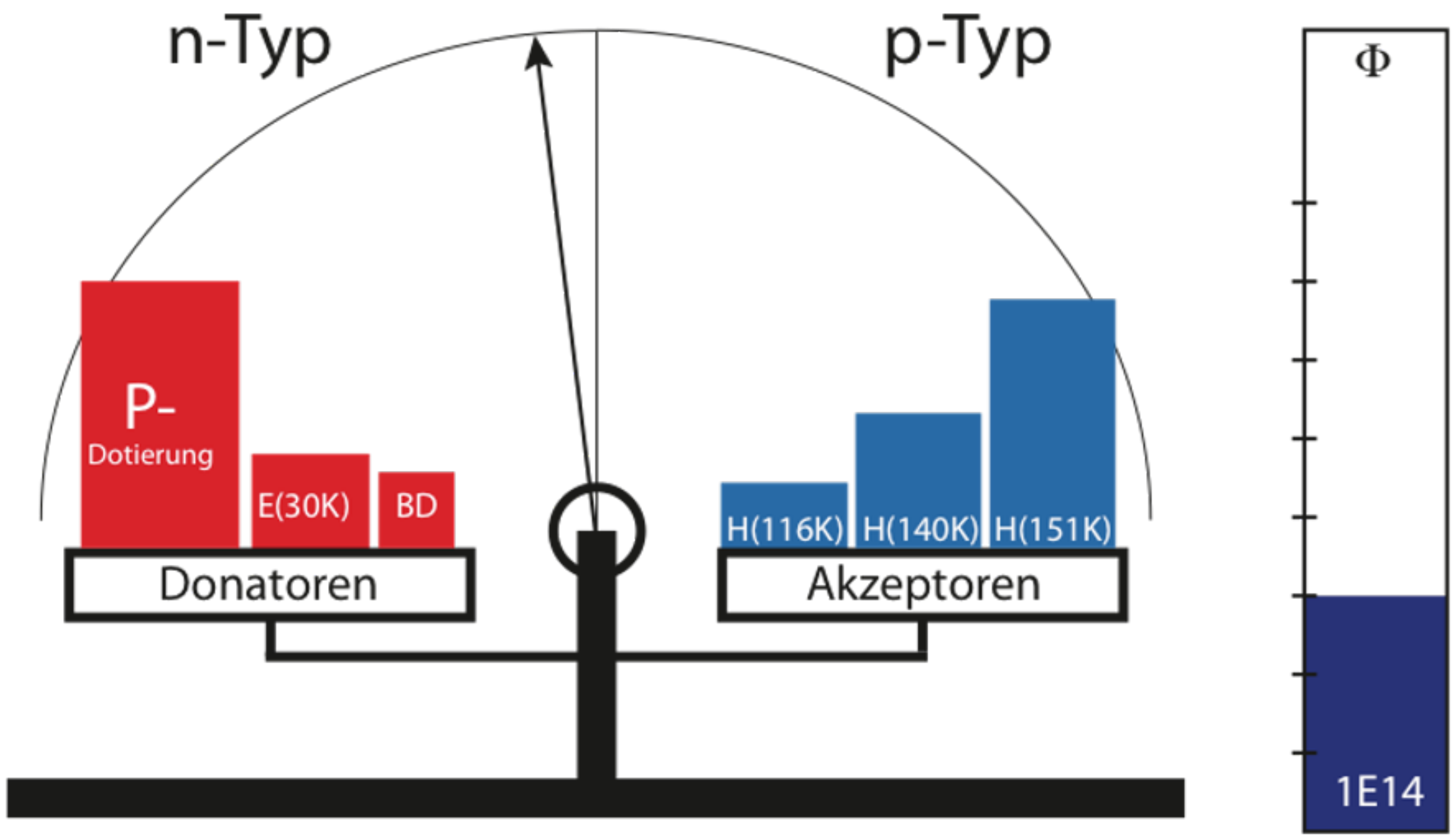
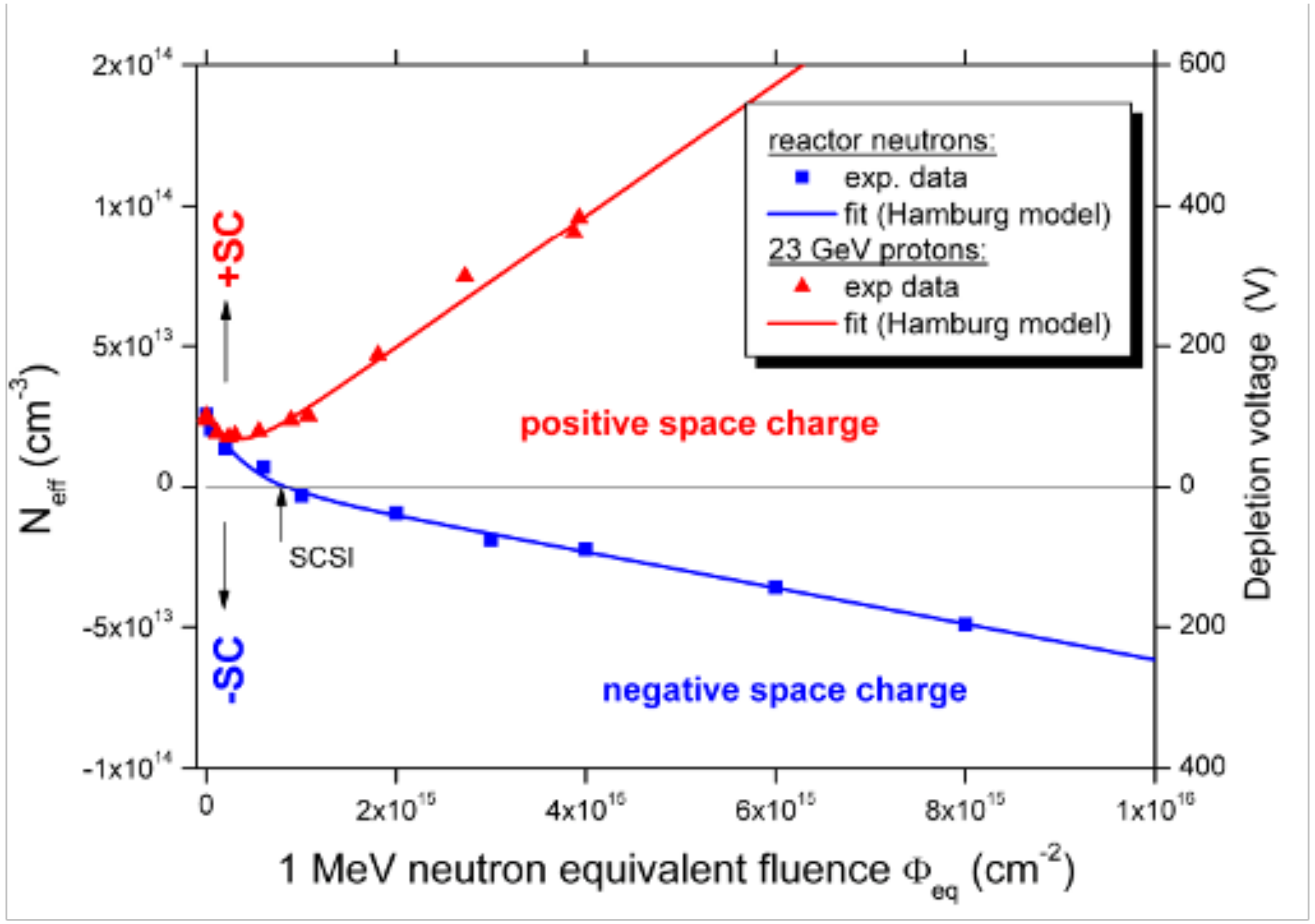
Neutrons


reactor neutrons:
exp. data
fit (Hamburg model)
23 GeV protons:
exp data
fit (Hamburg model)
positive space charge
negative space charge
+SC
-SC
SCSI
2x10^14
1x10^14
5x10^13
0
-5x10^13
-1x10^14
0
2x10^15
4x10^15
6x10^15
8x10^15
1x10^16
600
400
200
0
200
400
N_eff (cm^-3)
Depletion voltage (V)
1 MeV neutron equivalent fluence Φ_eq (cm^-2)


n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
1E14

Neutrons



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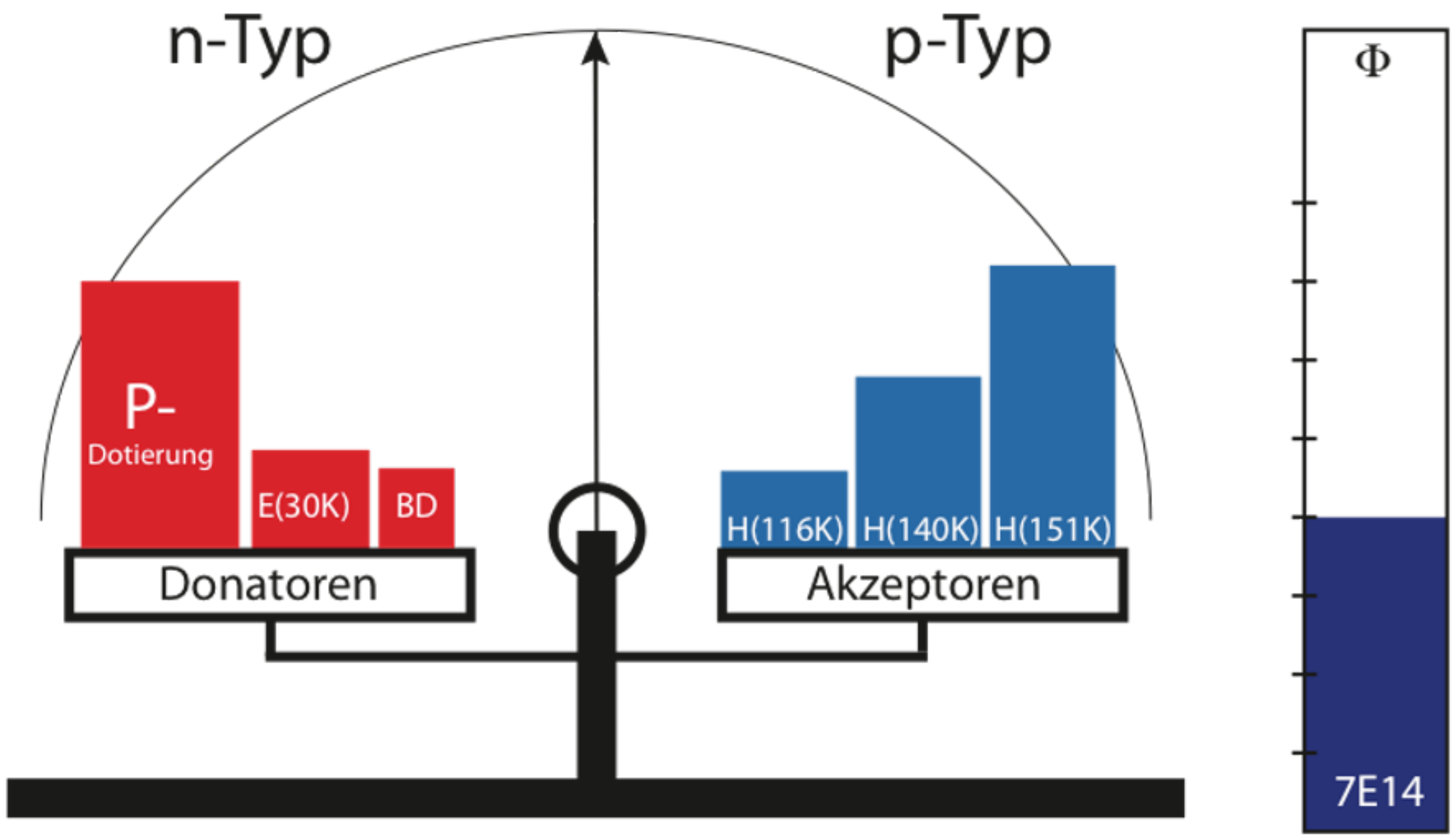

n-Typ
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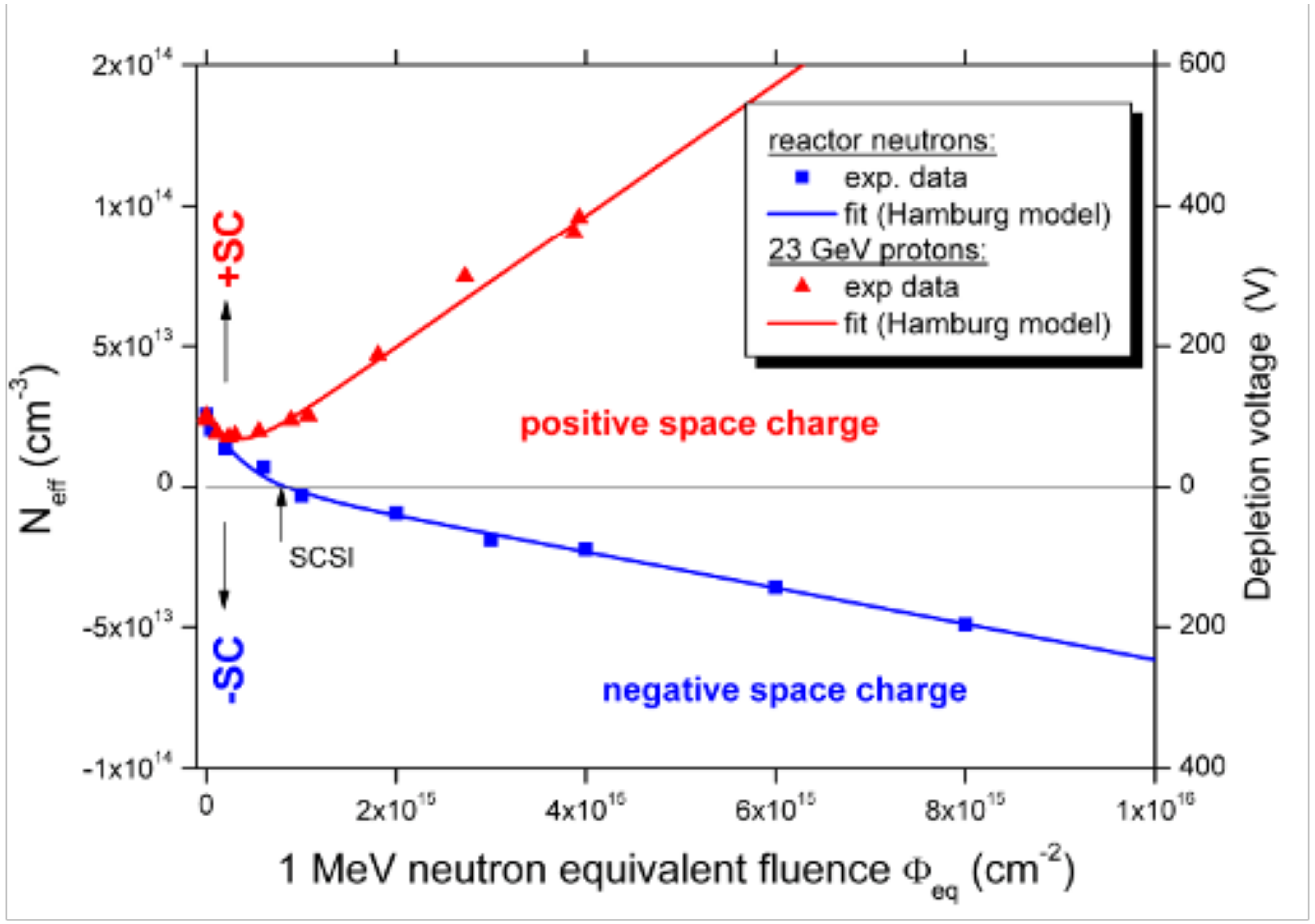
Neutrons



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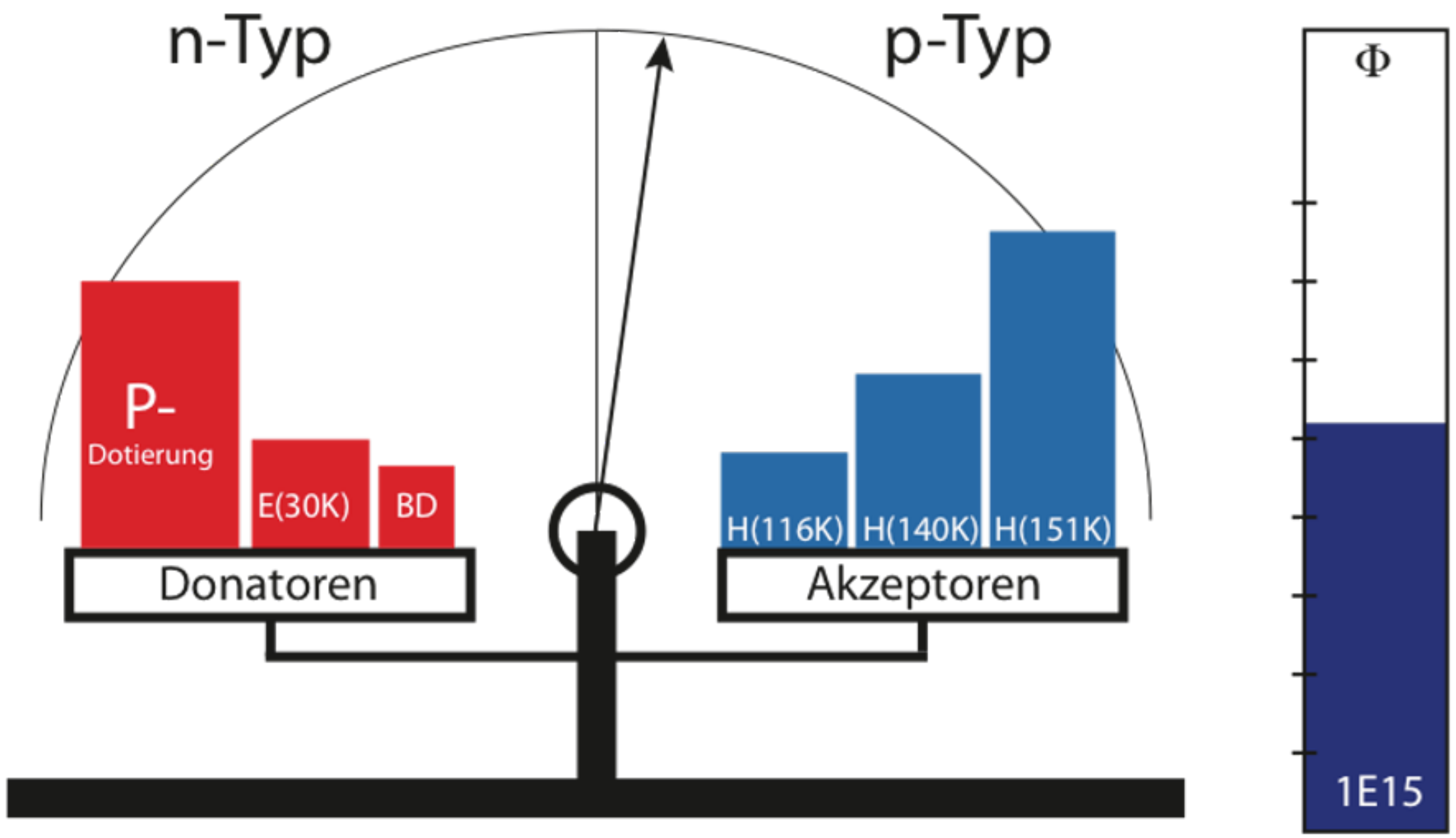

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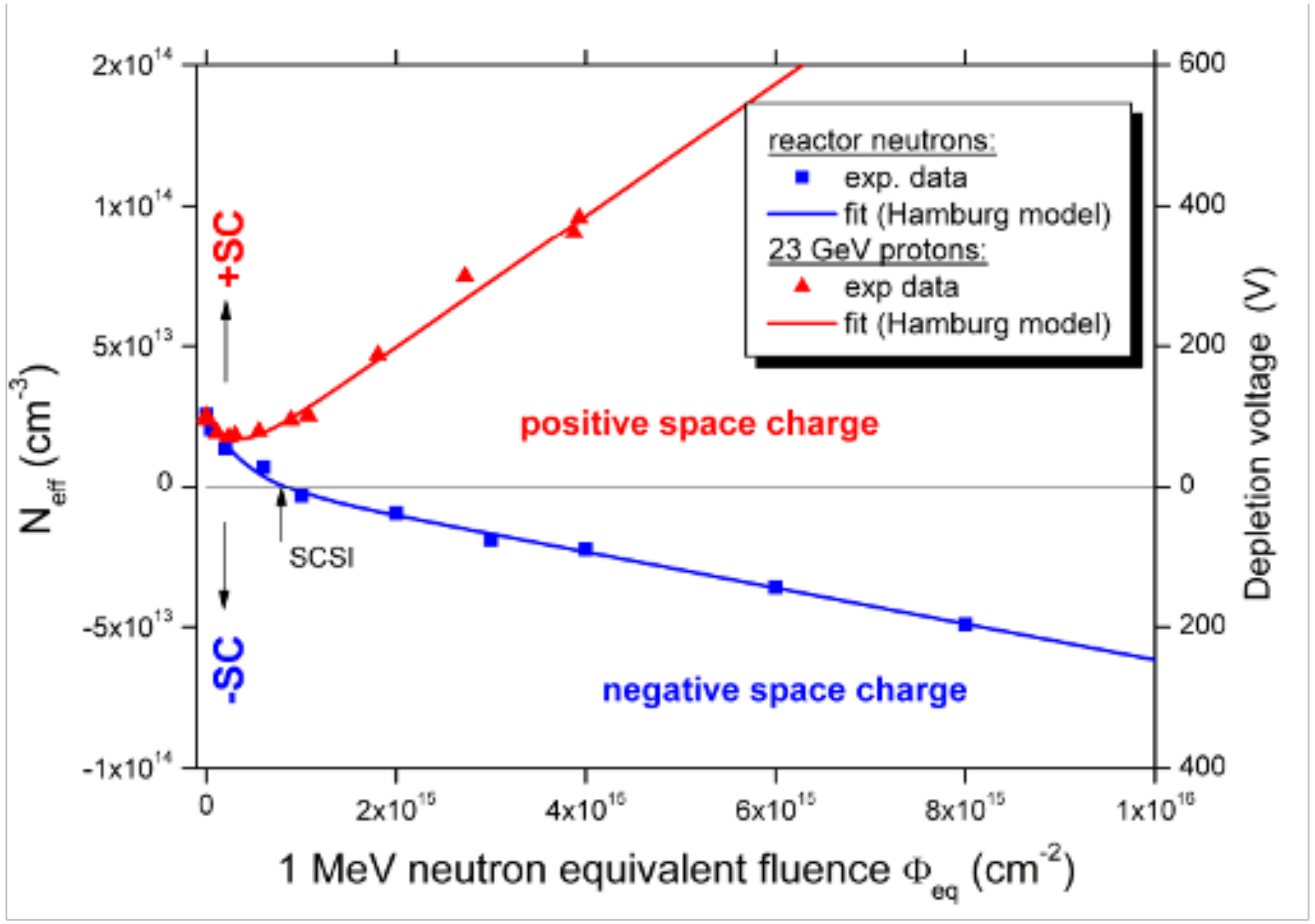
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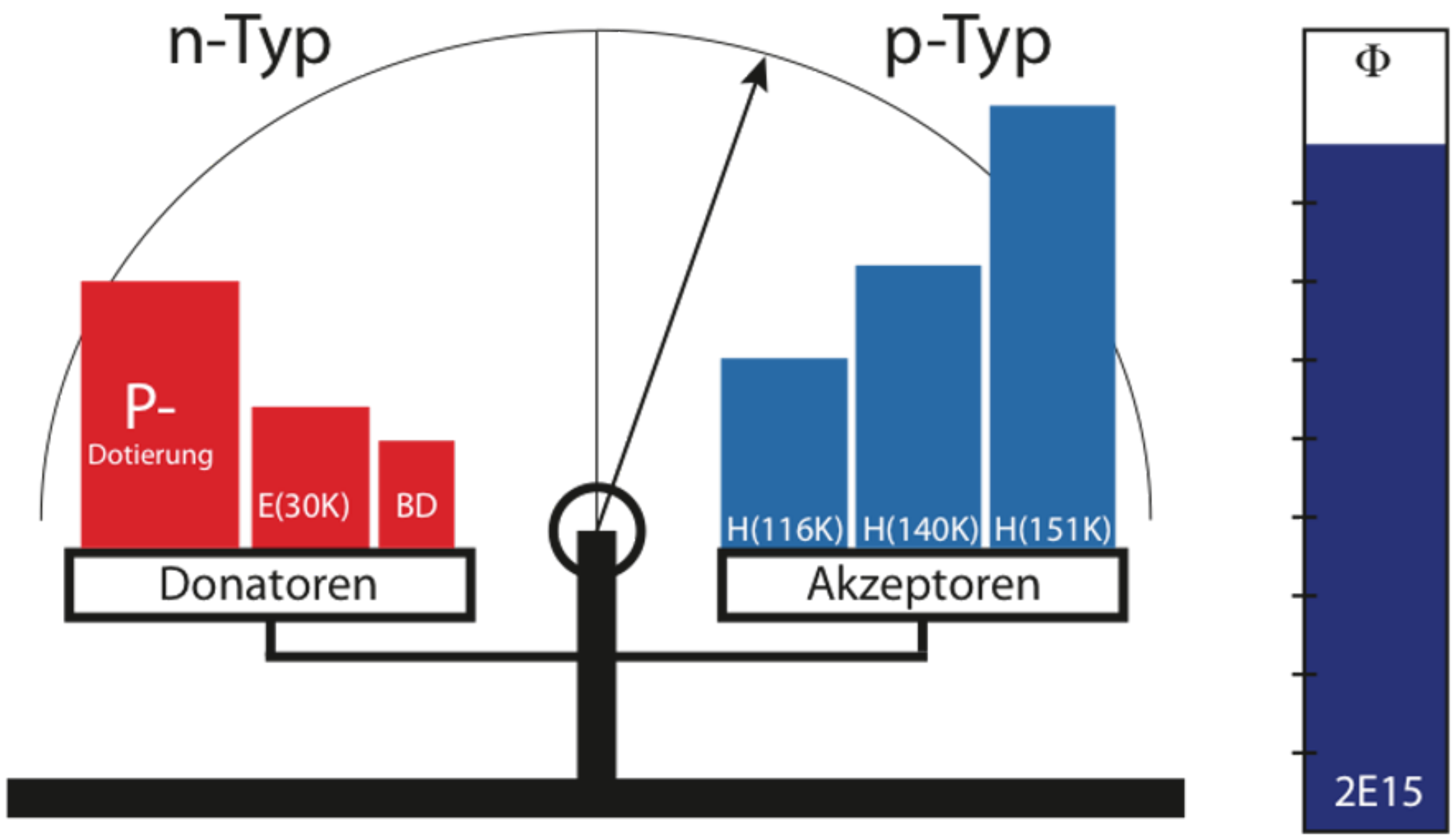
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Protons

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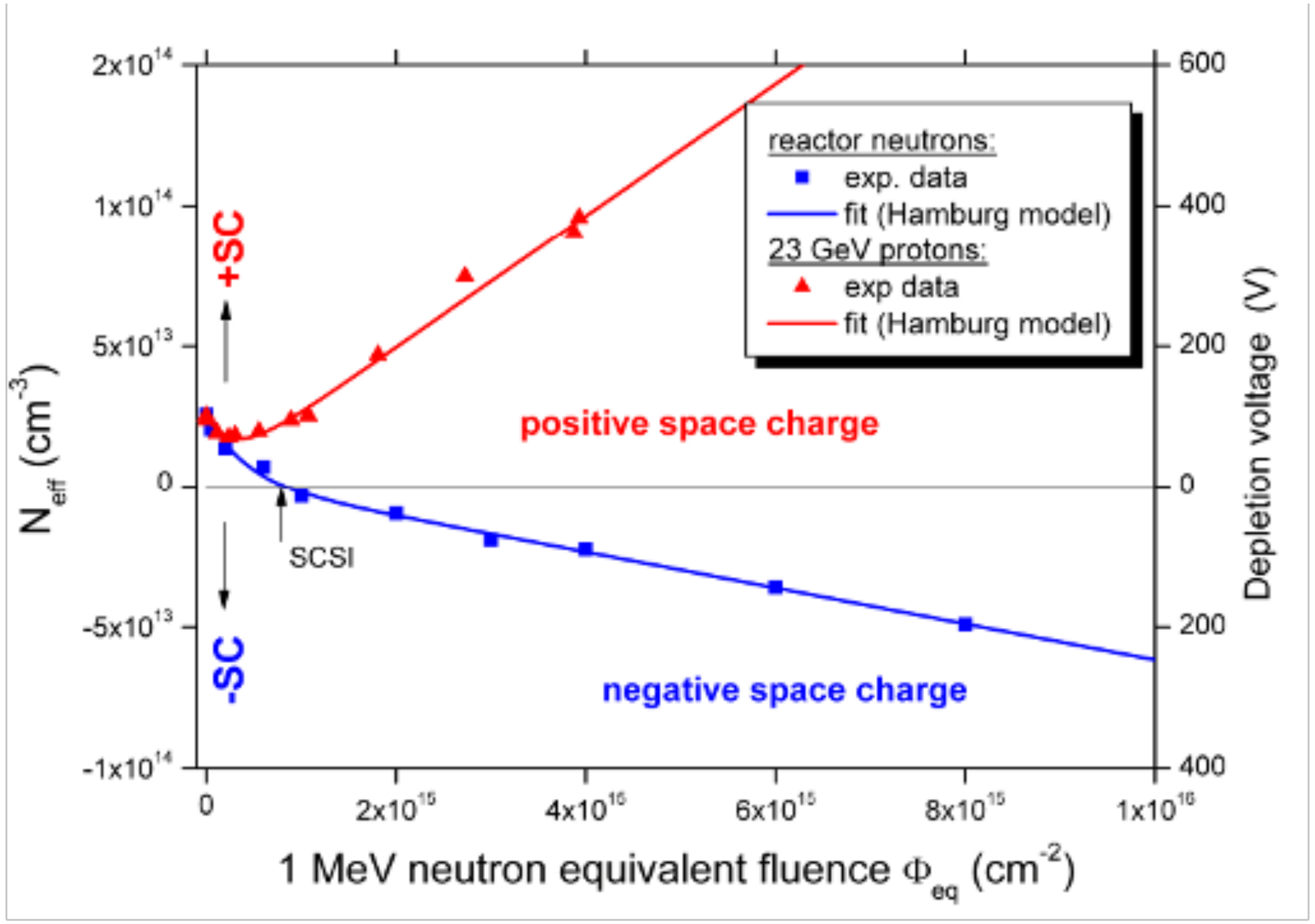
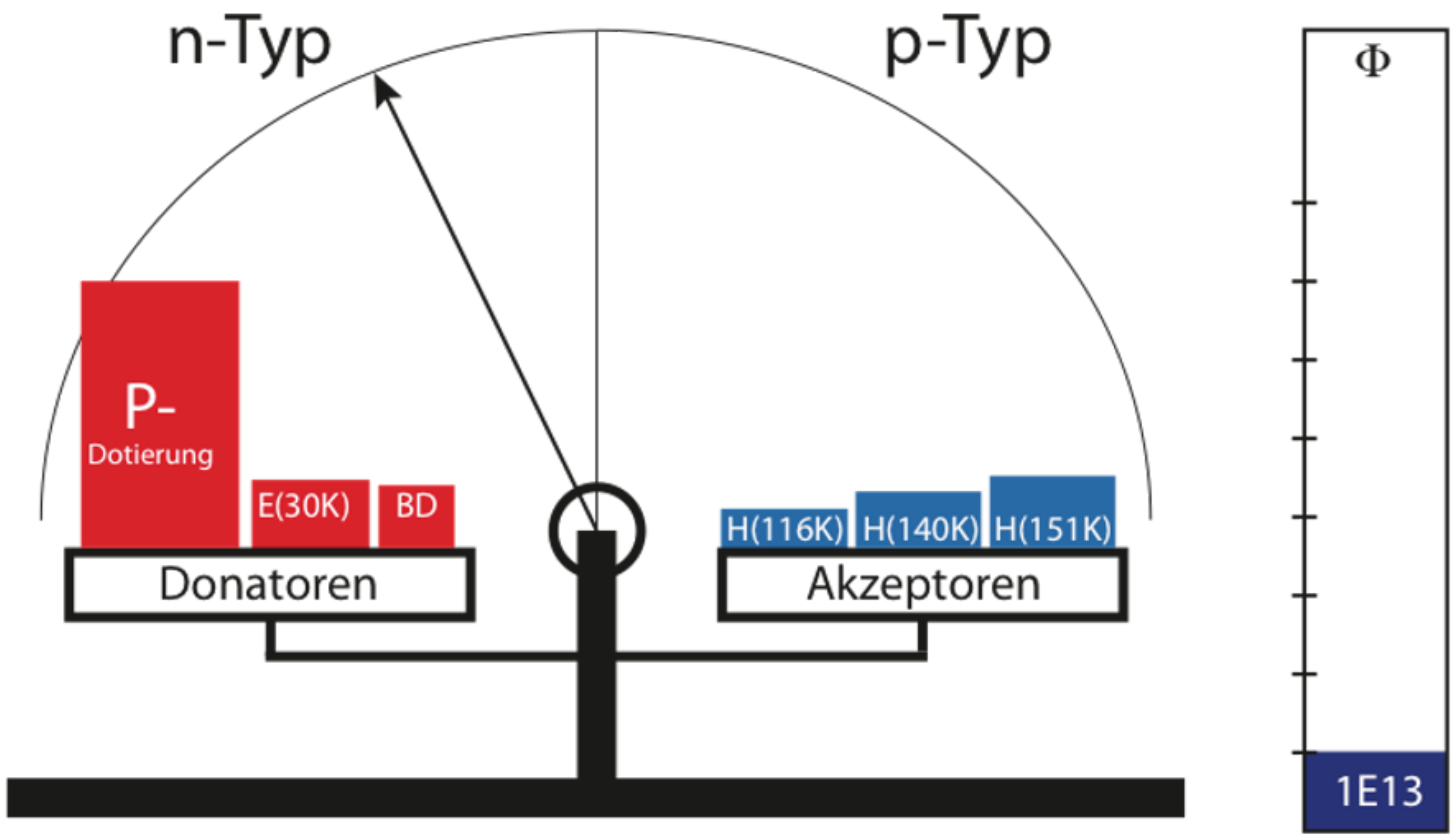
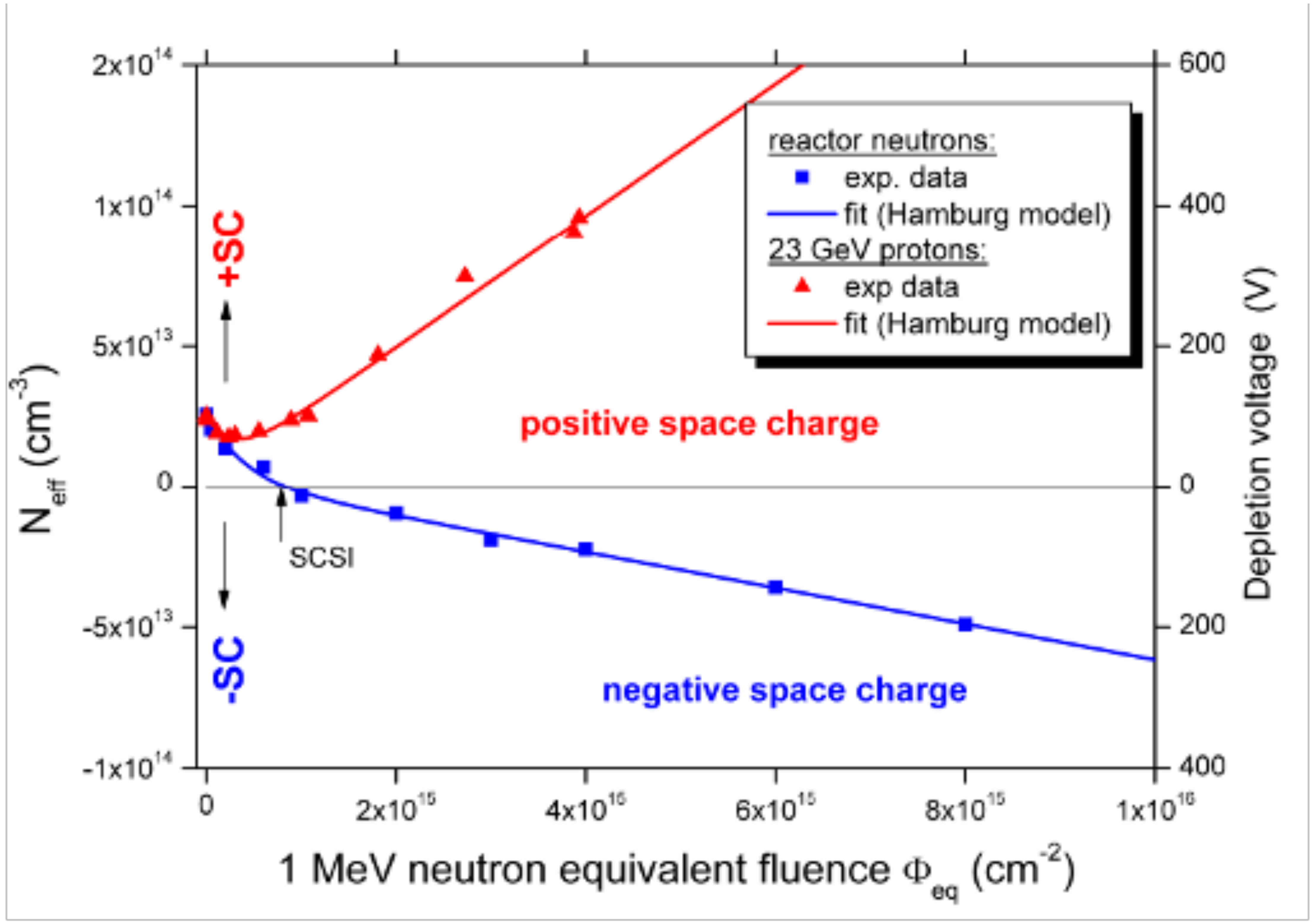
irradiated with 23 GeV Protons





Protons



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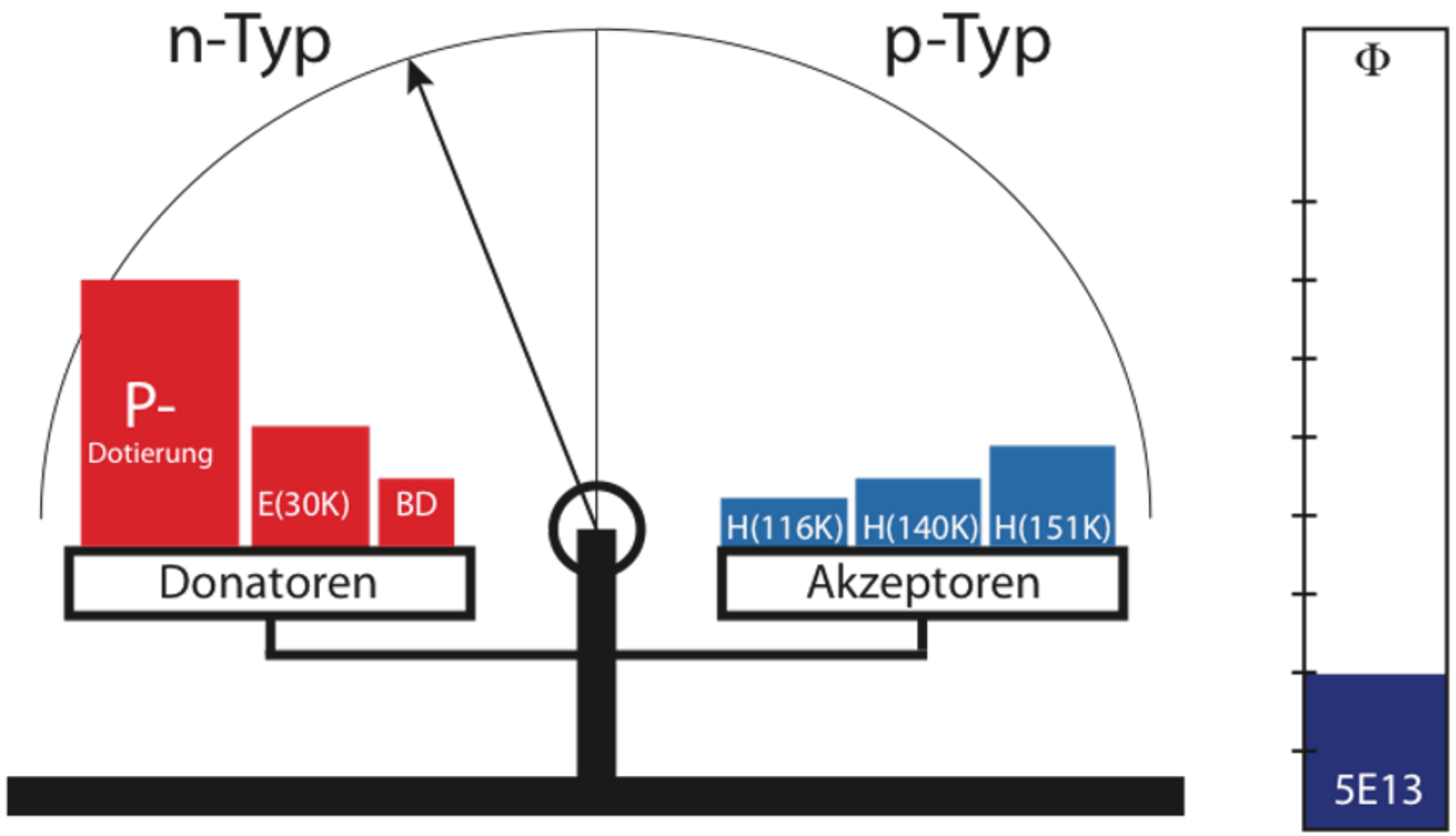
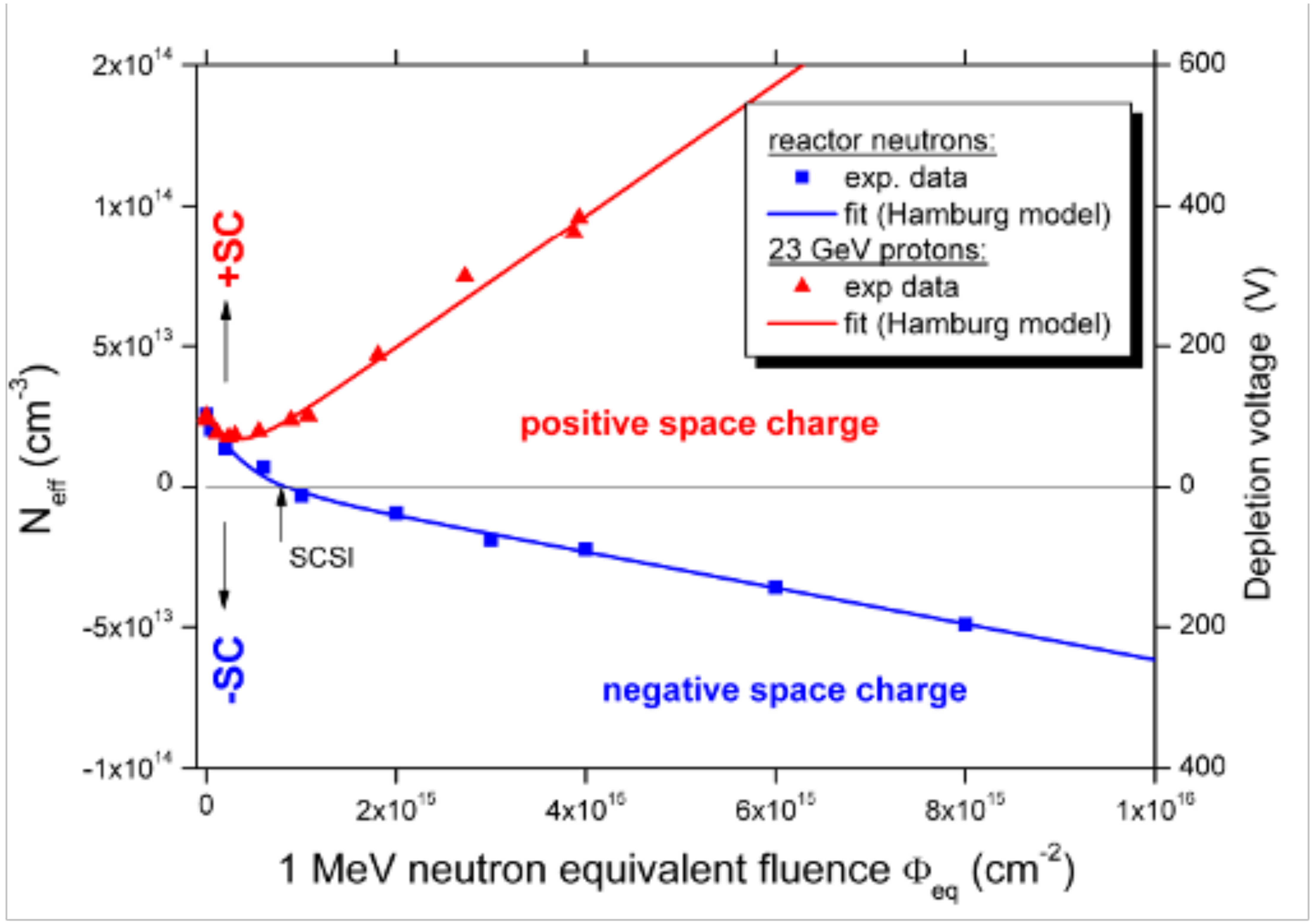
1x10^{16}
600
400
200
0
200
400

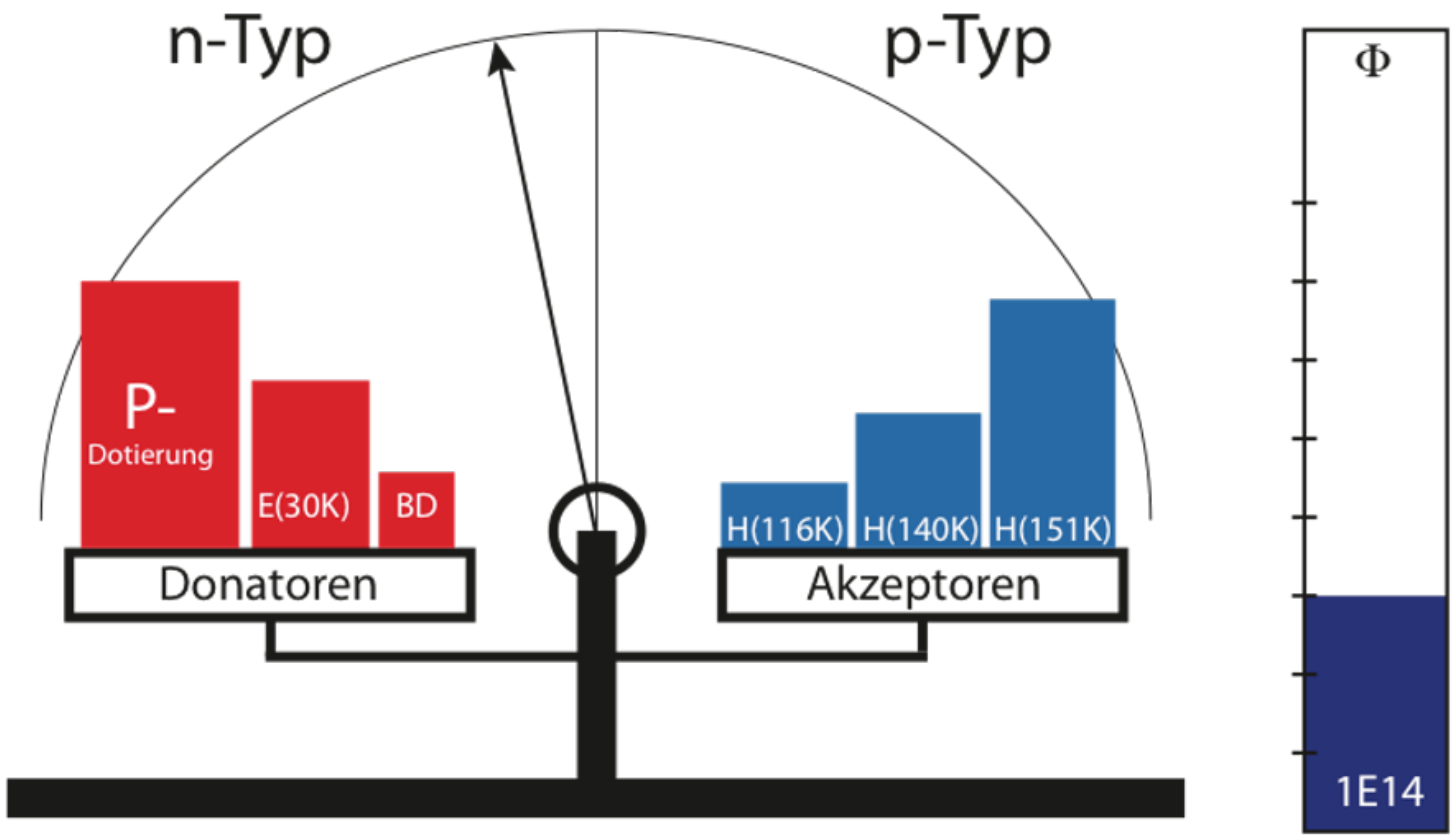


n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
5E13

Protons

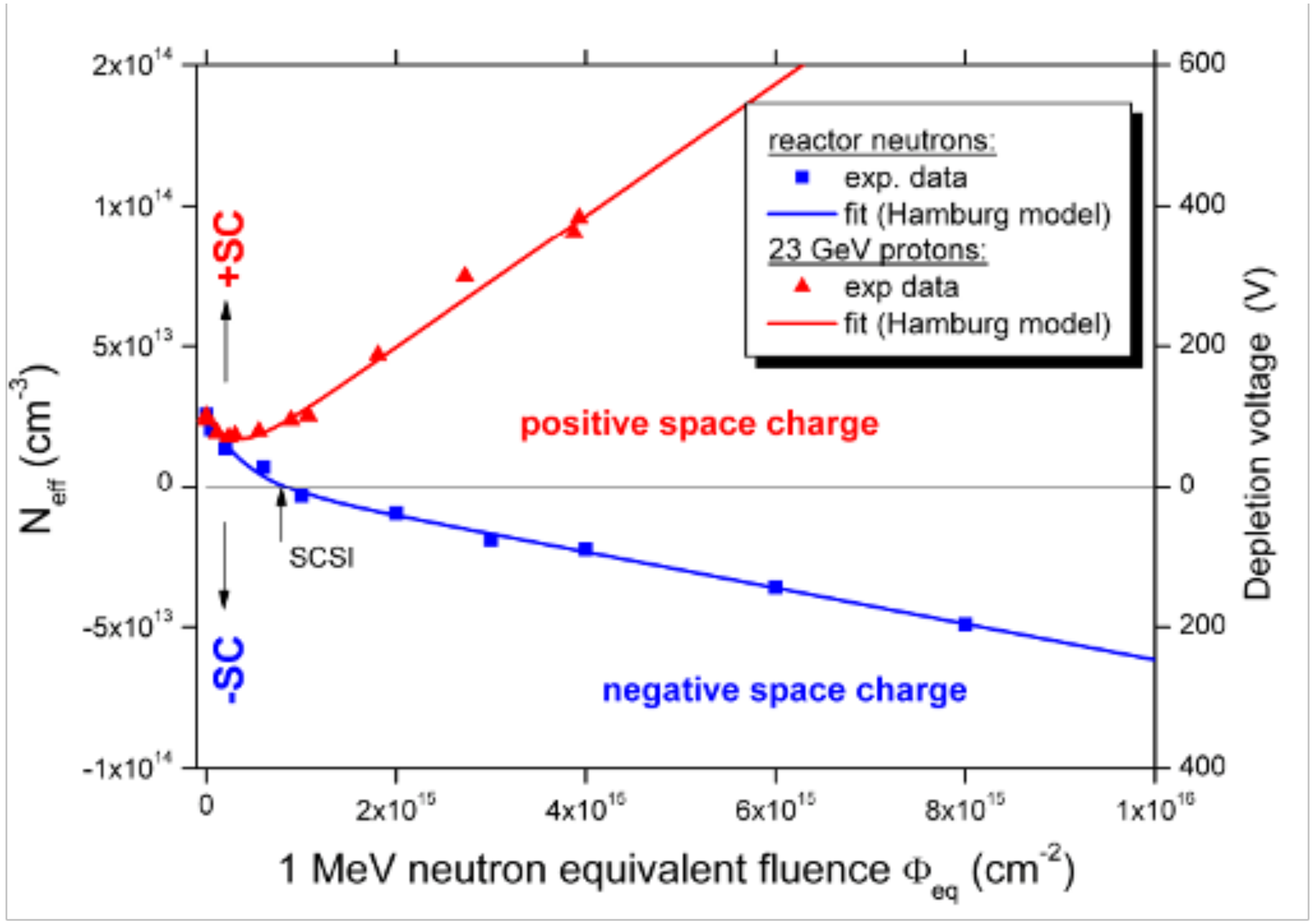


2x10^14
1x10^14
5x10^13
0
-5x10^13
-1x10^14
0
2x10^15
4x10^15
6x10^15
8x10^15
1x10^16
600
400
200
0
200
400
N_eff (cm^-3)
Depletion voltage (V)
1 MeV neutron equivalent fluence Φ_eq (cm^-2)
+SC
-SC
SCSI
reactor neutrons:
exp. data
fit (Hamburg model)
23 GeV protons:
exp data
fit (Hamburg model)
positive space charge
negative space charge

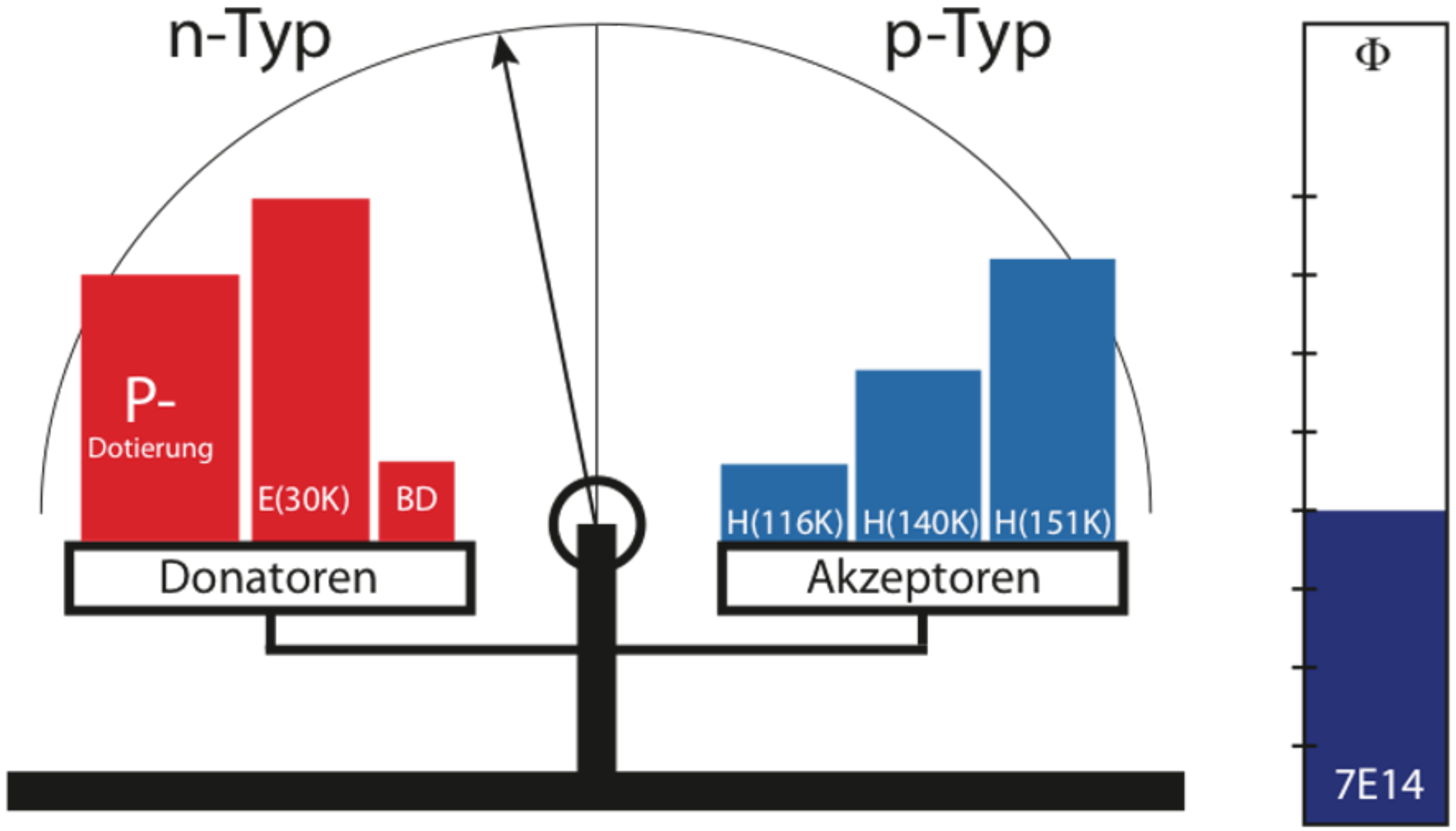


n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
1E14

Protons

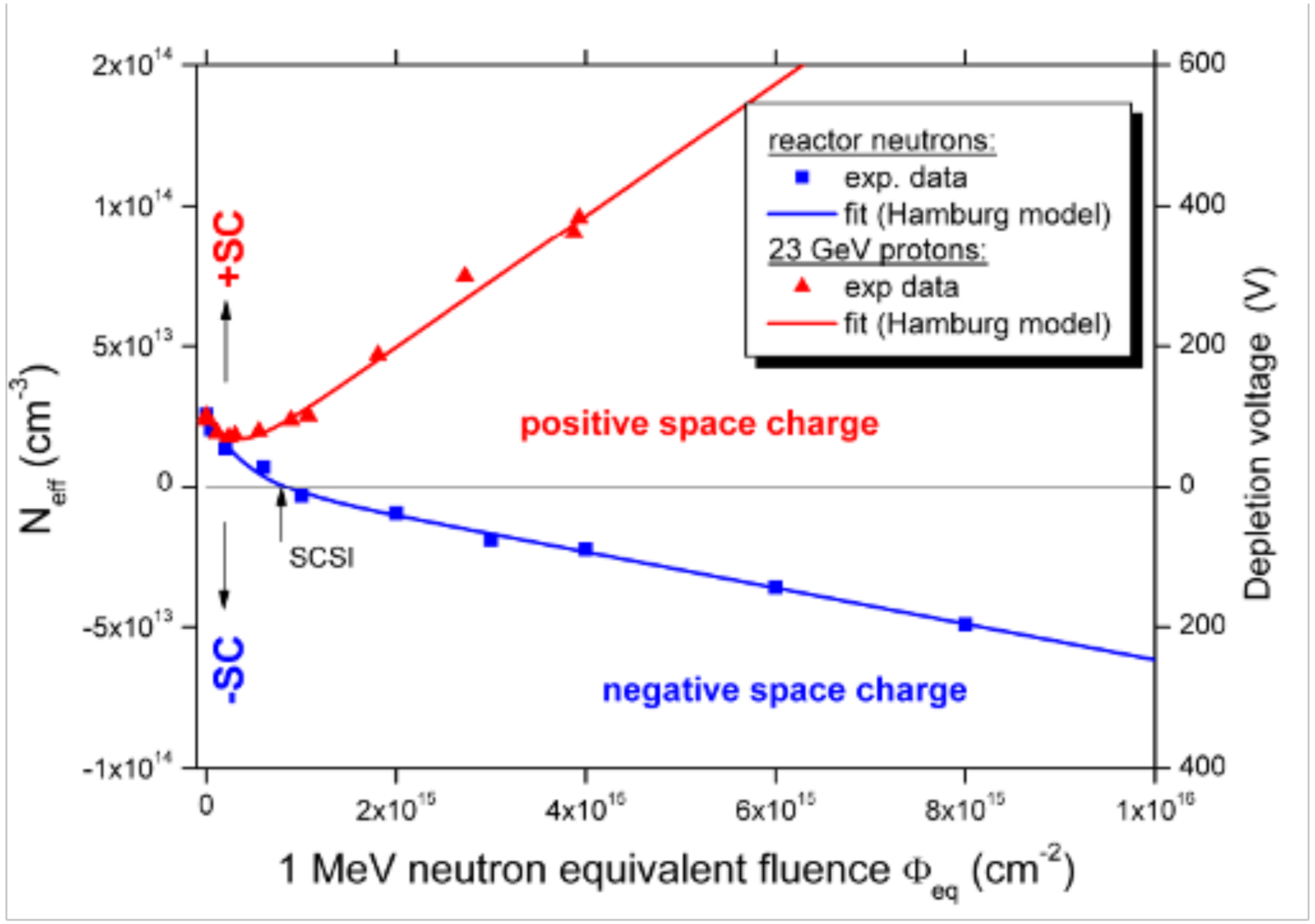


reactor neutrons:
exp. data
fit (Hamburg model)
23 GeV protons:
exp data
fit (Hamburg model)
+SC
-SC
positive space charge
negative space charge
SCSI
N_{eff} (cm^{-3})
Depletion voltage (V)
1 MeV neutron equivalent fluence Φ_{eq} (cm^{-2})
2x10^{14}
1x10^{14}
5x10^{13}
0
-5x10^{13}
-1x10^{14}
600
400
200
0
200
400
0
2x10^{15}
4x10^{15}
6x10^{15}
8x10^{15}
1x10^{16}

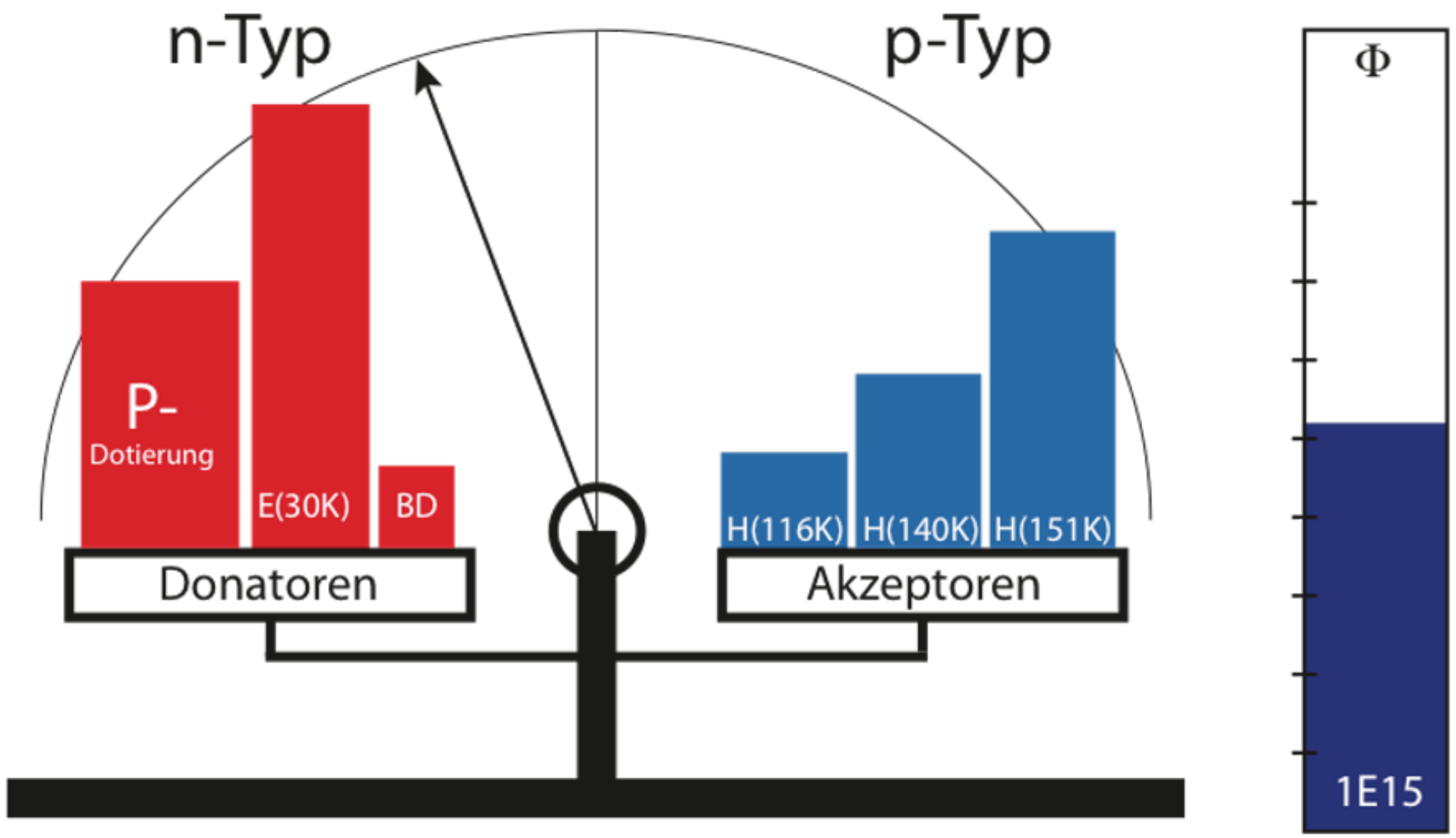


n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
7E14

Protons

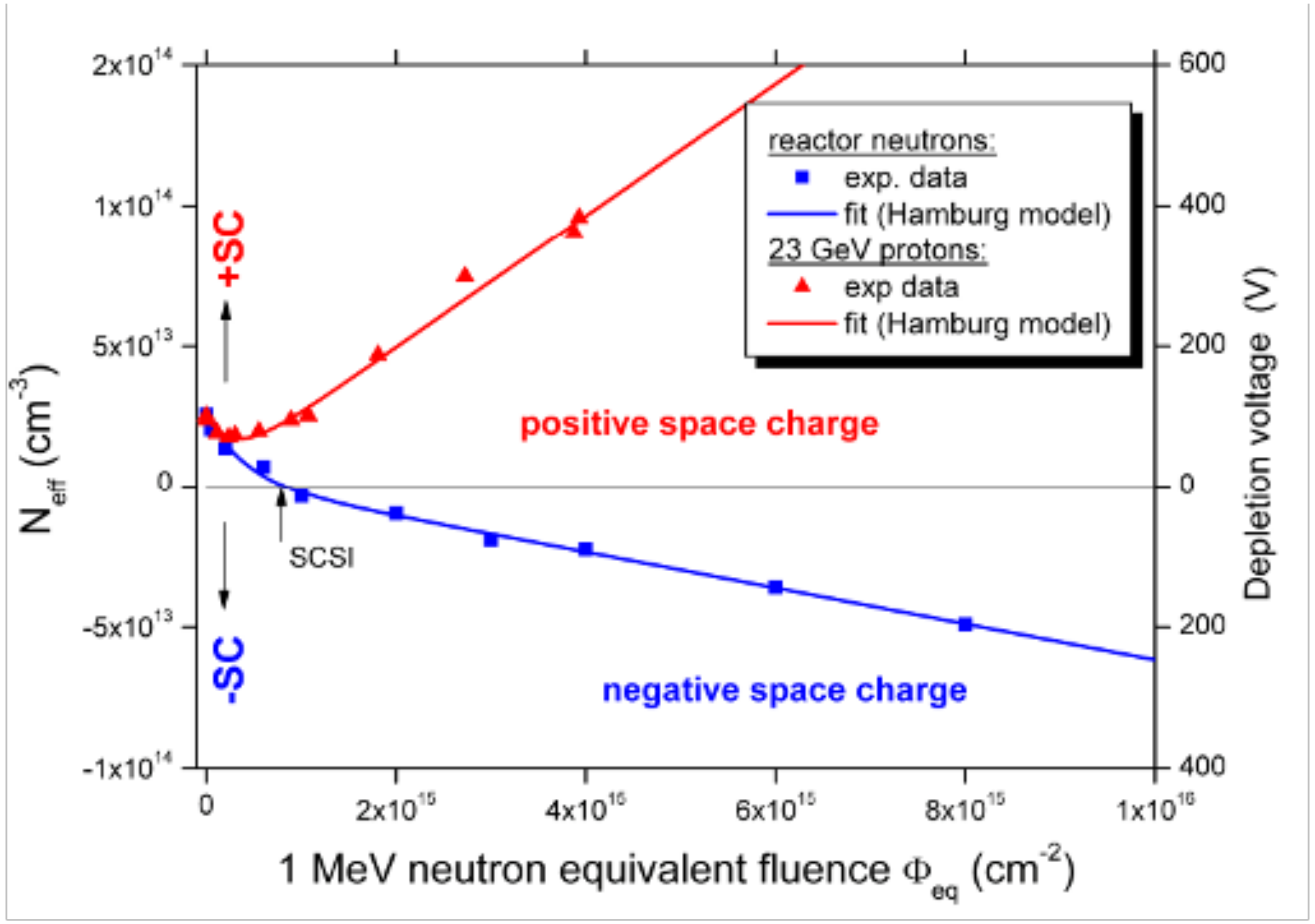


reactor neutrons:
exp. data
fit (Hamburg model)
23 GeV protons:
exp data
fit (Hamburg model)
+SC
-SC
positive space charge
negative space charge
SCSI
N_{eff} (cm^{-3})
Depletion voltage (V)
1 MeV neutron equivalent fluence Φ_{eq} (cm^{-2})

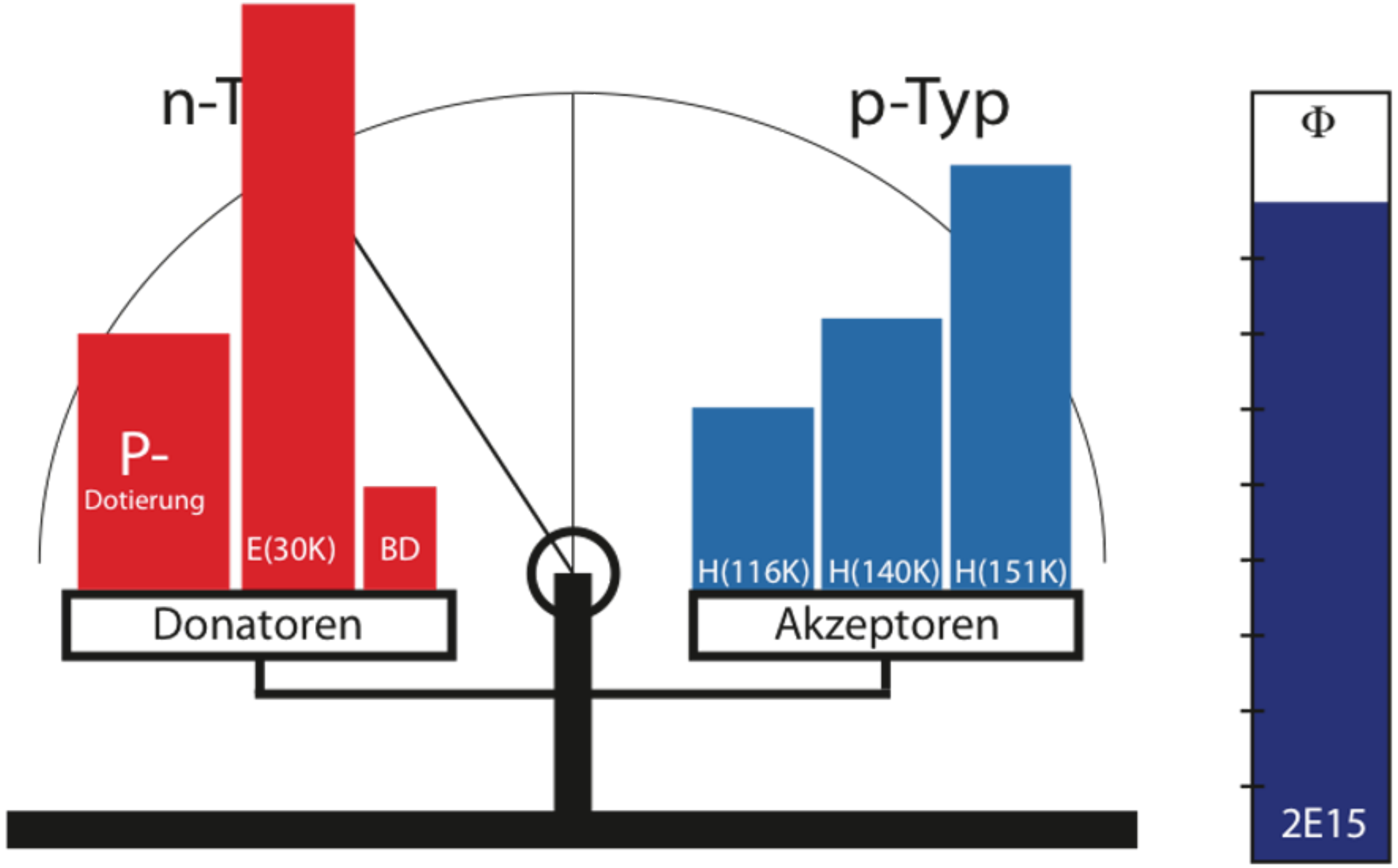


n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
1E15

Protons



reactor neutrons:
exp. data
fit (Hamburg model)
23 GeV protons:
exp data
fit (Hamburg model)
+SC
-SC
positive space charge
negative space charge
SCSI
2x10^14
1x10^14
5x10^13
0
-5x10^13
-1x10^14
600
400
200
0
200
400
0
2x10^15
4x10^15
6x10^15
8x10^15
1x10^16
N_eff (cm^-3)
Depletion voltage (V)
1 MeV neutron equivalent fluence Φ_eq (cm^-2)



n-T
p-Typ
P-
Dotierung
E(30K)
BD
H(116K)
H(140K)
H(151K)
Donatoren
Akzeptoren
Φ
2E15

Known defects in silicon

- **Calculate/Simulate effect on device properties if all defect parameters are known**

→ **cross section, ionization energy, concentration**

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm²

- $E_i^I = E_c - 0.545$ eV
  - $\sigma_n^I = 1.7\cdot10^{-15}$ cm²
  - $\sigma p^I = 9\cdot10^{-14}$ cm²

Cluster related centers

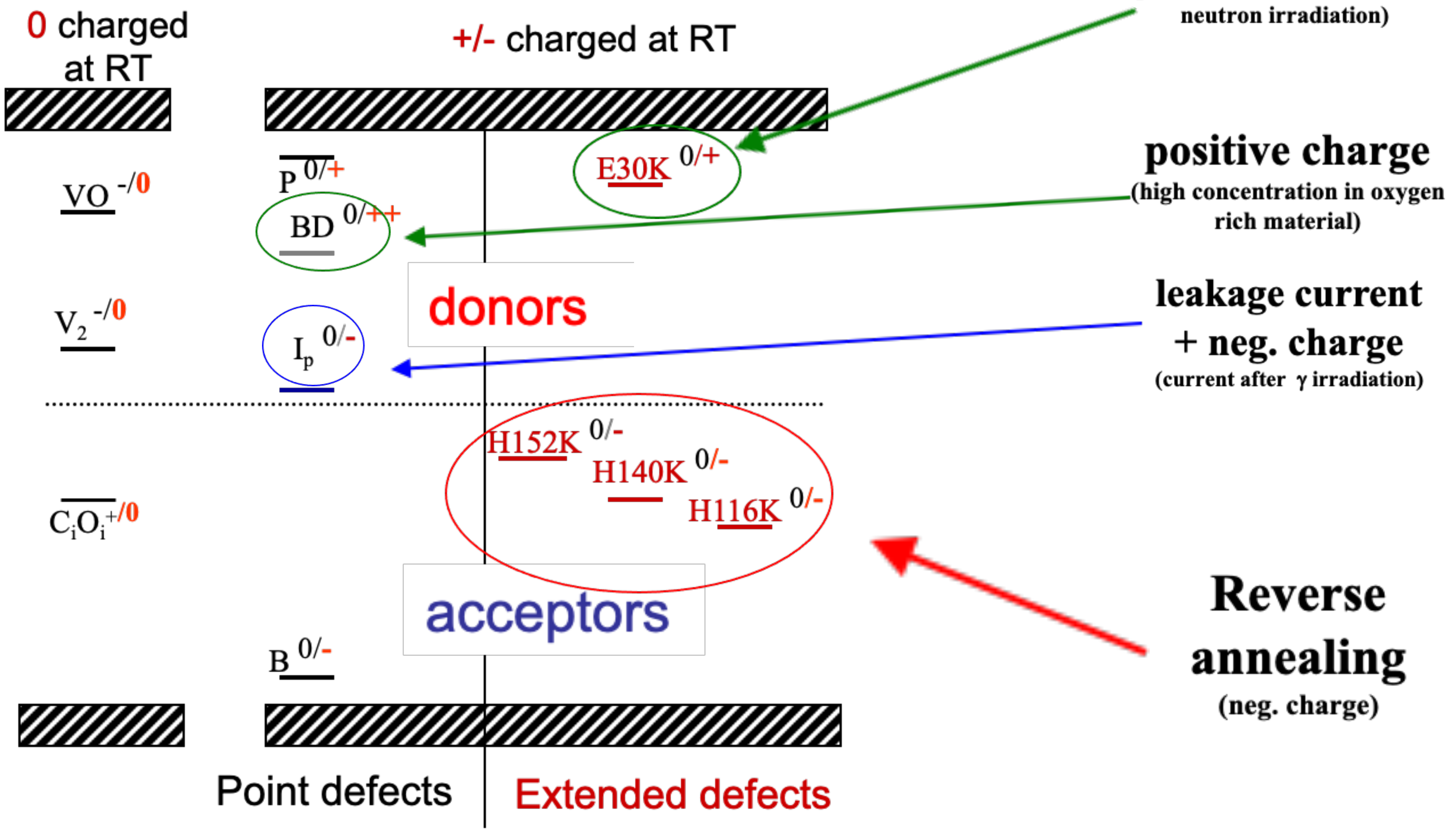
- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm²

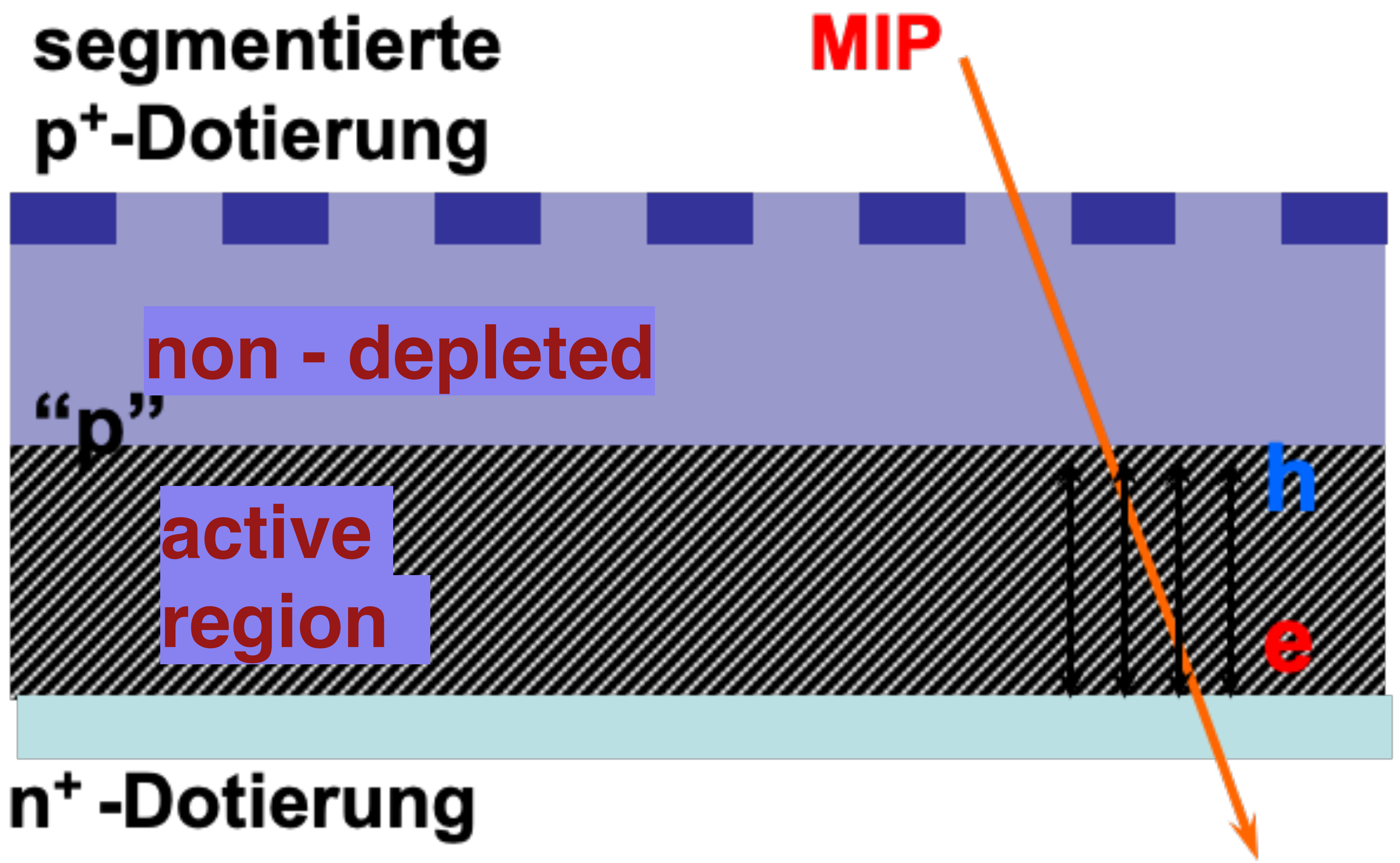
- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm²

[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]



Why p-type silicon (n-in-p) for HL-LHC

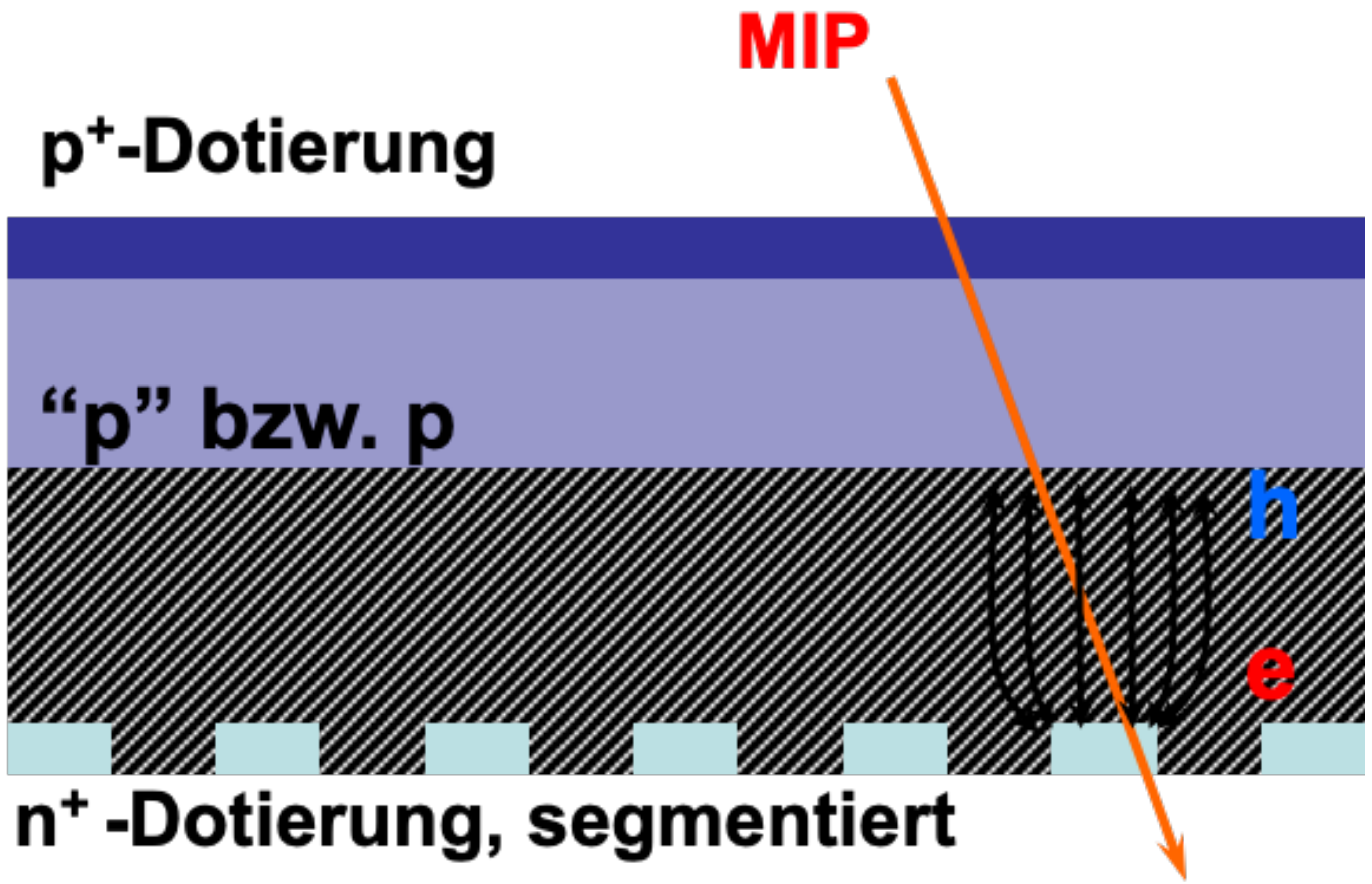
what happens in sensor after inversion:
p+ - in - n sensor:



- Depeletion Region grows from backside
- non-depleted, i.e. isolation layer beneath front side —> lose resolution as charge not collected on electrodes
- collect holes —> trapping

- ==> overall loss of CCE and (if not depleted) resolution

n+ - in- n or n+ - in - p sensor:



- Depeletion Region grows from segmented side
- non-depleted, i.e. isolation layer beneath front, non-segmented side —> lose charge but nor resolution
- collect electrons —> far less trapping

- ==> smaller loss of CCE

Summary

This is not an up-to-date status of radiation damage status

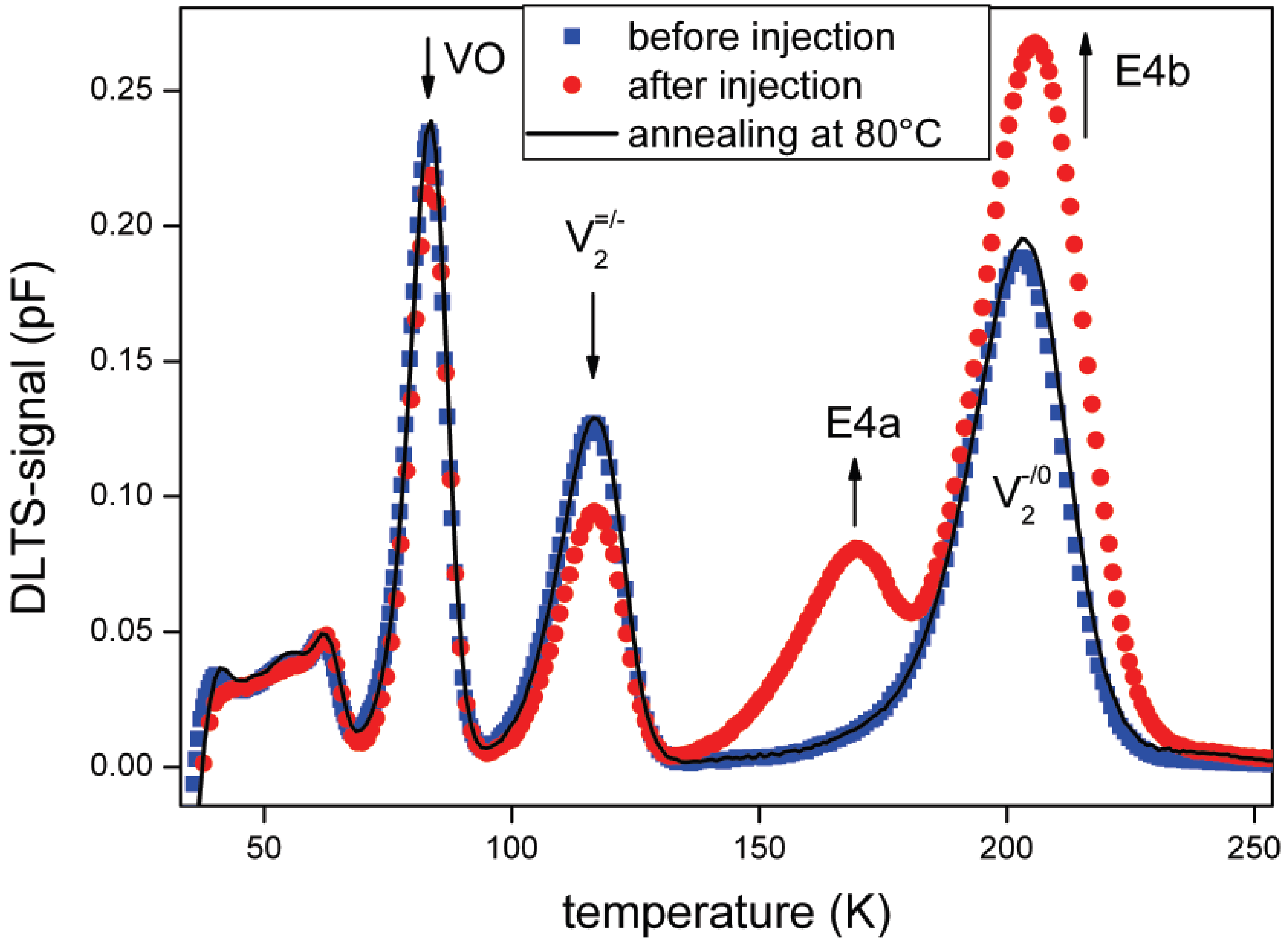
There are people which to-day work on these topics

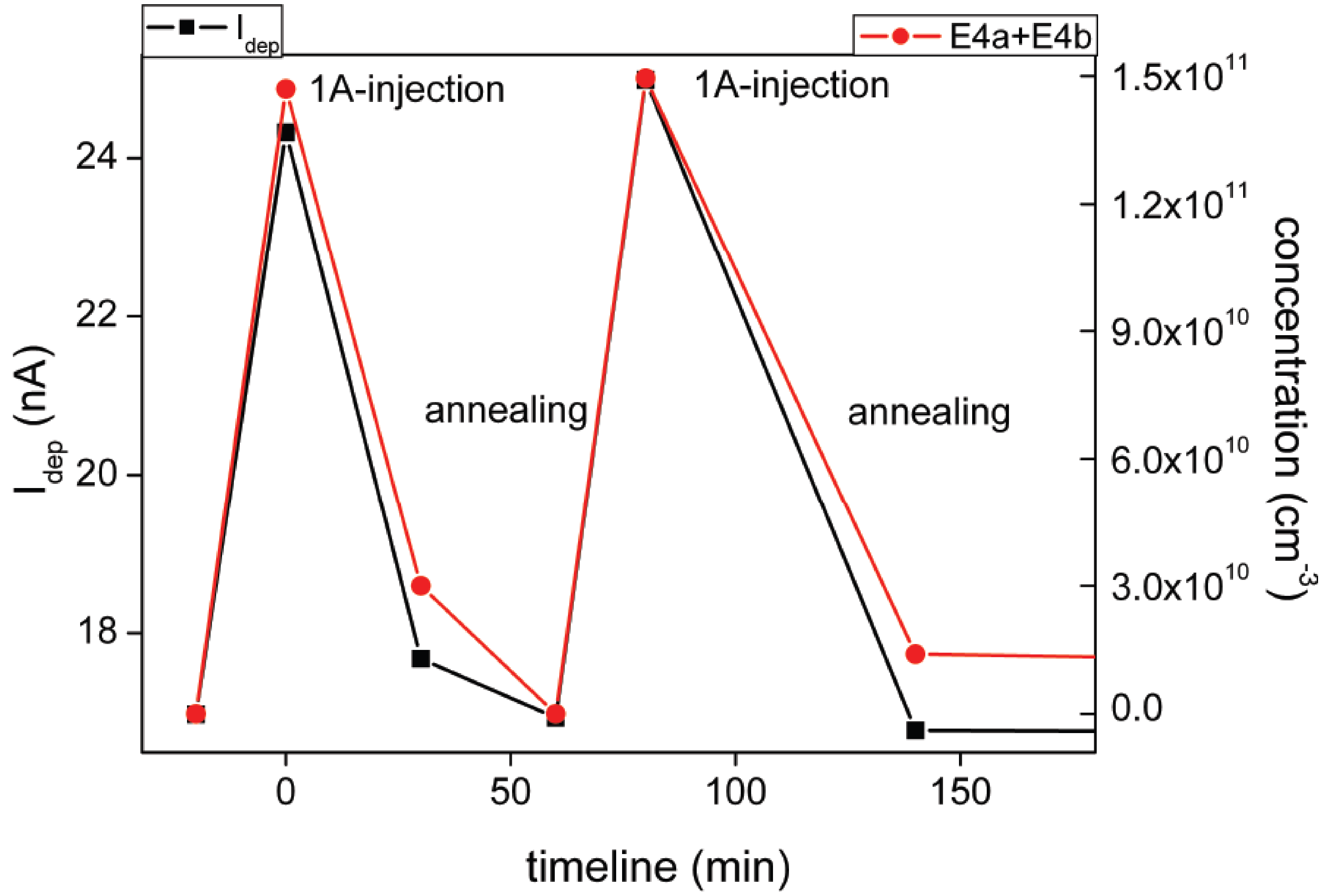
My aim is

- to give an introduction to radiation damage applicable to the silicon sensors currently used at the LHC
- to motivate the usage of n-in-p at HL-LHC
- to raise awareness that models are phenomenological descriptions and the defects used therein are not actual defects in silicon
- to raise awareness that acceptor-removal and donor-removal are simplifications of what actually happens in the lattice

Towards the Origin of the Leakage Current

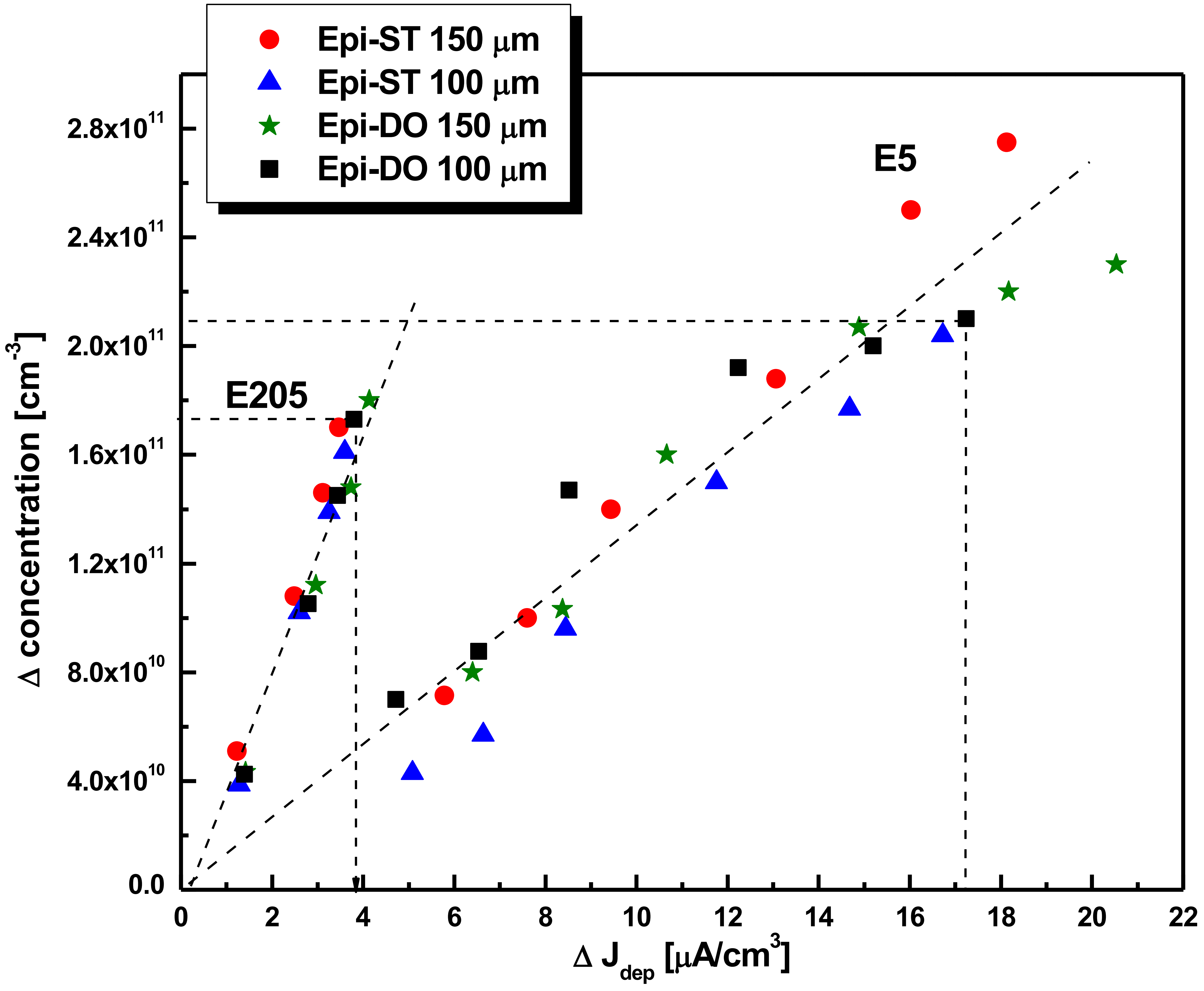
•Bistable defect E4/E5
•Correlation with leakage current found
→What type of defect is this?
→How large is the impact on the leakage current?





[A.Junkes at RD50 Workshop May/June 2010]

Towards the Origin of the Leakage Current



- Annealing study
- Disentangle different defects through their different annealing behaviour (change of cluster-configuration happens at different activation energies; E5 till 100°C, E205 starting from 140°C)
- Change in defect concentration vs. change in leakage current

[C.Privutouiu, 3rd MC-PAD Training event]

Work in progress…

Good progress in understanding the origin of leakage current