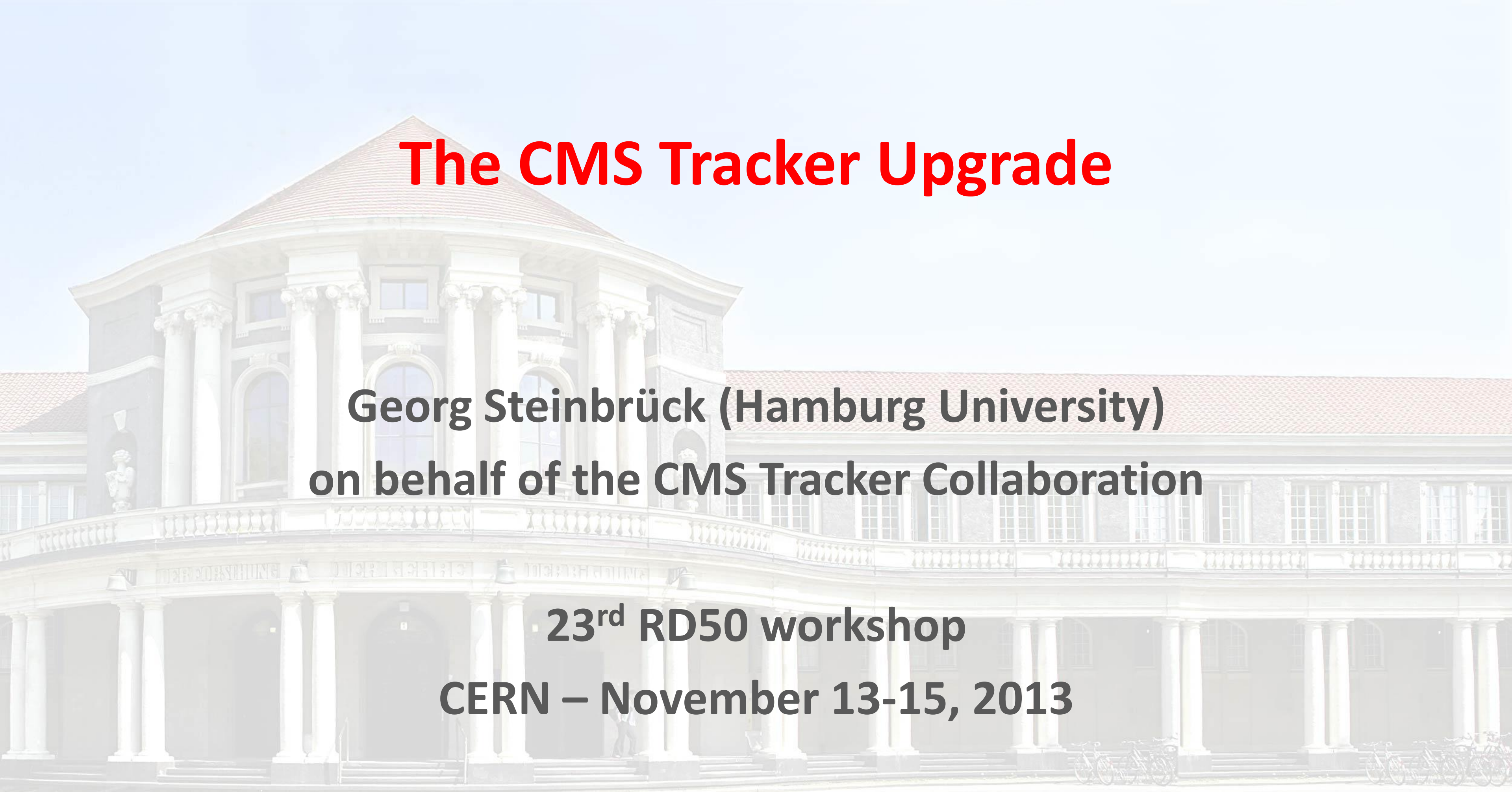


The CMS Tracker Upgrade

Georg Steinbrück (Hamburg University)

on behalf of the CMS Tracker Collaboration

23rd RD50 workshop

CERN – November 13-15, 2013

Content

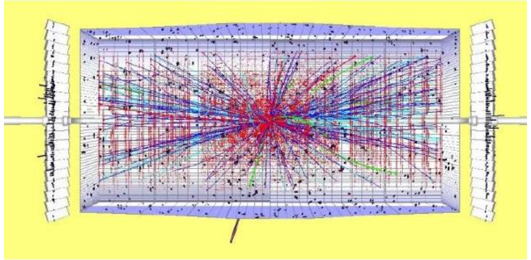
- Introduction to the Upgrade of the CMS Tracking Detectors for Phase II
- Triggering at L1
- Detector Modules for the Outer Tracker
- The HPK Measurement and Irradiation campaign
  - Leakage Current
  - Depletion Voltage
  - Signal
- Conclusions

- Note: CMS has seen non-Gaussian noise in irradiated p-in-n strip sensors. Not covered in this talk →See talk by Andreas Nürnberg

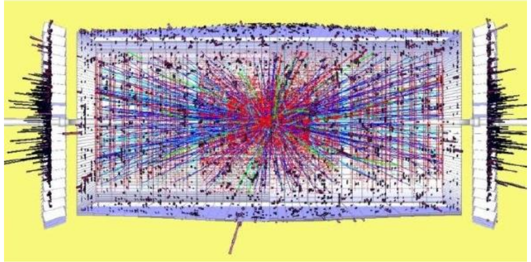
Upgrade of the CMS Tracker: Timeline

2013	**Long Shutdown 1**	• **Consolidation:** Improvement of tracker thermal and humidity insulation • New beam pipe • Installation of pixel test slice } preparation for phase-1
2014		
2015	*Data taking*	operation at lower temperature
2016		
	Technical stop	**Installation of new CMS phase-1 pixel detector**
2017	*“Phase-1“*	
2018	**LS2**	
2019	*Data taking* *“Phase-1“* *≈ 500 fb^{-1}*	Exchange of innermost pixel layer after ~ 250fb^{-1}
2020		
2021		
2022	**LS3**	**Installation of a new CMS tracker** • Phase-2 pixel detector • Phase-2 outer tracker • Track trigger
2023		
2024	*Data taking* *“Phase-2“* *≈ 3000 fb^{-1}*	
↓		

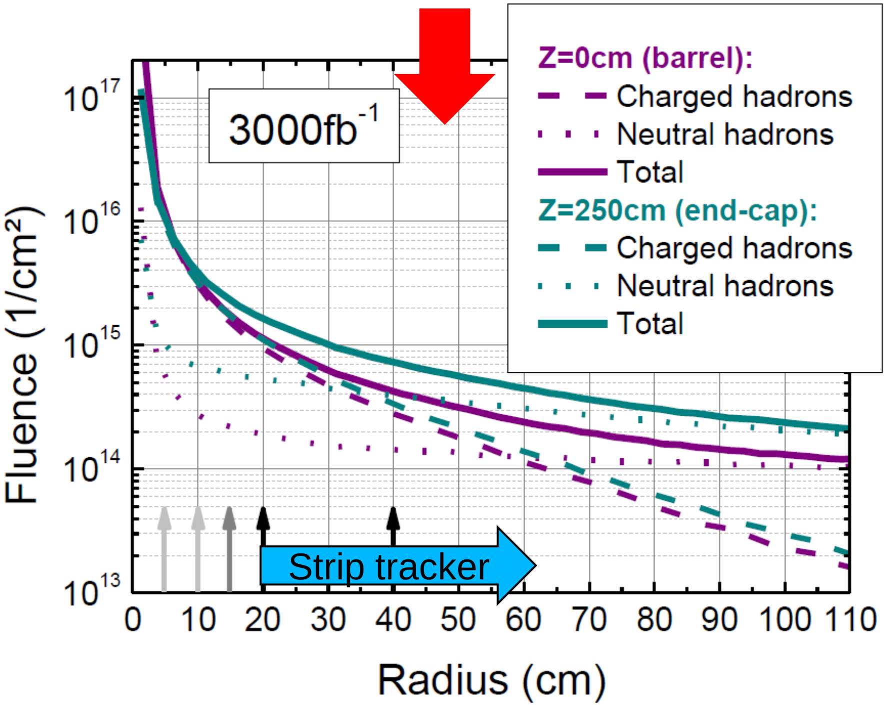
CMS Upgrade for HL-LHC: Challenges and Requirements



x5 in instantaneous luminosity:



x6 in integrated luminosity:



Up to 200 collisions per bunch X!

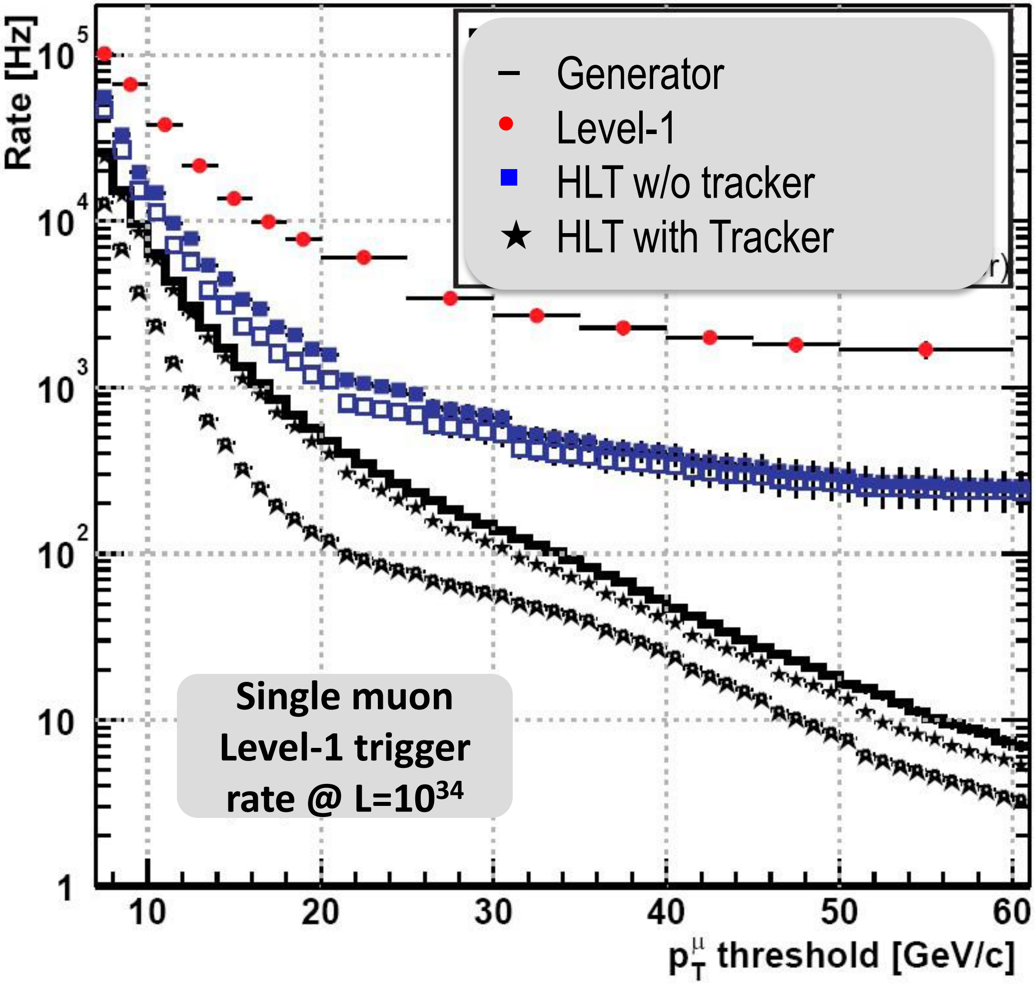
- Keep occupancy at %-level and resolve vertices → shorter strips
- Improve performance at high pT → smaller pitch
- Reduce rates→Triggering at L1
- Improve low pT tracking→material budget!

- Radiation hard silicon and suitable sensor designs needed
- Cooling to -20°C

Motivation for L1 Track Finding

- μ, e, jet rates would become unacceptably large at high luminosity
- Higher trigger thresholds would degrade physics performance and have a limit due to resolution: See single μ
- Use tracking information already at L1

- Goal: Reconstruct tracks above 2 GeV
- Identify their origin within 1mm along the beam axis



Single muon Level-1 trigger rate @ $L=10^{34}$

The CMS Tracker for the HL-LHC

Baseline tracker layout:

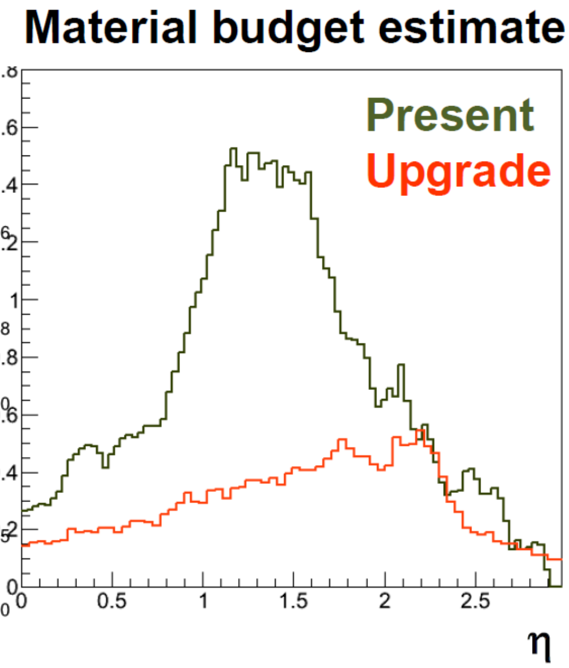
Barrel-Endcap design with 6 barrel layers and 5 endcap disks “BE5”

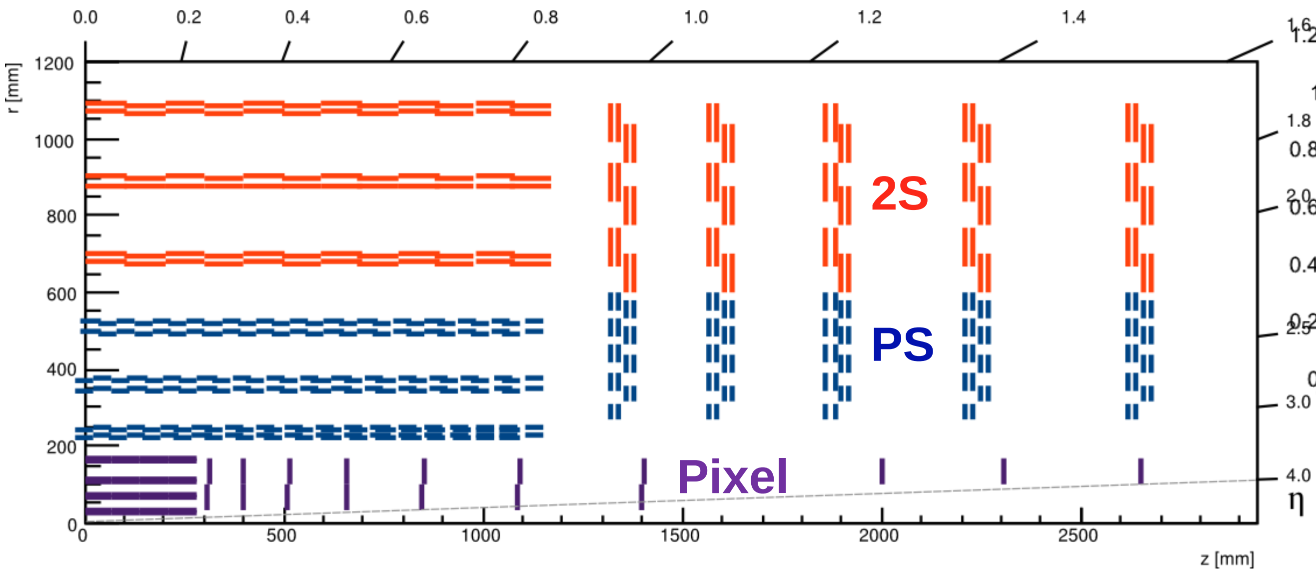
Layout driven by requirement to use tracks in L1 trigger (also by financial constraints)

→Two kinds of stacked modules

- Strip-Strip (2S) modules for r>60 cm
  - Spacing 1.8 and 4 mm
- Pixel-Strip (PS) modules for r<60 cm
  - Spacing 1.6, 2.6 and 4 mm

Material budget estimate





New versus Old: Numbers

Current CMS Tracker

- Total # of modules 15,148
- Total active surface 210 m^2
- Total # of strips 9.3 M
- Power in the tracking volume ~ 30 kW

Upgrade

- # of modules 15,508
  - 7084 PS modules
  - 8424 2S modules
- Total active surface 218 m^2
  - 155 m^2 strips (2S)
  - 31 m^2 strips (PS)
  - 31 m^2 macro-pixels (PS)
- Total # of strips 47.8 M
- Total # of pixels 218 M
- Power in the tracking volume ~70 kW

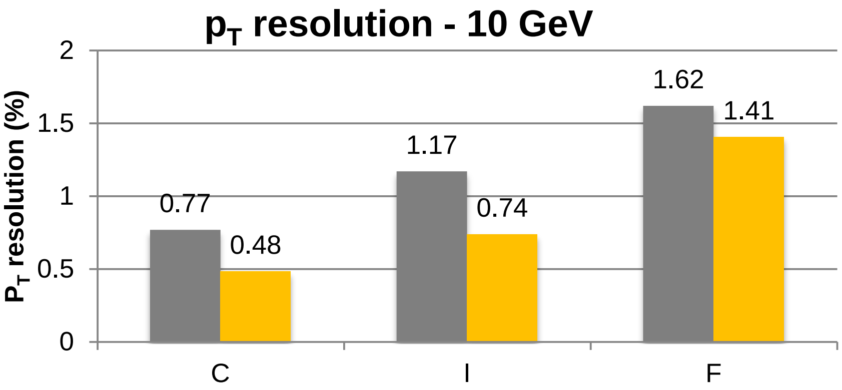
New versus Old: Performance

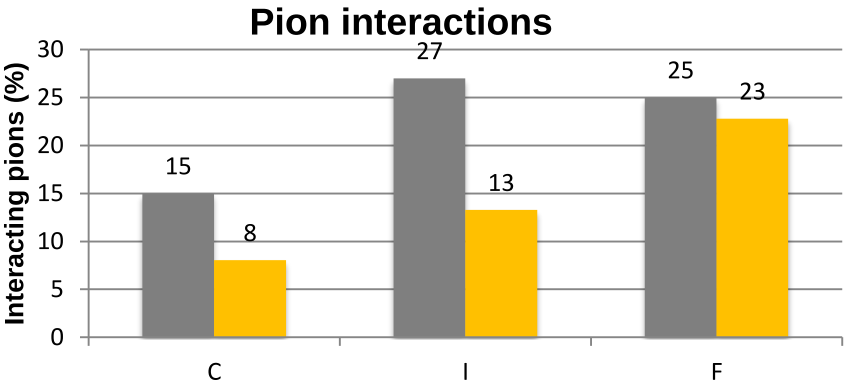
Calculated performance with a “phase-1” pixel detector

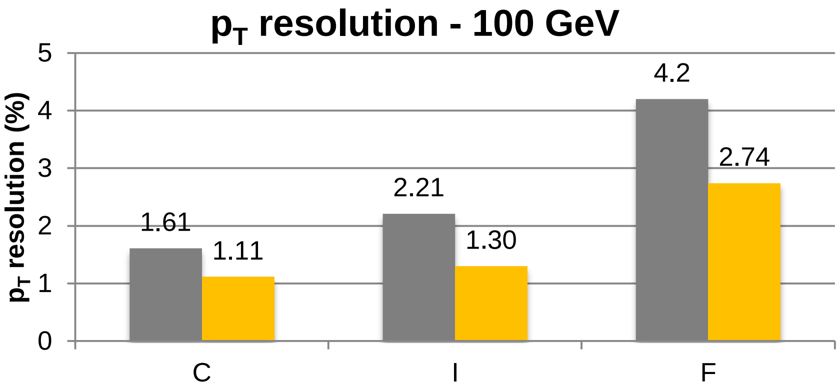
Rapidity regions

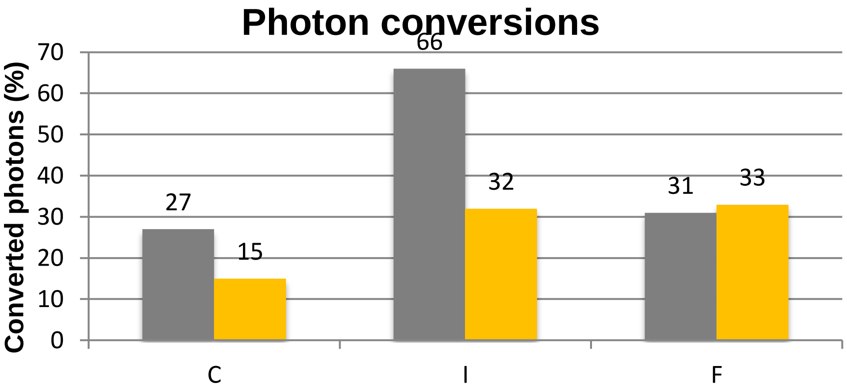
C 0 – 0.8
I 0.8 – 1.6
F 1.6 – 2.4

- CMS
- Upgrade

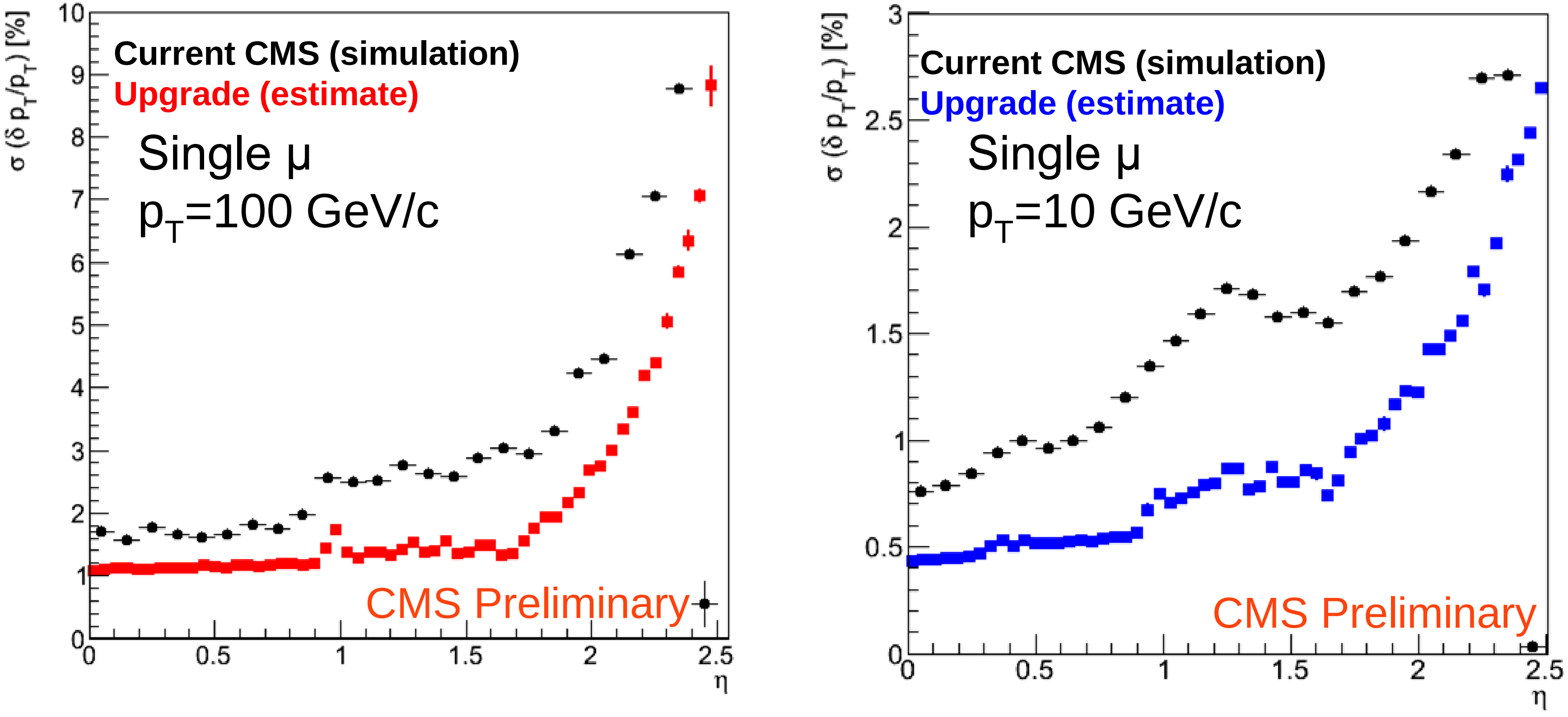

p_T resolution - 10 GeV


Pion interactions


p_T resolution - 100 GeV


Photon conversions

PT Resolution: Offline

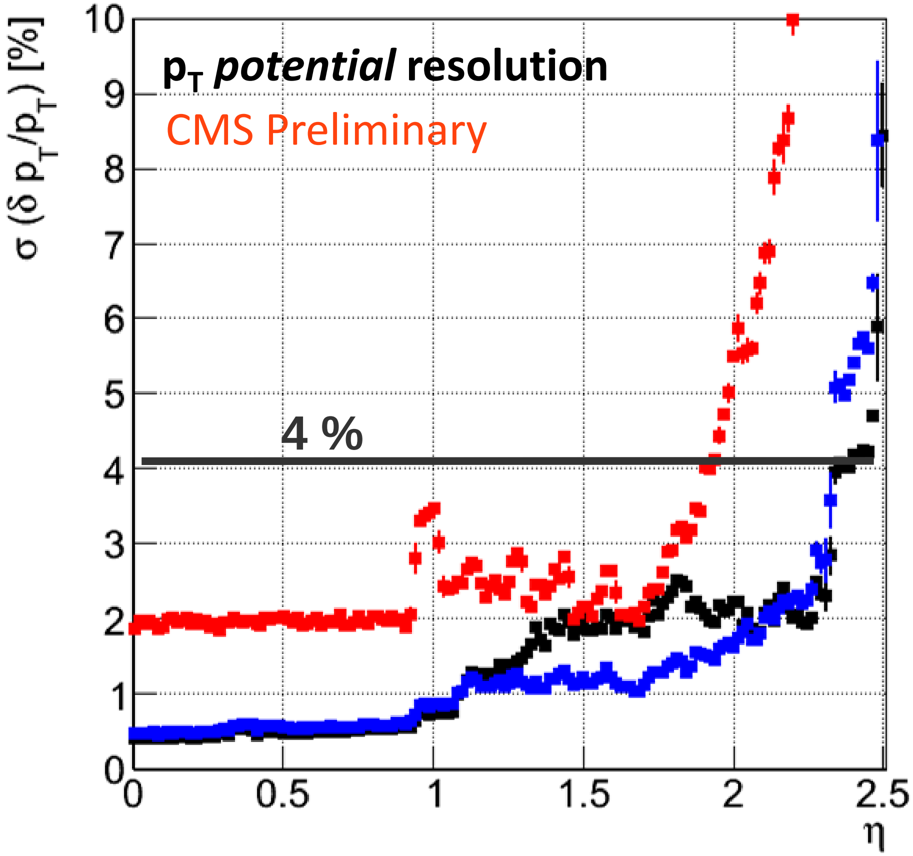


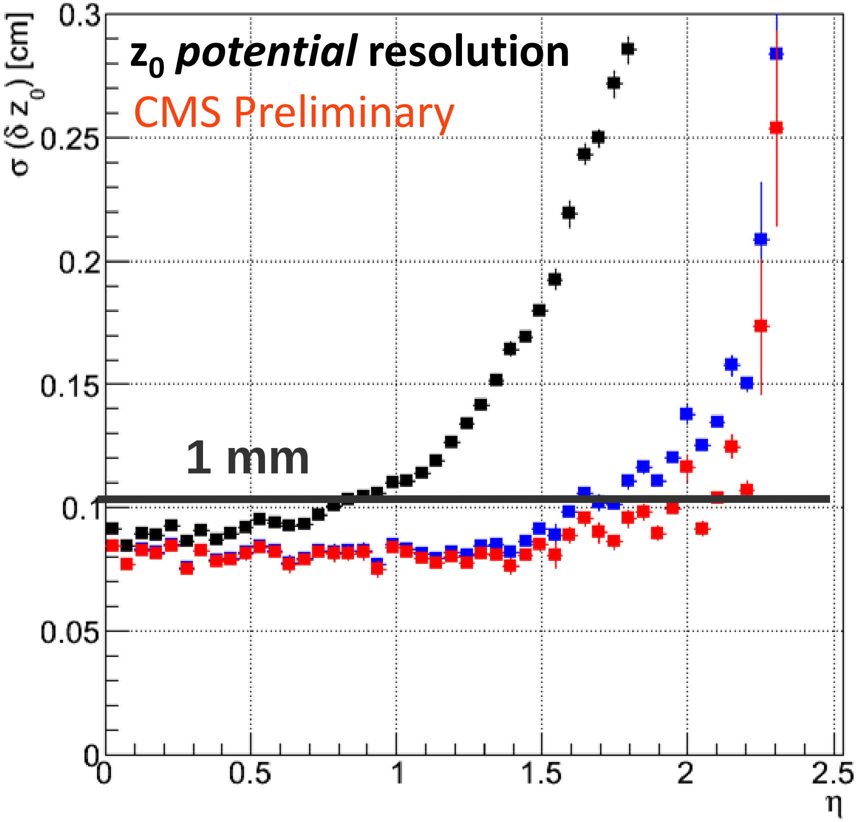
Significant improvement over all pT and eta range.

Tracking Resolution @L1

Potential p_T resolution using all stub info

Single μ p_T=2 GeV/c
Single μ p_T=10 GeV/c
Single μ p_T=100 GeV/c





Very good resolution, especially at low pT.

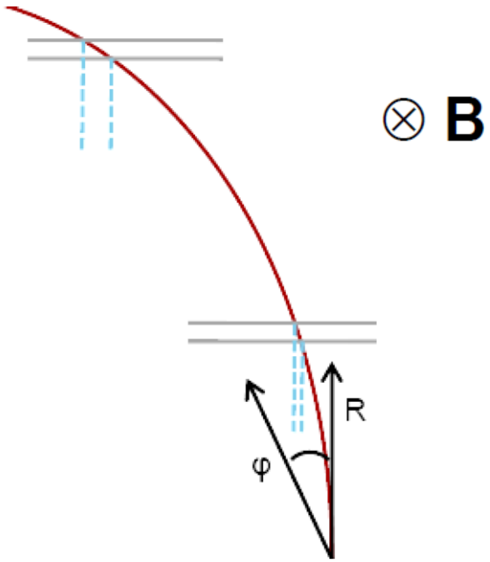
Track Finding @L1

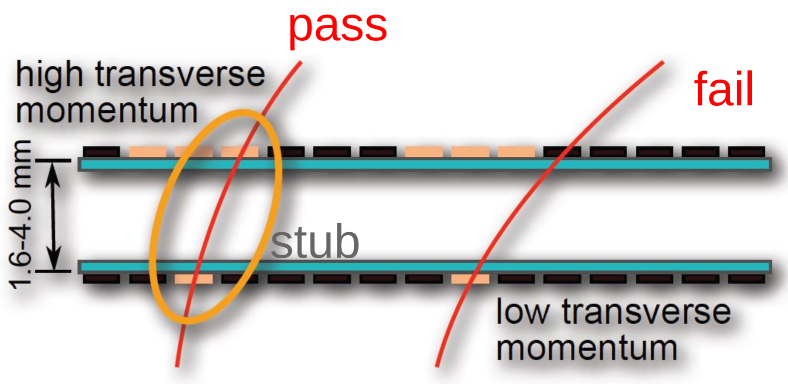
> modules provide at the same time information
  - to L1 Trigger (at 40MHz)
  - as "read out data" after L1 decision (at 100kHz)

  → the whole tracker sends out sparsified data at each bunch crossing

> p_T modules – modules with p_T discrimination
  - exploit bending in strong magnetic field
  - two closely spaced sensors read out by a single readout chip
  - correlate signals, look at cluster size

  → stubs sent out if within p_T cut





> sensor spacing and window optimized for best performance
  - same geometrical cut corresponds to different p_T

Modules: General Concept

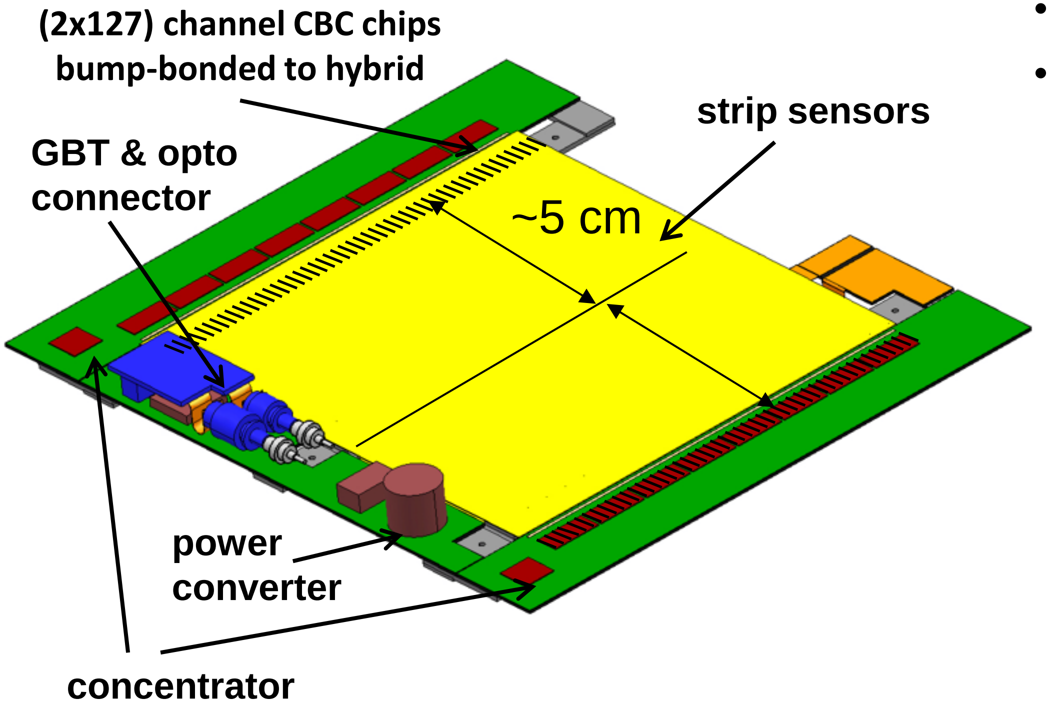
- binary readout – CBC
- low power giga-bit transceiver (LP-GBT) as data link
  - currently under development
  - integrated at module level
- powering via DC-DC conversion
  - already used in phase-1 pixel upgrade
  - input current at higher voltage (~10V) reduces conductor cross-section, material budget
  - integrated at module level
- two different module types
  - different sensor spacings are treated as ‚variants‘ of one module type with only minimal changes
  - requires optimization of only two designs
- evaporative CO_2 is the baseline cooling system
  - experience within CMS is being gained with the phase-1 pixel upgrade

module is a fully integrated entity

Modules for the CMS Tracker Upgrade

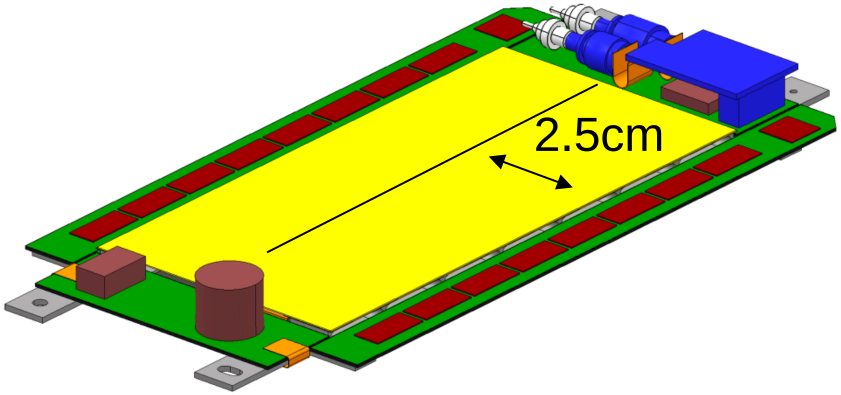
2S p_T module

- for r > 60cm
- 2 strip sensors on top of each other
- sensors wire-bonded to hybrid from top & bottom
- strip dimensions: 5cm x 90µm
- 10 cm x 10 cm

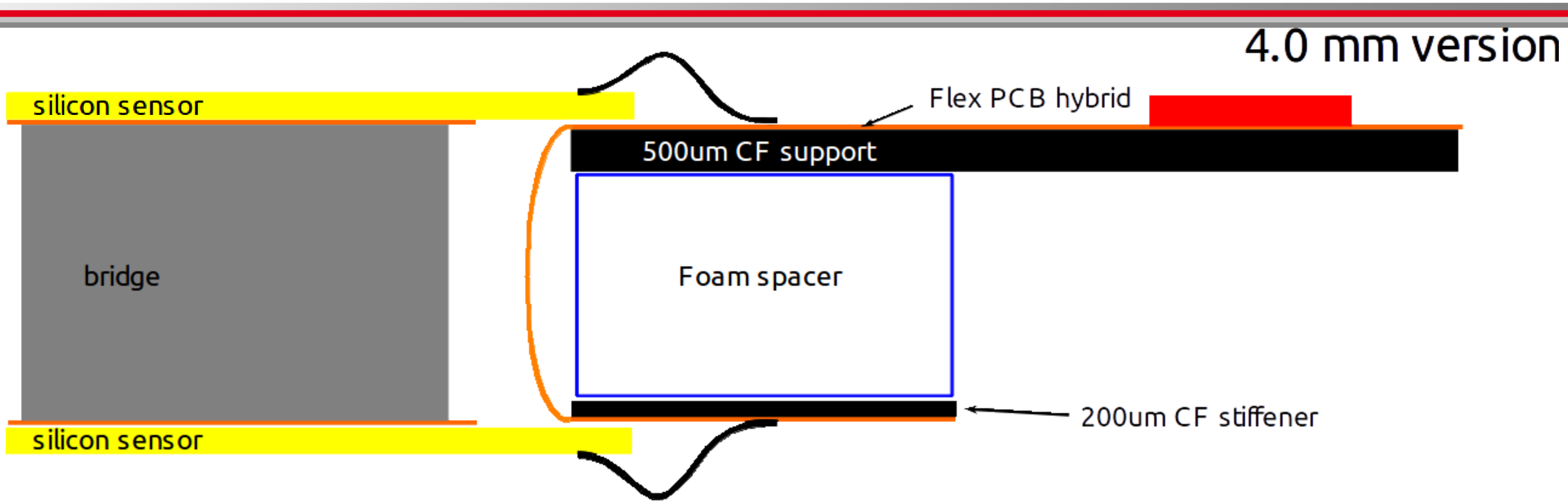


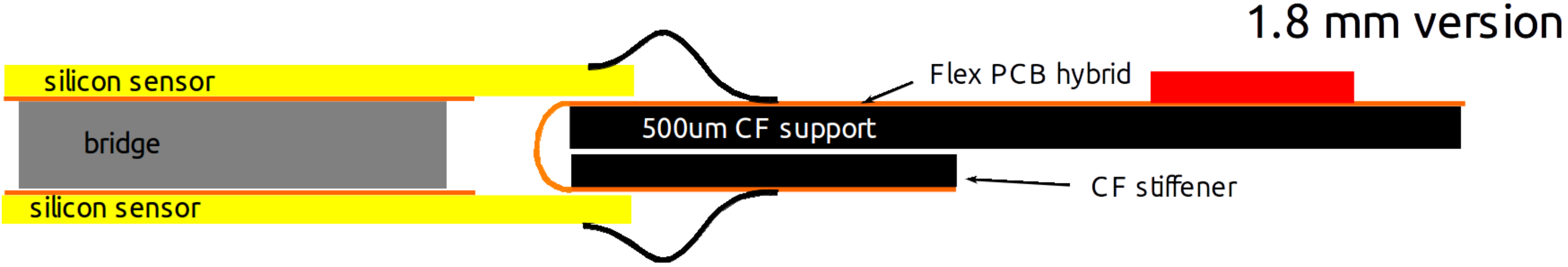
PS p_T module

- for r > 20cm
- 1 strip sensor and 1 pixel sensor on top of each other
- strip dimensions: 2.5cm x 100µm
- (macro)-pixel dimensions: 1.5mm x 100µm
- provides z information
- 5 cm x 10 cm



Connectivity/ hybrids





- **Different sensor spacings obtained by variations of the same design.**
- **Alternative, rigid design also under consideration.**

The CMS Binary Chip

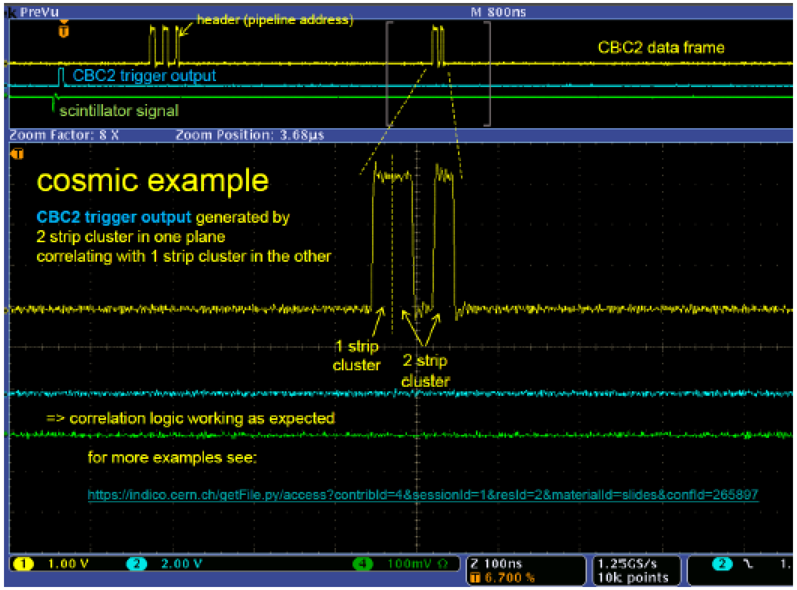
IBM 130nm CMOS process

binary, unsparsified architecture

- retains chip and system simplicity
- but no pulse height data

receives data from both sensors

stub finding works



cosmic example

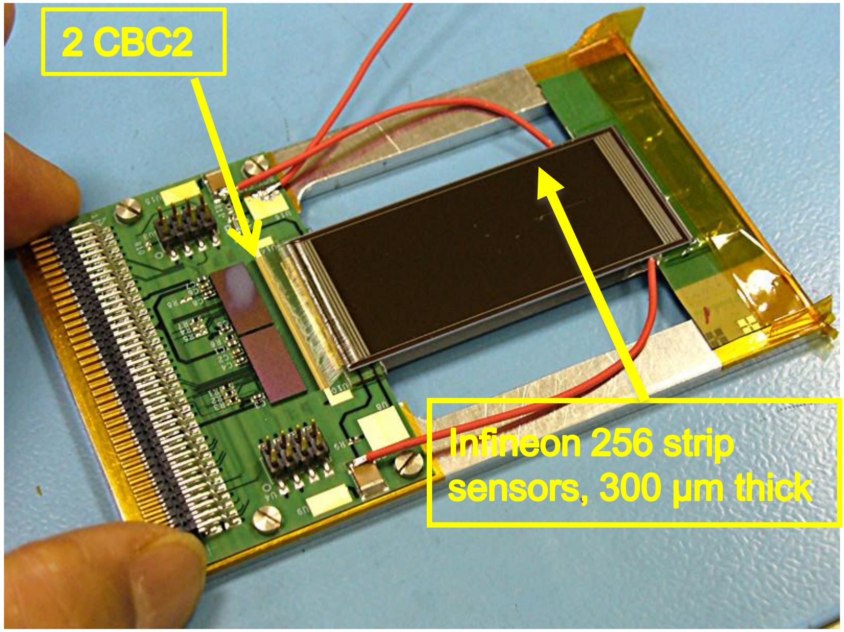
CBC2 trigger output generated by
2 strip cluster in one plane
correlating with 1 strip cluster in the other

=> correlation logic working as expected

for more examples see:

https://indico.cern.ch/getFile.py/access?contribId=4&sessionId=1&resId=2&materialId=slides&confId=265897

2 chip demonstrator module



- testbeam in preparation
- will use these CBC2 modules
- show trigger capability in beam

Silicon Sensor R&D@CMS

Campaign to identify a suitable silicon sensor material and design choices for the outer tracker of CMS. Important parameters:

- Bulk material: MCz vs. float zone: [O]
- Active sensor thickness
- Polarity: n versus p bulk
- Design parameters for strip detectors

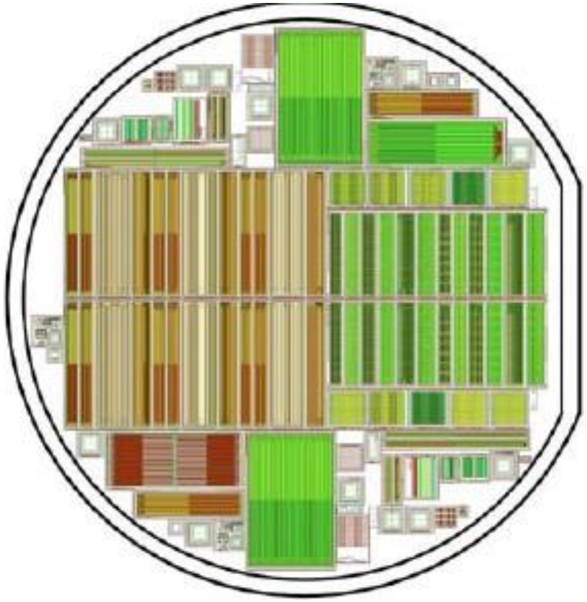
Chose single supplier (HPK) in order to compare sensors from same (or at least similar) processes.

Test radiation hardness:

- Irradiation with mix of protons and neutrons
- Fluences and neutron/proton ratio depend on radial distance from interaction point
- Study dependence on proton energy: 23 MeV, 800 MeV, 23 GeV

Structures include:

- Pad sensors (diodes) for material studies
- Mini-strip sensors for charge collection
- MSSD sensors to study geometry effects



> 100 wafers ordered

Sensors and Irradiations

Prototype sensors produced:

- **n-type**: p-on-n
- **p-type**: n-on-p
- Different oxygen concentr.
- Different thicknesses
- Different layouts (pad sensors, strip sensors, etc.)

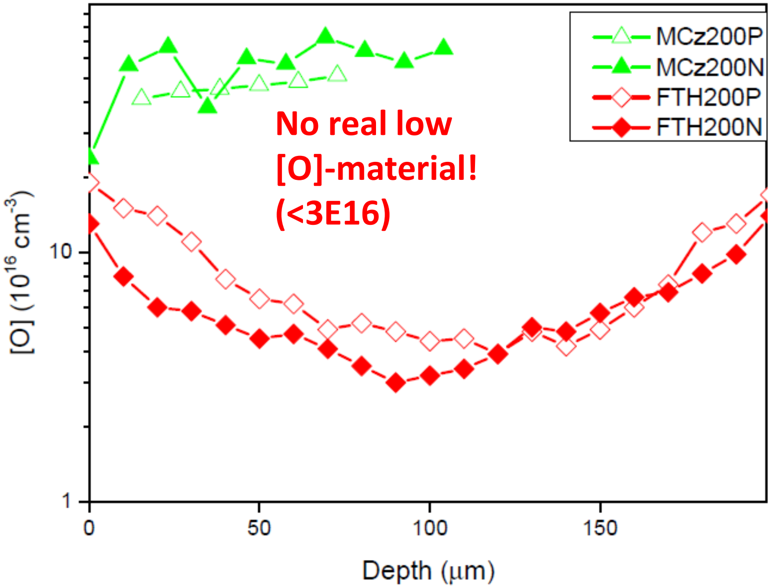
production method	active thickness (physical thickness)	full-depletion Voltage		oxygen content
		n-type	**p-type**	
FZ -200	200 µm	90 V	120 V	$8 \cdot 10^{16}$ cm^{-3}
MCz -200	200 µm	150 V	100 V	$5 \cdot 10^{17}$ cm^{-3}
dd-FZ -200	~200 µm (320 µm)	100 V	90 V	$3 \cdot 10^{17}$ cm^{-3}
dd-FZ -300	~300 µm (320 µm)	190 V	230 V	$1 \cdot 10^{17}$ cm^{-3}

Irradiations performed

- 23 MeV protons (at Karlsruhe cyclotron, cooled),
- **23 GeV protons** (at PS, CERN, up to 2weeks@RT),
- **neutrons (~1 MeV)** (at JSI, Ljublj., up to 10min@RT)

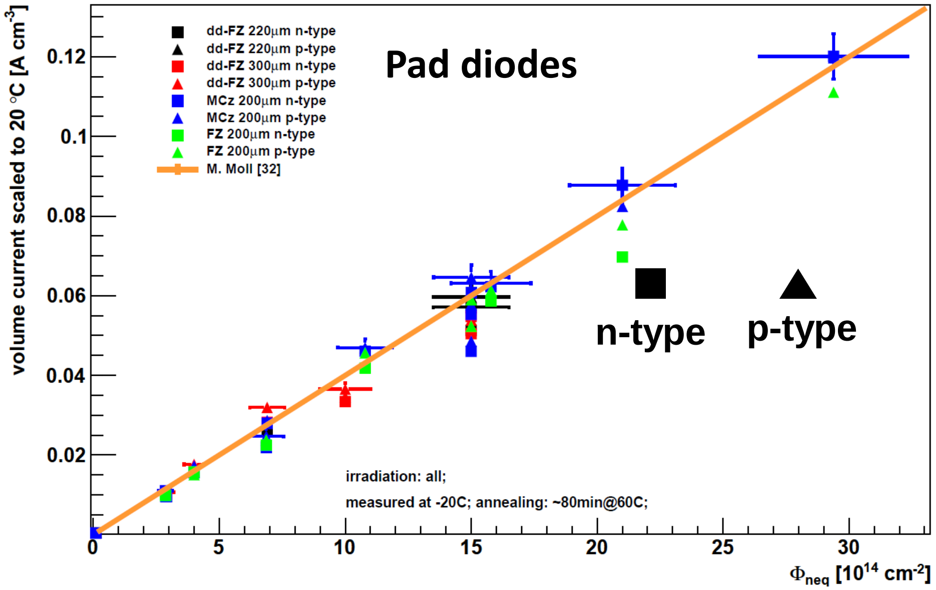
to particle fluences between $3 \cdot 10^{14}$ neq /cm^2 and $1.3 \cdot 10^{16}$ neq / cm^2

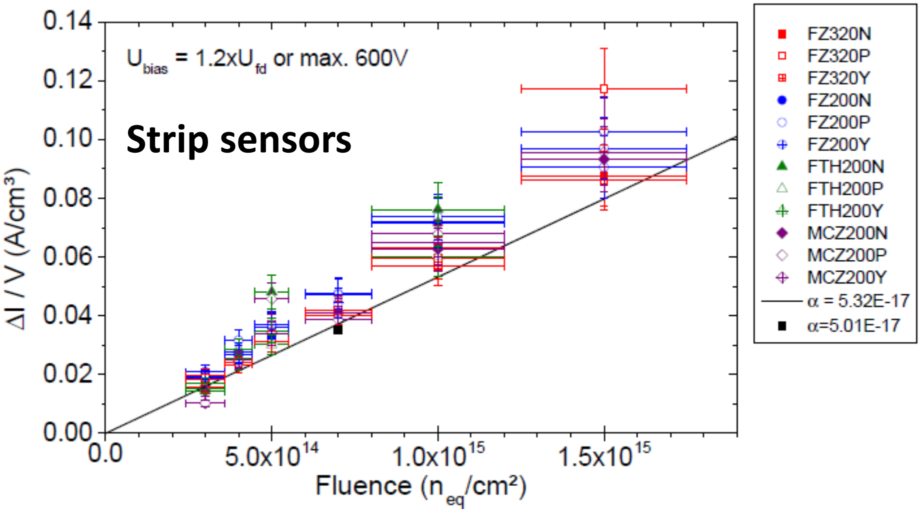
Strip detector: expect up to ~$2 \cdot 10^{15}$ neq/cm^2



No real low [O]-material! (<3E16)

Volume Current





Measured @V_dep+5%, -20°C, scaled to +20°C

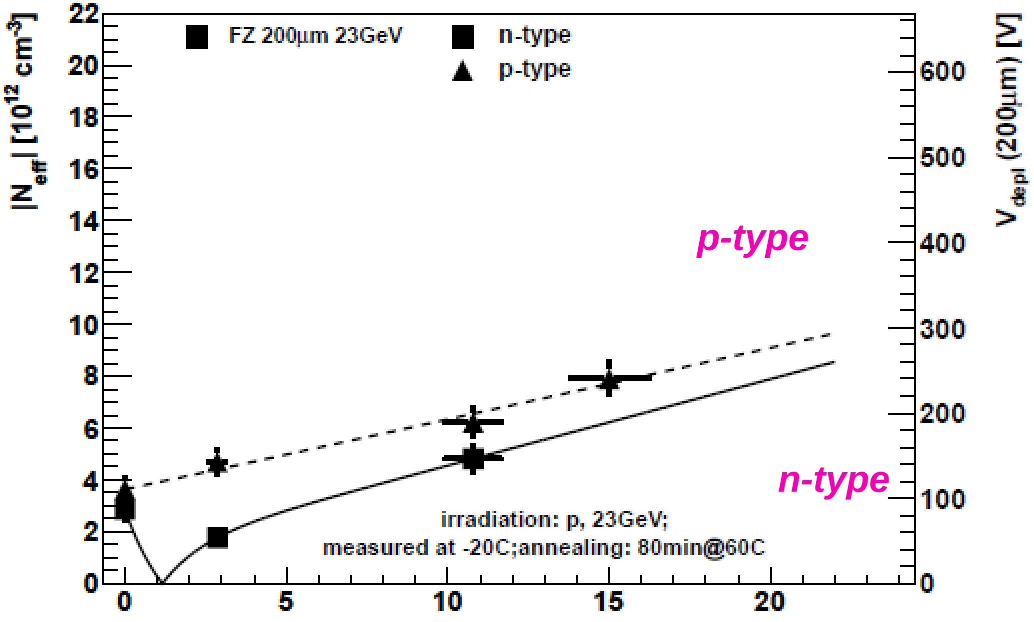
$$\frac{\Delta I}{V} = \alpha \Phi_{eq}$$

- Volume current scales with fluence:
- Scaling parameter independent of Si material, oxygen concentration
- Scaling parameter agrees with previous measurements M. Moll, PhD thesis, Hamburg 1999
- Note: Increased current seen in strip sensor

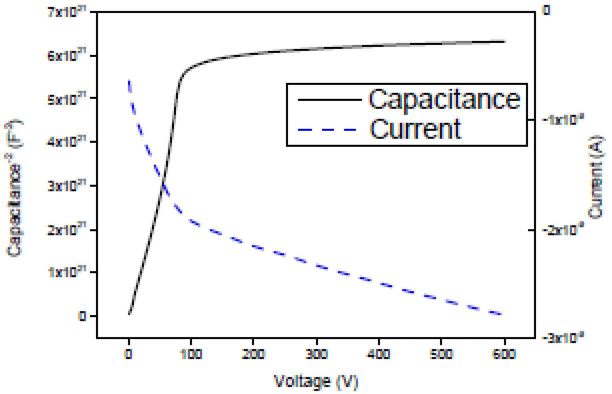
→ Current/ fluences understood
→ Independent of material
→ Independent of polarity
→ Cold operation necessary!

Depletion voltage:

FZ Silicon after 23 GeV Proton and Neutron Irradiation



annealing: 80min@60°C



extracted from capacitance measurements @-20°C, 455 Hz
(for comparisson also @0°C, 1 kHz and 20°C, 10 kHz for non-irradiated sensors)

V_{fd} determines the operation voltage needed

Note: Lower r→Higher Φ →Higher p/n ratio

⇒ Irradiation damage adds up, increase of V_{fd}

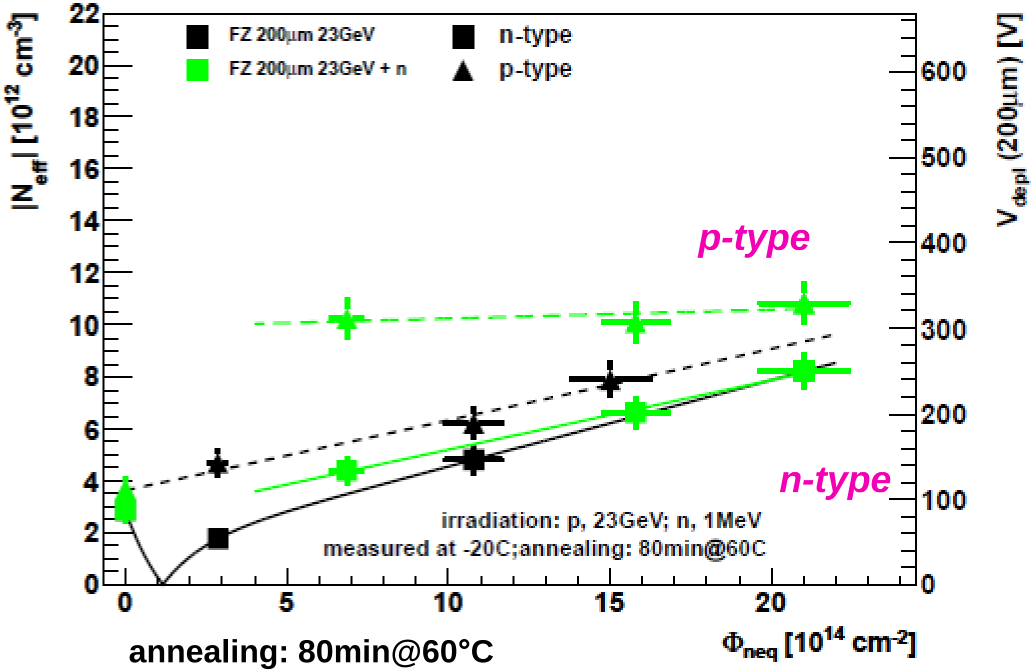
confirms →

(RD50)

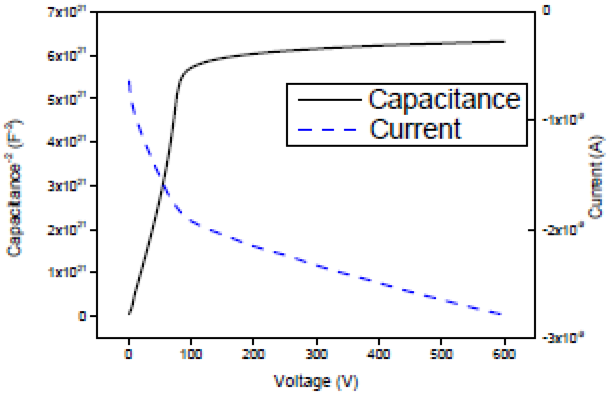
In low-oxygen material:
neutrons ⇒ acceptors
23 GeV protons ⇒ acceptors

Depletion voltage:

FZ Silicon after 23 GeV Proton and Neutron Irradiation



annealing: 80min@60°C



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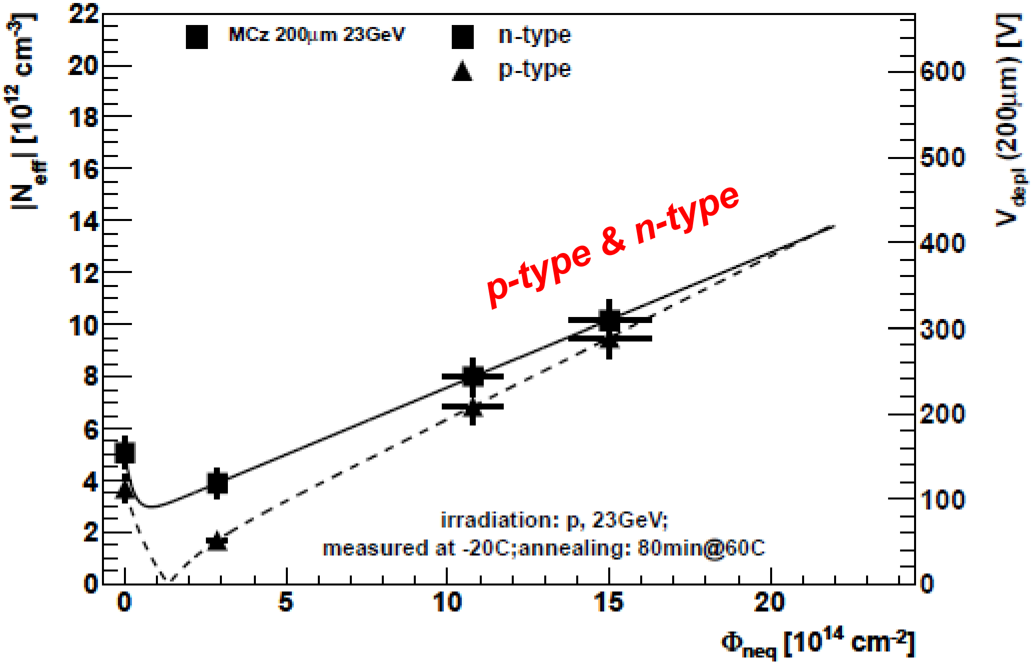
confirms →

(RD50)

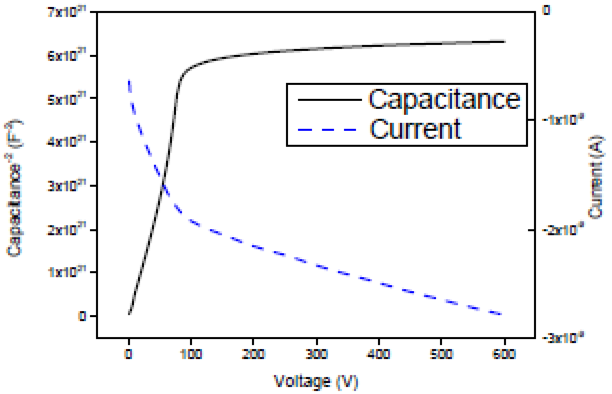
In low-oxygen material:
neutrons ⇒ acceptors
23 GeV protons ⇒ acceptors

Depletion voltage:

MCz Silicon after 23 GeV Proton and Neutron Irradiation



extracted from capacitance measurements (-20°C, 455 Hz), annealing: 80min@60°C



extracted from capacitance measurements @-20°C, 455 Hz
(for comparisson also @0°C, 1 kHz and 20°C, an 10 kHz for non-irradiated sensors)

V_{fd} determines the operation voltage needed

Note: Lower r→Higher Φ →Higher p/n ratio

⇒ Irradiation damage does not add up,
no (strong) increase of V_{fd}

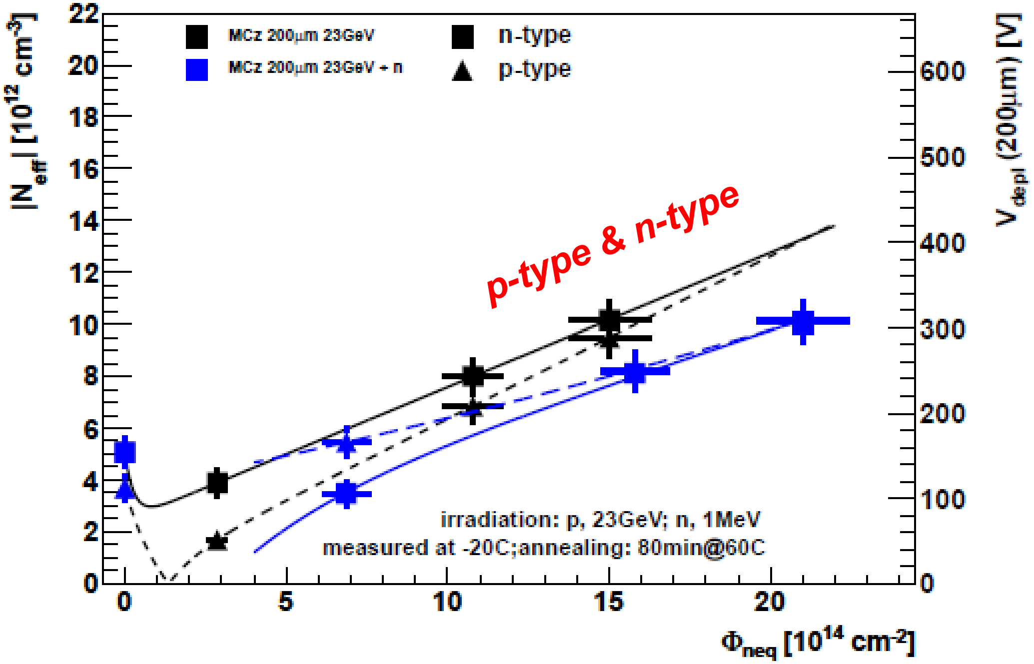
confirms →

(RD50)

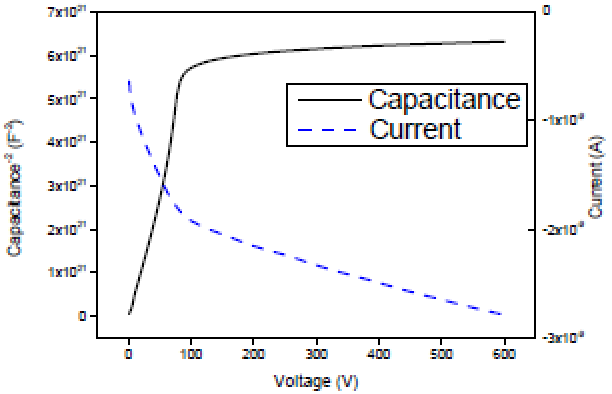
In high-oxygen material:
neutrons ⇒ acceptors
23 GeV protons ⇒ donors

Depletion voltage:

MCz Silicon after 23 GeV Proton and Neutron Irradiation



extracted from capacitance measurements
(-20°C, 455 Hz), annealing: 80min@60°C



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V_{fd} determines the operation voltage needed

Note: Lower r→Higher Φ →Higher p/n ratio

⇒ Irradiation damage does not add up,
no (strong) increase of V_{fd}

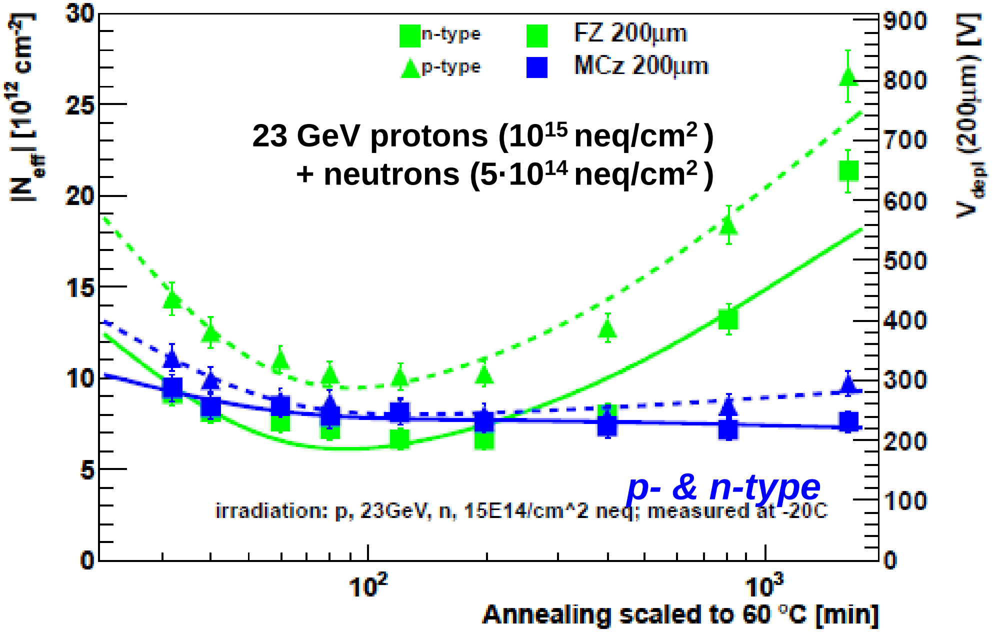
confirms

(RD50)

In high-oxygen material:
neutrons ⇒ acceptors
23 GeV protons ⇒ donors

Annealing of Full Depletion Voltage V_{fd} after Mixed Irradiation

V_{fd} after mixed irradiation



V_{fd} < 600 V **for FZ and MCz (200 µm)**
⇒ no signal loss at $V = 600$ V expected up to 400min@60°C (~7 weeks @ 20°C)

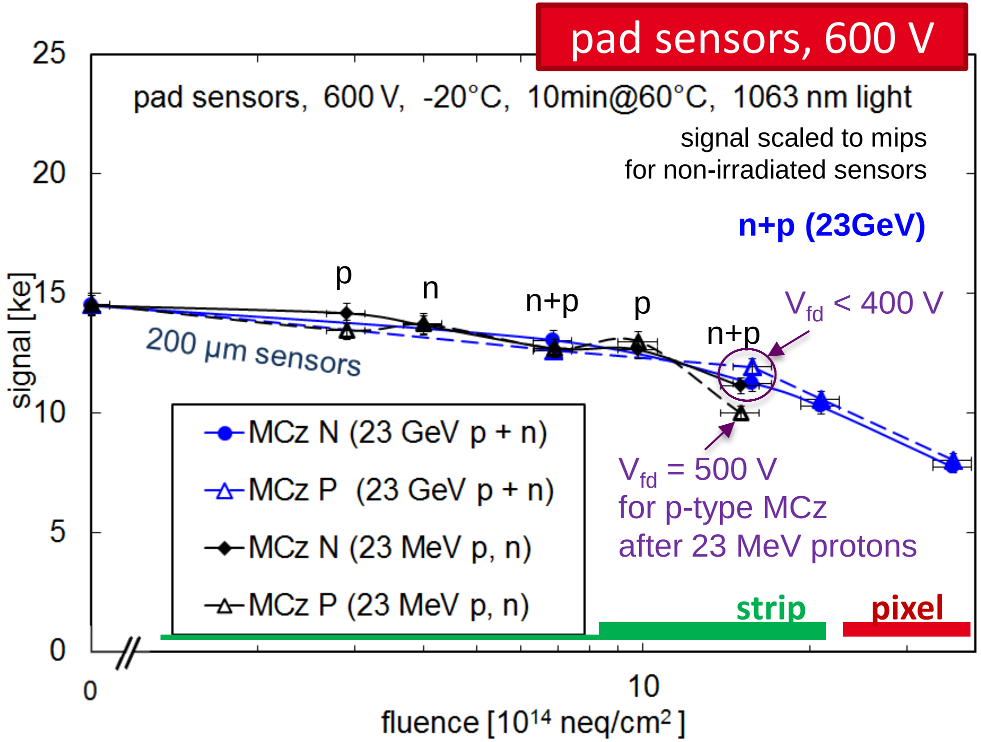
FZ: reverse annealing after ~100min@60°C (~12days @20°C)
⇒ **signal drop expected** for high annealing times

MCz: beneficial annealing only
⇒ **no signal drop expected**

→ Comparison at minimum not full story.
→ Annealing needs to be taken into account, also high Vdep @low t_{anneal}

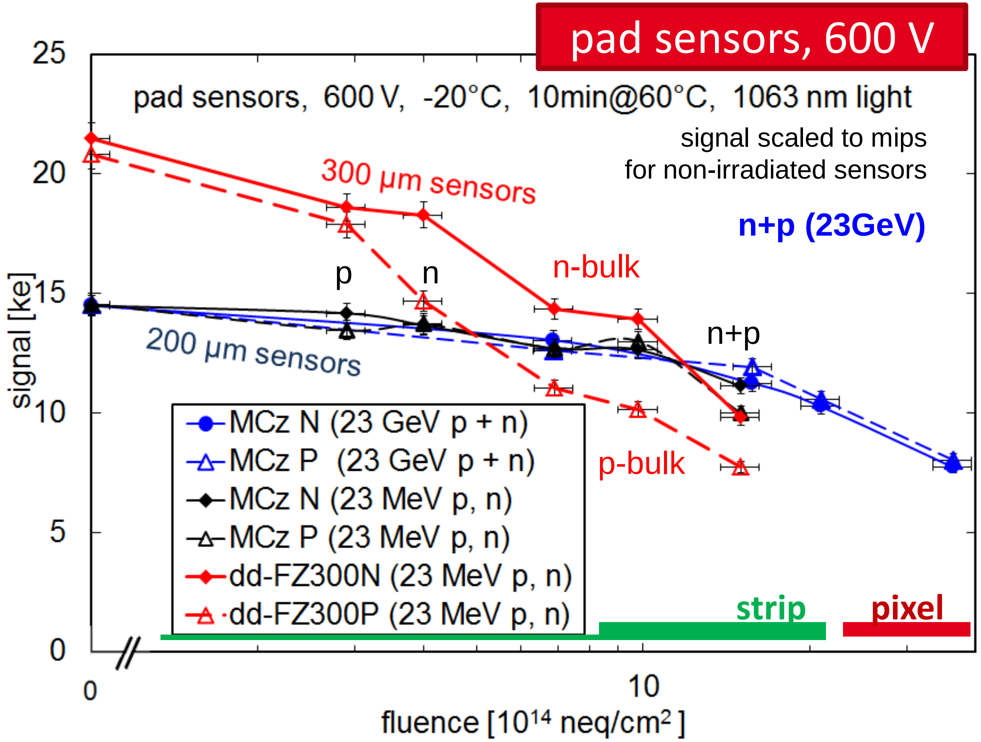
Charge Collection in Pad Sensors after Different Irradiation Types

pad sensors, 600 V



Signal independent of particle type (neutrons, 23 MeV protons, 23 GeV protons) and for pad sensors also of bulk doping (n-bulk vs. p-bulk) if $V \gg V_{fd}$

Charge Collection in Pad Sensors after Different Irradiation Types



Fully depleted (V_{fd} < 600 V)

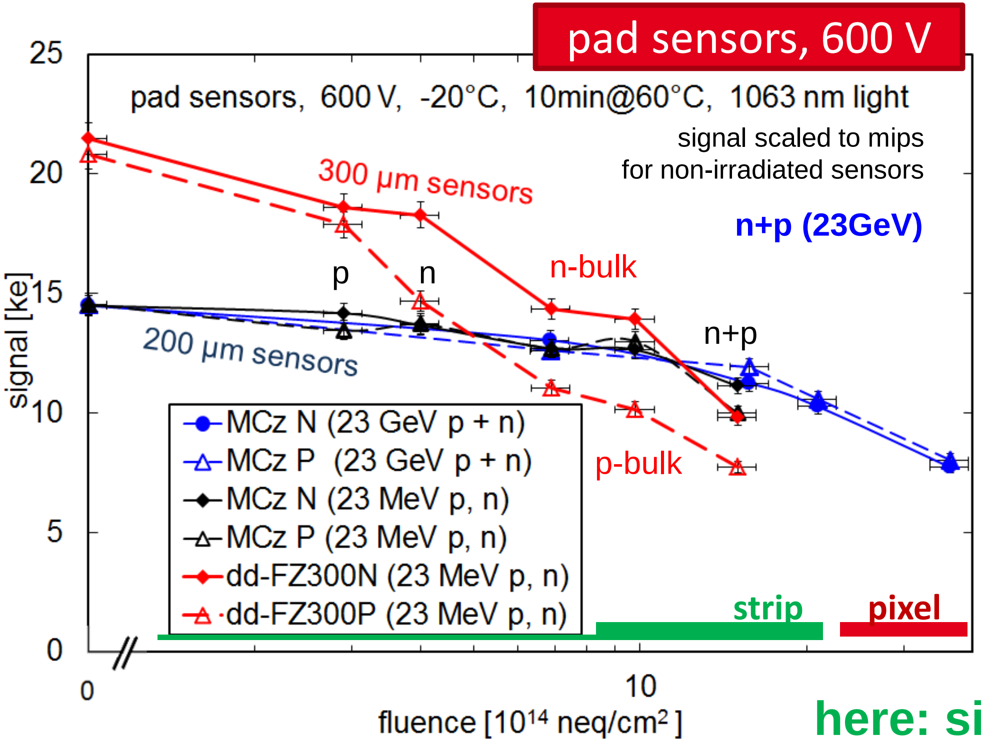
300 µm thick sensors:
not fully depleted (V_{fd} > 600 V)

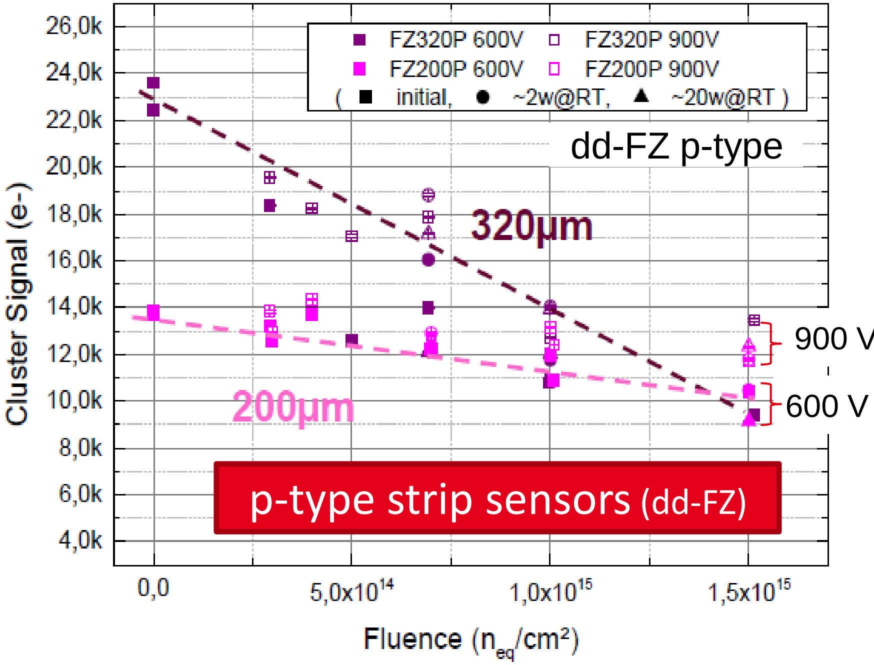
Signal independent of particle type (neutrons, 23 MeV protons, 23 GeV protons)
and for pad sensors also of bulk doping (n-bulk vs. p-bulk) if $V \gg V_{fd}$

300 µm sensors **fully depleted** at low fluences -> **higher signals** than 200 µm sensors

300 µm sensors **not fully depleted** at high fluences -> **lower signals** than 200 µm sensors

Charge Collection in Pad and Strip Sensors after Different Irradiation Types


pad sensors, 600 V


p-type strip sensors (dd-FZ)

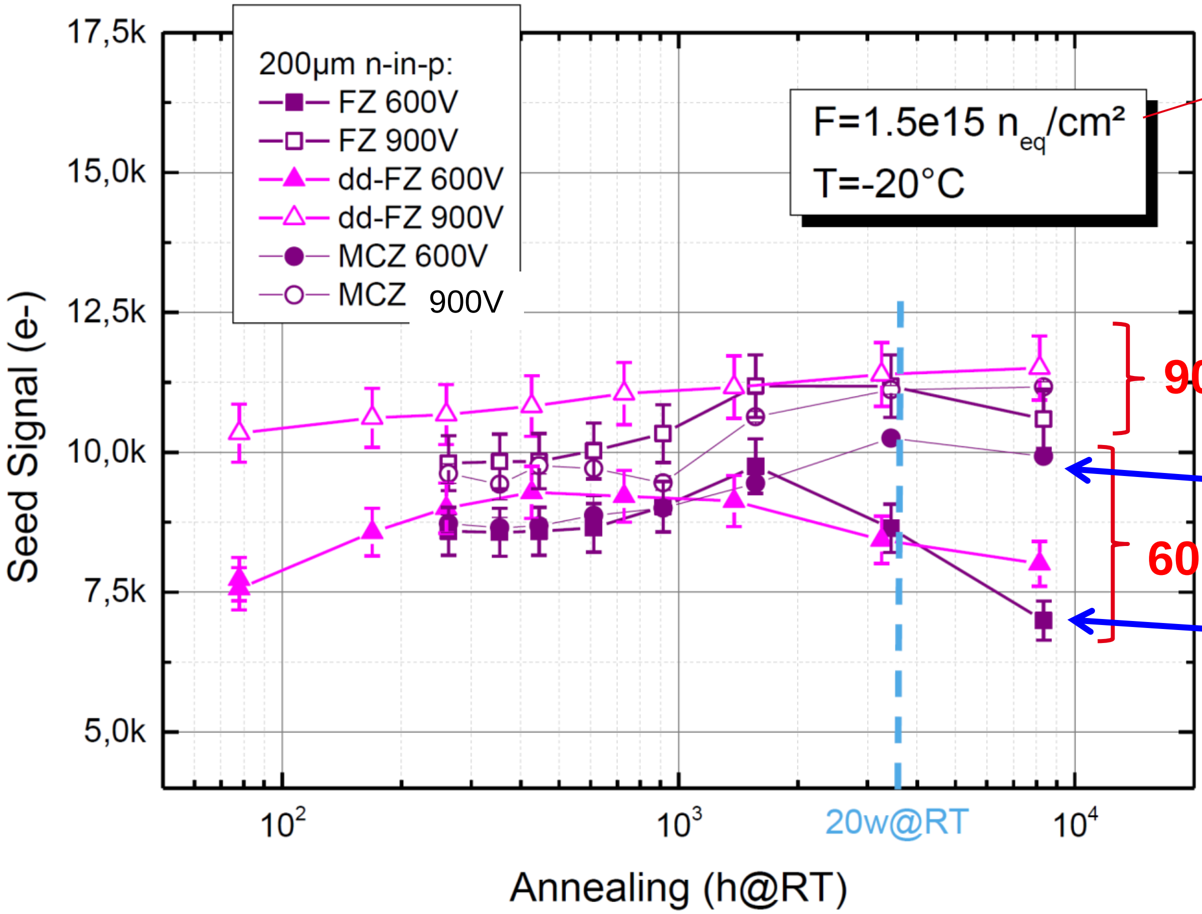
here: similar signals in p-type strip sensors

Signal independent of particle type (neutrons, 23 MeV protons, 23 GeV protons) and for pad sensors also of bulk doping (n-bulk vs. p-bulk) if V >> V_{fd}

300 µm sensors **fully depleted** at low fluences -> **higher signals** than 200 µm sensors

300 µm sensors **not fully depleted** at high fluences -> **lower signals** than 200 µm sensors

200 µm Thick p-Type Strip Sensors: Seed Signal as a Function of Annealing Time



Mixed irradiation: 10p + 5n
FZ, MCz: 1e15 23 GeV protons
dd-FZ: 1e15 23 MeV protons
all: + 5e14 reactor neutrons

900 V

MCz silicon

600 V

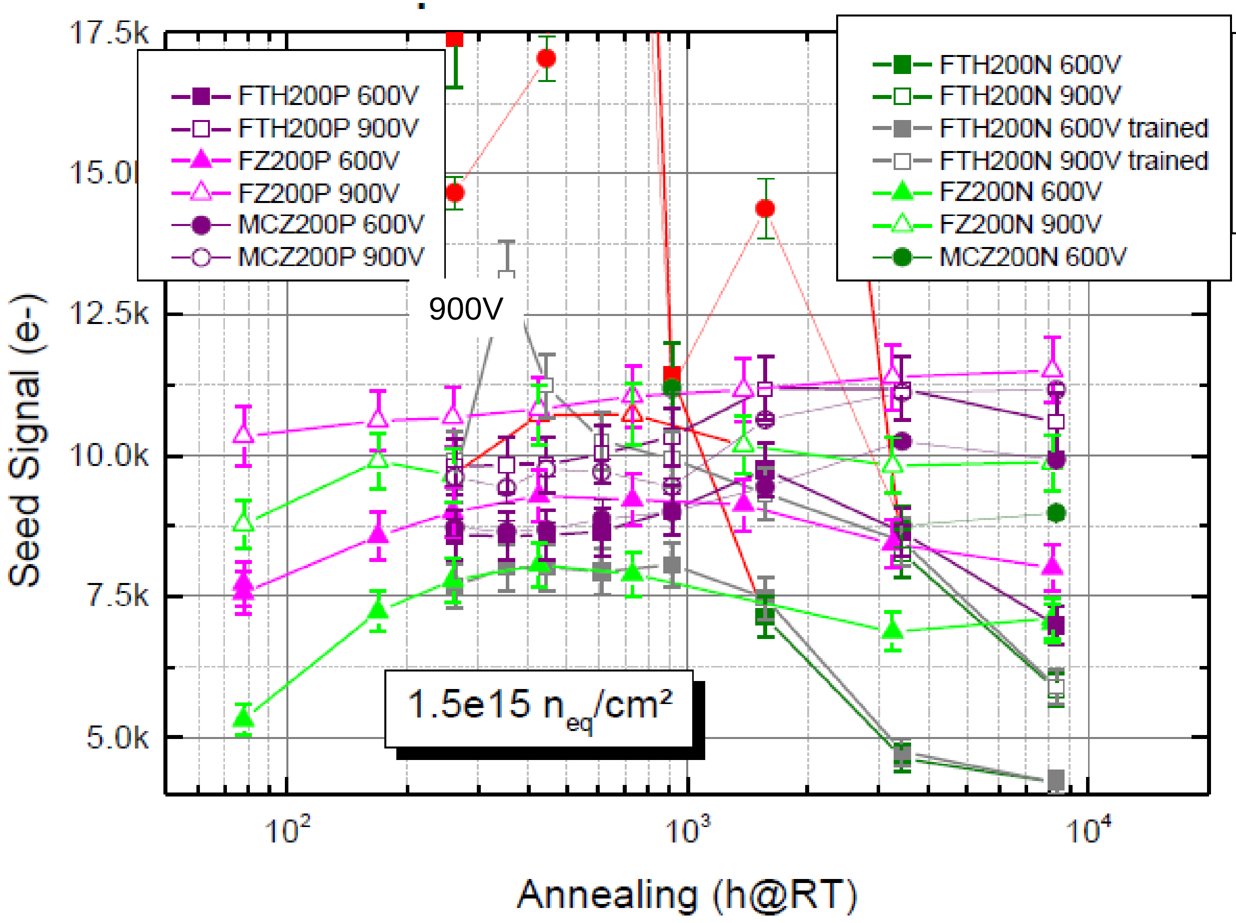
FZ silicon
(reverse annealing)

- 200 µm p-type sensors: seed > 8 ke- at $1.5 \cdot 10^{15}$ neq/cm^2 up to ~20 weeks at RT

⇒ Can be operated in CMS strip tracker with 2 weeks annealing per year

- MCz: seed >8 ke- up to ~50 weeks at RT (long-term beneficial anealing)

Now with p versus n



Mixed irradiation: 10p + 5n

FZ, MCz: 1e15 23 GeV protons

dd-FZ: 1e15 23 MeV protons

all: + 5e14 reactor neutrons

- n type sensors showed large noise, not all measurements reliable
- Tendency towards lower signal in n-type, drop at large annealing times

Summary and Conclusion

The R&D for the CMS outer tracker is well advanced

- Baseline tracker layout with barrel-endcap design
- Triggering at L1 →Trigger modules, 2S and PS →Module design
- CBC chip

CMS decided to use p-type silicon sensors for the phase II strip tracker.

- Seed signals > 8 ke @1.5E15, stable with annealing for up to 20 weeks@RT (FZ) at RT and even 50 weeks (MCz)
- Noise under control (Our n-type sensors are affected by non-Gaussian noise: Talk by A. Nürnberg)
- Known advantage: Depletion from the front side, electron collection

Depletion voltage after mixed irradiation (23 GeV protons + neutrons)

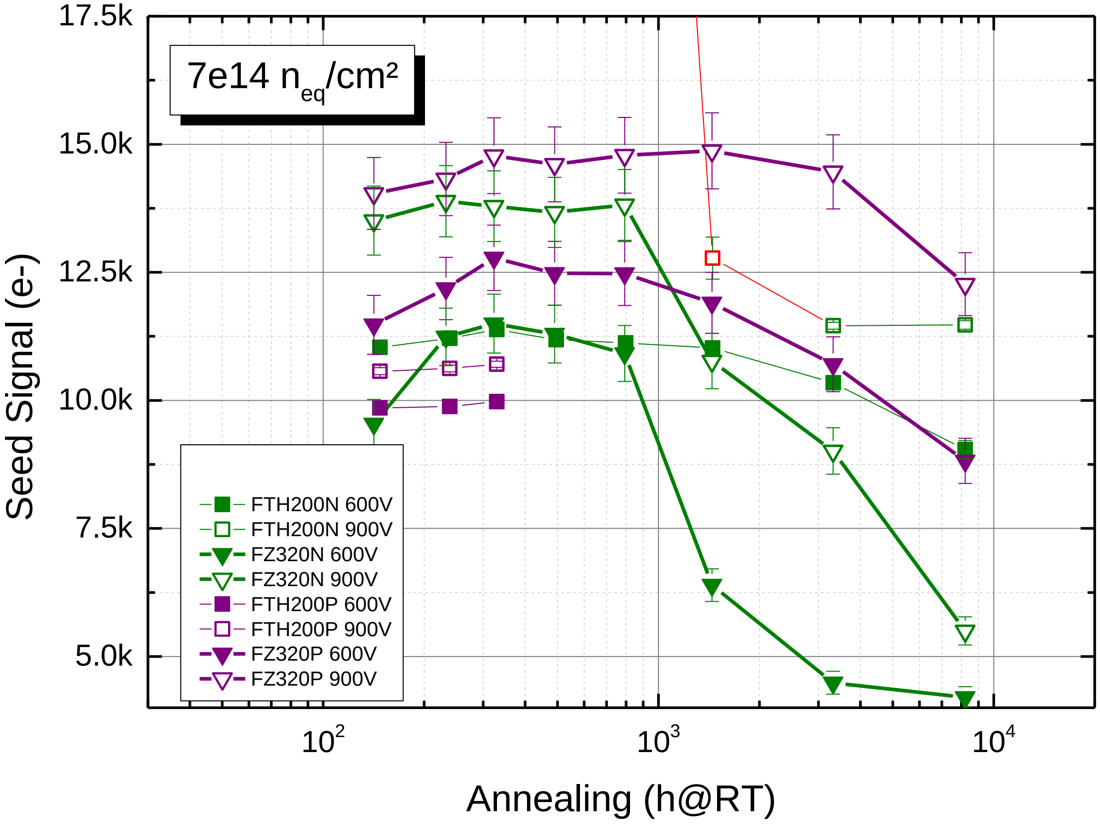
- MCz silicon benefits from the compensation effect for mixed irradiation and from long-term beneficial annealing
- FZ silicon: no compensation and reverse annealing after >12 days at 20°C (90 min at 60 °C)

Further Remarks:

- Campaign did not include real low [O] FZ silicon → Smaller material dependence than "typical"
- Differences in V_{dep} after 23 GeV vs. 23 MeV proton irradiation, but similar signal if $V>>V_{fd}$

Backup

Annealing – 7e14n_{eq}/cm² – FZ n and p

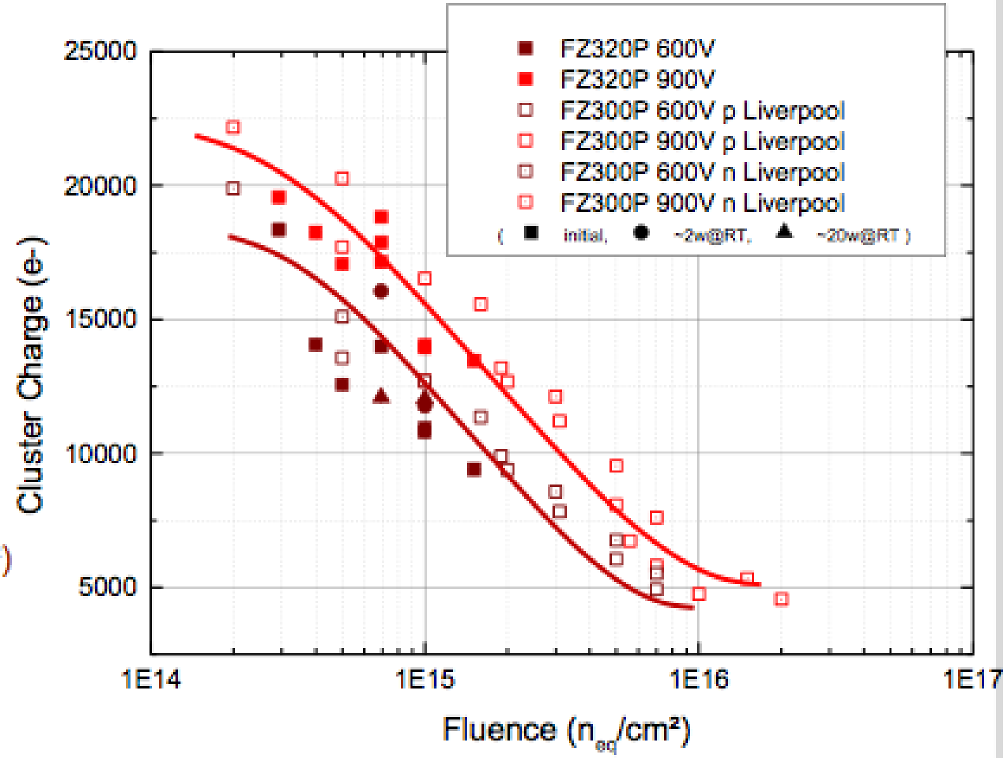


- n-type drops sharply after ~40days
- p-type very stable with annealing

Charge Collection – p-Type 300µm Strip Sensors

- Charge collection measured with Sr90 at -20°C with 600V and 900V bias
- Liverpool (SCT128A) and Karlsruhe (Beetle) results show reasonable agreement
- p-type strip sensors show uniform drop like exponential decay,
  - e.g. for 600V in the range of $F=(1e14-1e16)n_{eq}/cm^2$:

$CC \sim 5.7ke^- + 12.2ke^- \cdot \exp(-F/1.4e15 n_{eq}/cm^2)$

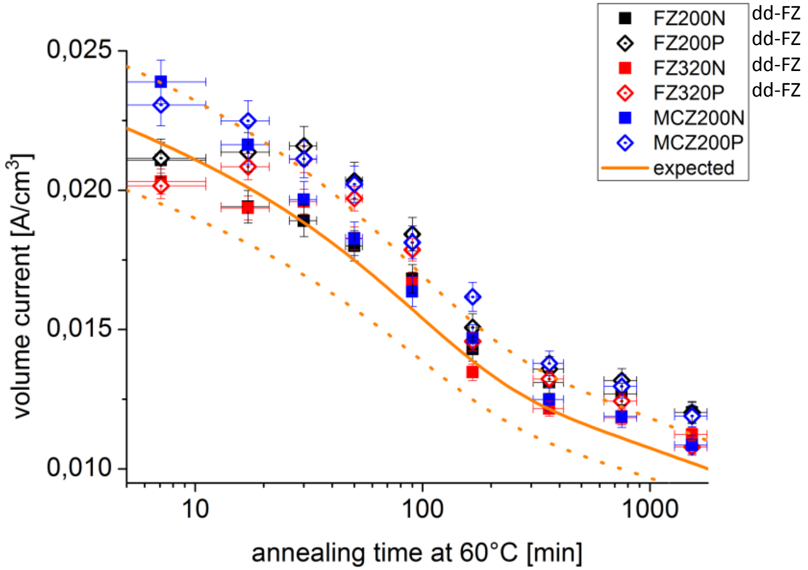


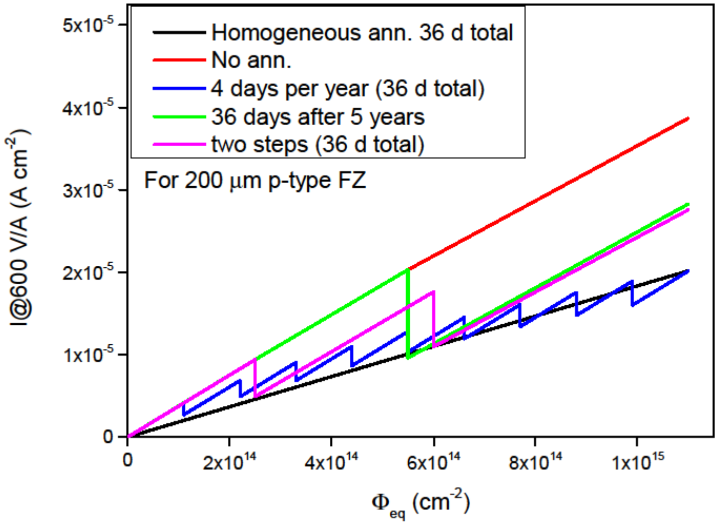
A. Dierlamm: Vertex 2013

Liverpool: NIM A 636 (2011) S56-S61

Annealing of Volume Current

1 MeV neutrons, $\phi_{eq} = 4 \cdot 10^{14}\ cm^{-2}$



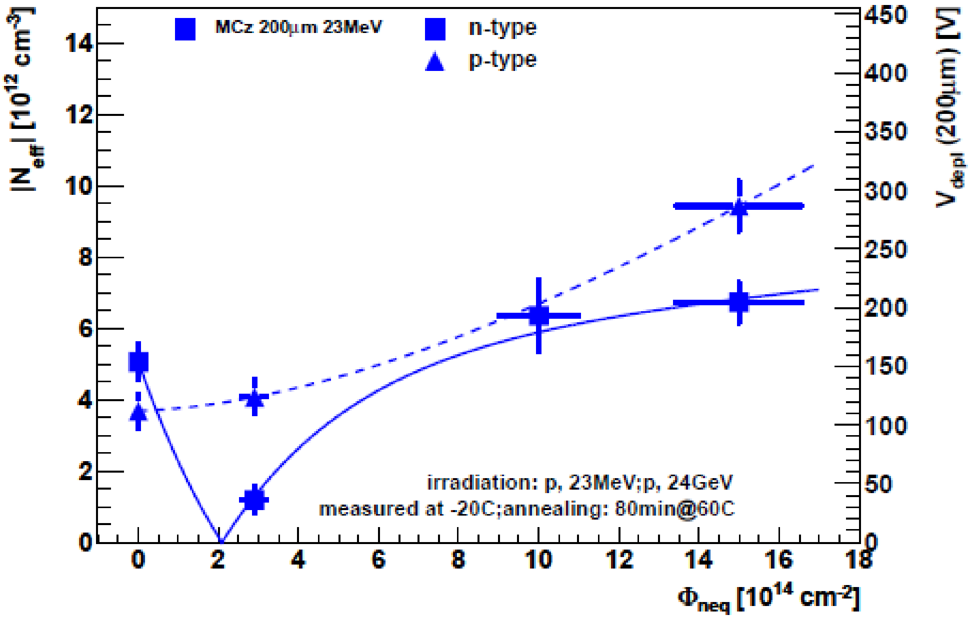


→ Current drop after annealing as expected

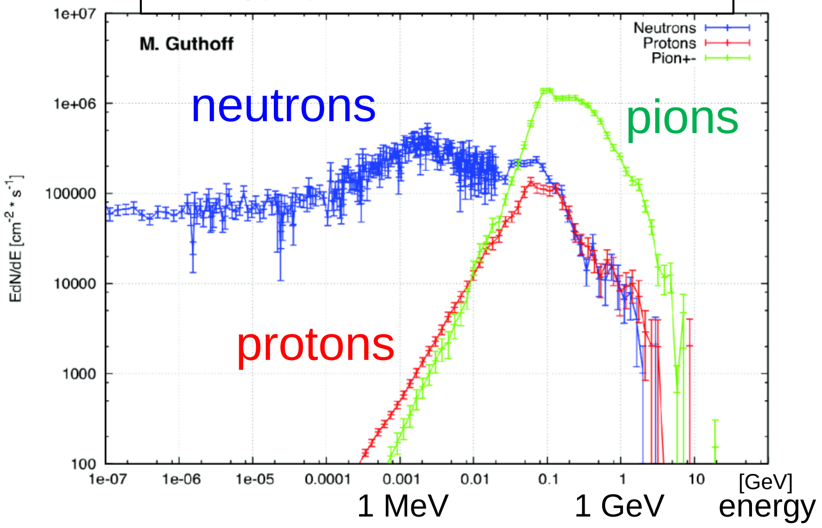
→ Warmup can be beneficial, but need to also look at annealing of V_{dep}

Depletion voltage: Energy Dependence

MCz Silicon after 23 GeV versus 23 MeV Proton Irradiation



energy spectra at z≈0, R≈30 cm



neutrons

pions

protons

1 MeV

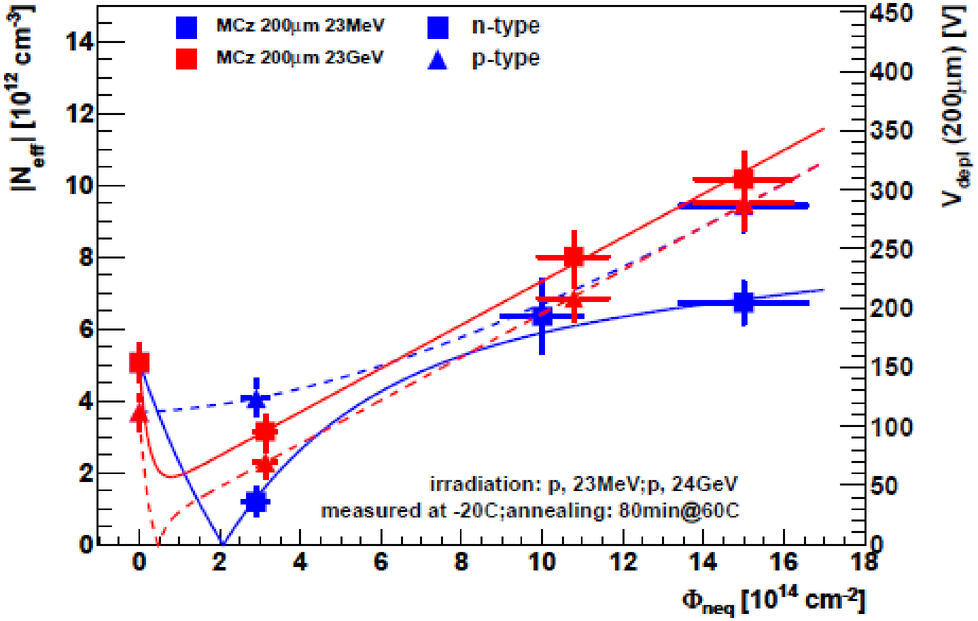
1 GeV

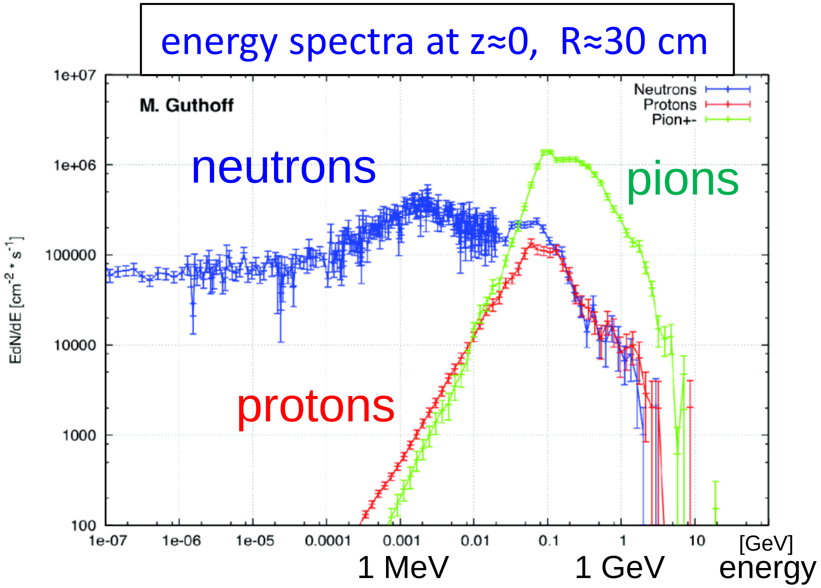
energy

Higher donor generation in 23 GeV protons ⇒

Depletion voltage: Energy Dependence

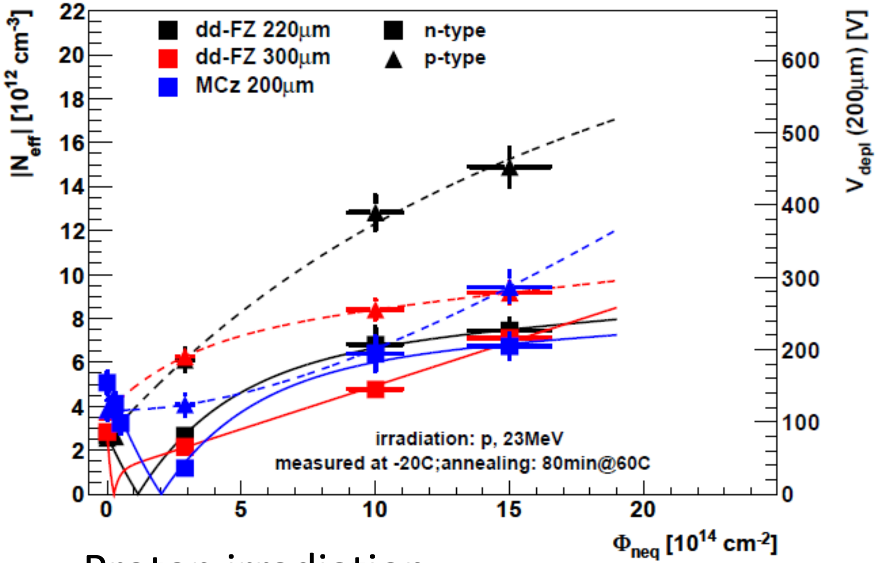
MCz Silicon after 23 GeV versus 23 MeV Proton Irradiation



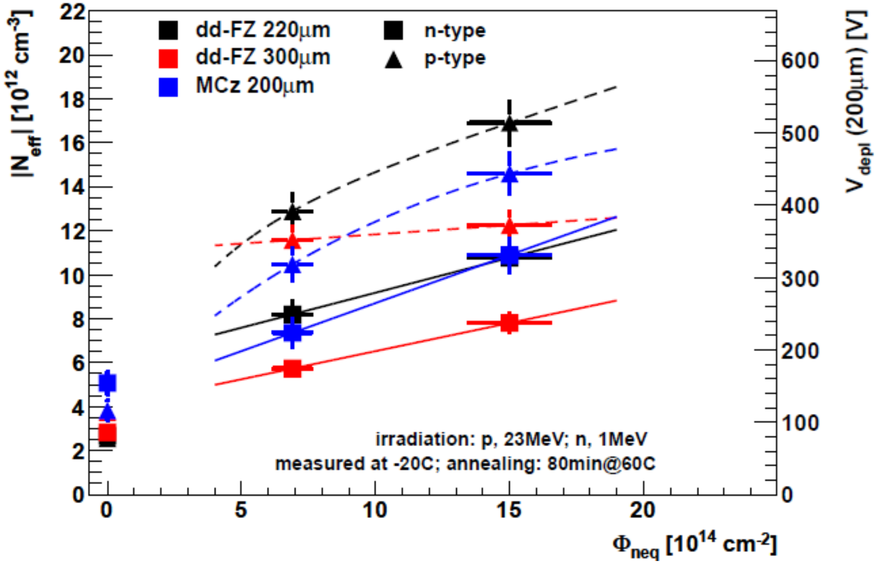


Higher donor generation in
23 GeV protons ⇒

200 dd versus MCZ, MeV irradiation

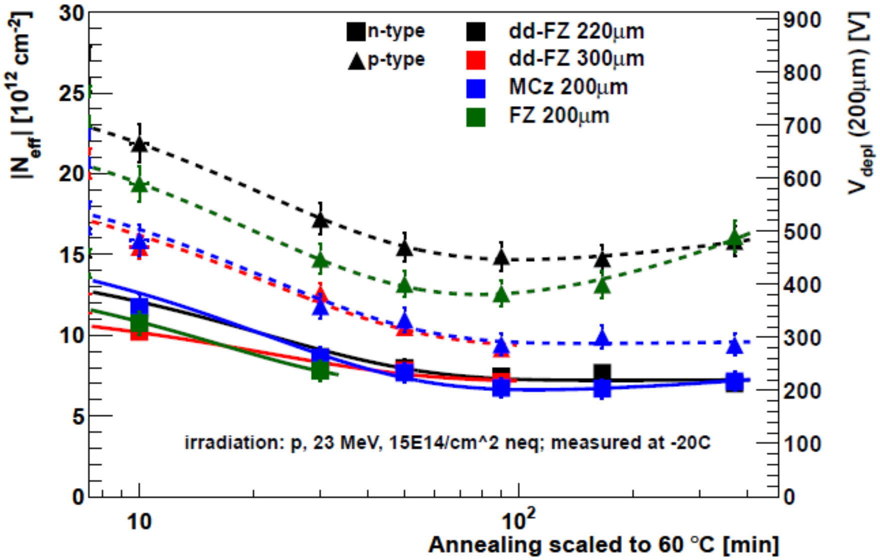


Proton irradiation

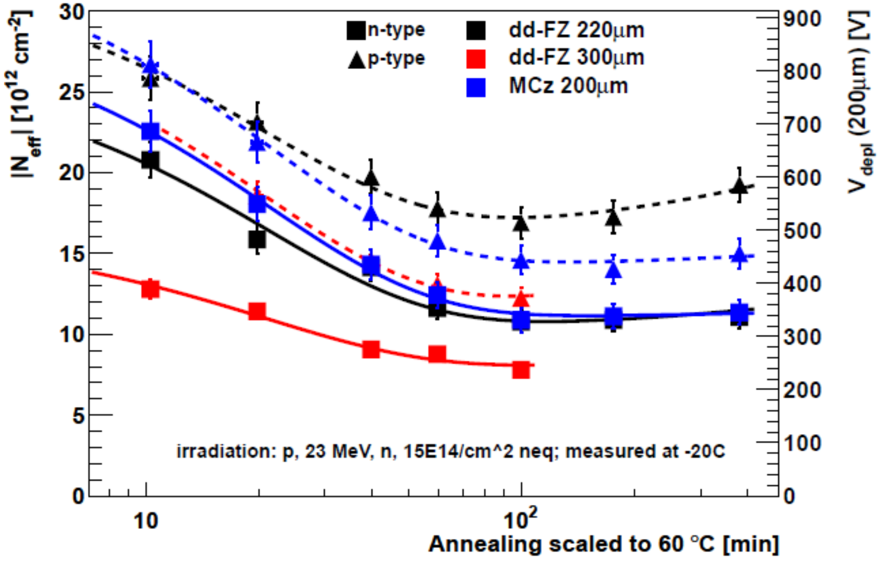


Mixed irradiation

200 dd versus MCZ, MeV irradiation



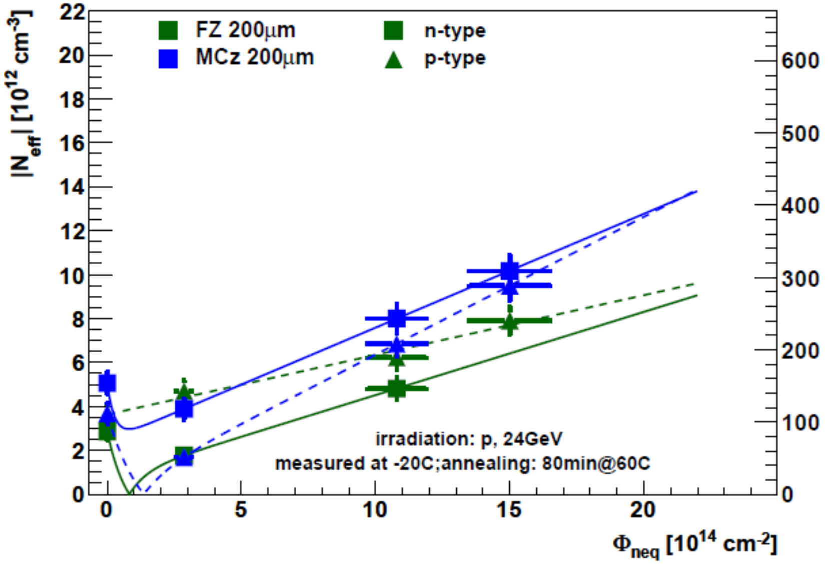
Proton irradiation



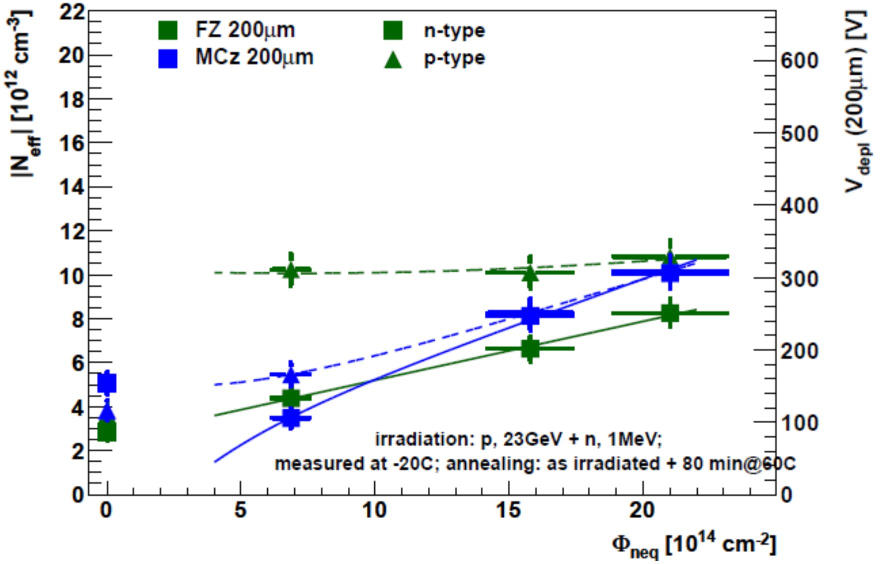
Mixed irradiation

Georg Steinbrück
georg.steinbrueck@desy.de

FZ 200 (FTH) versus MCZ, GeV irradiation

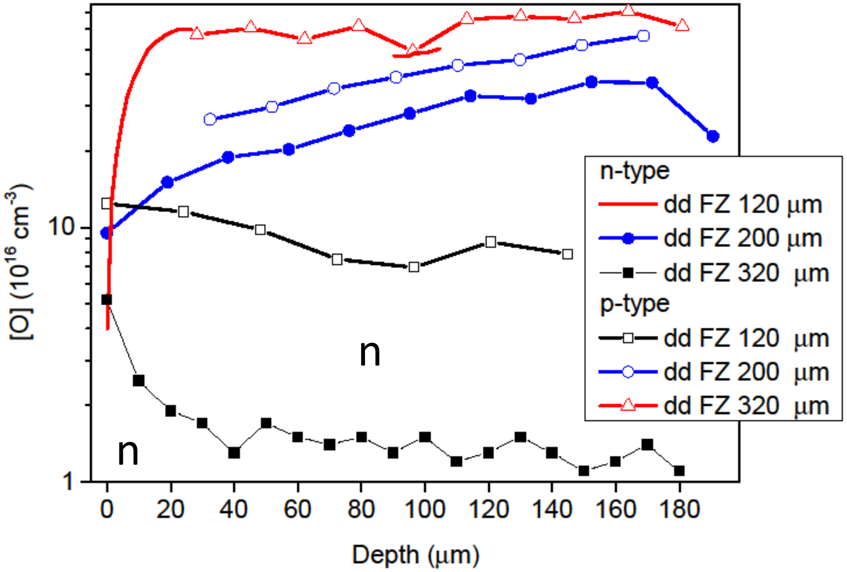


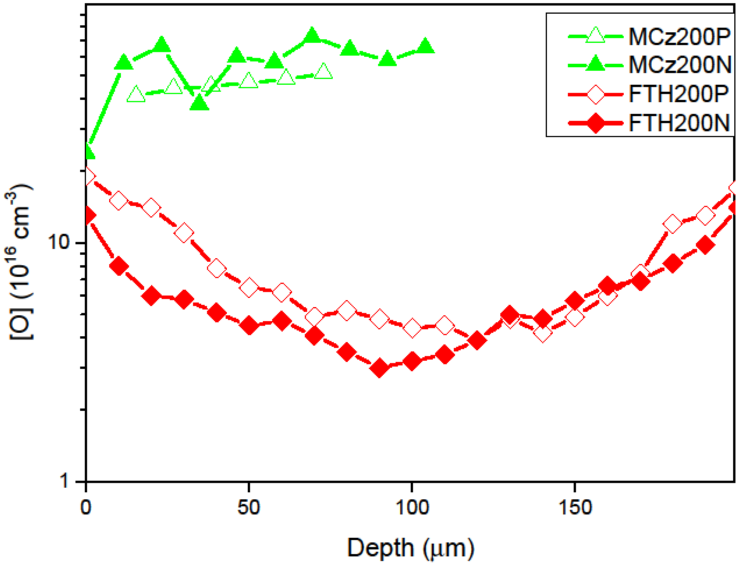
Proton irradiation



Mixed irradiation

Oxygen Content backup





- Deep diffused material: Higher [O] when active thickness lower
- [O] in p typically larger than n
- 120 dd extremely high!
- New: FTH and dd320n

- [O] FTH lower than MCZ but higher than typical FZ, more like DOFZ
- For reference: Standard FZ: <3x16^{16}, DOFZ*: 1x10^{17}

New measurements:
FTH and dd-FZ 320 n

*Diffusion 72h at 1150°C