Review Days, MPI Halbleiterlabor

- April 21, 2010 -

Development of radiation tolerant silicon detectors for the Super - LHC

… with strong focus on the results of the RD50 collaboration

Georg Steinbrück, Hamburg University

Most of the material provided by Michael Moll (CERN/PH): Thanks!

Outline

- **Motivation to develop radiation harder detectors**
  - **Super-LHC and expected radiation levels at the Super-LHC**
  - **Radiation induced degradation of detector performance**

- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**
  - **Microscopic damage (crystal damage)**

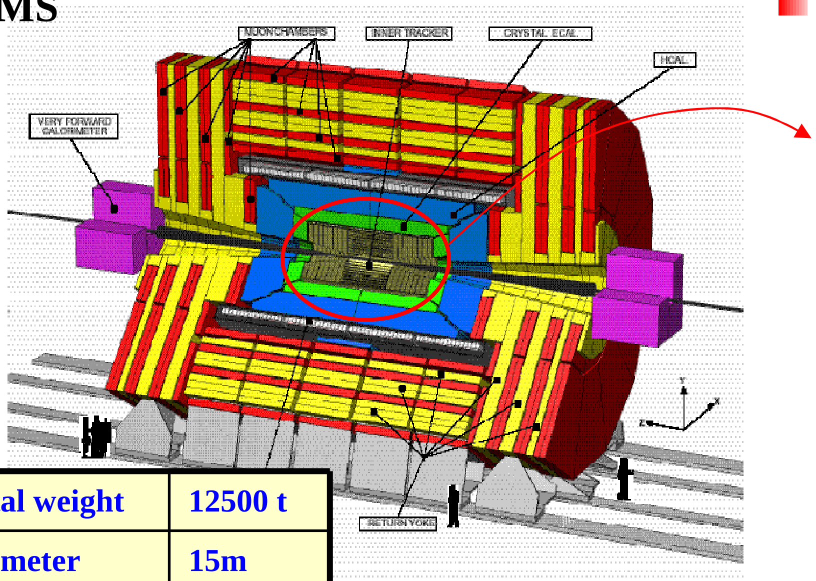
- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices

- **Silicon Sensors for the LHC upgrade and open questions**
  - **Collected Charge – Signal to Noise – Avalanche effects**
  - **Mixed irradiations**

- **Summary**

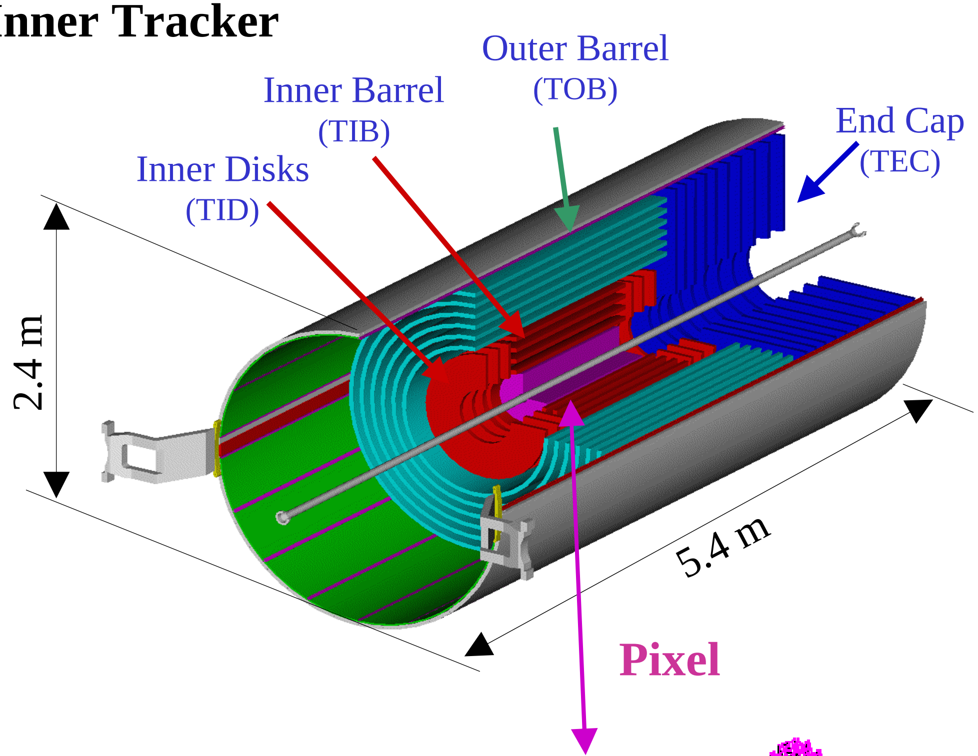
LHC example: CMS inner tracker

- **CMS**



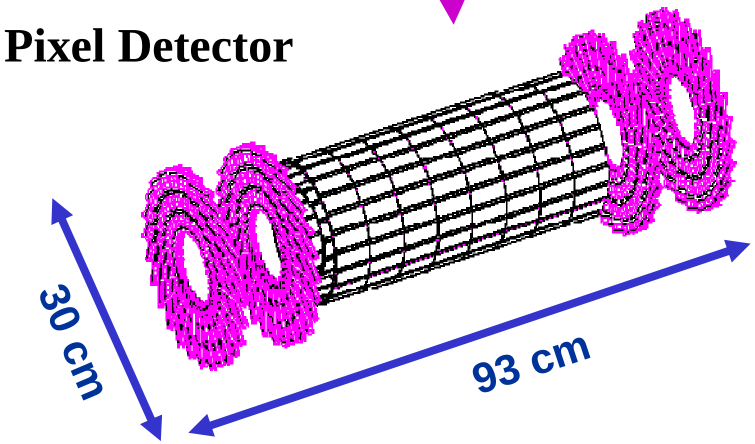
Total weight	**12500 t**
Diameter	**15m**
Length	**21.6m**
Magnetic field	**4 T**

- **Inner Tracker**



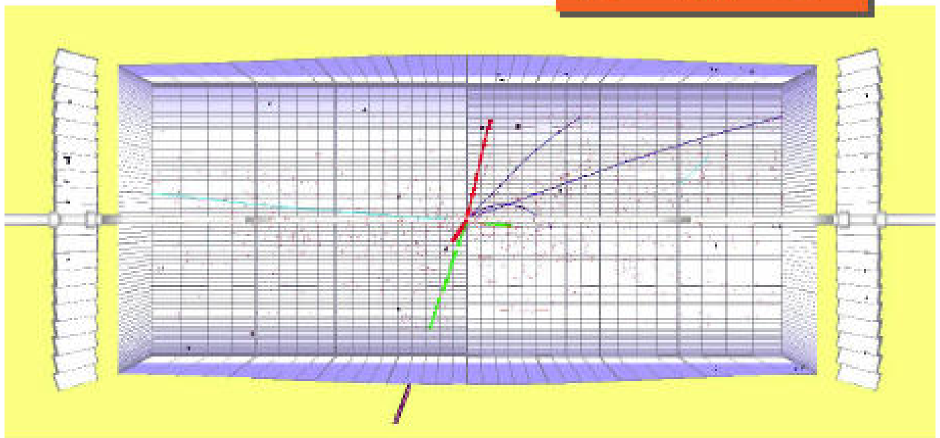
- **CMS – "Currently the Most Silicon"**
  - **Micro Strip:**
  - **~ 214 m² of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **Inner 3 layers: silicon pixels (~ 1m²)**
  - **66 million pixels (100x150μm)**
  - **Precision: σ(rφ) ~ σ(z) ~ 15μm**
  - **Most challenging operating environments (LHC)**

- **Pixel Detector**

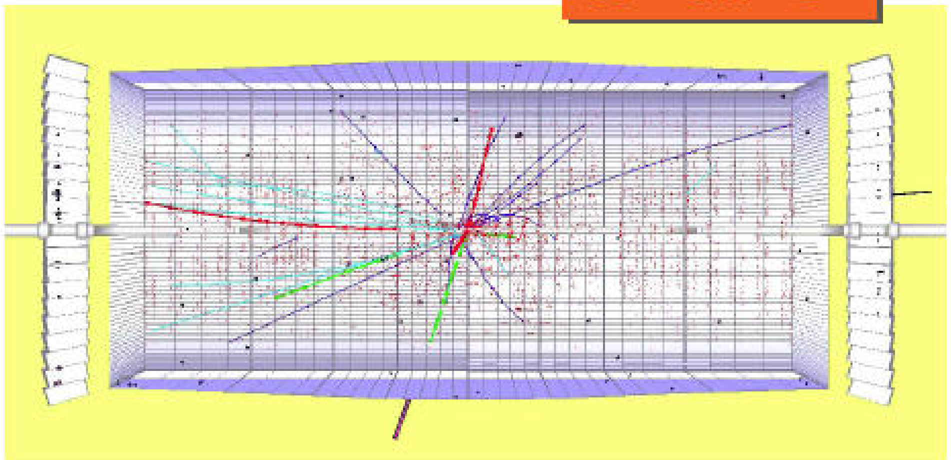


The challenge: Super LHC - visually

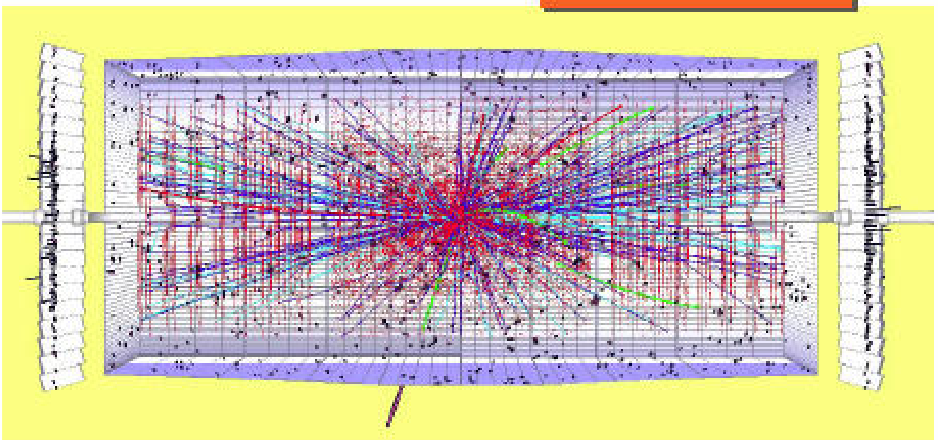
$10^{32}\ cm^{-2}\ s^{-1}$



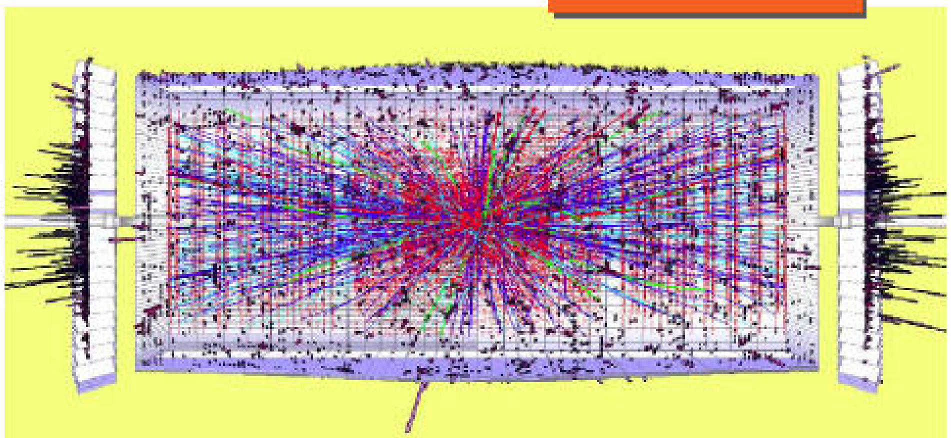
$10^{33}\ cm^{-2}\ s^{-1}$



$10^{34}\ cm^{-2}\ s^{-1}$



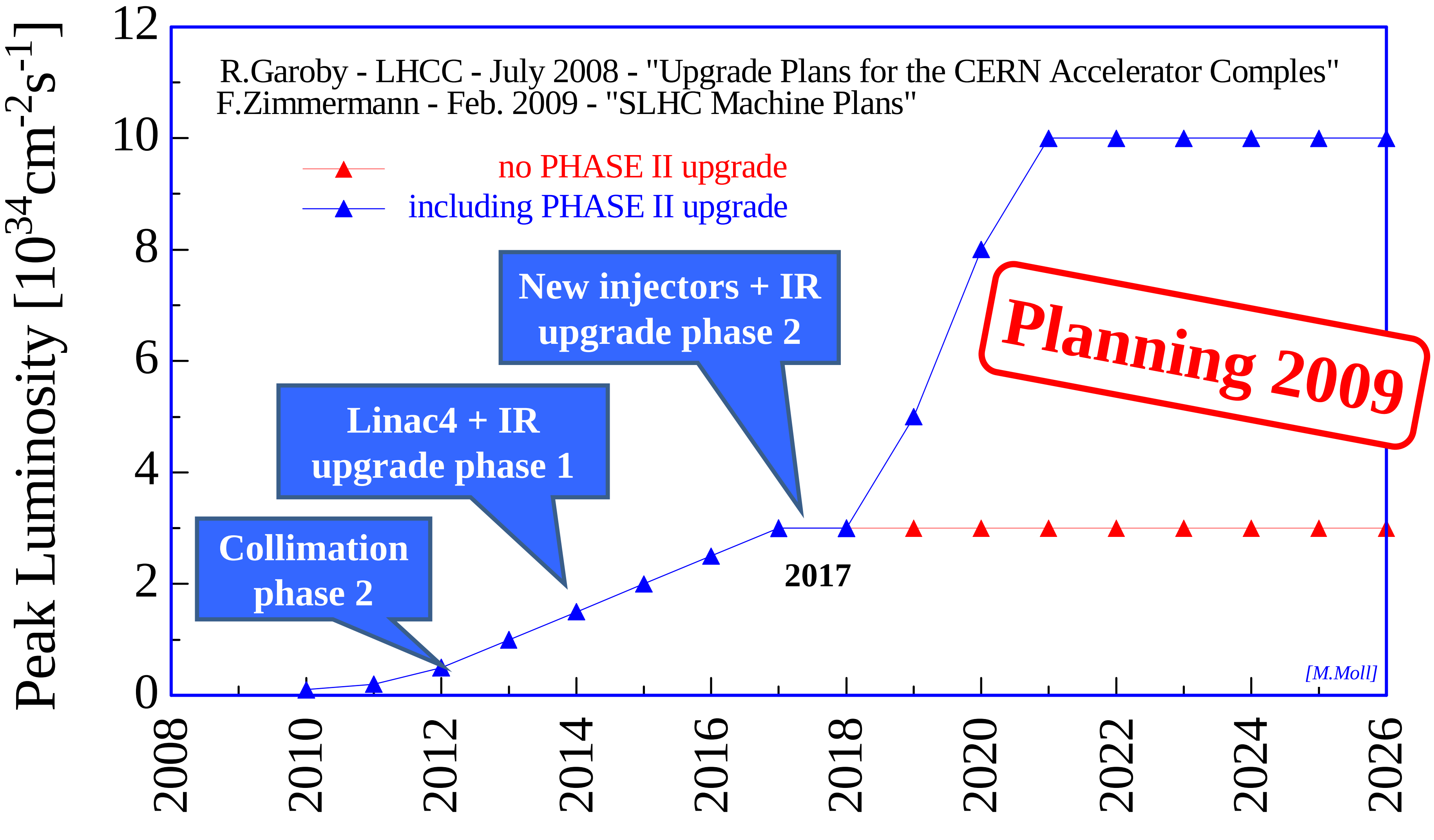
? $10^{35}\ cm^{-2}\ s^{-1}$



LHC nominal luminosity

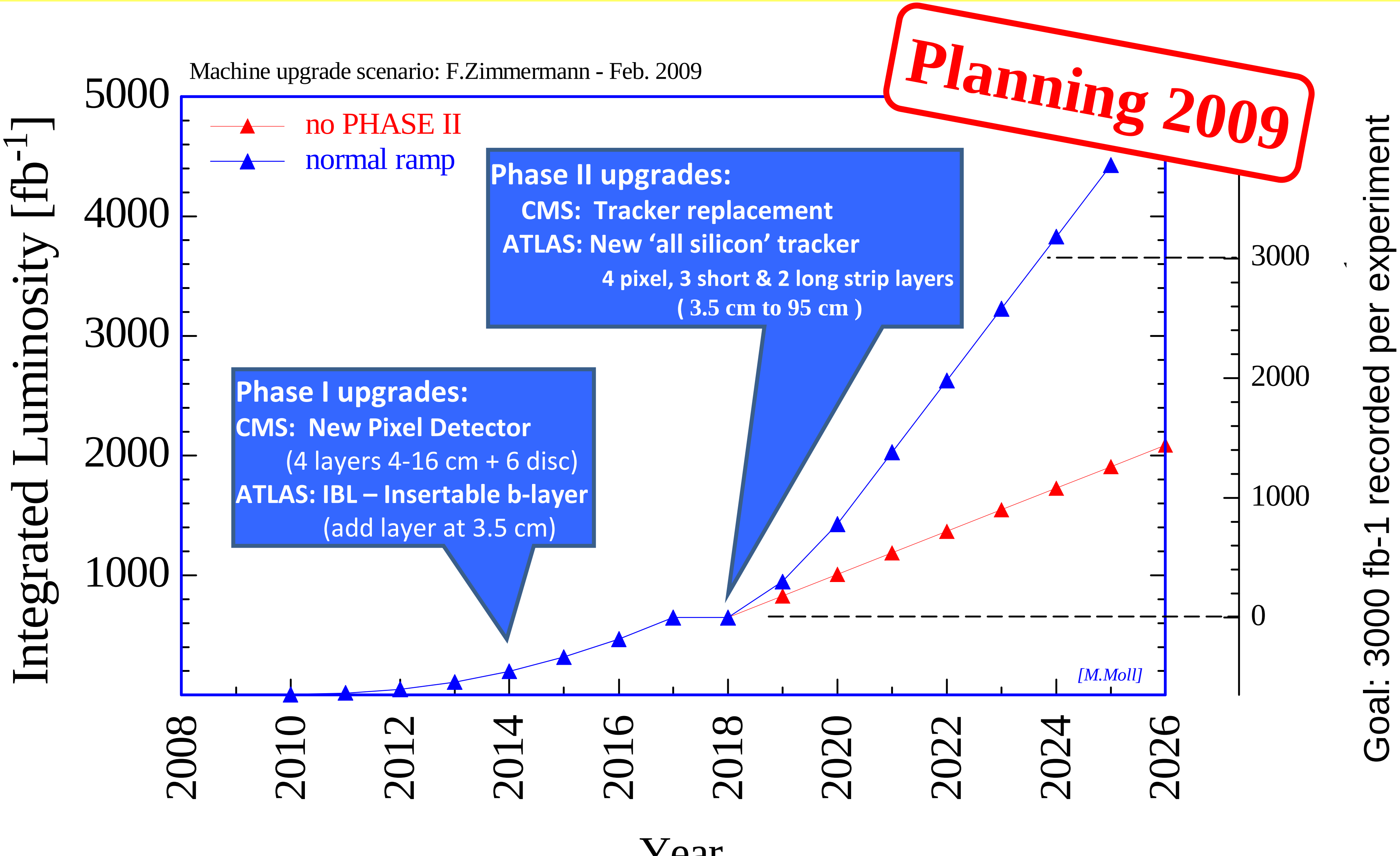
SLHC luminosity ~300-400 interactions/bx

Future Plans: Towards sLHC



- **Timeline shifting**

Future Plans: Towards sLHC



- **Timeline shifting: R&D programs need to be flexible!**

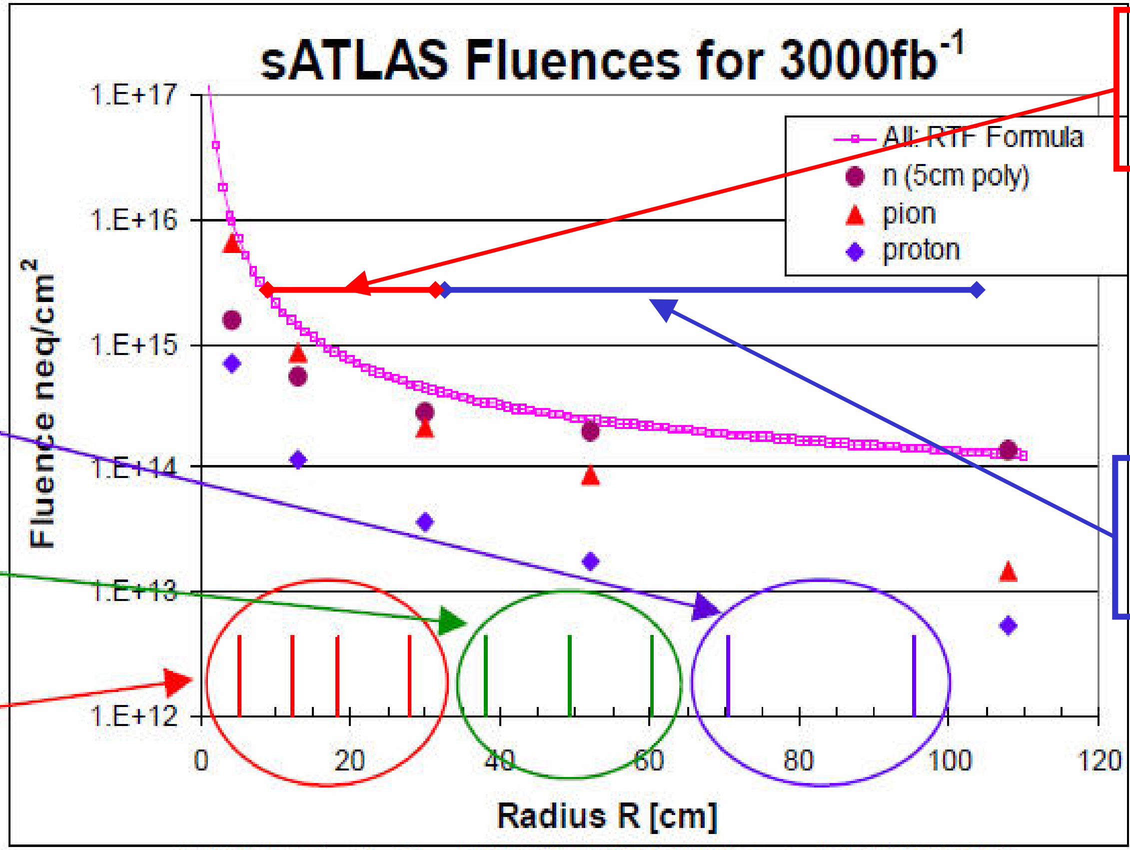
Radiation levels after 3000 fb^{-1}

Radial distribution of sensors determined by Occupancy

Long Strips
(up to $4x10^{14} cm^{-2}$)

Short Strips
(up to $10^{15} cm^{-2}$)

Pixels
(up to $10^{16} cm^{-2}$)



ATLAS Radiation Taskforce [ATL-GEN-2005-01] & H.Sadrozinski [IEEE NSS 2007]

Dominated by pion damage

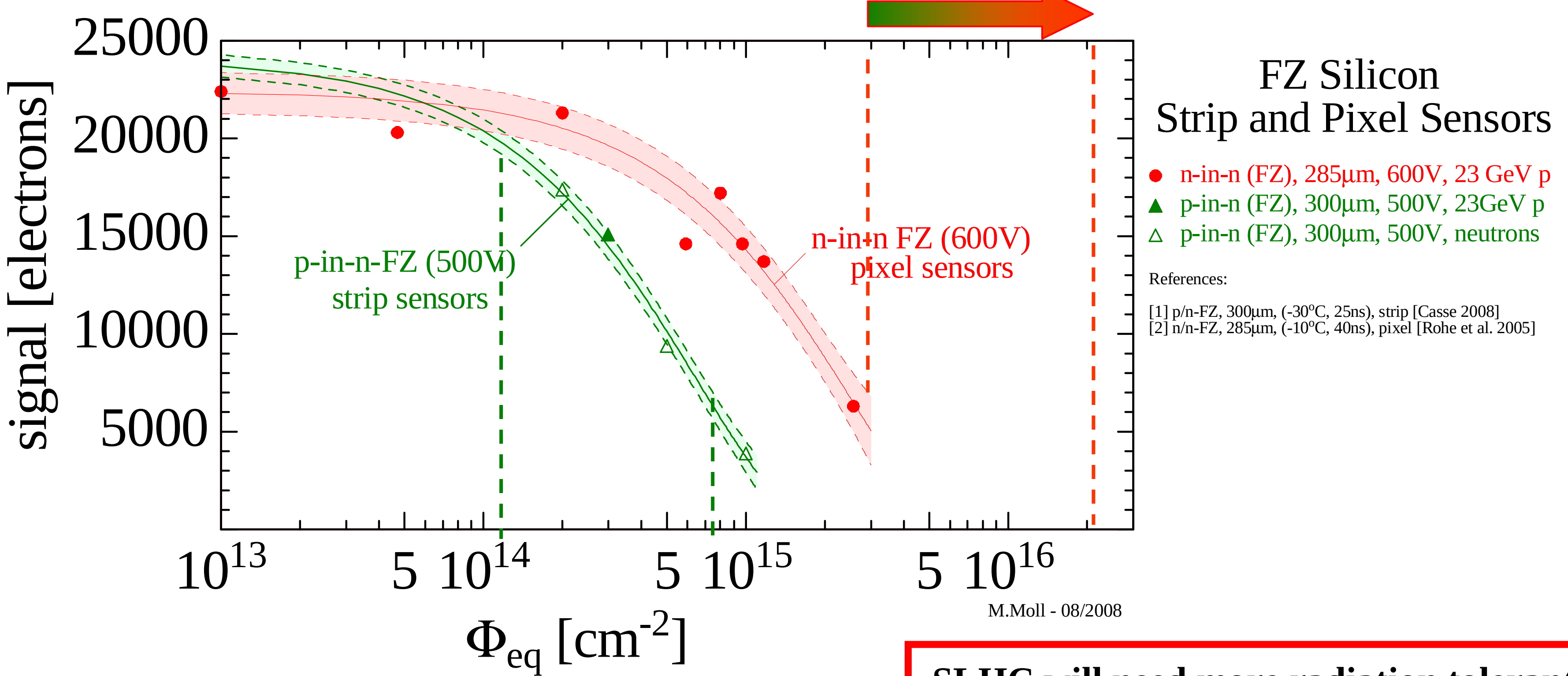
Dominated by neutron damage

- **Radiation hardness requirements (including safety factor of 2)**
  - **2×10^{16} n_{eq}/cm^2 for the innermost pixel layers**
  - **7×10^{14} n_{eq}/cm^2 for the innermost strip layers**

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC and SLHC

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges: Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!

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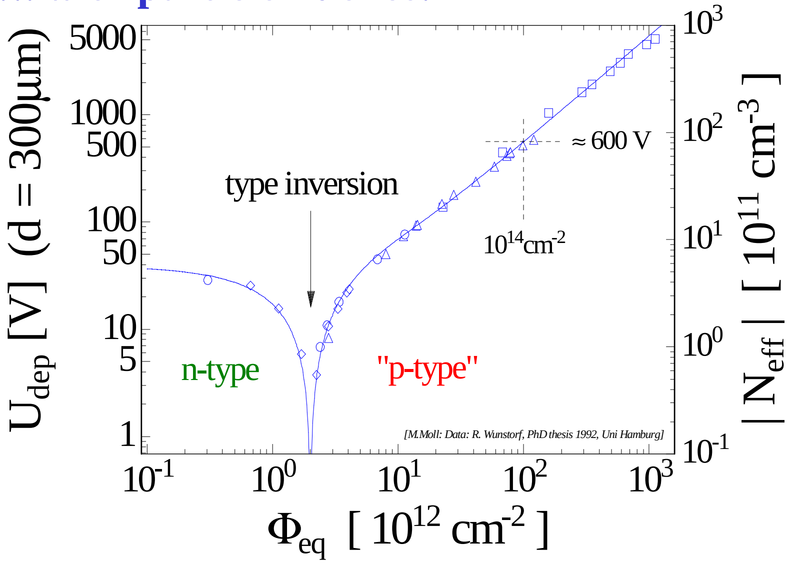
Macroscopic Effects – I. Depletion Voltage

- **Change of Depletion Voltage V_{dep} (N_{eff})**

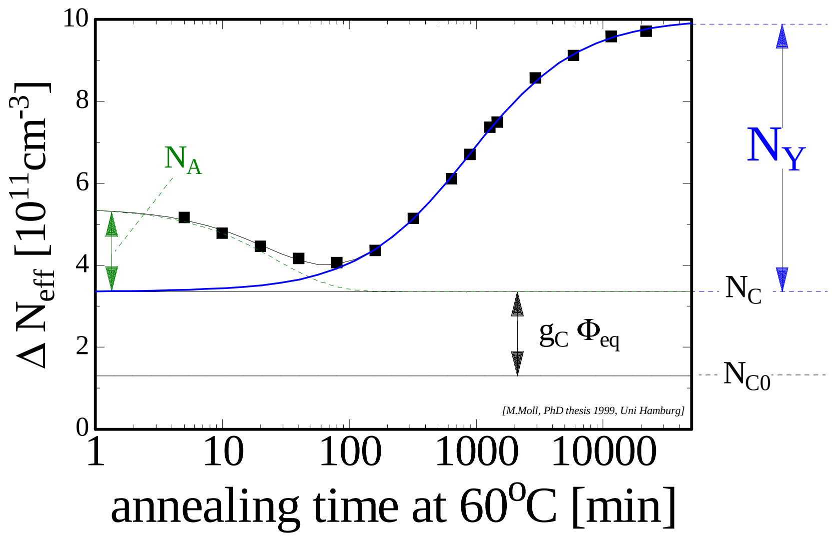
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

…. 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)

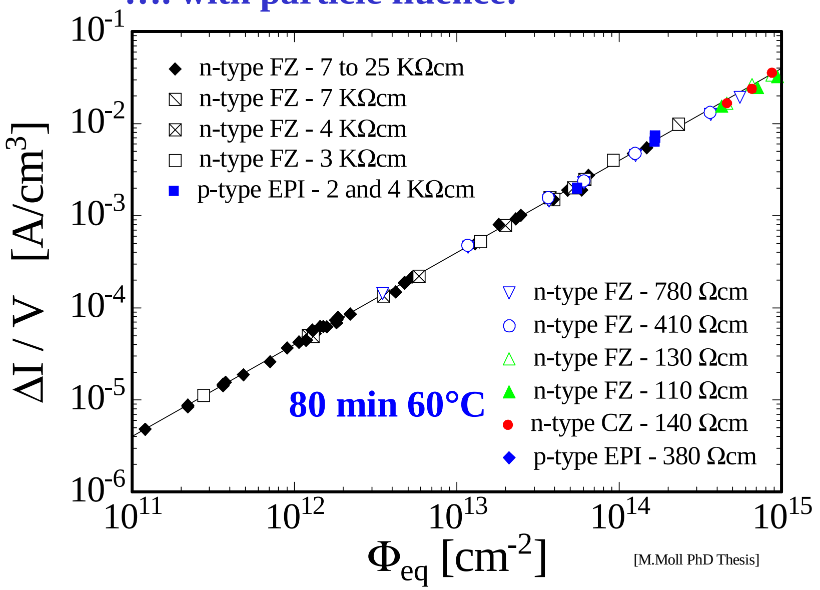
~ 21 hours (60°C)

- Consequence: **Detectors must be cooled even when the experiment is not running!**

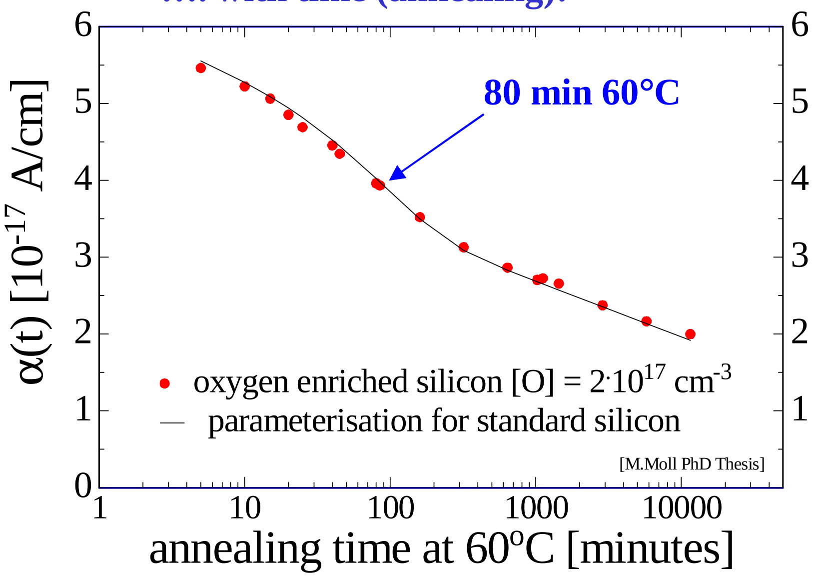
Radiation Damage – II. Leakage Current

- Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



…. with time (annealing):



- **Change in leakage current independent of material (=initial impurities in Si)**
- **universal damage parameter α (slope in figure)**
  ⇨ **can be used for fluence measurement**

- **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!

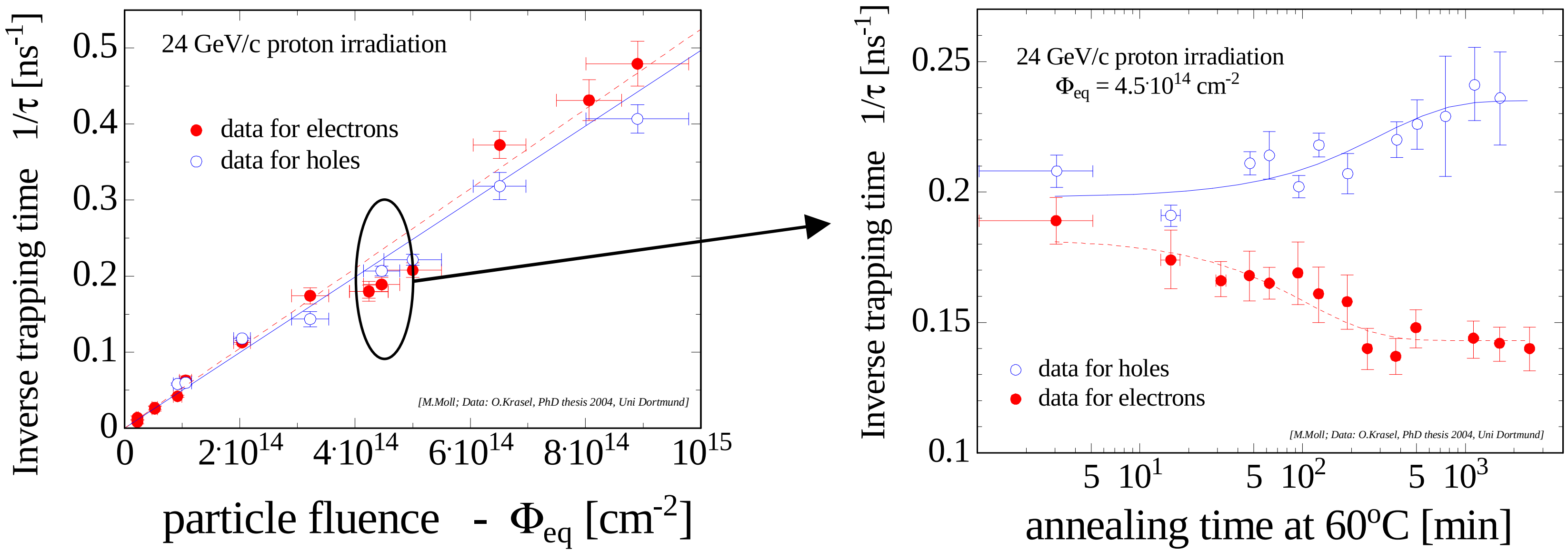
Example: I(-10°C) ~1/16 I(20°C)

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

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

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

Increase of inverse trapping time ($1/\tau$) with fluence ….. and change with time (annealing):



$1/\tau$ ~fluence, material independent

But: e and hole traps anneal differently

Summary: Radiation Damage in Silicon Sensors

- **Radiation damage to detector materials**

• Most relevant: **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
- displacement damage, built up of crystal defects –

Influenced by impurities in Si – Defect Engineering is possible!

I. Change of effective doping concentration (higher depletion voltage, under- depletion)

II. Increase of leakage current (increase of shot noise, thermal runaway)

III. Increase of charge carrier trapping (loss of charge)

Same for all tested Silicon materials!

- **Impact on detector performance and Charge Collection Efficiency**
(depending on detector type and geometry and readout electronics!)

Can be optimized!

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

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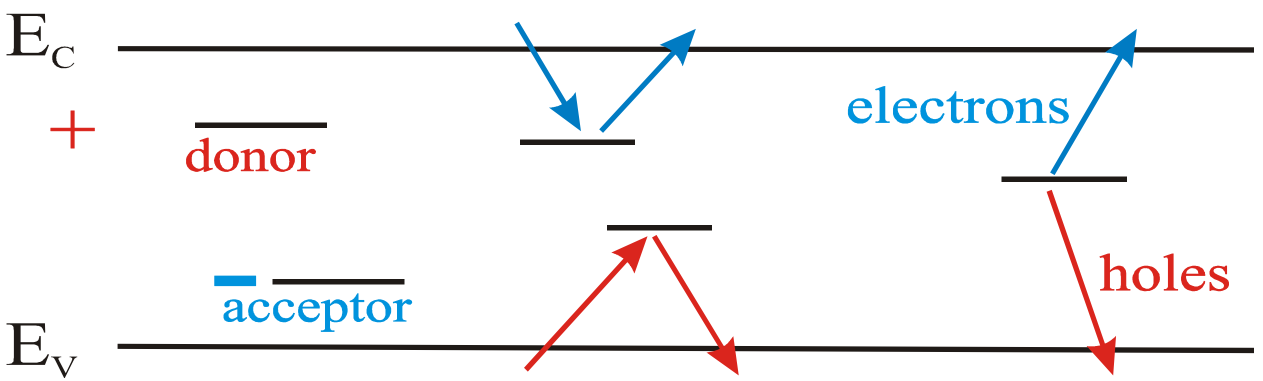
Impact of Defects on Detector Properties

Shockley-Read-Hall statistics



charged defects
$\Rightarrow$ **N_{eff} , V_{dep}**
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
$\Rightarrow$ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

generation
$\Rightarrow$ **leakage current**
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**

Defect Characterization - Methods

Methods used by RD50 Collaboration

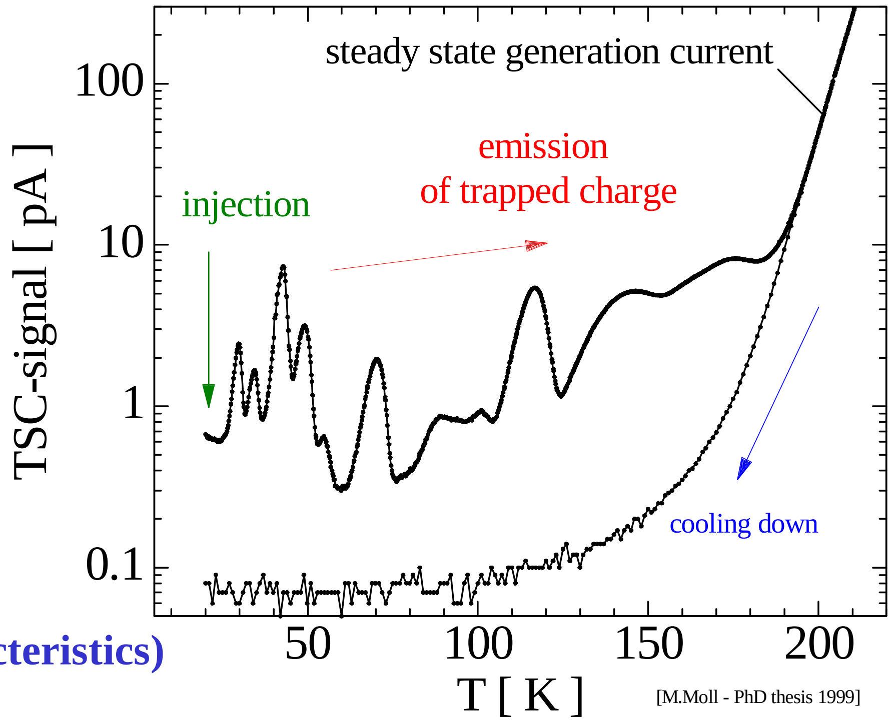
RD50-WODEAN project guided by G.Lindstroem (HH):

Most important methods (there are others):

- **C-DLTS** **(Capacitance Deep Level Transient Spectroscopy)**
- **TSC** **(Thermally Stimulated Currents)**
- **FTIR** **(Fourier Transform Infrared Spectroscopy)**
- **PL** **(Photo Luminescence)**
- **EPR** **(Electron Paramagnetic Resonance)**

- **Compare/ correlate with macroscopic methods:**
- **TCT** **(Transient Charge Technique)**
- **CV/IV** **(Capacitance- and Current-Voltage Characteristics)**

TSC (Thermally Stimulated Currents)



[M.Moll - PhD thesis 1999]

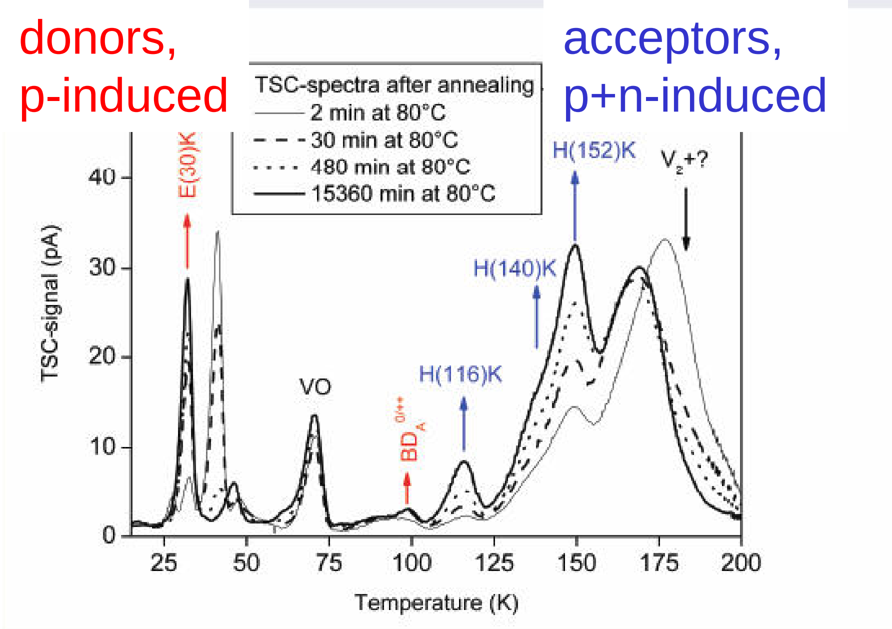
Example TSC:

- Cooling down of sample (e.g. 5K)
- Filling of traps (e,h, both) by light or forward bias
- Heating up →Emission of charge carriers at temperature corresponding to energy of trap in band gap
- Current measured →Need fluences > 10^{12} to get reasonable signals

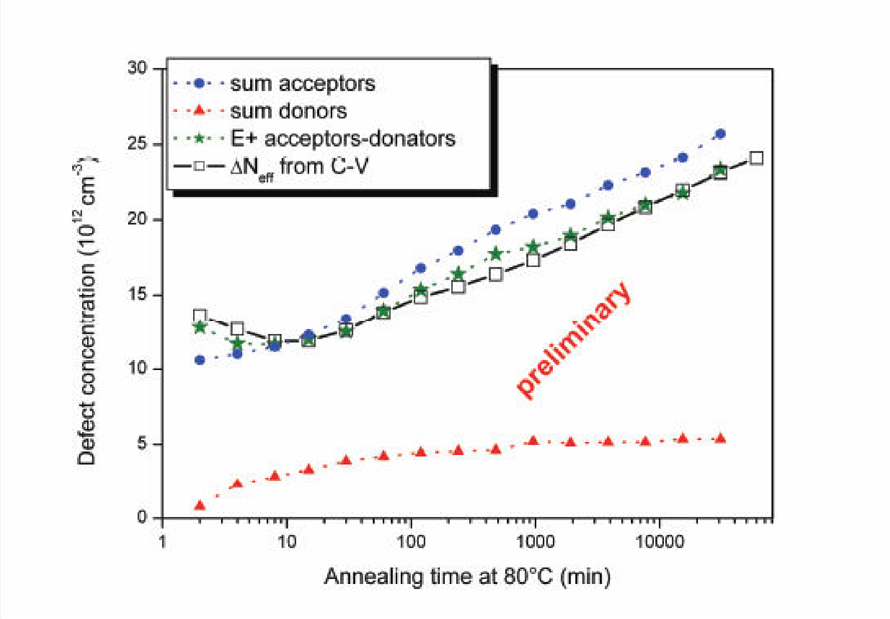
Correlation: Microscopic and Macroscopic data

- **TSC and CV measurements (Isothermal annealing after $2x10^{14}$ n/cm^2)**

TSC-results (EPI-ST)



comparison to ΔN_{eff}

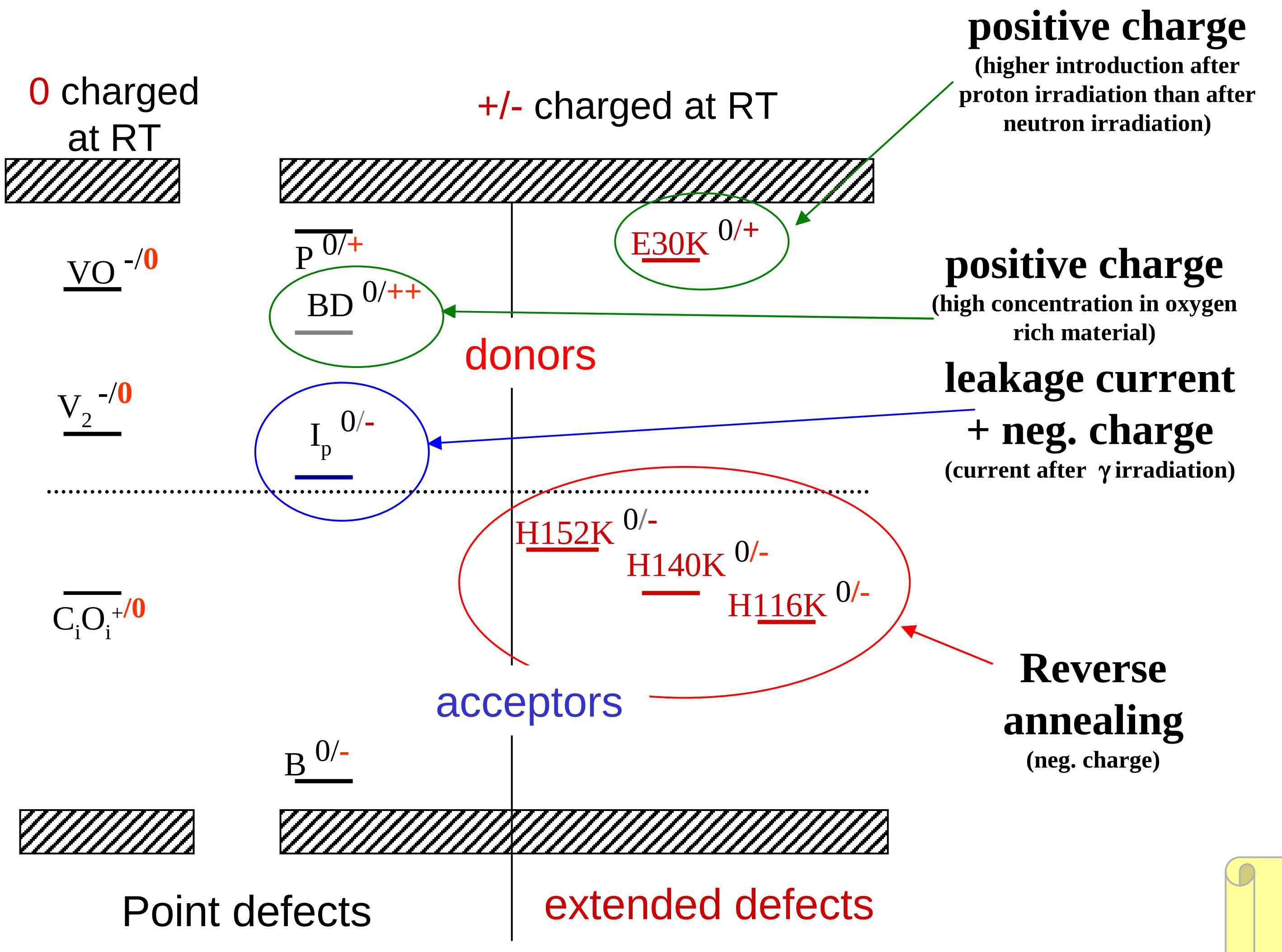


E: + space charge, electron traps H: - space charge, hole traps

- short term annealing well described
- microscopic results predict macroscopic findings!

[Alexandra Junkes, Hamburg University, RD50 Workshop June 2009]

Summary – defects with strong impact on the device properties at operating temperature



fairly complex picture

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

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Silicon Materials under Investigation by RD50

standard for particle detectors

used for LHC Pixel detectors

“new” silicon material

Material	Thickness [μm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	**50,100,150, 300**	**FZ**	**1–30×10 ^{3}**	**< 5×10^{16}**
Diffusion oxygenated FZ (n- and p-type)	**300**	**DOFZ**	**1–7×10 ^{3}**	**~ 1–2×10^{17}**
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	**100, 300**	**MCz**	**~ 1×10 ^{3}**	**~ 5×10^{17}**
Czochralski Si, Sumitomo, Japan (n-type)	**300**	**Cz**	**~ 1×10 ^{3}**	**~ 8-9×10^{17}**
Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)	**25, 50, 75, 100, 150**	**EPI**	**50 – 100**	**< 1×10^{17}**
Diffusion oxyg. Epitaxial layers on CZ	**75**	**EPI–DO**	**50 – 100**	**~ 7×10^{17}**

Important parameter for defect formation/annealing: Oxygen concentration.
Reason: Formation of Defect-Oxygen clusters like VO

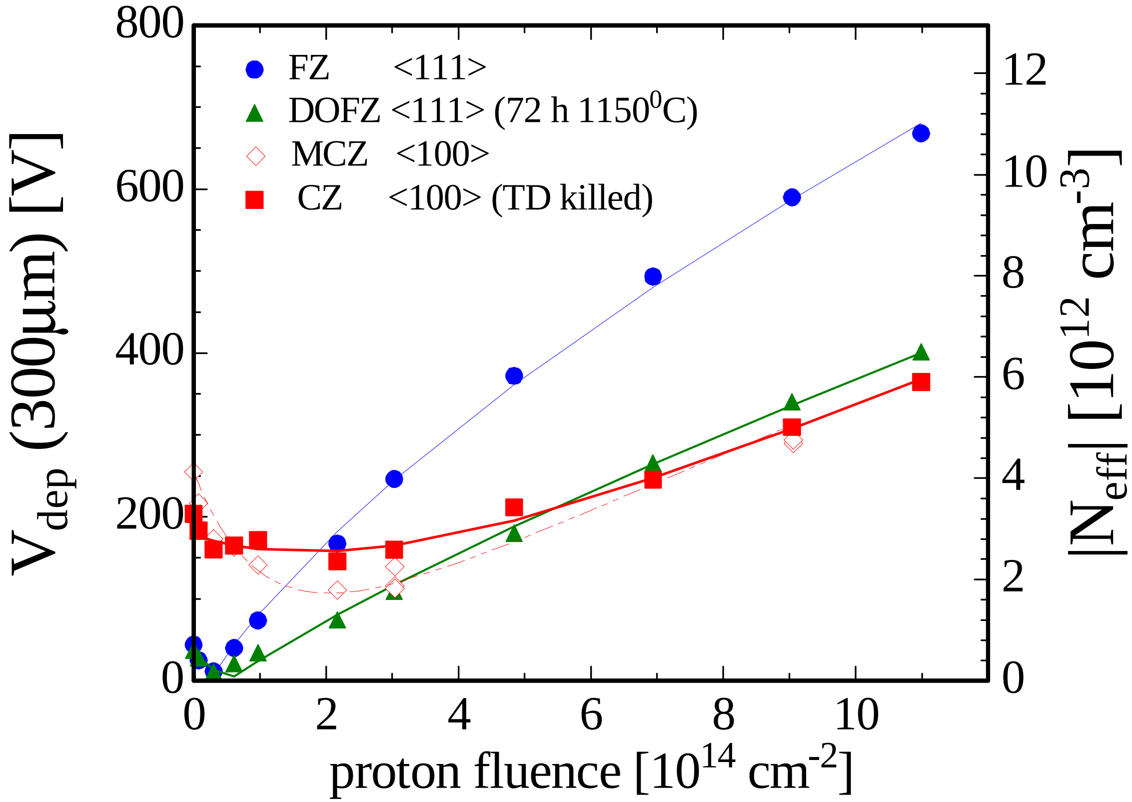
- **DOFZ and EPI:_ inhomogeneous O-profile**
- **CZ/MCZ and EPI-DO: homogeneous O-profile**

FZ, DOFZ, Cz and MCz Silicon

- **Strong differences in V_{dep}**
  - **Standard FZ silicon**
  - **Oxygenated FZ (DOFZ)**
  - **CZ silicon and MCZ silicon**

- **O-concentration!**
- **FZ/DOFZ: Not enough O→space charge sign inversion for n-type Si (SCSI)**
- **CZ/MCZ: High O→ no SCSI, V_{dep} rises less steep with fluence**

24 GeV/c proton irradiation
(n-type silicon)

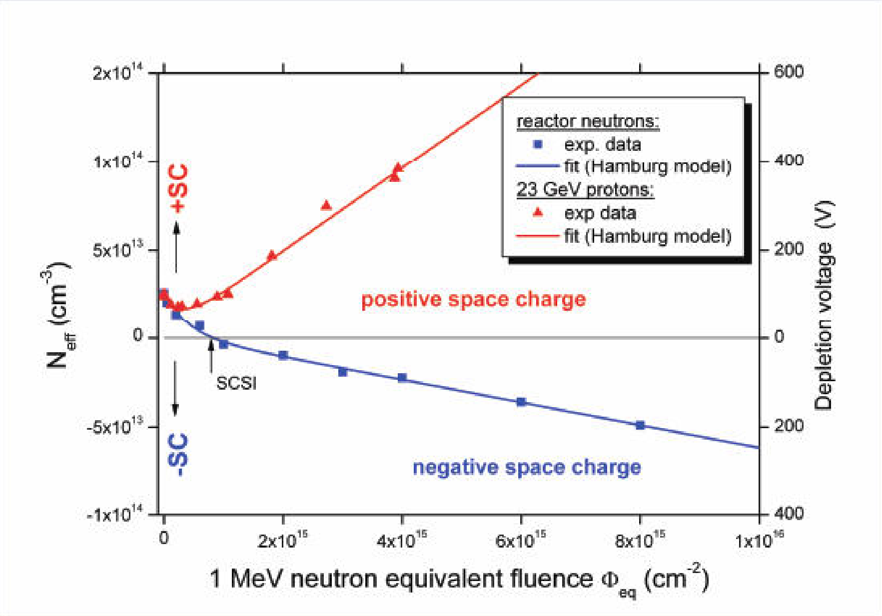


- **Common to all materials** *(after hadron irradiation, not after γ irradiation)*:
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Correlation: Microscopic and Macroscopic data

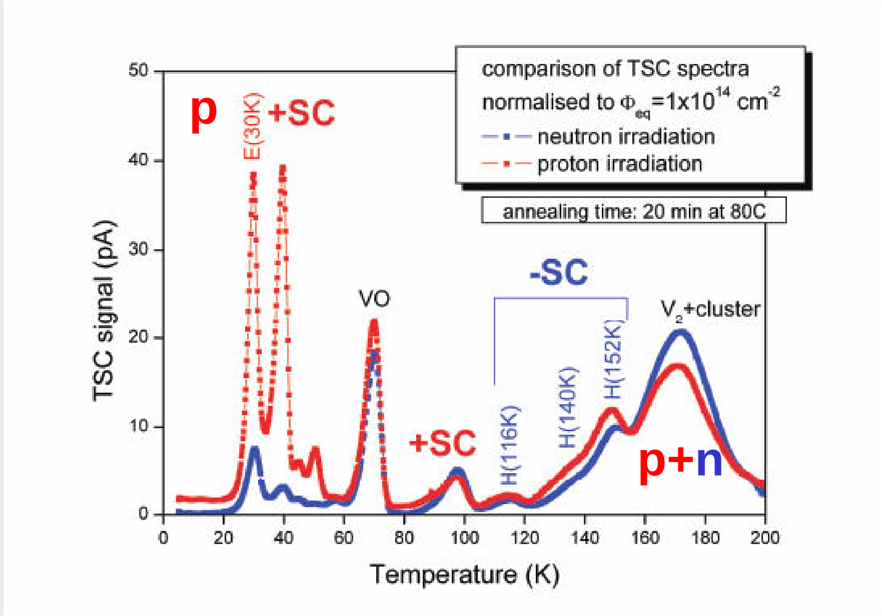
- **Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons**

delopment of N_{eff} for EPI-DO after neutron and proton irradiation



I. Pintilie, et al., to be published.

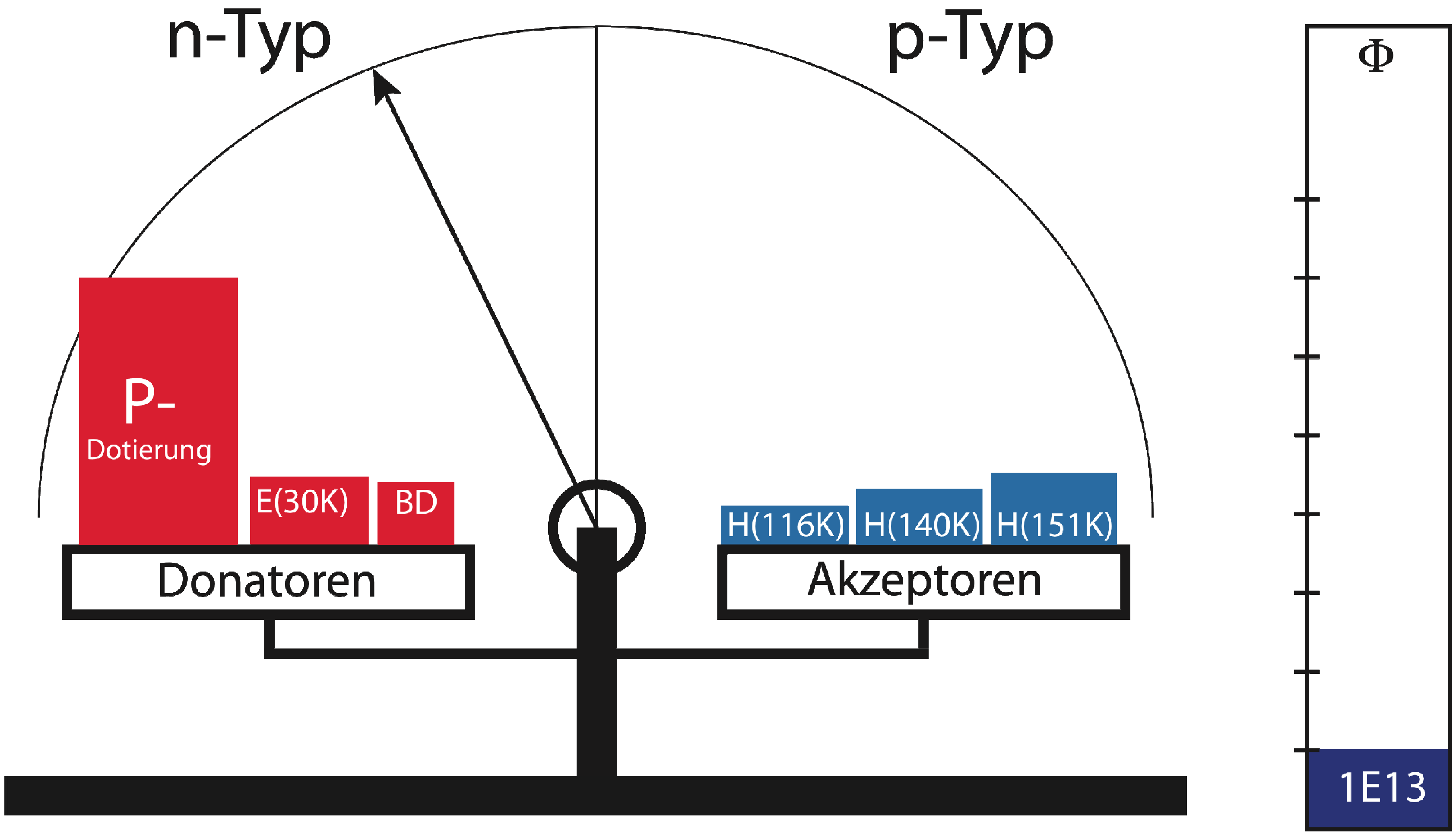
TSC results after neutron and proton irradiation



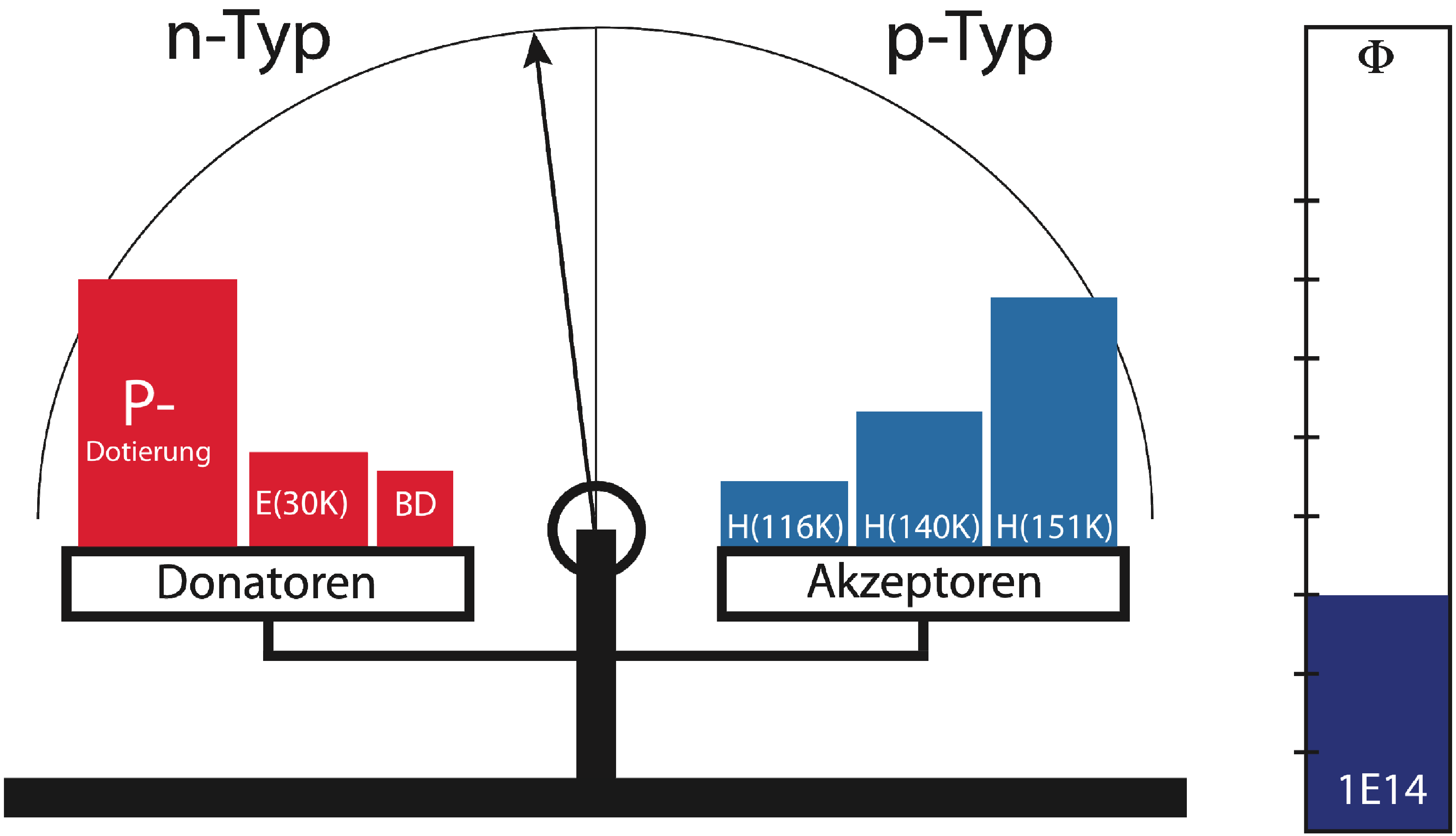
- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low Φ_{eq}

[A.Junkes, Hamburg University, RD50 Workshop June 2009]

Neutron Irradiation



Neutron Irradiation



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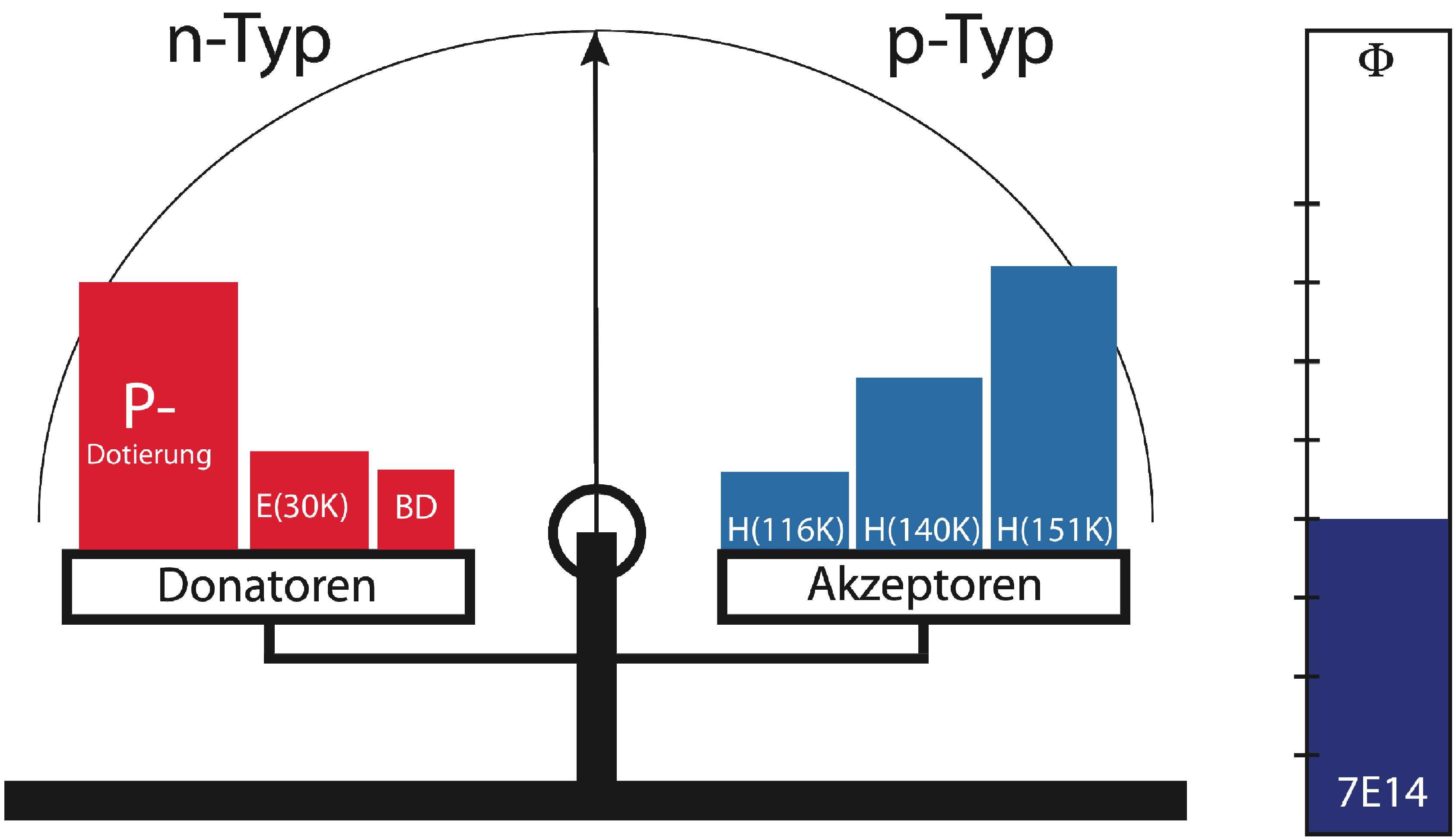

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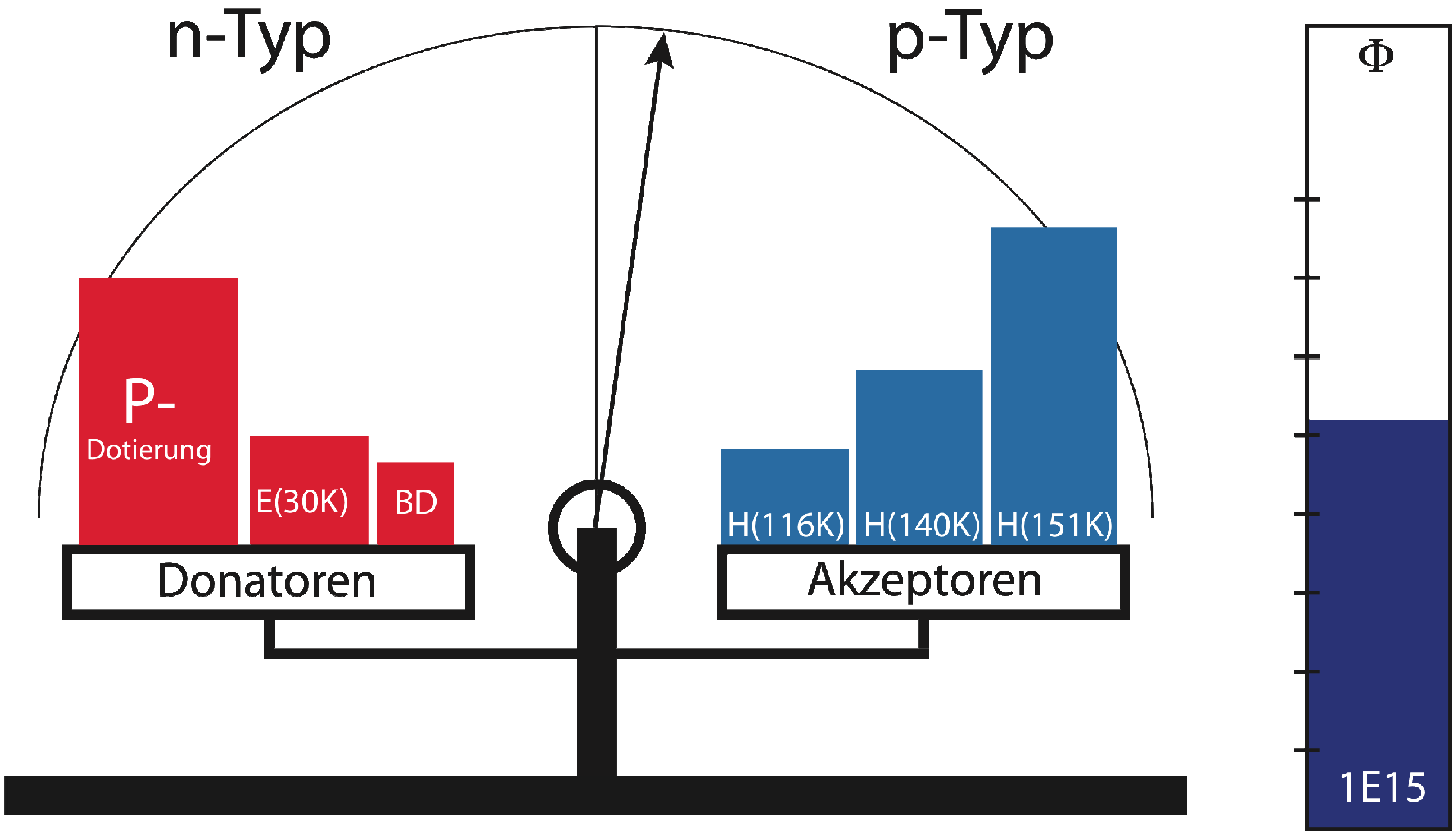

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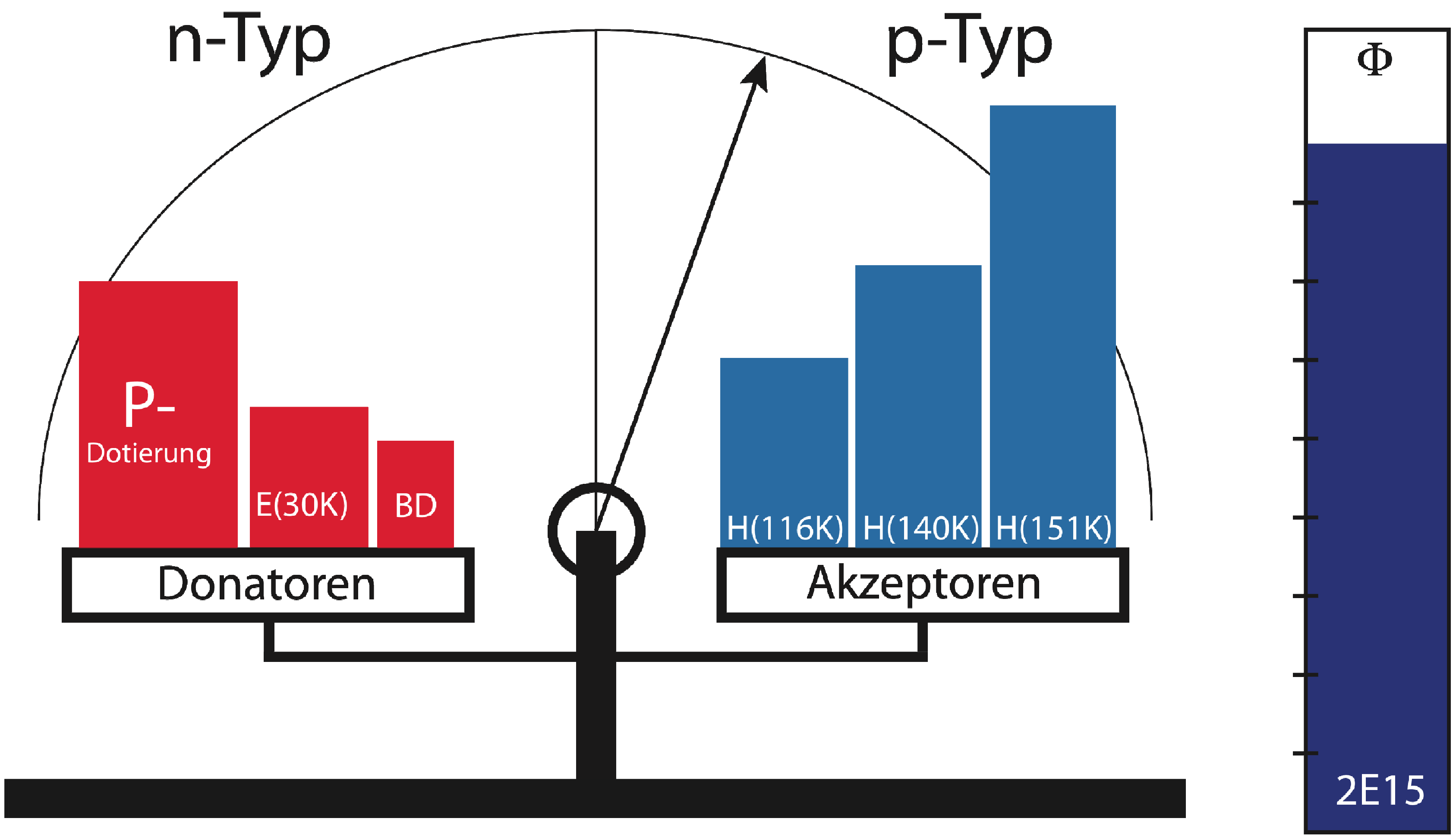
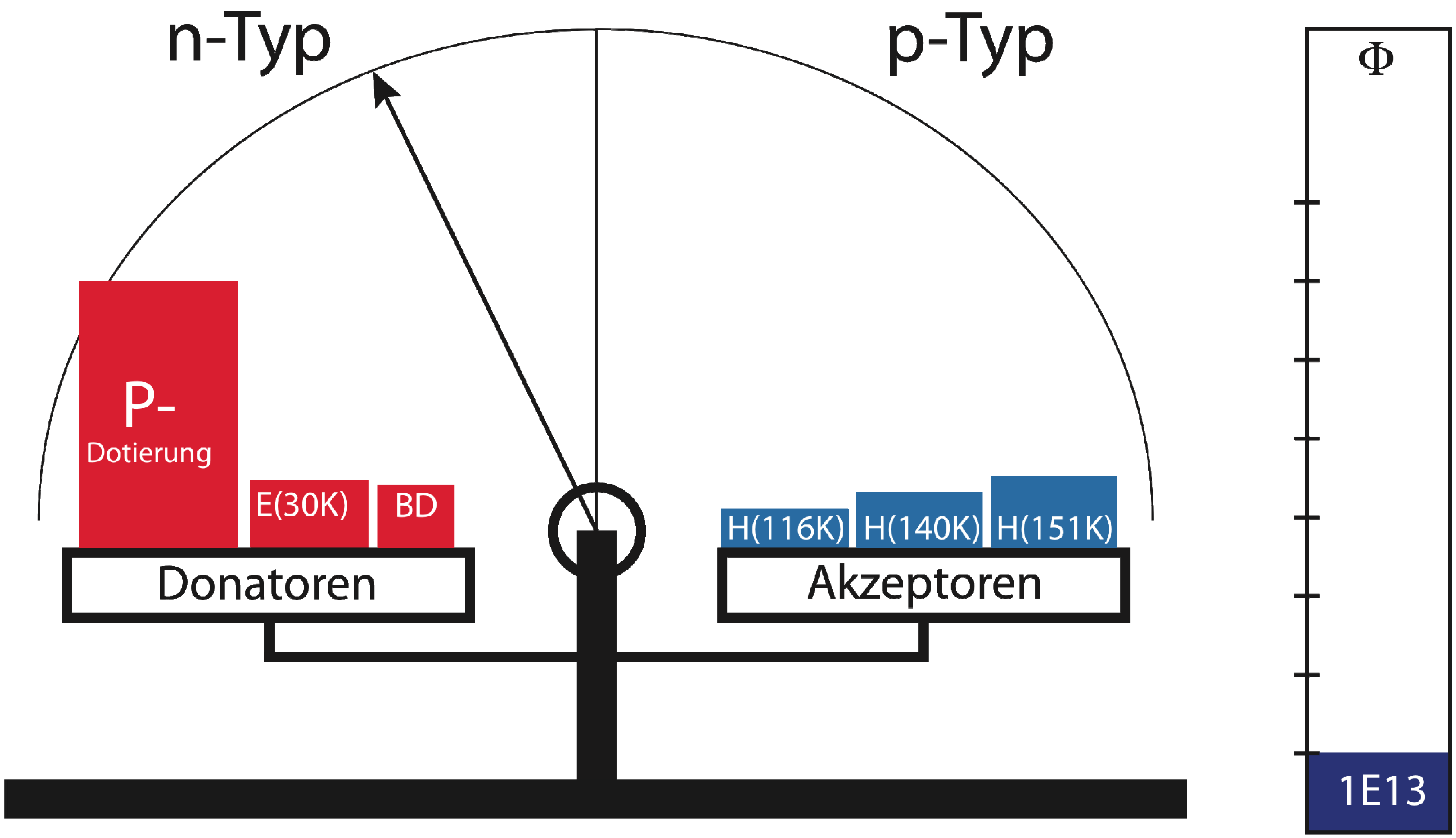
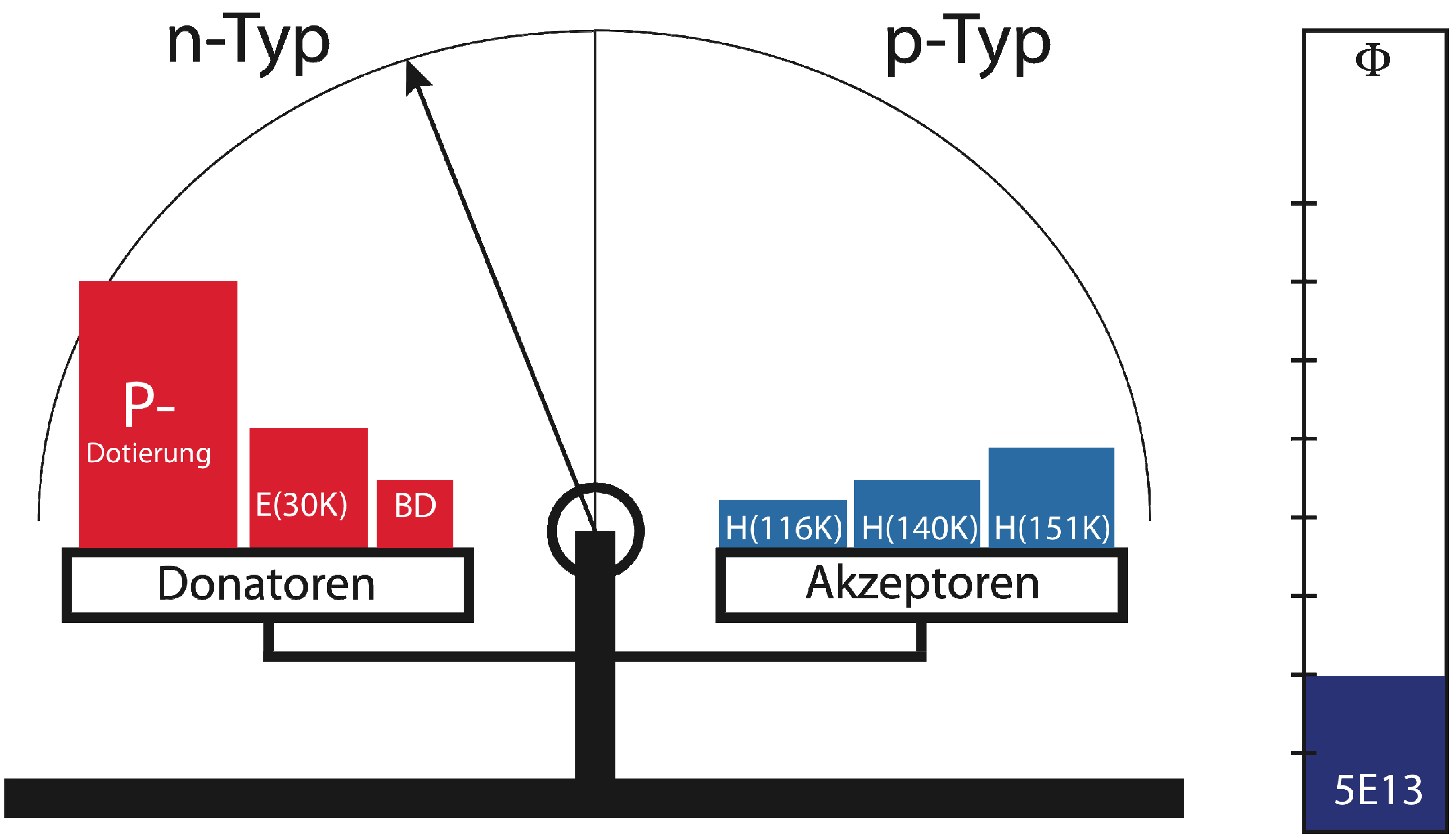
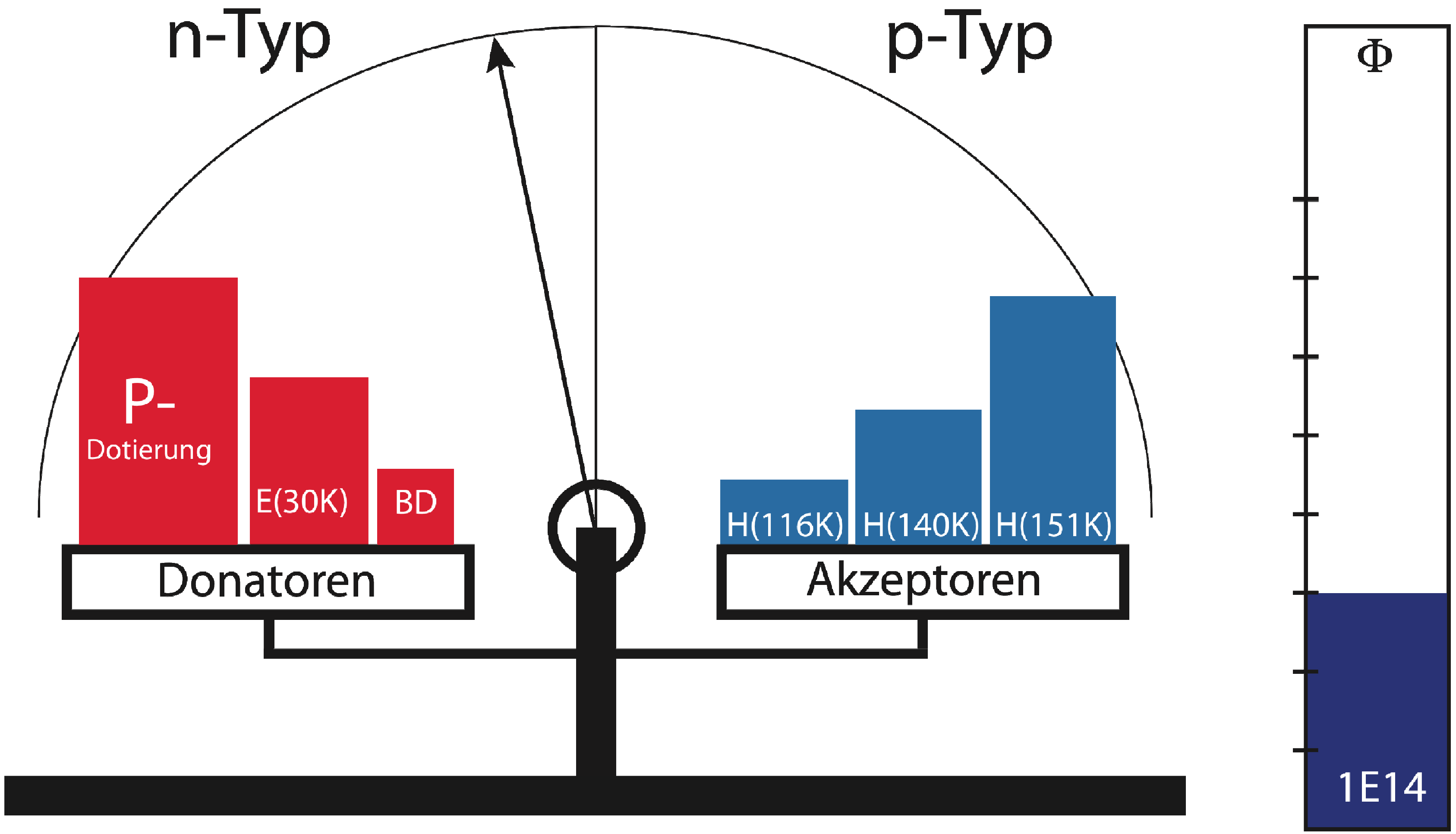



n-Typ
p-Typ
P-
Dotierung
E(30K)
BD
Donatoren
H(116K)
H(140K)
H(151K)
Akzeptoren
Φ
1E13

Proton Irradiation



Proton Irradiation



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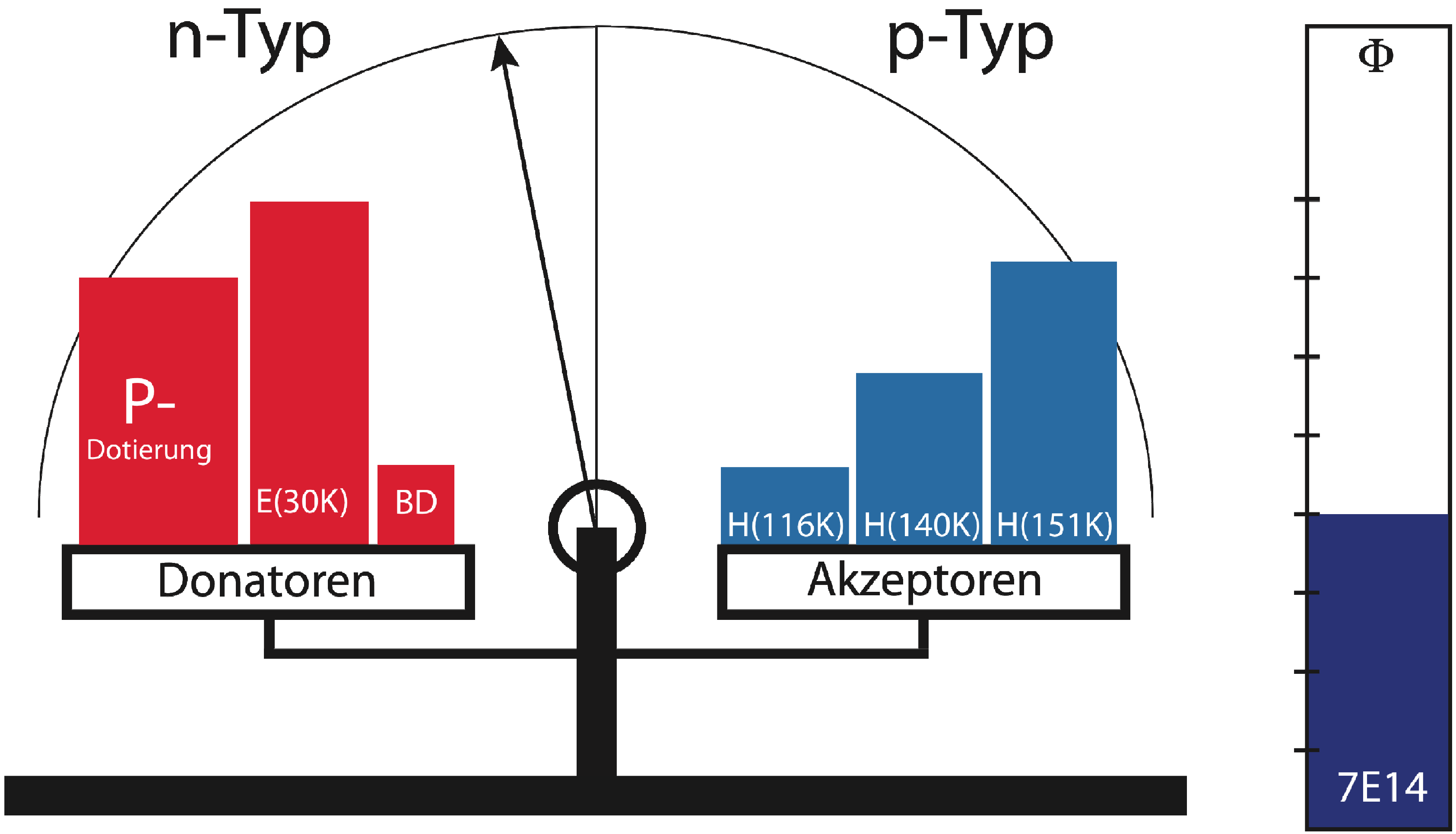

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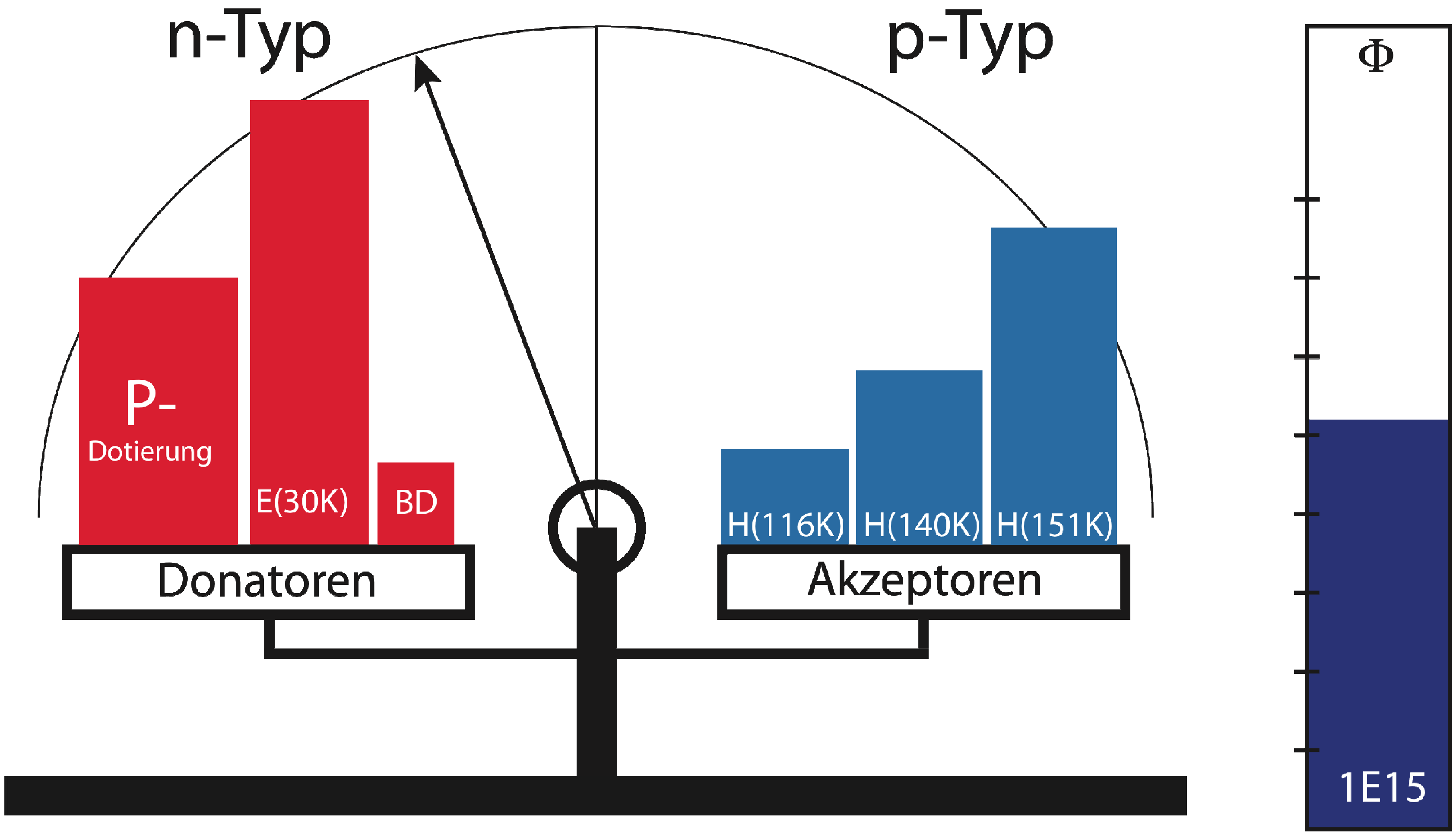

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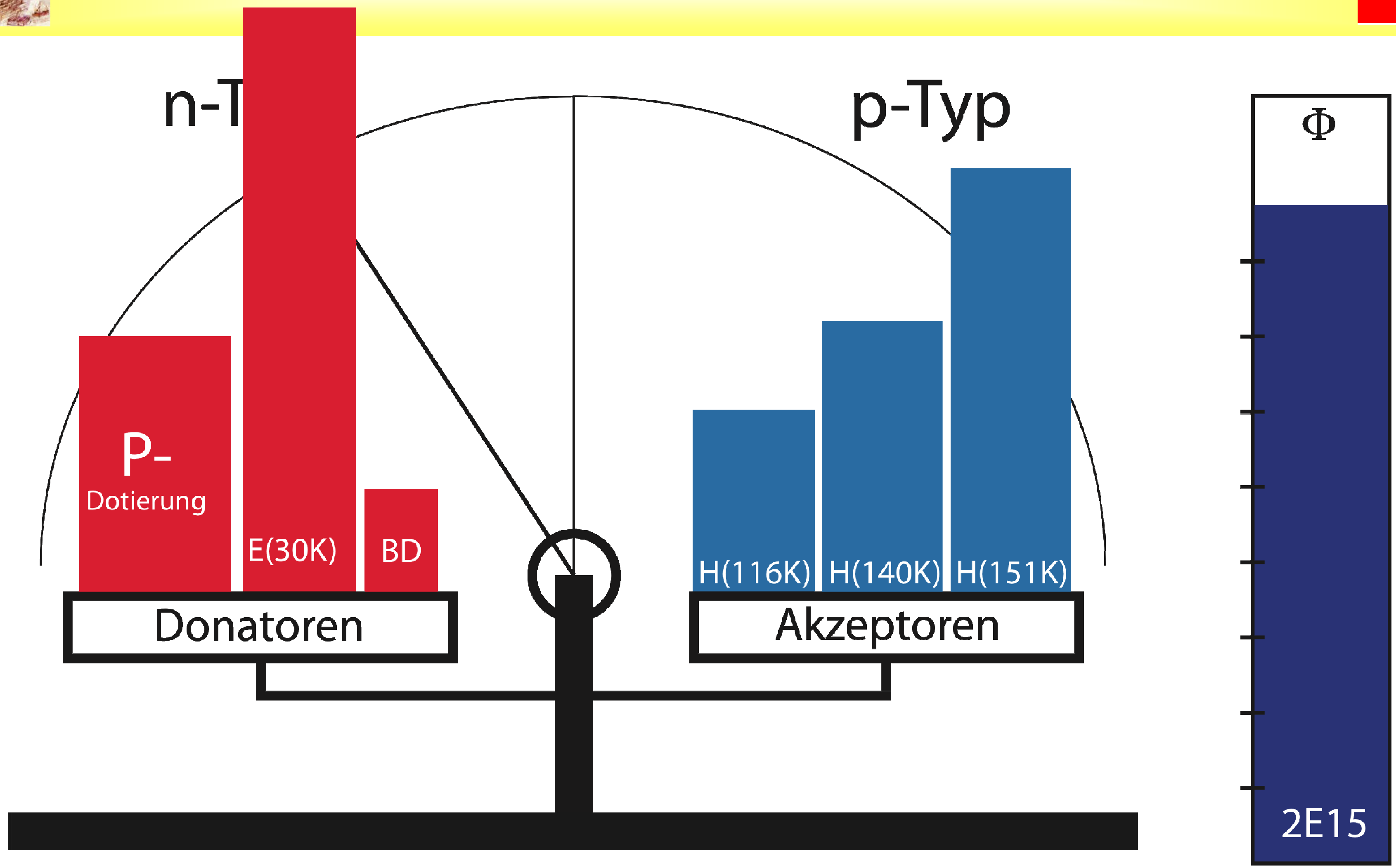
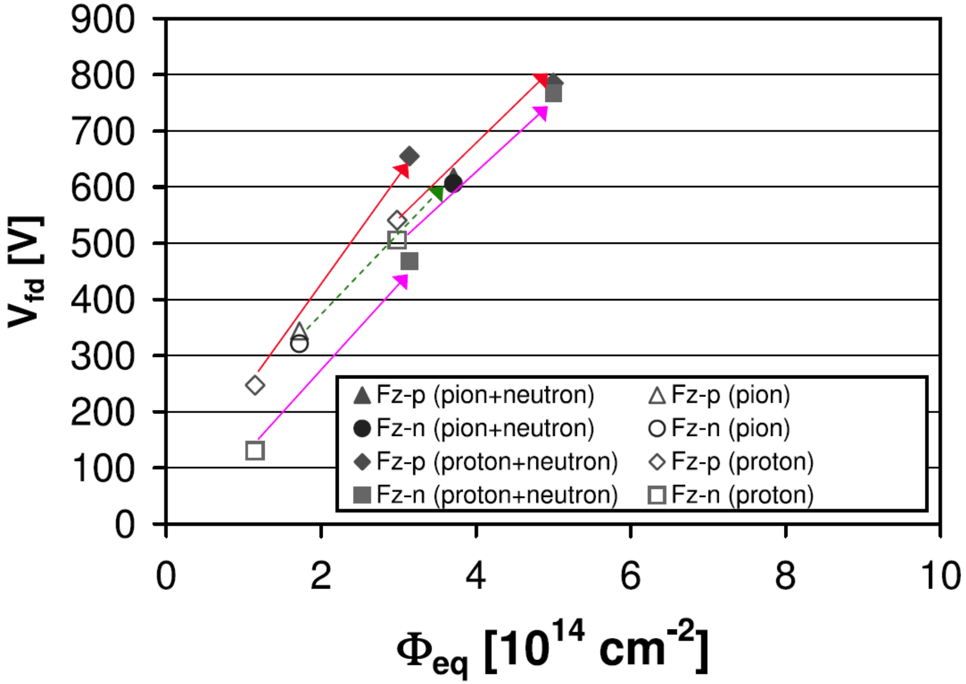


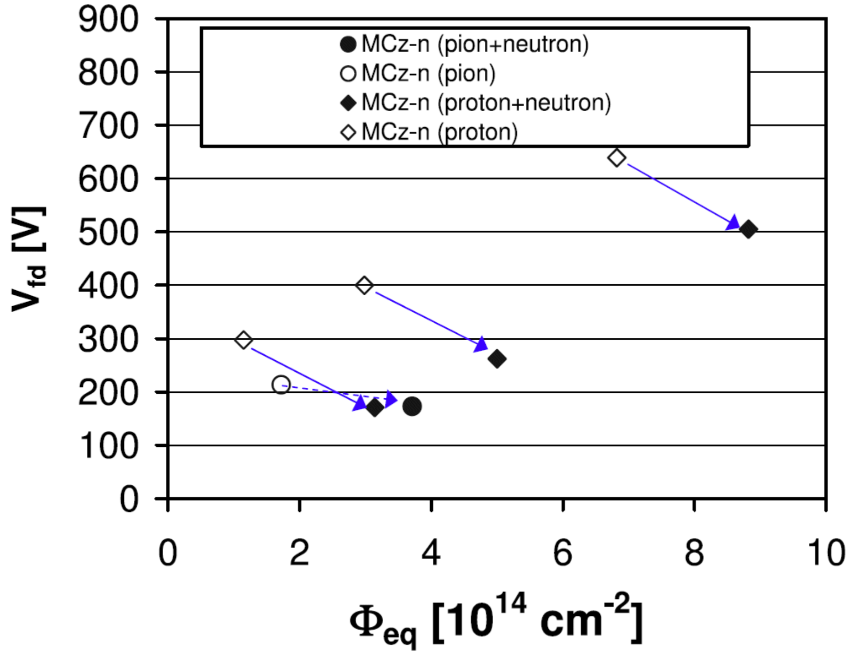
Mixed irradiations – Change of N_{eff}

- **Exposure of FZ & MCZ silicon sensors to 'mixed' irradiations**
  - **First step: Irradiation with protons or pions**
  - **Second step: Irradiation with neutrons**

FZ: Accumulation of damage



MCZ: Compensation of damage



[G.Kramberger et al., "Performance of silicon pad detectors after mixed irradiations with neutrons and fast charged hadrons", NIMA 609 (2009) 142-148]

Reason: E(30)K oxygen-related!

Ongoing Work / Open Questions

- Performance of MCZ silicon in mixed fields -

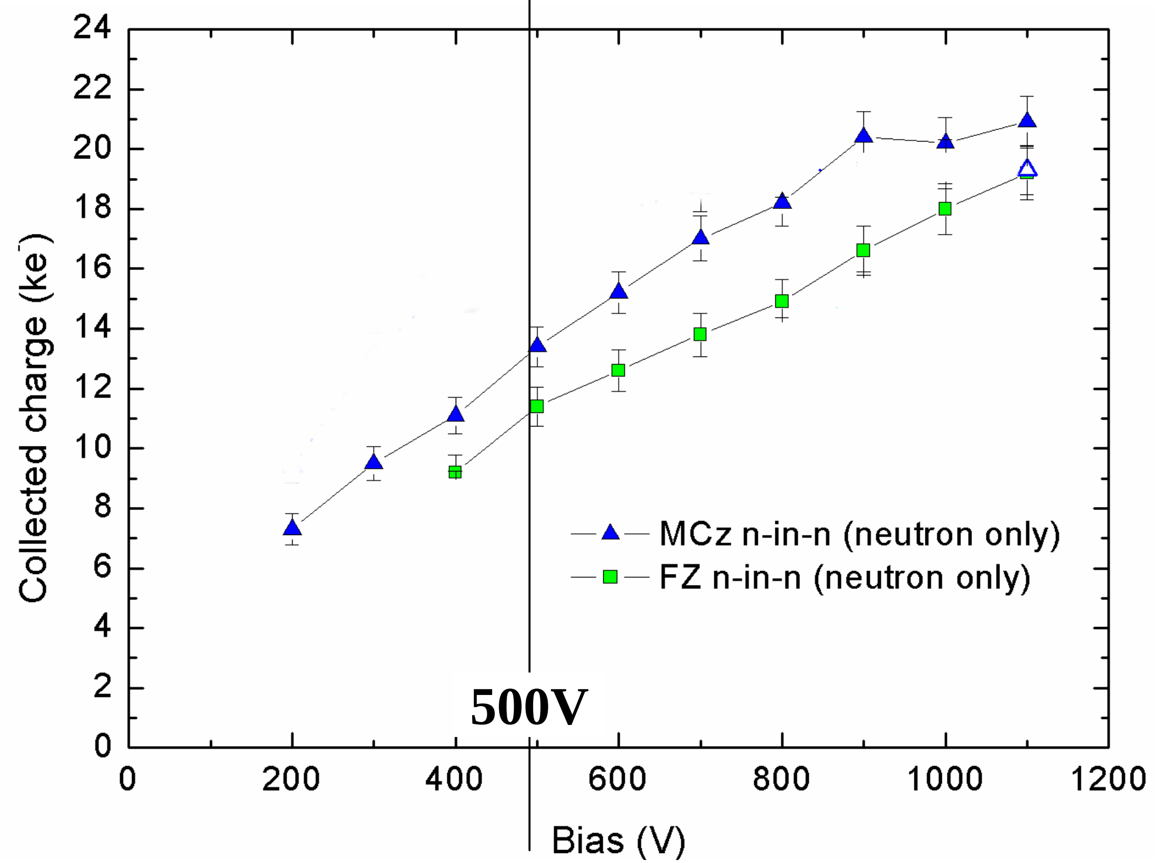
- **Is MCZ silicon (n- and p-type) an option for SLHC detectors?**
  - **Protons induce predominantly defects that are positively charged**
  - **Neutrons induce predominantly defects that are negatively charged**
  - **Mixed Fields: Compensation?**

- **Mixed irradiations:**
  - **(a) Φ_{eq}= 5x10^{14} neutrons**
  - **(b) Φ_{eq}= 5x10^{14} protons**

- **FZ (n-in-n)**

- **MCZ (n-in-n)**

[T.Affolder et al. RD50 Workshop, Nov.2008]



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  - **Mixed Fields: Compensation?**

[T.Affolder et al. RD50 Workshop, Nov.2008]

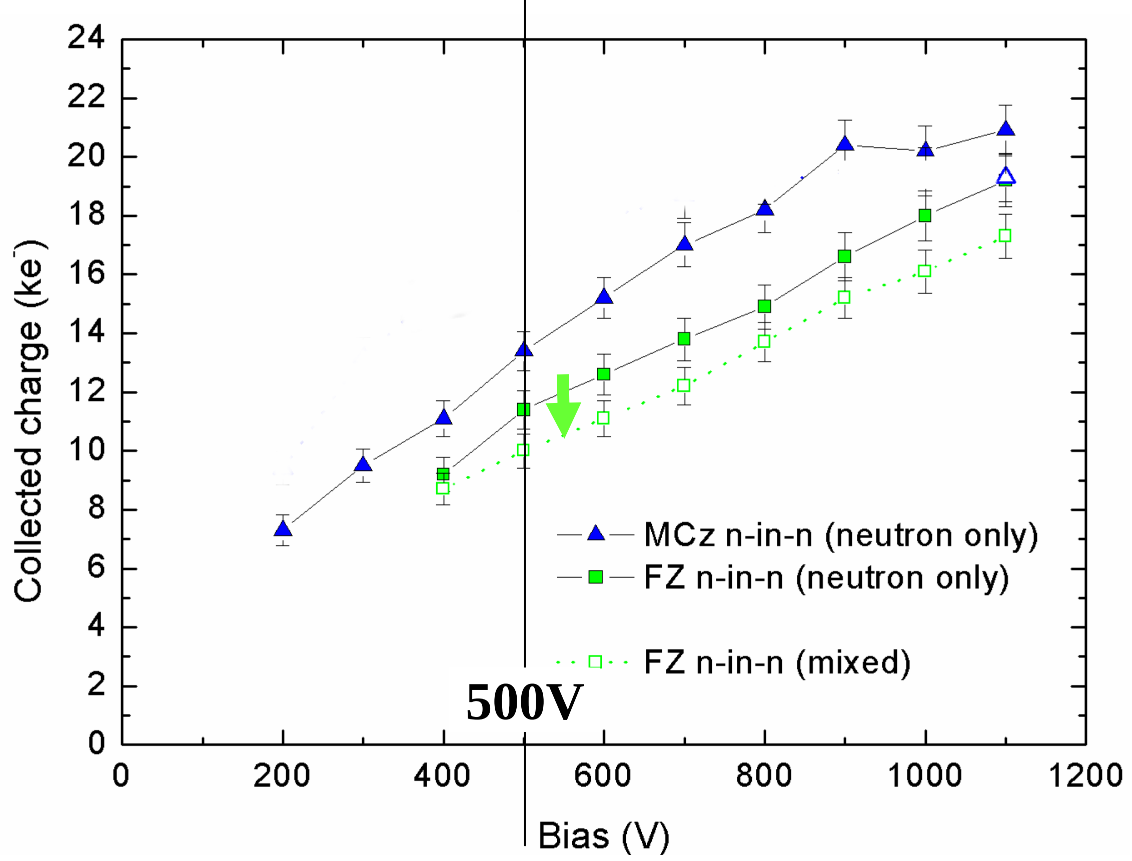
- **Mixed irradiations:**
  - (a) Φ_{eq}= $5x10^{14}$ neutrons
  - (b) Φ_{eq}= $5x10^{14}$ protons

- **FZ (n-in-n)**

  Mixed Irradiation:

  Damage additive!

- **MCZ (n-in-n)**



Ongoing Work / Open Questions
- Performance of MCZ silicon in mixed fields -

- **Is MCZ silicon (n- and p-type) an option for SLHC detectors?**
  - **Protons induce predominantly defects that are positively charged**
  - **Neutrons induce predominantly defects that are negatively charged**
  - **Mixed Fields: Compensation?**

- **Mixed irradiations:**
  - (a) Φ_{eq}= 5×10^{14} neutrons
  - (b) Φ_{eq}= 5×10^{14} protons

- **FZ (n-in-n)**

Mixed Irradiation:

Damage additive!

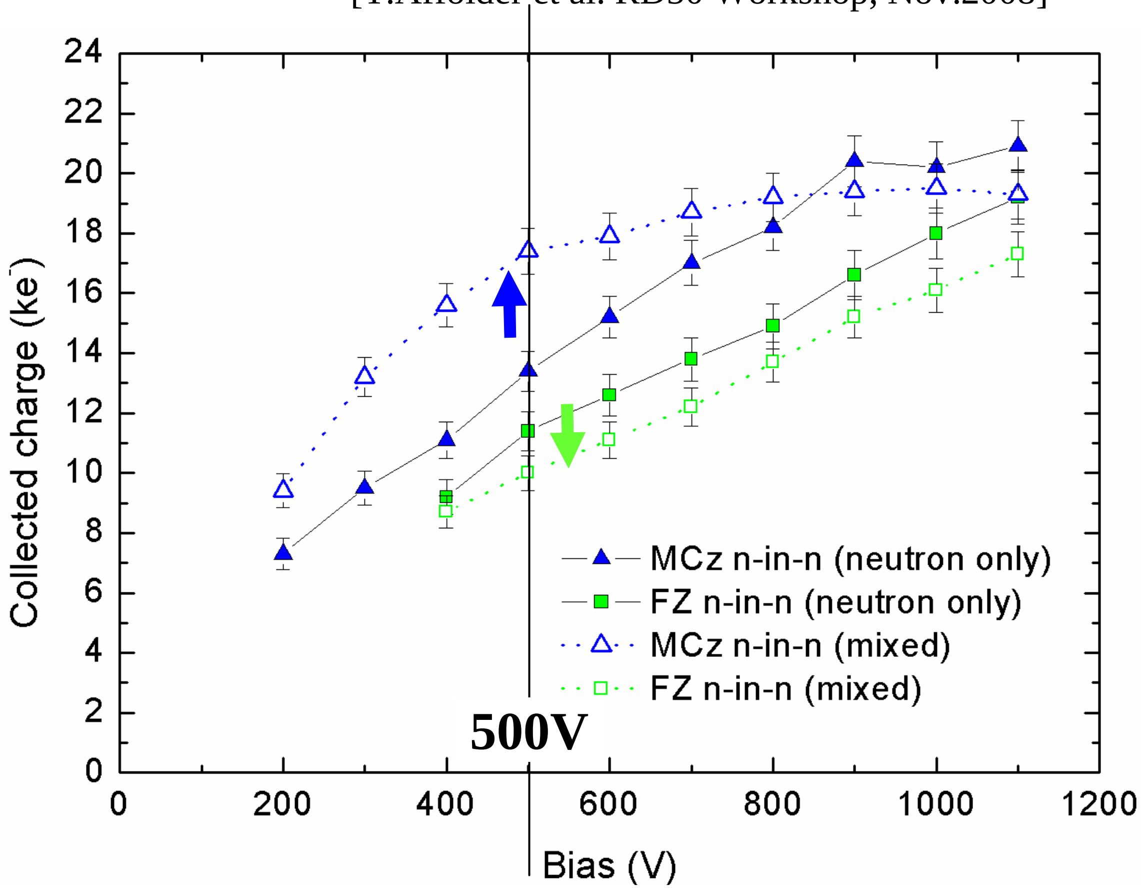
- **MCZ (n-in-n)**

Mixed Irradiation:

Proton damage "compensates" part of neutron damage (N_{eff})

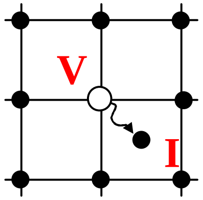
More charge collected at 500V after additional irradiation!!!

[T.Affolder et al. RD50 Workshop, Nov.2008]



Why is proton and neutron damage different?

particle → Si_S → E_K>25 eV



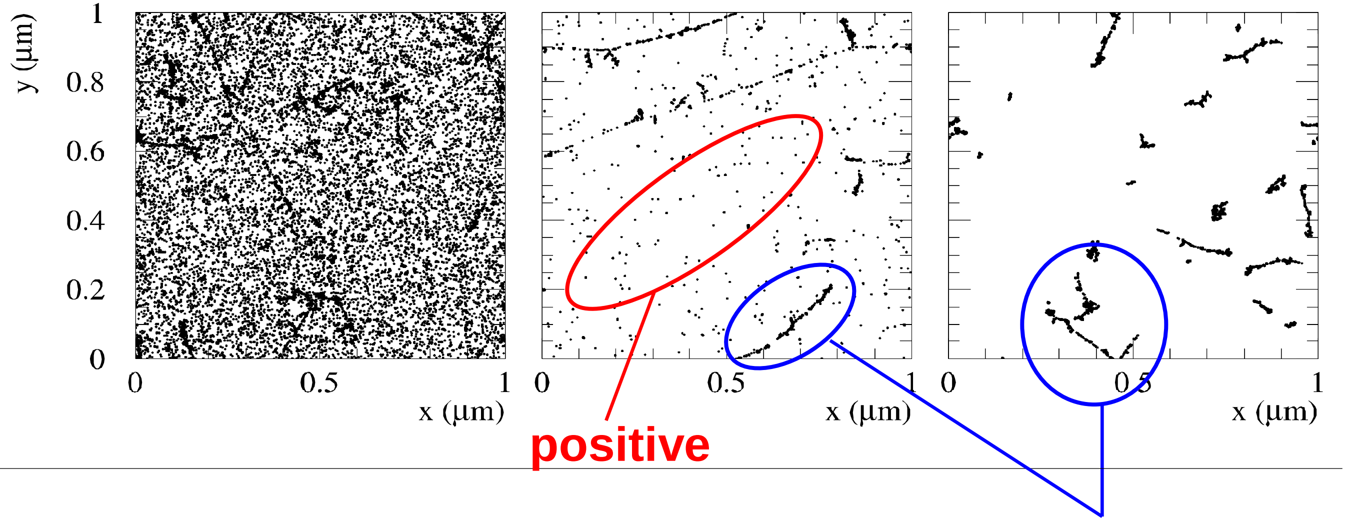
Vacancy + **I**nterstitial → *point defects (V-O, C-O, ..)*

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

Simulation:

Initial distribution of vacancies in (1µm)^3 after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]



- **A 'simplified' explanation for the 'compensation effects'**
  - Defect clusters produce predominantly **negative space charge**
  - Point defects produce predominantly **positive space charge** (in 'oxygen rich' silicon)

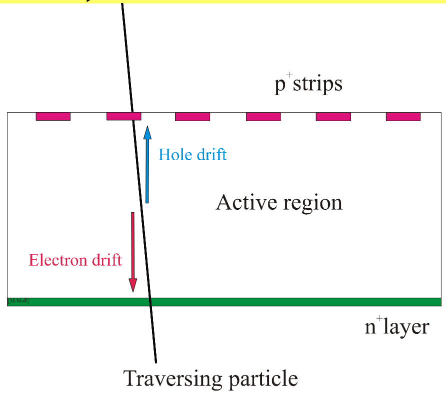
For the experts: Note the NIEL violation

Advantage of non-inverting material

p-in-n detectors (schematic figures!)

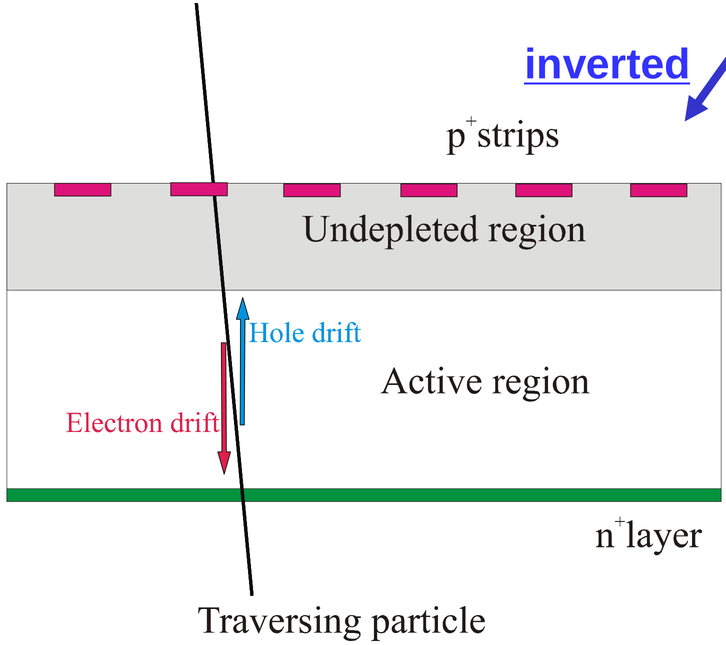
Be careful, this is a very schematic explanation, reality is more complex !

Fully depleted detector (non – irradiated):

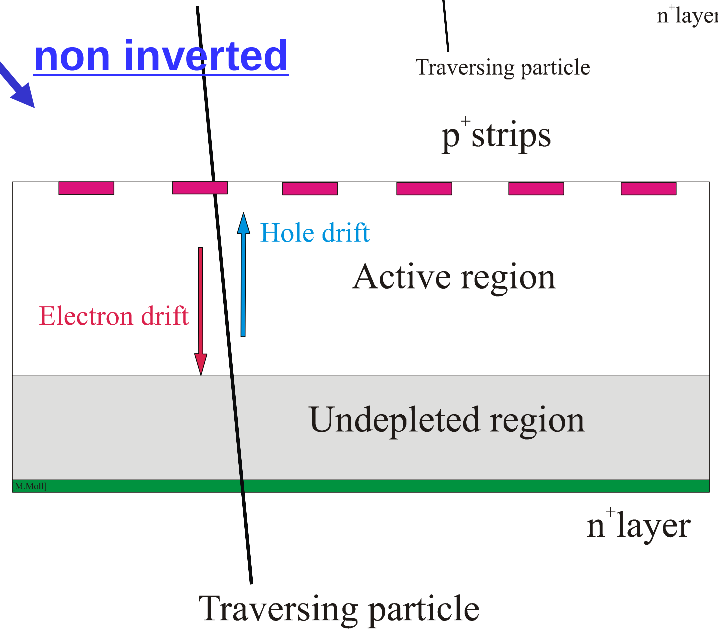


heavy irradiation

<u>inverted</u>



<u>non inverted</u>



<u>inverted</u> to "p-type", under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

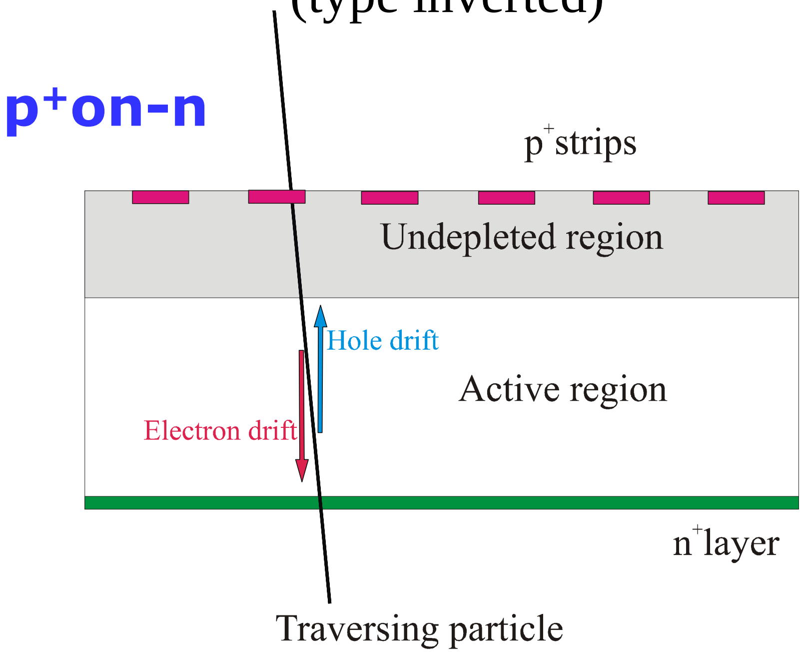
<u>non-inverted</u>, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**

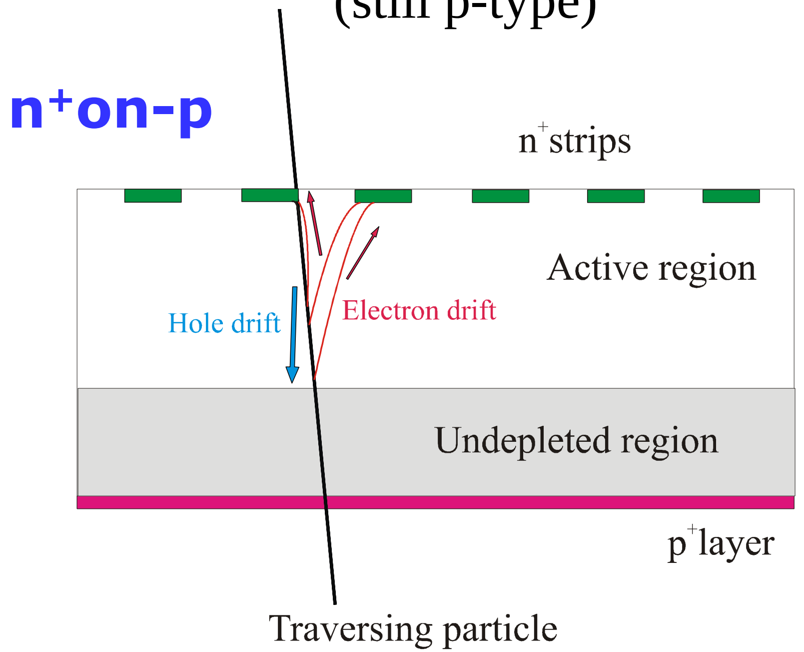
Device engineering

p-in-n versus n-in-p (or n-in-n) detectors

n-type silicon after high fluences:
(type inverted)



p-type silicon after high fluences:
(still p-type)



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

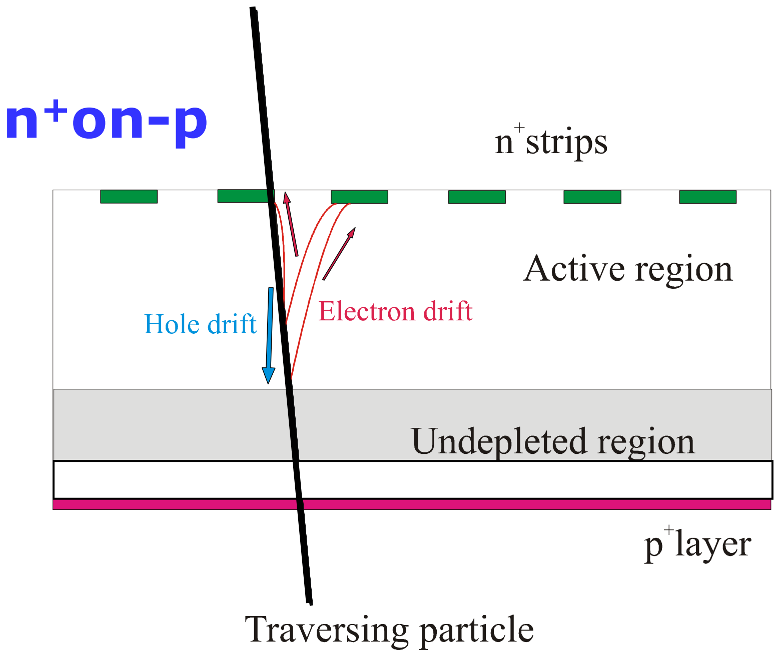
n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

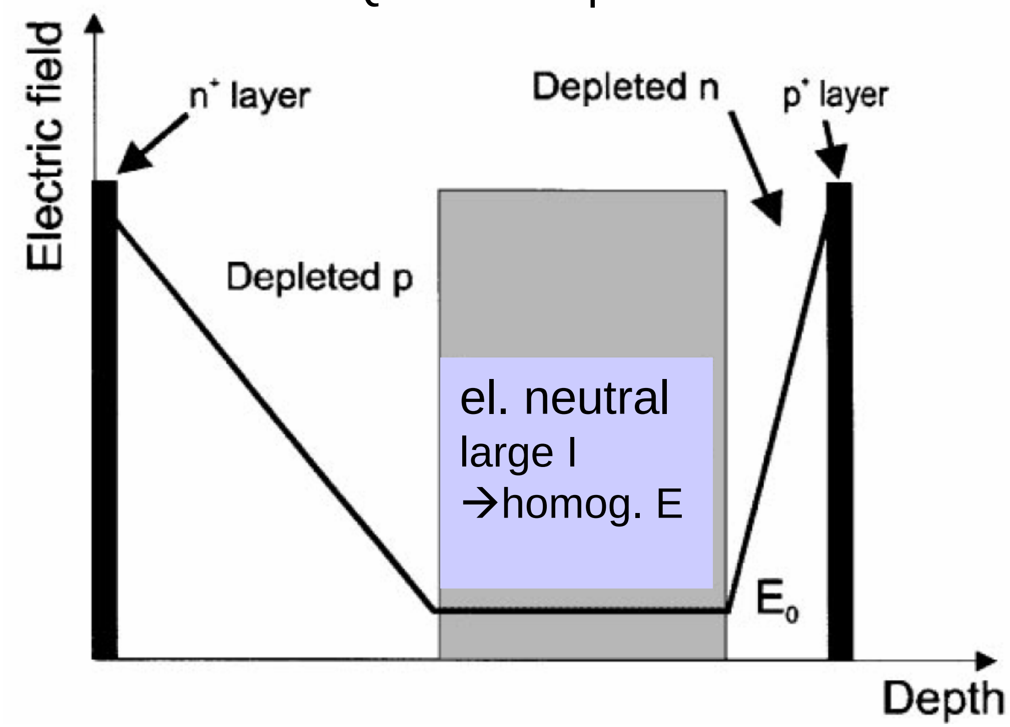
Comments:
- Instead of n-on-p also n-on-n devices could be used

Reality is more complex: *Double junctions*

p-type silicon after high fluences:
(still "p-type")

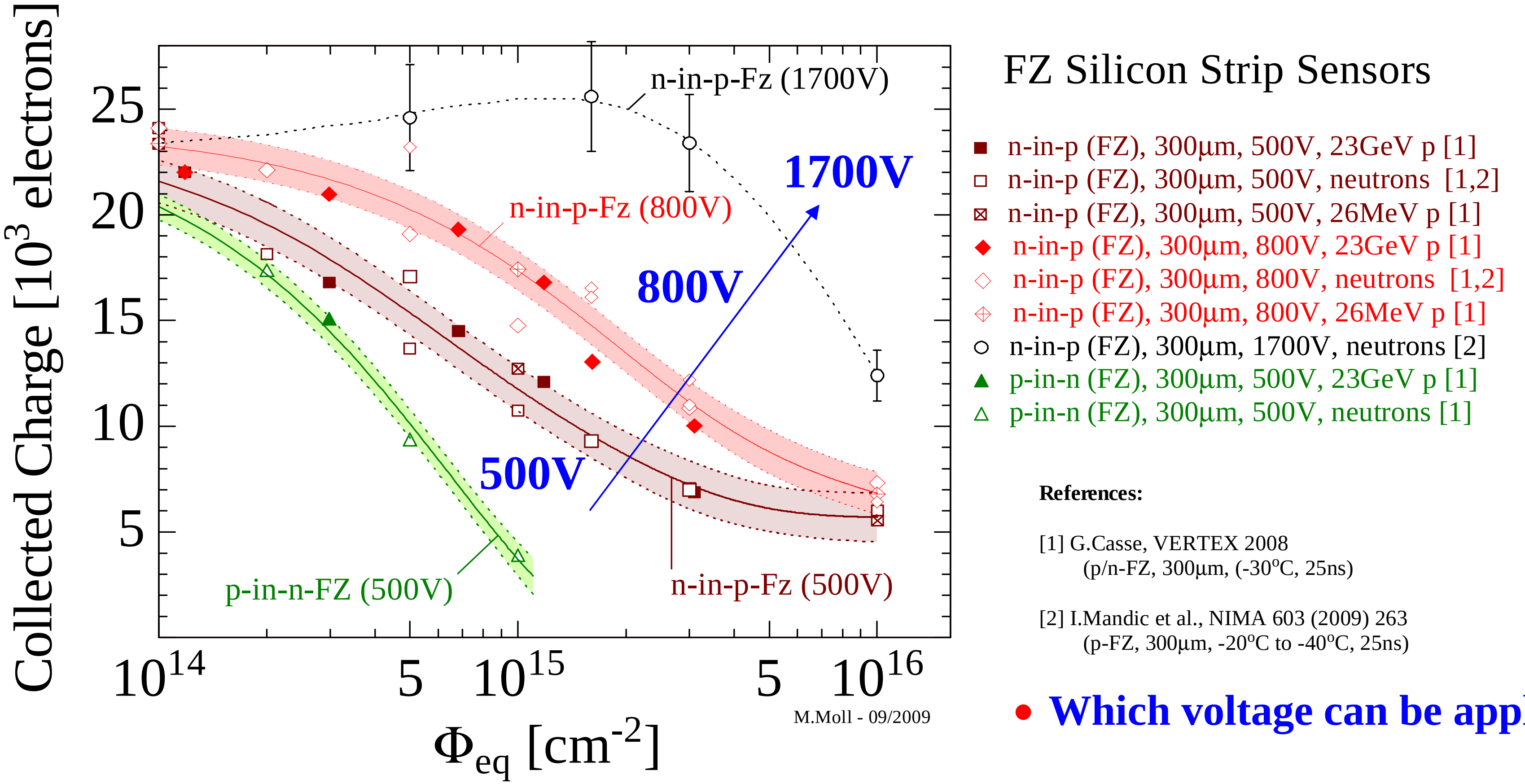


Qualitative picture



- **Dominant junction close to n+ readout strip for FZ n-in-p**
- **For MCZ p-in-n even more complex fields have been reported:**
  - **no "type inversion"(SCSI) = dominant field remains at p implant**
  - **"equal double junctions" with almost symmetrical fields on both sides**

Good performance of planar sensors at high fluence



References:

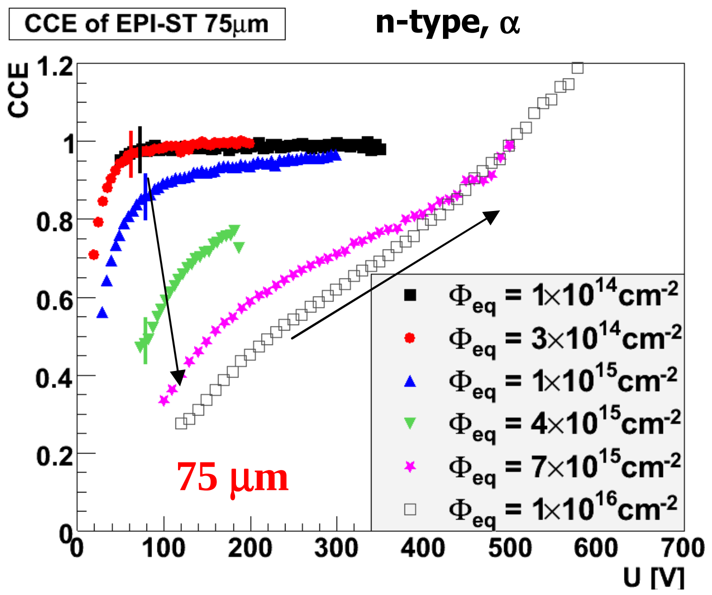
[1] G.Casse, VERTEX 2008
(p/n-FZ, 300µm, (-30°C, 25ns)

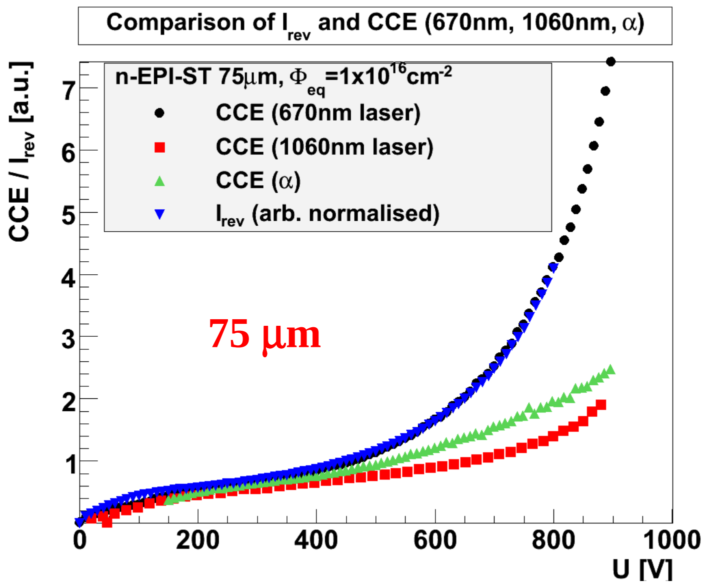
[2] I.Mandic et al., NIMA 603 (2009) 263
(p-FZ, 300µm, -20°C to -40°C, 25ns)

- **Which voltage can be applied?**

- **Planar silicon sensors with n-strip readout give higher signals after high levels ($>10^{15}$ cm^{-2} p/cm^2) of irradiation than expected from extrapolating trapping parameters**
- **Assumption: 'Charge multiplication effects' as even CCE > 1 was observed**

Charge Multiplication –Epi Diodes





[J.Lange et al., 14th RD50 Workshop, June 2009]

- **Studied Epi diodes, 75 and 150 μm thick**
- **Measured trapping probability found to be proportional to fluence and consistent with values extracted in FZ**
- **Multiplication effect stronger for 75 μm diodes: Larger E-field**

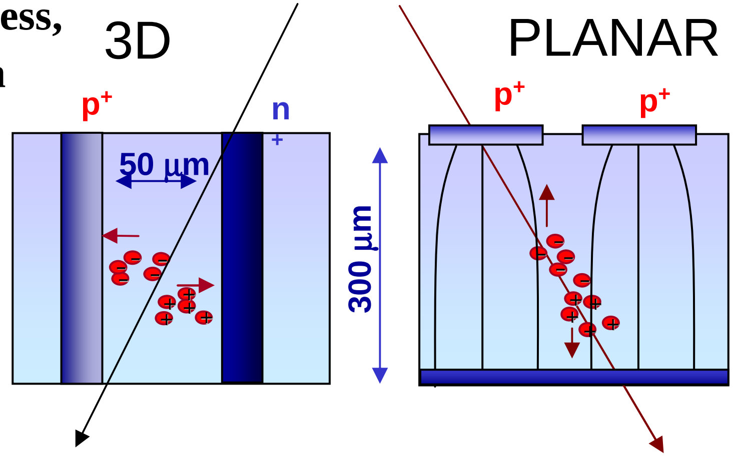
Under Study:

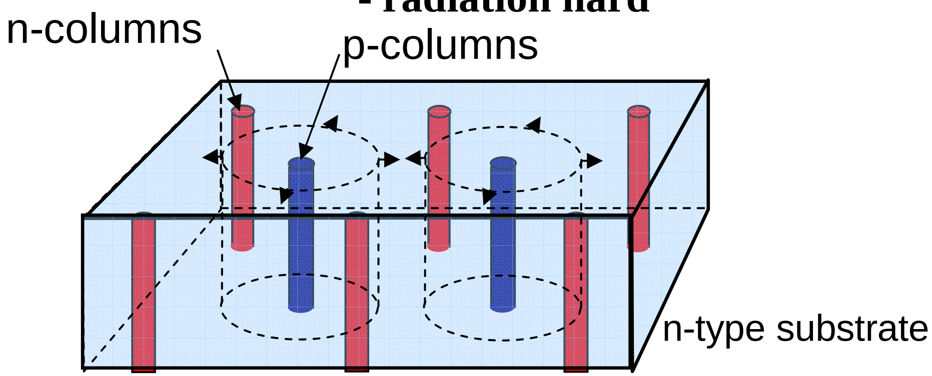
- **stability**
- **Where does charge multiplication take place?**
- **Smaller penetration depth (670 nm laser) → stronger charge multiplication**
- **homogeneity**

- **Can charge multiplication be used in a detector in a controlled way?**

3D detectors

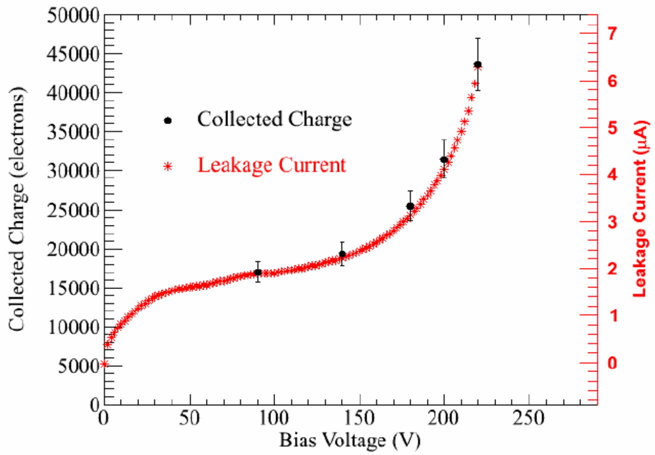
- **"3D" electrodes:** - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard



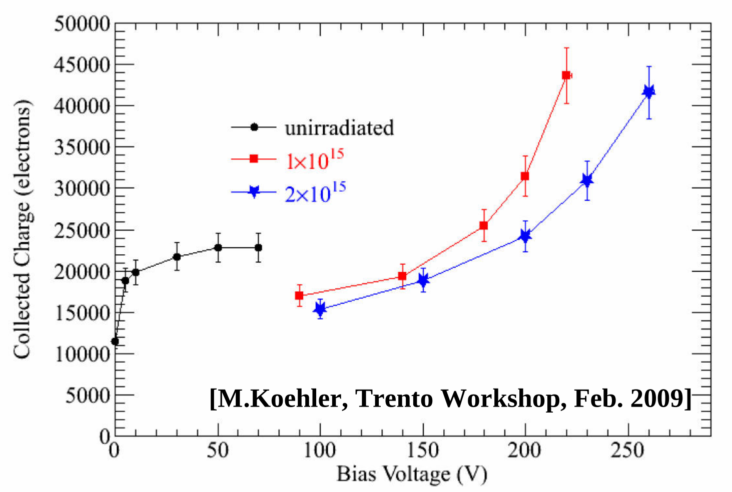


- **Signal scales with leakage current**

$1X10^{15}\ n_{eq}/cm^2$



Charge multiplication!



3 D looks promising

Use of other semiconductor materials?

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
e-h pairs/X_0	4.4	~2-3	4.5	10.1

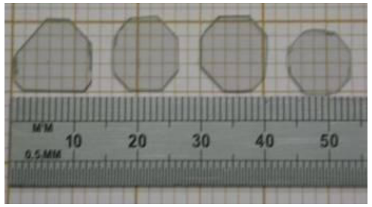
- **Diamond: wider bandgap**
  ⇒ lower leakage current
  ⇒ less cooling needed
- **Signal produced by m.i.p:**
  Diamond 36 e/μm
  Si 89 e/μm
  ⇒ Si gives more charge than diamond

- **GaAs, SiC and GaN ⇒ strong radiation damage observed**
  ⇒ no potential material for sLHC detectors
  (judging on the investigated material)

- **Diamond (RD42) ⇒ good radiation tolerance**
  ⇒ already used in LHC beam condition monitoring systems
  ⇒ considered as potential detector material for sLHC pixel sensors

poly-CVD Diamond –16 chip ATLAS pixel module

single crystal CVD Diamond of few cm^2



Diamond sensors are heavily used in LHC Experiments for Beam Monitoring

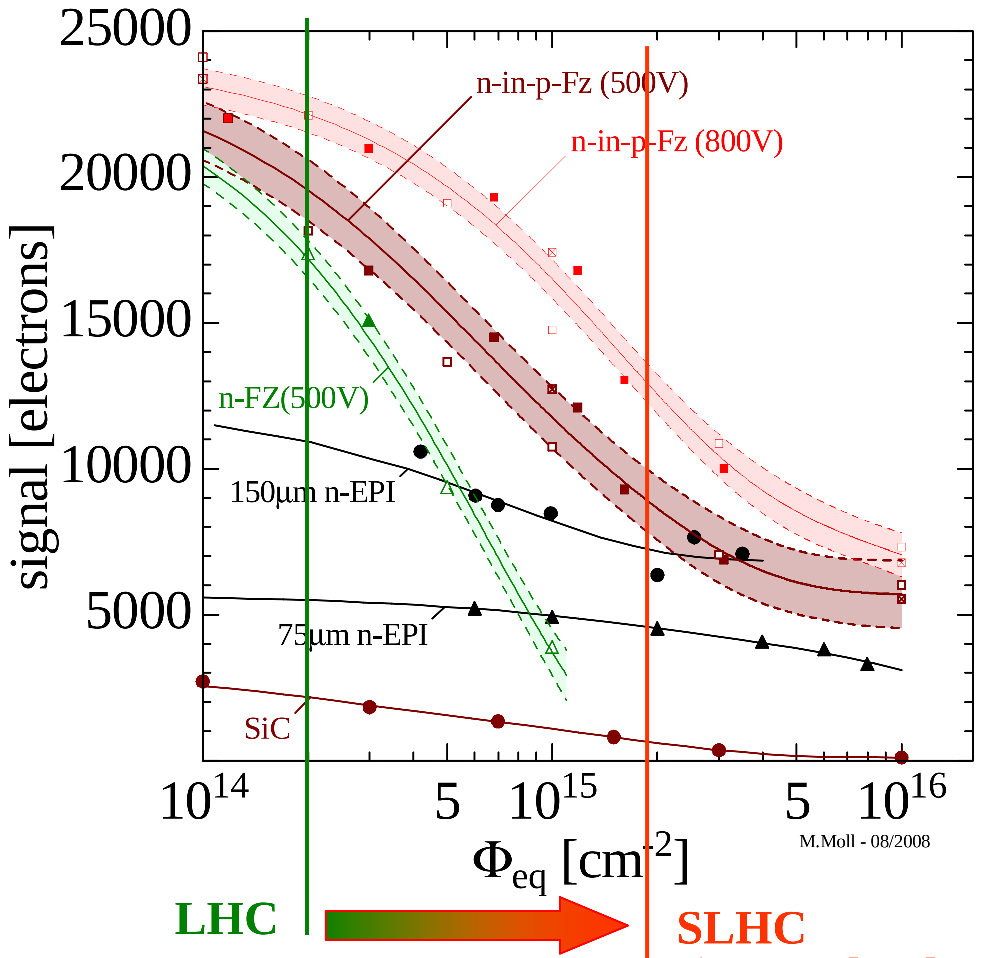
Outline

- **Motivation to develop radiation harder detectors**
  - **Super-LHC and expected radiation levels at the Super-LHC**
  - **Radiation induced degradation of detector performance**
- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**
  - **Microscopic damage (crystal damage)**
- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices
- **Silicon Sensors for the LHC upgrade**
  - **Collected Charge – Signal to Noise – Avalanche effects**
  - **Mixed irradiations**
- **Summary**

Silicon materials for Tracking Sensors

• Signal comparison for various Silicon sensors

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!



Silicon Sensors
- ● p-in-n (EPI), 150 µm [7,8]
- ▲ p-in-n (EPI), 75µm [6]
- ■ n-in-p (FZ), 300µm, 500V, 23GeV p [1]
- □ n-in-p (FZ), 300µm, 500V, neutrons [1]
- ⊠ n-in-p (FZ), 300µm, 500V, 26MeV p [1]
- ■ n-in-p (FZ), 300µm, 800V, 23GeV p [1]
- □ n-in-p (FZ), 300µm, 800V, neutrons [1]
- ⊠ n-in-p (FZ), 300µm, 800V, 26MeV p [1]
- ▲ p-in-n (FZ), 300µm, 500V, 23GeV p [1]
- △ p-in-n (FZ), 300µm, 500V, neutrons [1]

Other materials
- ● SiC, n-type, 55 µm, 900V, neutrons [3]

CMS: ➔Investigate
- -p-in-n-FZ(100µm, 200µm, 300µm),
- -p-in-n-MCz(200µm)
- -n-in-p-FZ(100µm, 200µm, 300µm),
- -n-in-p-MCz(200µm),
- -p-in-n EPI(75µm, 100µm)
- -n-in-p EPI(75µm, 100µm)

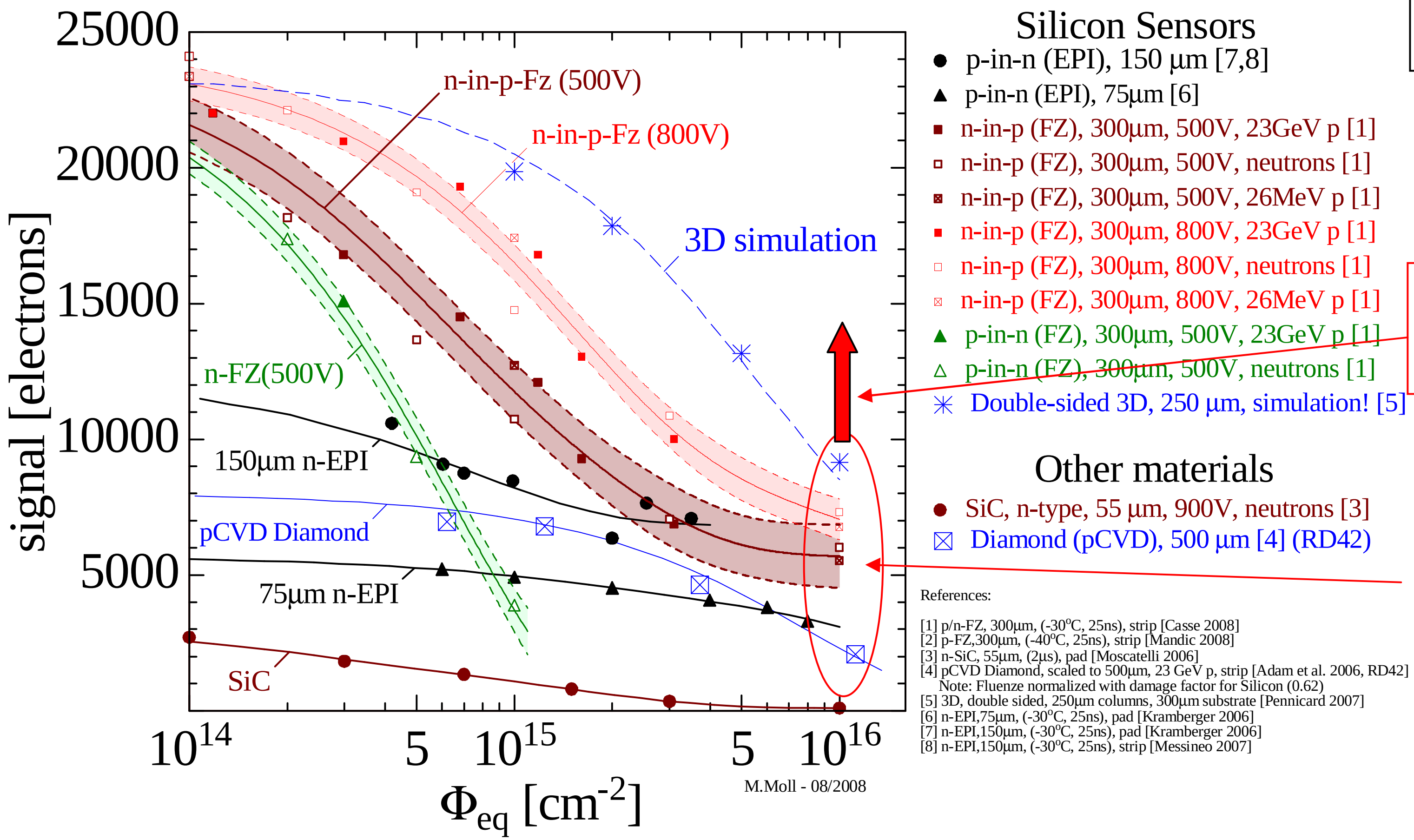
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Higher Voltage leads to charge multiplication

Beware: Signal shown and not S/N !

- **All sensors suffer from radiation damage**
- **Presently three options for innermost pixel layers under investigation:**
  - **3-D silicon sensors** (decoupling drift distance from active depth)
  - **Diamond sensors**
  - **Silicon planar sensors**

Summary

- **Effects of Radiation Damage in Silicon Detectors:**
  - Change of **Depletion Voltage** (material-dependent)
  - Increase of **Leakage Current** (same for all silicon materials)
  - Increase of **Charge Trapping** (same for all silicon material

- **Microscopic defects & Defect Engineering:**
  - Large progress in correlating microscopic defects with macroscopic properties
  - Still many open questions: I.e. Which are the defects responsible for the trapping?

- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** explore and develop new silicon materials
  - **Device Engineering:** 3D, thin sensors, n-in-p, n-in-n, …

- **Silicon for SLHC:**
  - Outer layers of SLHC strip tracker: Main Issues: $\mathbf{V_{depl}}$ and large area of Si
    - Promising: MCZ : n-MCZ compensation effects in mixed fields
    - p-type silicon
  - Inner strip layers, pixel: Fluences > 10^{15}cm^{-2}
    - Trapping! Collection of electrons essential: Use n-in-p or n-in-n detectors!
  - Innermost SLHC pixel:~10^{16}: 3D detectors? EPI? Diamond?

Acknowledgements

- **Michael Moll (RD50 spokesperson)**
- **Some material taken from the following summary talks:**
  - ***RD50 presentations on conferences: http://www.cern.ch/rd50/***
  - ***Nigel Hessey: Eiroforum RADHARD 2010 Workshop, Lisbon 16-18 March 2010 (Path to upgrade)***
  - ***Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (sATLAS fluence levels)***
  - ***Frank Hartmann: Presentation at the VCI conference in February 2010 (Diamond results)***
  - ***… most references to particular works given on slides.***

Further information about RD50 activities: http://cern.ch/rd50/

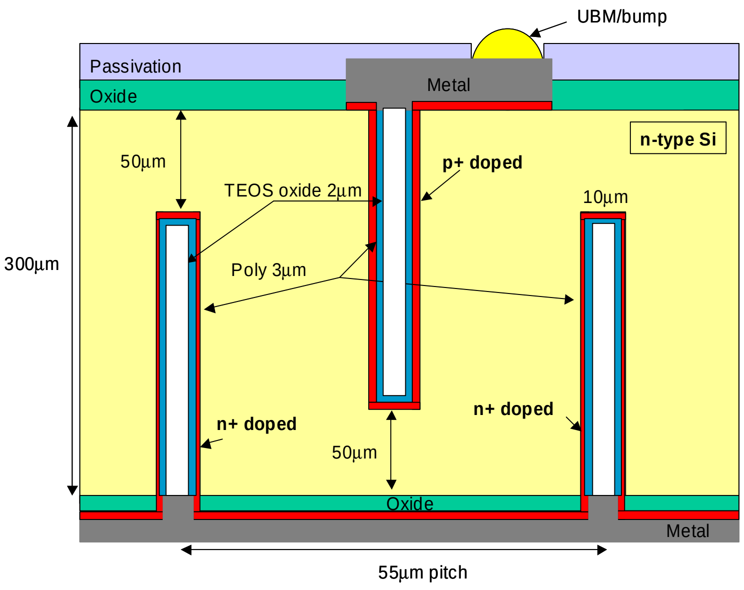
Further R&D: RD42, RD39, ATLAS & CMS detector upgrade meetings

BACKUP

Example: Testbeam of 3D-DDTC

- **DDTC – Double sided double type column**

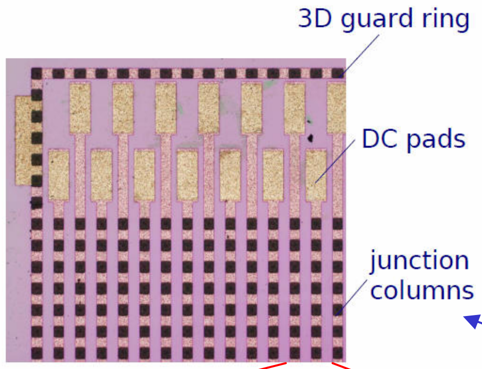
[G.Fleta, RD50 Workshop, June 2007]

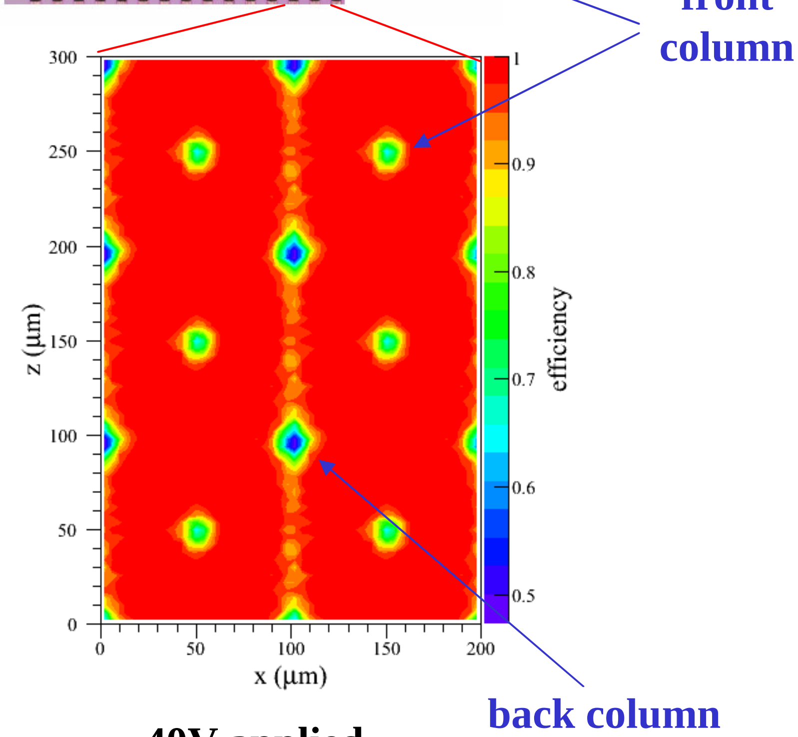


- **Testbeam data – Example: efficiency map**
  [M.Koehler, Freiburg Uni, RD50 Workshop June 09]

- **Processing of 3D sensors is challenging, but many good devices with reasonable production yield produced.**

- **Competing e.g. for ATLAS IBL pixel sensors**





40V applied
~98% efficiency