Radiation Damage in Silicon: Investigation and Simulation

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"Physics at the Terascale"

Universität Hamburg
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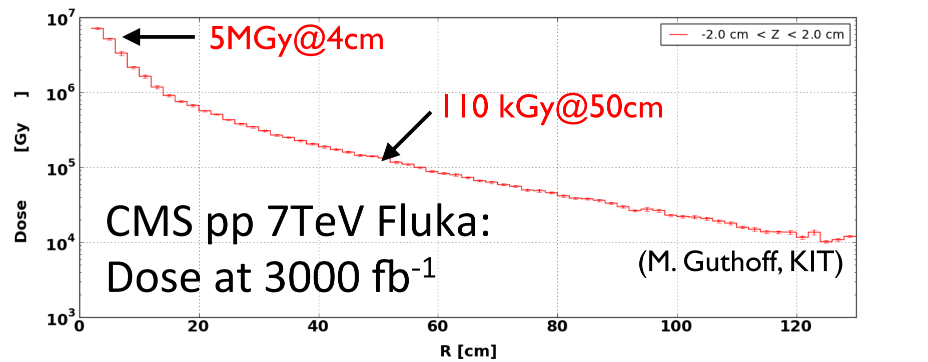
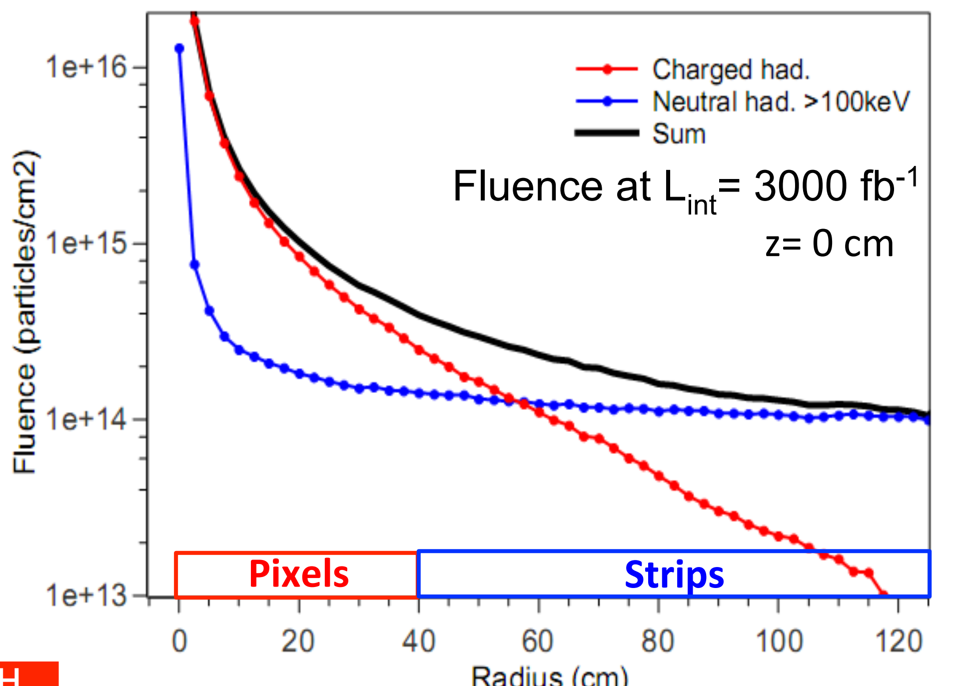
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

CMS
Compact Muon Solenoid

Radiation Damage in Pixel Sensors





Radiation hardness to $\Phi \approx$2E16 cm^{-2} for innermost pixel layer

- Phase 2 will yield 3,000 fb^{-1} and about 300 fb^{-1}/year.
- Radiation damage of the previous 10 years in only one year!

Surface damage not negligible for pixel region:

- Dose at 4 cm: 5 MGy
- Dose at 50 cm: 110 kGy

→ Understand impact

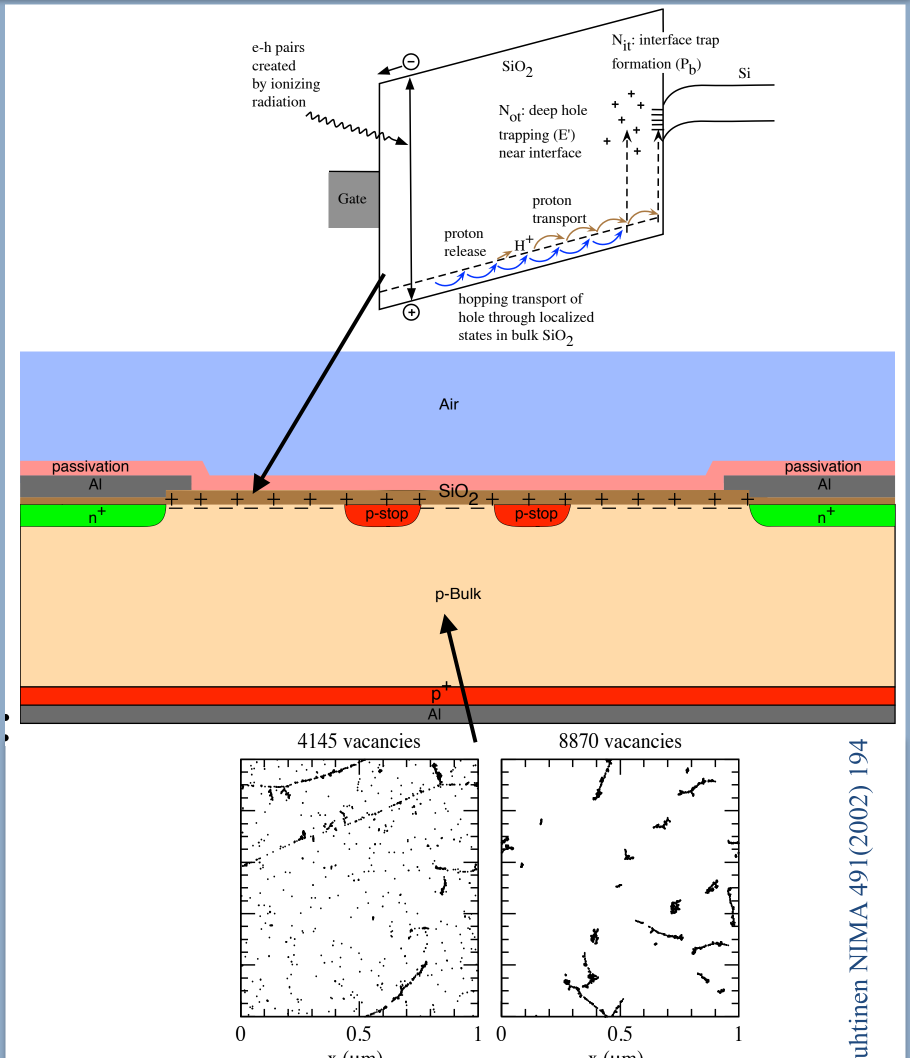
Impact of Radiation damage

Surface damage (Ionising Energy Loss):
- Increase of oxide charge
- Increase of interface traps

➔ Increase of leakage current
➔ Change of break-down voltage
➔ Change of charge collection

Bulk damage (Non-Ionising Energy Loss):
- Cluster and point defects

➔ Change of the space charge
➔ Change of depletion voltage
➔ Change of leakage current
➔ Change of trapping



Vacancies after $\Phi_{eq}=10^{14}$ cm^{-2}

Surface and Bulk damage

Today's knowledge:

Surface defects in p-on-n sensors:

- Oxide-charges build-up from photons
- Some understanding of the generation of interface-states

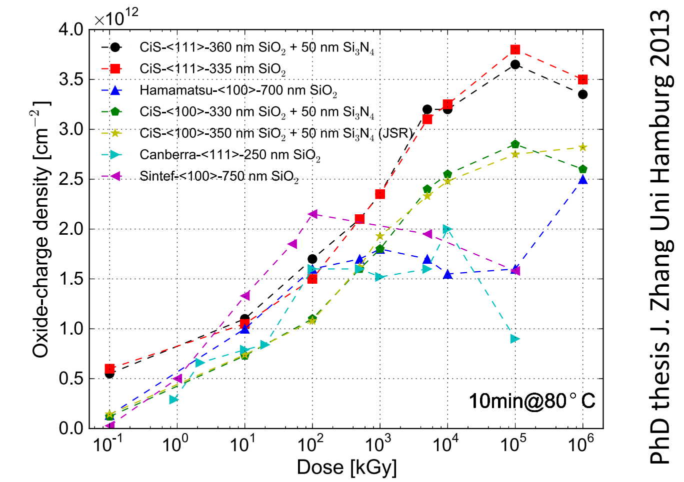
→ Effective model for simulations

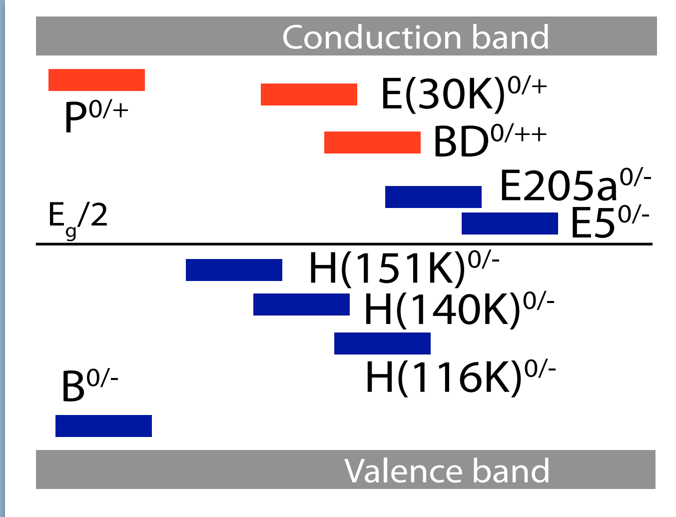
Bulk defects meanwhile also in n-on-p sensors:

- Leakage current scales with fluence, originates from cluster defects, mechanism not fully understood
- Several bulk defects with impact on depletion voltage found, impact on space charge not fully understood
- Some defects suspected to do trapping

→ Several models with 2-, 3-, 5- levels ("free parameters") available for up to $\Phi=10^{15}$ cm^{-2}

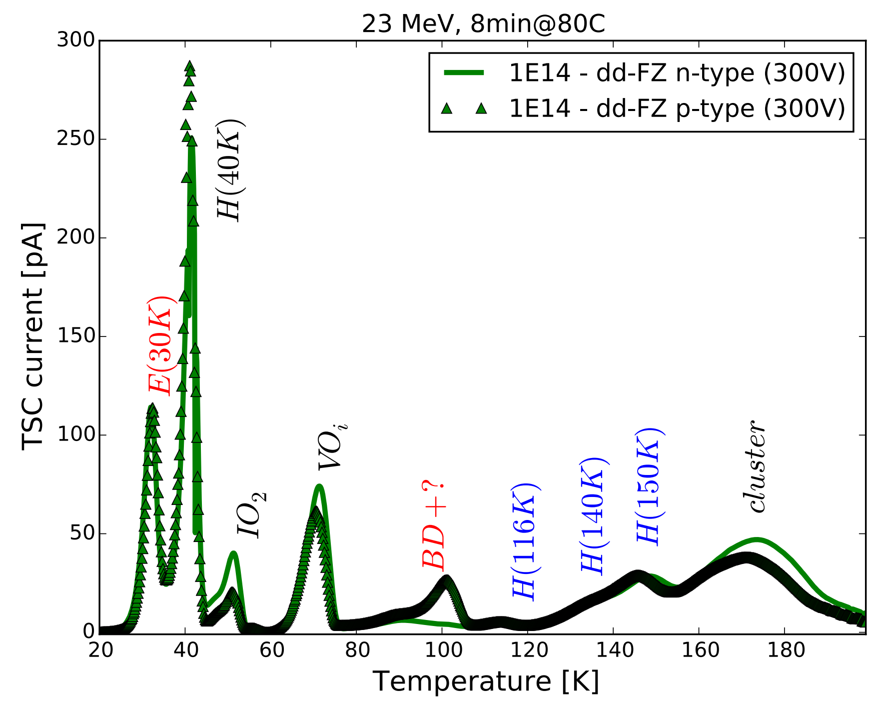
Dose dependence of oxide-charge density



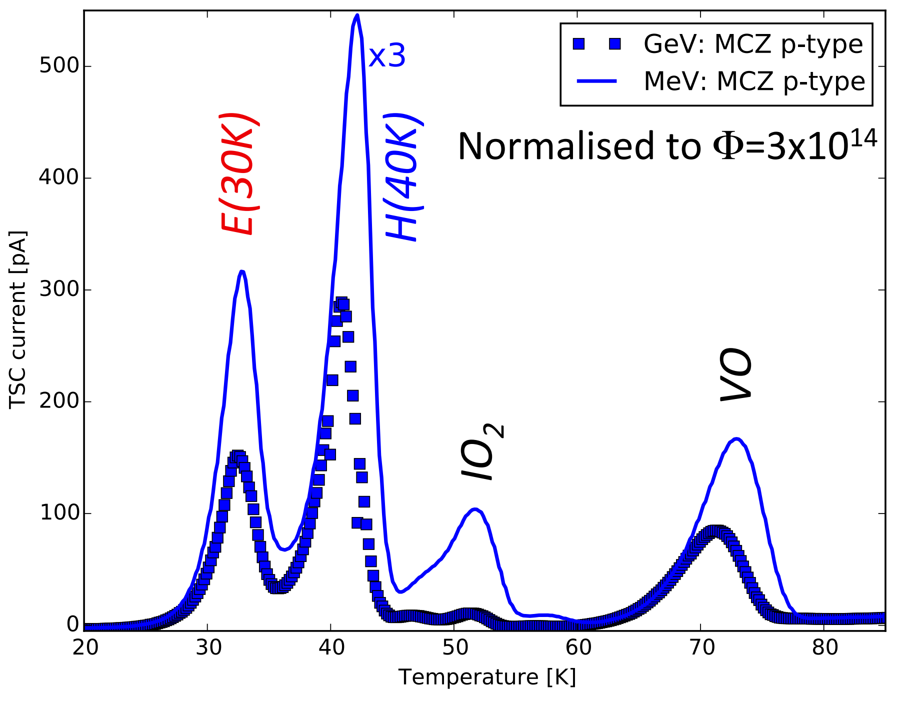


Defect Studies with TSC

Comparison n- vs. p-bulk



GeV proton vs. MeV proton irradiation

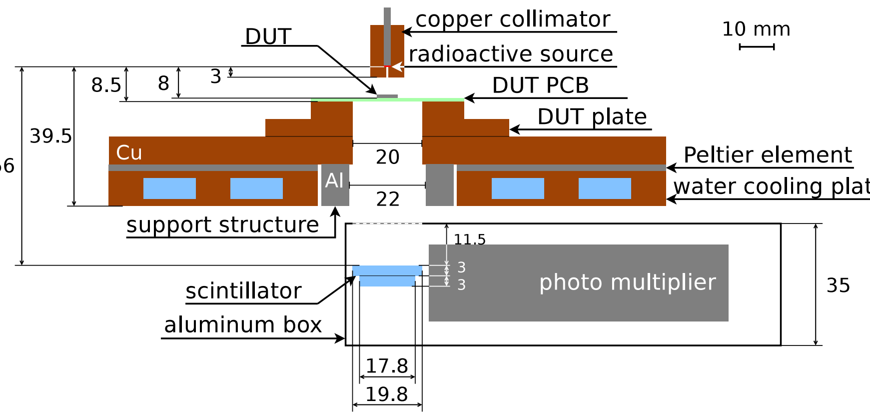


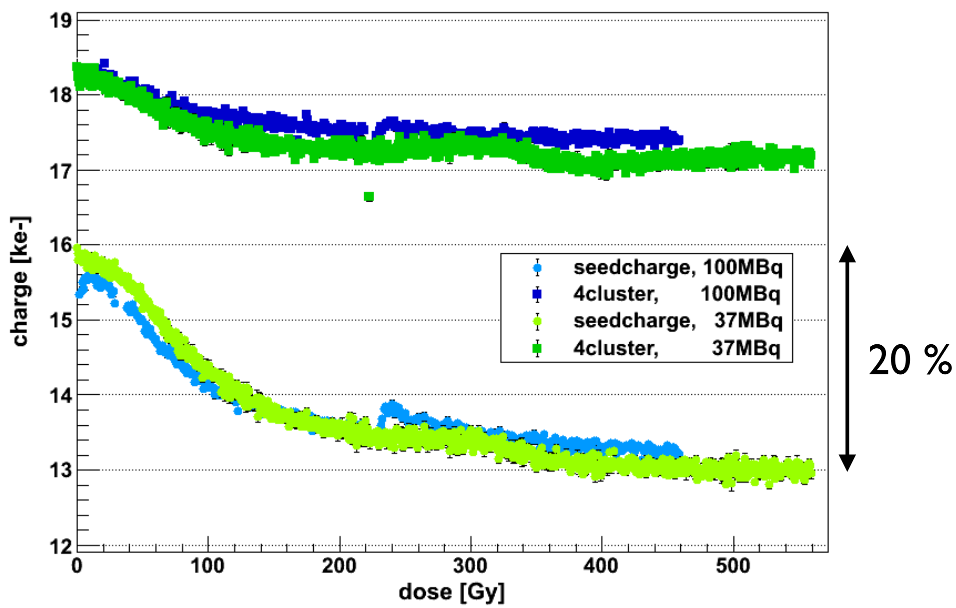
- No big differences between n- & p-bulk sensors
- N-type models valid also for p-type

- Big difference seen in low-Temperature region
- Point-like defect (donor-like defects) suppressed

Relevance of Surface Damage

- β-Setup + ALiBaVa for readout
- ^{90}Sr source with 37 and 100 MBq
- Dose rate ≈ 2.1 Gy/h for 100 MBq source
- AC-coupled n^+-p sensor (MCZ200P):
  - p-stop isolation
  - pitch 80 µm, implant width 19 µm, metal width 31 µm, thickness 200 µm
- Non-irradiated sensor at 600V

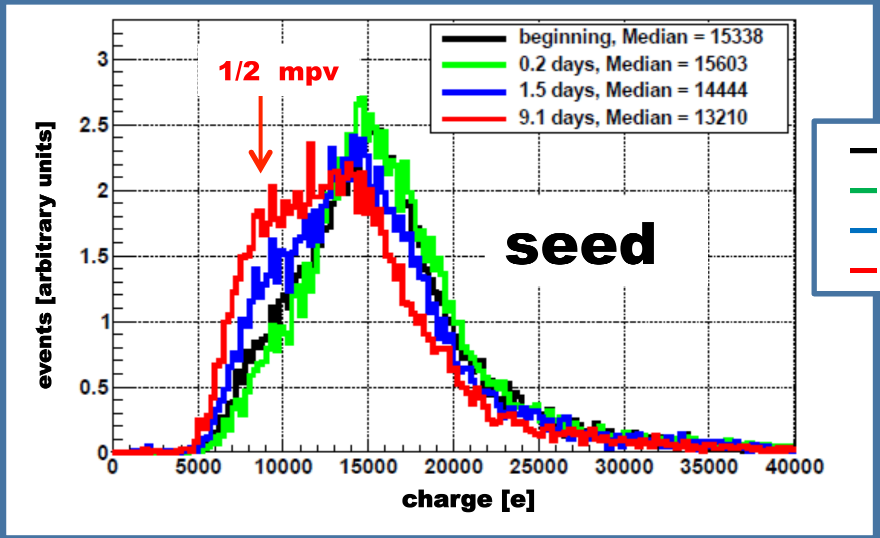


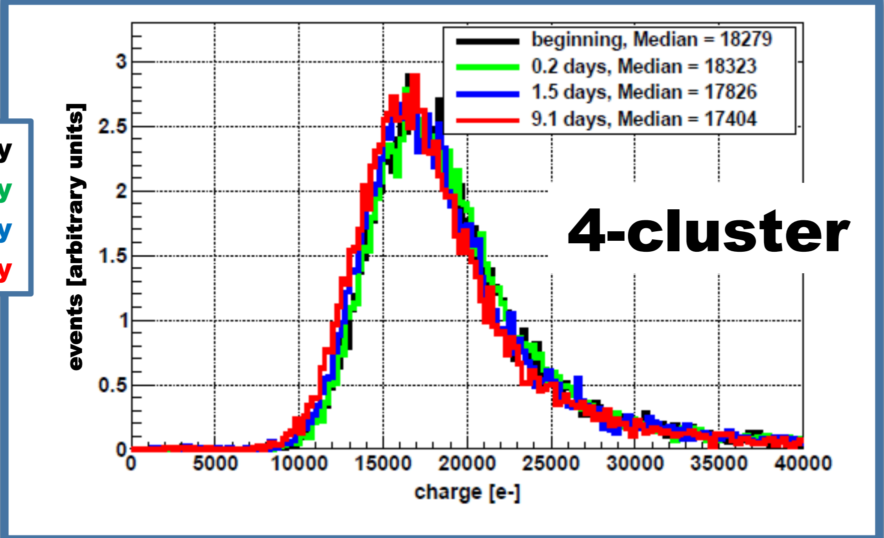


- Already at ~ 200 Gy signal loss in seed strip ≈ 20 %
- Loss similar to bulk damage after $1.5 \cdot 10^{15}$ neq/cm^2

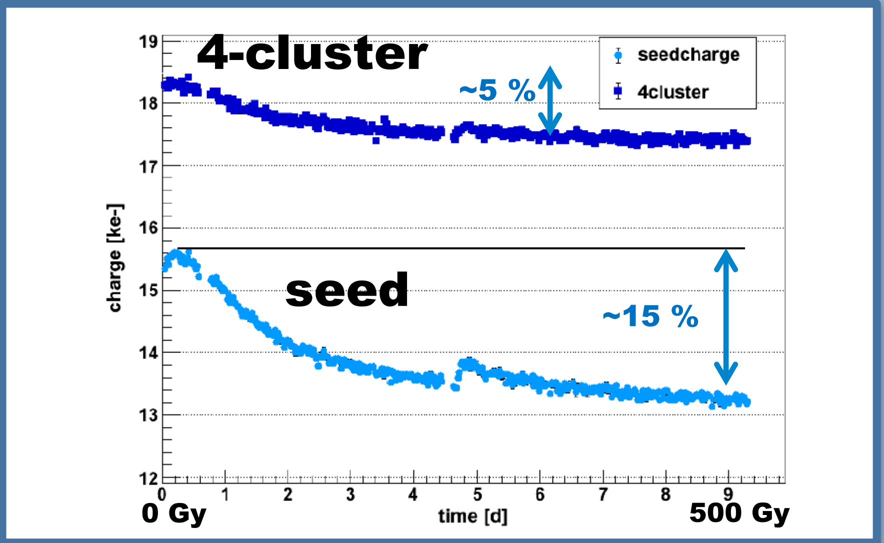
(figures Chr. Henkel, BSC-Thesis)

Charge Losses Surface Damage





- Degradation of Landau-Gaussian distribution due to more charge sharing
- Still 5% reduction in seed strip for Φ_{eq}=2.1x10^{15} cm^{-2} irradiated sensor
- Depends strongly on strip parameters



- **ATLAS results do not show this feature**
  → See next talk by A. Dierlamm

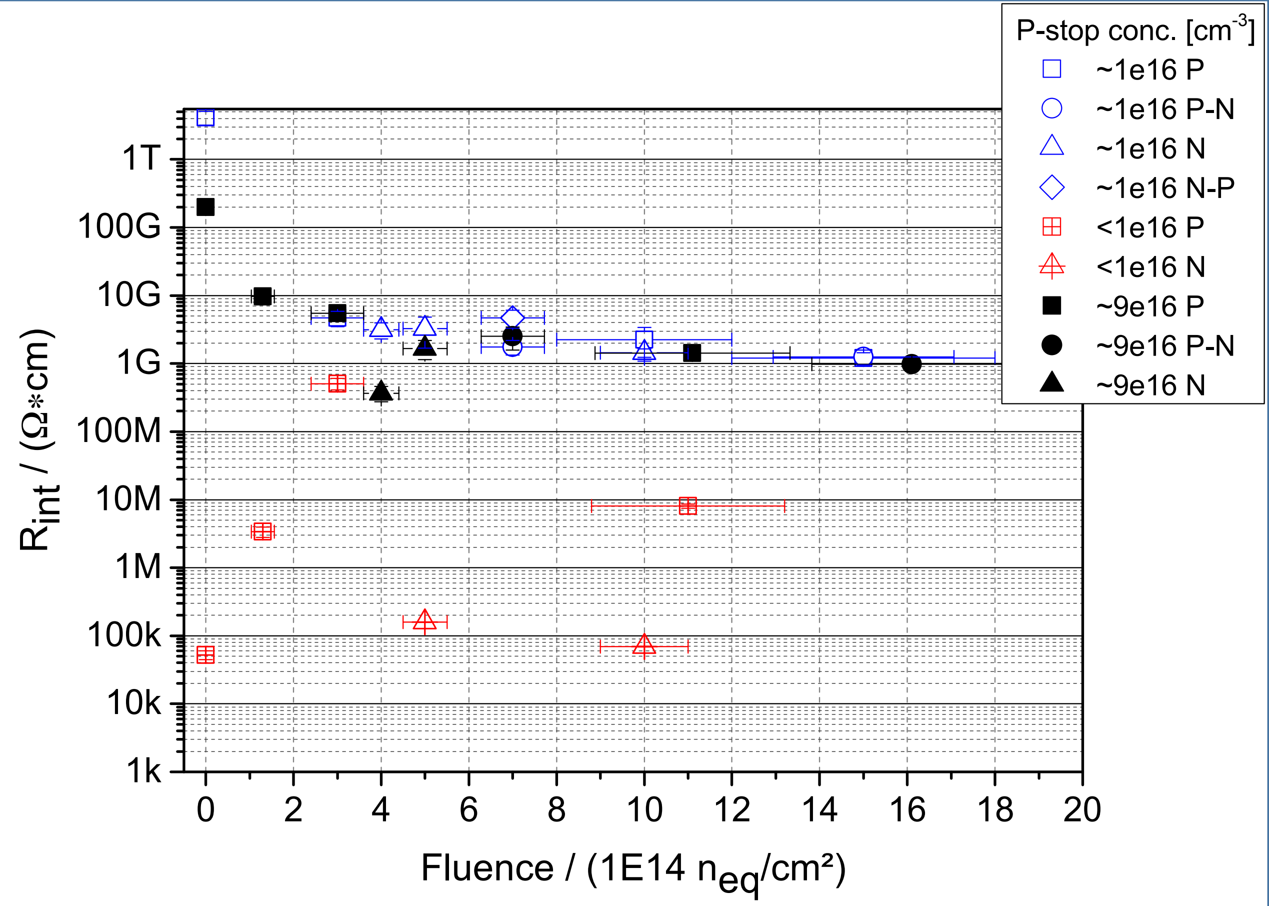
Inter-strip Resistance

Strip isolation for n-in-p sensors: p-stop concentration:

- $< 1x10^{16}$ cm^{-3}
→ R_{int} in MΩ-range
→ Not suffient

- $> 1x10^{16}$ cm^{-3}
→ R_{int} > 200 MΩ
→ Sufficient strip isolation

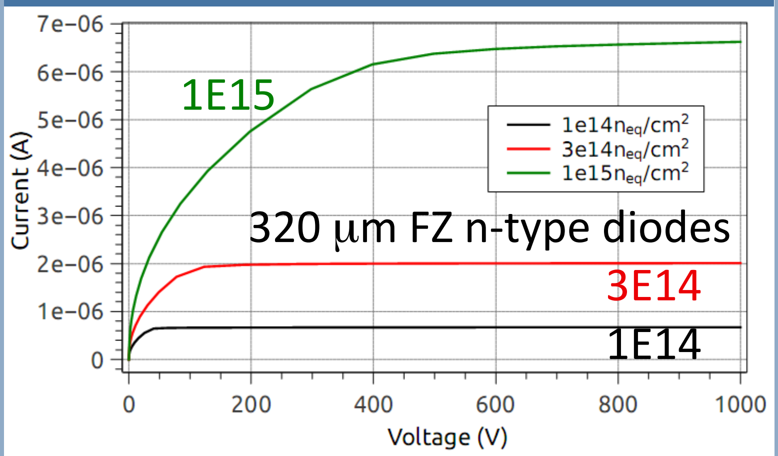
- $= 9x10^{16}$ cm^{-3}
→ High noise after irrad.



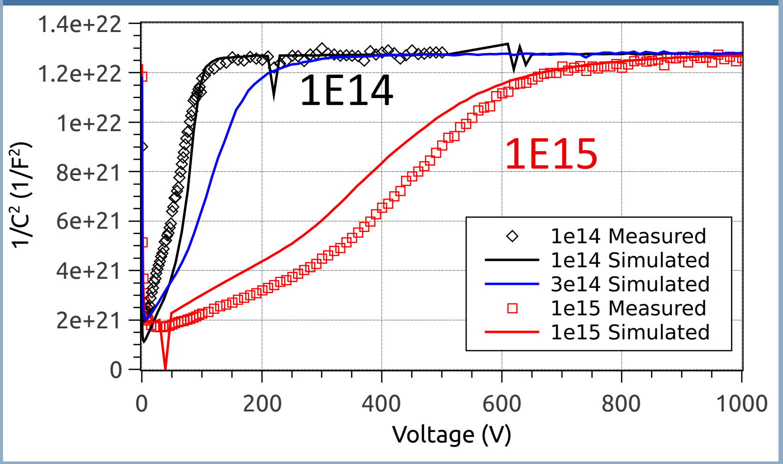
Optimal p-stop concentration between $1x10^{16}$ cm^{-3} and $9x10^{16}$ cm^{-3}

Simulation: Effective Two-Trap Model

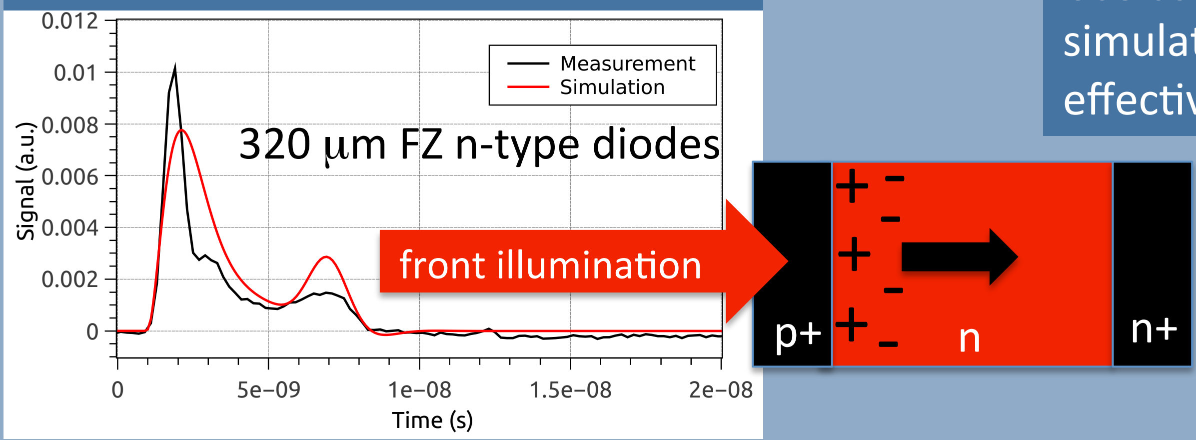
Current-Voltage measurements



Capacitance-Voltage measurements



Red laser TCT measurements



Use comparison of measurement and simulation to adjust parameters for effective donor and acceptor levels:

- Energy levels (E_a)
- Hole & electron capture cross sections ($\sigma_{e,h}$)
- Concentrations (N_D)

Simulation Models

Based in the 2-trap EVL model
V. Eremin, NIM A 535 (2004) 622-63.

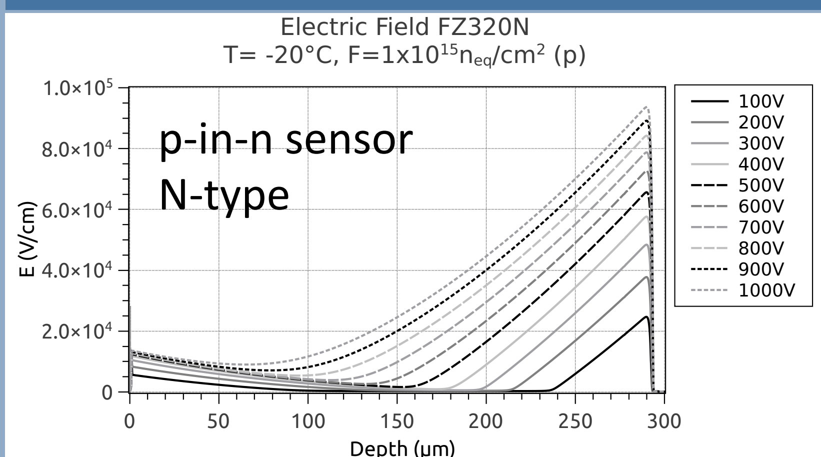
Effective neutron two-trap model:

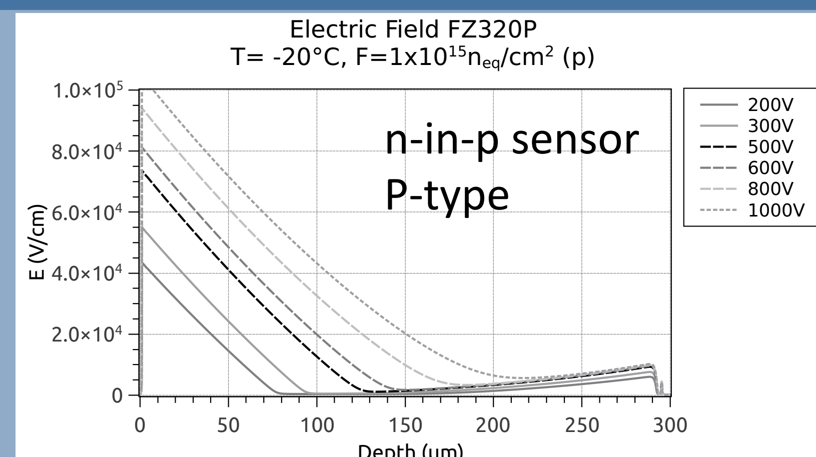
Parameter	Donor	Acceptor
Energy [eV]	E_V+0.48	E_C-0.525
Concentration [cm^{-3}]	1.395 $cm^{-1} \times$ F	1.55 $cm^{-1} \times$ F
σ_e [cm^2]	1.2×10^{-14}	1.2×10^{-14}
σ_h [cm^2]	1.2×10^{-14}	1.2×10^{-14}

Effective proton two-trap model:

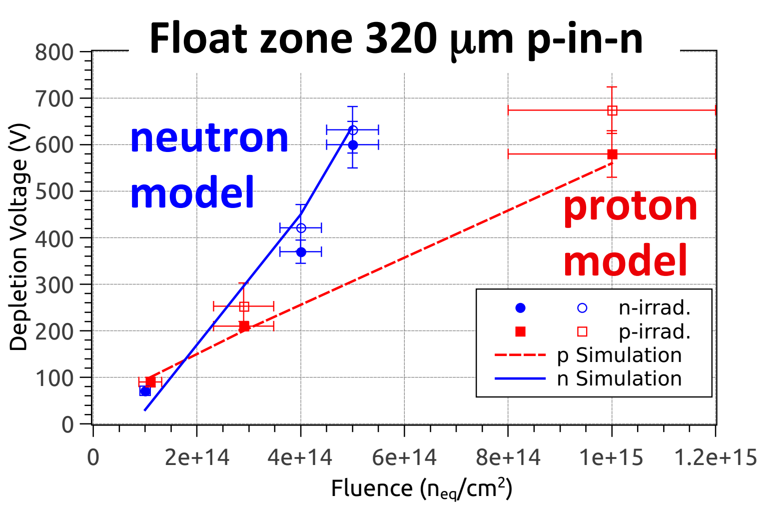
Parameter	Donor	Acceptor
Energy [eV]	E_V+0.48	E_C-0.525
Concentration [cm^{-3}]	$5.598\ cm^{-1} \times F - 3.949 \cdot 10^{14}$	$1.189\ cm^{-1} \times F + 6.454 \cdot 10^{13}$
σ_e [cm^2]	1.0×10^{-14}	1.0×10^{-14}
σ_h [cm^2]	1.0×10^{-14}	1.0×10^{-14}

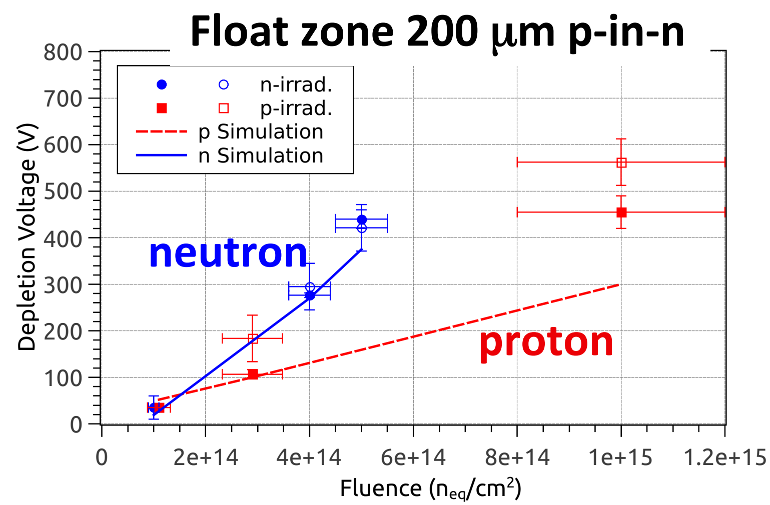
Electric Field at $\Phi=1x10^{15}\ cm^{-2}$ proton irradiation for 300 μm float zone sensors

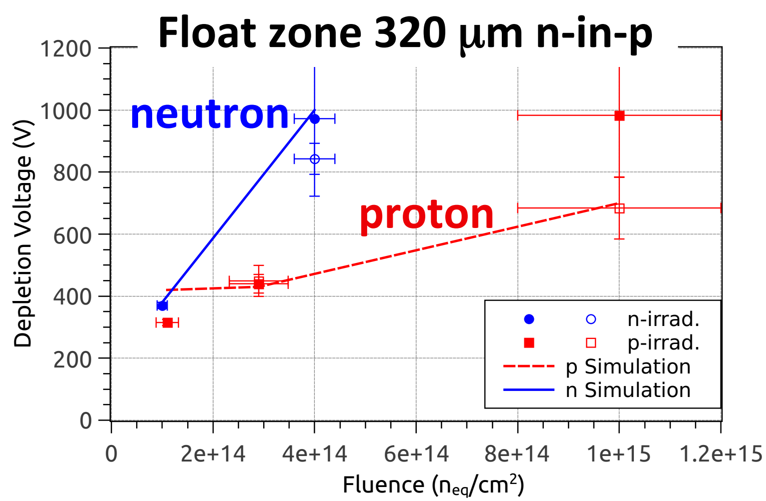


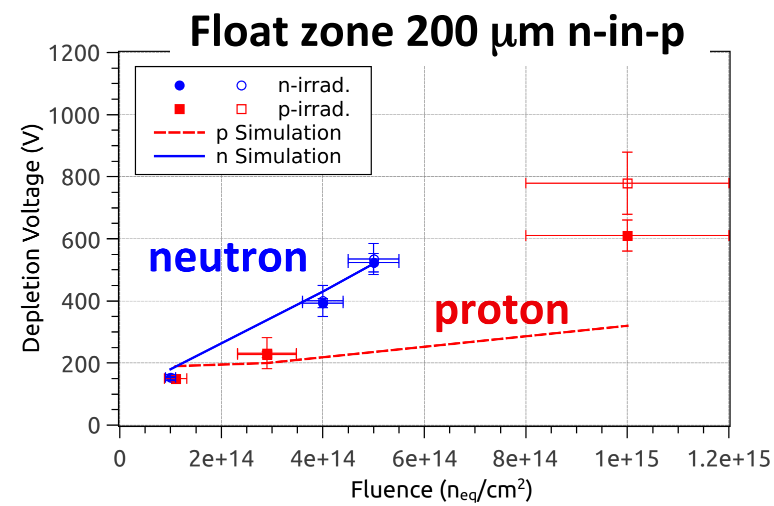


Simulation of the Depletion Voltage

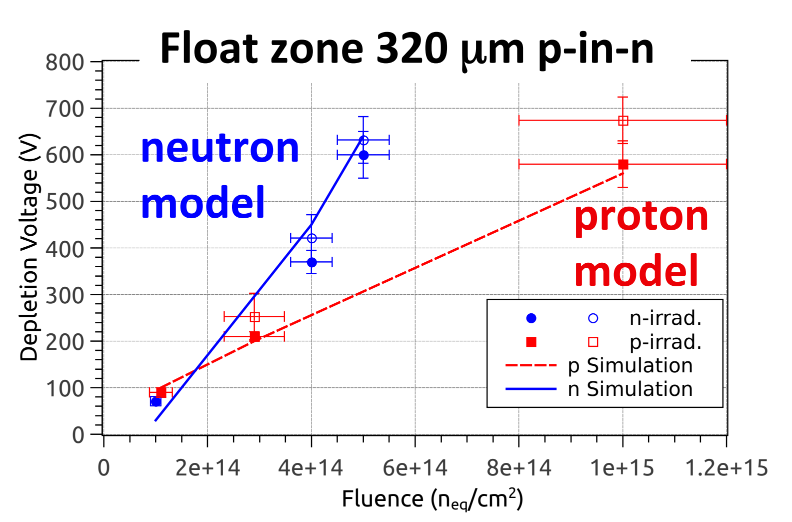


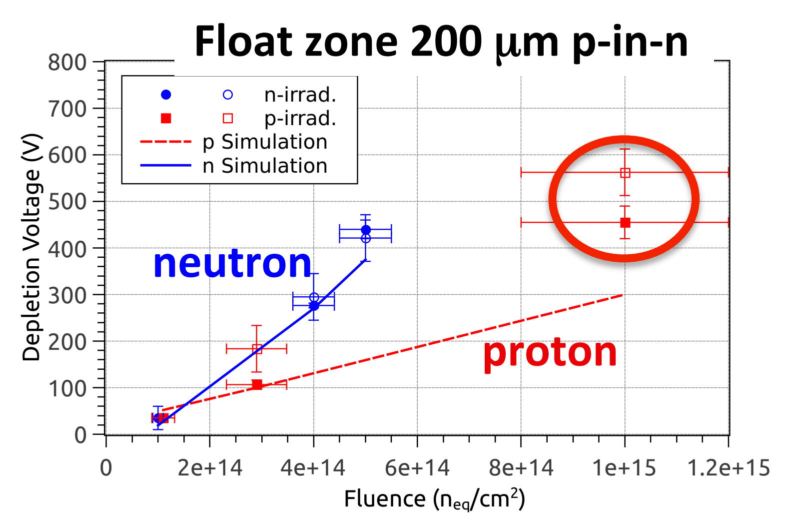


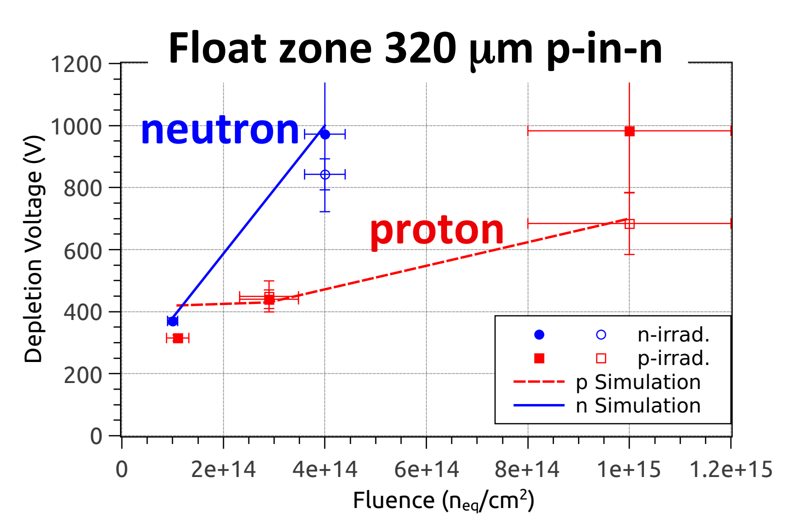


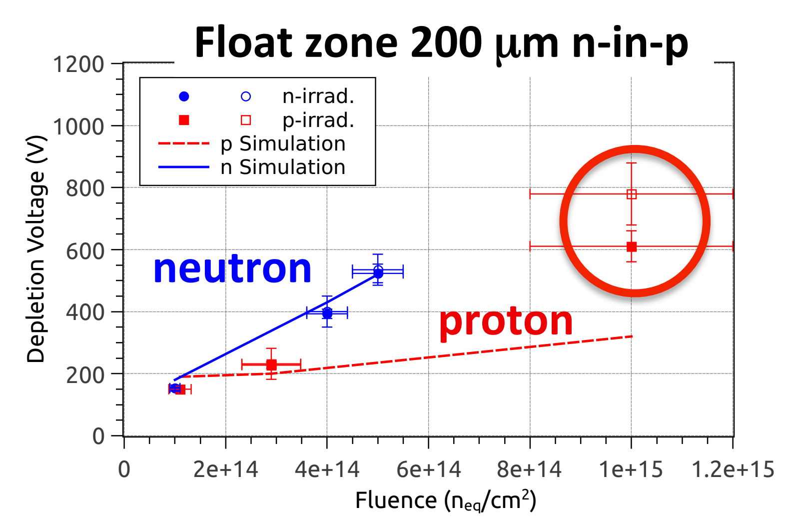


Simulation of the Depletion Voltage



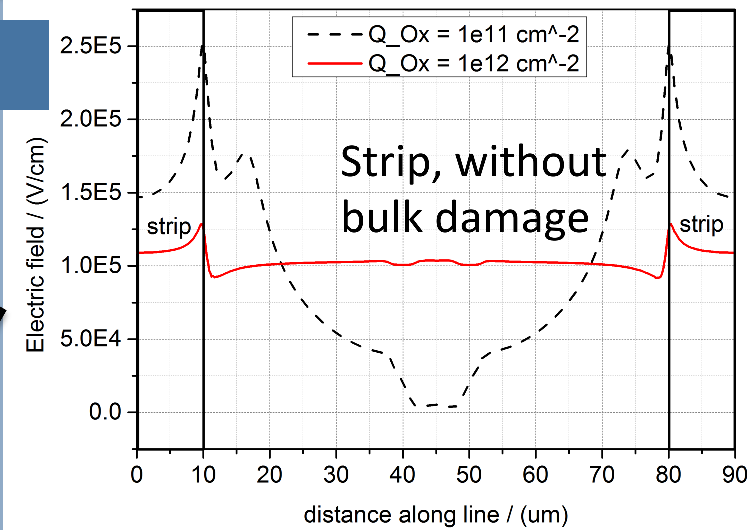






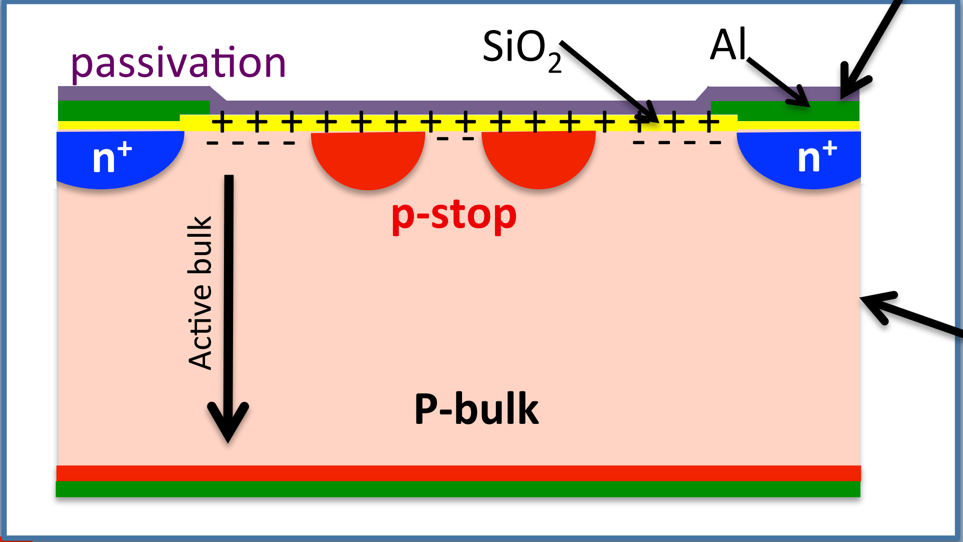
Simulation of electric field

Introducing oxide charges to simulation

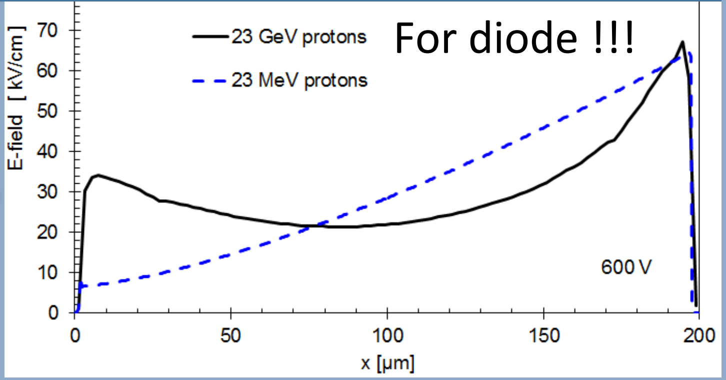


[M.Printz, CMS-CR-2013-267]

Important ingredients to describe an irradiated sensor

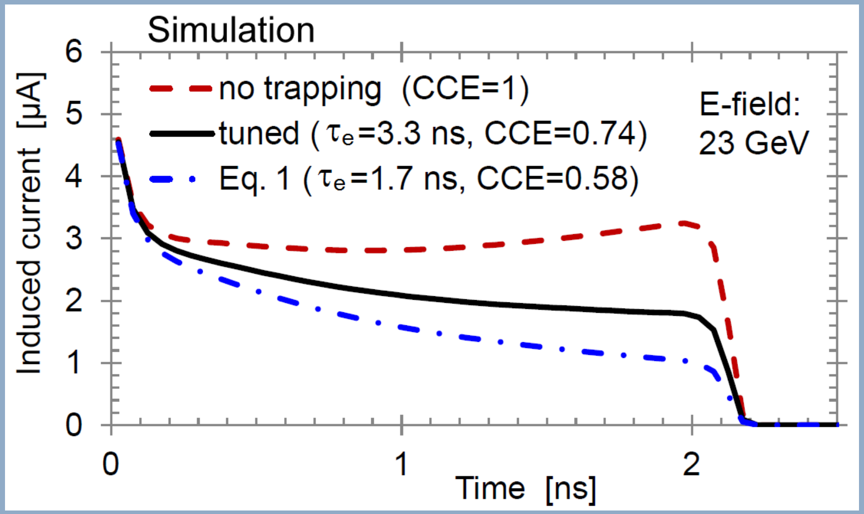


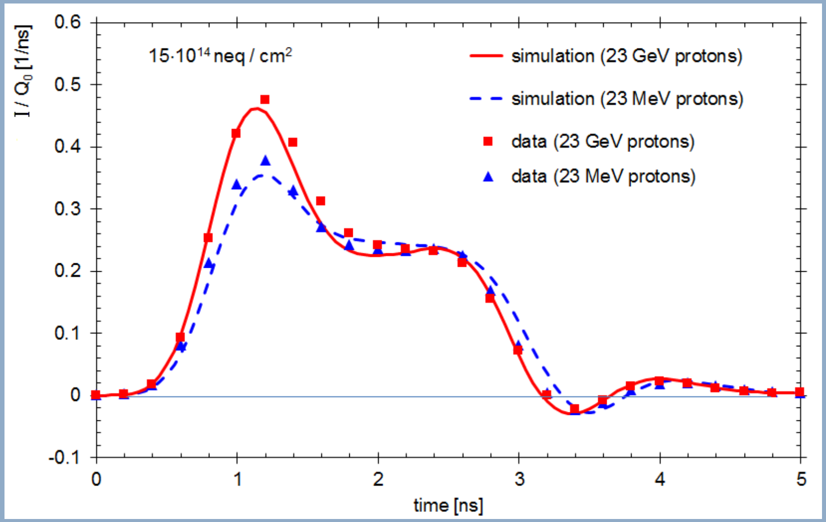
Bulk damage



Extraction of effective Trapping Rates

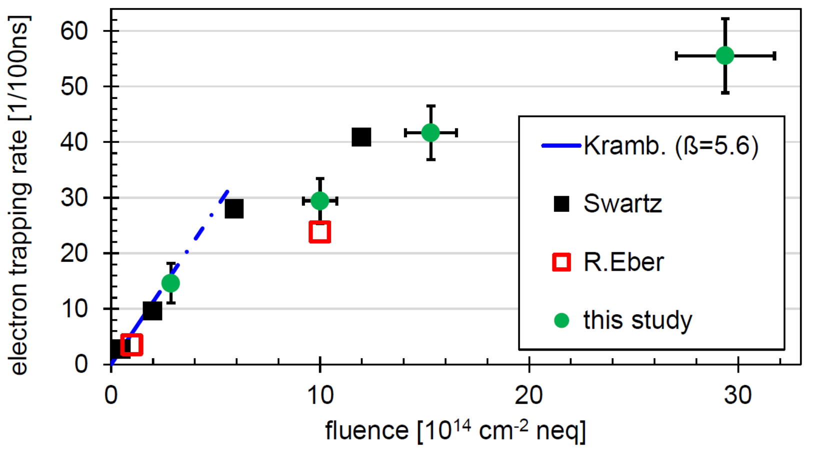
Adjust (tune) simulated time-resolved pulse by varying trapping time until it CCE expectation





Extracted trapping rates for electrons for $\Phi=3x10^{15}$ cm^{-2}

→ Impact of trapping less severe than expected from extrapolation of measurements at low fluences!!!



Summary

- Bulk defect generation very similar for p-type and n-type

→ Physics motivation to have models valid for both polarities

→ Work required to understand proton damage for different energies

- Impact of surface damage on HL-LHC sensors cannot be neglected

→ Oxide charge included in simulation models

→ Work required to integrate interface states

- Achieved good progress in simulation accuracy for irradiated sensors

→ Effective models for neutrons and protons developed

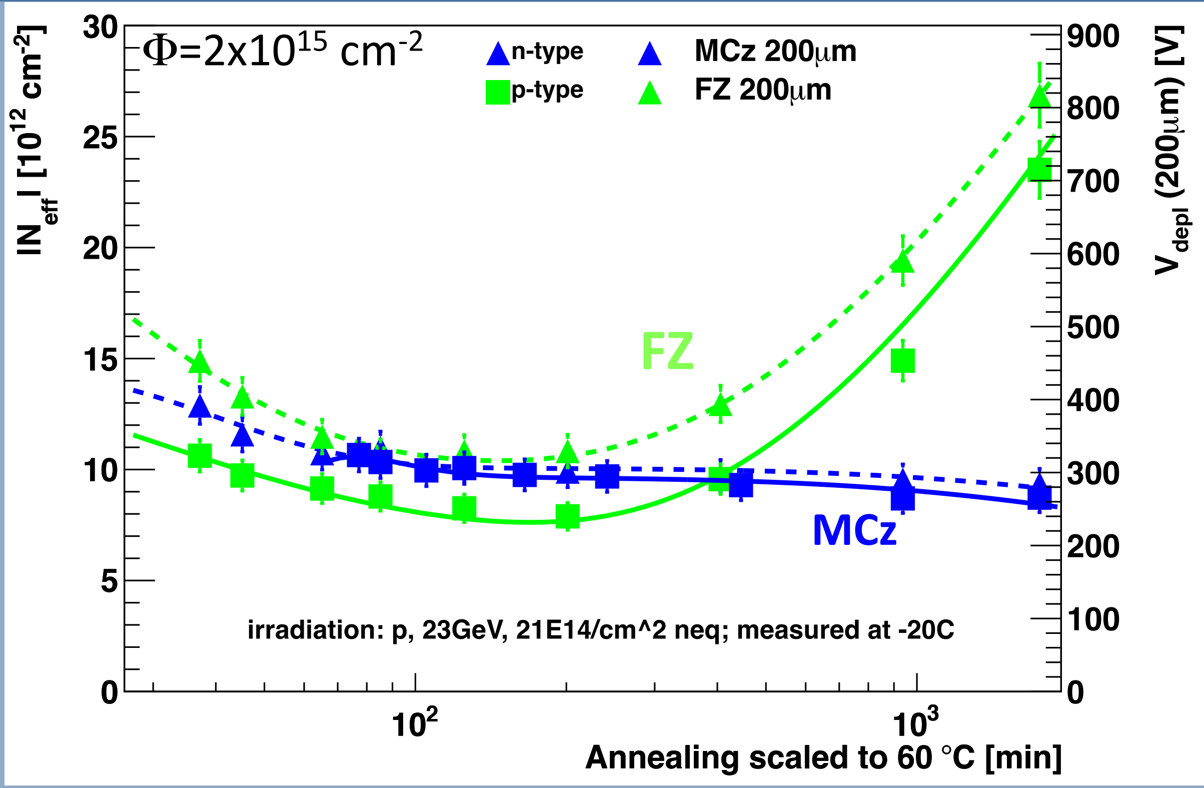
→ Depletion voltage, leakage current, TCT pulses well reproduced vs. fluence

→ Effective trapping rates extracted

Back up

Annealing Behavior for magnetic Czochralski

23 GeV proton + neutron irradiated pad-diodes



FZ: Depletion requires highervoltage
MCz is much more stable in time
→ Longer "warm" periods possible with MCz