Planar silicon sensors for the CMS Tracker upgrade

On behalf of the CMS Tracker Collaboration

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13th VCI Conference
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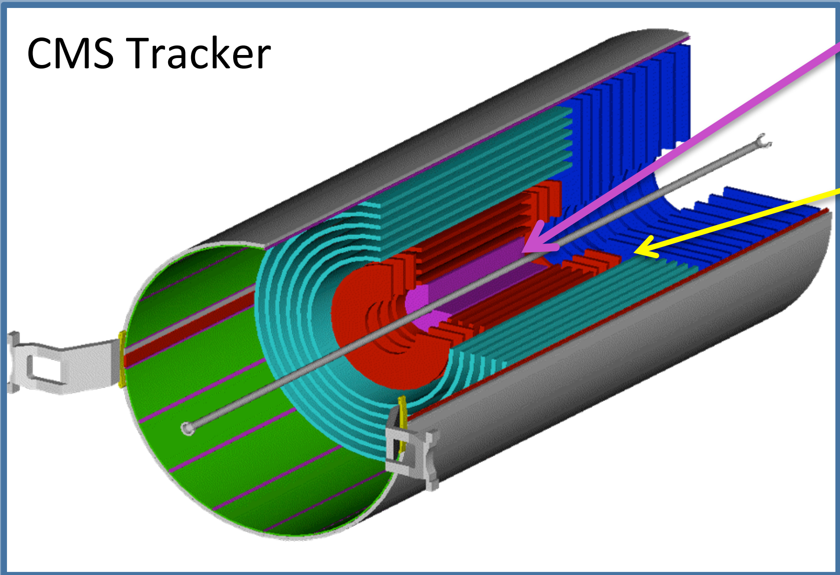
BROWN

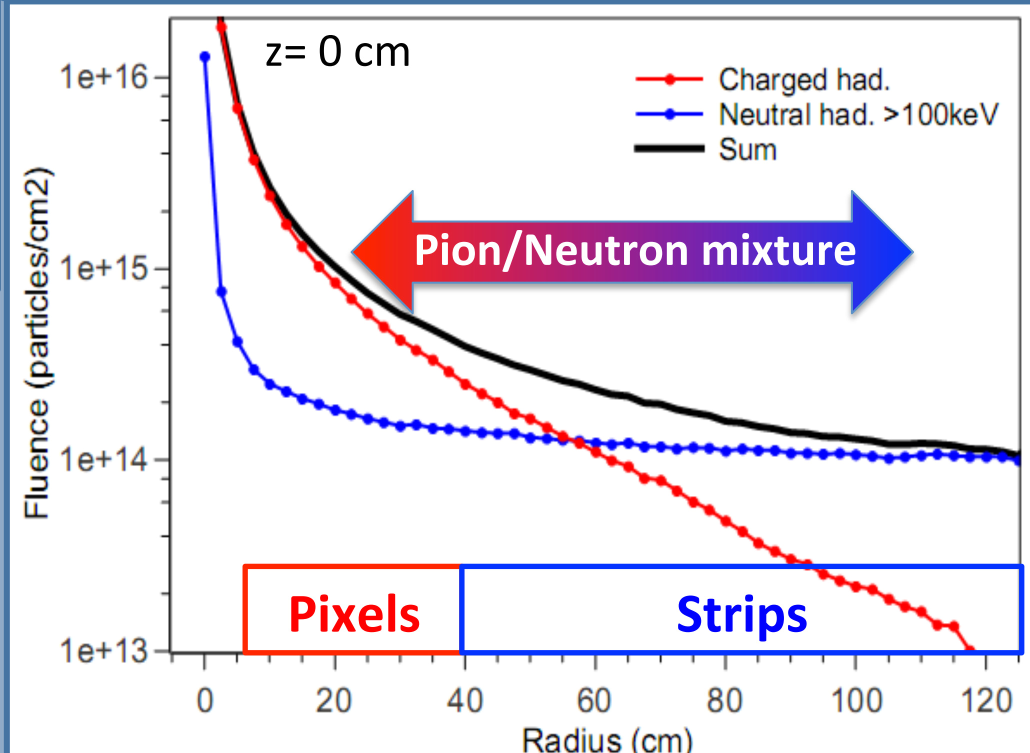
Outline

- Introduction to the CMS tracker upgrade campaign
- Influence of the production process on sensors
- Current above depletion
- Depletion Voltage
- Charge Collection
- Summary

The CMS tracker upgrade



Expected radiation depending on position in detector



Major Upgrade of the LHC ~2022:

x5 in instantaneous luminosity

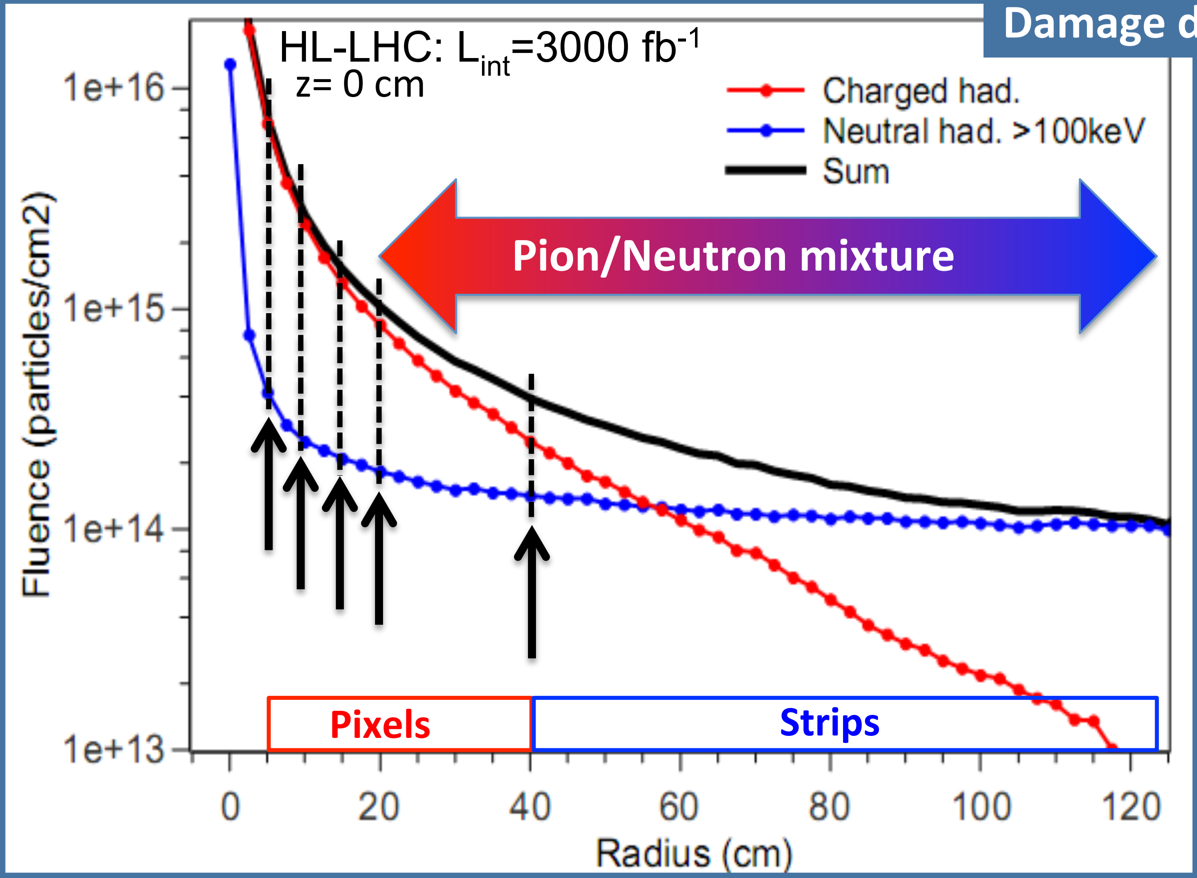
- → Smaller segmentation needed
- → Triggering at L1

x10 in integrated luminosity:

HL-LHC L_{int}=3000 fb^{-1}

- → Radiation hard silicon and suitable sensor designs needed

Expected radiation damage in the CMS detector



Damage different for pions and neutrons!

Choice of Irradiations:

Neutrons

- 1 MeV (TRIGA reactor Ljubljana)

Protons

- 23 MeV (Karlsruhe cyclotron)
- 800 MeV (Los Alamos proton facility)
- 23 GeV (PS CERN)

Mixed Irradiations:

- 23 MeV protons + neutrons

Make a sensor campaign with candidate materials!

Selection of Materials and Sensors

Radiation hardness of silicon defined by growth process

- Oxygen content (**MCz, FZ, dd-FZ, Epi**)
- Influence of doping and sensor thickness (100 μm – 320 μm, concentrate on 200 μm)

➔ Study diodes

➔ Obtain: V_{dep}, I_{leak}, C_{end}, CC, defect parameters

Study best design parameters for structured devices

- Strip layout & and influence of sensor thickness
- Influence on n-type and p-type material

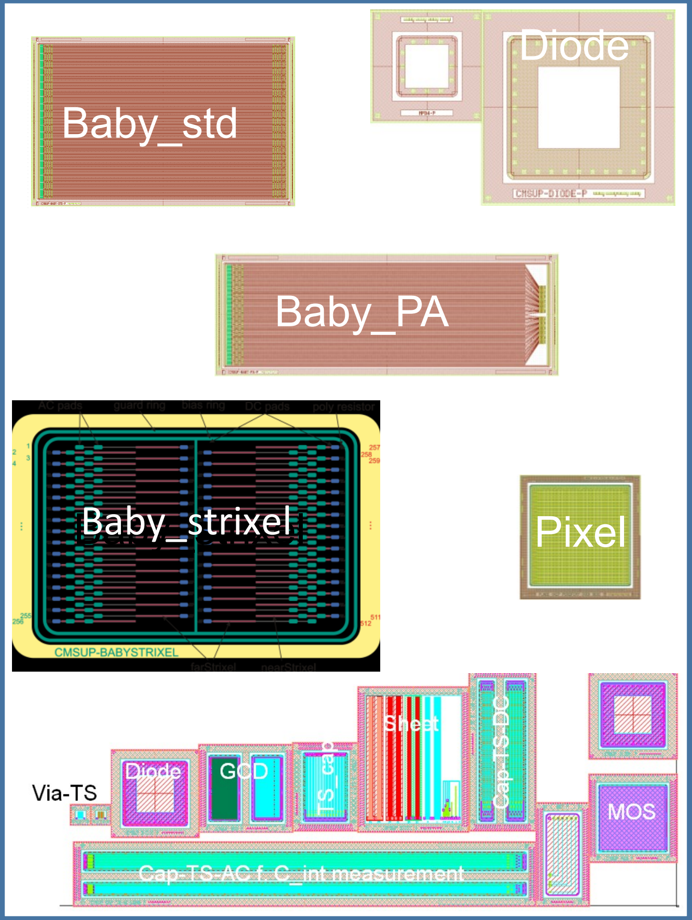
➔ Strip and multi-geometry strip sensors

➔ Obtain: V_{dep}, I_{leak}, CC, S/N, strip parameters

Available techniques:

CV/IV, TCT, e-TCT, source measurements, DLTS, TSC

Minimize differences in processing by using one vendor!



Dimensions not up to scale

Selection of Materials and Sensors

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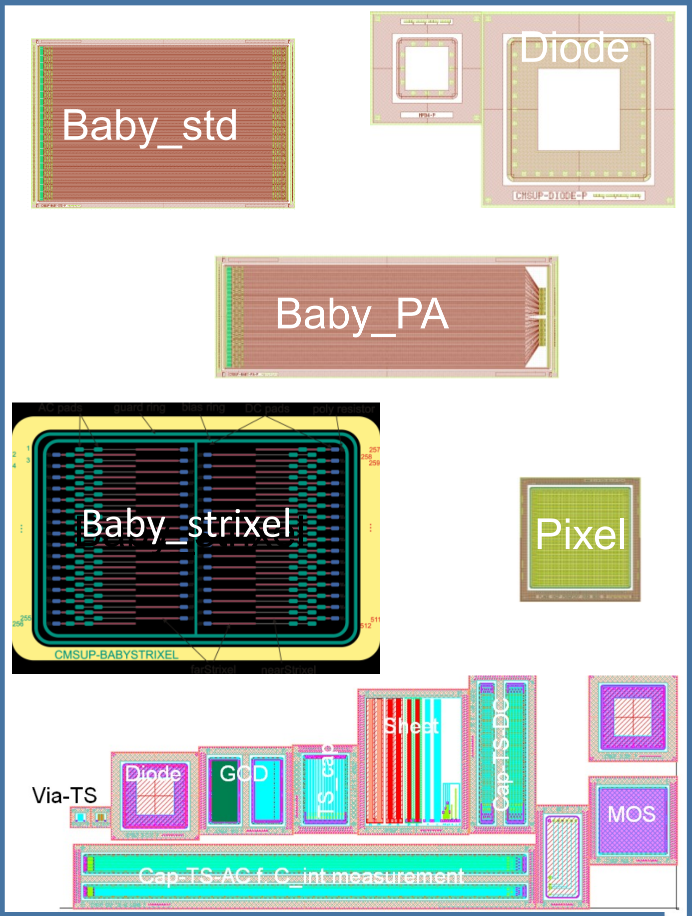

Minimize … le

This presentation mainly addresses the strip region

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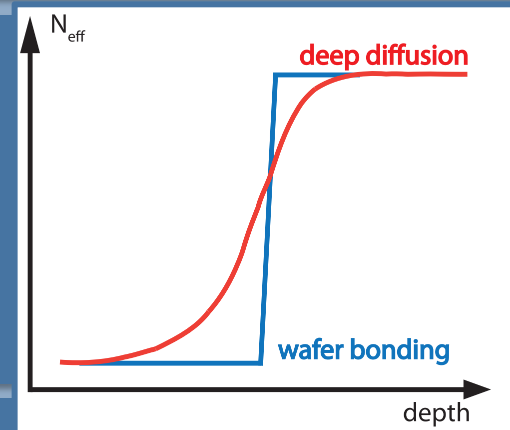
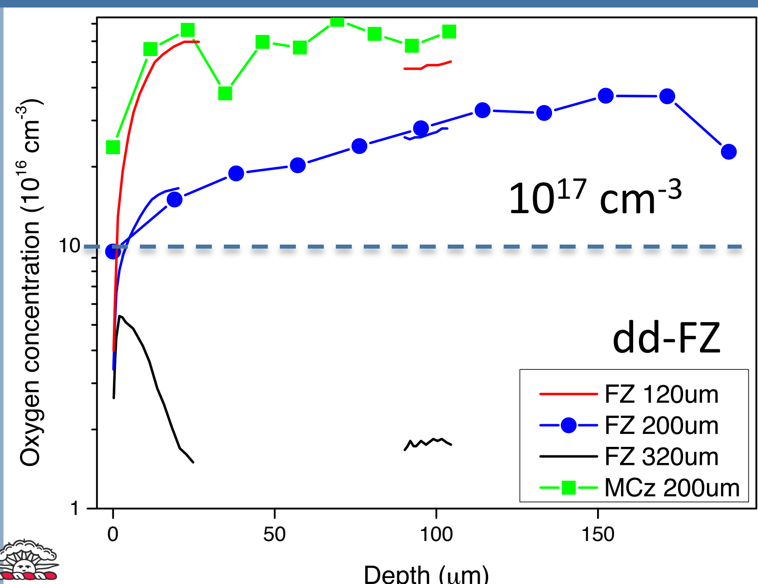
“deep diffusion” thinning process

Silicon growth process defines [O]:
Typically:
Float Zone (FZ): [O]= 1-5x10^{16} cm^{-3}
Magnetic Czochralski (MCz):
[O]= 5x10^{17} cm^{-3}
Epitaxial=5x10^{16} cm^{-3}

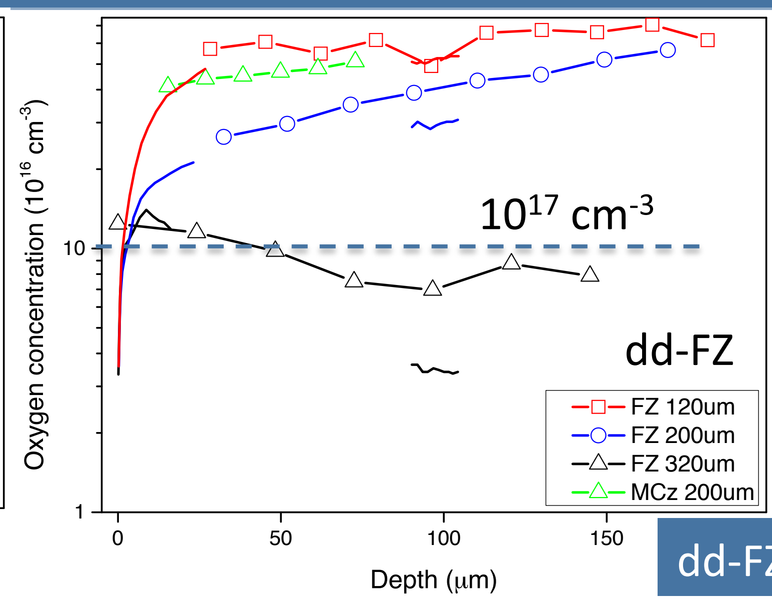
Diffusion of dopants from rear-side -> active volume
Process requires:
- Heat treatment
  - Introduces [O] into bulk
  - dd-FZ is O-rich



Oxygen in n-type material



In p-type material



dd-FZ wafer: 320 μm

"deep diffusion" thinning process

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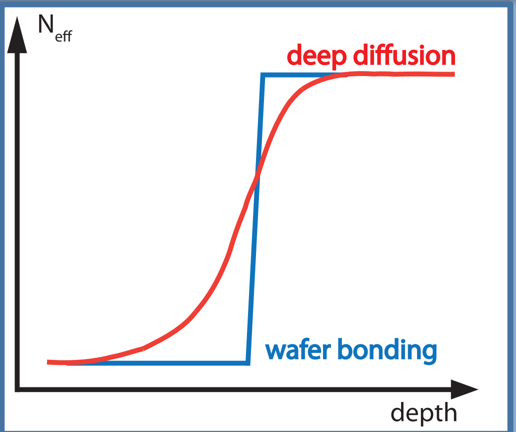
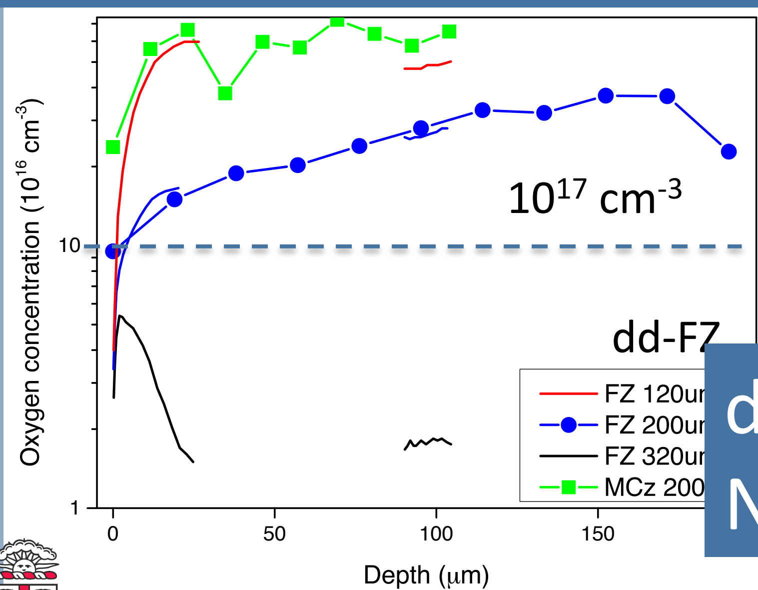
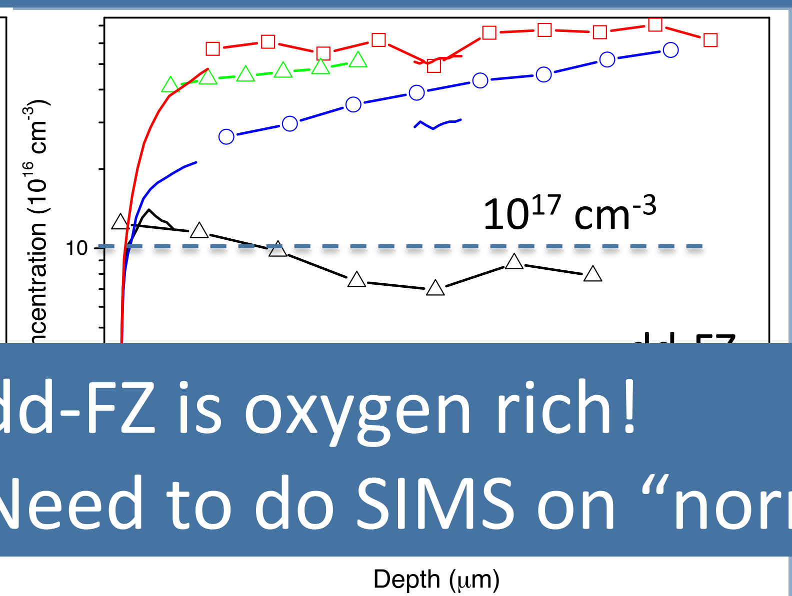


Oxygen in n-type material

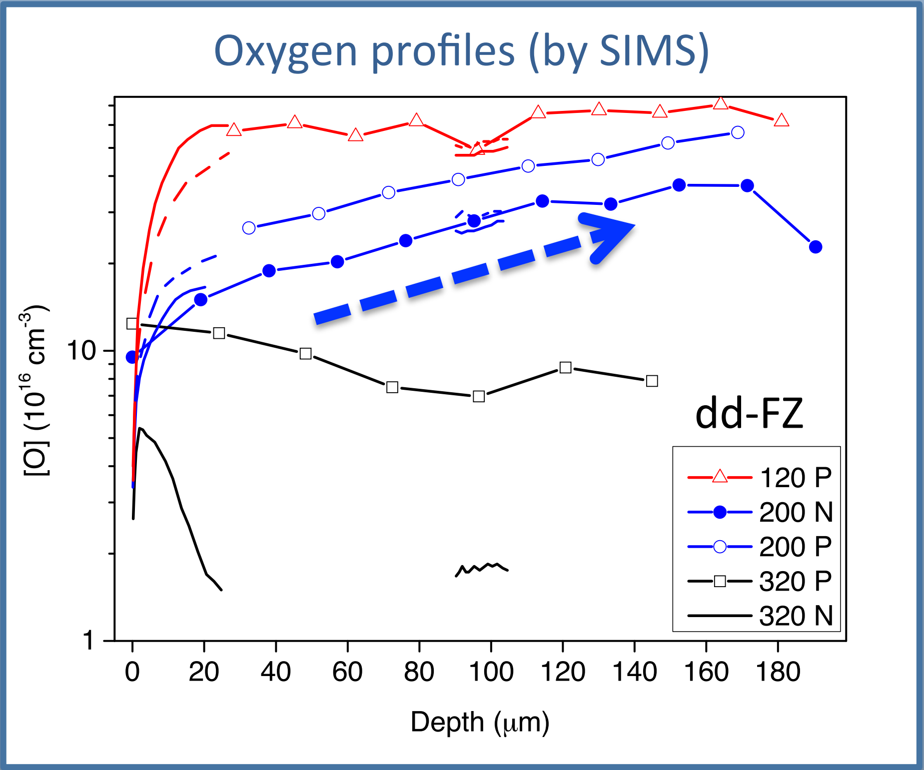


In p-type material



dd-FZ is oxygen rich!
Need to do SIMS on "normal" FZ

Impact of dd-process on Doping

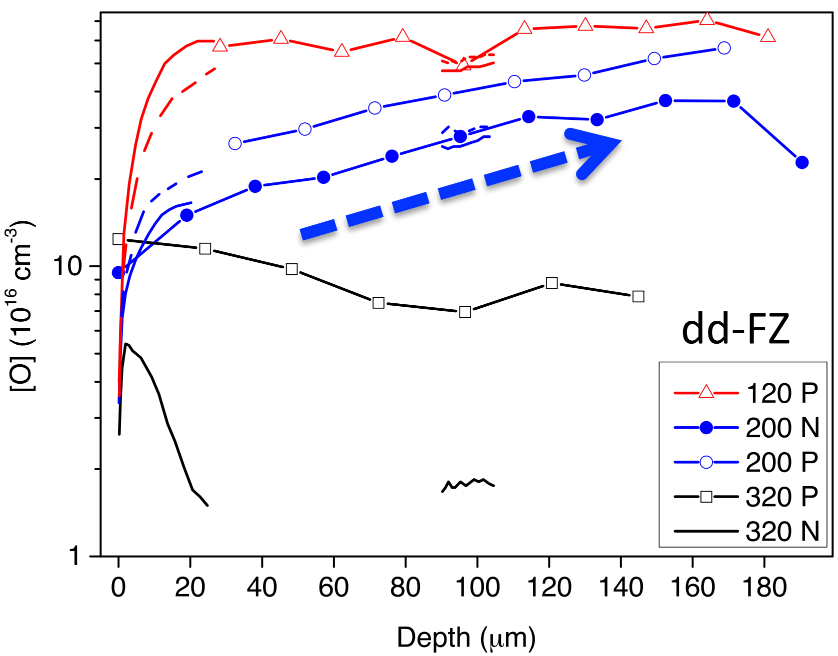


- Bulk defect analyses revealed material defects (e.g. Thermal Donors TD)
- Thermal Donors generated during processing
- TD influence the doping concentration

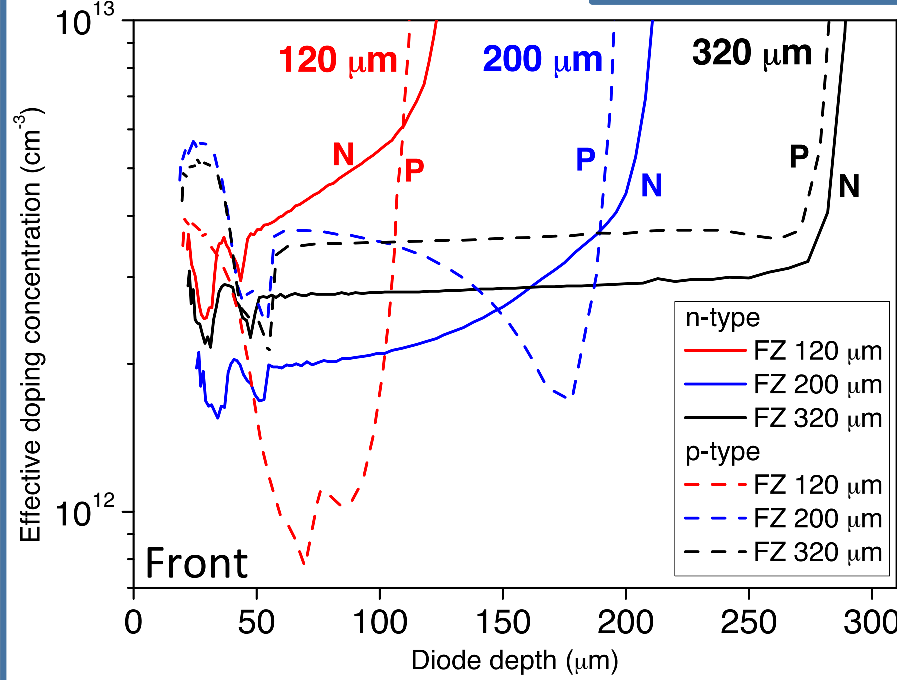
Impact of dd-process on Doping

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 |N_{eff}|}$$

Oxygen profiles (by SIMS)



Doping profile (from CV)



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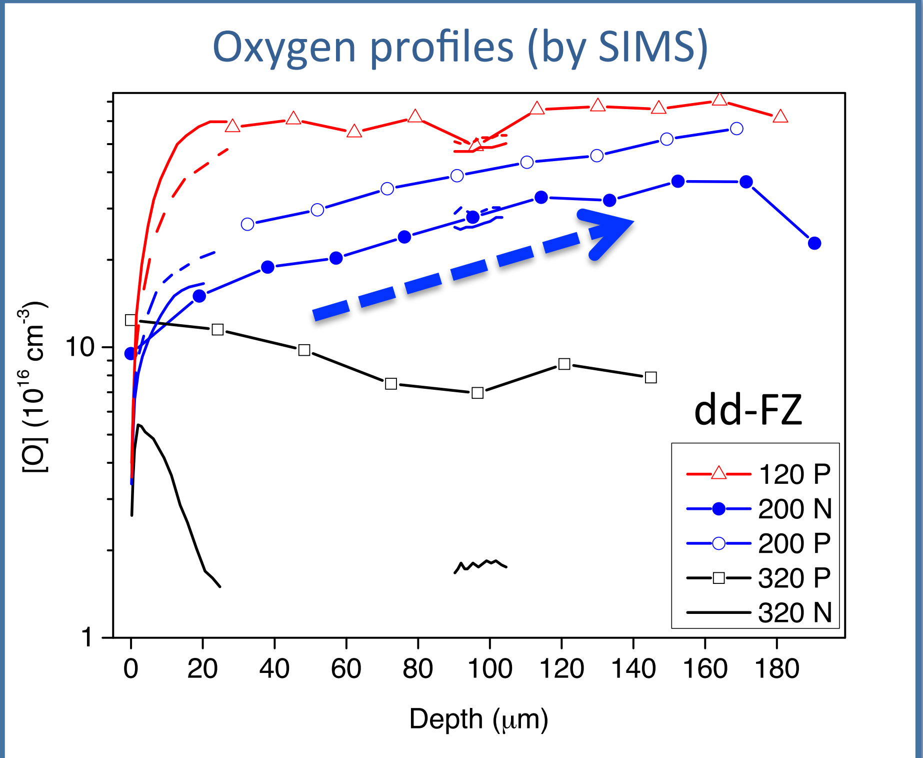

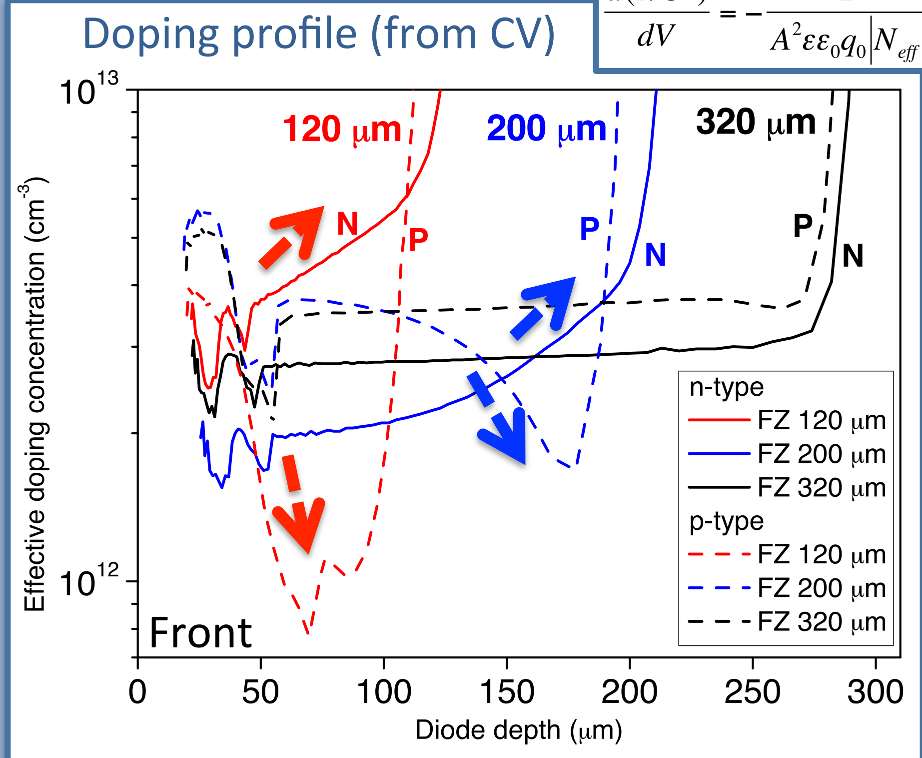

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 |N_{eff}|}$$

- Bulk defect analyses revealed material defects (e.g. Thermal Donors TD)
- Thermal Donors generated during processing
- TD influence the doping concentration (seen also for MCz material)

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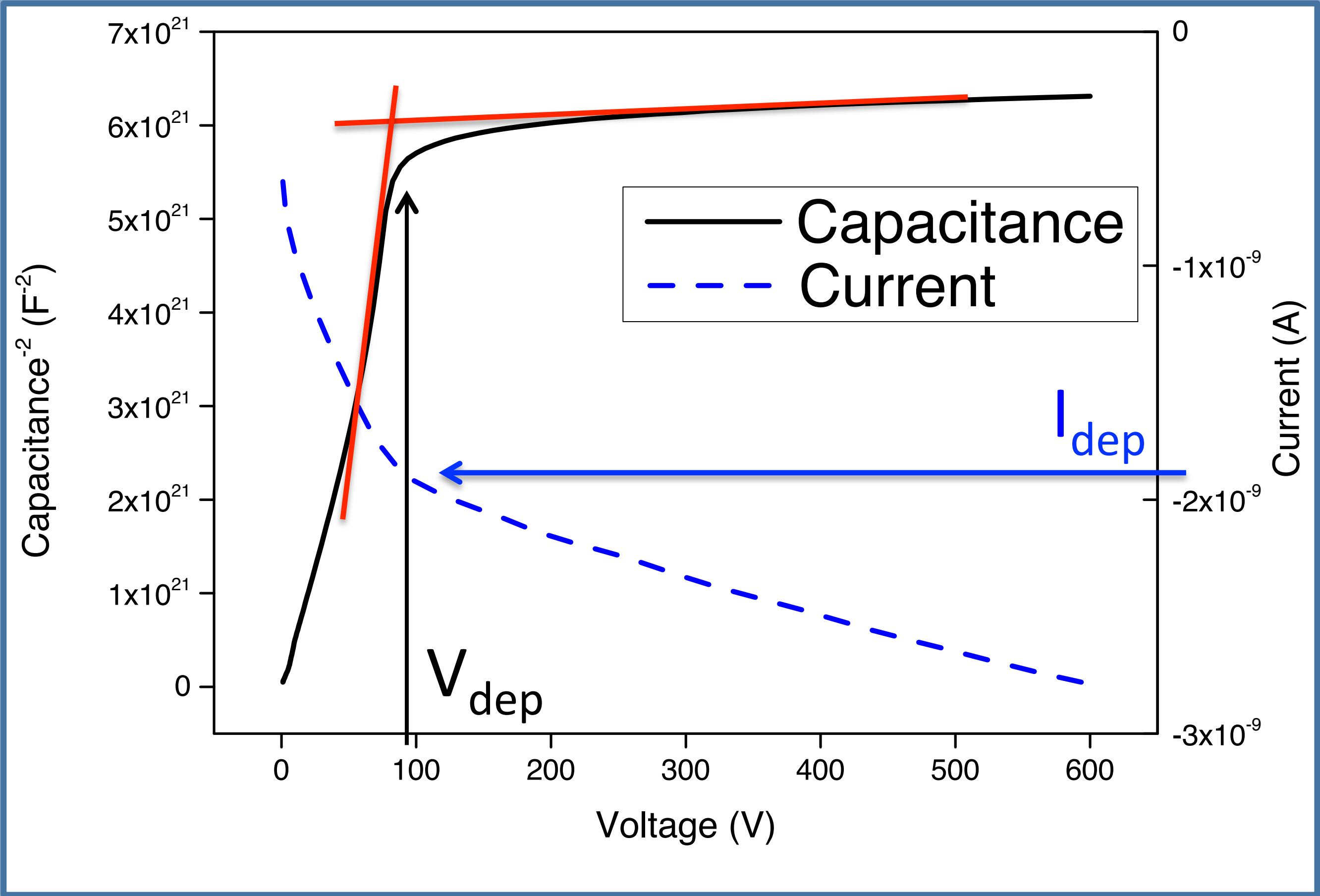
Extraction of depletion voltage

Capacitance-Voltage and Current-Voltage measurement



Capacitance measurement:

- 0 °C (at 1 kHz)
- -20 °C

(at 1 kHZ & 455 Hz)

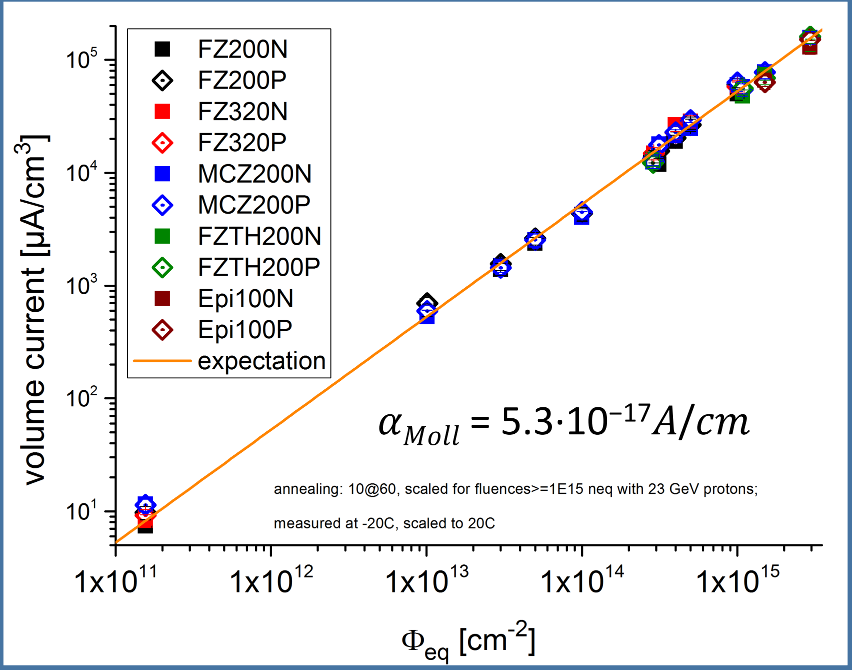
➔ Extract depletion voltage V_{dep}

➔ Calculate:

$N_{eff} = 2\varepsilon\varepsilon_0 V_{dep}/q_0\, d^2$

Current above full depletion

Diode measurement

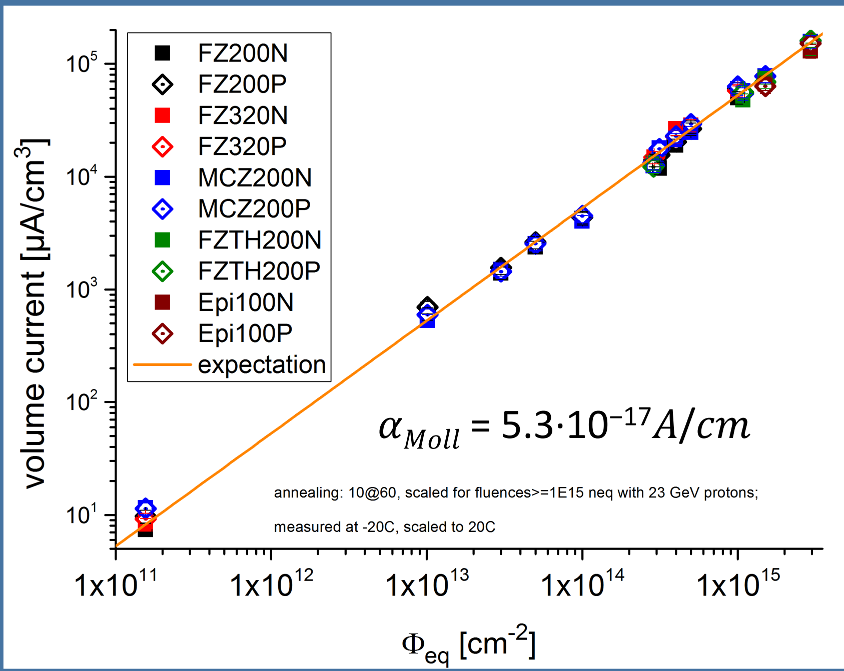


Current taken at V_{dep} + 5%

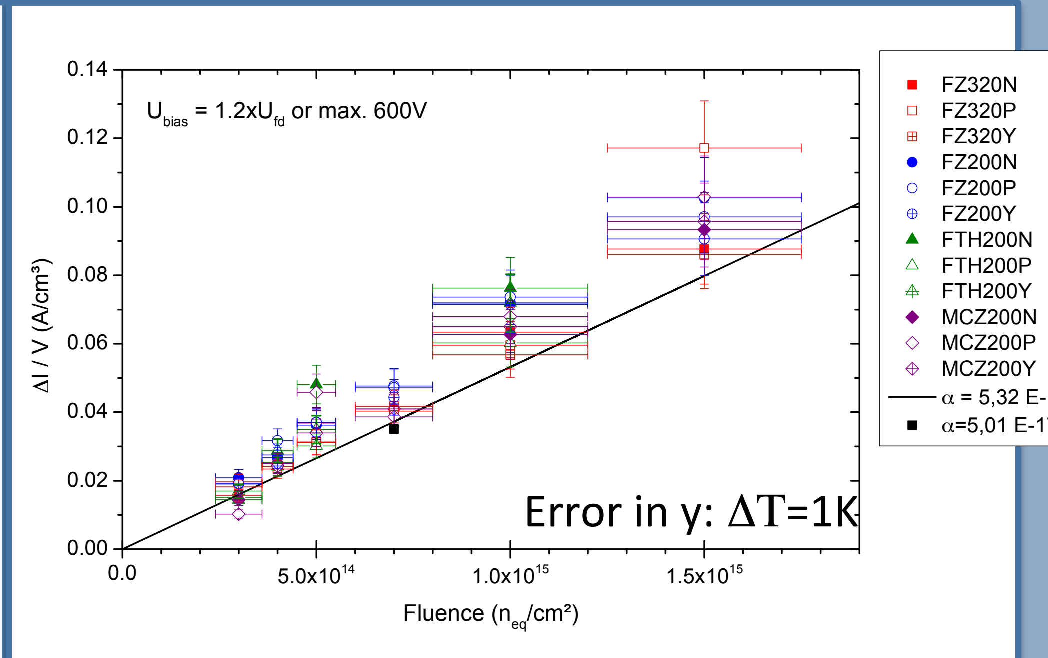
- Independent of material and irradiation type $I/V = \alpha \cdot \Phi_{eq}$

Current above full depletion

Diode measurement



Strip measurements at max 600 V



Current taken at V_{dep} + 5%

- independent of material and irradiation type $I/V = \alpha \cdot \Phi_{eq}$

Thickness taken from CV measurements on diodes

- Some sensors not fully depleted at 600 V
- Leakage currents of strip sensors higher than expected from diodes

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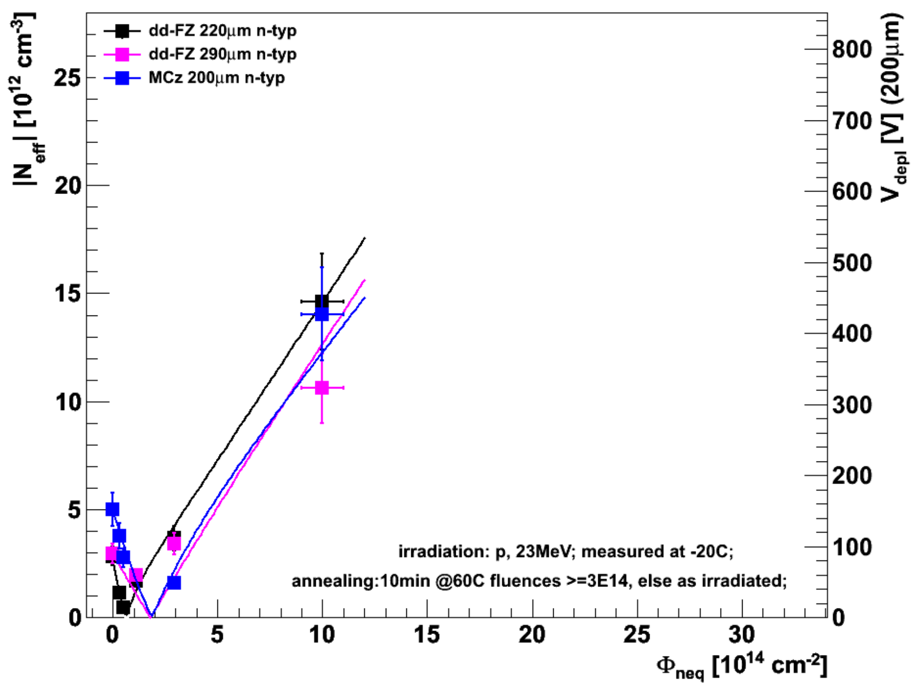
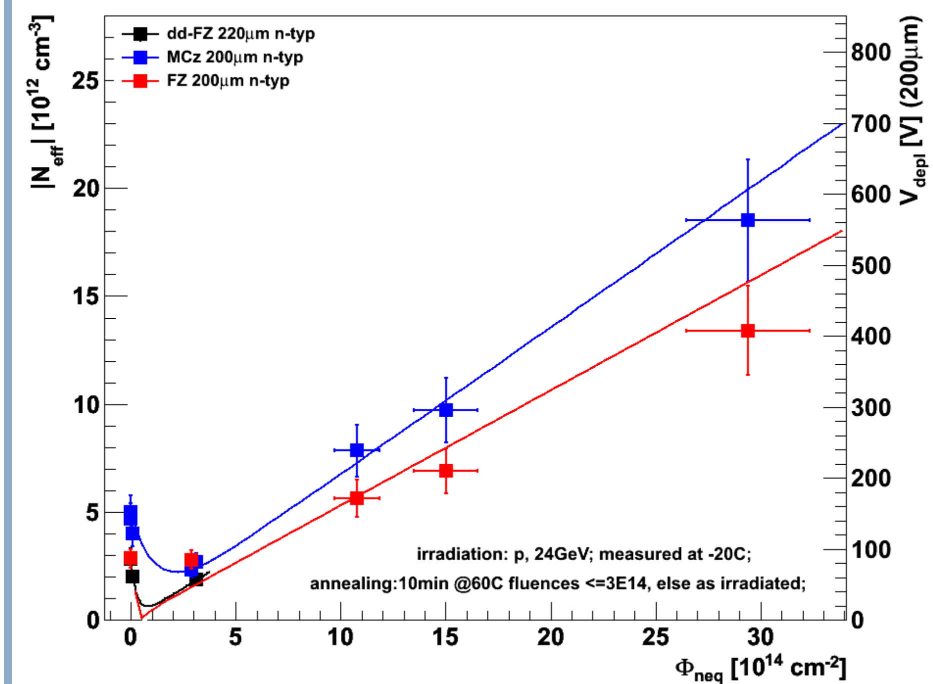
Depletion Voltages for 200 μm (n-type)

23 MeV protons



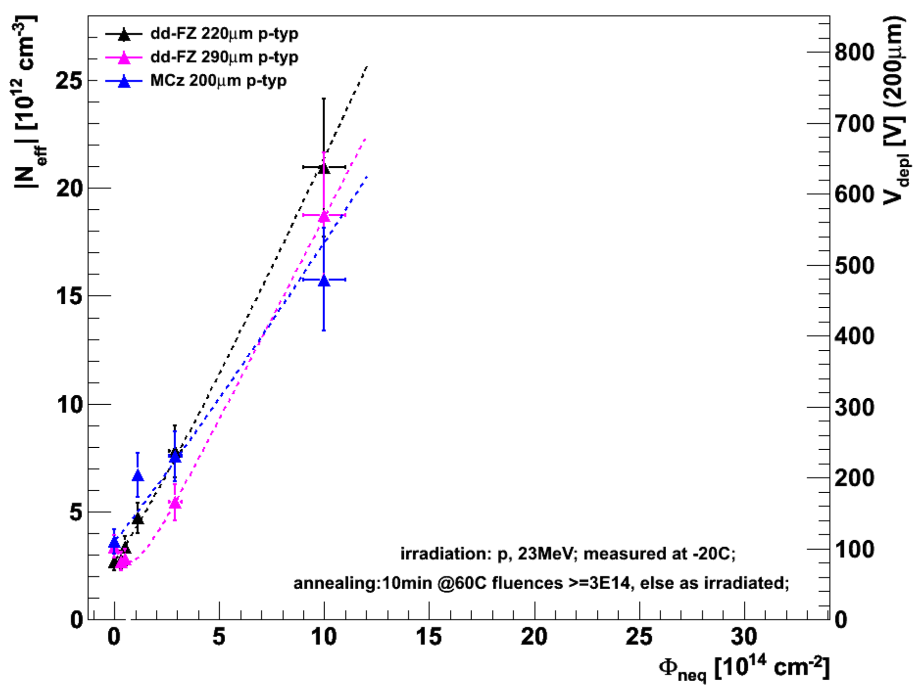
23 GeV protons



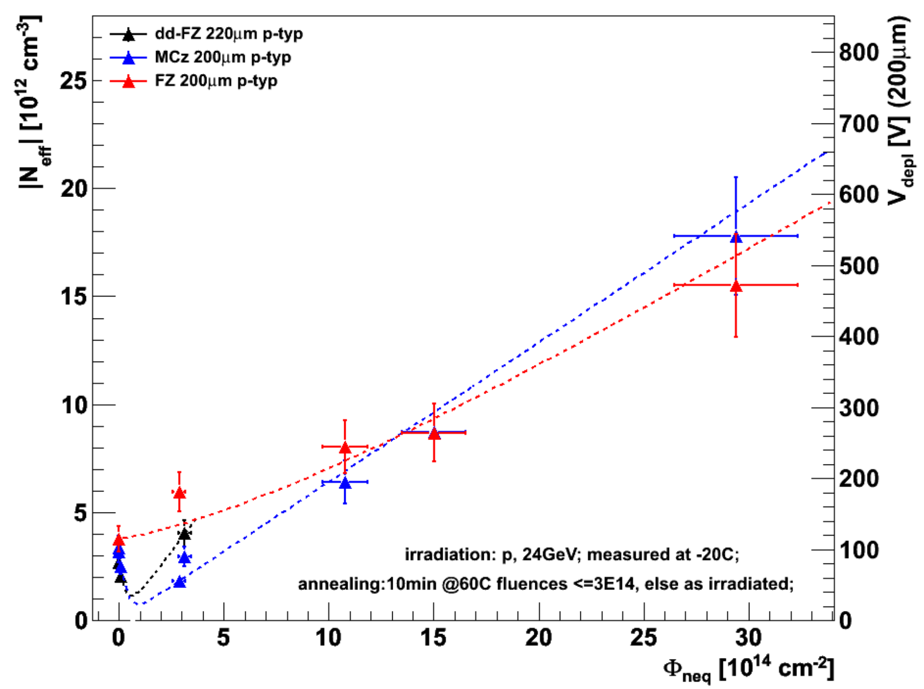
→ MCz and dd-FZ behave similar due to similar O concentration
→ 200 μm FZ has lower depletion voltage than MCz 200 μm for GeV p
→ Proton energy dependence found

Depletion Voltages for 200 μm (p-type)

23 MeV protons



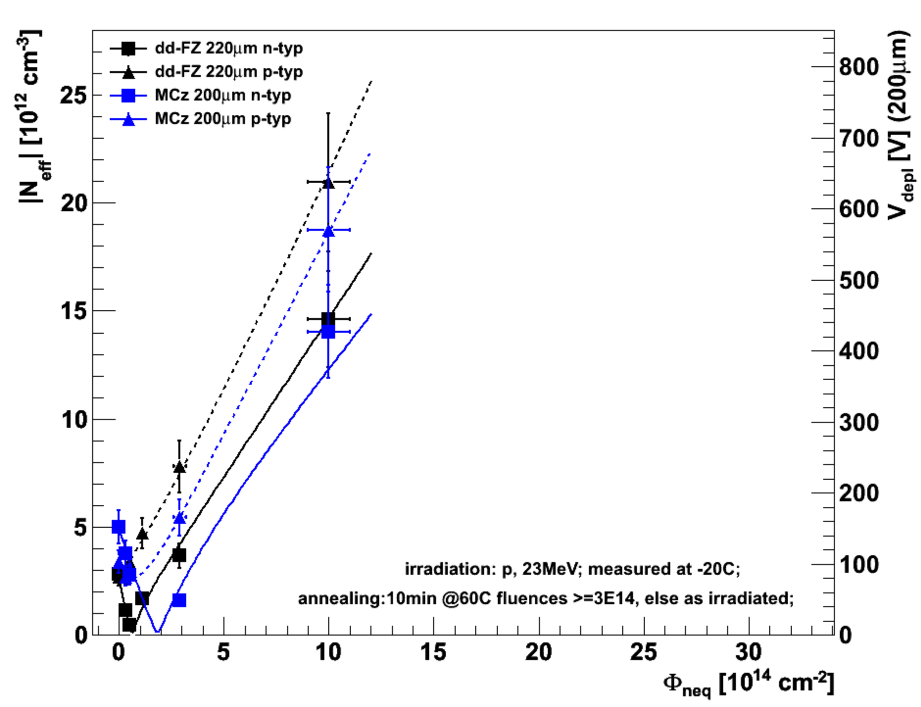
23 GeV protons



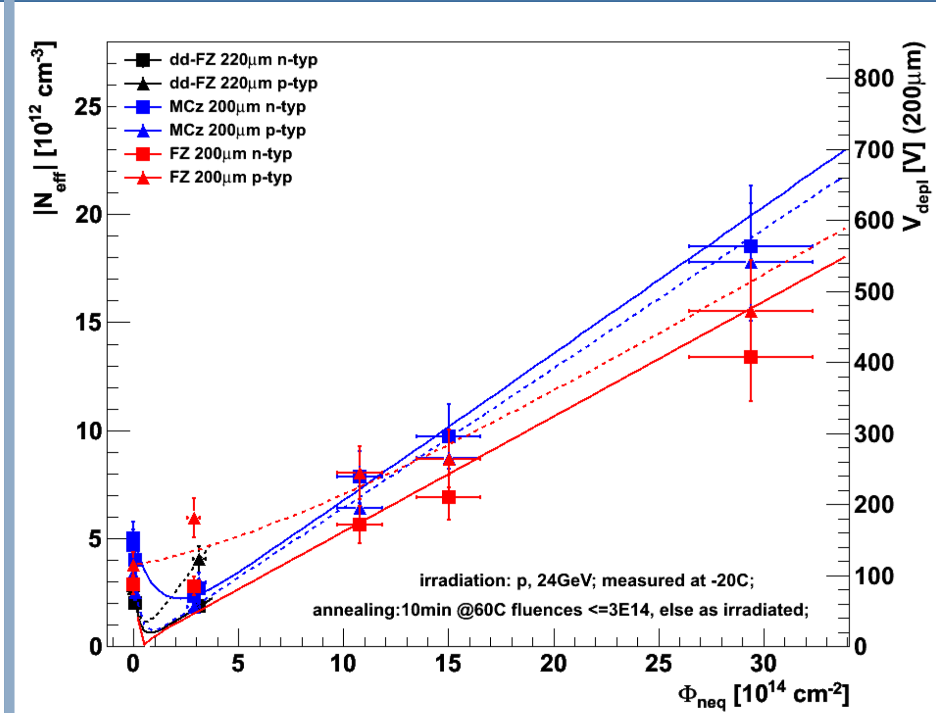
→ p-type rise from start after 23 MeV protons
→ Acceptor removal seen for 23 GeV protons

Material comparison

23 MeV protons

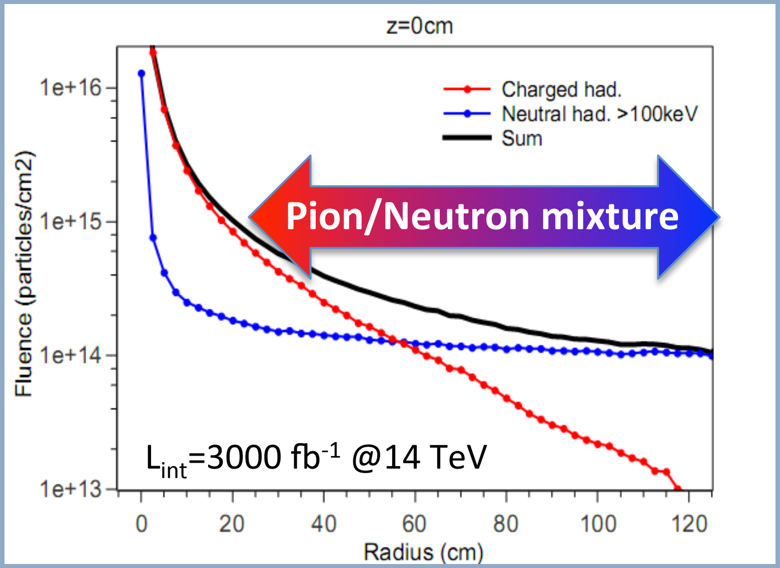


23 GeV protons

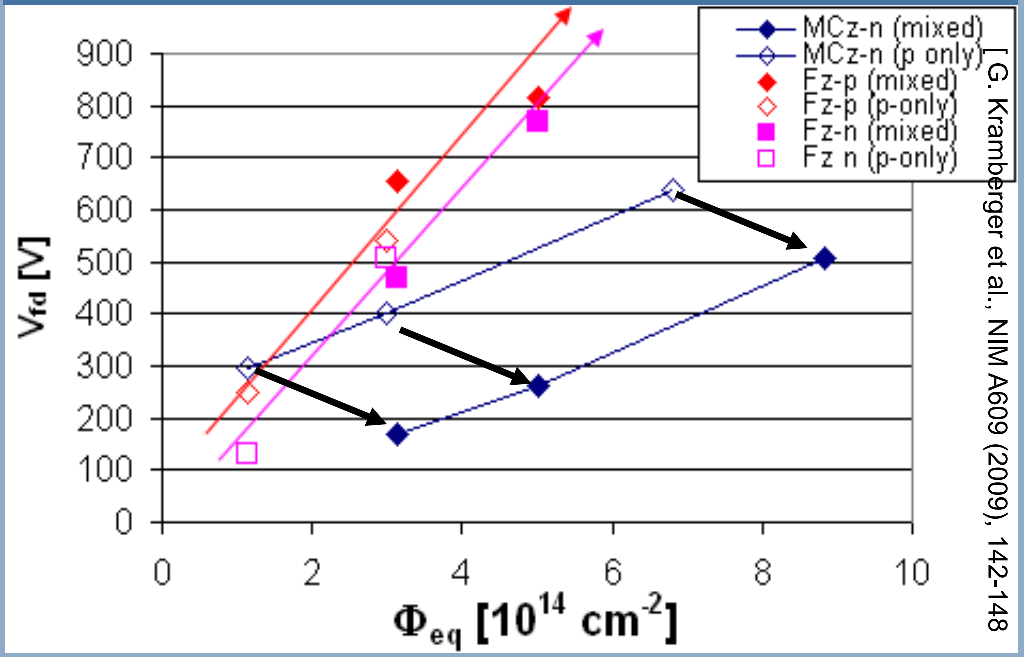


→ p-type depletion voltage higher after 23 MeV proton irradiation
→ Depletion voltage very similar after 23 GeV proton irradiation

Expectation for mixed irradiations



Neutron + 23 GeV proton irradiation

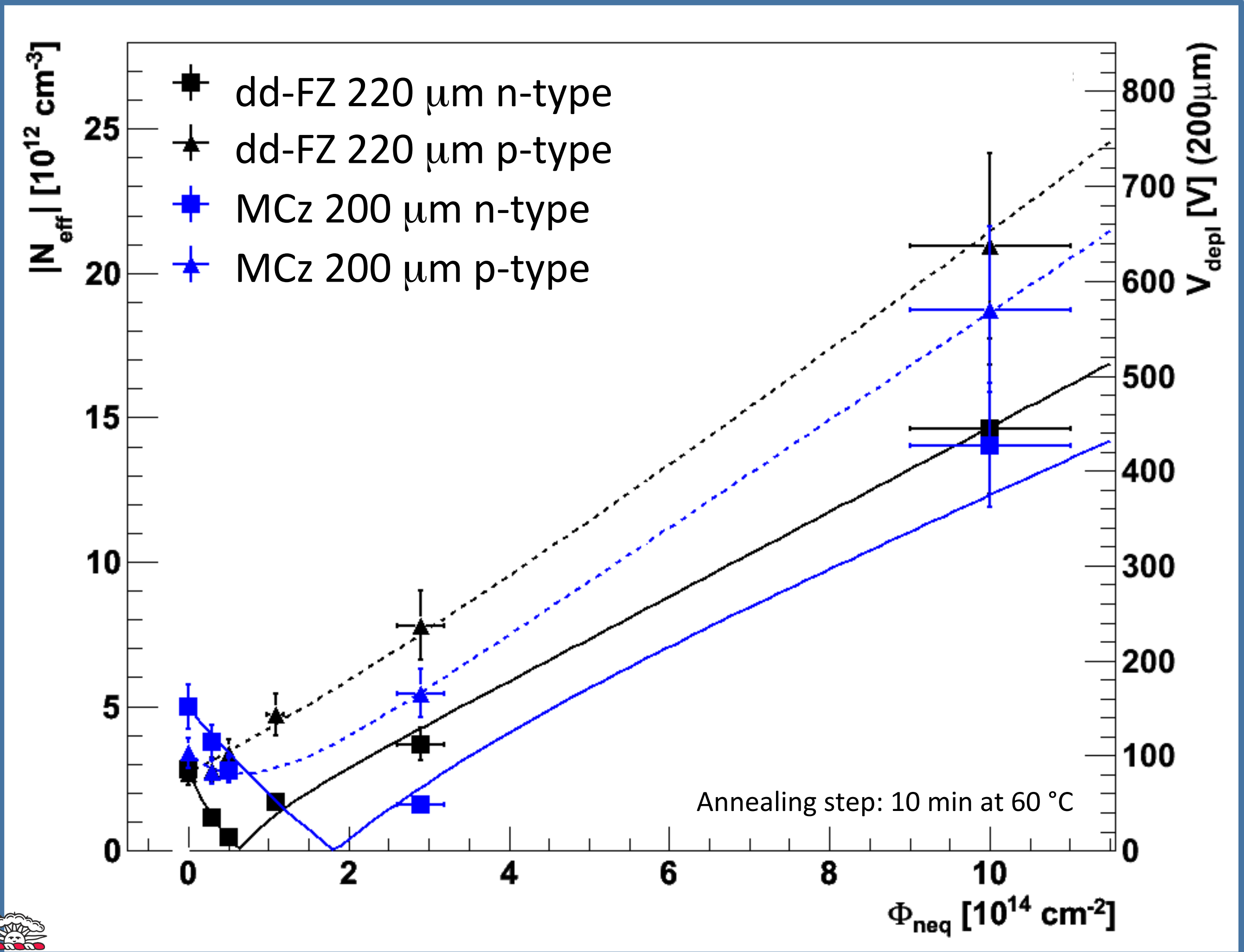


[G. Kramberger et al., NIM A609 (2009), 142-148]

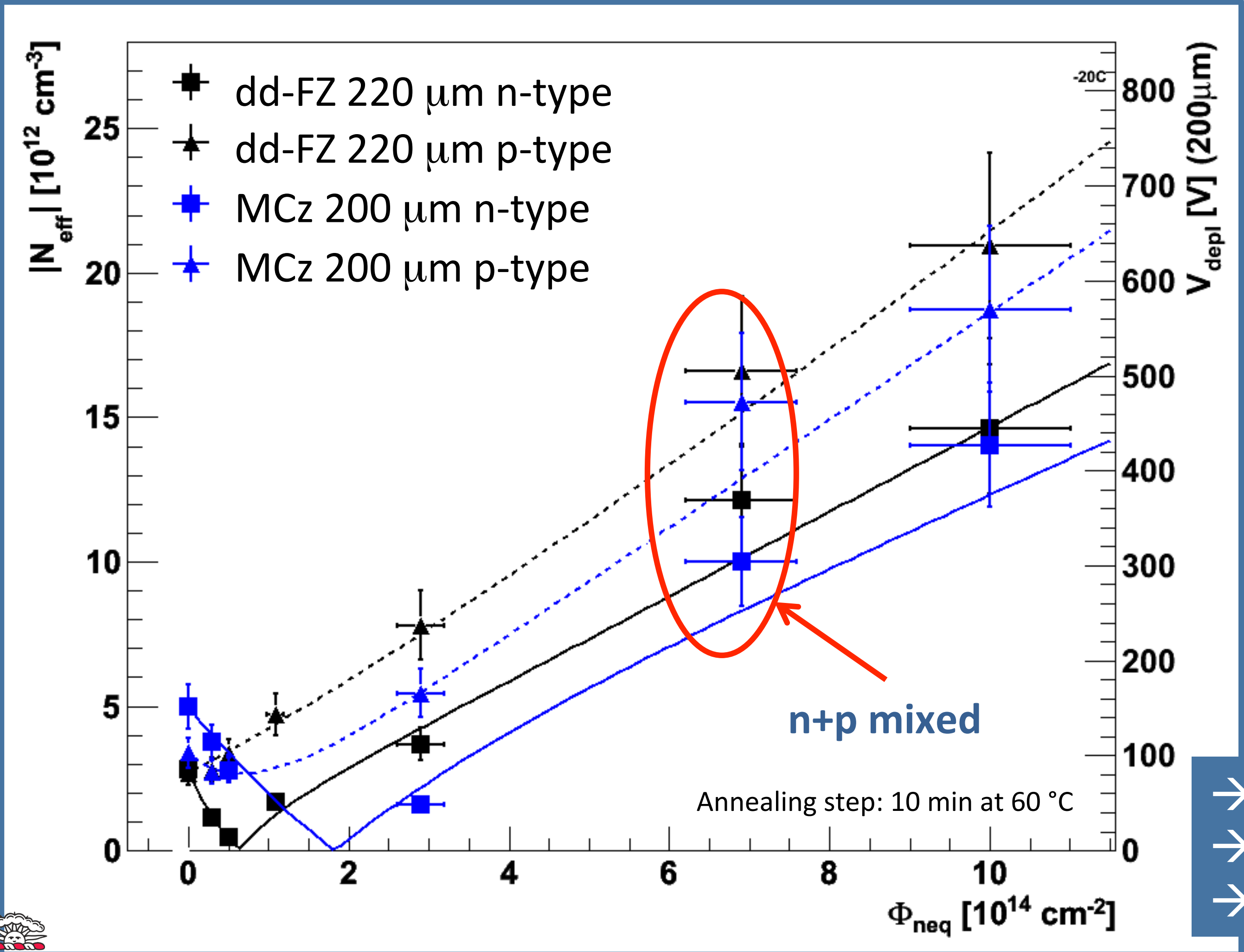
- Leakage current increases in accordance with received Φ_{eq}
- FZ: damage accumulated
- MCz-n: damage compensated

➔ Donors introduced in p irradiation compensated by acceptors introduced in n-irradiation

Mixed irradiations: 23 MeV Protons



Mixed irradiations: 23 MeV Protons + Neutrons



- → Fluences add up
- → No compensation effect
- → Test with 23 GeV p

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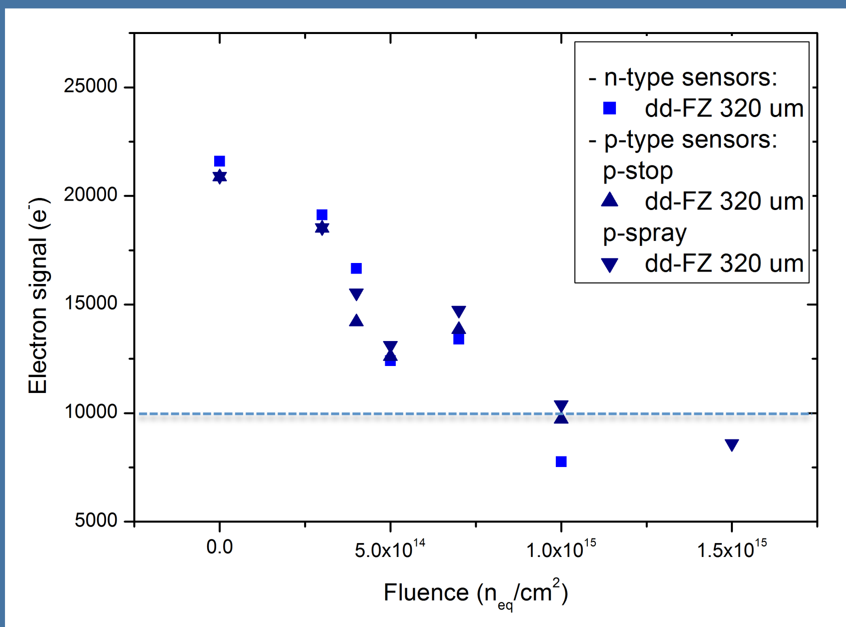
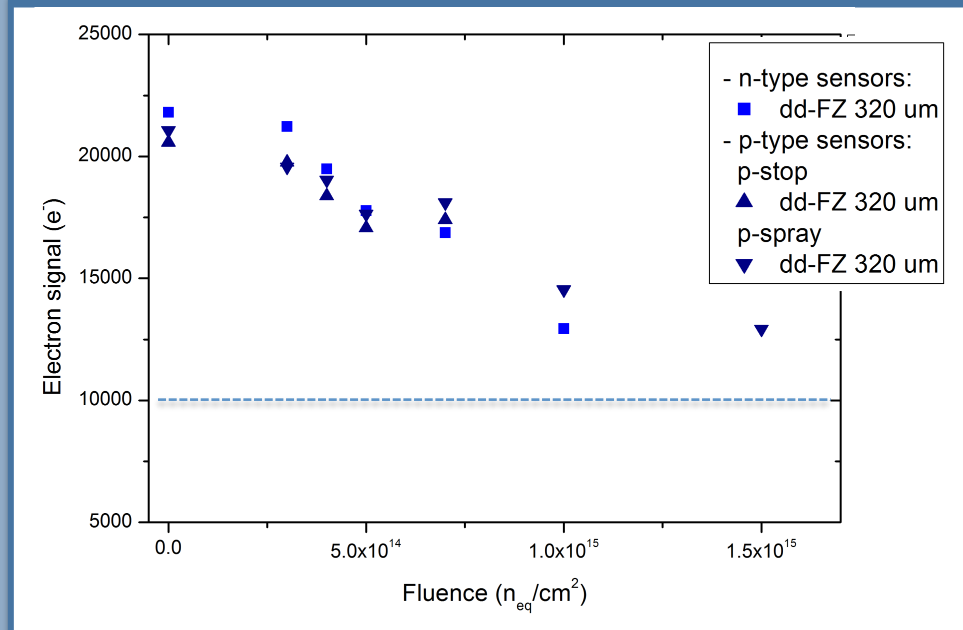
Charge Collection from strip sensors

V_{bias} = 600 V



V_{bias} = 900 V



Measurement: β-setup with Alibava read-out

- FZ320 collects more charge up to $\Phi_{eq}=1\text{x}10^{15}$ cm^{-2}
- No significant difference between 200 μm and 300 μm above $\Phi_{eq}=1\text{x}10^{15}$ cm^{-2}

Charge Collection from strip sensors

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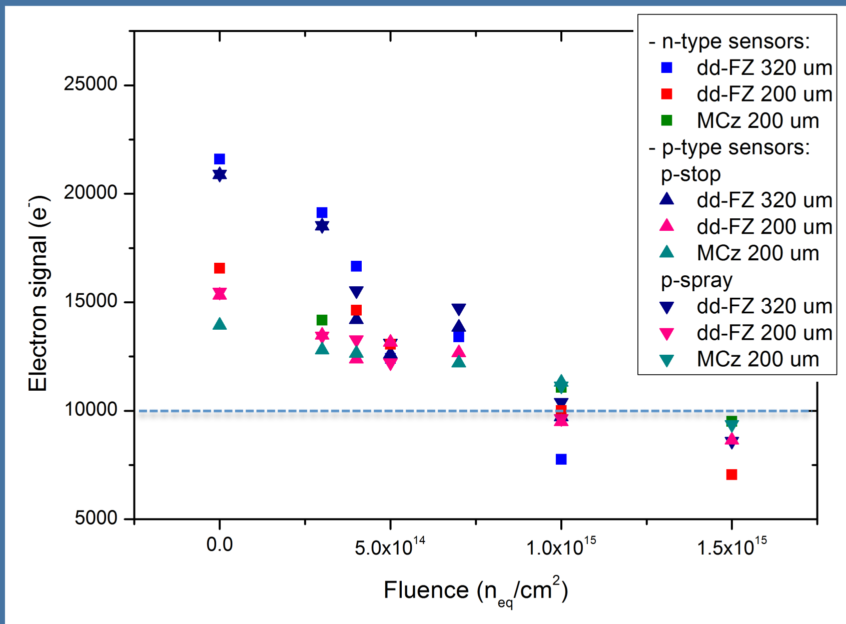

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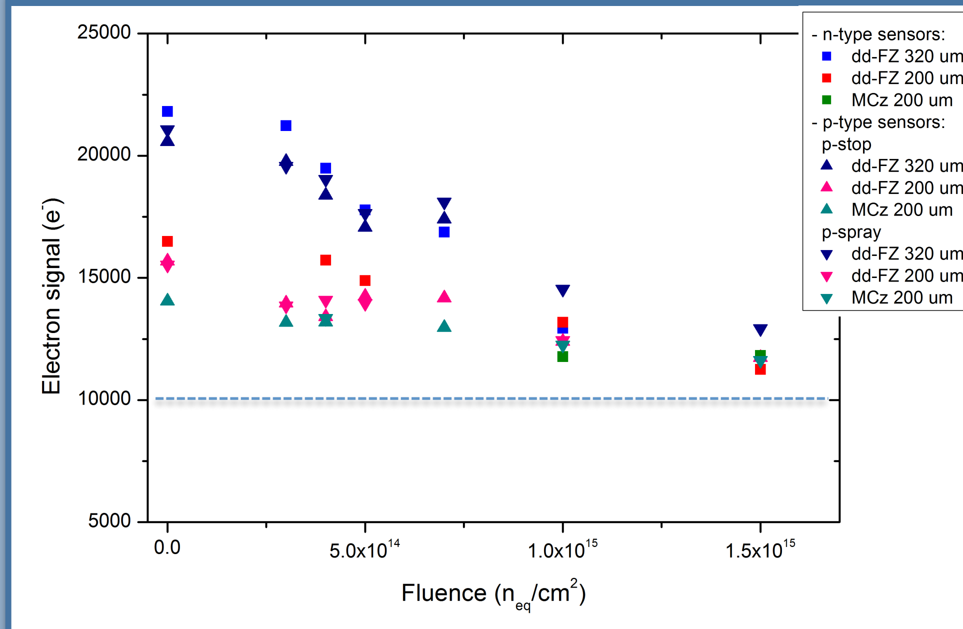

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Summary

- Materials overall of very good quality
  - At Φ_{eq}=1.5x10^{15} cm^{-2} still signal on most 200 μm strip sensors of about 10 ke
- No significant difference between 200μm and 300μm above Φ_{eq}=1x10^{15} cm^{-2}
- Excess of leakage current of strip sensors compared to diodes
- No compensation effect observed in mixed irradiation

- Deep diffusion process introduces [O] into bulk material
- All materials behave very similarly due to similar O-concentration

Not addressed in this presentation…

Measurements on Multi-Strip and Multi-Pixel ongoing

- Evaluation of Strip parameters
- Test beam results

Defect analysis still ongoing

- Comparison of defects in different materials
- Comparison

Simulation efforts very strong

- Simulation of strip parameters ongoing
- Trap model for radiation damage under development

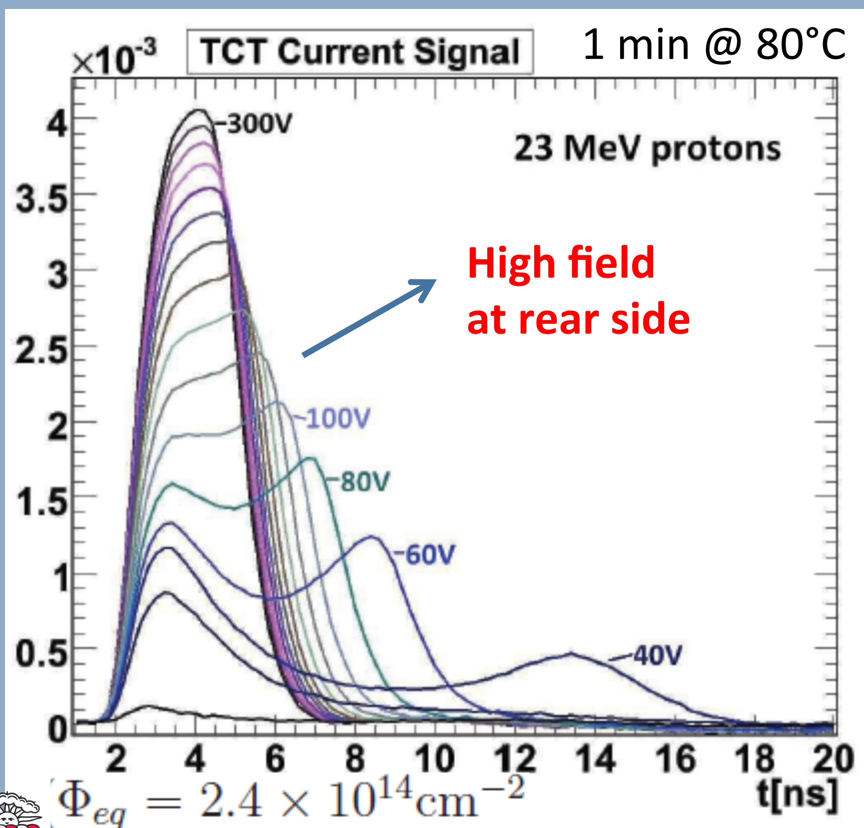
Double metal layer structures and new designs

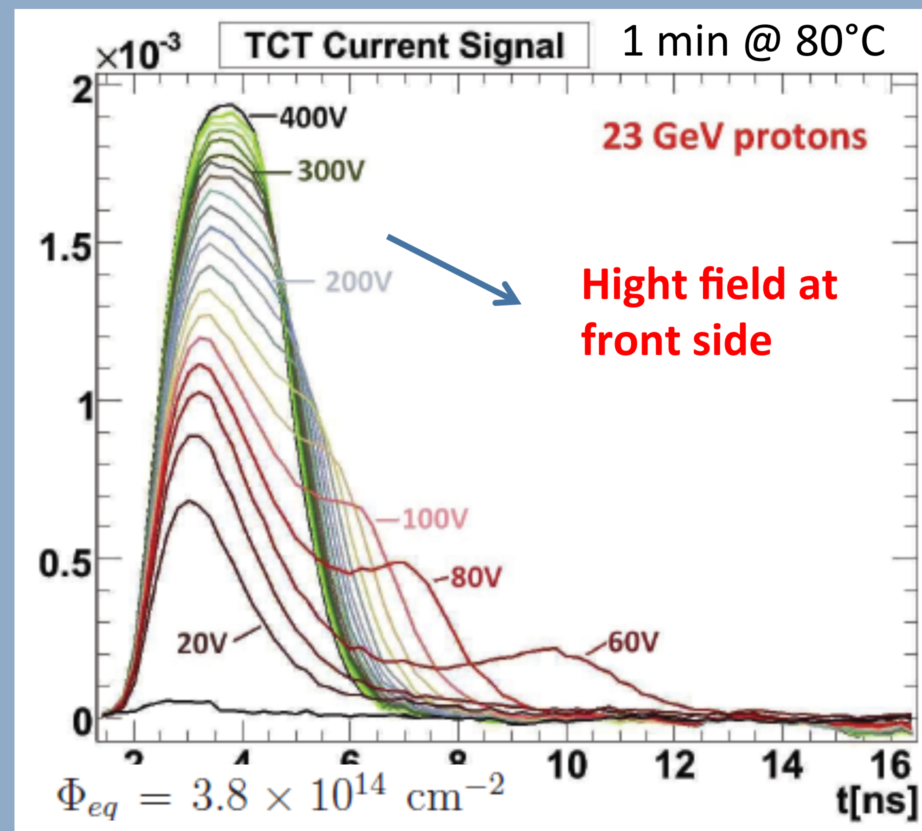
Back up

MCz after 23MeV and 23 GeV Protons

Red laser TCT illumination from front:

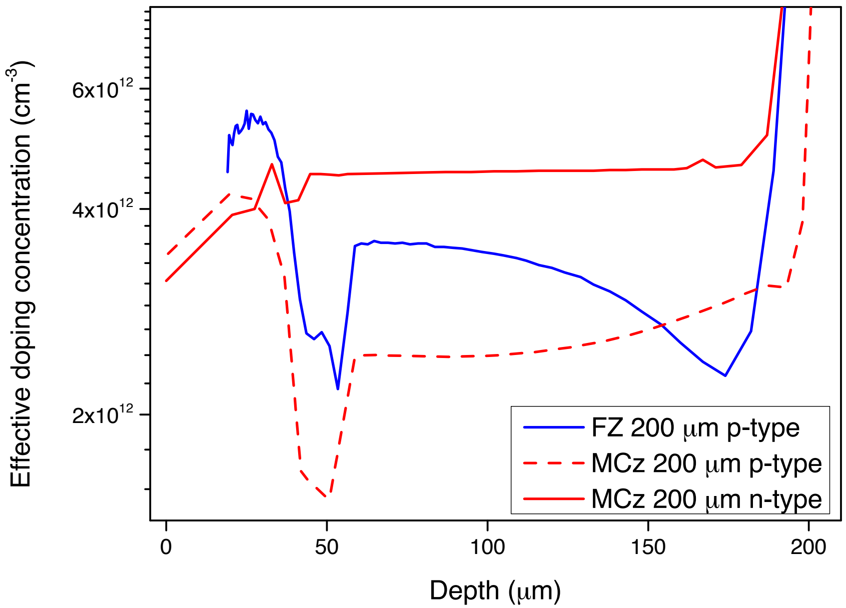
→ Charge injected close to p+ electrode
→ Electrons drift through bulk to backplane



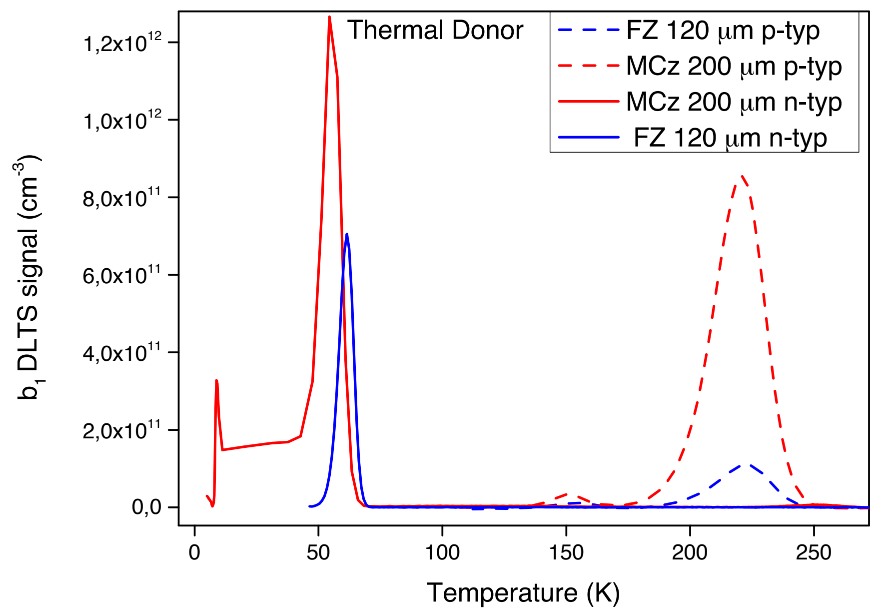


Thermal Donor concentration in MCz

- Highest concentration of Thermal Donors in MCz
- Evaluation difficult due to inhomogeneity in FZ



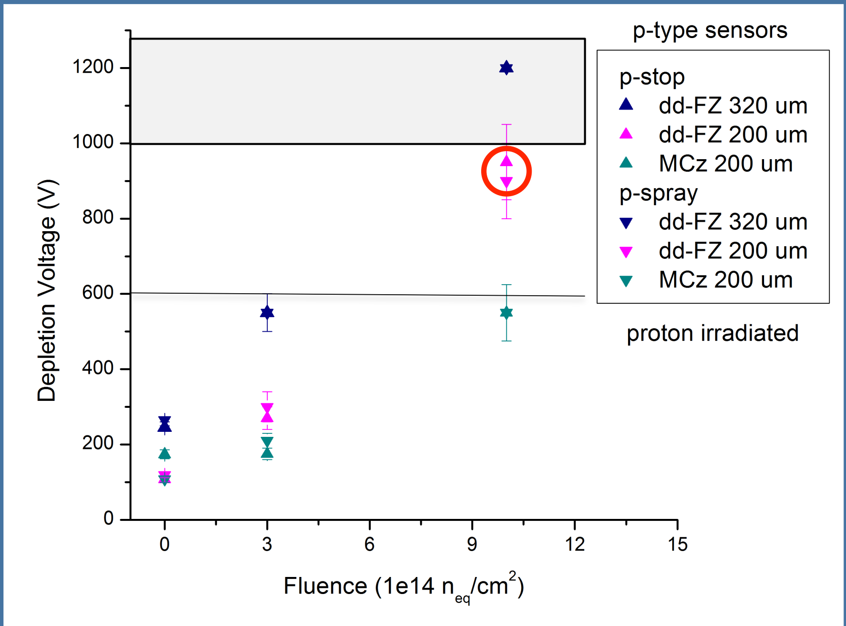
Depth corresponding to ~90 μm



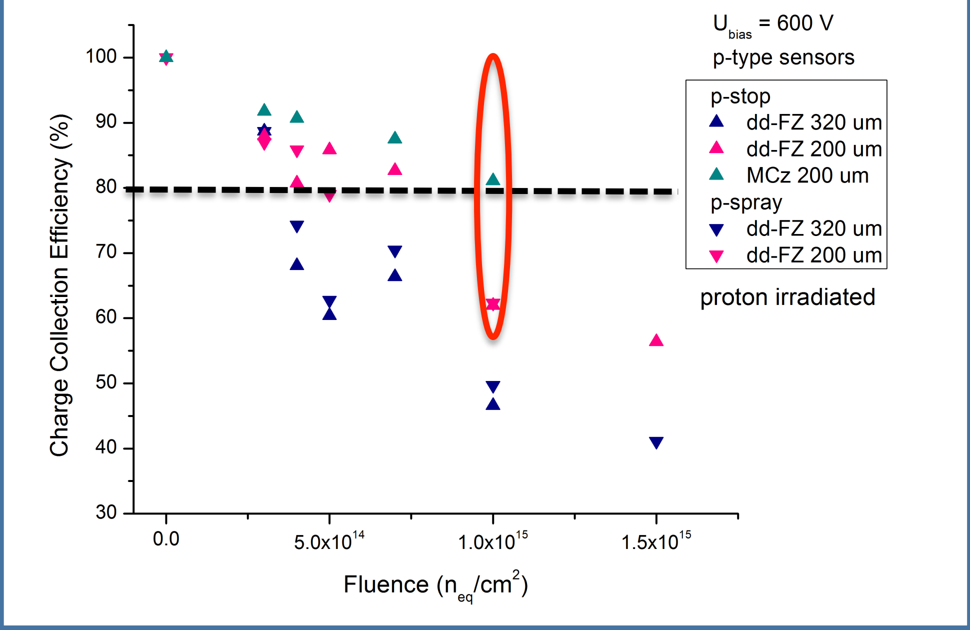
- More homogeneous than in dd-FZ
- TD levels the doping concentration

Loss in CCE due to "under-deplection"

Depletion Voltage



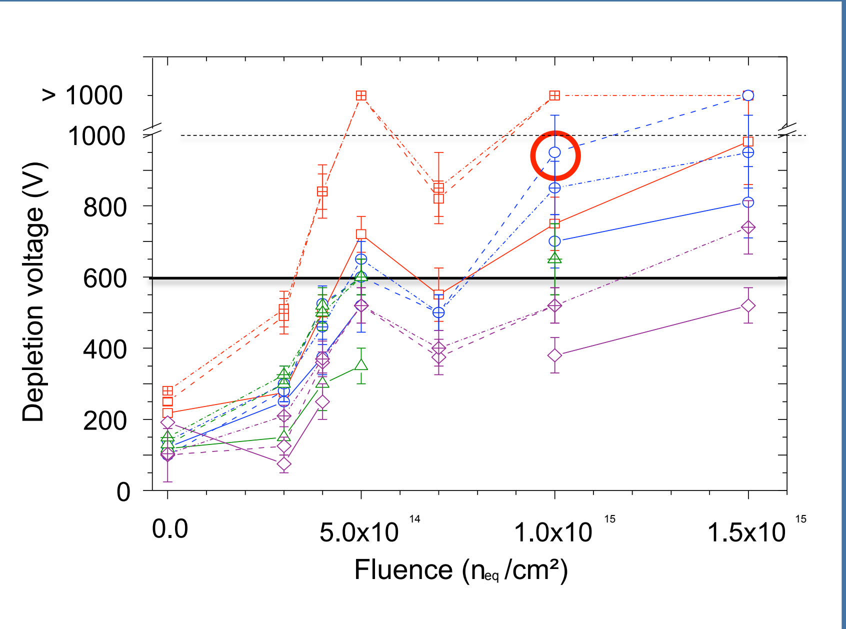
Charge Collection Efficiency at 600 V



- FZ 200 μm: V_{dep}= 950V at $\Phi_{eq}=1x10^{15}$ cm^{-2} → -20 %
- Loss in Charge Collection due to „under-depletion"
- Loss in Charge Collection due other effects: additional 20%

Loss in CCE due to “under-depletion”

Depletion Voltage



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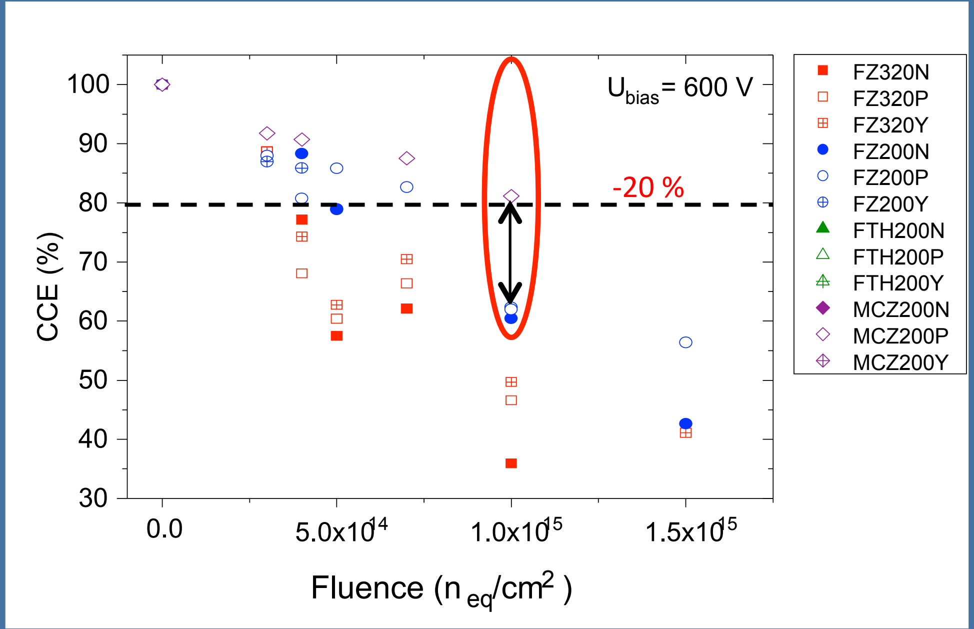

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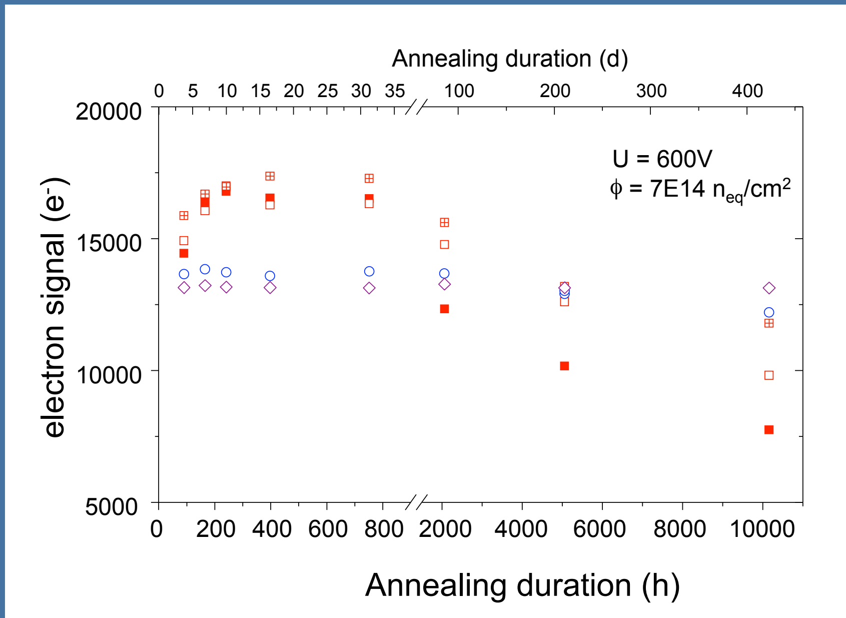
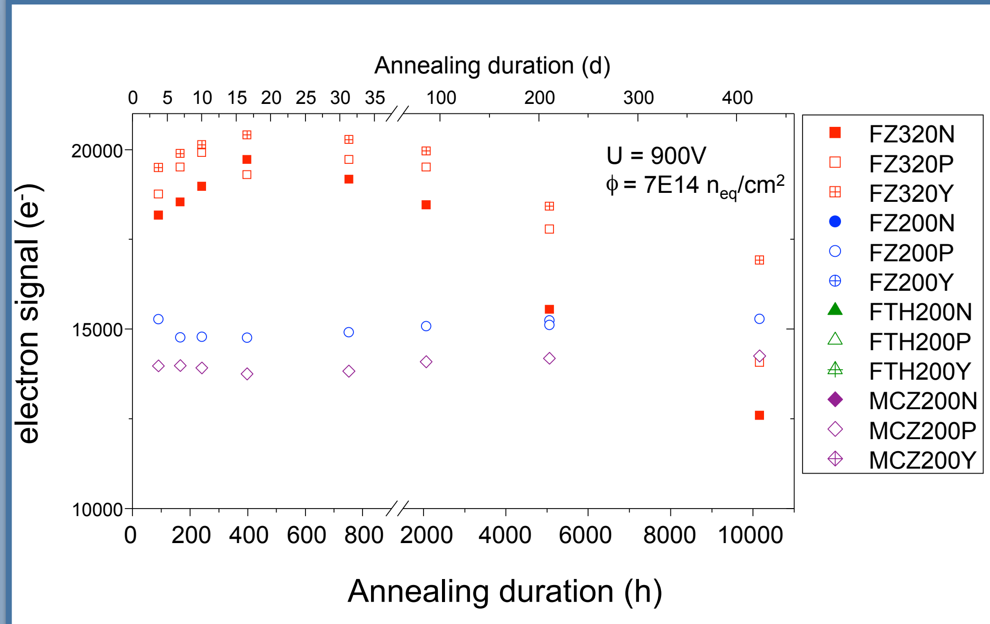
Annealing Study on Charge Collection

Φ_{eq}=7x10^{14} cm^{-2}, Annealing time projected to room temperature

V_{bias}= 600V



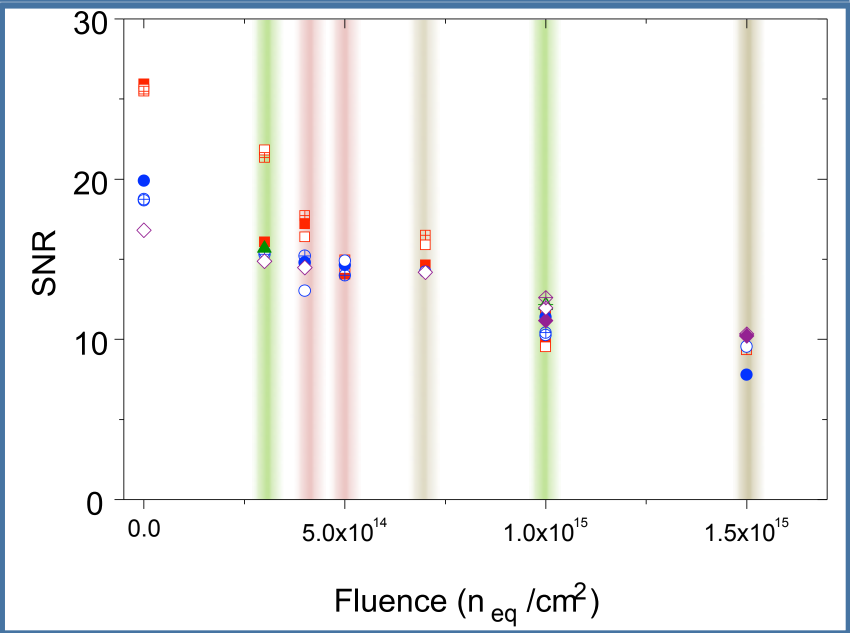
V_{bias}= 900V



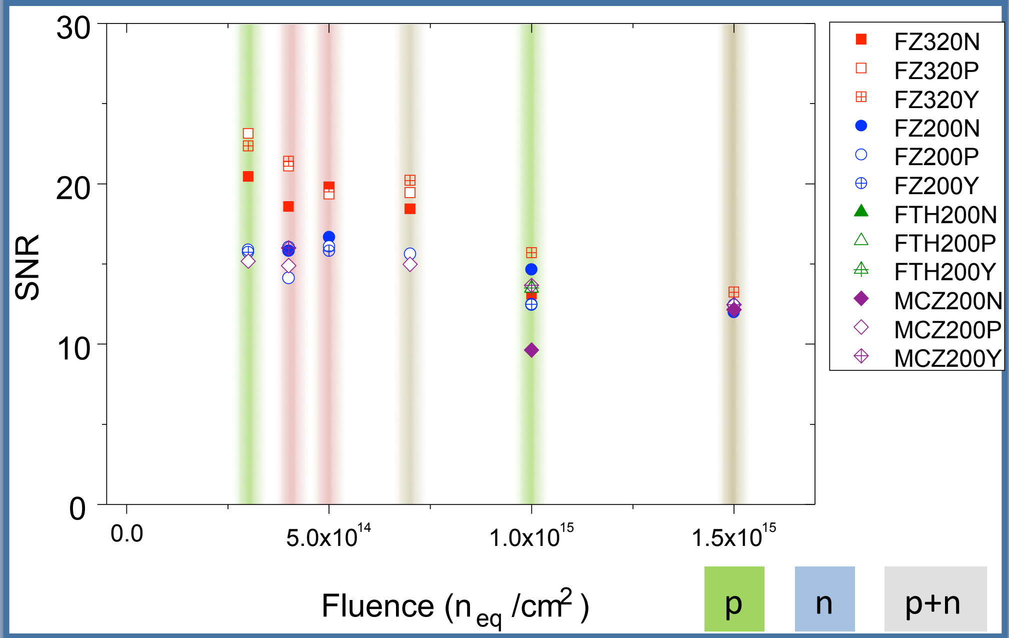
- Electron signal of FZ320 sensors increases during the first 15 days of annealing at RT (*beneficial annealing*), afterwards continues decrease (*reverse annealing*)
- 200 µm sensors remain nearly constant

Irradiation Study: Signal-to-noise ratio

V_{bias}= 600V



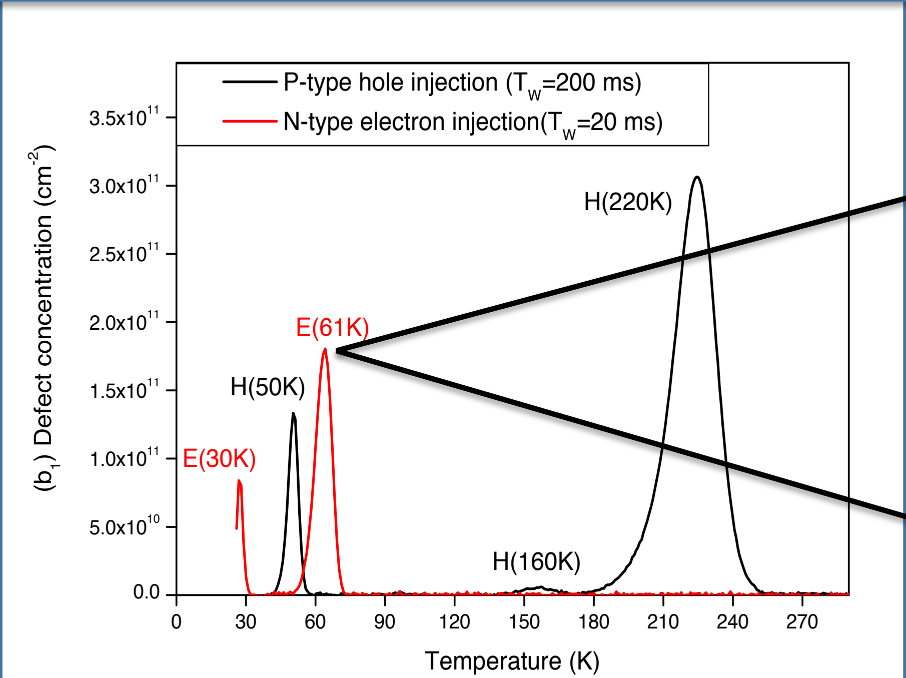
V_{bias}= 900V



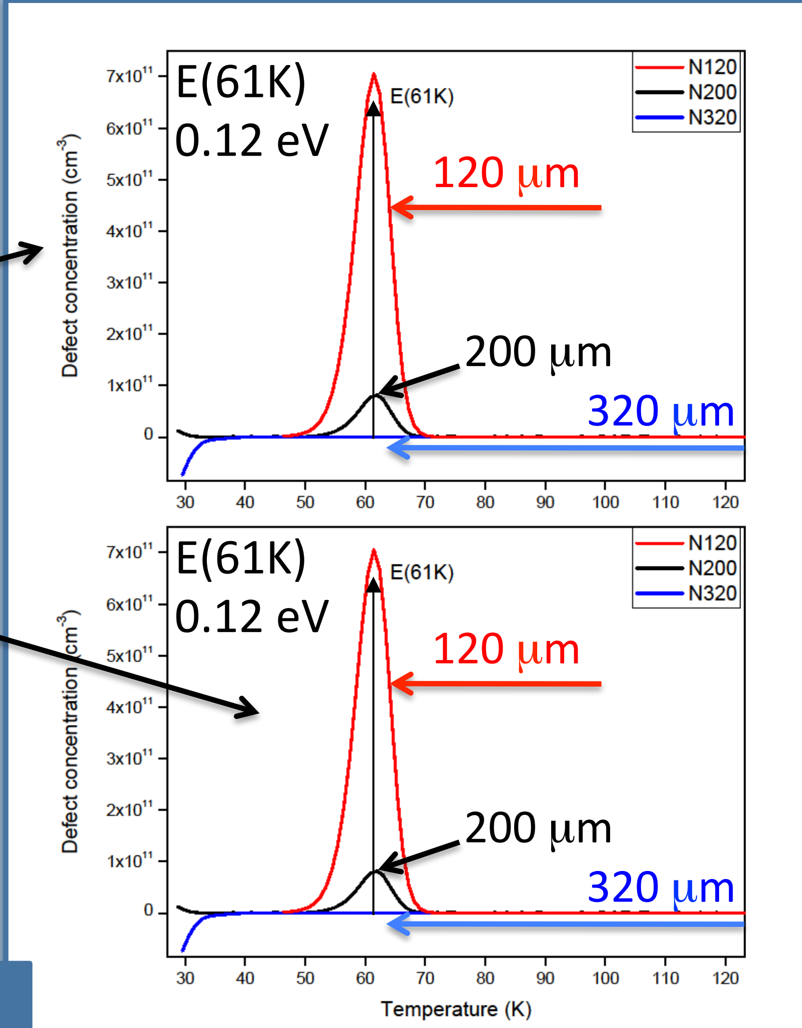
- S/N higher for FZ 300 μm up to $\Phi_{eq}=7\times10^{14}$ cm^{-2}
- No significant difference between 200 μm and 300 μm at higher fluences
- Signs of "microdischarges" found in n-type sensors (only!) above $\Phi_{eq}=1\times10^{15}$ cm^{-2} (further investigation required)

Material defects found in O-rich material

Crystal defects in FZ (DLTS results)

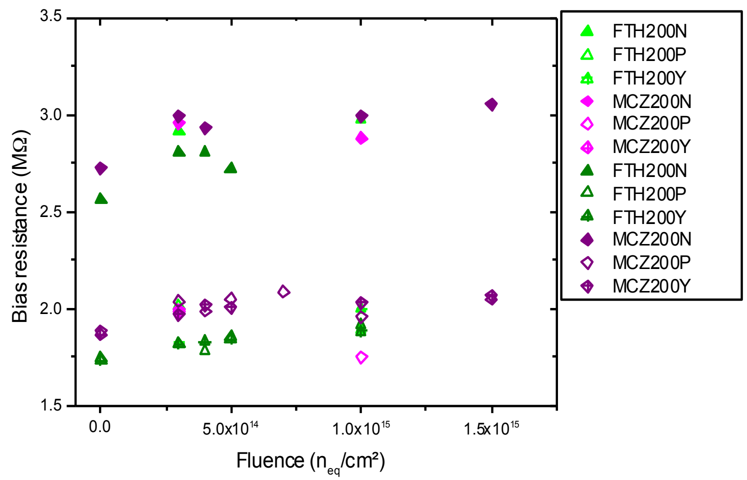


H(220K) in p-type: Current generator at 0.44 eV
E(61K): Thermal donor, increases n-type doping



Correlation of [O] and defect concentration

Strip parameters



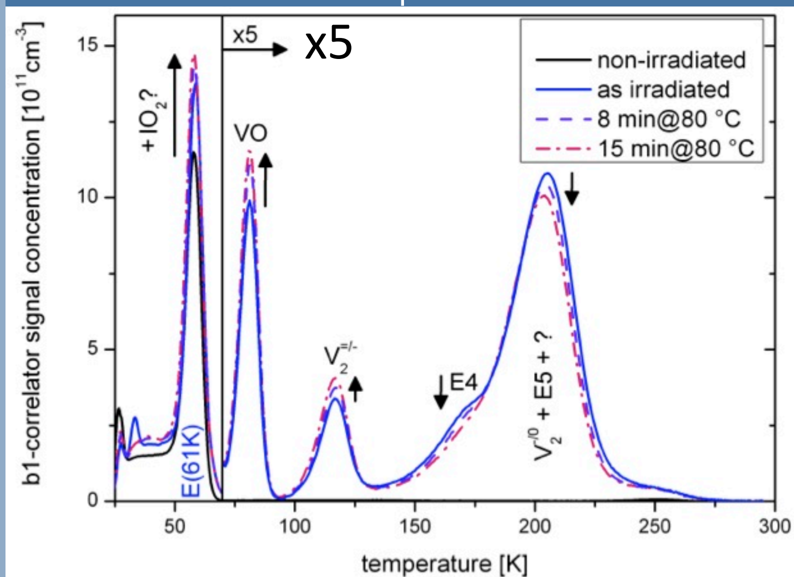
Irradiation Study (MeV+GeV)
Bias resistance R_{poly} (600V)

- Measurements in non-irradiated case done at 20°C and scaled to -20°C
- no significant differences between MeV and GeV proton irradiation

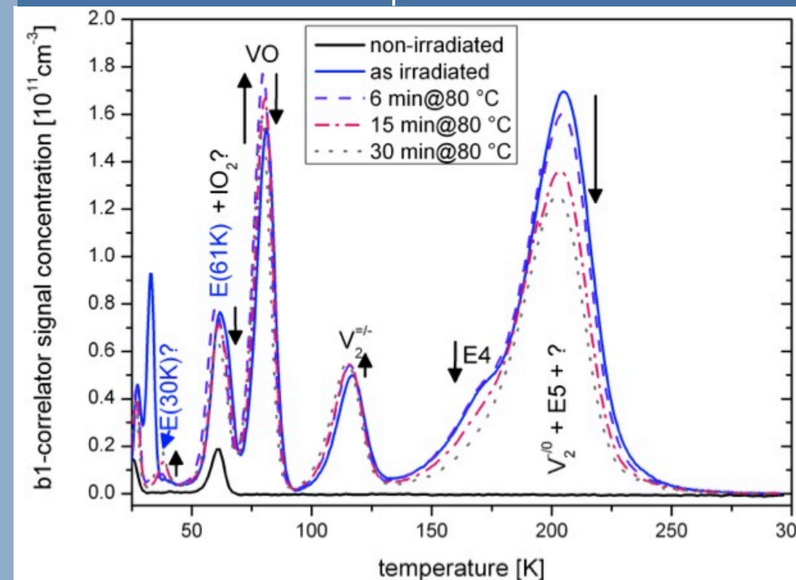
- R_{poly}: ~10% increase after initial irrad., then constant
- R_{int}: drops strongly with irrad.; lowest value @ 1.5e15n_{eq}/cm^2 still about 200 MΩcm
- C_{int}: minor variation (±10 fF/cm or 2%) and no systematic dependence on Φ observed; thick sensors have about 10% higher C_{int}
- C_c: minor variation (~3%) over fluence range; p-type sensors have ~7% higher C_c; trend observed that p-type increase, while n-type decrease at same fluence (?)

Radiation induced defects (23 GeV p)

MCz200N, Φ_{eq}= 1 x 10^{11} cm^{-2}



FZ200N, Φ_{eq}= 1 x 10^{11} cm^{-2}

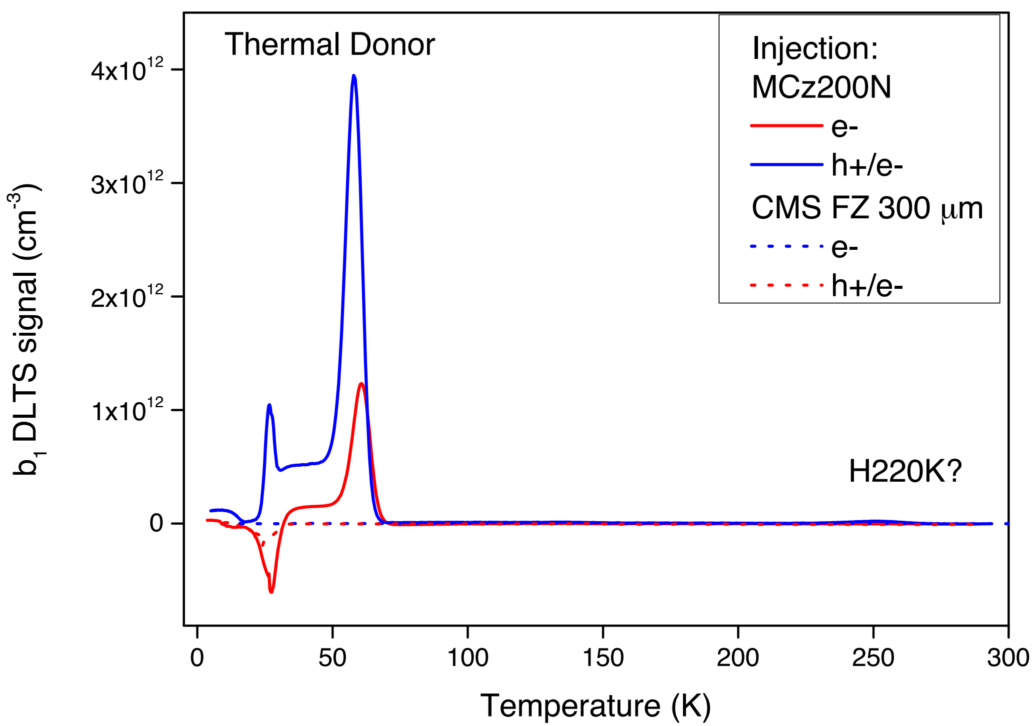


Defects similar to normal spectra, except for E(61K)

MCz200N dominated by E(61K)
Low contribution in FZ200N
Dependence of defects on sensor depth should be investigated

No defects found in old CMS FZ 300 μm

U_B=-20 V, U_p=-0.1 V, t_w=200 ms

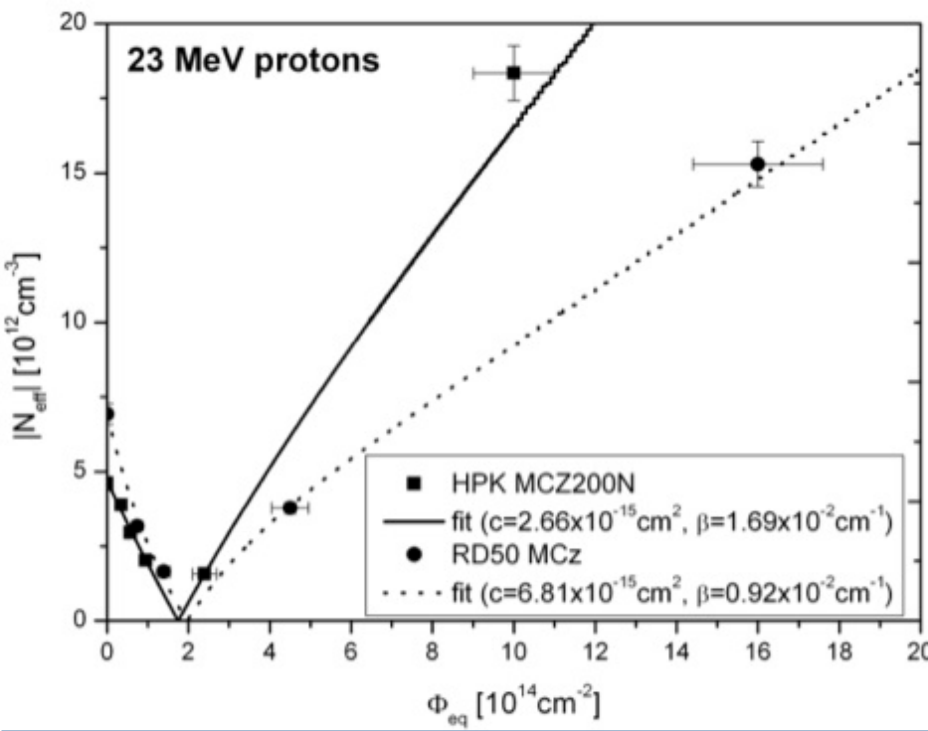


- Has HPK changed the processing?
  - ➢ For sure… but what is the reason for the defect generation?

Is the processing responsible for the introduction of defects?

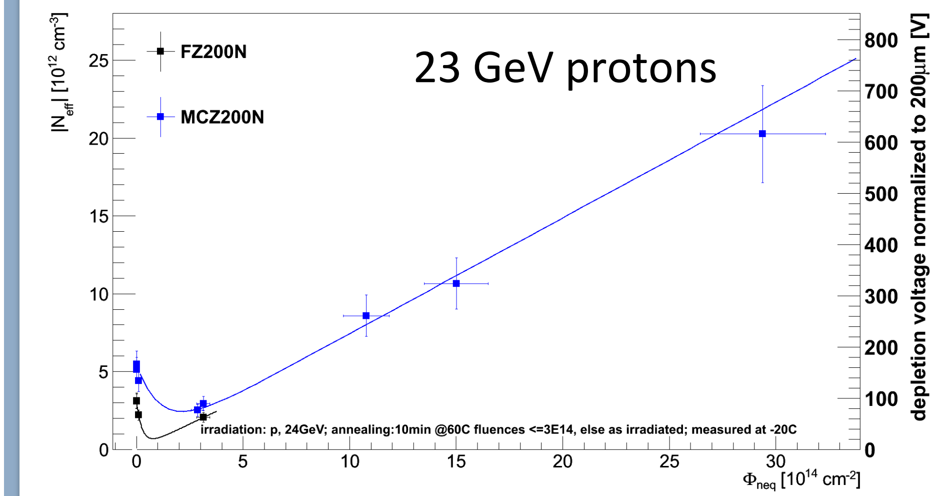
Part I: Influence of the production process on sensors

Comparison of MCz200N and CiS MCz



Difference in V_{dep} found

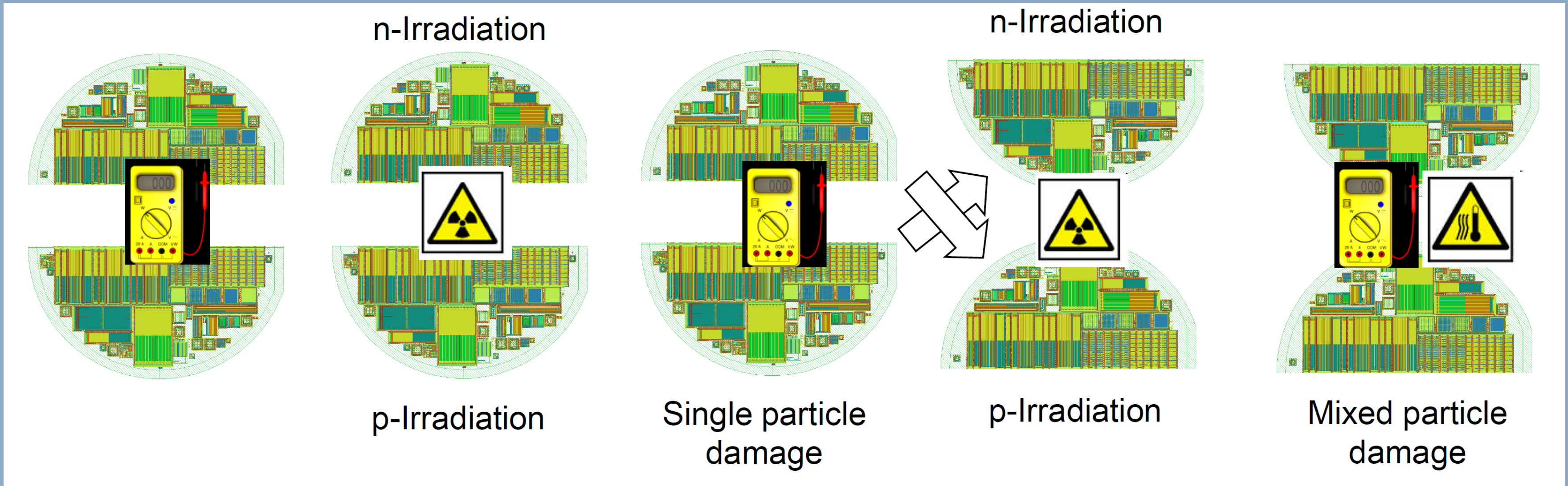
Comparison of MCz200N and FZ200N



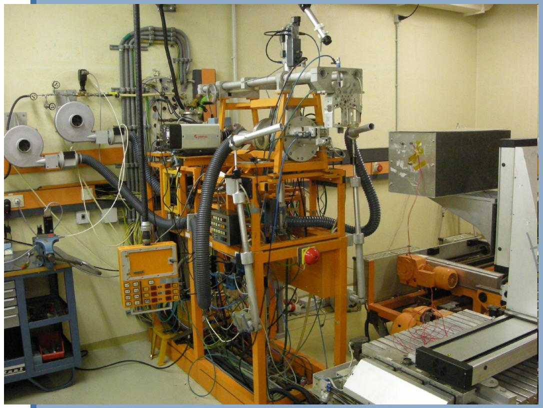
FZ200N does not "type invert"

The name of the material does not always reflect the behavior!
We need to understand the material before we order!

Irradiation procedure…



- Initial measurements of all parts
- Irradiation with n/p
- Short annealing 10min @ 60°C
- Measurement of devices
- Irradiation with p/n
- Short annealing 10min @ 60°C
- Annealing studies

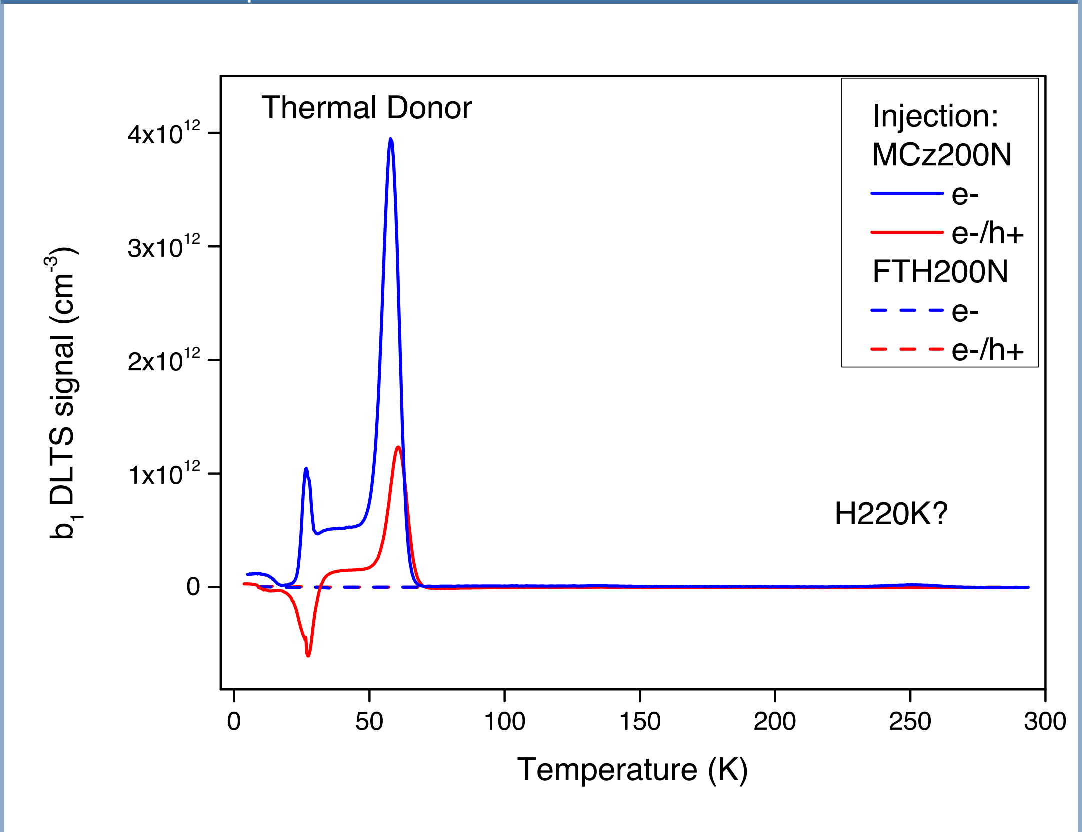


Proton cyclotron, KIT

TRIGA reactor, Ljubljana

No defects found in FTH200N

U_B=-20 V, U_p=-0.1 V, t_w=200 ms



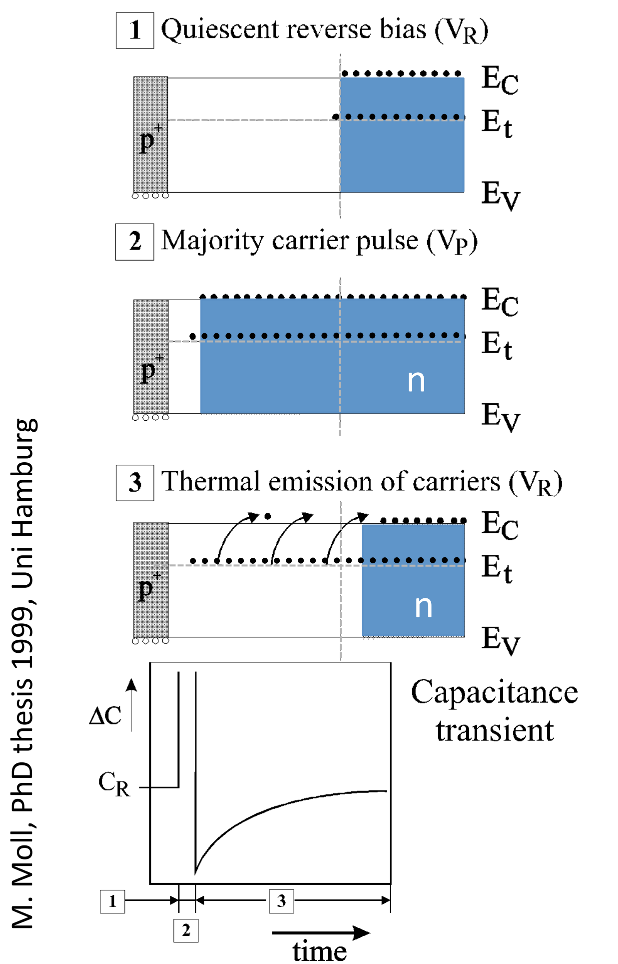
- FTH200N supposedly the material with the lowest [O]
- SIMS not yet available
- Process induced defects only found in O-rich material

- Deep diffusion introduces O but most likely not the defects
- Defects very likely introduced during processing in O-rich material

Sometimes defects make things more interesting

Deep Level Transient Spectroscopy

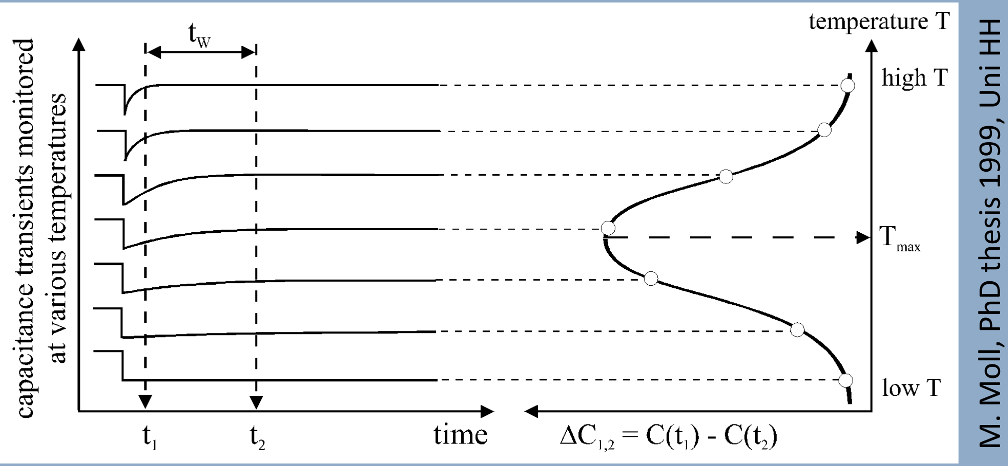
DLTS principle (electron traps)



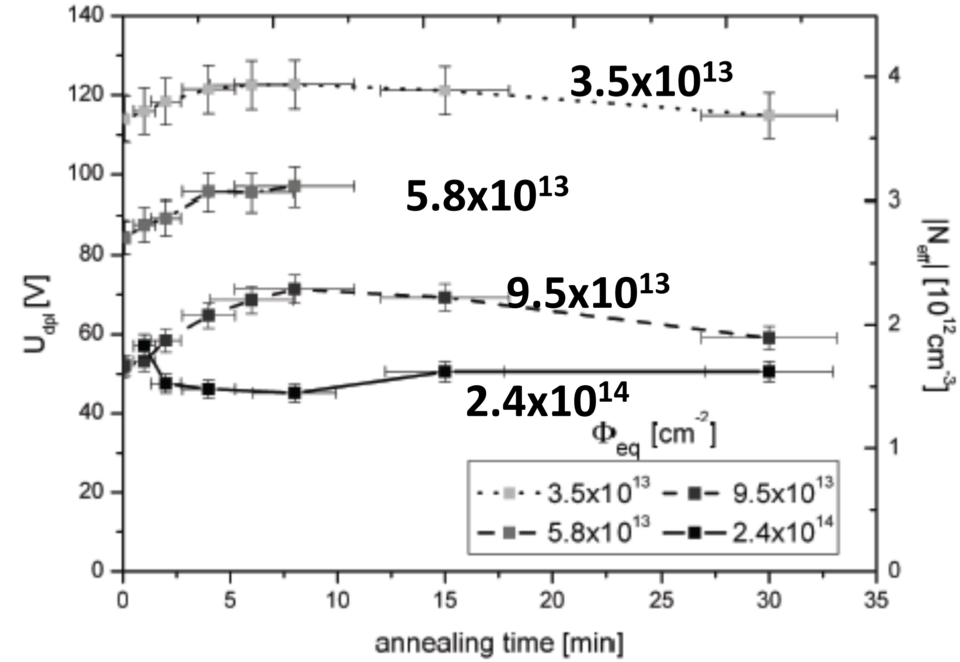
Multi shot technique during T-scan:

1. Diode under reverse-bias
2. Filling of traps with charge carriers at various T
3. Emission from filled traps → change of capacitance

- Capacitance transients recorded as function of T
- Transient follows: $\Delta C(t,T) = \Delta C_0 \exp(-e_n(T) \cdot t)$
- Emission from transient shape
- Concentration: $N_t \approx 2N_D \dfrac{\Delta C}{C_0}$



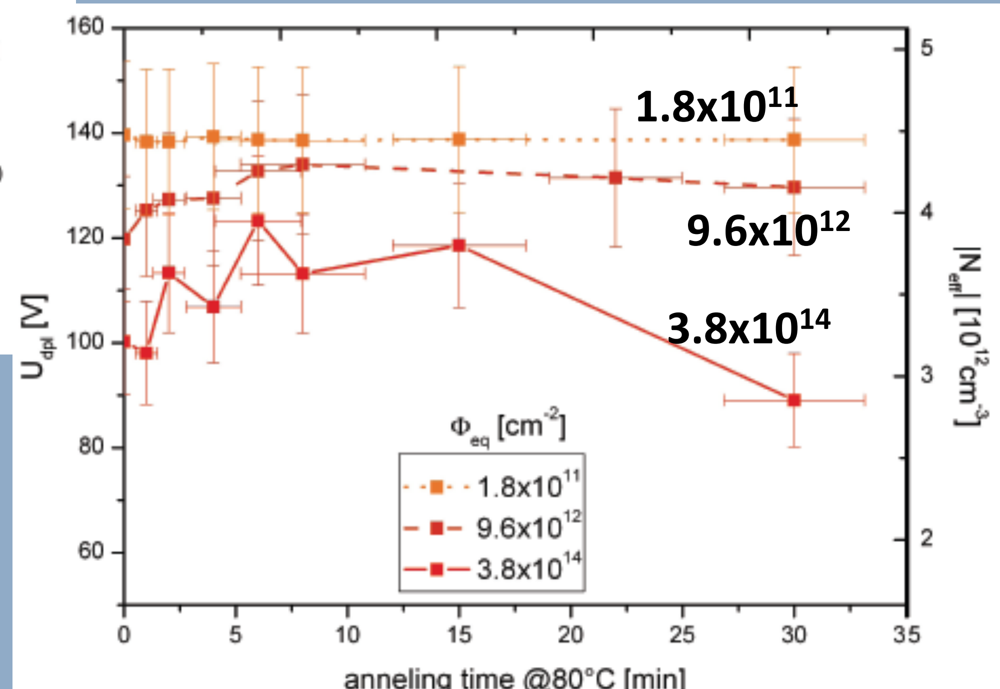
MCz200N after 23MeV and 23 GeV
ons



(a) 23 MeV protons

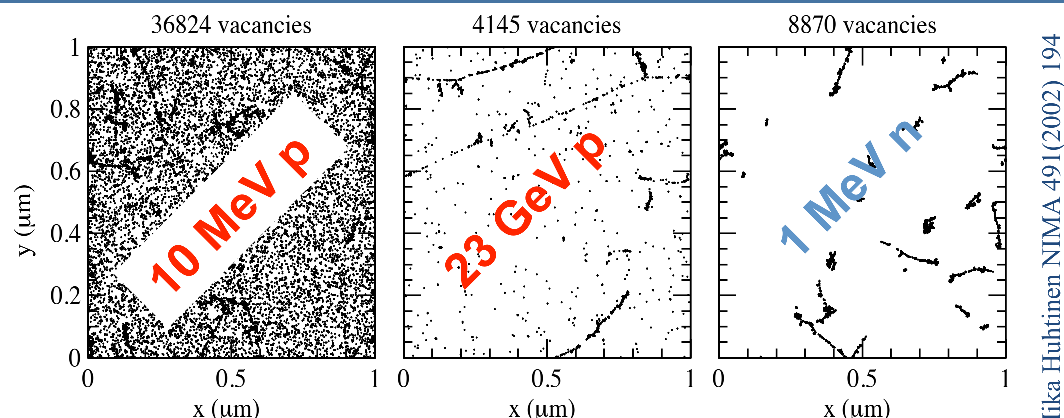
With increasing fluence the annealing behaviour:

- Changes to p-type after 2.4x10^{14} 23MeV p
- Stays n-type up to 3.8x10^{14} 23GeV p



(c) 23 GeV protons

Unfortunate NIEL violation



Simulation: Distribution of vacancies after Φ_{eq}=10^{14} cm^{-2}

1MeV n → Large damaged regions

23GeV p → Point defects and cluster

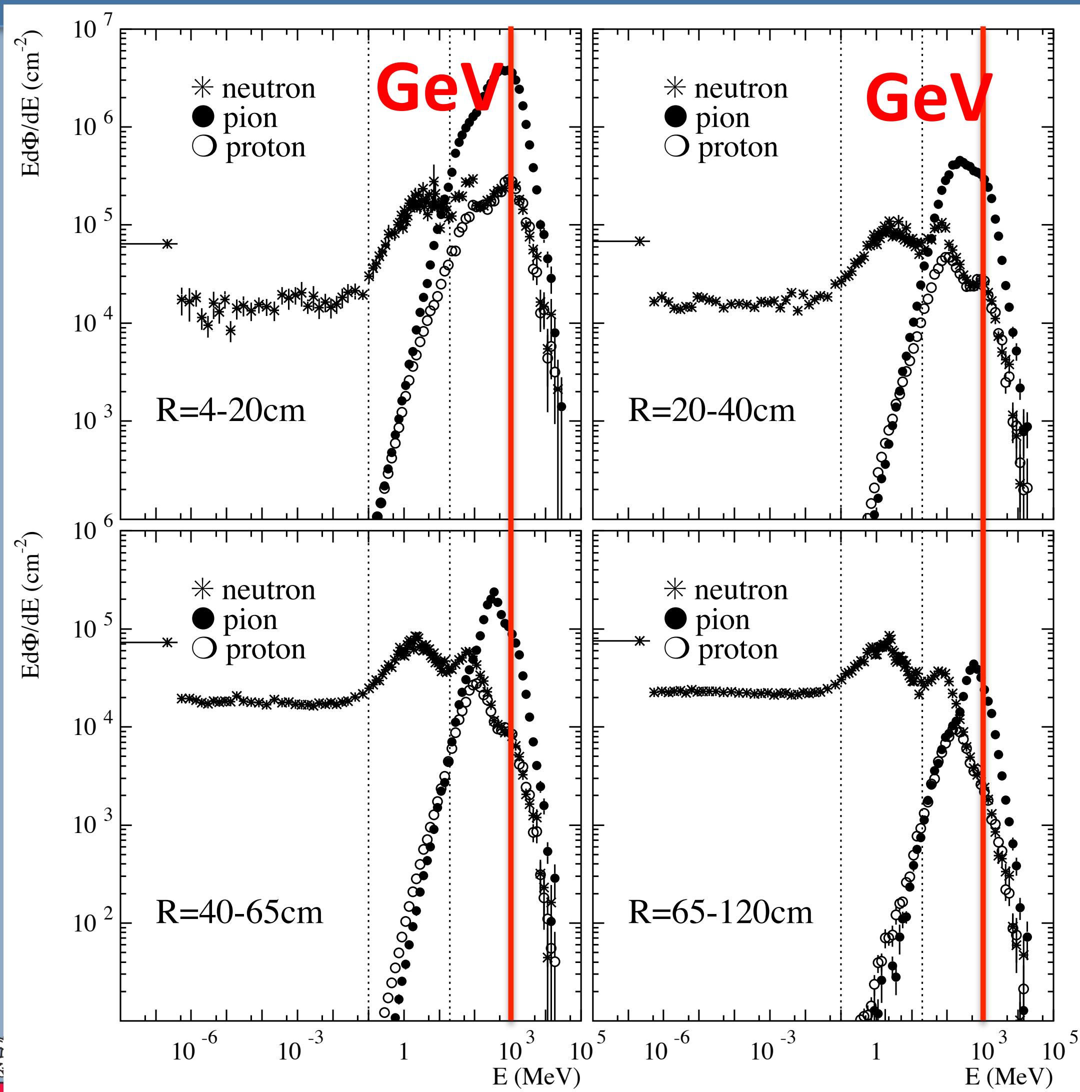
10MeV p → high number of point defects and less cluster defects

	Point defects	Cluster defects
Acceptors	"VP", IP	H(116K), H(140K), H(151K)
Donors	BD	E(30K)+?

Mixture of point and cluster defects responsible for difference between 23 GeV and 25 MeV p

Acceptor generation relatively constant for 1 MeV n and 23 GeV p, no impurity correlated
Donor generation higher for 23 GeV-> size of cluster important, shielding in large cluster and impurity related - oxygen!

Energy distribution for LHC

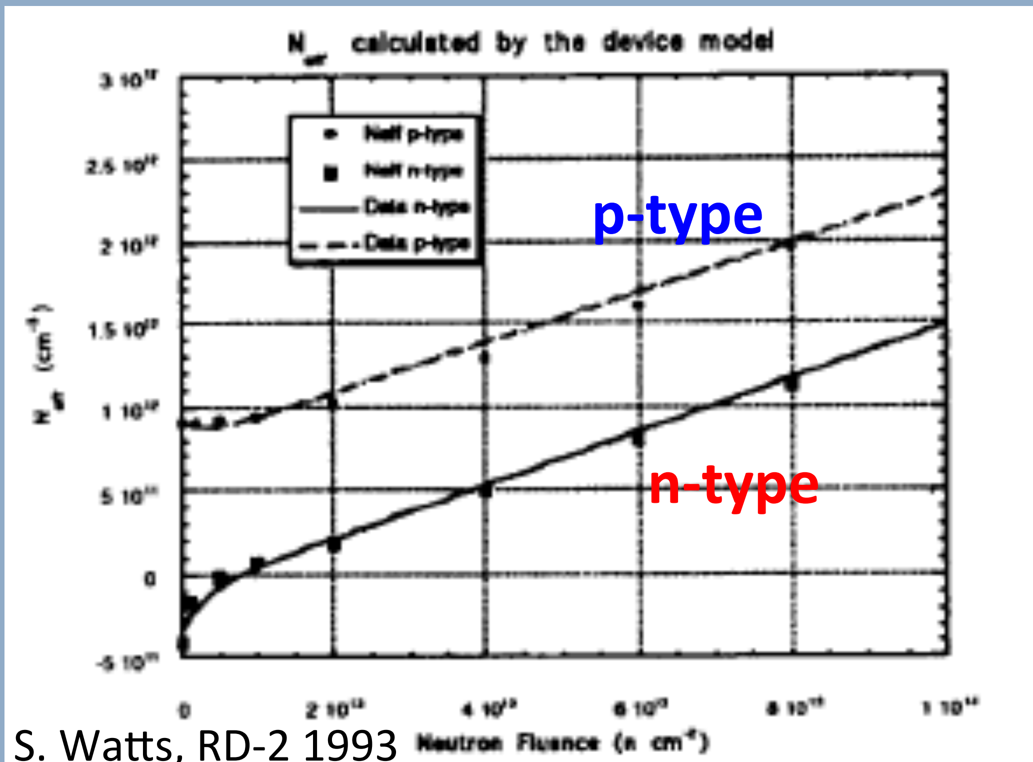


M. Huhtinen, Radiation Effects Course: 10 April 2000

Pion damage dominant in inner region

Pion energies in few hundred MeV to few GeV

Impact of radiation damage



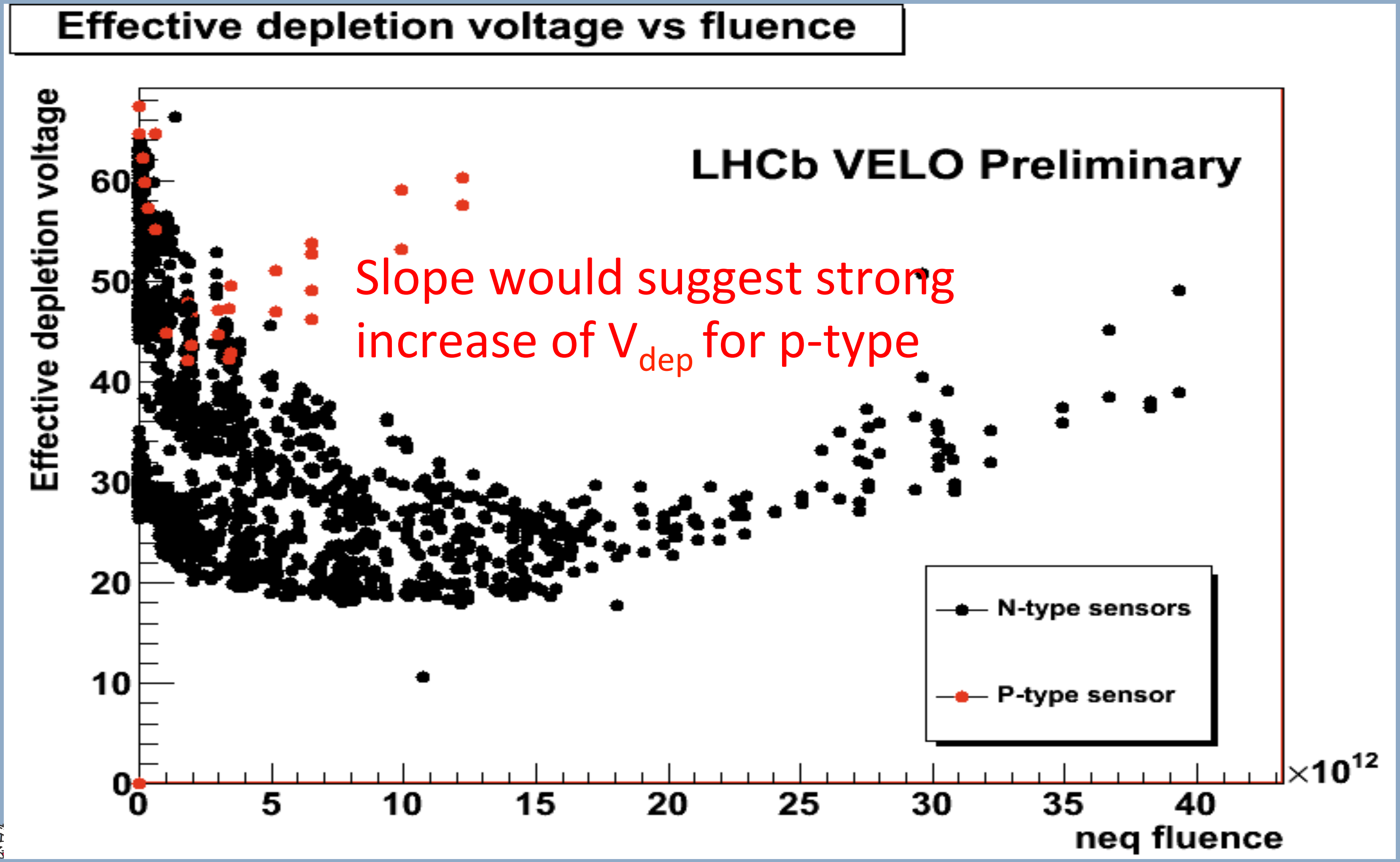
S. Watts, RD-2 1993

- Neutron irradiation
- Similar material

➡ Similar slope after initial doping concentration was overcome

Should affect p-type at high fluences

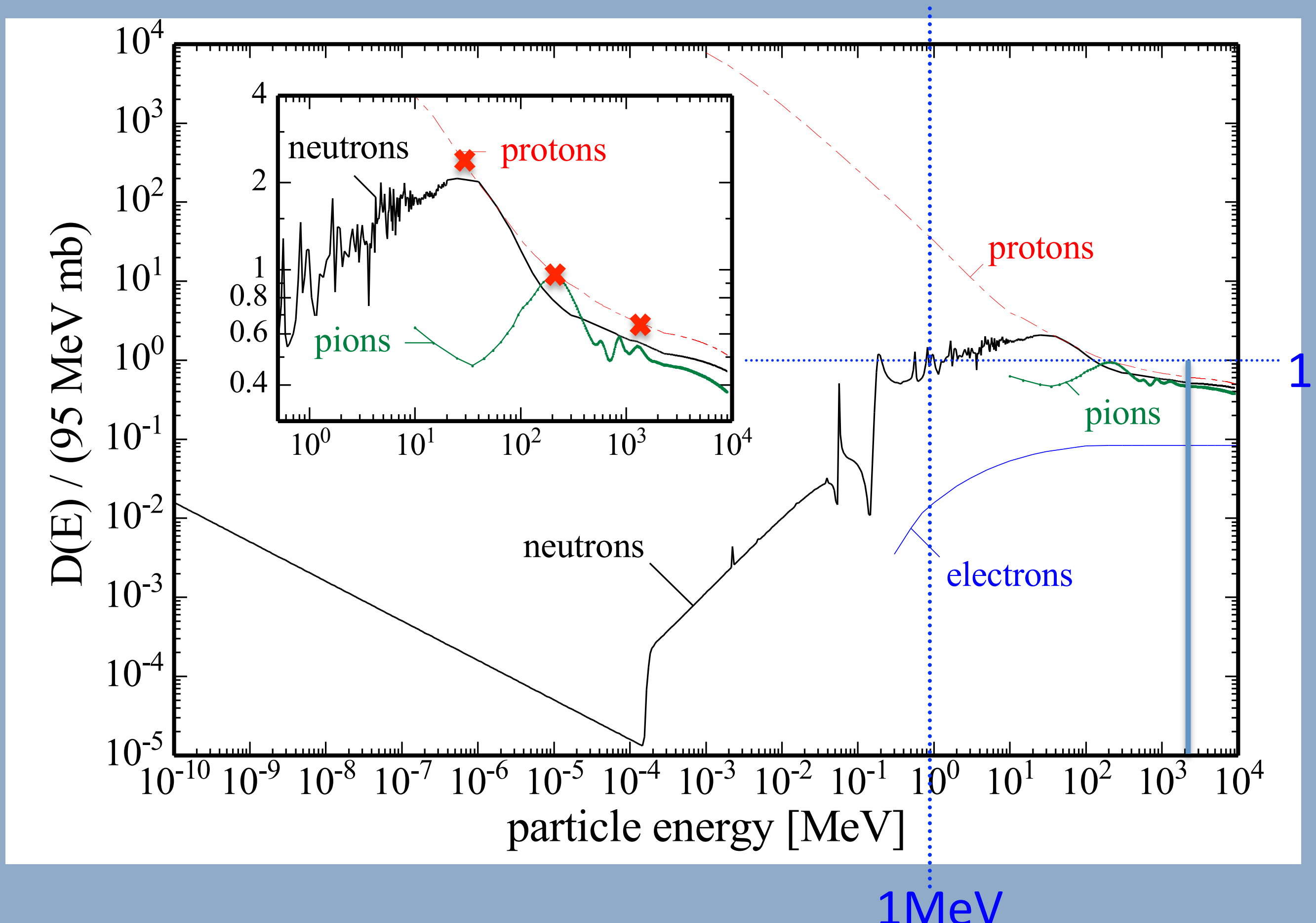
Depletion voltage: LHCb VELO



Slope would suggest strong increase of V_{dep} for p-type

C. Parkes, 19th RD50 workshop, CERN

Unfortunate NIEL violation

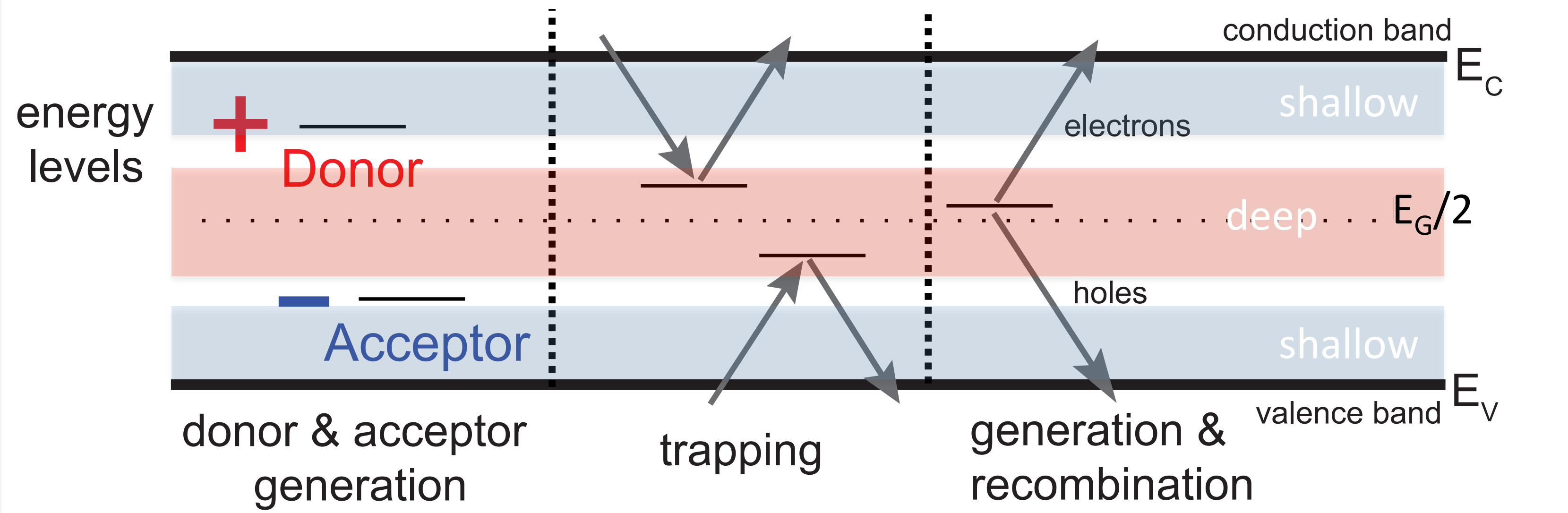


1 MeV neutron equivalent damage

NIEL used to normalise to equivalent fluence: NIEL violation

Impact of defects on detector properties

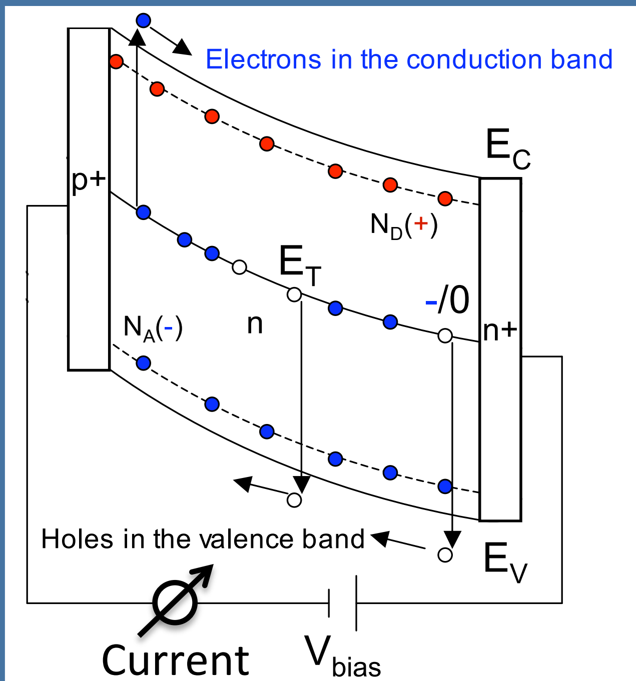
Determined by Shockley-Read-Hall statistics



Charged defects (at RT)	Deep defects	Levels close to midgap
➔ N_{eff} , V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	➔ CCE (Shallow defects do not contribute due to de-trapping)	➔ I_{dep} (NOISE) (Defect levels close to midgap most effective) ➔ Cooling during operation helps!

Thermally Stimulated Current technique

TSC principle

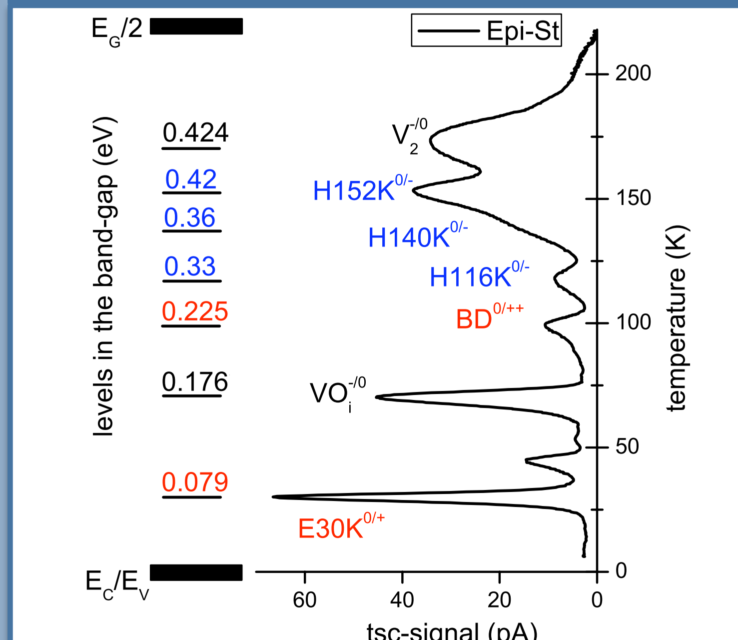


Single shot technique:

1. Filling of traps with charge carriers at low T (<30 K)

→Filling (majority carriers with zero bias, majority and minority carriers by forward bias, light)

- Signal as function of temperature



2. Recording of charge emission ($e_{n,p}$) from filled traps during constant heating
3. N_t from integral of TSC-current