CMS Outer Tracker Upgrade Plans

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for the CMS Tracker Collaboration

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HELMHOLTZ | ASSOCIATION

DESY

Outline

- Upgrade of CMS
- Tracker
  - requirements
  - concept
  - geometry
- Module development
- Sensor development
  - HPK Campaign
  - Plans
- Summary

CMS Tracker Upgrade - Timeline

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

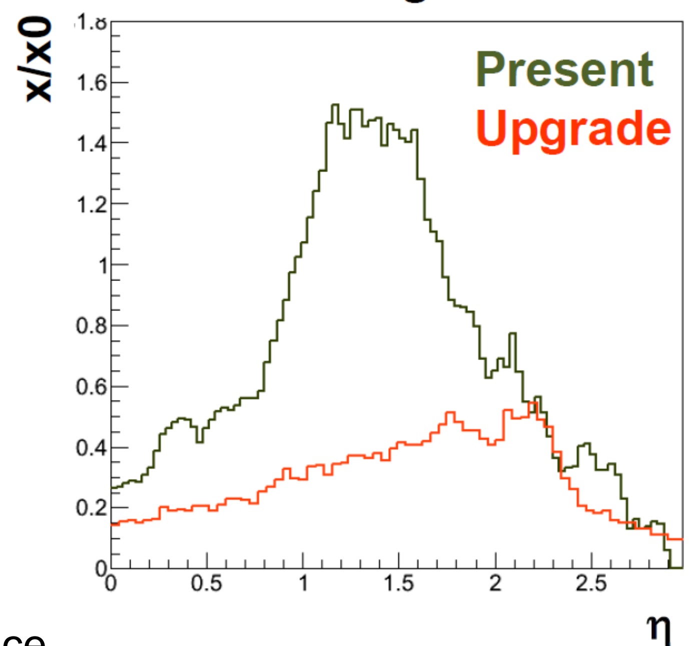
Requirements

- radiation hardness
  - aim for $3000fb^{-1}$
    - → sensors have to be radiation hard and thus cooled to $-20^{o}C$
- granularity
  - resolve up to 200 collisions per bunch crossing, keep occupancy at % level
    - → much shorter strips required
- improve tracking performance
  - improve performance at high pT
    - → reduce the average strip pitch

Increased channel count

  - improve performance at low pT and reduce rate of secondary interactions
    - → reduce material
- input to Level-1 trigger
  - μ, e and jet rates exceed 100kHz at high luminosity
  - increasing thresholds would reduce physics performance
  - need tracker information already in Level-1 trigger decision

Material budget estimate



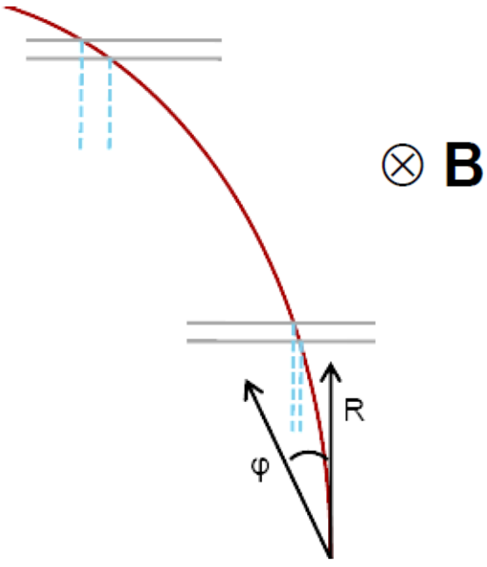
General Concept of Phase-2 Outer Tracker Modules – I

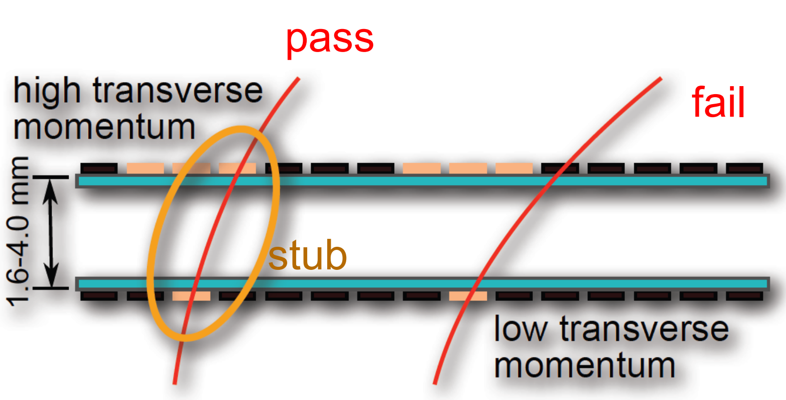
- modules provide at the same time information
  - to L1 Trigger (at 40MHz)
  - as “read out data” after L1 decision (at 100kHz)

  → 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

General Concept of Phase-2 Outer Tracker Modules –II

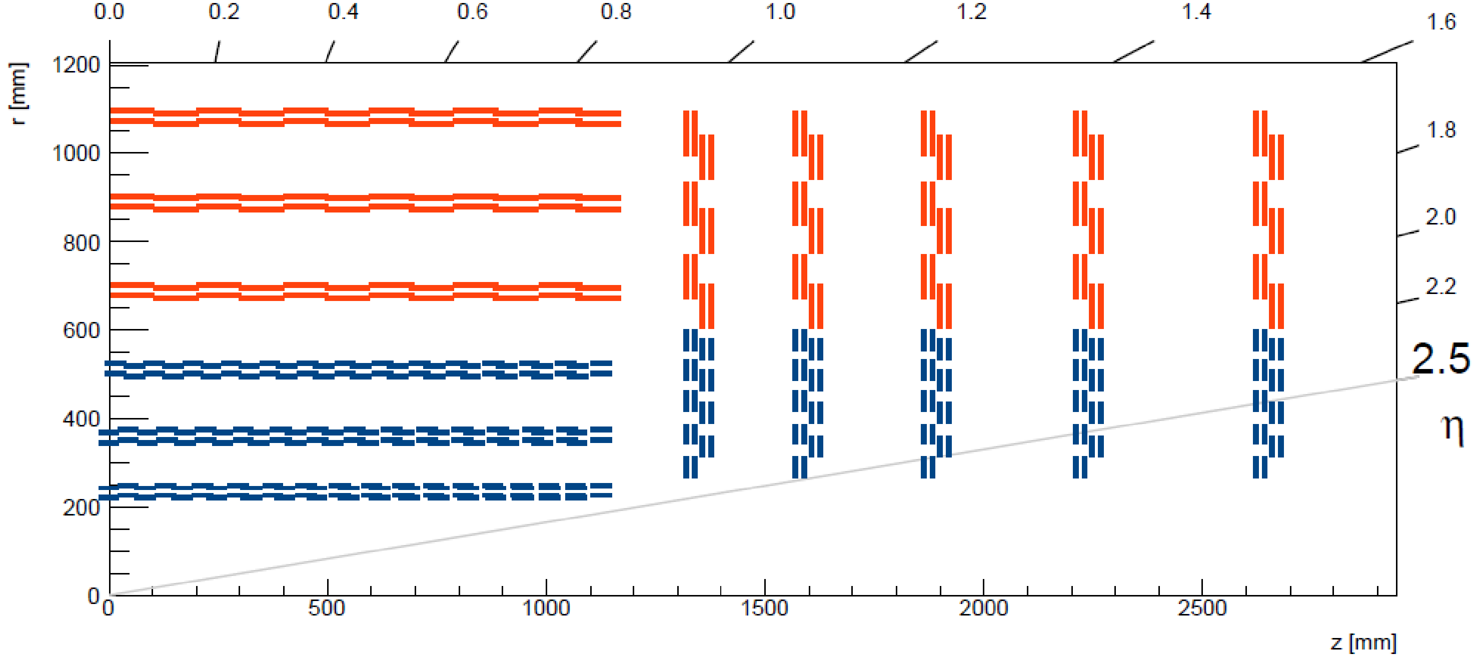
- binary readout – CBC
- low power giga-bit transceiver (LP-GBT) as data link
  - currently under development
  - integrated at module level
- powering via DC-DC conversion
  - already used in phase-1 pixel upgrade
  - input current at higher voltage (~10V) reduces conductor cross-section
    substantial reduction of material budget
  - integrated at module level

module is a fully integrated entity

see talk of Lutz Feld

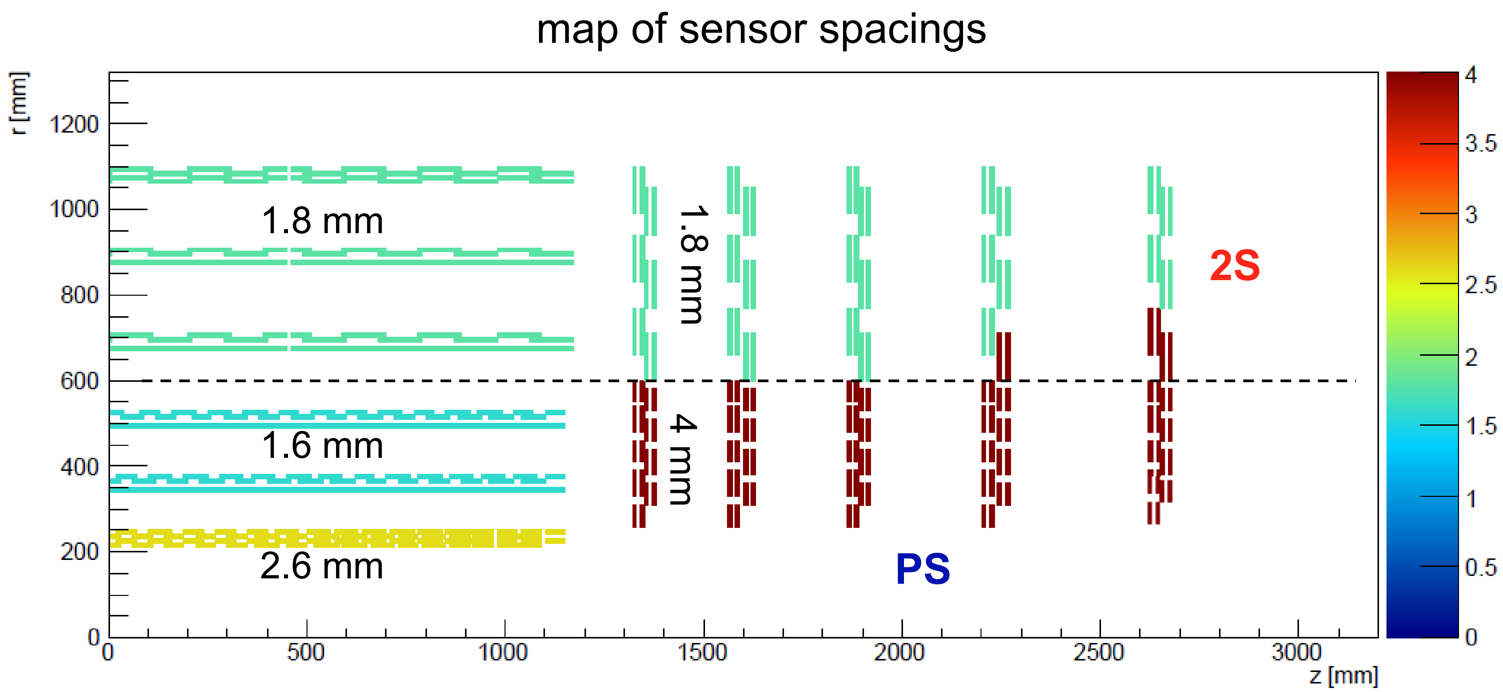
- two different module types
  - different sensor spacings are treated as ‚variants' of one module type with only minimum changes
  - requires optimization of only two designs
- evaporative CO_2 is the baseline cooling system
  - experience within CMS is being gained with the phase-1 pixel upgrade

Baseline layout



- baseline layout with 6 barrel layers and 5 endcap disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (**PS**)
  - stack of two strip sensors at r > 60 cm (**2S**)

Baseline layout – module configuration



> baseline layout with 6 barrel layers and 5 endcap disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (**PS**)
  - stack of two strip sensors at r > 60 cm (**2S**)

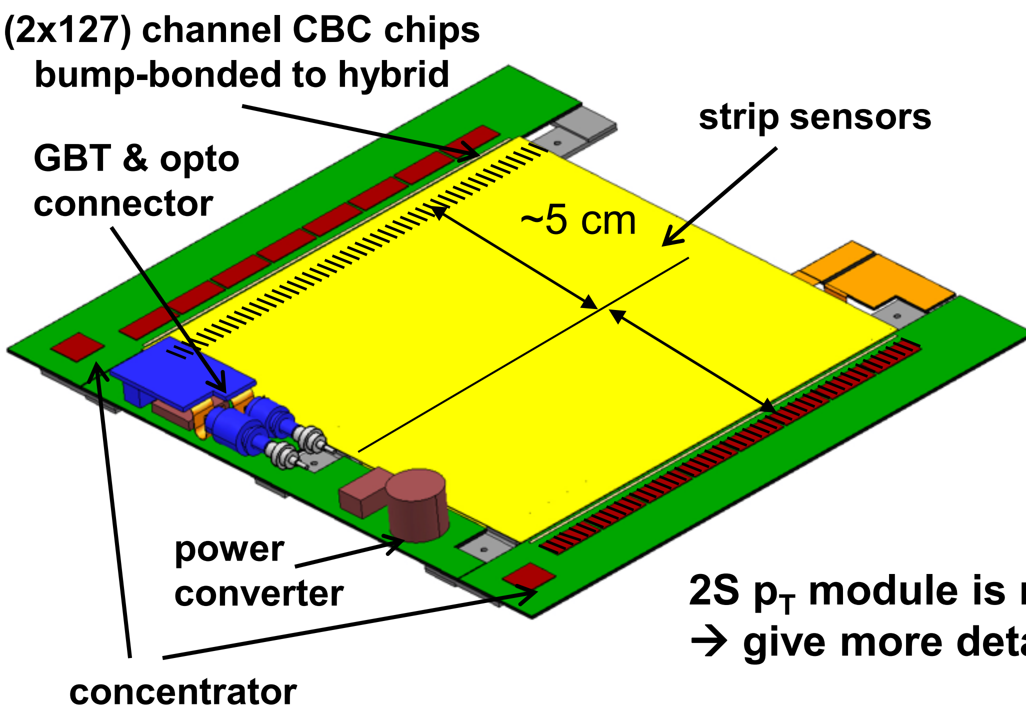
> PS modules
  - sensor spacings: 1.6 mm, 2.6 mm and 4 mm

> 2S modules
  - sensor spacings: 1.8 mm and 4 mm

The Outer Tracker Modules

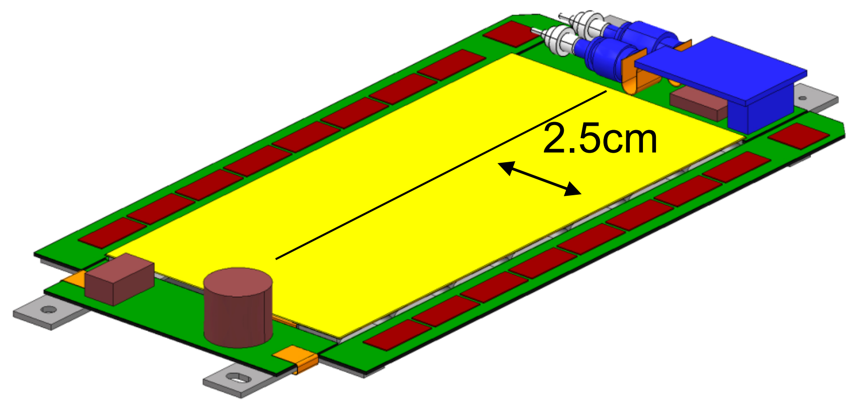
2S p_T module

- for r > 40cm
- 2 strip sensor on top of each other
- sensors wire-bonded to hybrid from top & bottom
- strip dimensions: 5cm x 90µm
- 10 cm x 10 cm



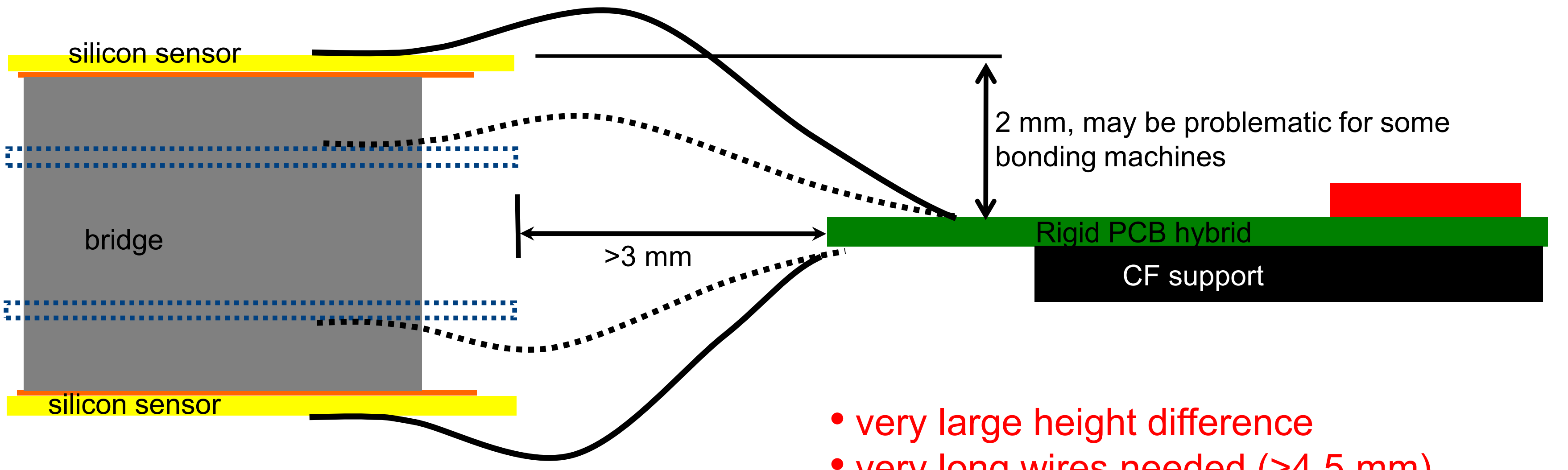
PS p_T module

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



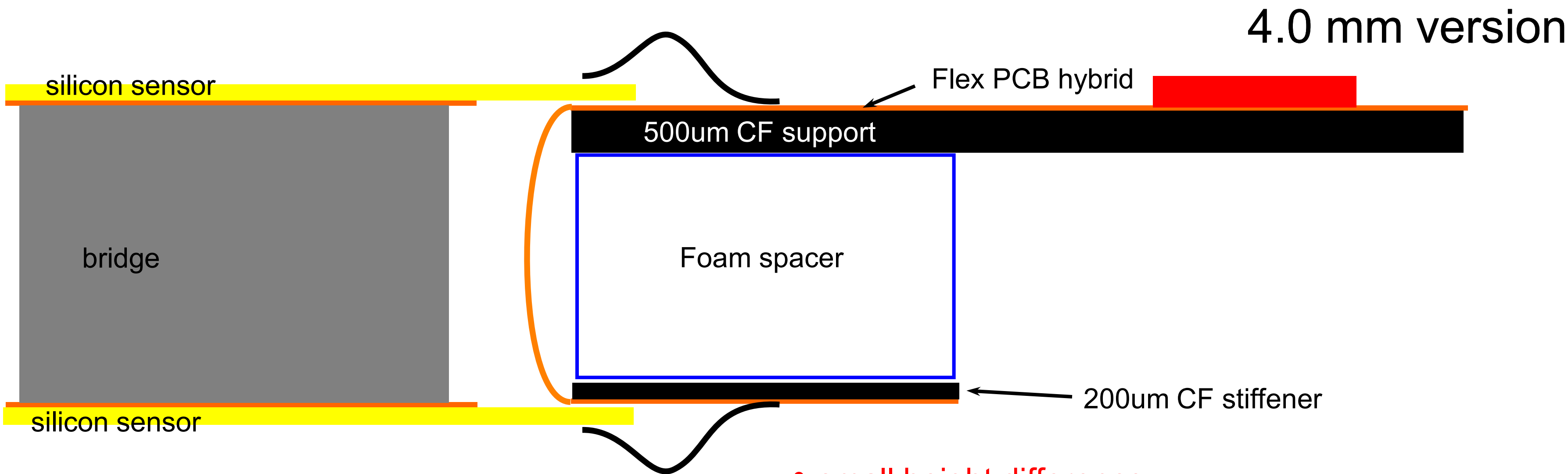
2S p_T module is more advanced than PS module
→ give more details on 2S

2S Module - Rigid Hybrid Option

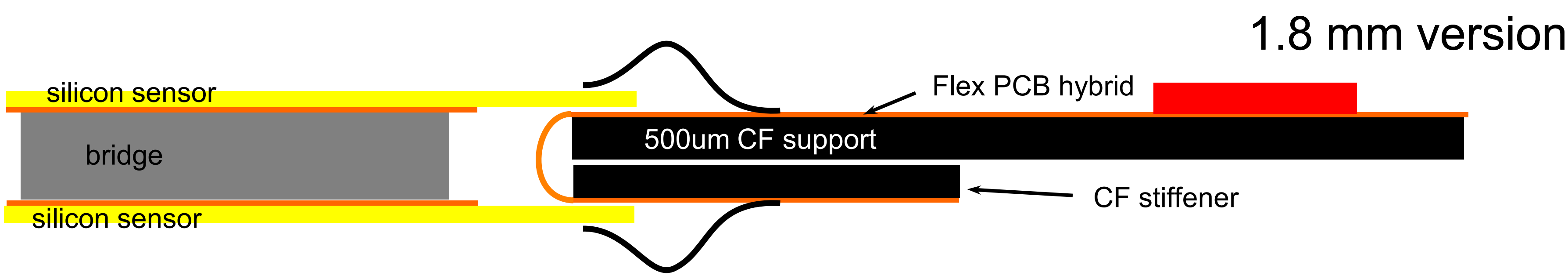


- very large height difference
- very long wires needed (>4.5 mm)

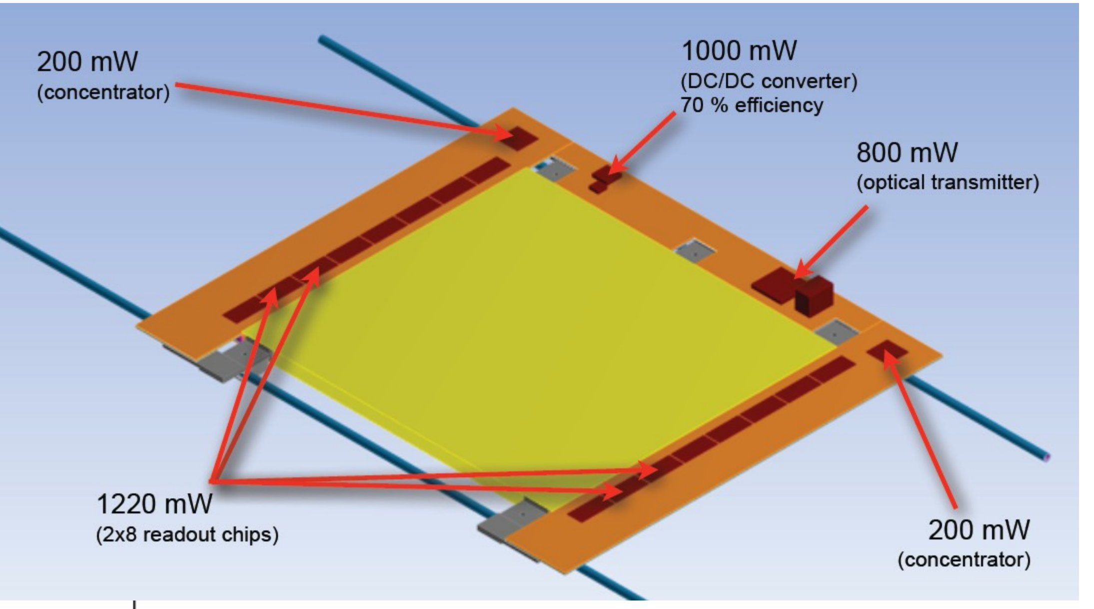
2S Module - Flexible Hybrid Option



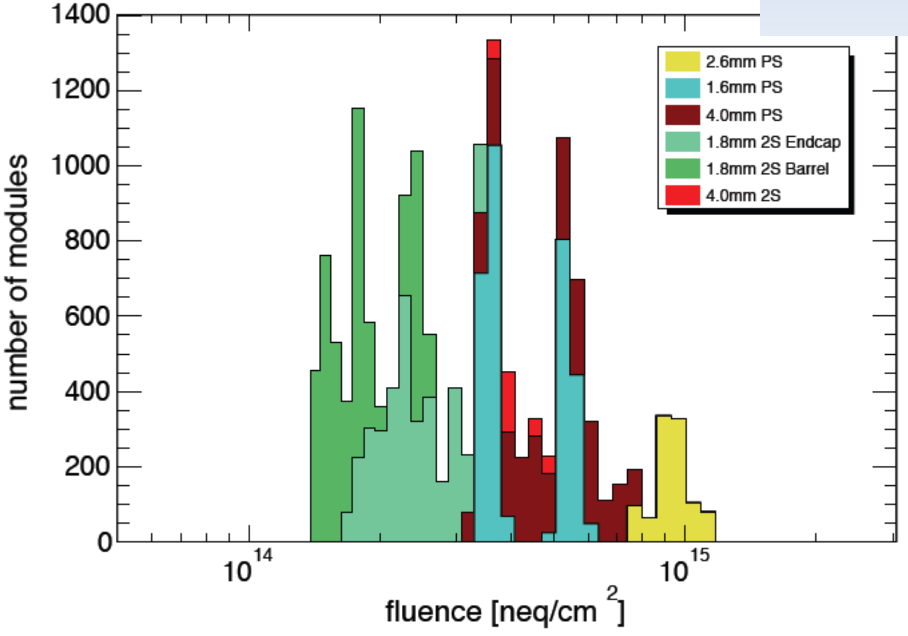
- small height difference
- short wires (<3 mm)
- encapsulation of bond wires possible



Module Power Dissipation



- > 3.42 W
- > plus sensors

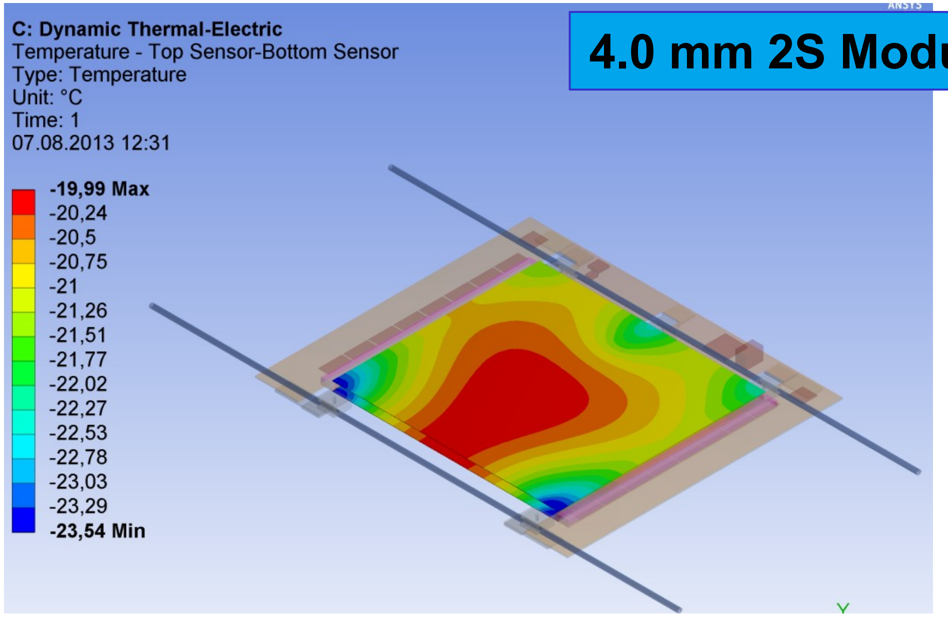


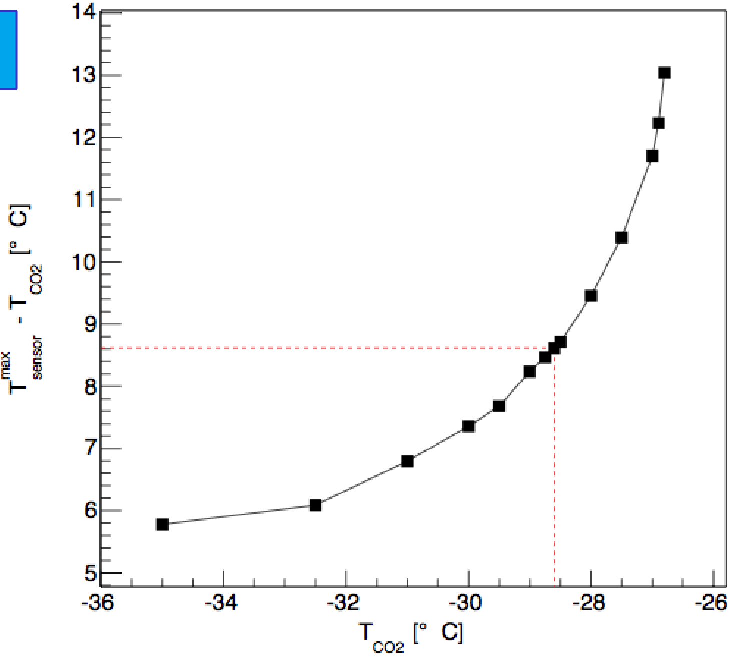
- > combination of # of modules and fluence vs. module position
- > fluence obtained from FLUKA for 3000 fb-1
- > safety factors for fluence applied: 50%

  → 2S: 7e14n_{eq}/cm² (R>60cm)
  → PS: 1.6e15n_{eq}/cm² (20cm<R<60cm)

- > sensor thickness 200µm

Example Results of Thermal FEA

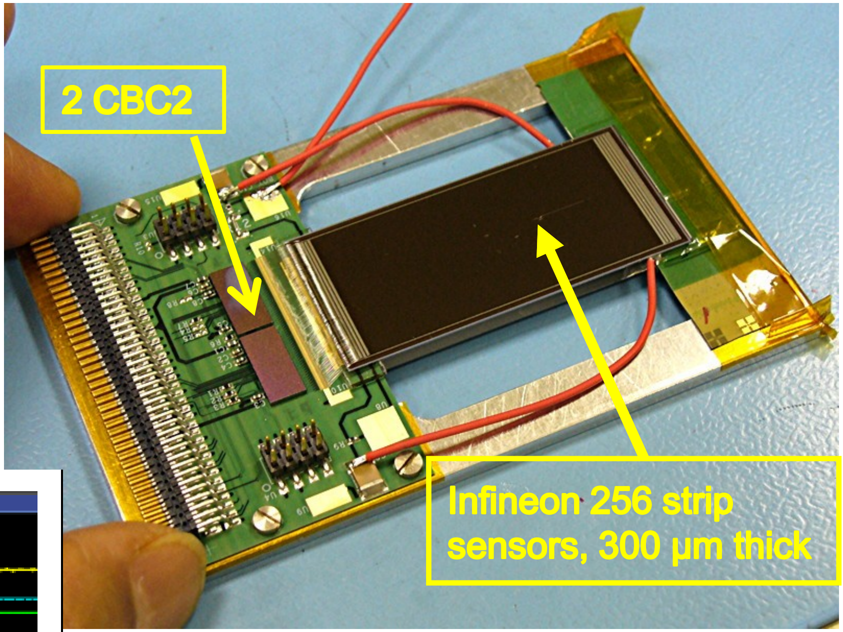


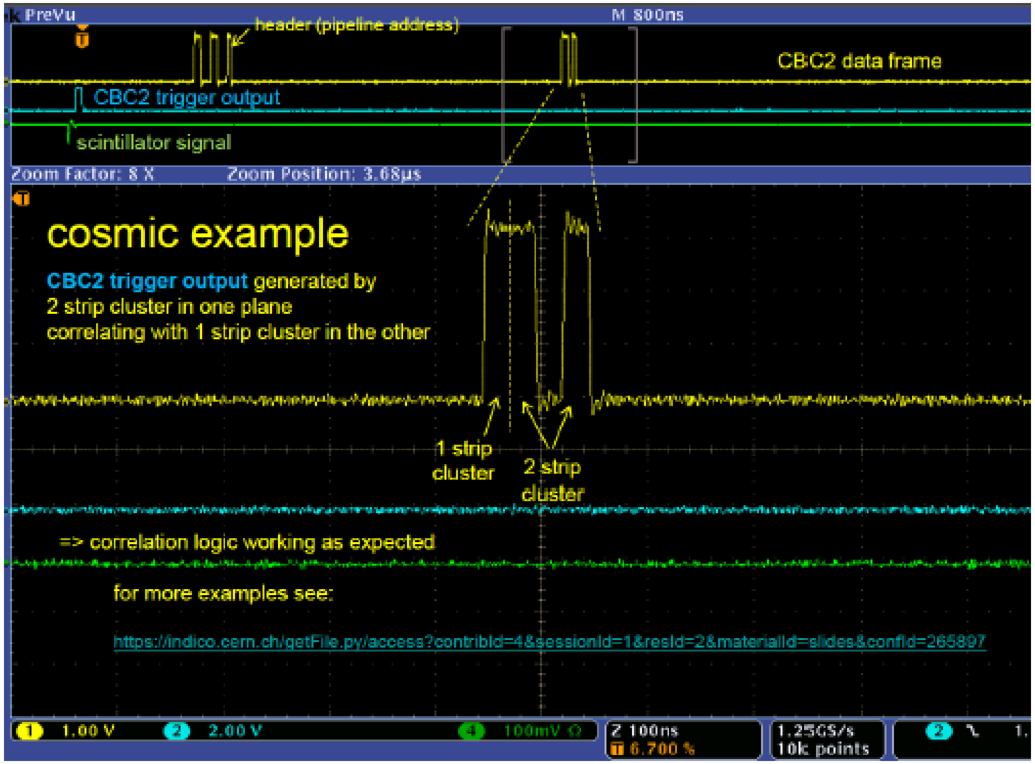


- heat transfer coefficient from pipe to CO_2 is 5000 W/m2/K
- heat transfer coefficient from module to cooling blocks is 10000 W/m2/K
- fluence for sensor power dissipation calculation is **7.35×10^{14} n_{eq}/cm^2**
- temperature of CO_2 tuned to obtain -20 °C max. T on sensors
- temperature gradient on sensors **3.5 °C**
- cooling contacts have to be kept at **-28.6 °C** to obtain -20 °C max. T on sensors
- thermal runaway reached at **~ -27 °C**

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

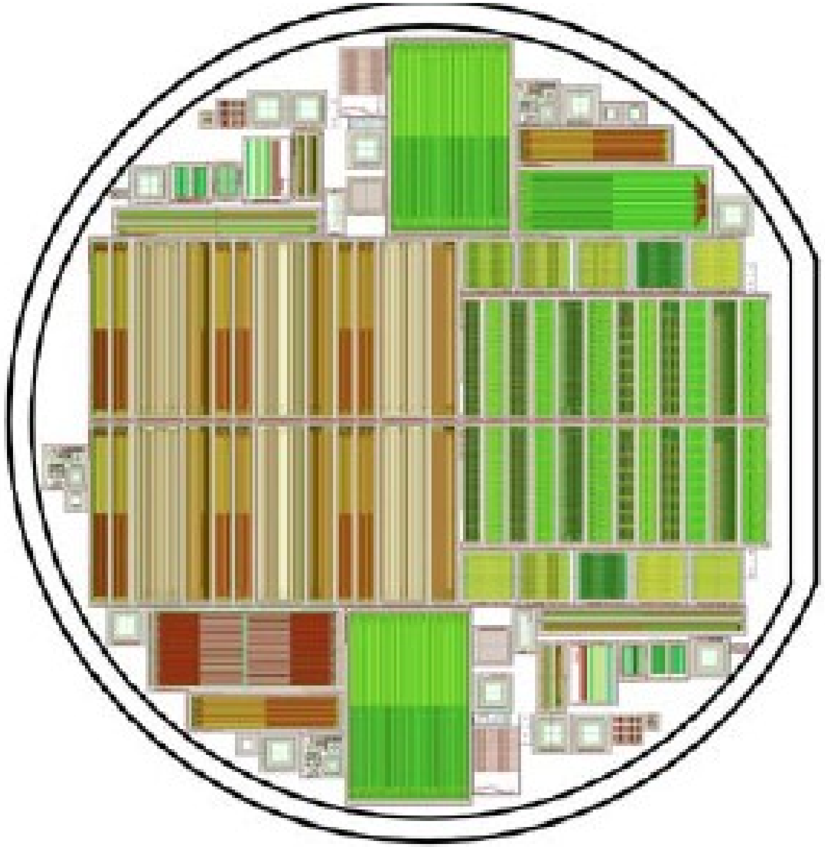




- testbeam in preparation
- will use these CBC2 modules
- show trigger capability in beam

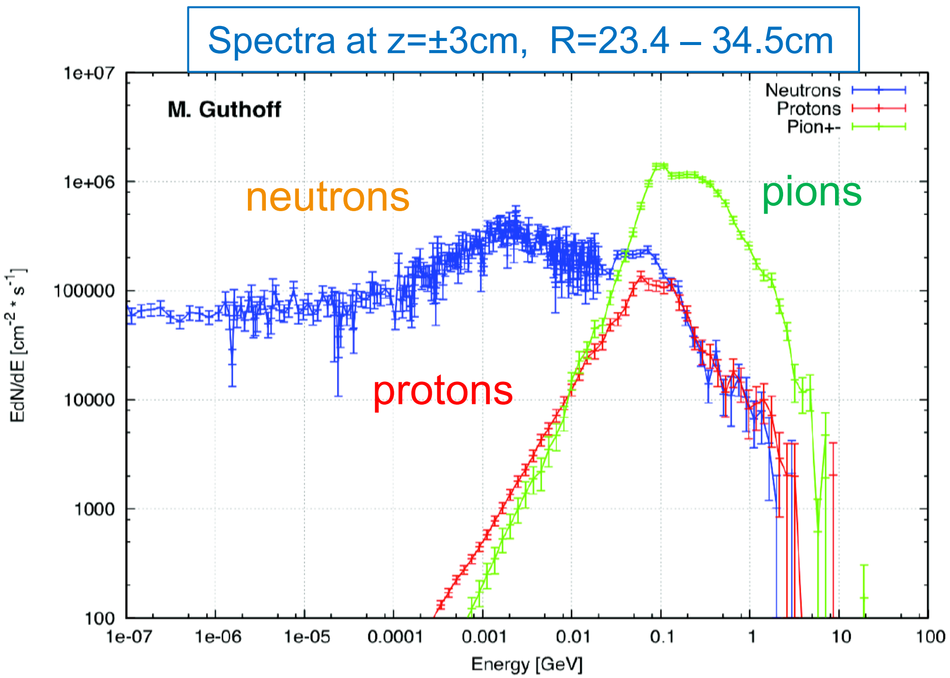
Sensors for the Phase-2 Outer Tracker

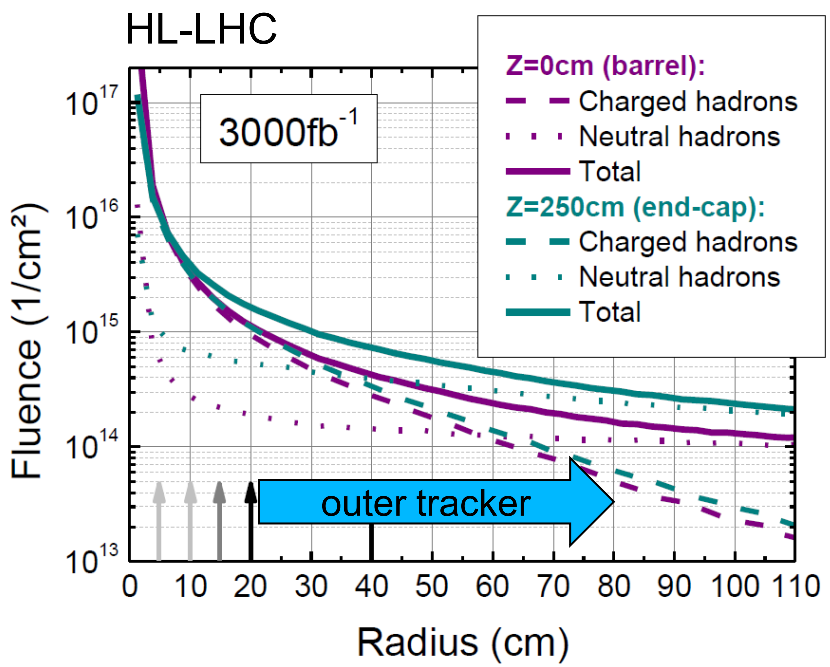
- campaign to identify sensors (material and polarity) for the Phase-2 Outer Tracker
- chose single supplier (HPK) in order to compare sensors from same (or at least similar) processes
- different structures, for example:
  - pad sensors (diodes) for material studies
  - mini-strip sensors for charge collection
  - MSSD sensors to study geometry effects



Irradiations: p, n and mixed

Radius	Protons Φ_{eq} [cm^{-2}]	Neutrons Φ_{eq} [cm^{-2}]	Total Φ_{eq} [cm^{-2}]
40 cm	$3 \cdot 10^{14}$	$4 \cdot 10^{14}$	$7 \cdot 10^{14}$
20 cm	$1 \cdot 10^{15}$	$5 \cdot 10^{14}$	$1.5 \cdot 10^{15}$
15 cm	$1.5 \cdot 10^{15}$	$6 \cdot 10^{14}$	$2.1 \cdot 10^{15}$





Energy of charged hadrons peaks between 100 MeV and 1 GeV

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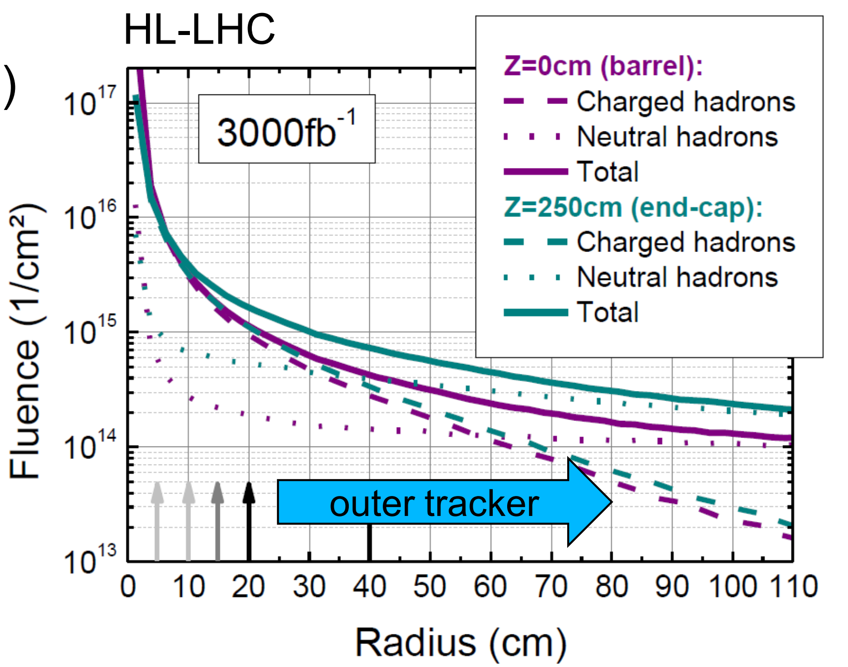
Neutrons: 1 MeV (TRIGA reactor Ljubljana)

Protons: 23 MeV (Karlsruhe cyclotron)

23 GeV (CERN PS)

crosscheck:

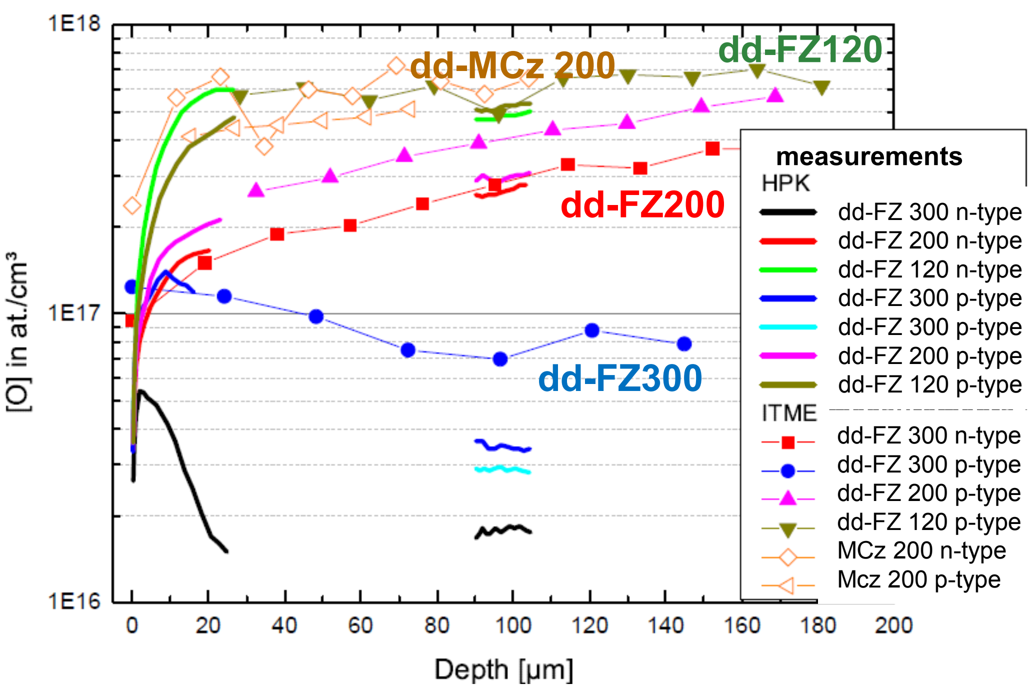
800 MeV (Los Alamos)

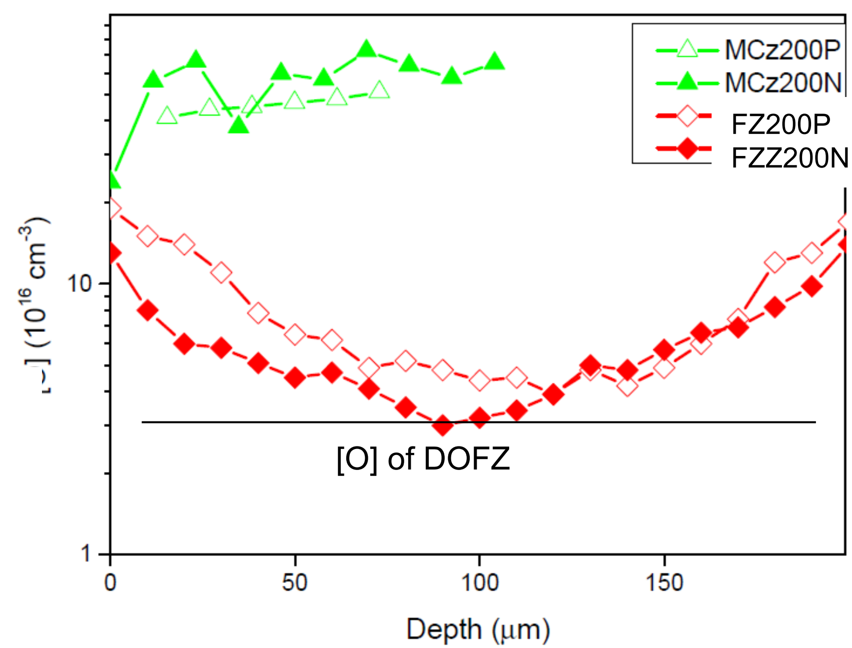


Energy of charged hadrons peaks between 100 MeV and 1 GeV

Materials and their Oxygen Content

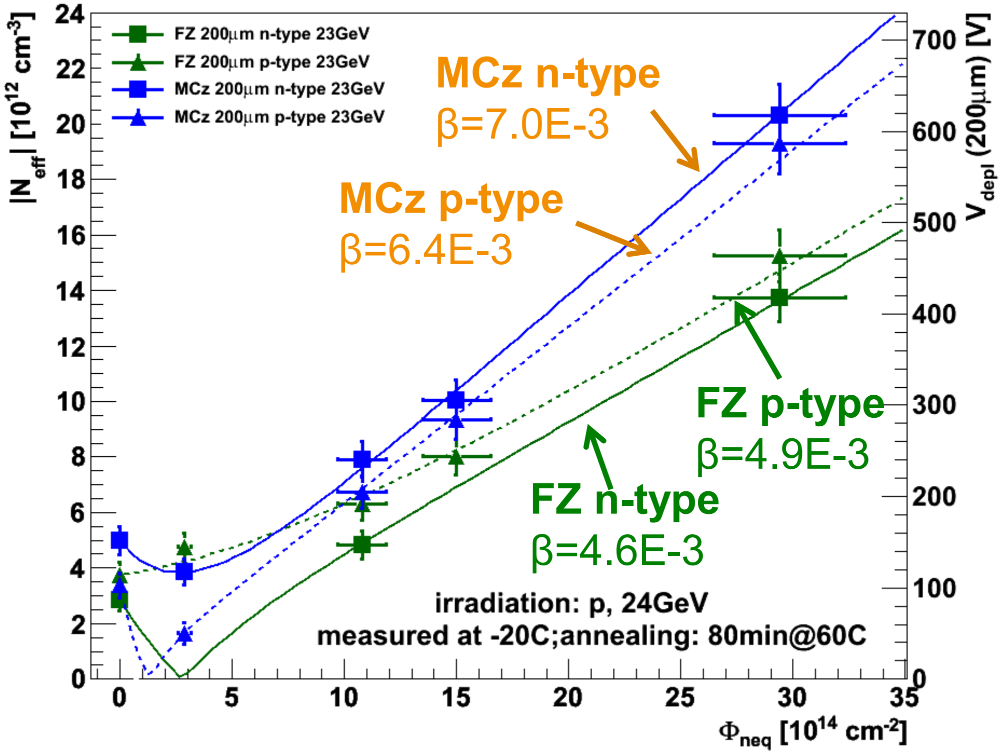
Material	Thinning method	Active thickness [µm]	Wafer thickness [µm]	[O] [10^{17} cm^{-3}]
dd-FZ	deep diffusion	200, 300	320	3, 1
FZ	wafer thinning	200	200	0.5
MCz	---	200	200	4



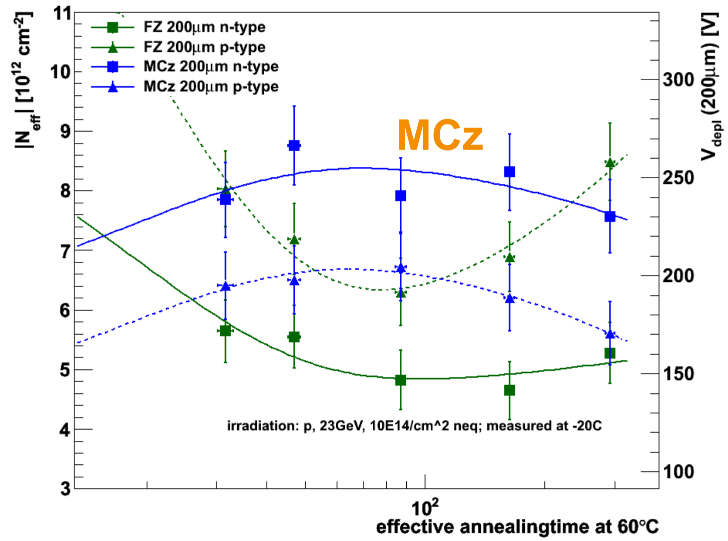


Depletion Voltage after 23 GeV protons

Irradiated with 23 GeV protons (PS)



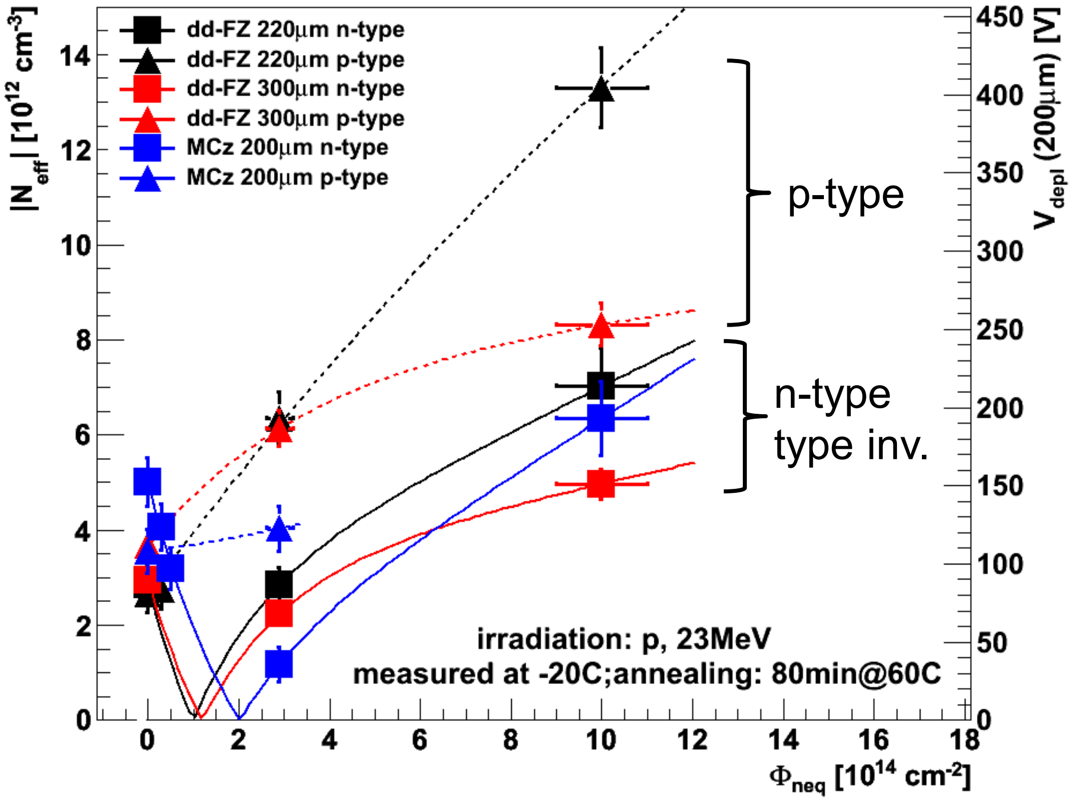
Annealing→Info about type inversion



Type inversion	FZ	MCZ
N-type	yes	no
P-type	no	yes

Depletion voltage below 600V at highest Φ (200µm)
Introduction rate smaller for FZ than for MCz

Depletion Voltage after 23 MeV protons



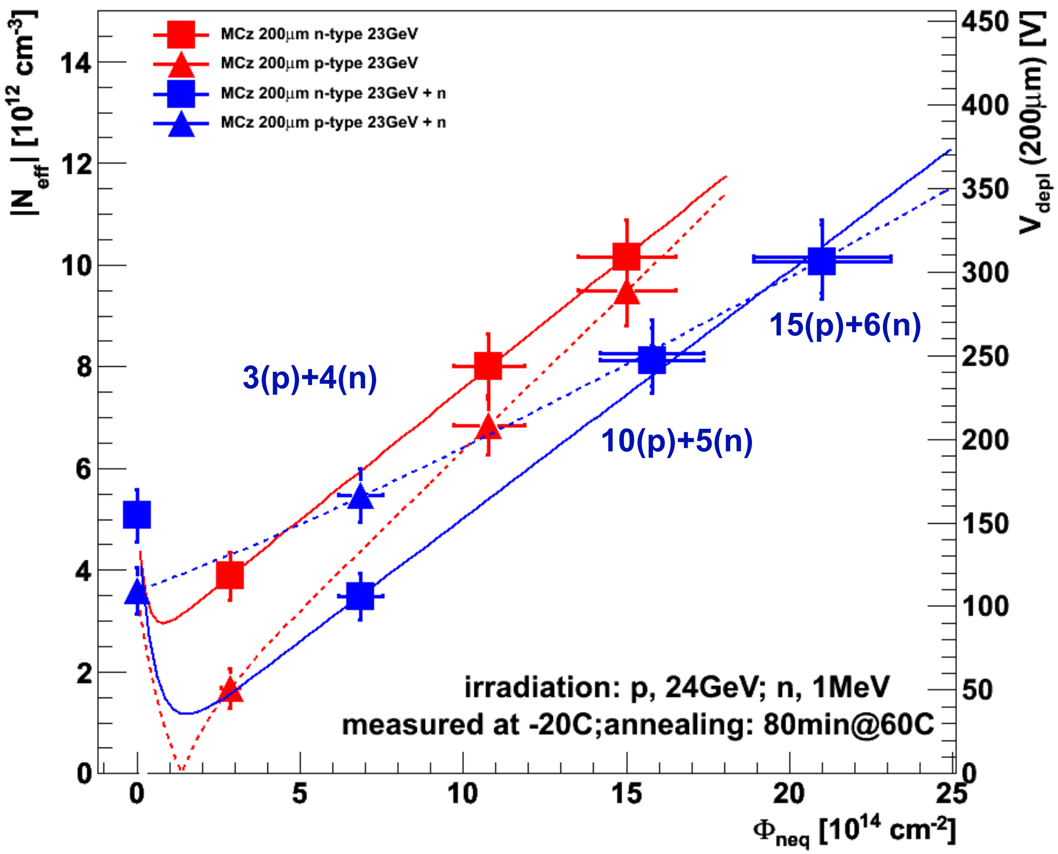
different picture compared to GeV irradiation:

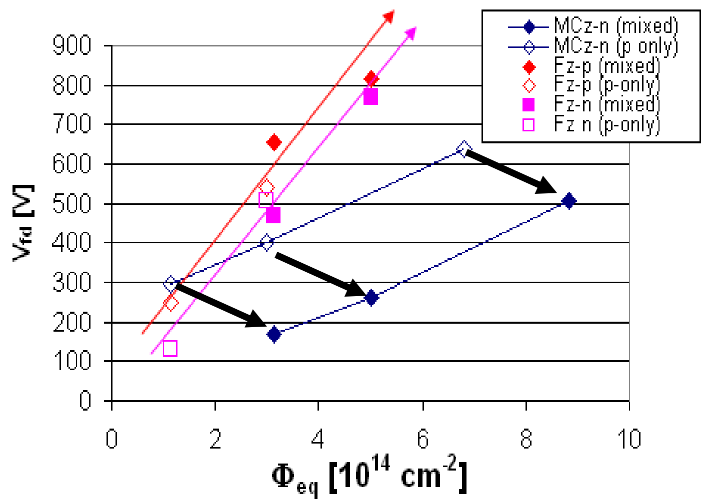
Type inversion	dd-FZ	MCZ
N-type	yes	yes
P-type	no	no

lower depletion voltage for n-type due to type inversion

Compensation in MCz

- compensation effect seen by Kramberger et al. of depletion voltage after mixed (p+n) irradiation in MCz
- not seen in Fz
- attributed to oxygen content



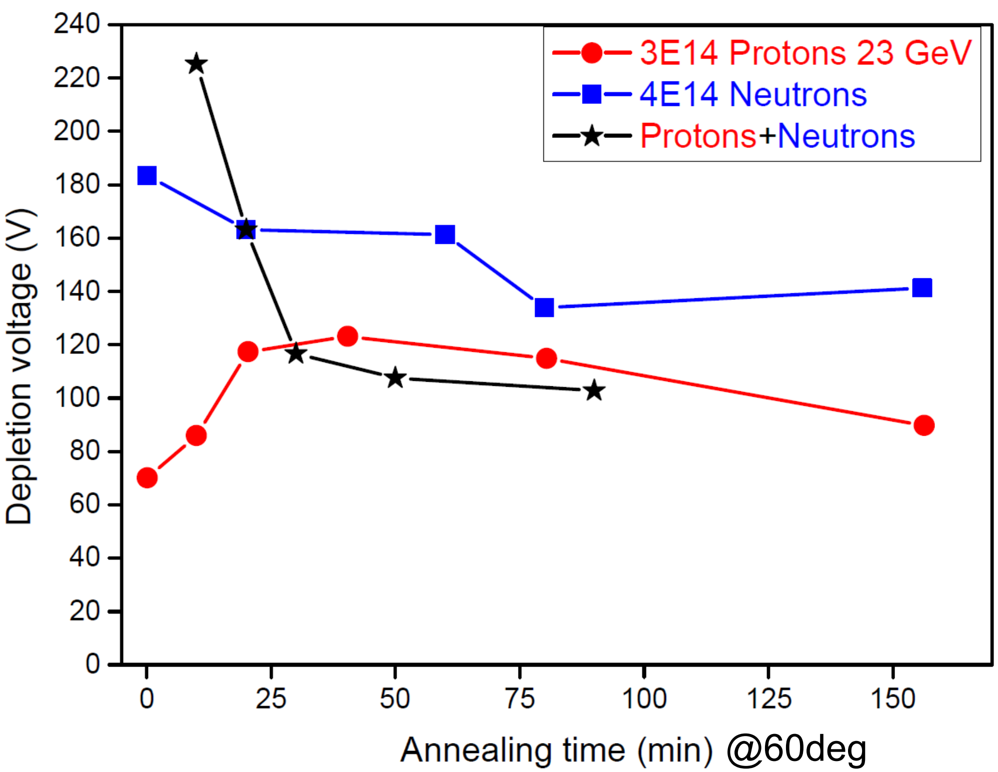


[G. Kramberger et al., NIM A609 (2009), 142-148

➔ Compensation seen in both polarities of MCz

Compensation in n-type MCz - annealing

- 23 GeV p irradiation: n-type annealing →no type inversion
- n irradiation: p-type annealing →type inversion
- mixed: strong drop of depletion voltage

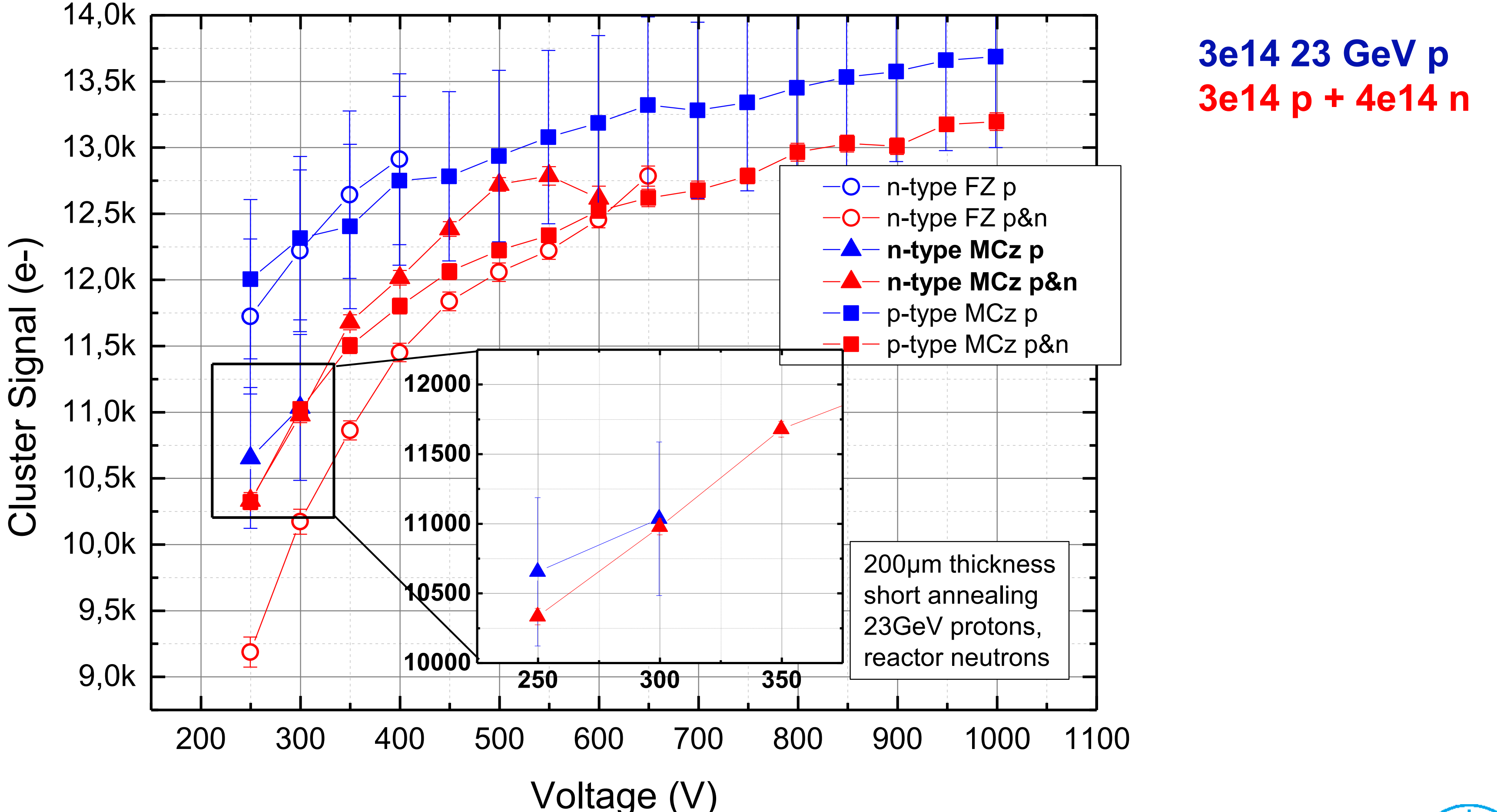


- depletion voltage after mixed irradiation lower than sum of individual depletion voltages

→dramatic annealing effect

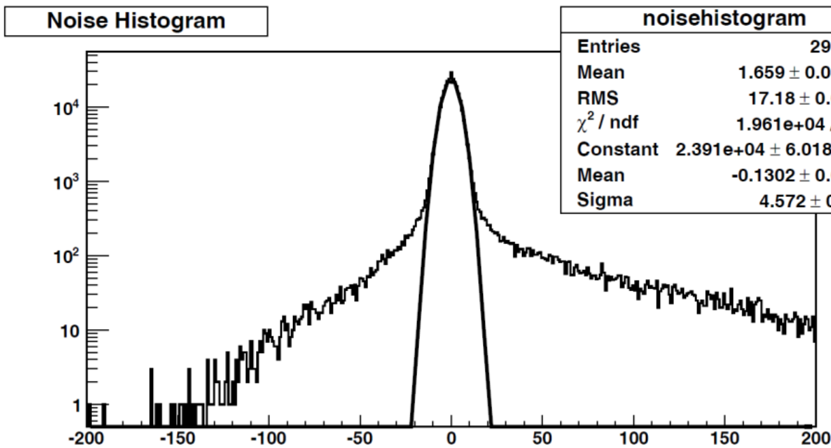
Charge Collection – Compensation in n-MCz?

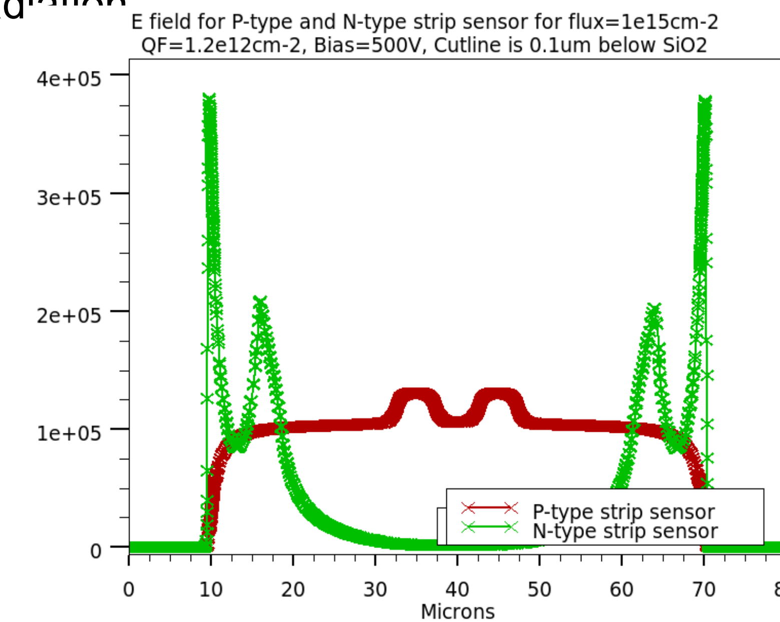
- CC measurements confirm benefit of n-MCz, but measurements only up to 300V (RGHs for p only sample)

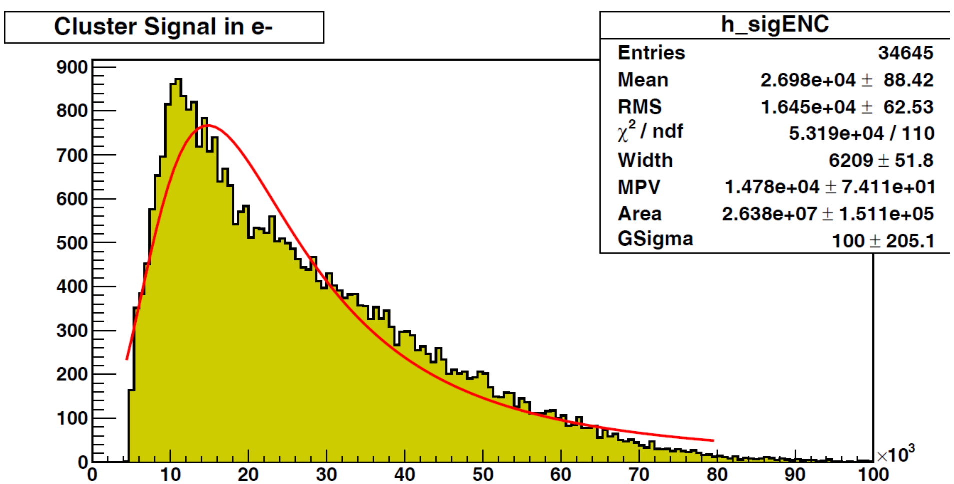


Random Ghost Hits in n-type sensors

- random ghost hits appear after (charged) hadron irradiation
- seen in n-type sensors
- here: FZ 200um thin strip sensor
- sets in at different bias voltages, annealing





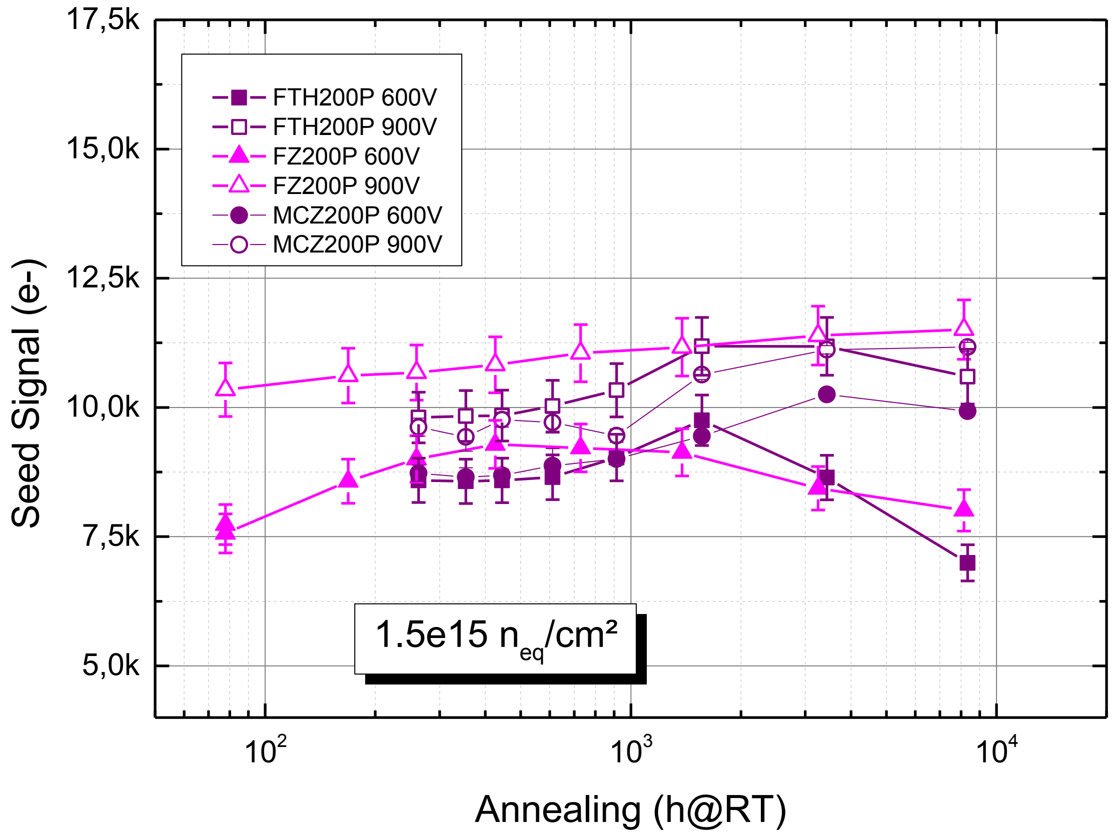


simulations :

Important is the **interplay** between **bulk damage** (traps) and **surface damage** (oxide charge)

P-type: peak E-field decreases with increasing Qf
N-type: peak E-field increases with increasing Qf
➔ higher probability for break-down in n-type

Annealing of seed signal for 1.5e15n_{eq}/cm² p-type



- **thin p-type sensors work well**
- **show seed signals above ~8ke- at 600V until ~ 20w@RT**
- **Annealing scenario with Tracker at RT for 2 weeks each year works**

Choice of sensor polarity for Phase-2 Outer Tracker

- there are only a few measurements for which n-type material shows higher seed signal than p-type
- above $7x10^{14} n_{eq}/cm^2$ random ghost hits appear in n-type material
- this noise feature was studied in detail → **see talk of A. Dierlamm**
  - measurements confirmed by device simulations
  - in n-type material bulk defects and surface charge generate high E-fields close to the implants,

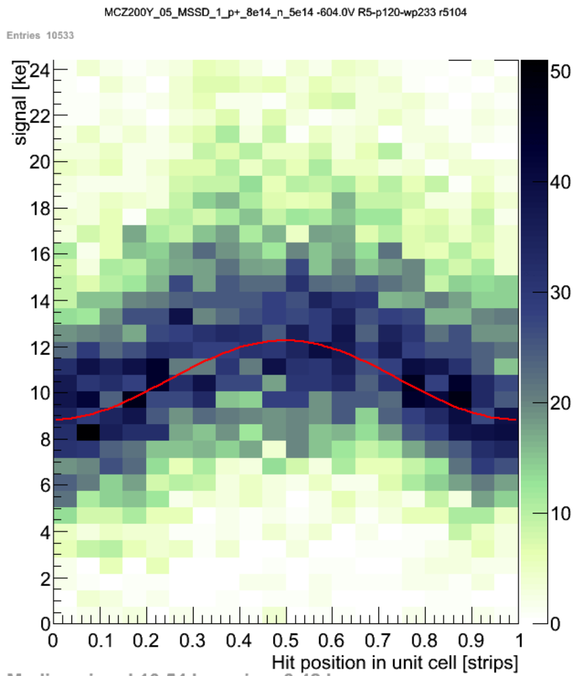
    →generate fake hits under certain conditions
- the 200µm p-type sensors we have in hands would work for the entire Tracker under HL-LHC conditions:
  - no dramatic noise issue
  - flat annealing behavior
  - seed charge > 8ke- @ 600V (~10k@900V) for max. fluence (threshold <~6ke)

➔ **CMS decided to concentrate on p-type material**!

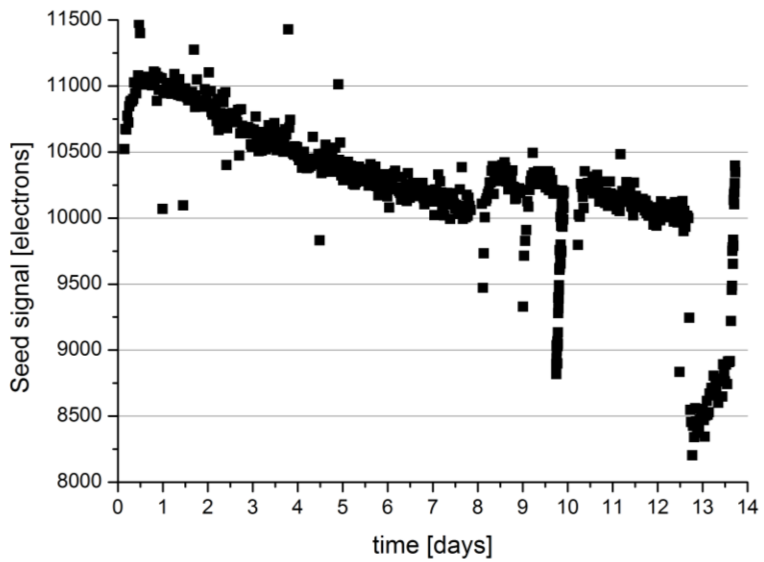
Some Sensor open issues

- study in more detail effect of [O] on p-type
- study signal losses between strips
  - after irradiation to fluences ~1.5x10^{15} all materials and polarities show up to 30% signal loss between strips
  - could possibly be prevented by design (surface effect?)
- long-term studies
  - signal degradation in seed strip, partially due to charge
  - spread into neighbors

MCz p-spray type

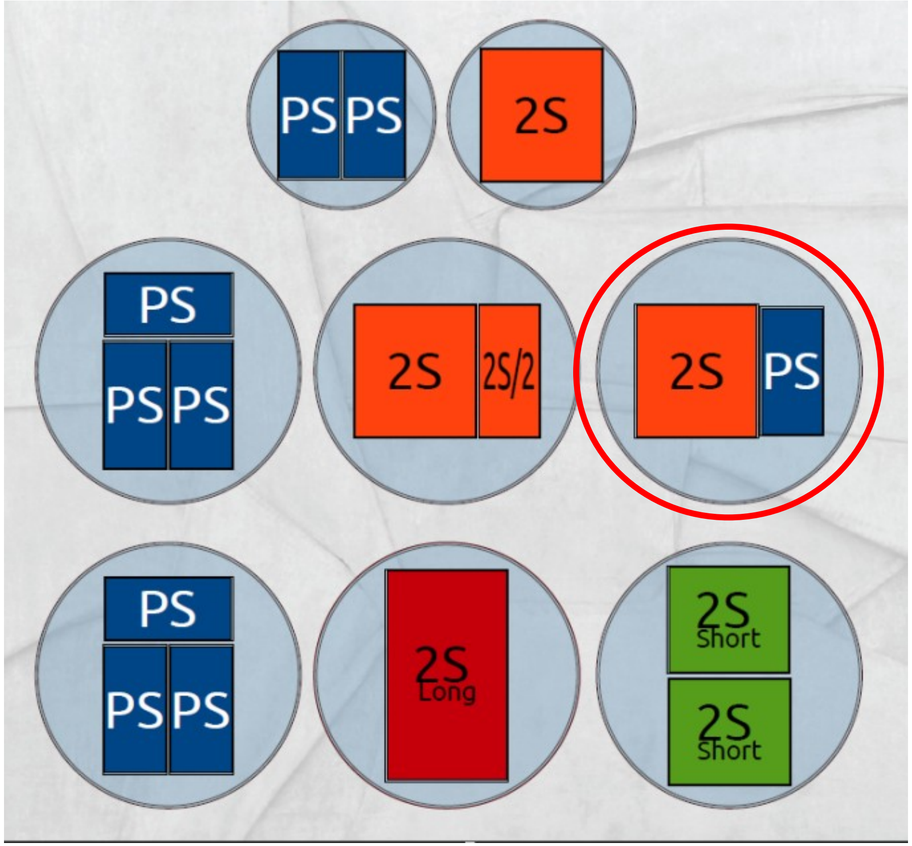


Median signal 10.54 ke swing 3.42 ke



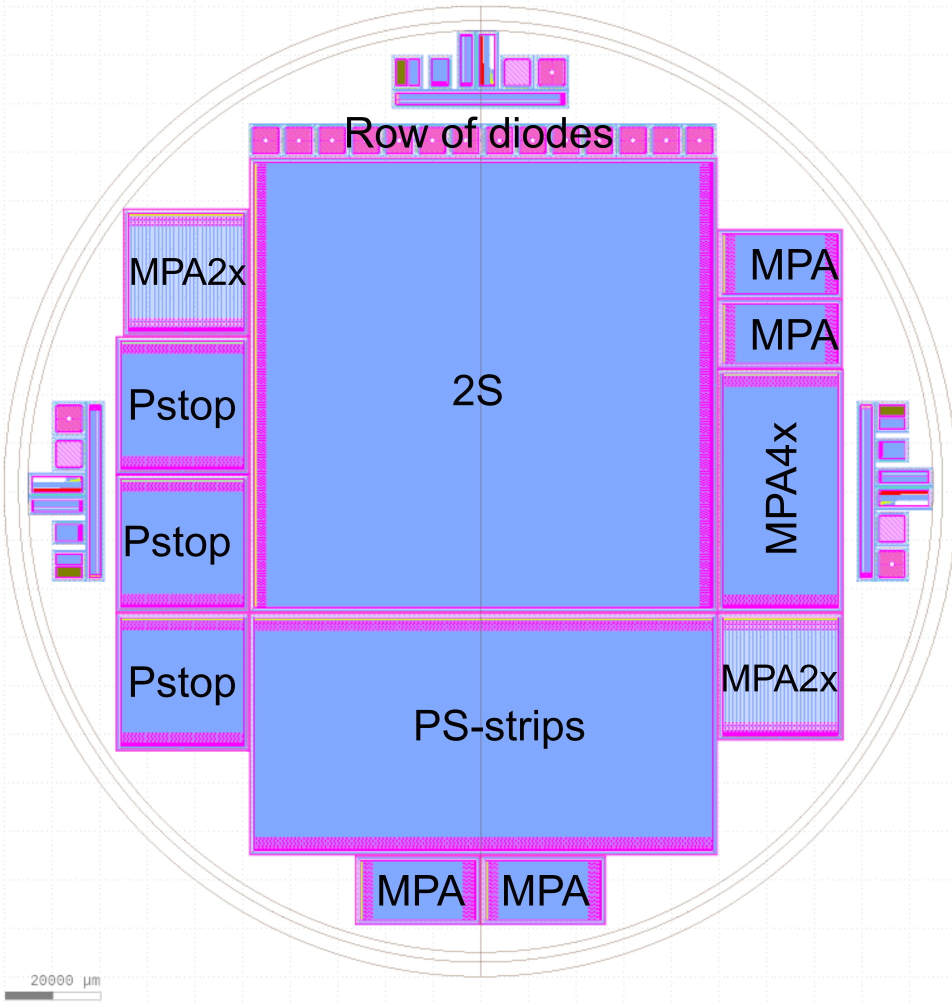
FZ 200um p-spray type
annealed to 156min@60
biased at 1000V

Future Plans: 8“ Sensors



- Following a prototype run with Infineon, a follow-up is proposed with the aim to evaluate the Infineon process on 8“
- Seek compatibility with 6“
  - implies that we do not use 8“ area optimal
  - But better suitable for existing module designs
- Need a layout which is suitable for
  - Building module prototypes (2S and PS)
  - Evaluate 8“ production (n-on-p)
  - P-stop studies

Future Plans: 8“ Sensors



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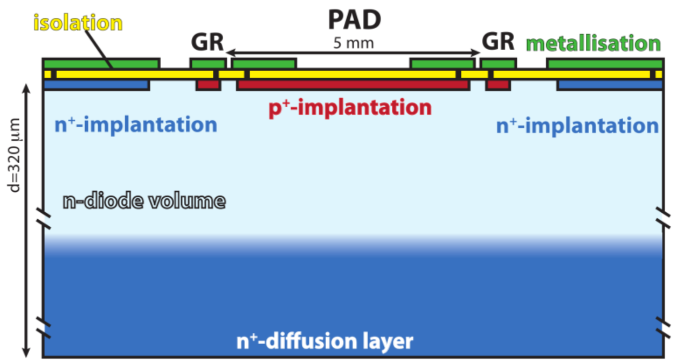
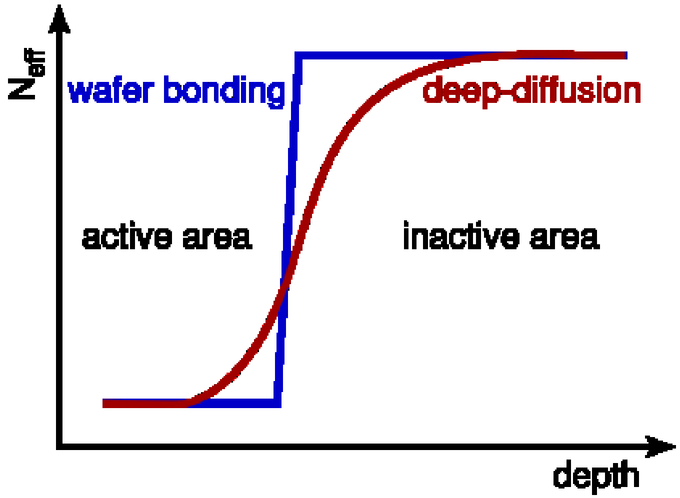
- Need a layout which is suitable for
  - Building module prototypes (2S and PS)
  - Evaluate 8“ production (n-on-p)
  - P-stop studies
- Proposal for 1x2S, 1xPS-strips, several MPA (PS-pixel) sensors, different p-stop layouts

Summary

- The Phase-2 Outer Tracker baseline layout has been chosen
- The 2S module design is well advanced
- Track trigger requirement presents an unprecedented challenge
- Sensor R&D with HPK campaign lead to choice of sensor polarity
- Now concentrating on p-type material for sensor optimization
- Infineon as a possible vendor is being evaluated
- Technical proposal in 2014

> BACKUP


isolation
GR
PAD
5 mm
GR
metallisation
d=320 µm
n+-implantation
p+-implantation
n+-implantation
n-diode volume
n+-diffusion layer


N_eff
wafer bonding
deep-diffusion
active area
inactive area
depth