Silicon Detectors for High Luminosity Colliders

RD50 Status Report

Ulrich Parzefall

University of Freiburg

- On Behalf of the RD50 Collaboration -

Overview

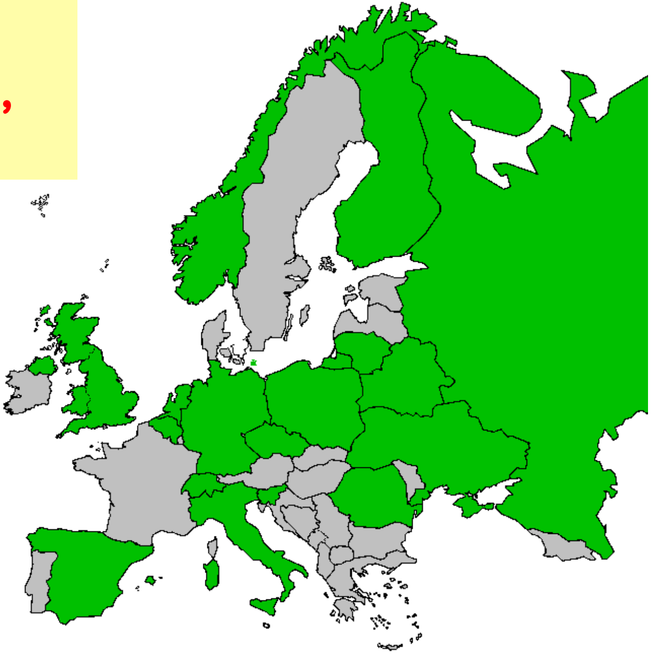
- The RD50 Collaboration
- Motivation: HL-LHC (“S-LHC”) & radiation damage
- Defects and effective doping concentration
- Electric field after heavy irradiation
- Charge multiplication: signal and noise
- Annealing
- Conclusions and outlook

- **Several RD50 colleagues are at TIPP 2011, presenting related work**
- **This talk tries to focus on some important areas of RD50 activity, whilst avoiding unnecessary duplication of topics from other talks**

The RD50 Collaboration

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Cooperation across experimental boundaries for ATLAS, CMS, LHCb and many smaller collaborations



38 European institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Florence, Padova, Perugia, Pisa, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Glasgow, Lancaster, Liverpool)

8 North-American institutes

Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

257 Members from 47 Institutes

Detailed member list: http://cern.ch/rd50

RD50

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Co-Spokespersons

Gianluigi Casse and ***Michael Moll***

University of Liverpool

CERN PH-DT

Defect / Material Characterization

Mara Bruzzi

(INFN and Uni Florence)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

- Wodean – Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem)

Defect Engineering

Eckhart Fretwurst

(HamburgUniversity)

Development and testing of defect engineered silicon:

- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

- Wafer procurement (M.Moll)

Pad Detector Characterization

Gregor Kramberger

(Ljubljana University)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irradiations
- Standardisation of measurements (A.Chilingarov)
- New Materials (E. Verbitskaya)

New Structures

Richard Bates

(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems

Gianluigi Casse

(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors

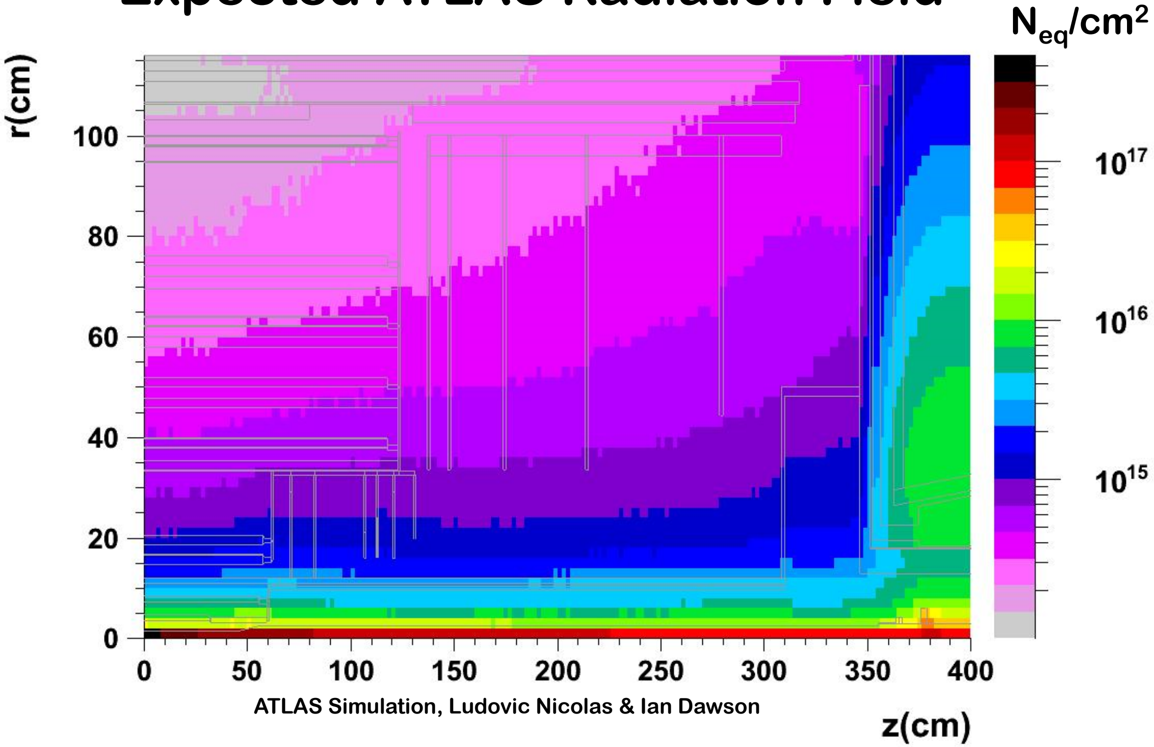
- Comparison of detectors made by different producers

CERN contact: Michael Moll

The Radiation Challenge

- LHC Upgrade will seriously increase radiation levels
  - ATLAS scenario for 3000fb^{-1} (HL-LHC or Phase II)
- Very strong radial and significant z dependence
- HL-LHC is entering new area of fluences above 10^{16} N_{eq}/cm^2 at low radii
- LHC silicon sensors would not survive this for long
- Need to develop new generation of radiation hard silicon for HL-LHC

Expected ATLAS Radiation Field



ATLAS Simulation, Ludovic Nicolas & Ian Dawson

- Radiation hardness requirements (including safety factor of 2)
  - 2×10^{16} n_{eq}/cm^2 for the innermost pixel layers
  - 1×10^{15} n_{eq}/cm^2 for the innermost strip layers

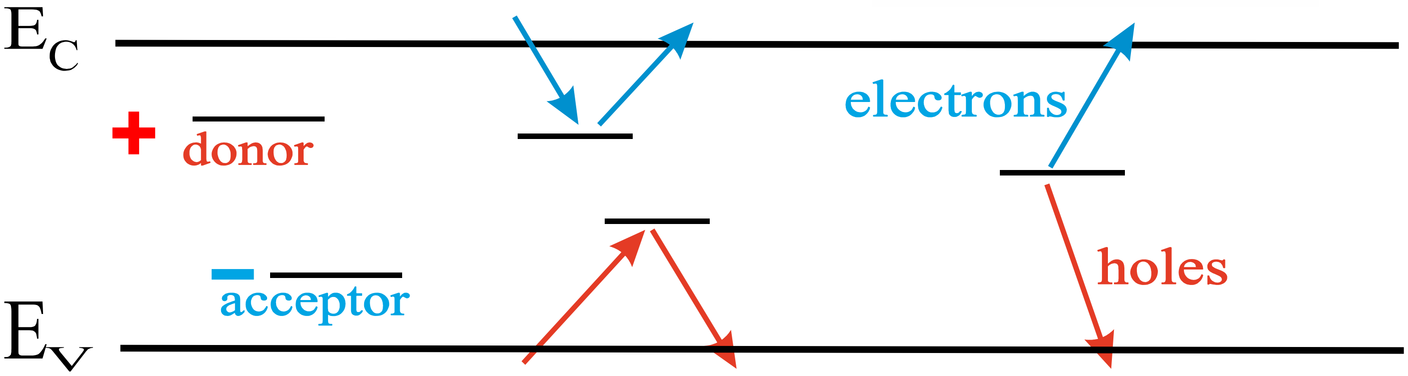
Radiation Damage in Silicon

I. **Surface Damage** due to **Ionizing Energy Loss (IEL)**

II. **Crystal (Bulk) damage** due to **Non-Ionizing Energy Loss (NIEL)**

- **Defects in the crystal**
- **Point defects and "cluster" defects**

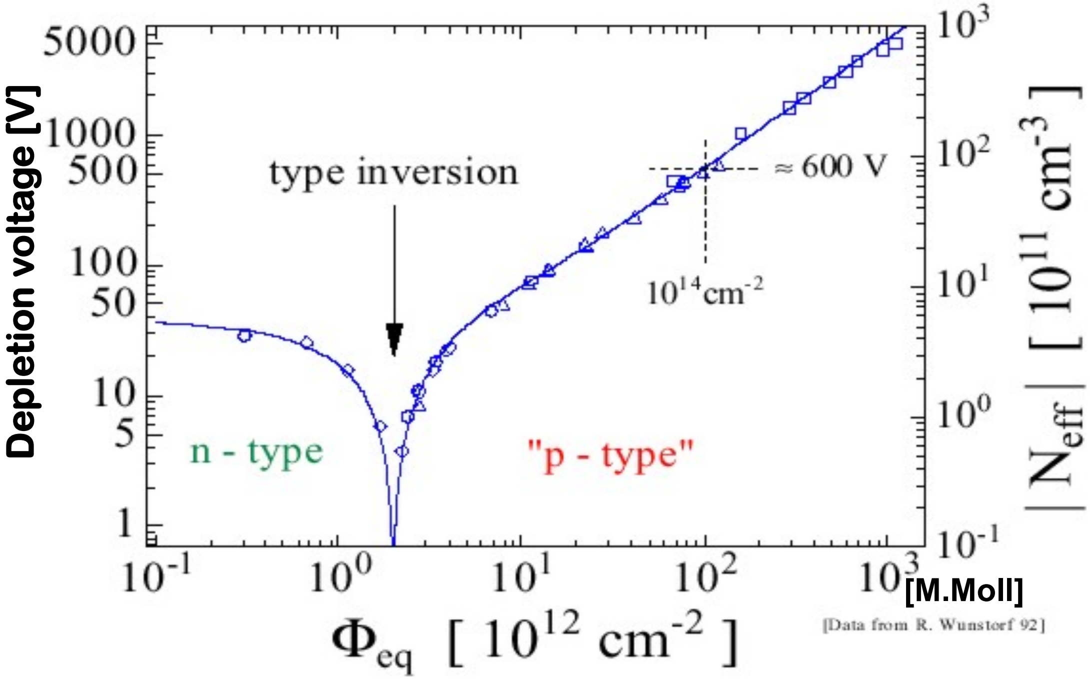
➔ New energy levels in the band gap



charged defects	**deep traps (e and h), recombination centres**	**deep traps, generation centres**
⇒N_{eff} , V_{dep}	⇒ **Charge Collection Efficiency**	⇒ **Leakage current**

Radiation Damage I: Doping

- Normalise dose Φ_{eq} to damage of 1-MeV-neutrons
- Damage
  - Several types of electrically active defects
  - Charged defects affect doping concentration
- Net effect: n-type Si becomes p-type „type inversion“ ➔ Space Charge Sign Inversions (SCSI)
- Detector becomes p-in-p (still with n back side)
- p-n-junction changes to back side for p-in-n Si
- This creates problems…

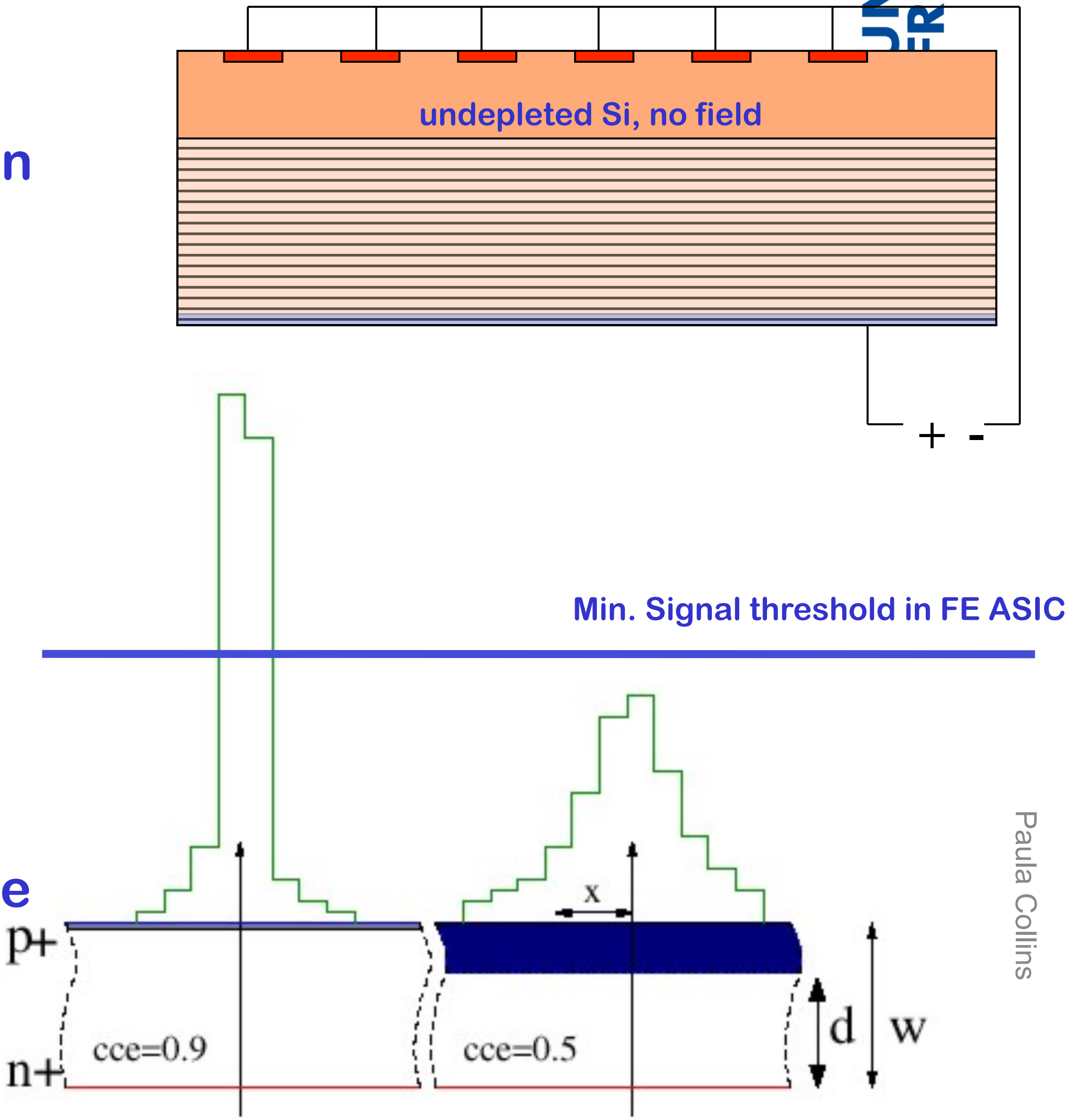


[M.Moll]

[Data from R. Wunstorf 92]

Partial Depletion after Type Inversion

- Full depletion voltage V_{FD} grows with Φ
- Bias limit impose (breakdown or HV power supplies)
- Strips end up in un-depleted silicon layer
    - No measurable charge generated in this layer
    - Strips are "shorted"
    - MIPs create larger cluster, which may hide in noise
    - Problem for binary readout and small pitch
- Strips should be on back side
- N-in-p detectors



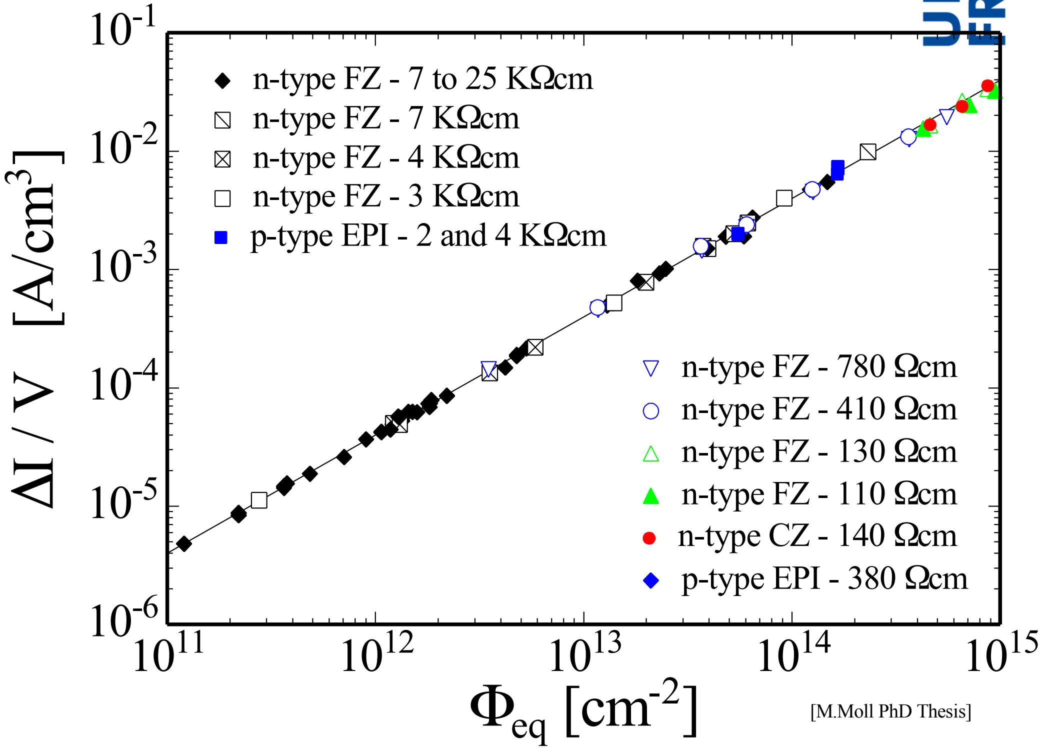
Paula Collins

Radiation Damage II: Current

- New energy levels deep in band gap, acting as generation centres
- Reverse current increases
- Effect independent of Si material or particle type
- Radiation-induced current dominates

$$\frac{I_{vol}}{V} = \frac{I_{vol,\Phi=0}}{V} + \alpha\Phi_{eq}$$

- I_{vol} has very strong temperature dependence
  - I_{vol} doubles ~each 8°

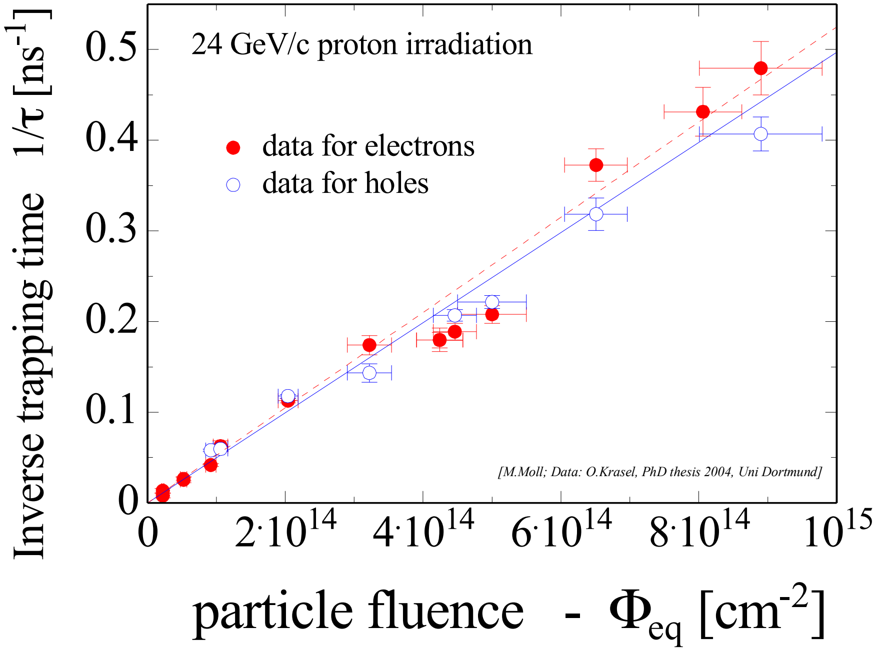


[M.Moll PhD Thesis]

- Increased shot noise
- Increased power dissipation (heat)
- Risk of thermal runaway

Radiation Damage III: Trapping

- Defects also act as trapping centres
- Reduction of collectable charge
- Trapping quantified as effective trapping time τ_{trap} for e^- and h^+
- Trapping limits charge collection distance, even at max. drift velocity
- Trapping is dominant radiation effect at $10^{15} n_{eq}$ and above
- Trapping similar for e^- and h^+
- Collection time ~3x smaller for e^-
- Radiation hard detectors collect e^-
- Need n-side readout (n-in-p or n-in-n detectors)



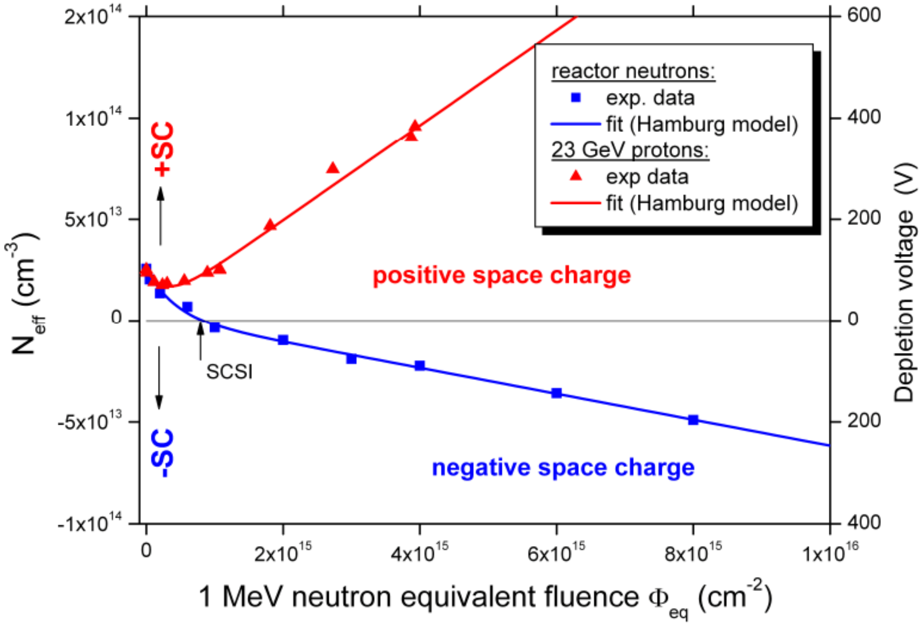
[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

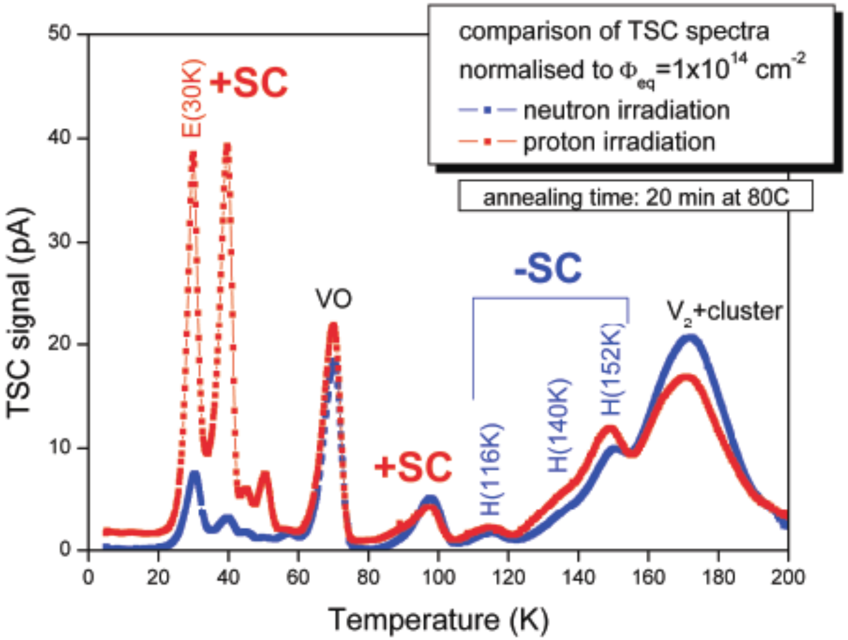
$$\tau_{eff}(10^{15} n_{eq}) = 2ns \qquad w = v_{sat}\tau_{eff} = 200\,\mu m$$

$$\tau_{eff}(10^{16} n_{eq}) = 0.2ns \qquad w = v_{sat}\tau_{eff} = 20\,\mu m$$

Effective Doping Concentration N_{eff}

- Epi-Silicon irradiated with 23 GeV protons vs reactor neutrons



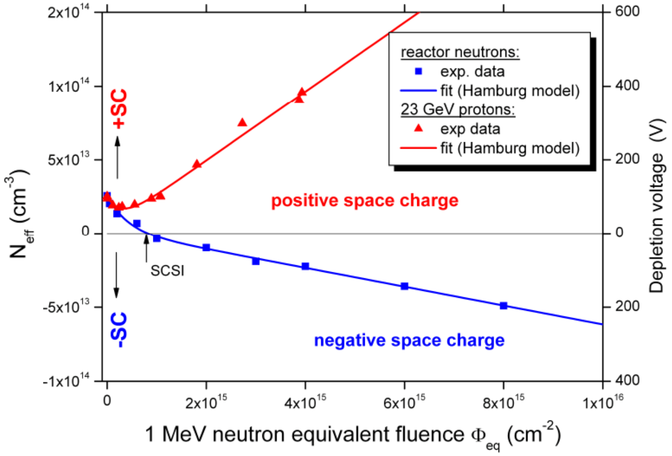


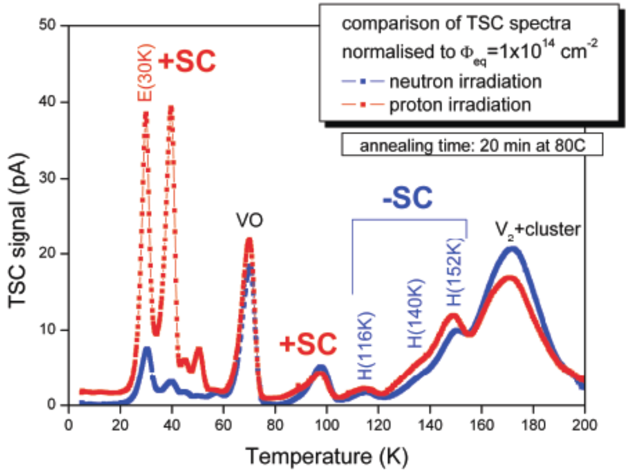
- SCSI “Type Inversion” after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low Φ_{eq}

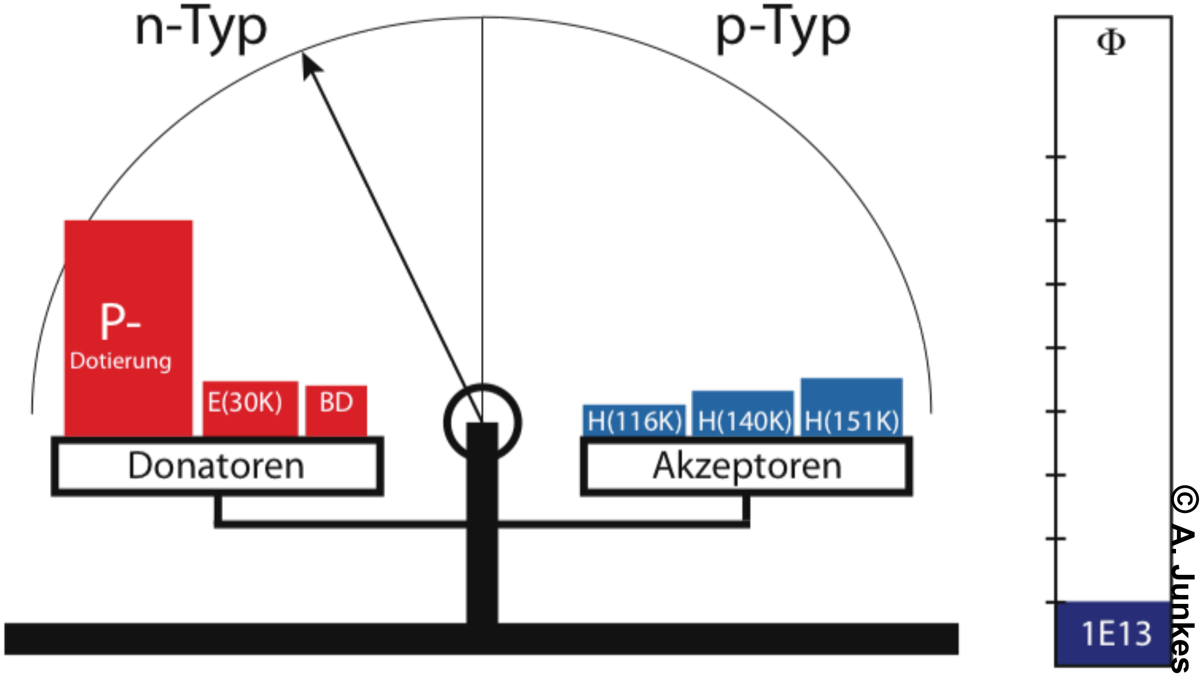
[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

N_{eff}: Neutron irradiation

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







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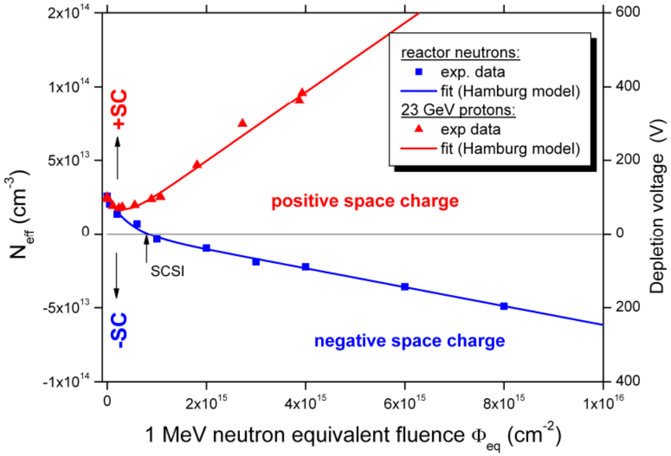
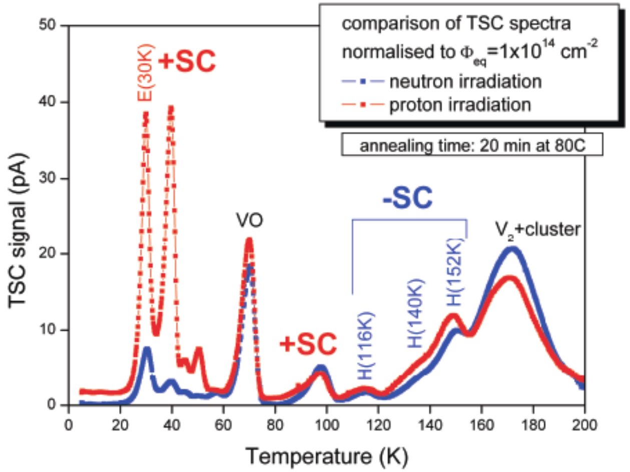
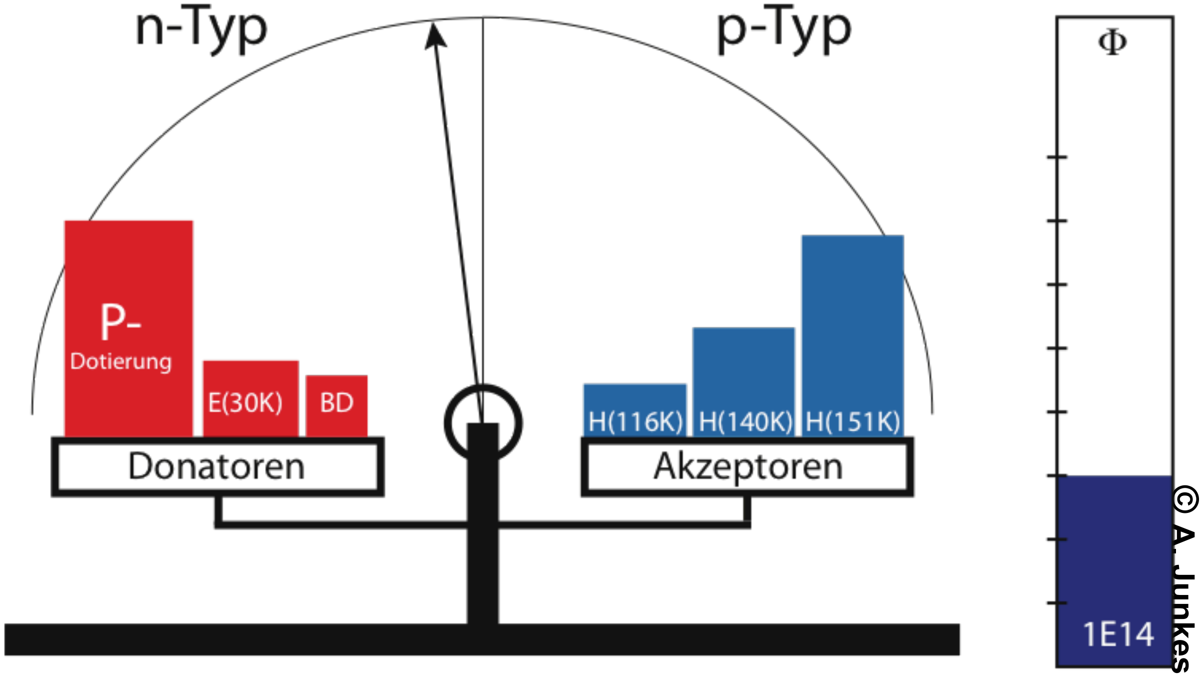


Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)* irradiated with reactor neutrons





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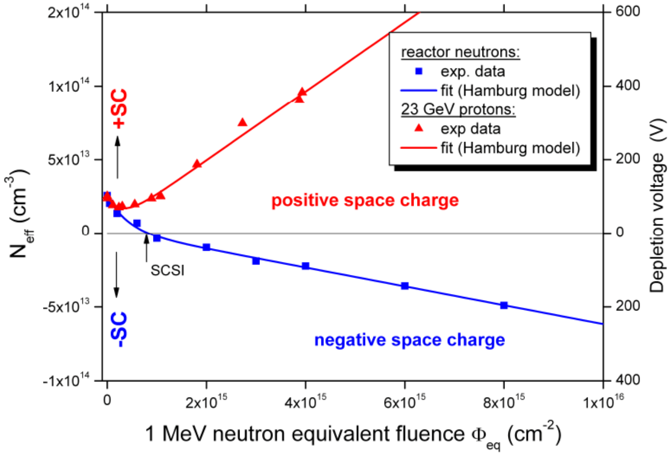

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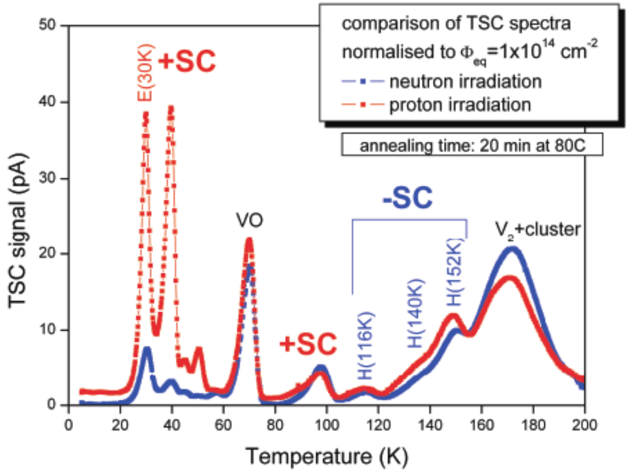

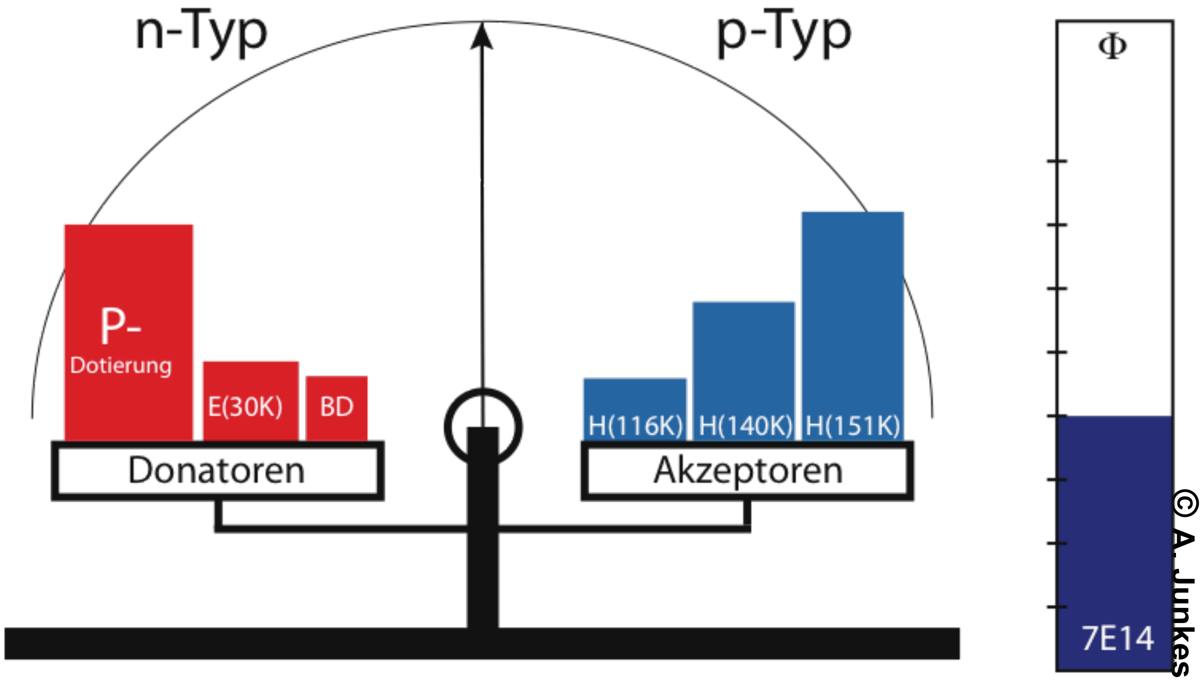

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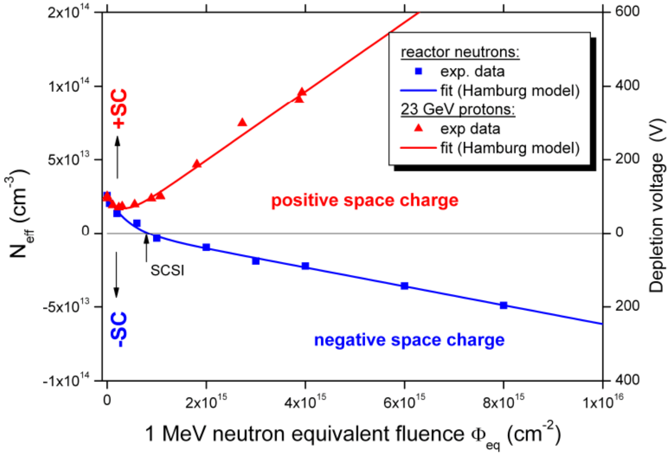

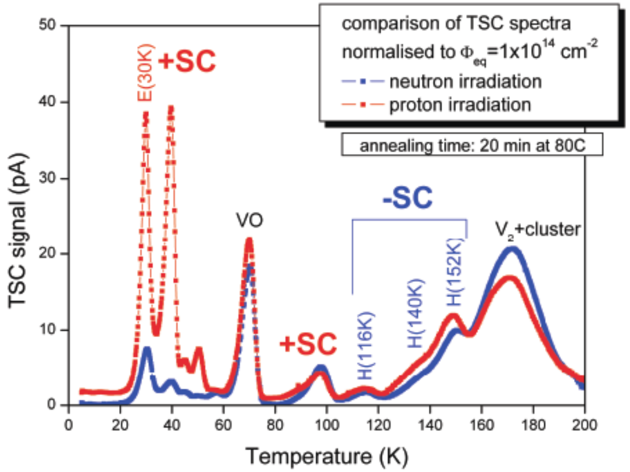

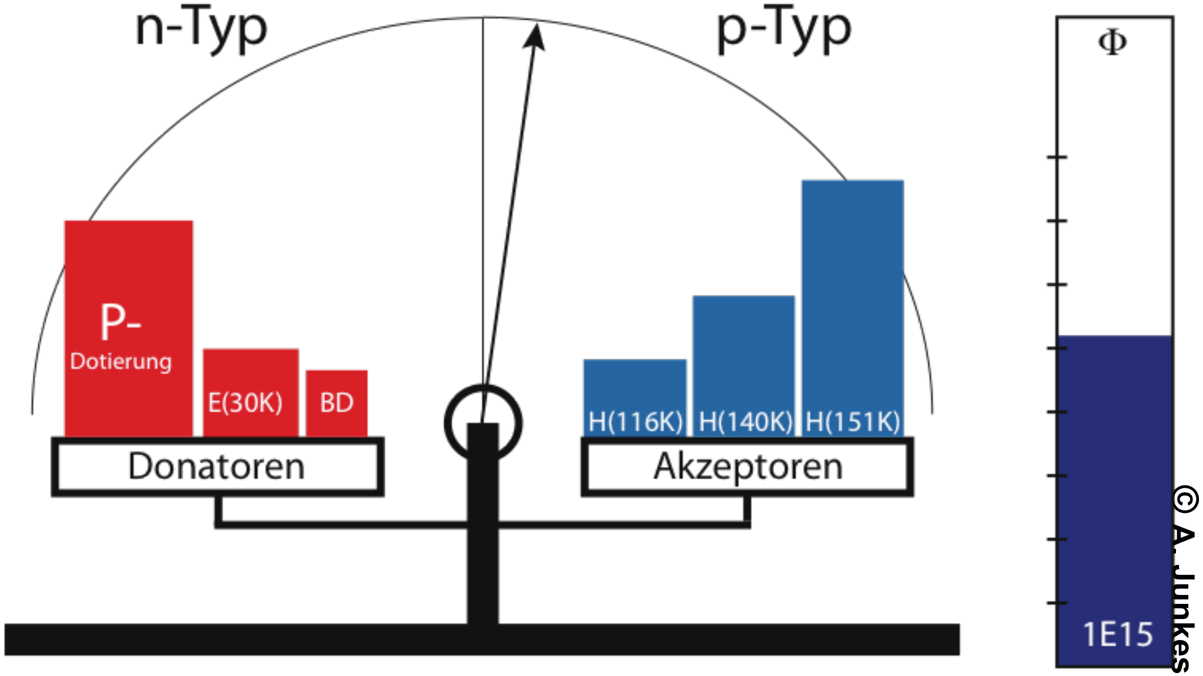

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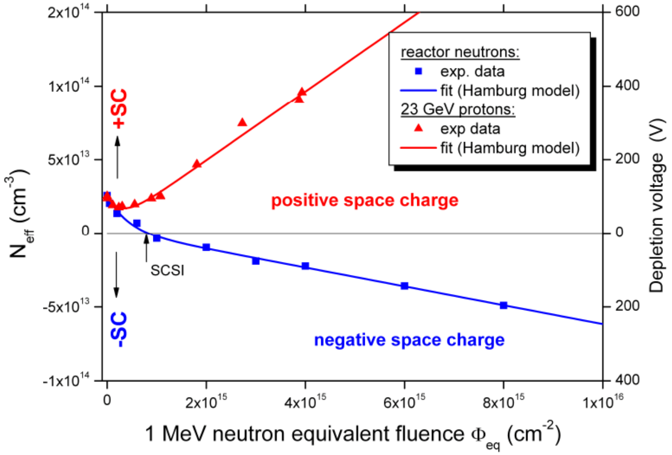
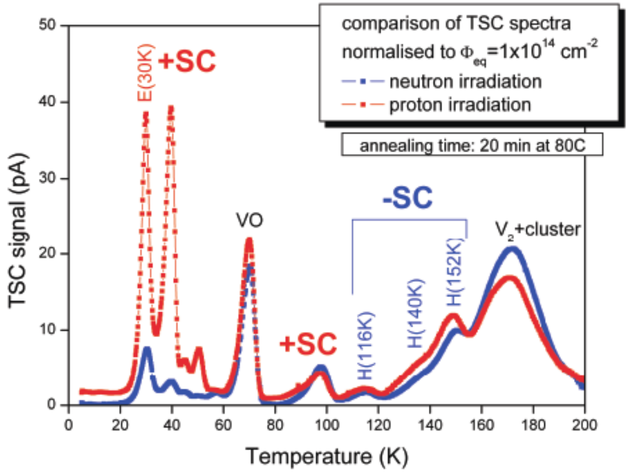
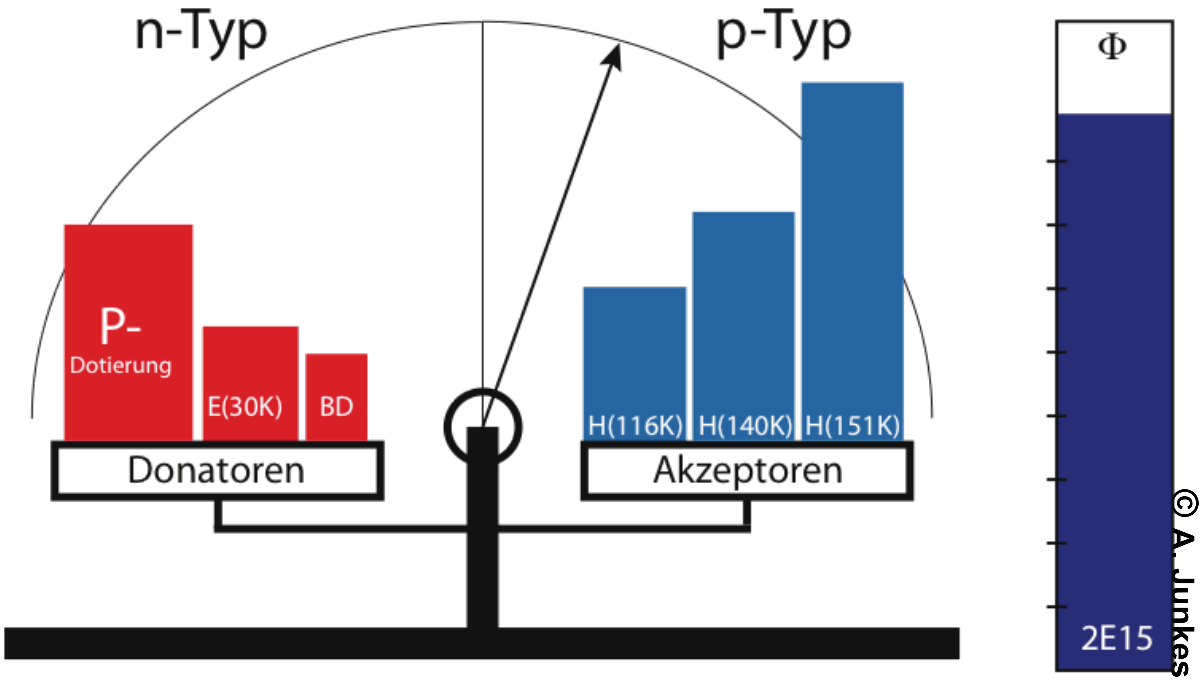




Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)* irradiated with <u>reactor neutrons</u>



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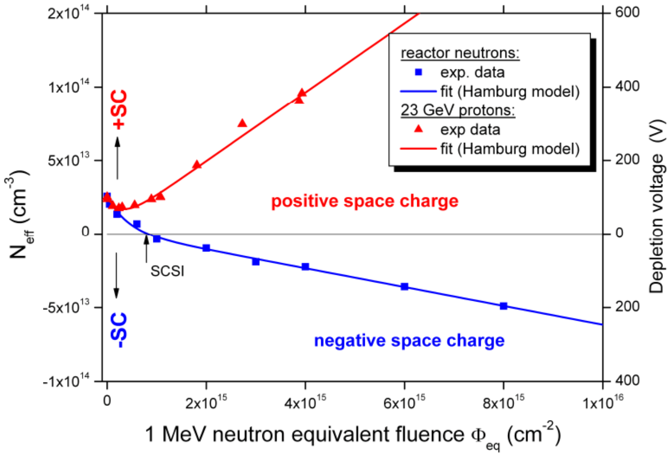
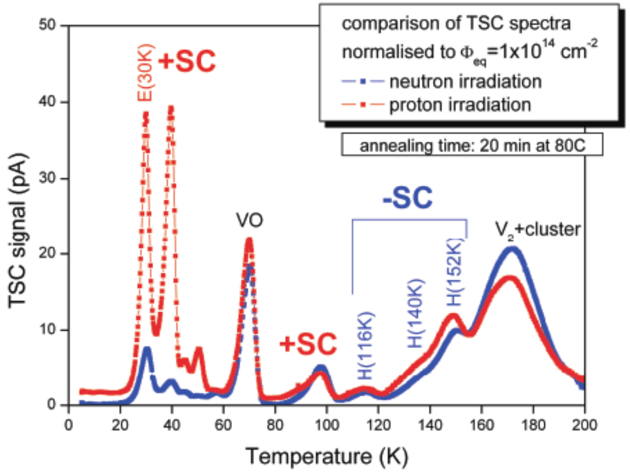
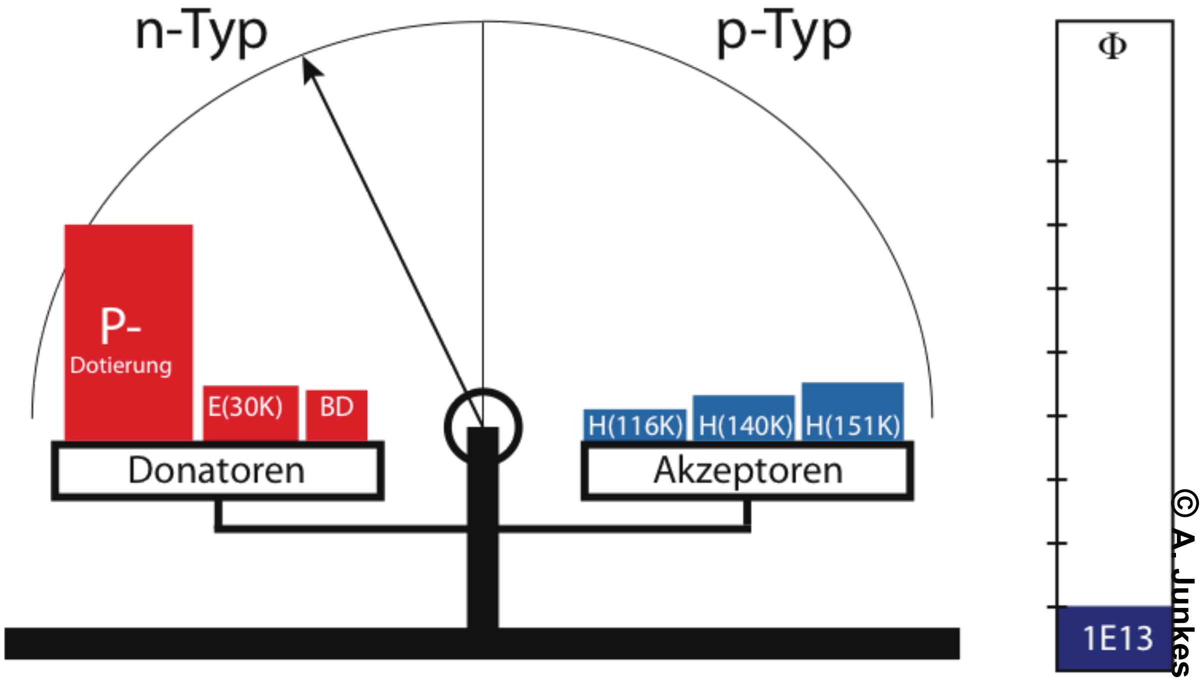
N_{eff}: Proton irradiation



Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)* irradiated with 23 GeV protons





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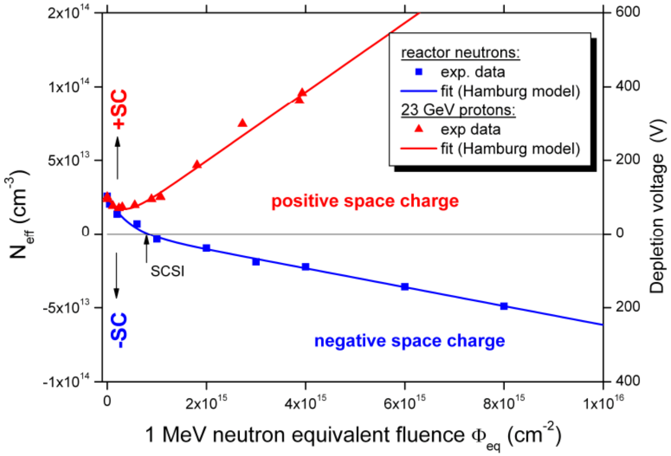

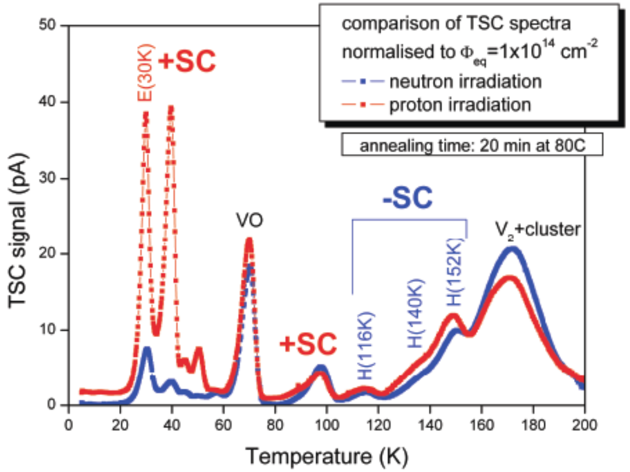

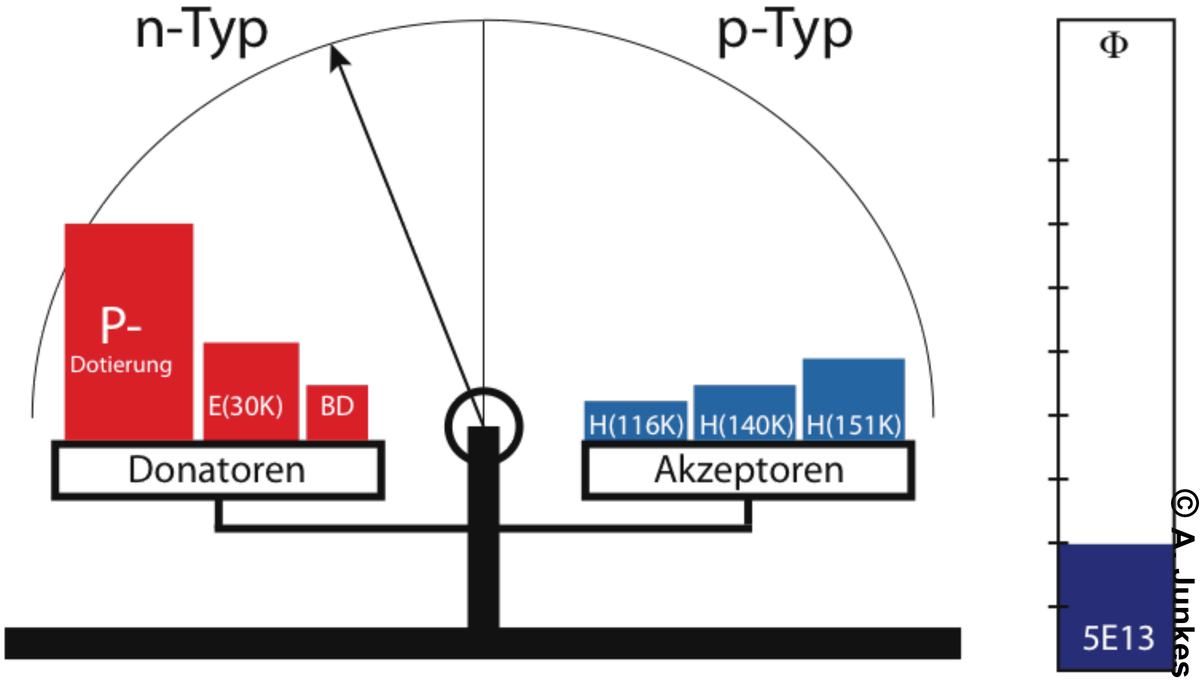

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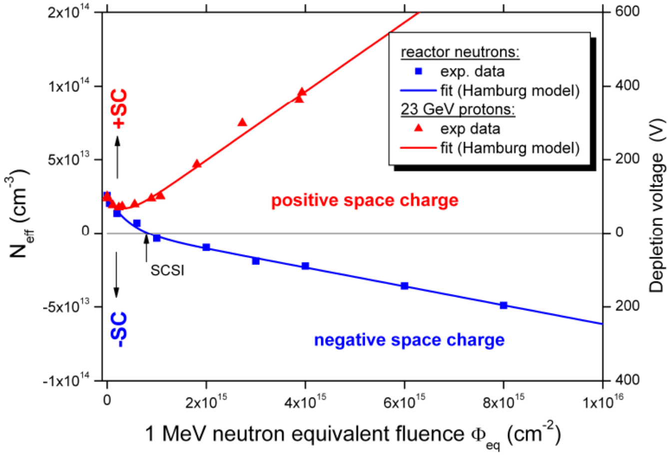

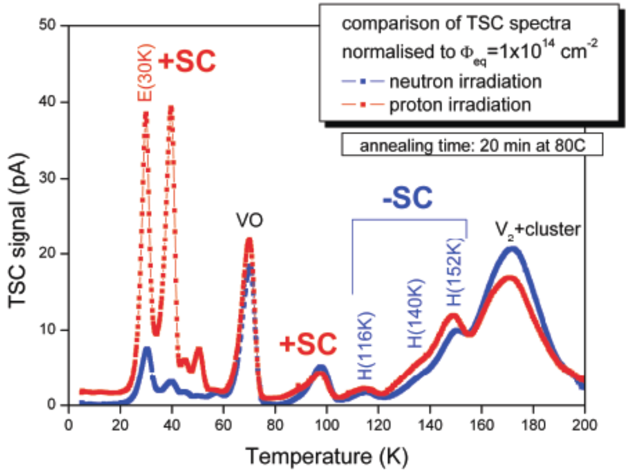

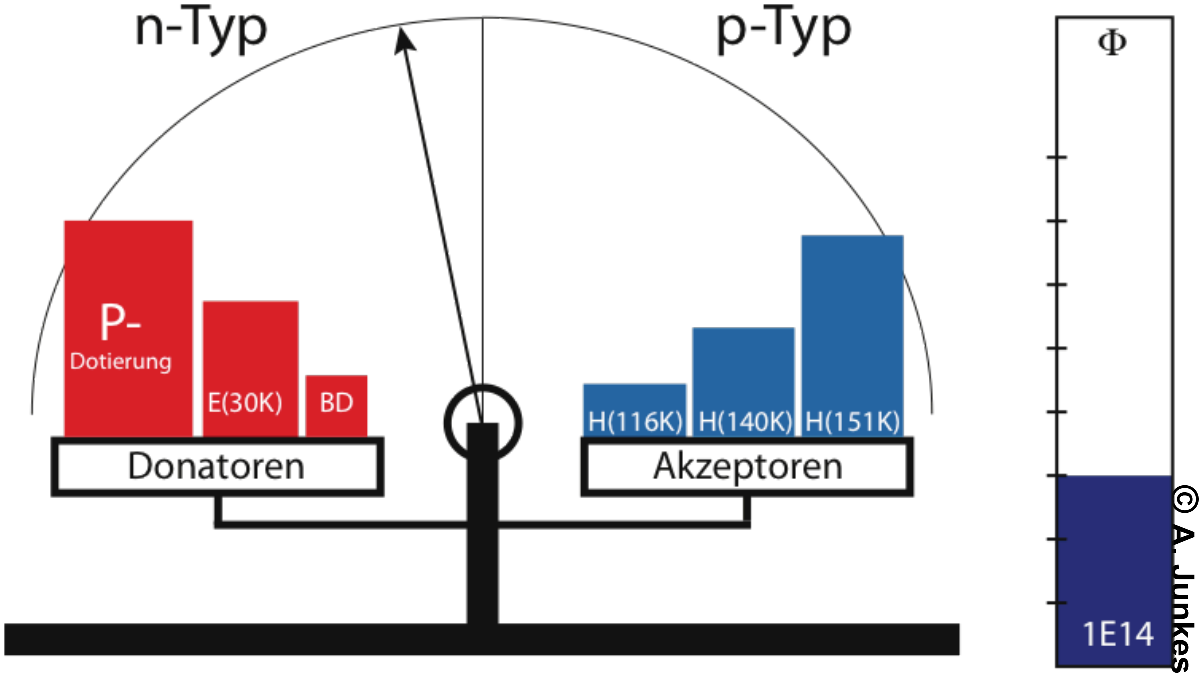

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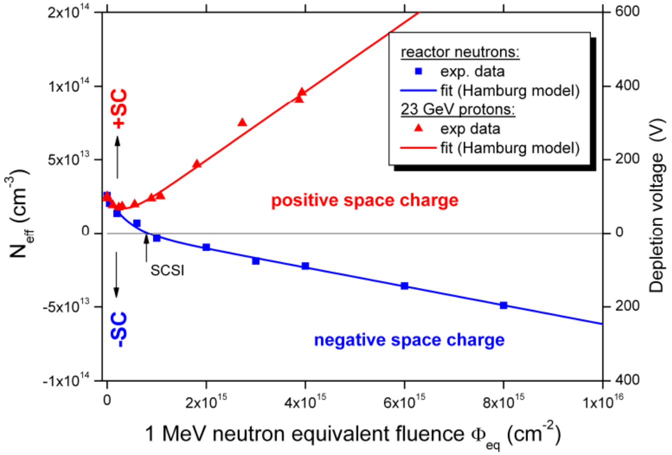

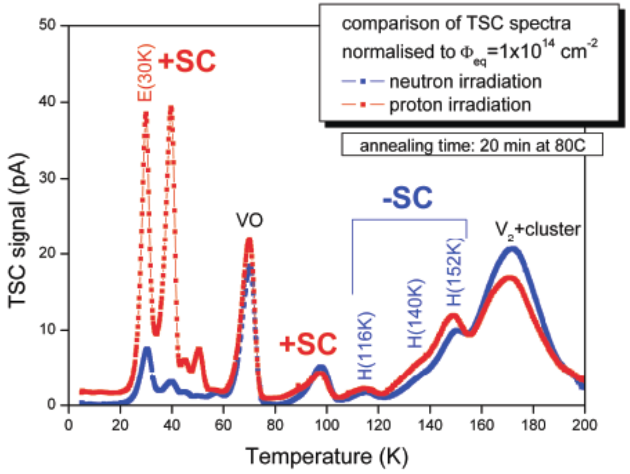

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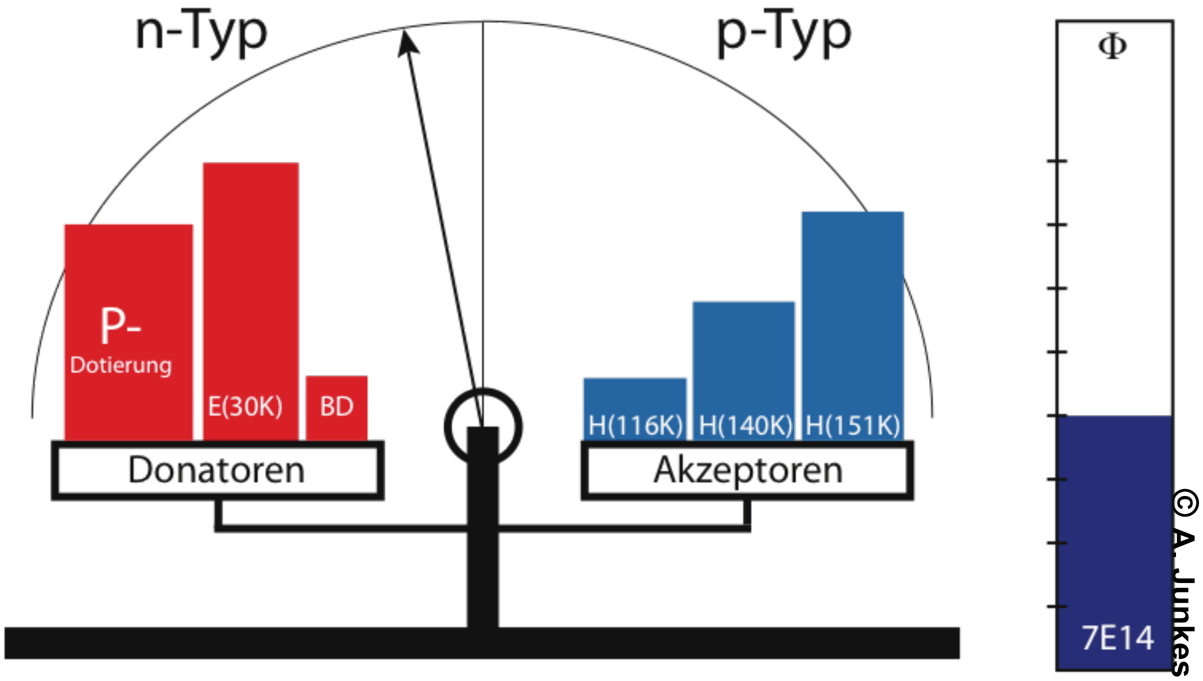

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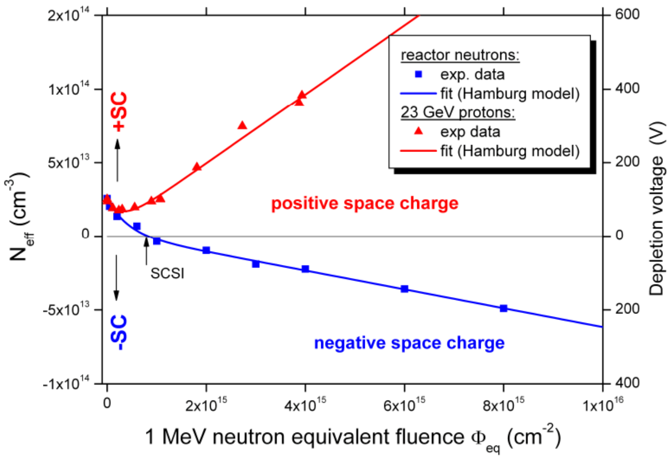

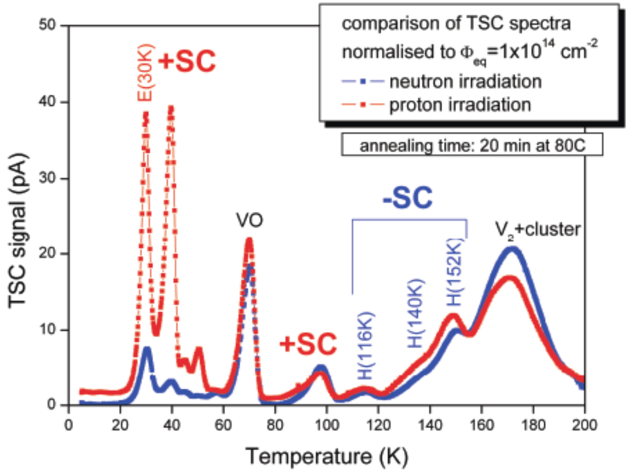

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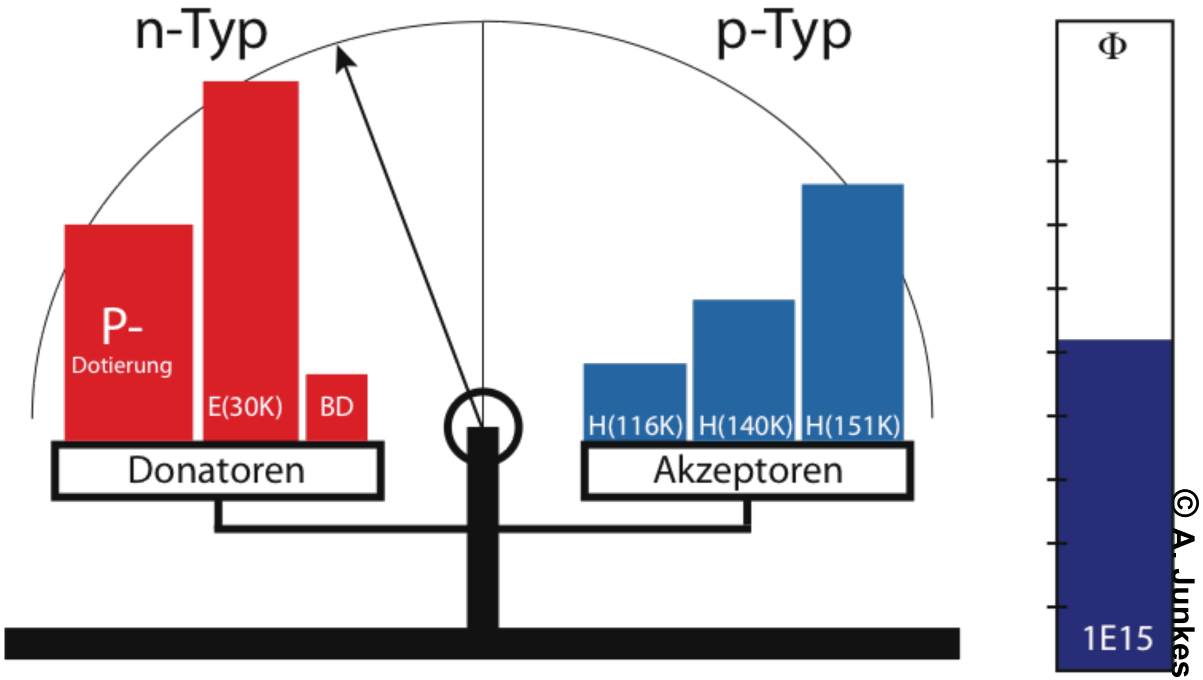

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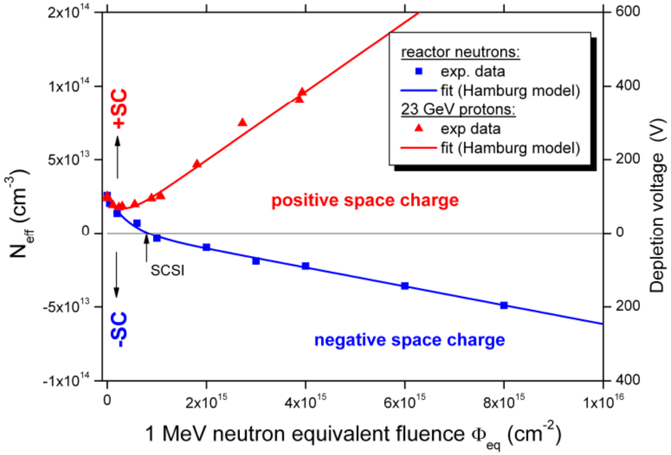

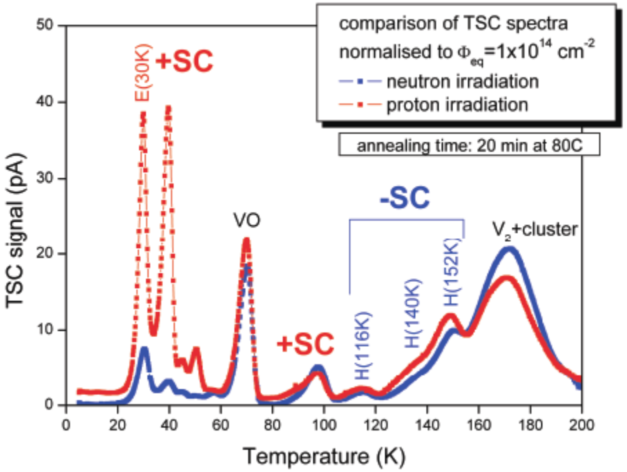

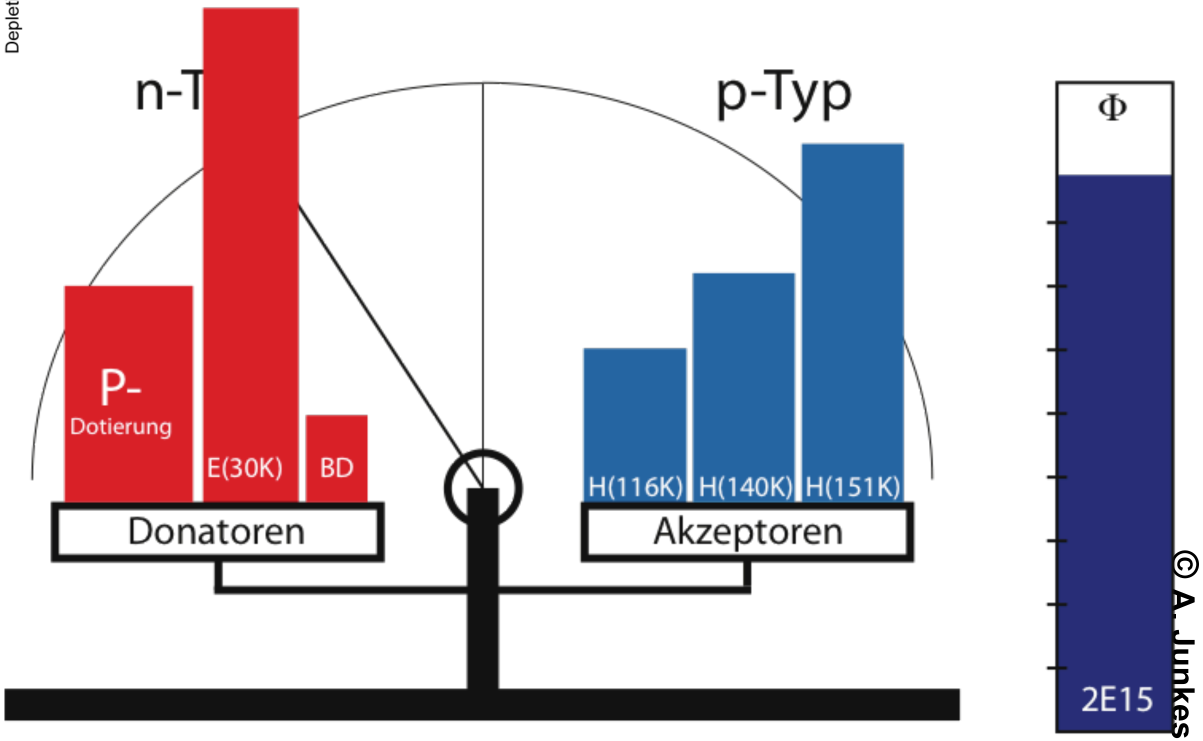

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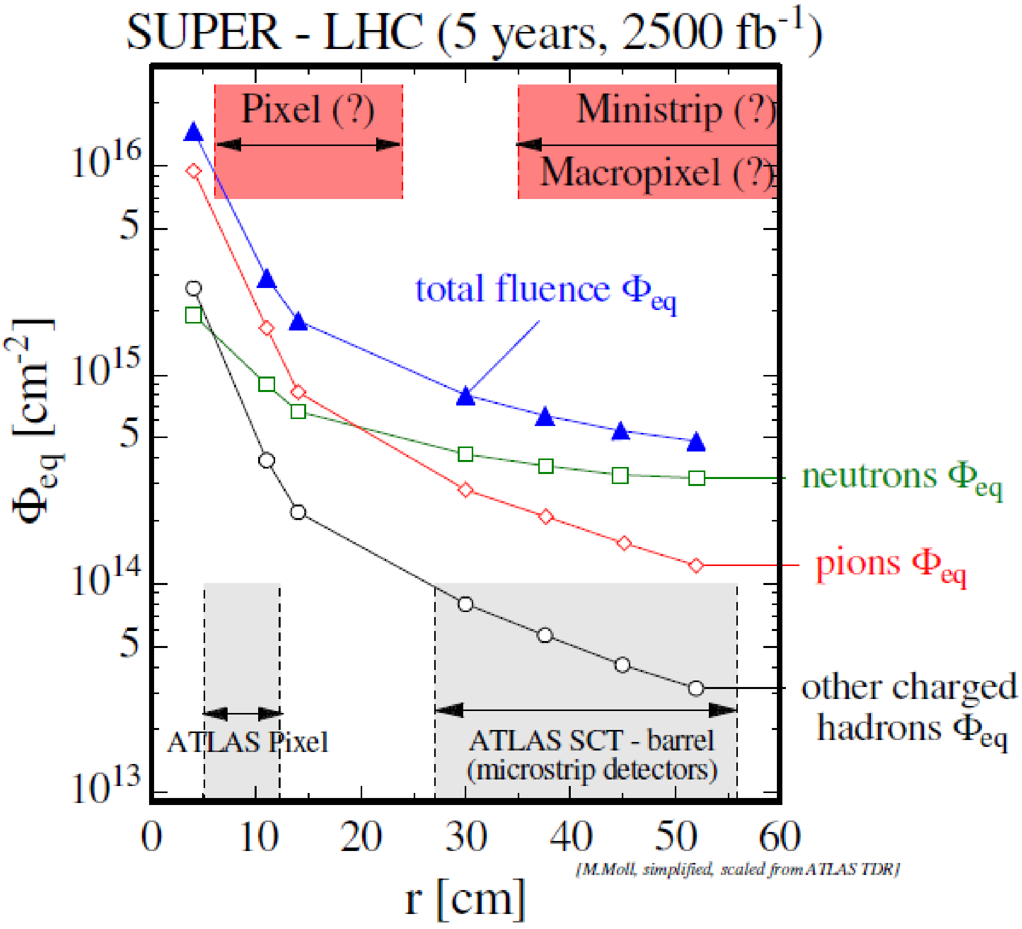
Mixed Irradiations: Neutrons and Protons

- HL-LHC experiments will be exposed to both charged hadrons and neutrons

- Small radii: pion dominated
- Large radii: neutron dominated

- Expect damage from different particles to add up
  - ➔ "total fluence ϕ_{eq}"
  - Affects V_{fd}, CCE and leakage current in the same way
- Measure what happens after mixed irradiations



[M.Moll, simplified, scaled from ATLAS TDR]

Mixed Irradiations: Change of N_{eff}

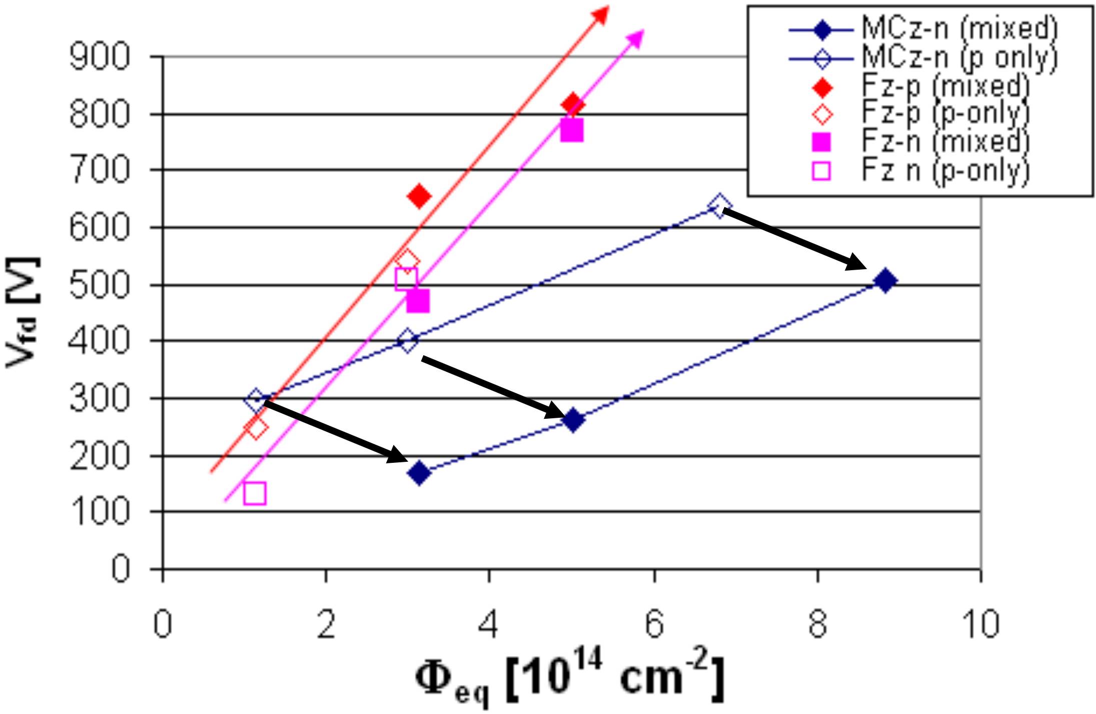
- **S-LHC detectors see charged hadrons and neutrons**
- **NIEL Scaling: Damage should add up. Irradiate in two steps:**
  - **First step: Irradiation with protons**
  - **Second step: Irradiation with neutrons**

[G. Kramberger et al., NIM A609 (2009), 142-148

- **Float-Zone (FZ): damage accumulated**
- **Magnetic Czochralski (MCz): damage compensated:**
- **Donors introduced in p irradiation appear compensated by acceptors introduced in n irradiation**

No compensation observed

- **in other Si materials beside MCz**
- **for the leakage current**
- **for the trapping**
- **both current and trapping continue to scale with Φ_{eq}**

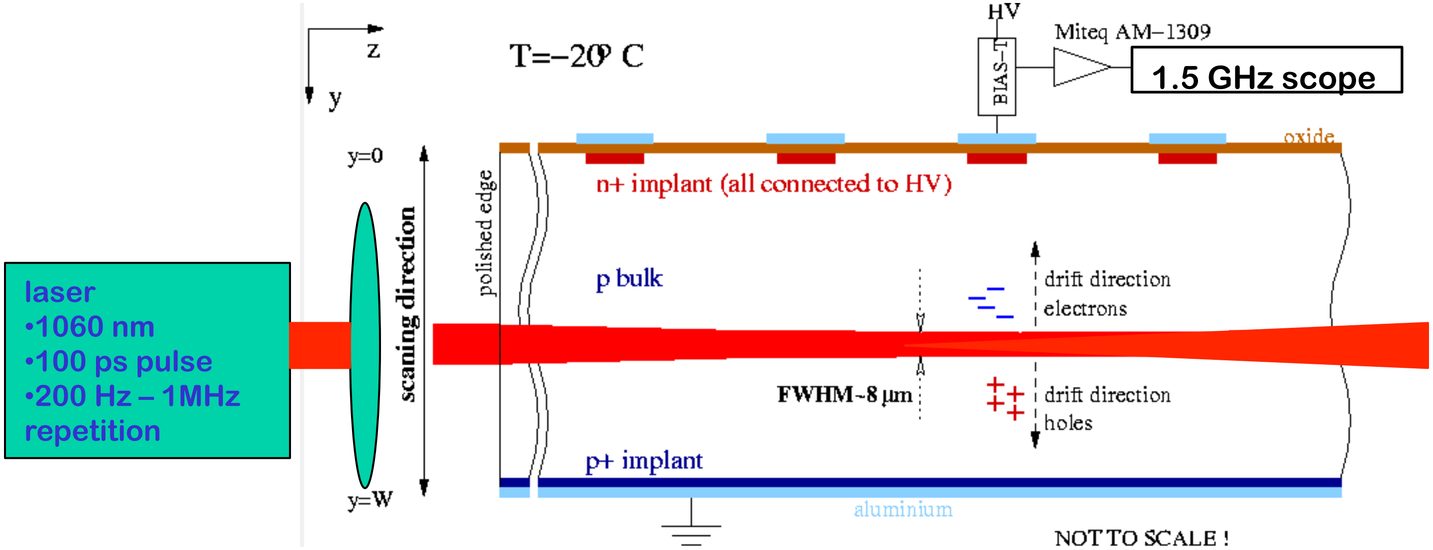


$$\Phi_{eq} = \kappa_p \Phi_p + \kappa_n \Phi_n$$

Edge-TCT to Study Fields

- Edge-TCT: Illuminate sensor from the side
- Scan across detector thickness
- Measure induced current as function of depth
- Reconstruct electric field and charge

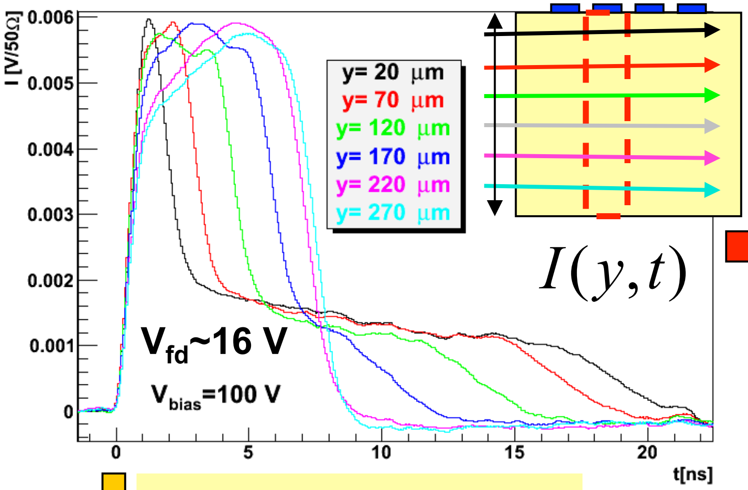
- Field expectation
  - Significant electric field only in depleted silicon
  - Charge generated in undepleted part of detector is lost
- Edge-TCT is powerful tool to probe field deep inside detectors



[G. Kramberger]

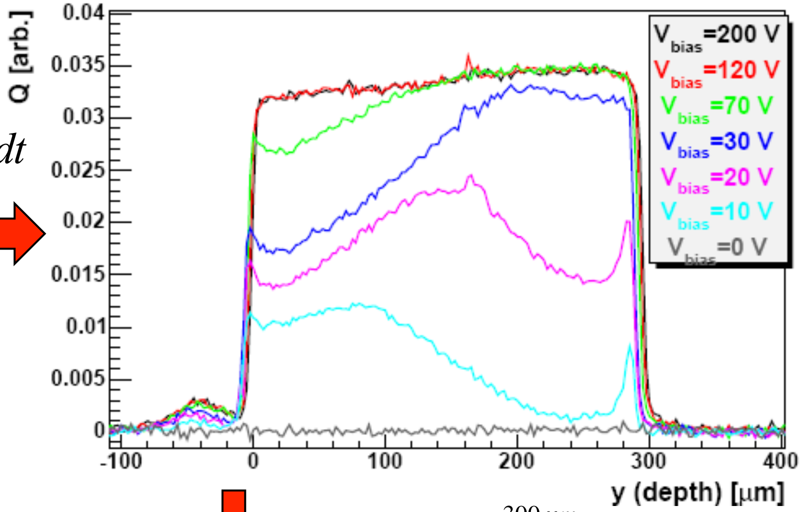
Edge-TCT: Charge and Velocity

RD50 Micron p-type sensor



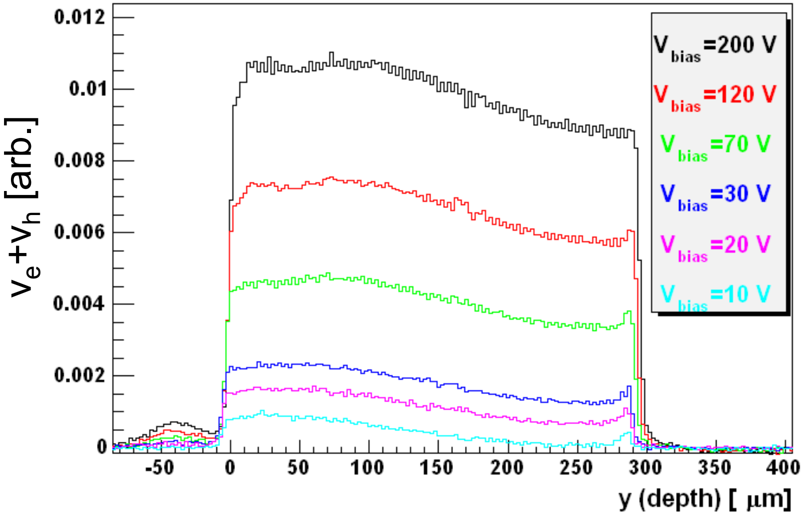
$$Q(y)=\int_0^{25ns} I(y,t)\,dt$$

CHARGE COLLECTION PROFILE

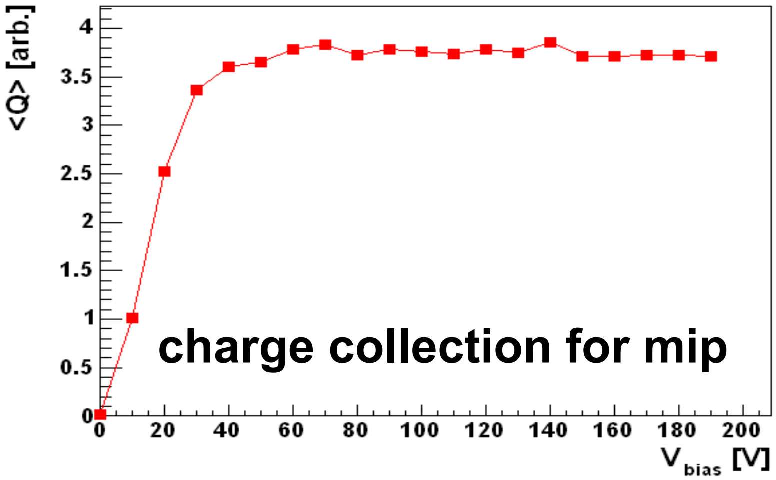


$$I(y,t\sim 0)\propto v_e+v_h$$

VELOCITY PROFILE



$$Q_{mip}\propto\langle Q\rangle=\int_0^{300\,\mu m} I(y,t)\,dy$$



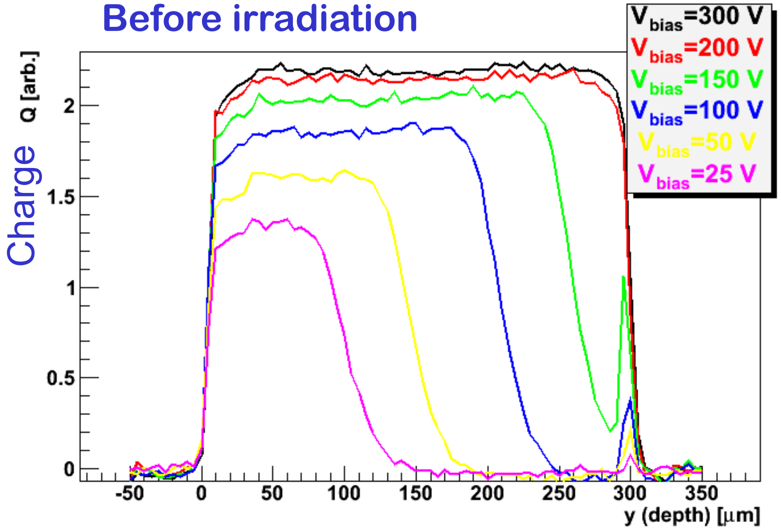
charge collection for mip

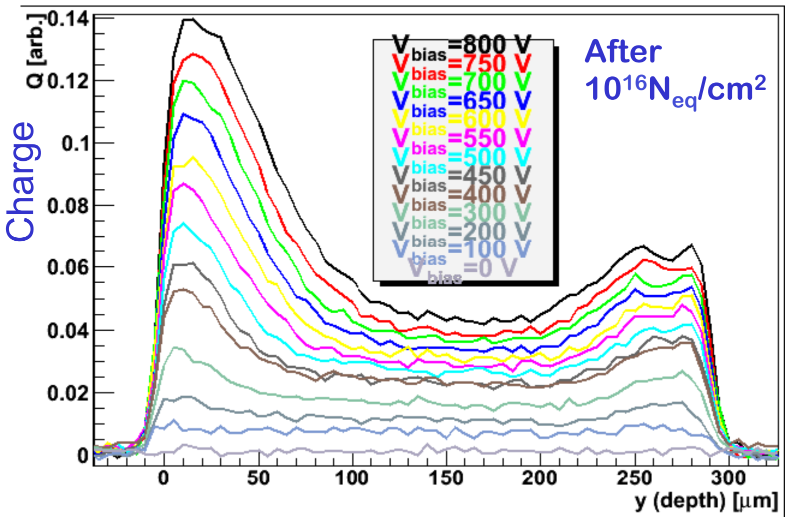
[G. Kramberger]

Field in Irradiated Sensors

- **Un-irradiated p-type detector**
  - Charge only collected from depletion zone
  - Depletion growing with bias until full depletion voltage (~180V)
  - No charge from undepleted part of sensor (no field)
- **Heavily irradiated p-type detector**
  - Even at low V_{bias}, charge is collected from all regions
  - High fields at front (strips) and also back side
  - Large field present in entire detector volume
    - Field in middle of detector around 0.5 V/µm at 700 V
  - Field results in additional signal

Before irradiation





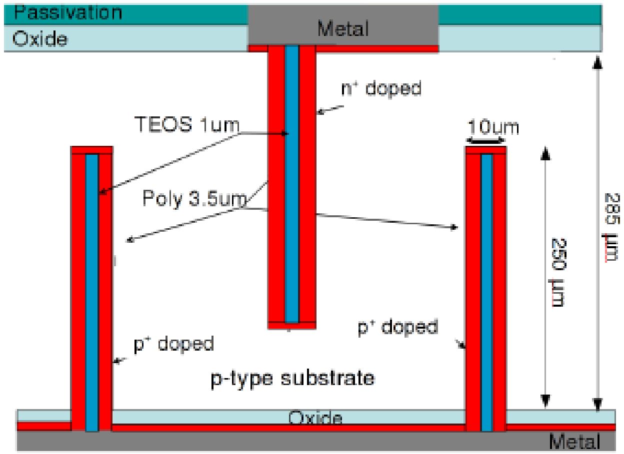
After $10^{16} N_{eq}/cm^2$

[G. Kramberger]

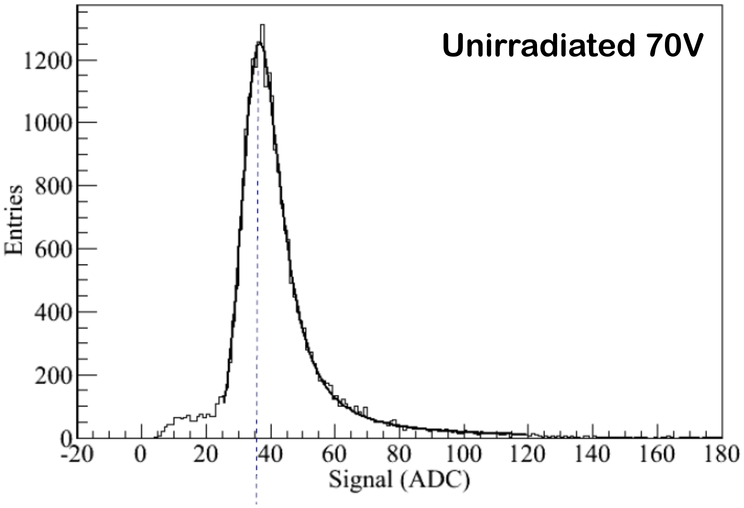
Depth (from surface of detector)

For details of technique and results see e.g.:
http://indico.cern.ch/materialDisplay.py?contribId=7&sessionId=3&materialId=slides&confId=111191

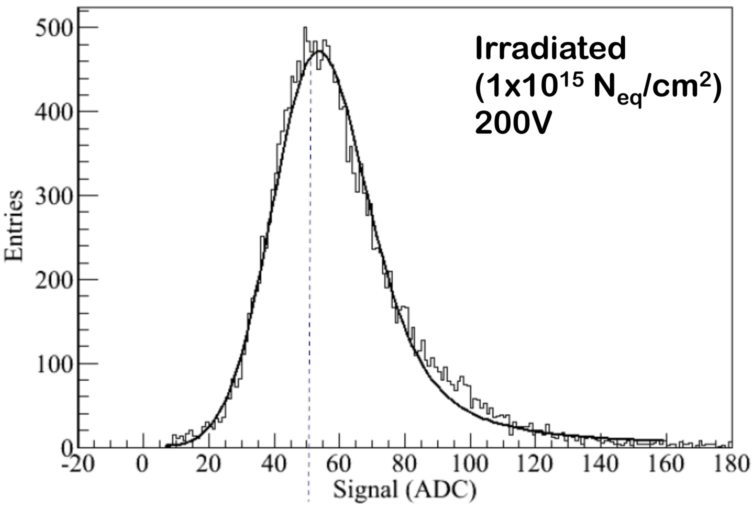
Charge Collection – 3d Detectors



- Double Sided 3d p-type sensors (made by CNM) in SPS testbeam
- Irradiation at Karlsruhe KIT cyclotron with 26MeV protons
- Higher signal after irradiation than before
  - Charge multiplication



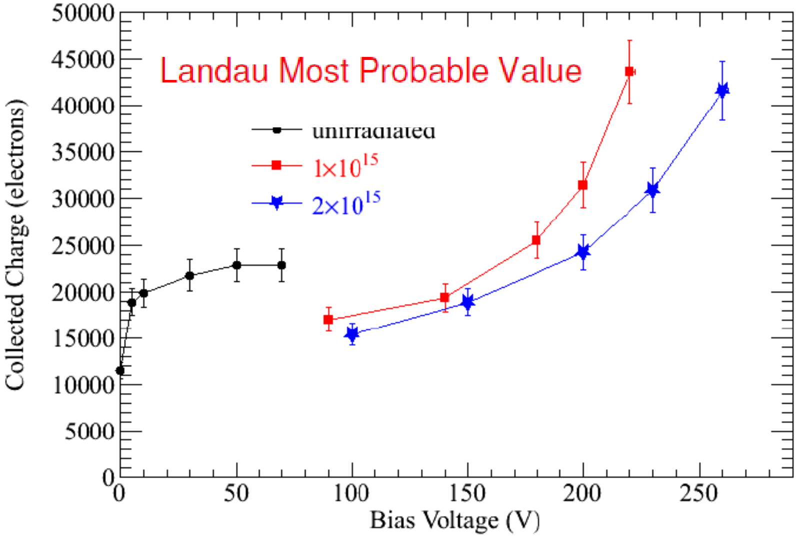
Landau MPV: 35 ADC

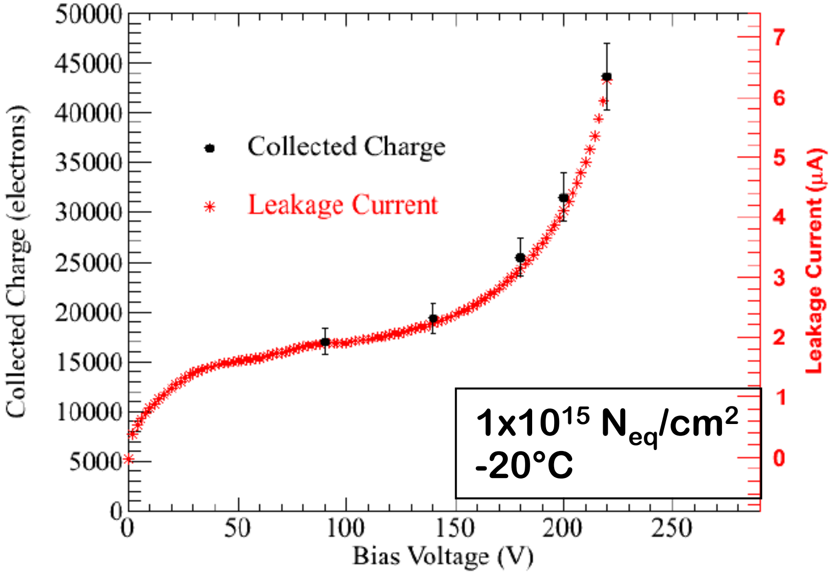


Landau MPV: 49 ADC

[M.Koehler et al., RD50 Workshop, May/June 2010]

Charge Collection – 3d Detectors



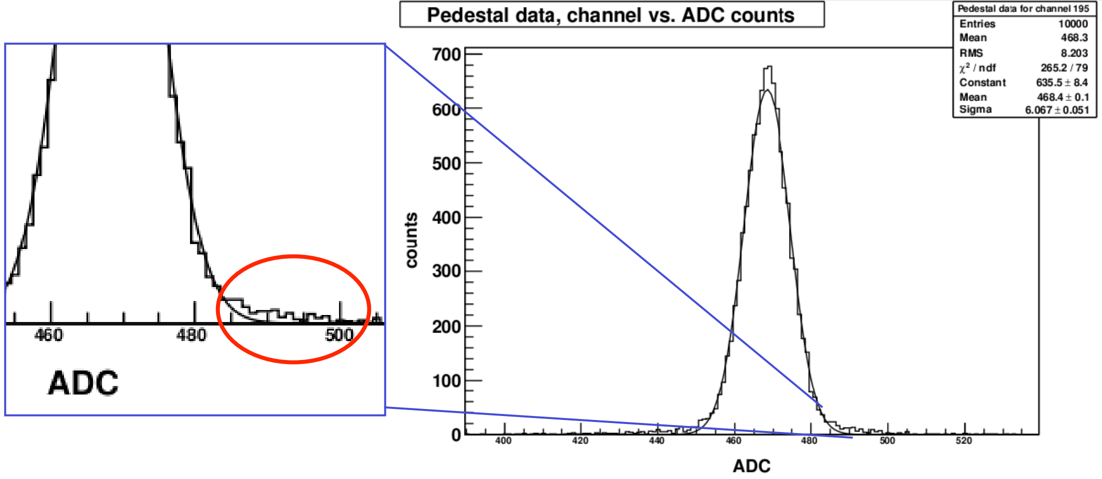


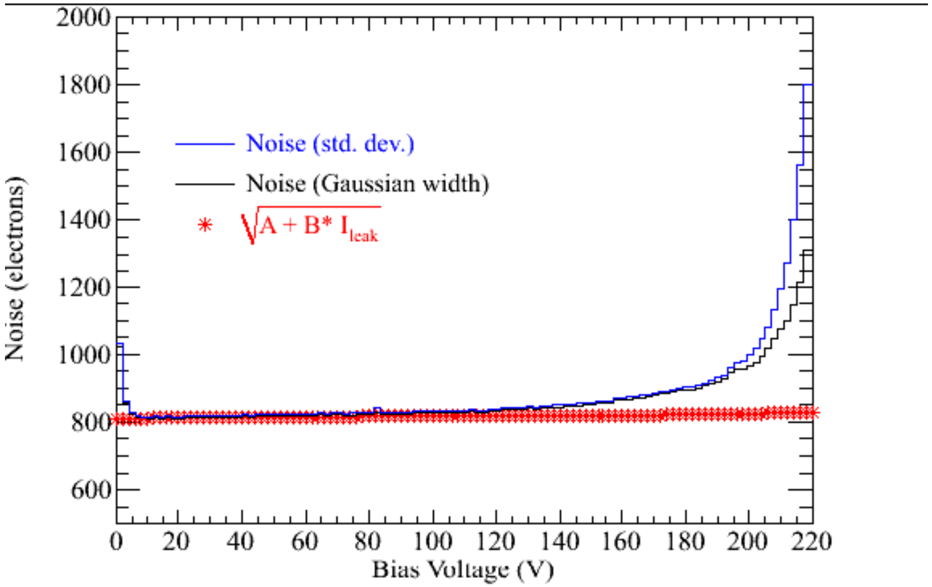
[M.Koehler et al., RD50 Workshop, May/June 2010]

- All charge is multiplied (also thermally generated charge)
- Origin: avalanche multiplication in high-field region close to junction columns
- P-type detector: e^- drifting near columns get multiplied
  - Effect has also been observed on similar n-type 3D DDTC, but to lesser extent
  - Holes seem to not multiply so easily (due to 3x lower mobility ?)
- Charge multiplication also in irradiated planar p-type detectors, but for higher V_{bias}
- High field in 3D detectors facilitates charged multiplication compared to planar designs

Noise and Charge Multiplication

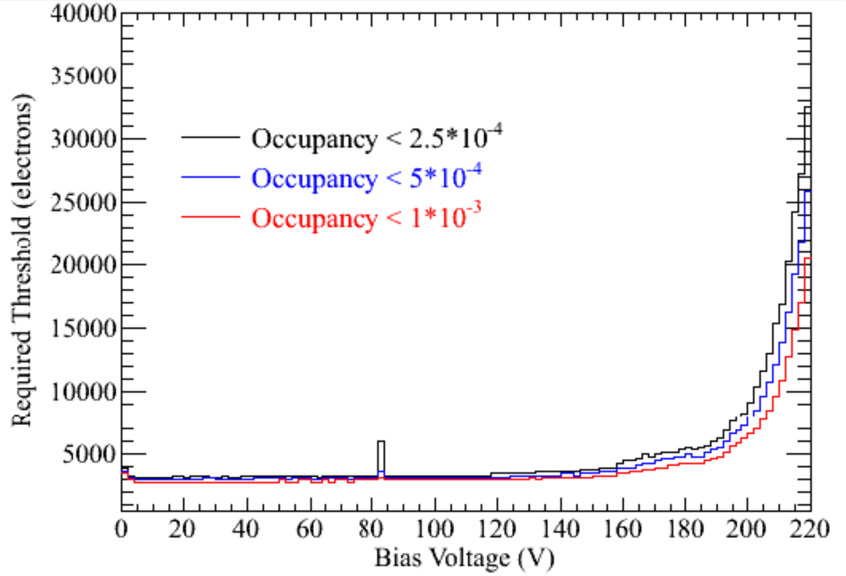
- Charge multiplication results in tails in pedestal distribution
- This non-Gaussian tails may appear tiny, but mean extra noise
- Noise increases, especially in high gain regime
  - This is not an effect of I_{Leak} (shot noise)
  - Gaussian assumption would underestimate noise

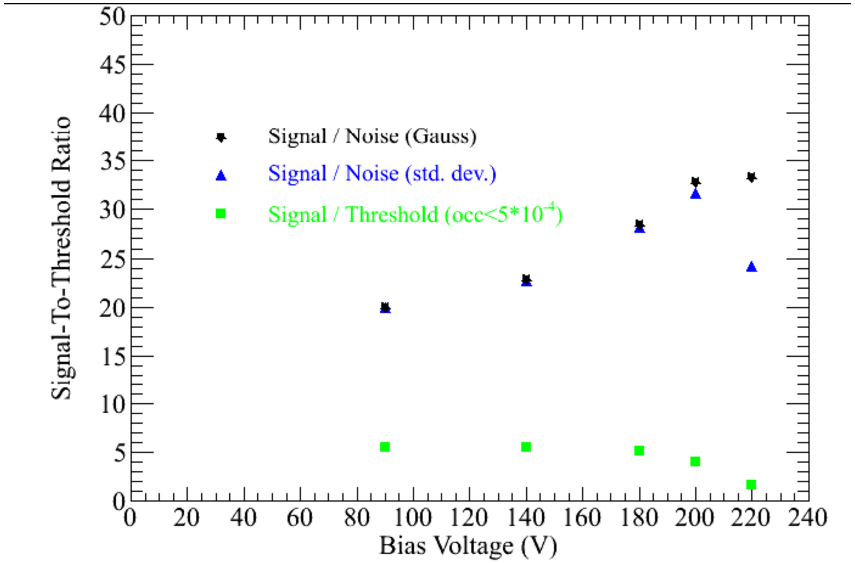




Noise and Charge Multiplication

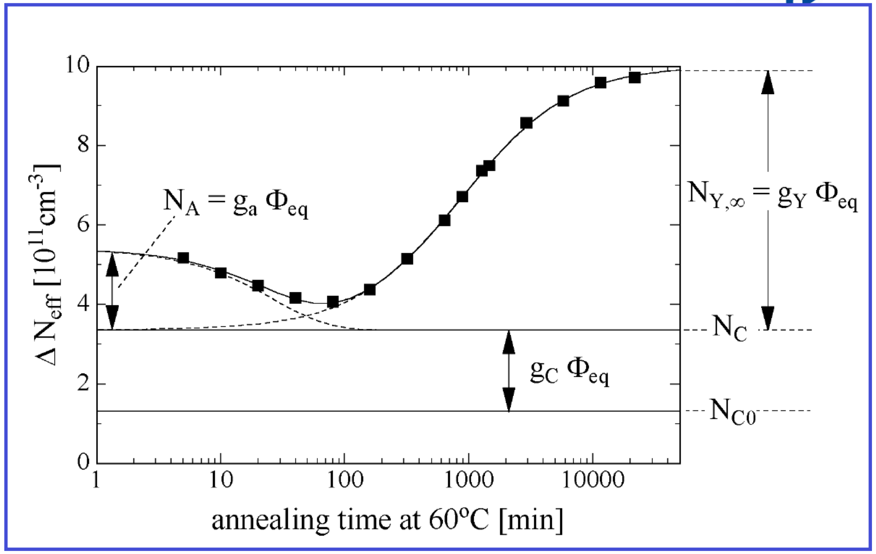
- Noise possible problem for real detector operation
- HL-LHC silicon strip systems will likely use binary readout - need to look at noise occupancy in addition to S/N
- Charge multiplication (CM) is beneficial for S/N…
- But: CM not necessarily useful for S/Threshold!
- These results were derived from few 3D DDTC sensors
  - Studies on other detectors ongoing
- Two dedicated RD50 CM sensor productions in the pipeline



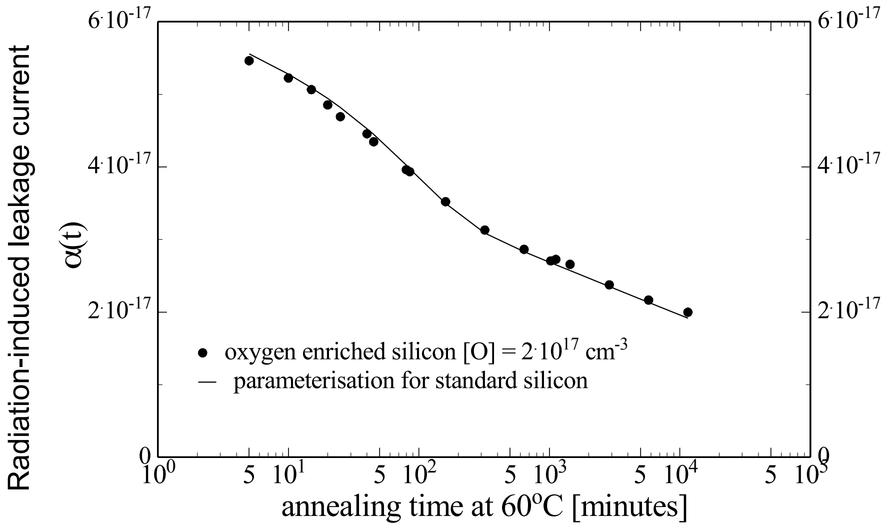


Annealing

- Defects change as function of time and temperature
- Use accelerated annealing
    - Rescale short annealing times at high temperatures to very long annealing at 20°C
    - E. g. at 60 °C, scaling factor 550
    - Based mainly on older (ROSE) N_{eff} studies and lower fluences
    - HL-LHC benchmark is signal (Charge Collection Efficiency CCE) or signal/noise at very high fluences
    - Charge multiplication effects play a significant role
- **Recent results indicate that our scaling needs modification for HL-LHC**



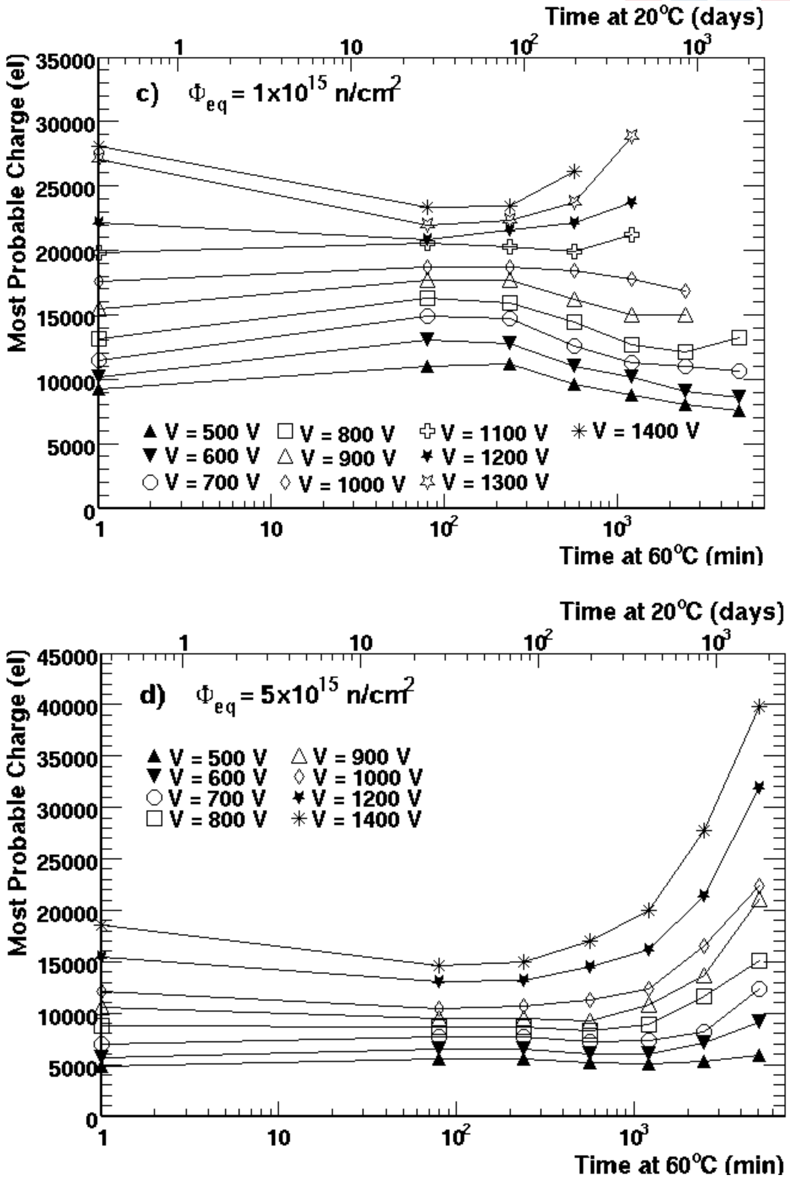
M. Moll



M. Moll

Annealing of CCE

- Signal (CCE) in irradiated HPK n-in-p mini detectors as function of annealing time and V_{bias}
- CCE at high fluences & high voltages (charge multiplication regime)
  - Most probable charge drops due to short term (“beneficial”) annealing
    - N_{eff} drops → smaller peak electric field → less multiplication
  - Most probable charge rises due to long term (“reverse”) annealing:
    - N_{eff} rises → larger peak electric field → more multiplication
- No need to fear reverse annealing if charge multiplication can be usefully exploited

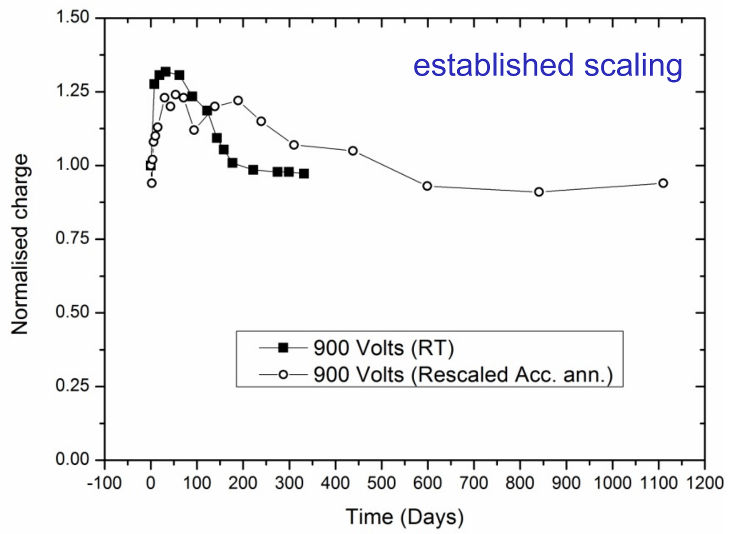


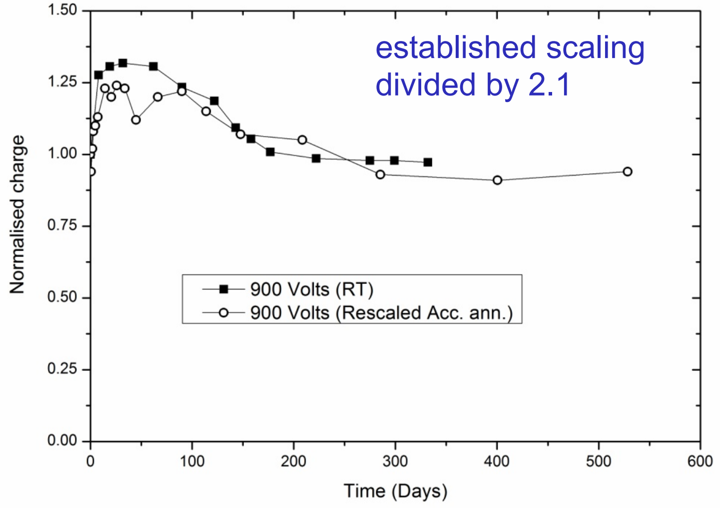
I. Mandić, 17th RD50 Workshop, CERN, 17 – 18 November 2010

Accelerated Annealing

Albert-Ludwigs-Universität Freiburg

- Compare room temperature and accelerated annealing
  - HPK FZ n-in-p, 1 and 1.5×10^{15} n_{eq} cm^{-2} (26MeV p irradiation)
- Normalised CCE as benchmark
- Scaling seems factor ≈2 too large

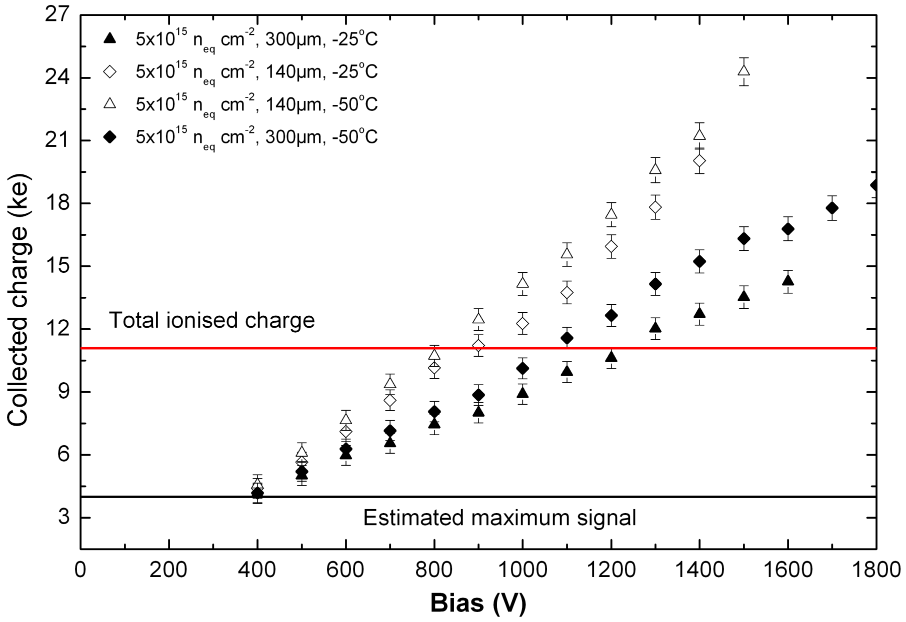




G. Casse, 18th RD50 Worksho, Liverpool, May 2011

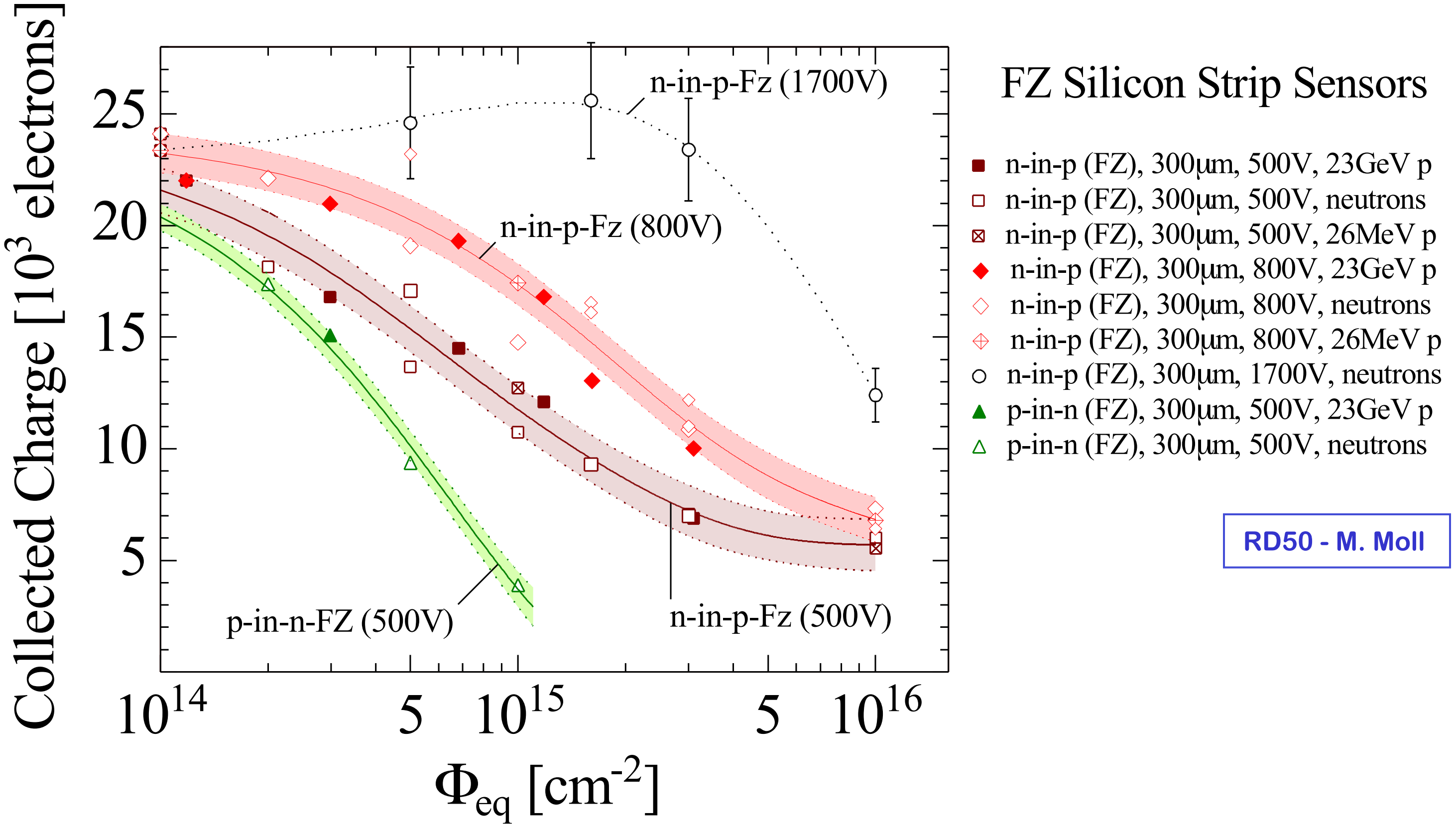
Sensor Thickness

- **Charge deposition proportional to thickness**
- **Should be the same for collected charge**
- **Charge multiplication occurs after heavy irradiation and high bias voltages**
  - **This changes the game**
- **Compare thin and normal sensors**
  - **140 and 300 μm n-in-p Micron micro-strip sensors after $5\mathrm{x}10^{15}$ n_{eq} (26MeV protons)**
  - **Charge much higher in thin sensors**
  - **Thin sensors also mean less radiation length**
  - **NB: Current in thin sensors is higher than in normal ones (thermally generated charges get also multiplied)**



G. Casse, 18th RD50 Workshop, Liverpool, May 2011

Planar Detector Compilation



RD50 - M. Moll

- p-in-n fades away well before $10^{15}N_{eq}/cm^2$
- n-in-p still gets 50% charge at $10^{16}N_{eq}/cm^2$ at high bias voltages
- n-in-p benefits from charge multiplication (at high bias voltages)
- n-in-p (n-in-n) superior material for high radiation environments

Conclusions

- RD50 working across experiment boundaries on developing radiation-hard silicon detectors for e.g. the HL-LHC
- Large progress in understanding the effective doping concentration
- For high fluences, significant electric field exists even in undepleted region, resulting in higher signals
- Charge amplification observed on many sensors. CCE benefits from it, but open questions remain
  - The S/N ratio benefits too (mostly), but this may be an issue of the way we derive the noise
  - Can the extra signal be exploited to increase the radiation hardness ?
  - Need to study long-term stability

Recommendations

- Disclaimer: some views may be biased
- Planar detectors do better than expected
  - P-type detectors reduce trapping effects and can operate partially depleted
  - Significant electric field exists in undepleted region
  - Charge multiplication gives extra signal

- HL-LHC Si detector recommendations:
- N-in-p (n-in-n) planar detectors
  - good enough for most regions, well understood, expect this to be the default material at HL-LHC
- 3D detectors
  - could add extra radiation hardness and facilitate operation at lower voltage if required for innermost HL-LHC tracking layer(s)
  - watch out for extra costs and risks
- Credits: Tony Affolder, Gianluigi Casse, Paula Collins, Doris Eckstein, Alexandra Junkes, Michael Köhler, Gregor Kramberger, Igor Mandic, Michael Moll, Ioana Pintilie