Impact of low-dose electron irradiation on the charge collection of n^+p silicon strip sensors

R.Klanner (UHH)

for the

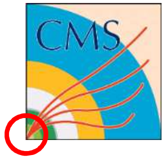
CMS Tracker Collaboration

in close collaboration with

J.Erfle, E.Garutti, C.Henkel, A.Junkes,
S.Schuwalow,J.Schwandt and G.Steinbrück

Table of Content

Introduction



- Silicon detectors: The central detectors of most collider experiments
- Silicon detectors have shown extraordinary performance
  ! no Si = no Higgs, no precision top-, b-physics, and more !
- The HL-LHC (High-Luminosity LHC) upgrade poses extraordinary challenges
  - Track densities
  - Hadron fluences (10^{16} n_{eq}/cm^2)
  - Surface damage (MGy's in SiO_2)
- ATLAS and CMS have decided on n^+p sensors and binary readout for tracker
- Decision for pixels progressing

This work: Study effects of low-dose irradiations by a β–source on the charge collection properties of non-irradiated and irr-radiated n^+p sensors + discuss relevance for HL-LHC upgrade

Sensors investigated

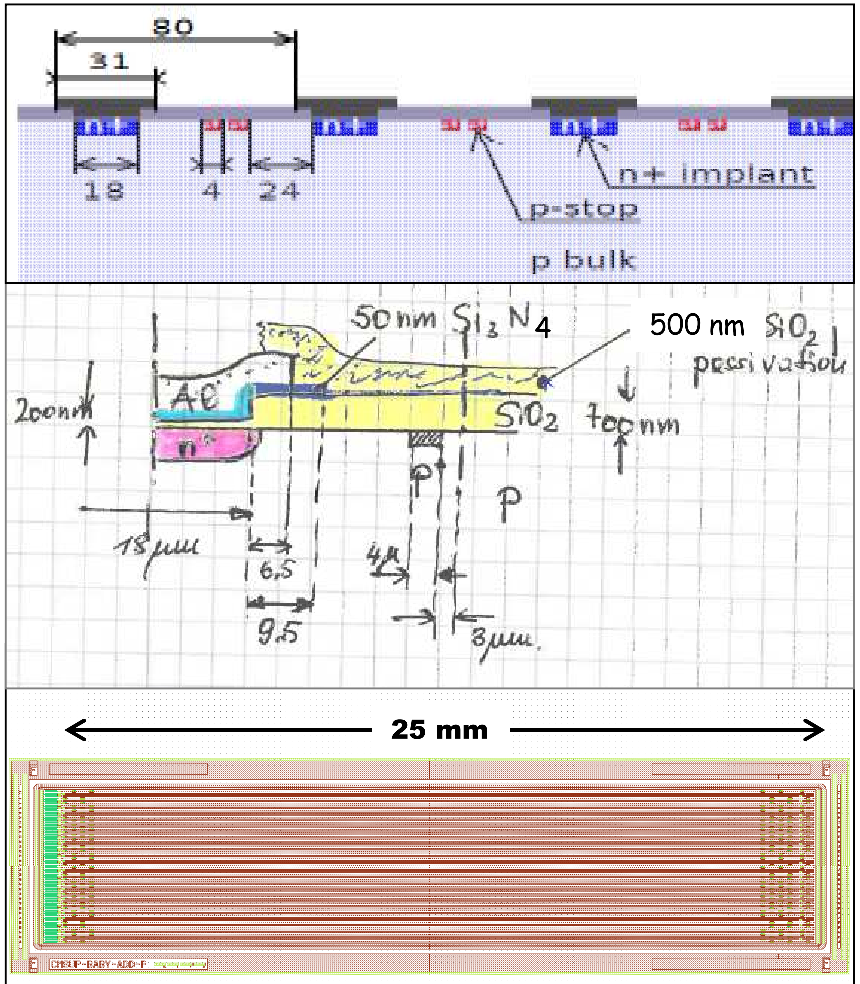
"Baby add. from HPKCampaign"

- FZ p-doping: $3.7 \cdot 10^{12}$ cm^{-3}
- [O]: ~$5 \cdot 10^{16}$ cm^{-3}
- ➢ p-spray: ~$5 \cdot 10^{10}$ cm^{-2}
- ➢ p-stop: ~$2 \cdot 10^{11}$ cm^{-2}
- 64 AC-coupled strips
- Strip length: 25 mm
- Pitch: 80 µm
- Implant width: 19 µm
- Al overhang: 5 µm
- d_{Si}: 200 µm
- d_{SiO2}: 650 nm + 130 nm
- d_{Si3N4}: 50 nm

Irradiations:

- No irradiation
- Irradiation [cm^{-2}]:
  23 GeV protons $15 \cdot 10^{14}$ 1MeV neq +
  reactor neutrons $6 \cdot 10^{14}$ 1MeV neq
  → r ~ 15 cm for 3000 fb^{-1} HL-LHC
  (→ ~750 kGy ionizing dose in SiO_2)

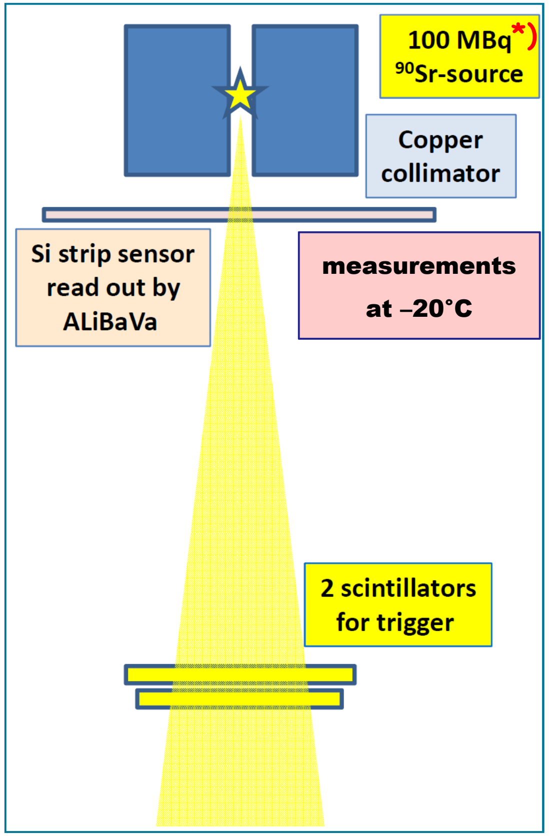
Details of sensor layout (p-stop):



64 AC-coupled strips with 80 µm pitch

Measurement setup + dose rates

Layout, readout + e-irradiation



100 MBq*) ^{90}Sr-source

Copper collimator

Si strip sensor read out by ALiBaVa

measurements at –20°C

2 scintillators for trigger

*) Measurements also with 37 MBq ^{90}Sr source

Energy spectra for electrons and γ's from ^{90}Sr in SiO_2

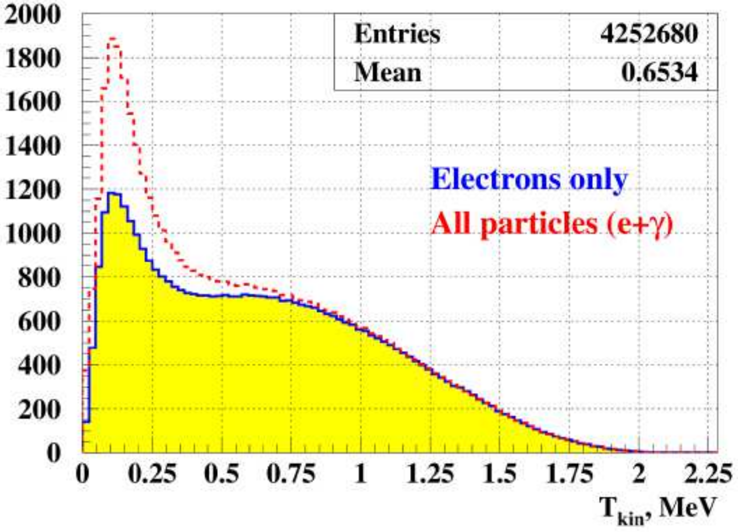
Rate:

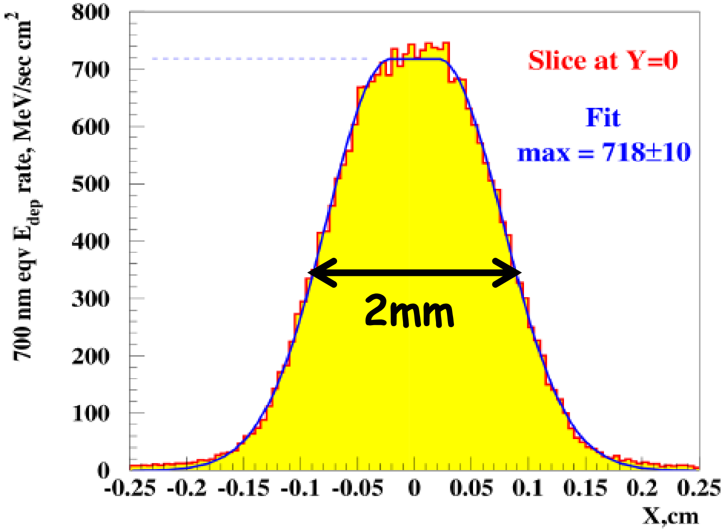
- SiO_2: 50 Gy/day (O(2%) HL-LHC)
- Si-bulk: 10^8 neq/(cm^2·day)

Width: ~2 mm

Proj. angular spread: ±100 mrad (±20μm for 200μm)

dE/dx for trigger e: Landau mpv= 56keV (54keV for mip)



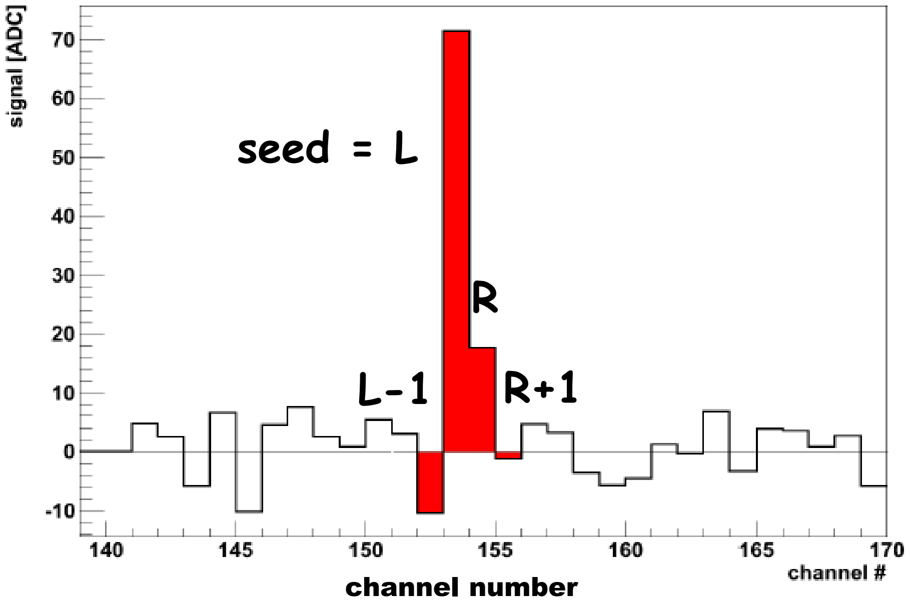


Compared to HL-LHC (or XFEL) very low local doses and dose rates

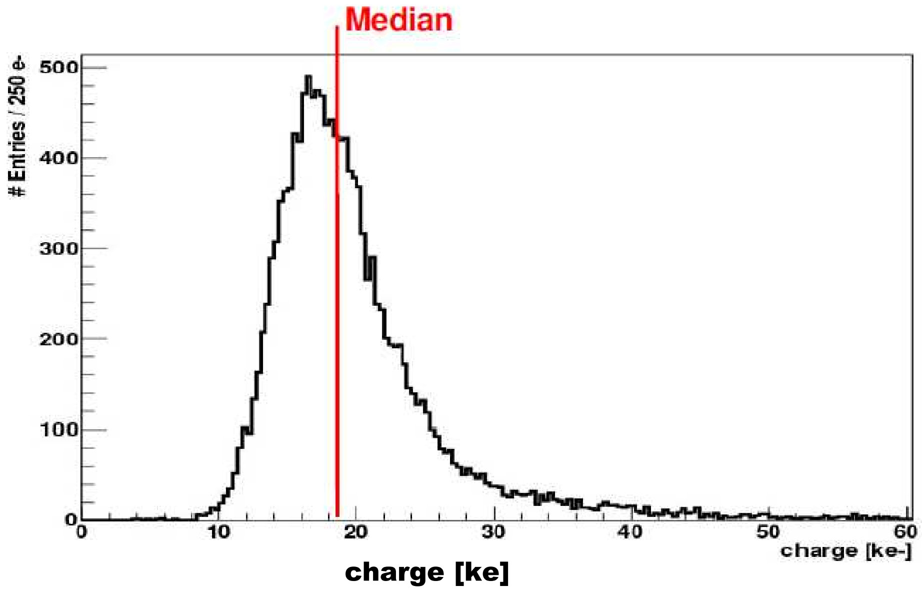
Analysis

- Select events ±5 ns in phase with 40 MHz clock
- **Seed**: biggest signal in event
- **4 signal strips**: L-1, L, R, R+1
- **4-cluster PH**: Σ (4 signal strips)

Strip pulse heights for single event



4-cluster pulse height for 5000 events

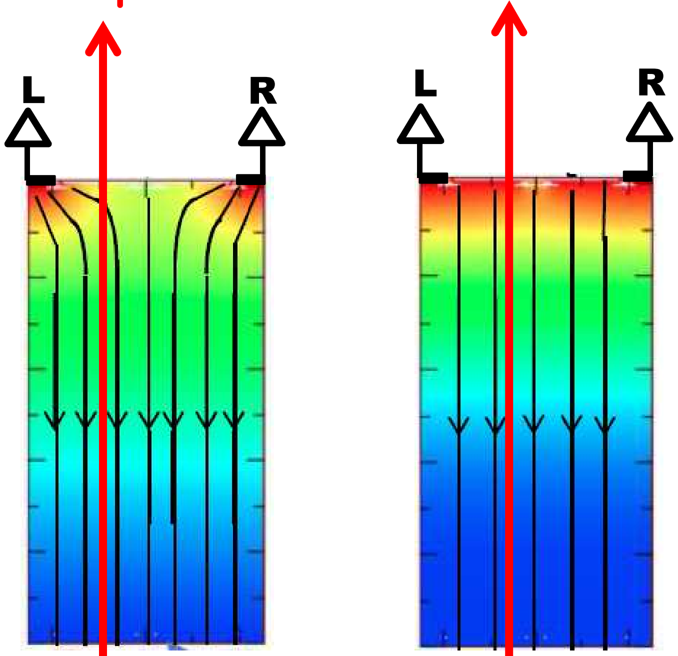


Comment: As individual pulse height distributions ≠ Landau distributions, we prefer to use **median**; statistical uncertainty similar to **Gauss x Landau fits**, however sensitive to noise pulses!

Analysis

Charge sharing: $$\eta = \frac{PH(R)}{PH(L)+PH(R)}$$ *)

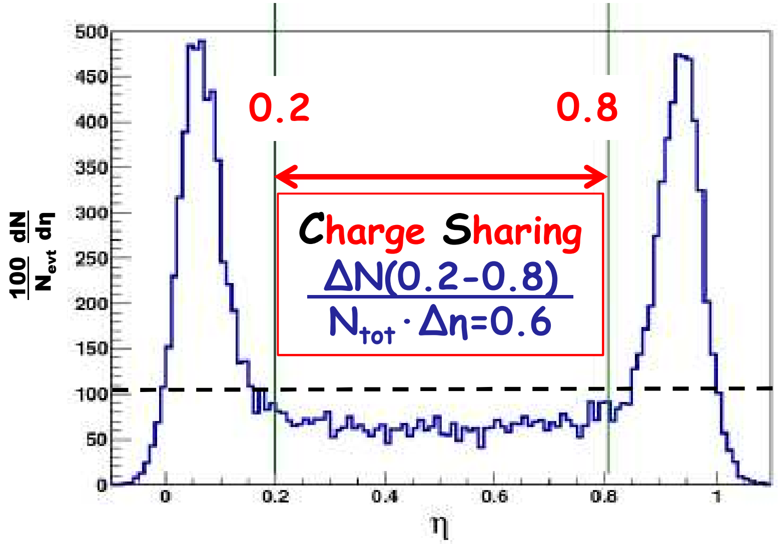
particle track at 0°



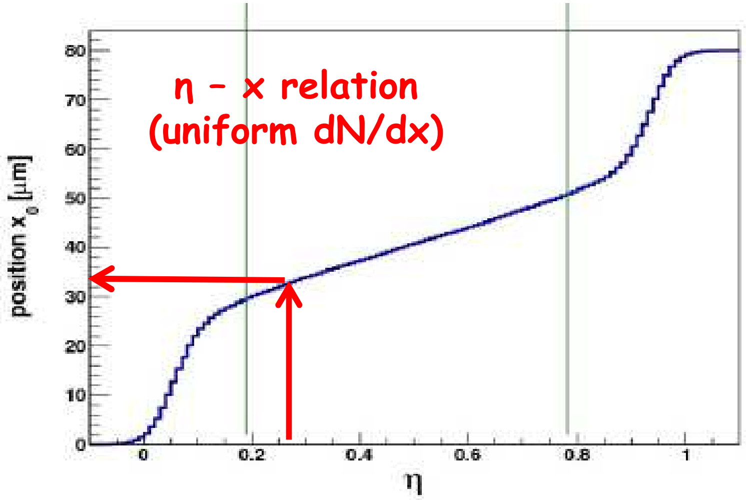
δ-function uniform

η-distribution

CS << 1 CS = 100%



Charge Sharing $\frac{\Delta N(0.2-0.8)}{N_{tot} \cdot \Delta\eta} = 0.6$

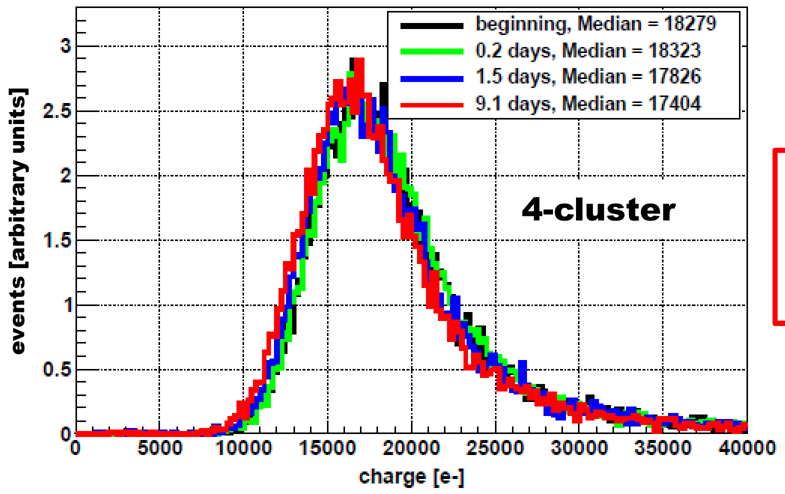


η – x relation (uniform dN/dx)

*) E.Belau et al., NIM 214 (1983) 253

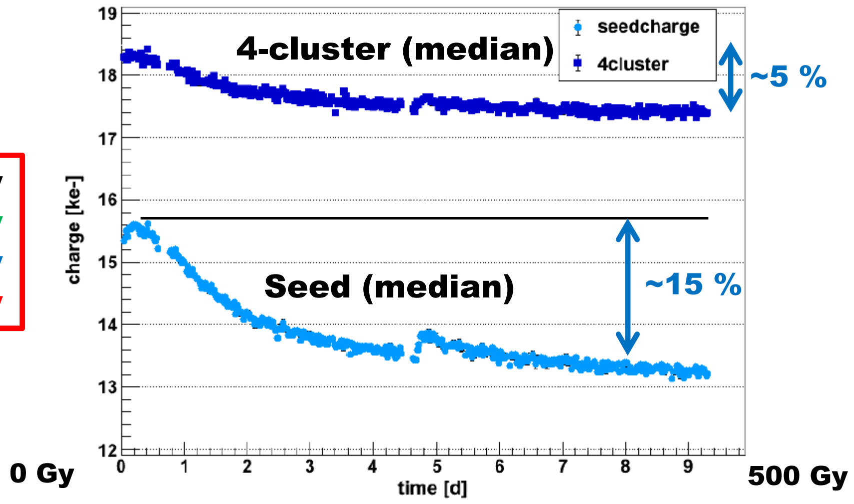
η-distribution -> Information on E-field + particle track position

Observations for V_{bias} = 600 V (non irr. p-stop sensor)

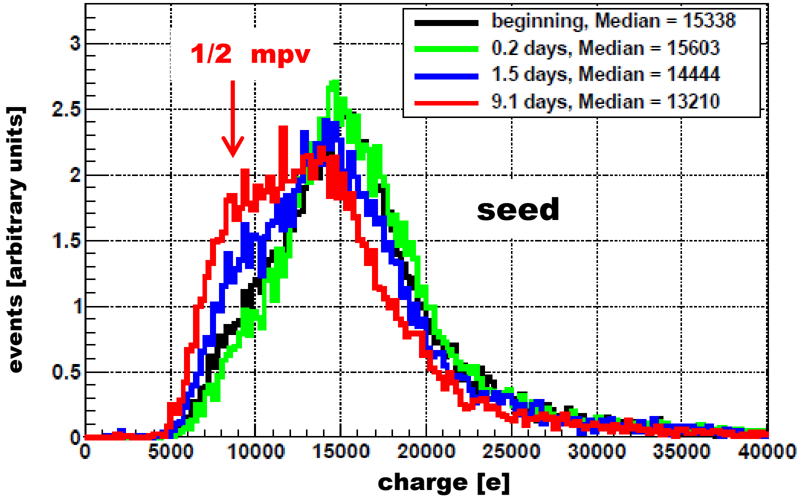


— 0 Gy
— 10 Gy
— 75 Gy
— 500 Gy

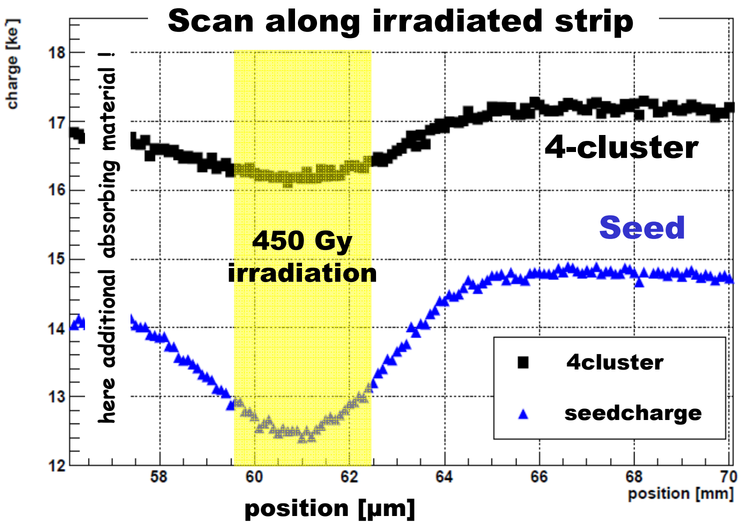
Little change in 4-cluster distribution



Decrease in PH(seed) and PH(4-cluster)

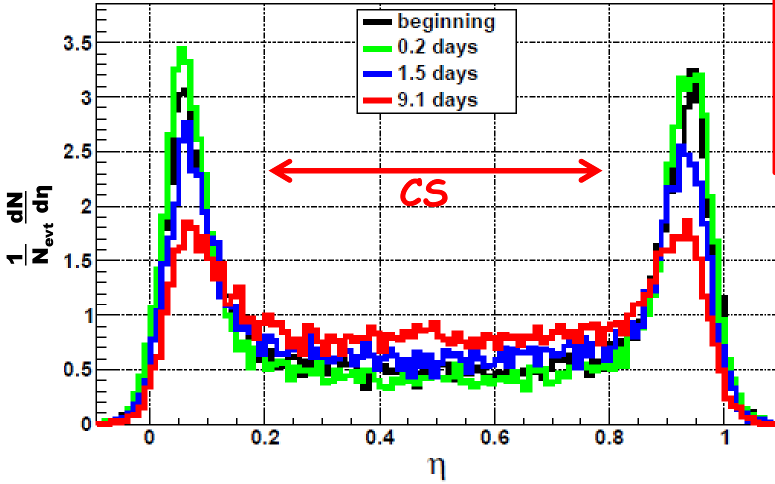


Change in seed distr. – events at <0.5·mpv !

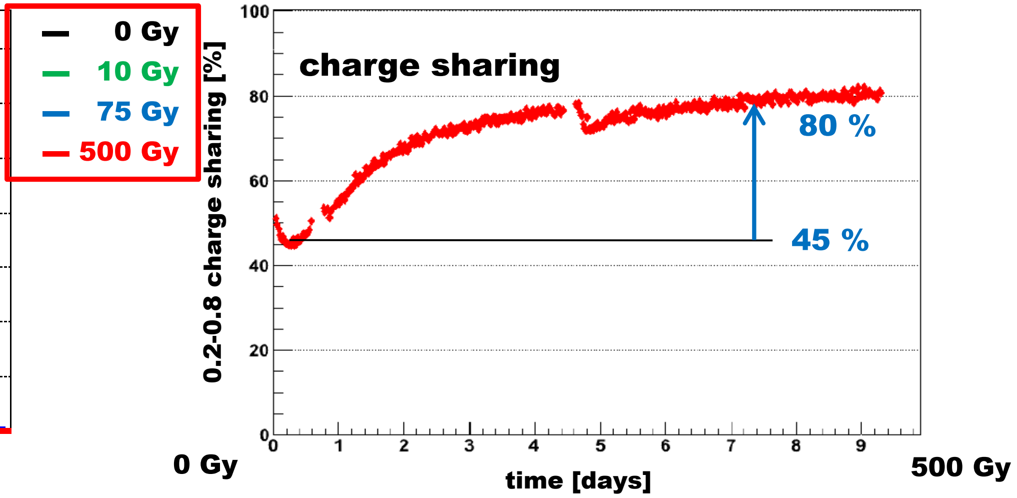


Effect only where sensor irradiated

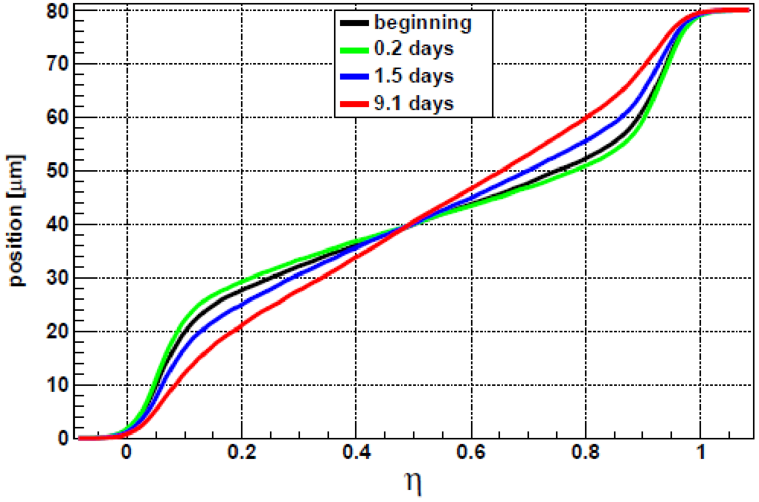
Observations for V_{bias} = 600 V (non irr. p-stop sensor)



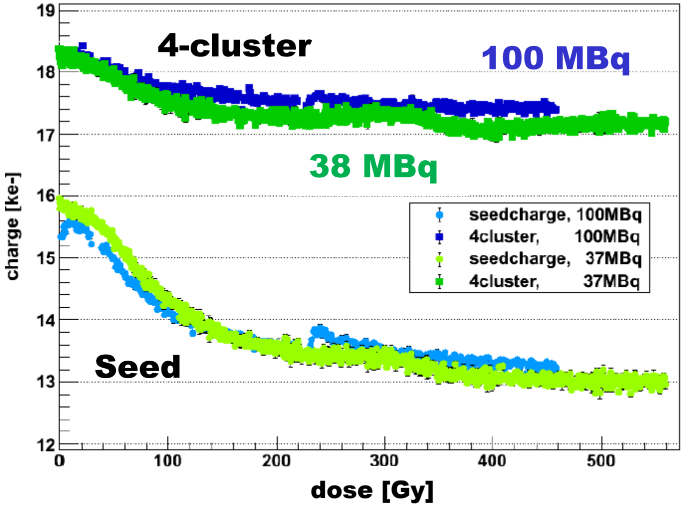
Significant increase in charge sharing



Increase in charge sharing

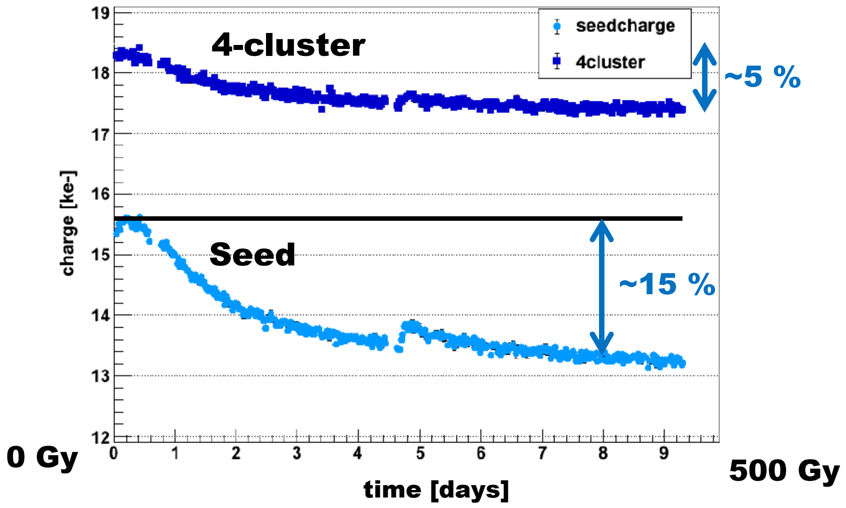


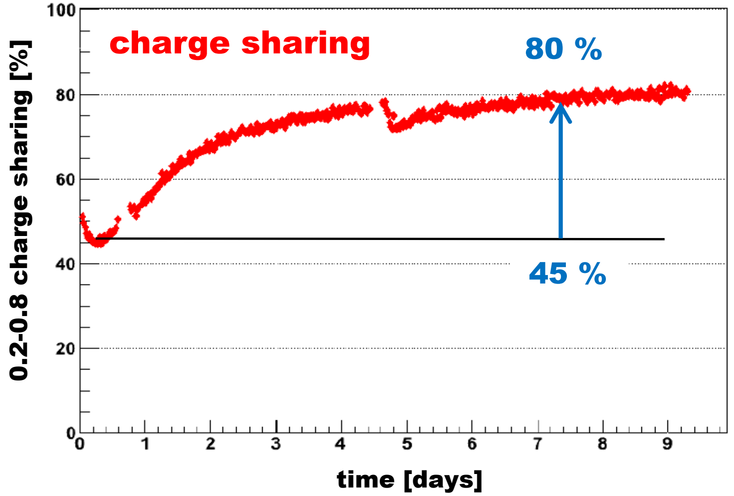
Change of η vs. position relation



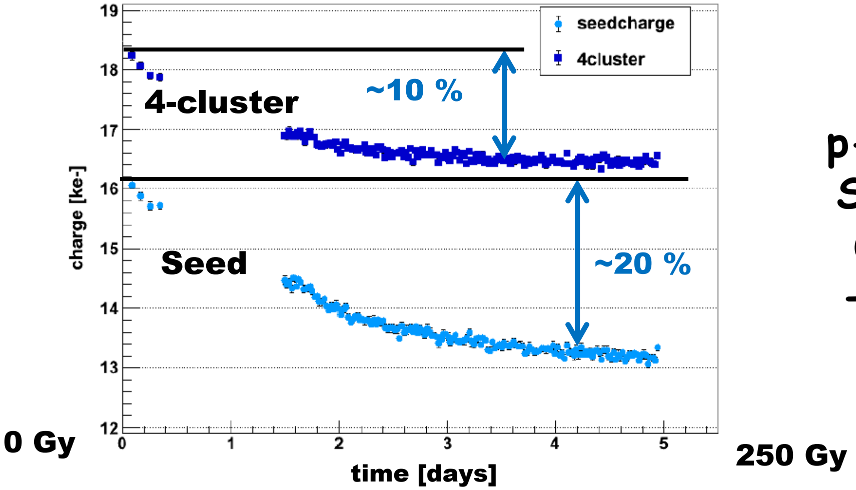
Change depends on dose – not dose rate

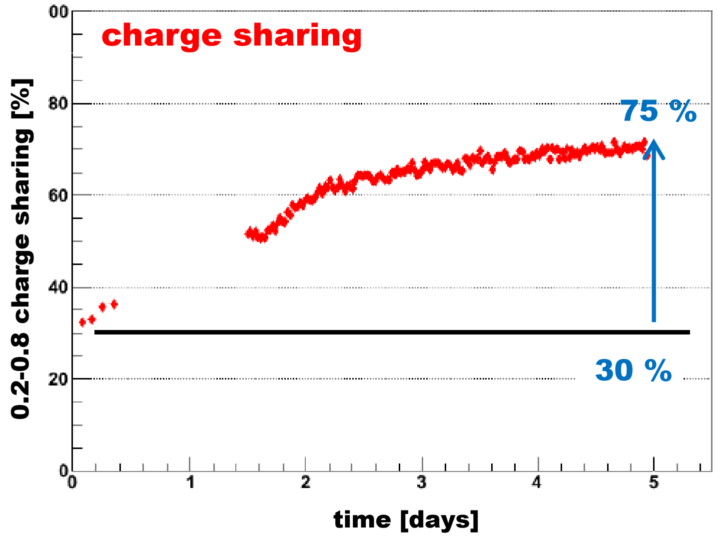
Comparison p-stop vs. p-spray (non-irradiated)





p-stop
Sensor
600 V
-20°C

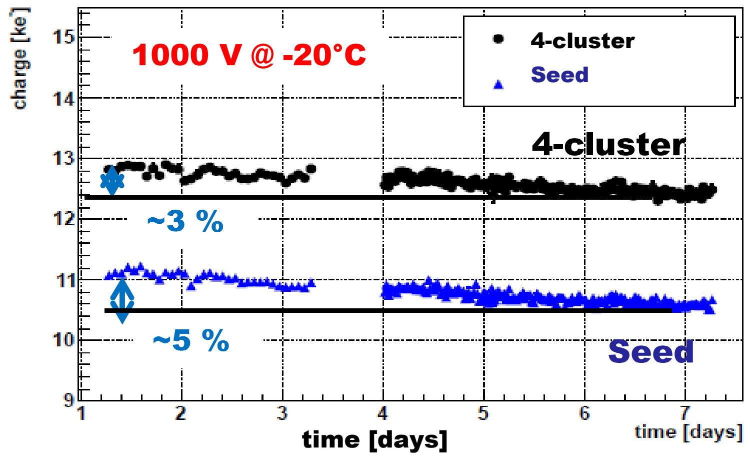


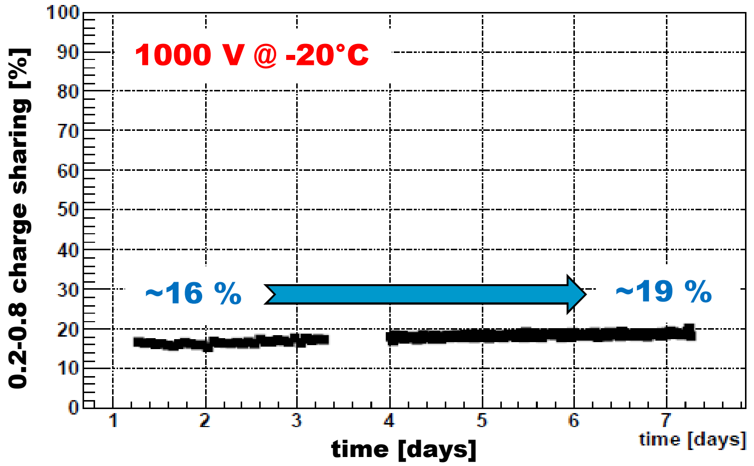


p-spray
Sensor
600 V
-20°C

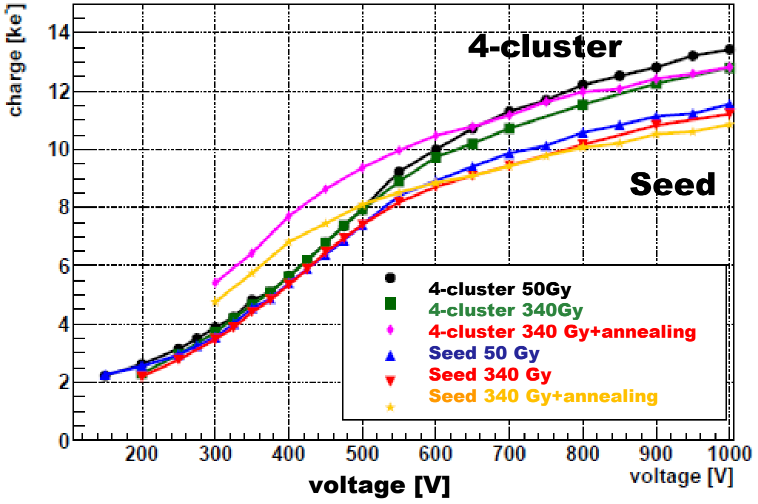
Effects bigger for p-spray than for p-stop sensor

Irradiated (p-stop) sensor @ 1000 V

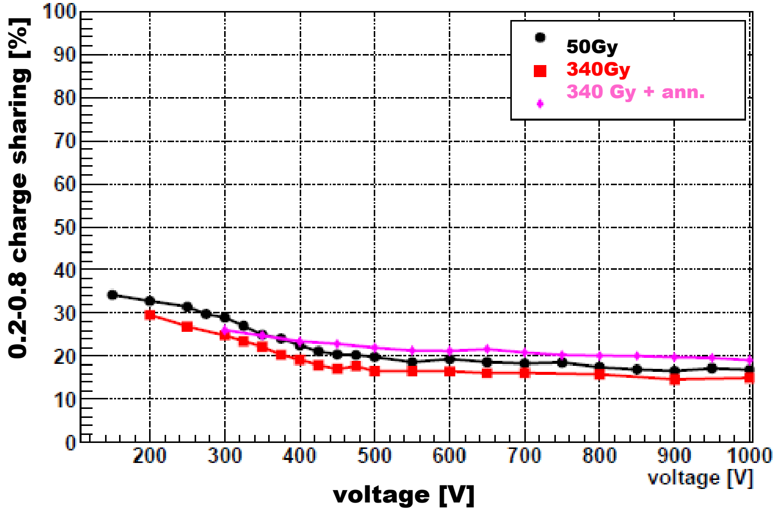




irradiated
$15 \cdot 10^{14}$ GeV p
$+6\ 10^{14}$ n
p-spray
Sensor
1000 V
-20°C



annealing = 12 h @ 80°C



Small effect for irradiated sensor at 1000 V
+ annealing has only a small effect

Summary of observations → surface damage

Low dose [O(kGy)] ionizing irradiation changes charge collection in n^+p Si strip sensors: Increase in charge sharing + increase in charge losses

- Effect decreases with: p-spray → p-stop → hadron irradiated sensor

Suspected cause: Surface damage + charge build-up in/on insulators

Surface damage is complicated !!!

We will only consider build up of surface charges with density

N_{ox}@doses < 1 kGy*):

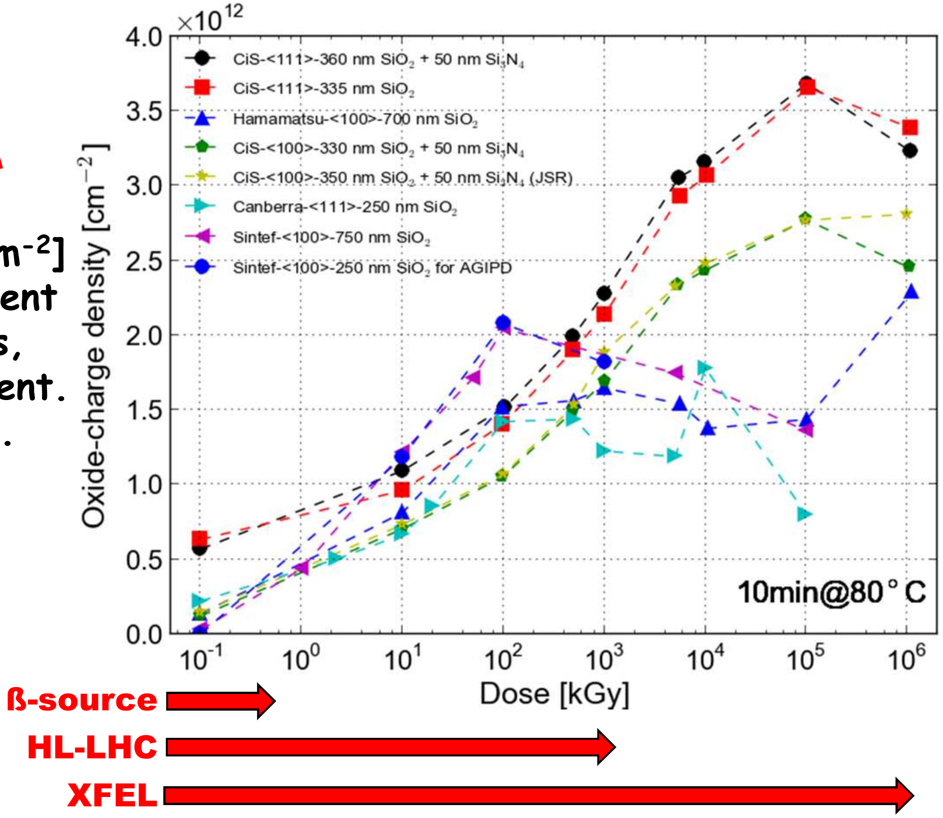
few·10^{10} cm^{-2} <100>

~ 10^{11} cm^{-2} <111>

+4·10^{11} cm^{-2}·D[kGy]

and effects of surface boundary conditions

Nox[10^{12}cm^{-2}] for different producers, crystal orient. d_{ox}, etc.



for more information see:

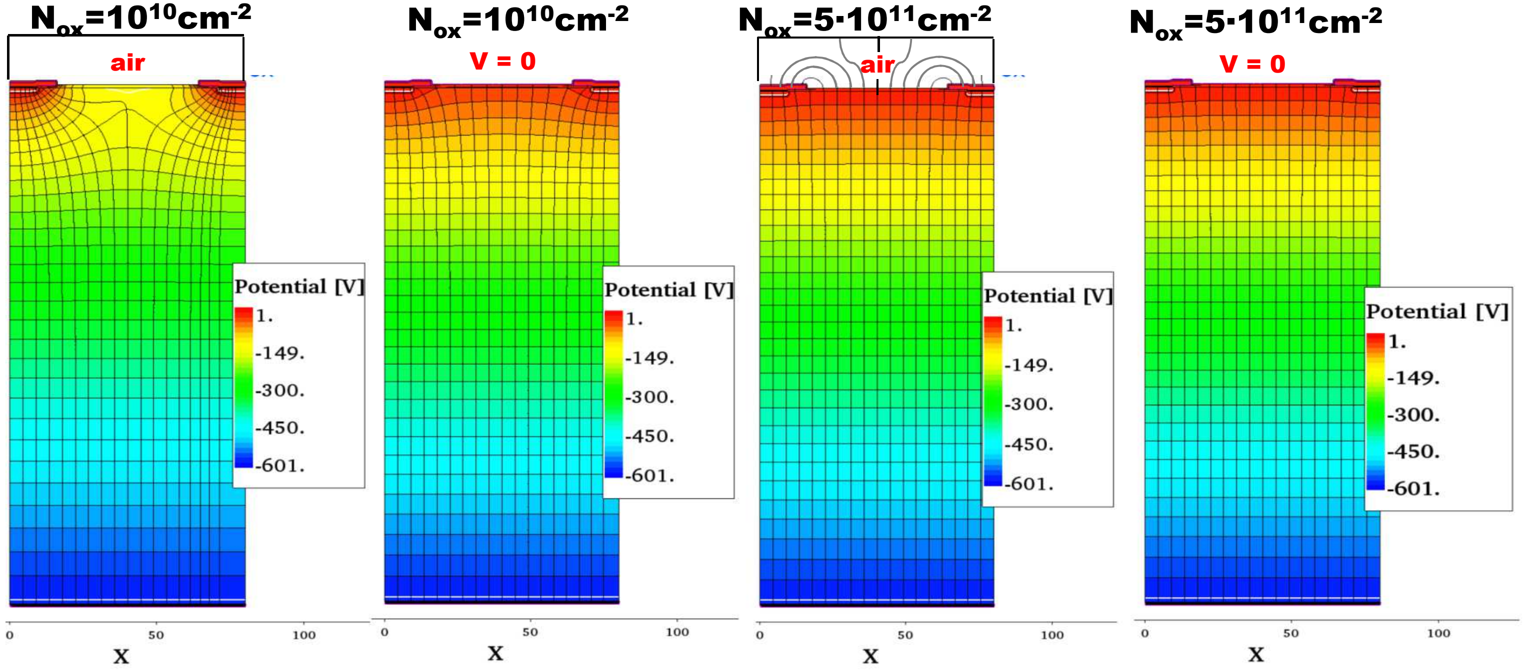
***) J.Zhang et al., JSR 19 (2012) 340;**
J. Schwandt et al., arXiv-140213;
T.Poehlsen et al., NIM-A 721 (2013) 26.

Synopsys TCAD simulation of p-spray sensor vs. N_{ox}

Results on simulations depend also on boundary conditions:

1. "Dirichlet": SiO_2 surface on potential of readout strips (0 V)
2. "Air": 500 μm above strips Dirichlet with potential of readout strips

$N_{pspray} \sim 2.5 \cdot 10^{11} cm^{-2}$



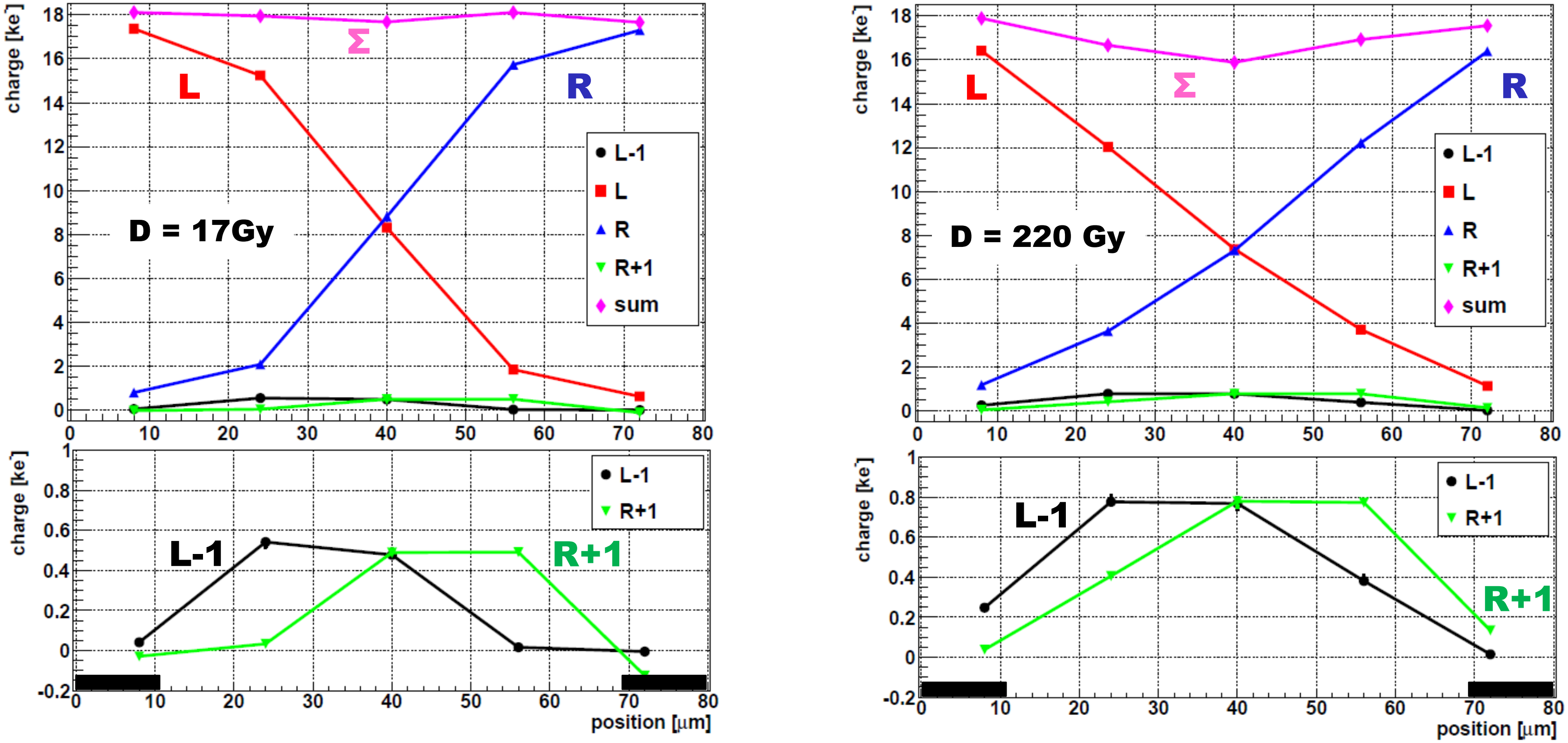
$N_{ox}<N_{p\text{-}spray}$: E-field lines end at readout strips → no charge sharing

$N_{ox}>N_{p\text{-}spray}$: E-field lines end at Si-SiO_2 interface → charge sharing

Increase of oxide charge density N_{ox} → Change of charge sharing

Charge sharing and charge losses

Using the η-x transformation we can study pulse-heights vs. position

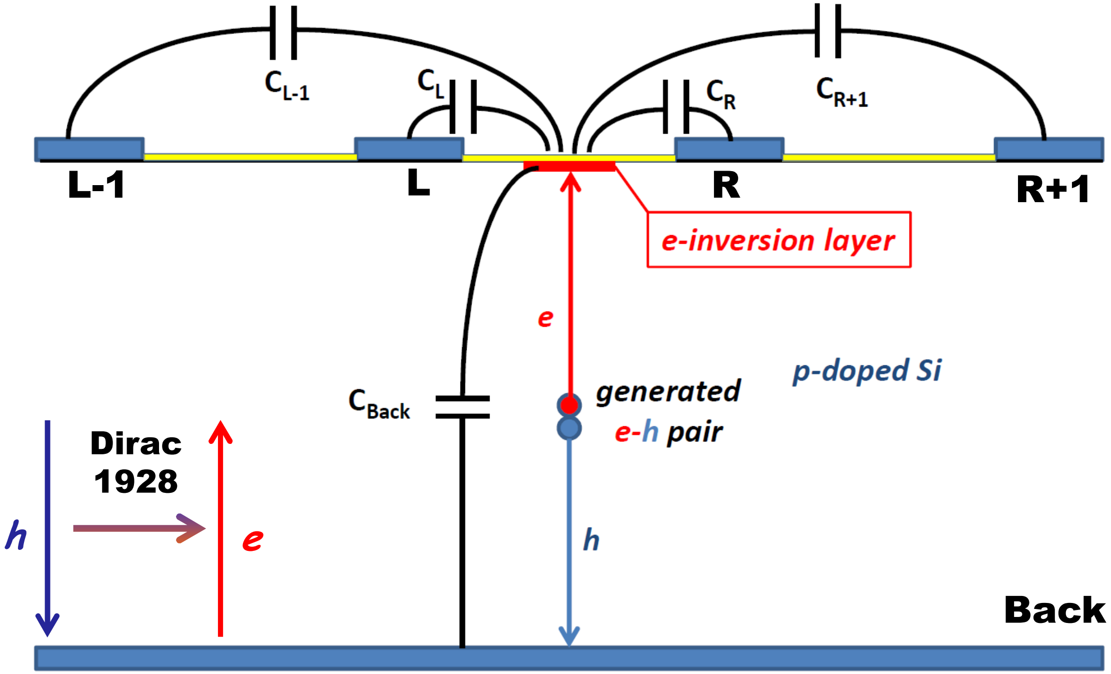


Increasing dose:
- increased charge sharing
- increased charge losses
- increase of signal in L-1 and R+1 strips

Charge sharing versus charge losses

Explained with weighting fields taking charge layers*) into account !

(*) with dielectric relaxation time $\tau_{\text{charge layer}}$ < charge collection time)



C_i … depend on position where *e* gets stuck

$$C_{tot} = \Sigma C_i$$

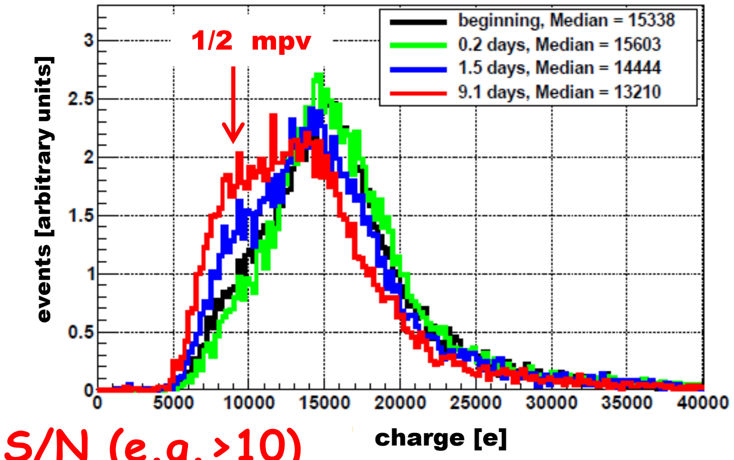
$$\text{Signal}_i = q \cdot (C_i / C_{tot}) = q \cdot [C_i / \Sigma(C_{strips} + C_{back})]$$

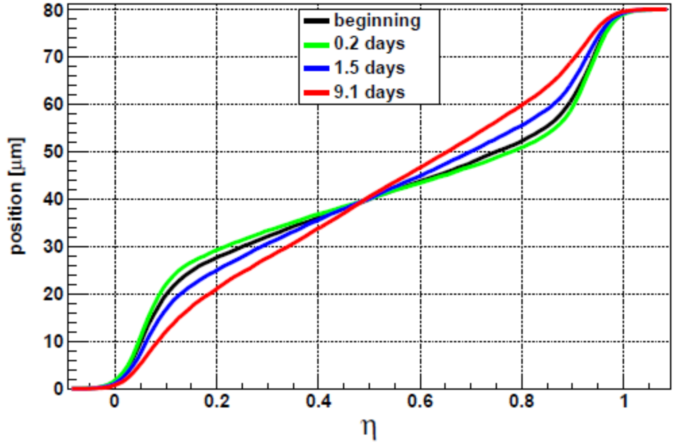
C_{back} determines the charge losses (C_{back} = 0 → no losses)

Relevance for sensor design

Impact depends on S/N, readout scheme, track angle, dose, etc.

Here only qualitative discussion – needs quantitative estimation for a specific design





Good S/N (e.g.>10)

- **analog readout**: **Charge Sharing improves the position resolution (δ ~ 1/(dx/dη))**
- **binary readout: CS improves the resolution and worsens the track separation**

Poor S/N (e.g.<10)

- **analog readout: as long as low signal pulses are red out, CS improves the position resolution**
- **binary readout: unless low threshold, loss in efficiency; threshold < 0.4·mpv → for 3σ noise cut S(cluster)/N > 7.5 required**

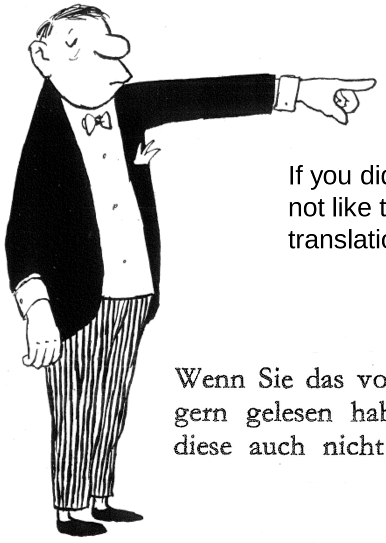
Charge Sharing important for design of efficient sensor - of similar importance as Charge Collection Efficiency

Conclusions

- Low-dose ionizing radiation changes oxide (+interface) charges
  → for n^+p segmented sensors change of charge collection:
  charge losses, charge sharing, signals in next-to-next strips
- Impact depends on track angle, signal/noise (S/N), readout
  → good S/N: resolution improves @ small angles
  → poor S/N: efficiency decreases drastically
  effective threshold < 0.4 mpv → 3σ noise cut = S/N > 7.5 !
- Oxide (+other dielectrics) damages have to be taken into account in sensor design (+ sensor simulations)
  → for n^+p probably N(p-spray/stop) > few 10^{12}cm^{-2} and broader n^+-implants if charge sharing should be minimized
  → in addition impact on breakdown voltage + guard ring design to be considered

More work needed on understanding of charge build-up in dielectrics and interfaces (e.g. dependence on E-field, annealing, technology) and how to implement this information in realistic sensor simulations

References to Work from UHH-Group



If you did not like this talk, you will also not like the following publications (free translation from V. von Bülow “Loriot”)

Wenn Sie das vorliegende Buch ungern gelesen haben, werden Ihnen diese auch nicht so recht gefallen.

V. von Bülow “Loriot”

AGIPD:

AGIPD (Adaptive Gain Integrating Pixel Detector) http://photon-science.desy.de/research/technical_groups/detectors/projects/agipd**/**

B. Henrich et al., The adaptive gain integrating pixel detector AGIPD a detector for the European XFEL, NIM-A 6333 Supp.(2011)S11; doi:10.1016/j.nima.2010.06.107

Low-dose effects in segmented Si sensors:

C. Henkel, Impact of low dose-rate electron irradiation on the charge collection of n$^+$p silicon strip sensors, BSC thesis, University of Hamburg, March 2014, unpublished

J. Erfle Irradiation study of different silicon materials for the CMS tracker upgrade, PhD thesis, University of Hamburg, April 2014, unpublished

Charge trapping at the Si-SiO$_2$ interface:

T. Poehlsen et al., Study of the accumulation layer and charge losses at the Si–SiO2 interface in p+n-silicon strip sensors, NIM-A 721 (2013) 26; doi: 10.1016/j.nima.2013.04.026

T. Poehlsen et al., Time dependence of charge losses at the Si-SiO2 interface in p+n-silicon strip sensors, in press NIM-A; doi: 10.1016/j.nima.2013.03.035

T. Poehlsen, Charge Losses in Silicon Sensors and Electric-Field Studies at the Si-SiO2 Interface, PhD thesis, University of Hamburg, DESY-Thesis-2013-025 (2013)

X-ray radiation damage:

J. Zhang et al., Study of radiation damage induced by 12 keV X-rays in MOS structures built on high-resistivity n-type silicon, J. Synchrotron Rad. 19 (2012) 340; doi: 10.1107/S0909049512002384

R. Klanner et al., Study of high-dose X-ray radiation damage of silicon sensors, in press NIM-A; doi: 10.1016/j.nima.2013.05.131

J. Zhang et al., X-ray induced radiation damage in segmented p+n silicon sensors, PoS (Vertex 2012) 019

J. Zhang, X-ray Radiation Damage Studies and Design of a Silicon Pixel Sensor for Science at the XFEL, PhD thesis, University of Hamburg, DESY-THESIS-2013-018 (2013)

Sensor optimization for high X-ray dose :

J. Schwandt et al., Optimization of the radiation hardness of silicon pixel sensors for high x-ray doses using TCAD simulations, 2012 JINST 7 C01006; doi: 10.1088/1748-0221/7/01/C01006

J. Schwandt et al., Design of the AGIPD sensor for the European XFEL, 2013 JINST 8 C01015; doi: 10.1088/1748-0221/8/01/C01015

J. Schwandt et al., Design and First Tests of a Radiation-Hard Pixel Sensor for the European X-Ray Free-Electron Laser, accepted for publication in IEEE TNS, arXiv-140213

J. Schwandt , Design of a radiation hard pixels sensor for X-ray science, PhD thesis, University of Hamburg, May 2014, unpublished