Preparing for the Future
Upgrades of the CMS Pixel Detector

Benedikt Freund

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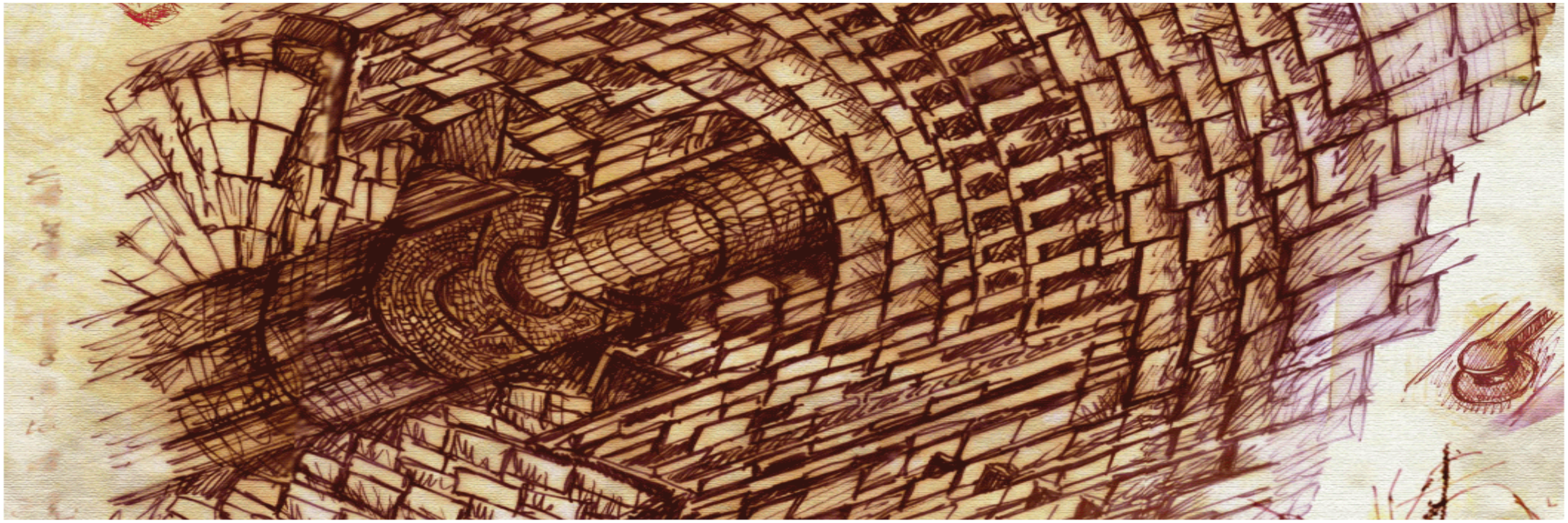
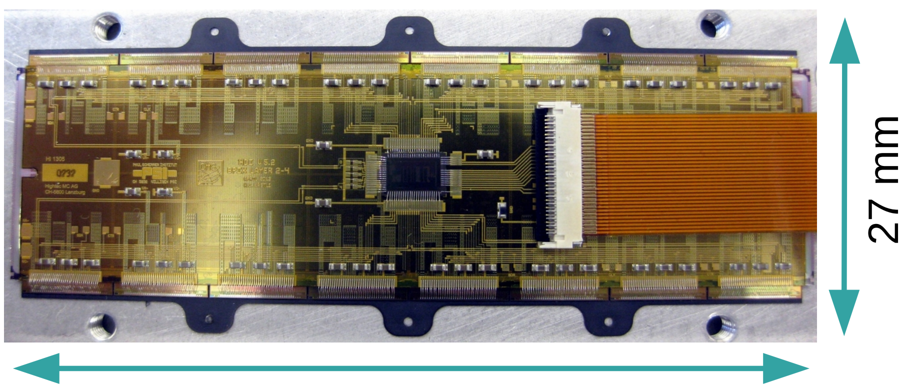
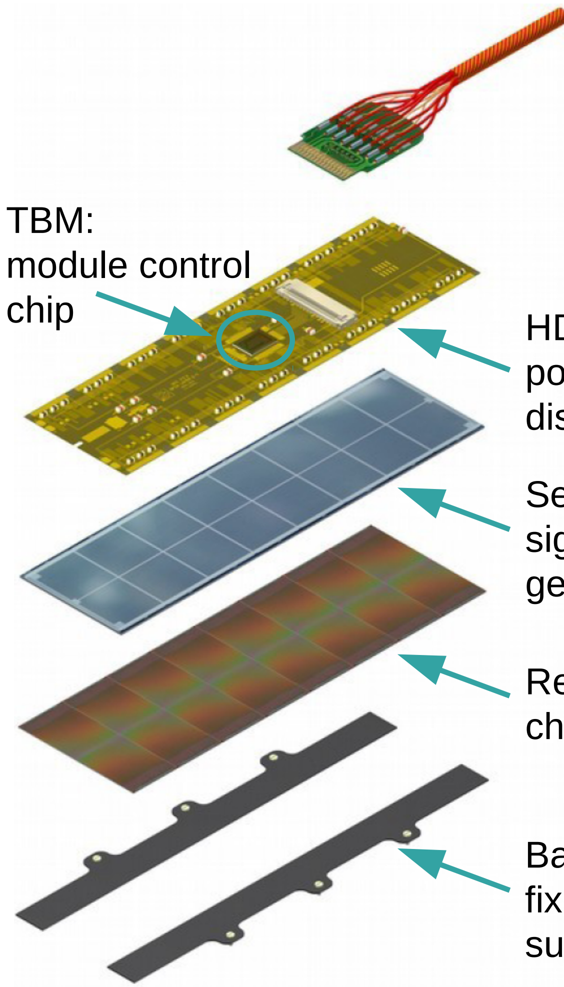


Reminder:
Module Production for the Phase I Upgrade

- Current CMS Pixel Detector will be replaced in early 2017
- KIT produced significant number of detector modules
- Production at KIT finished June 2016
- Link to KSETA Plenary Talk 2016

CMS pixel detector module





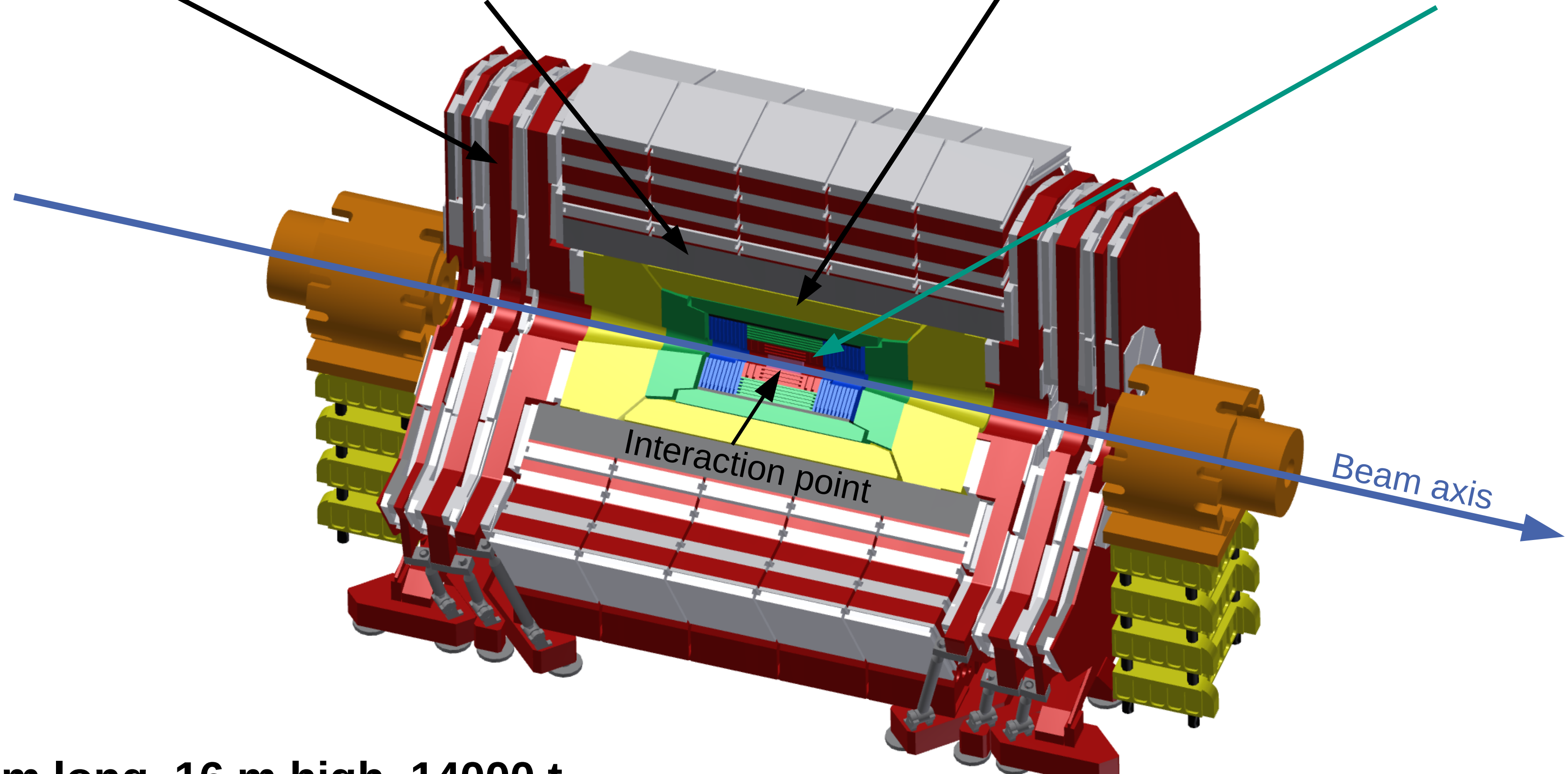
Compact Muon Solenoid (CMS)

Muon detectors
in magnet yoke

Superconducting coil
(3.8 T): Deflection of charged particles

Calorimeters
Determination of energies

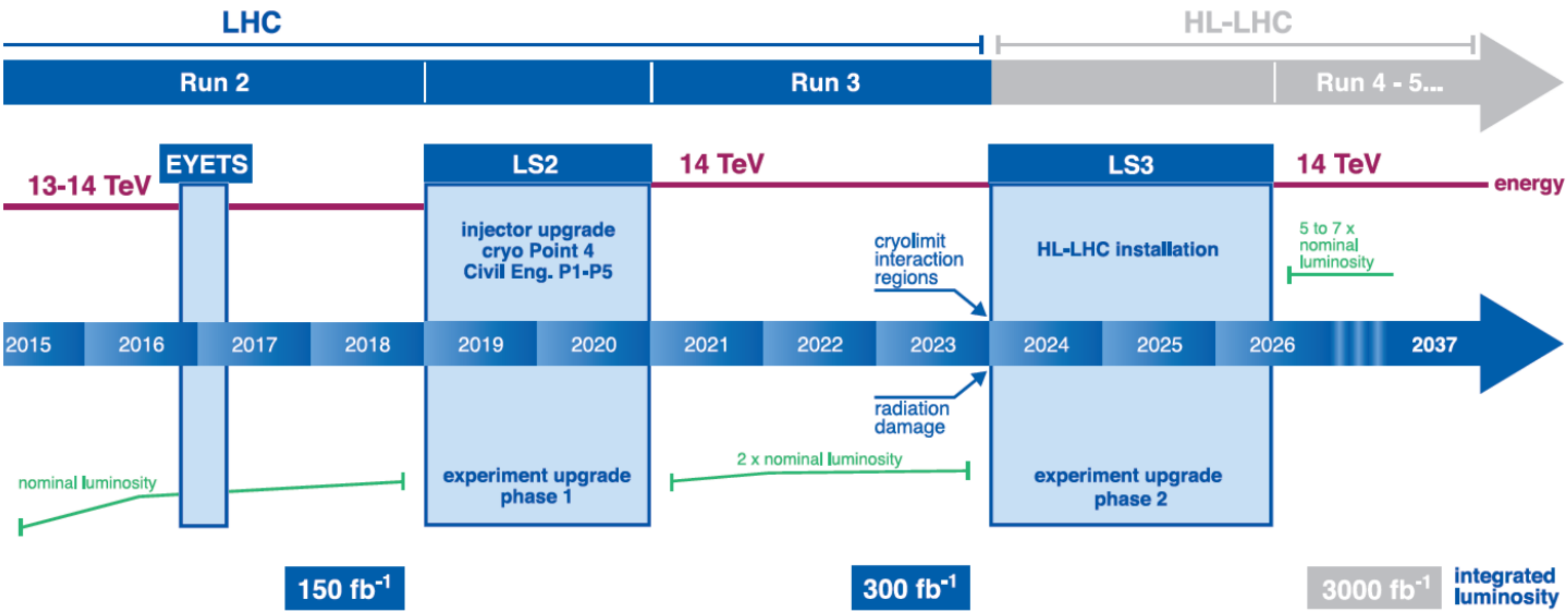
Tracker
Determination of trajectories



21 m long, 16 m high, 14000 t
(ATLAS: 46 m long, 25 m high, 7000 t)

LHC Schedule

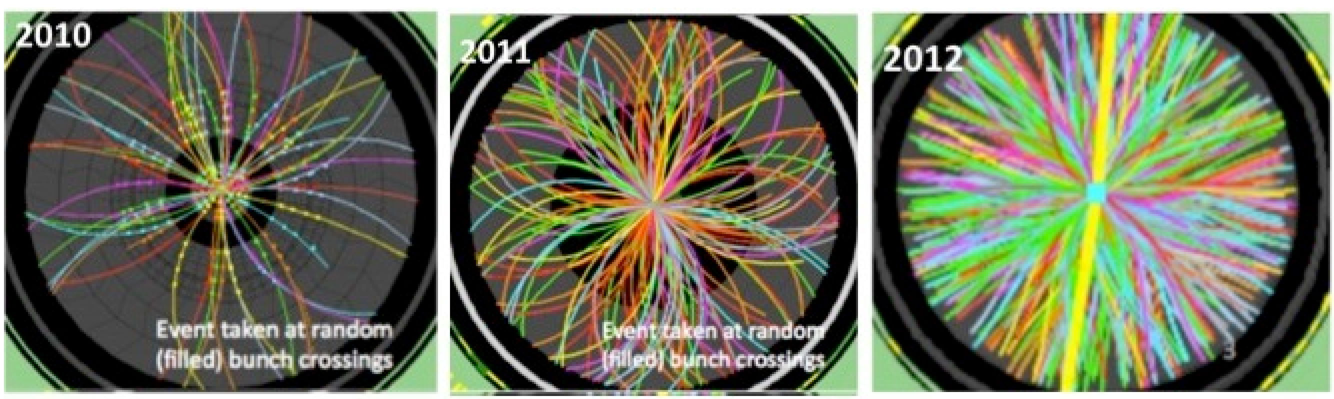
- Future for LHC:



- Two upgrades planned for CMS:
  - Phase 1: Replacement of **pixel detector**, new readout for calorimeters, …
  - Phase 2: Replacement of **complete silicon tracker**, new L1 trigger system, new forward calorimeters, extension of muon system, …

Why the CMS tracker needs to be upgraded?

- LHC luminosity will be increased successively which in turn leads to an increased number of collisions per bunch crossing
- Phase I Upgrade (2 × design luminosity - 2016/17)
  - New readout chip with larger on-chip buffers and faster readout to avoid data loss
- Phase II Upgrade (5-7 × design luminosity - 2022/23)
  - Higher granularity (smaller pixels) to compensate higher track density
  - New sensors and readout chips with higher radiation tolerance



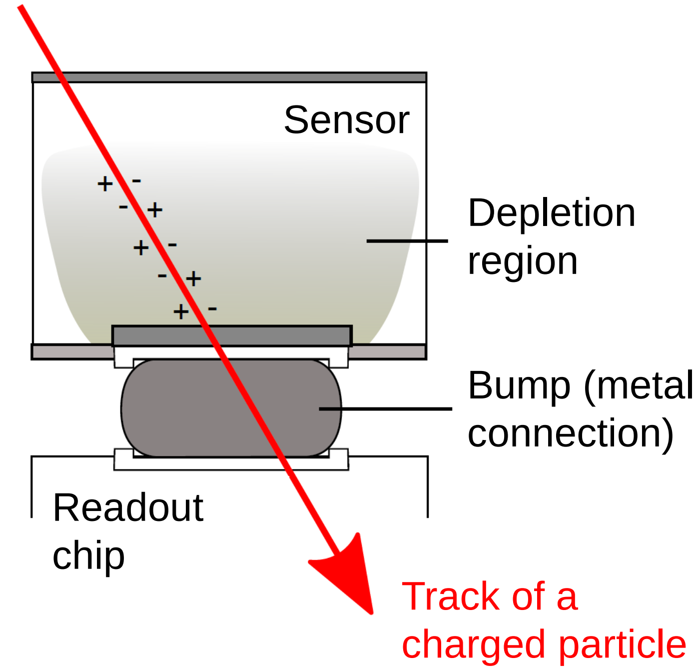
Semiconductor Detectors

- 10^9 free charge carriers in a standard silicon sensor used in high enery physiscs

- Only 2×10^4 electrons are generated by a charged particle
  - ~70 electron-hole pairs per µm silicon
  - Signal would be lost in the amount of free charge carriers
  - Free charge carriers need to be removed to identify charged particles traversing the detector

- Working principle: diode
  → exploit depletion region of pn junction which is extended by reverse biasing

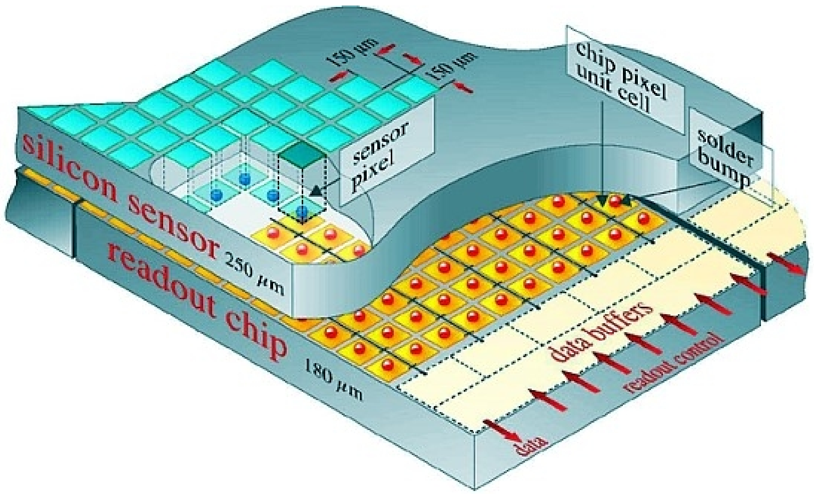
cross section of a single pixel



CMS Pixel Detector

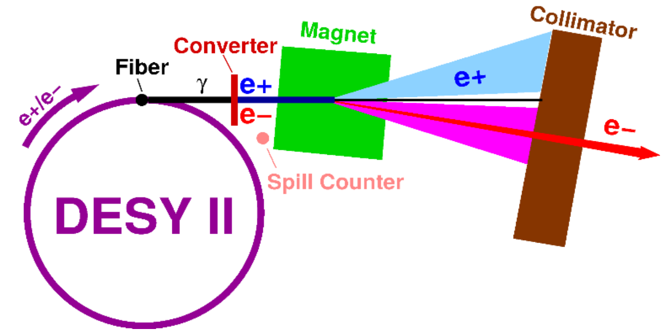
- Pixel array with 80 rows × 52 columns = 4160 pixels (pn junctions) in total
- Pixel size: 150 µm × 100 µm
- Each pixel (sensor side) has its own readout channel
- Test samples to investigate the performance of the next CMS pixel detector (for 2017) and for R&D on its successor (for 2024)

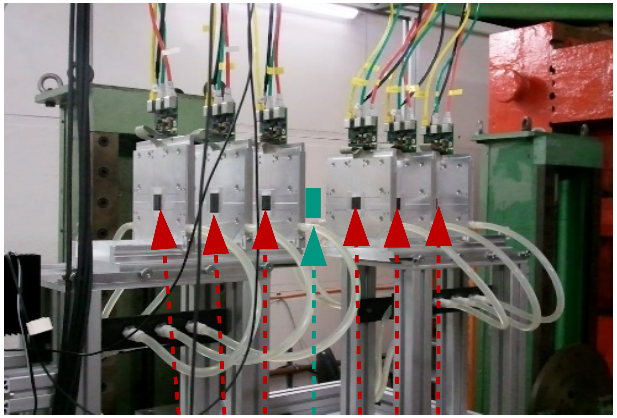
cross section of a pixel detector



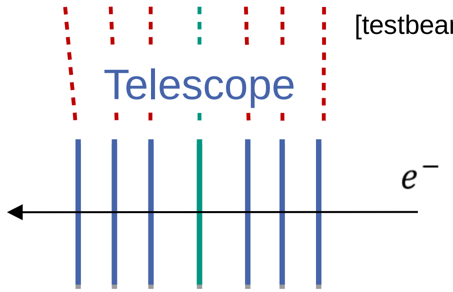
Test Beam Measurements

- Energy of electron test beam at DESY is sufficiently high, so particles penetrate several detector layers
- Telescope with 6 detector planes to reconstruct tracks of electrons
- Tracks are extrapolated to (tiltable) Device Under Test (DUT)
- To be measured:
  - Charge collection efficiency
  - Tracking eff. $= \dfrac{\textit{Tracks with DUT entry}}{\textit{Telescope Tracks through DUT}}$
  - Charge cluster size
  - Hit resolution





[testbeam.desy.de]



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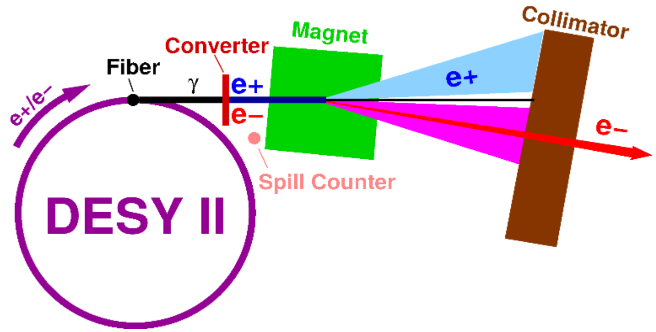

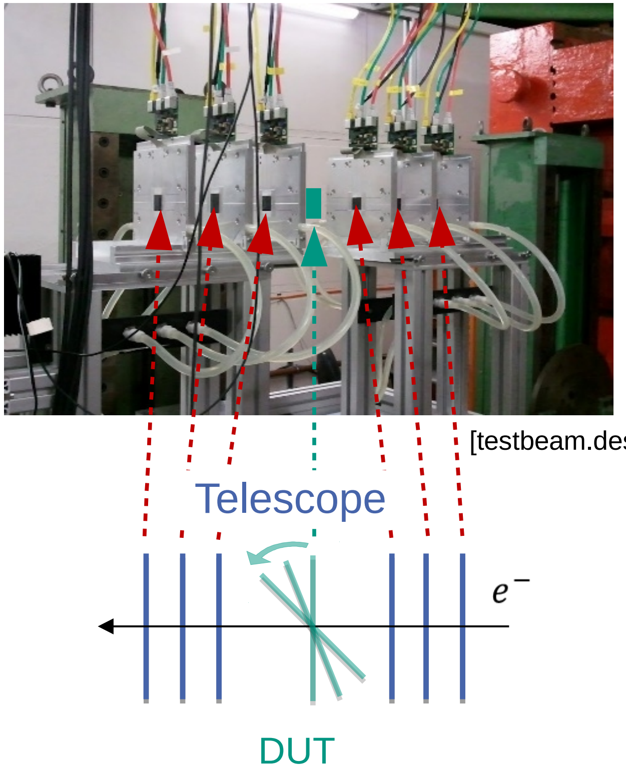

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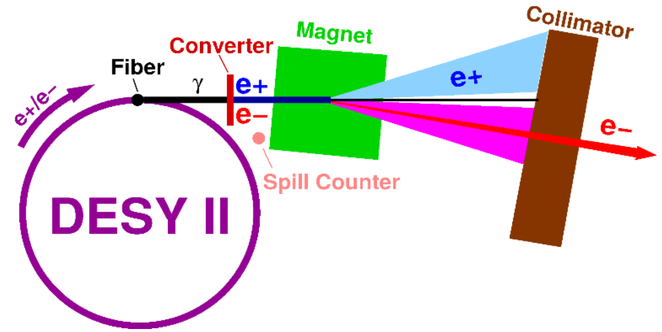

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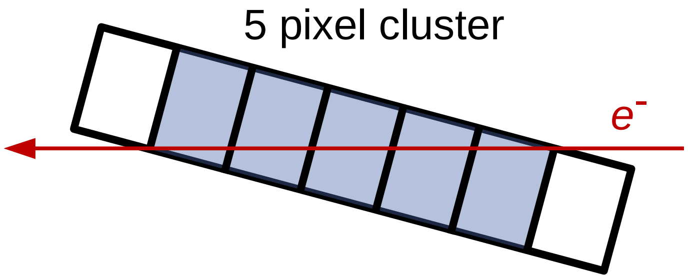
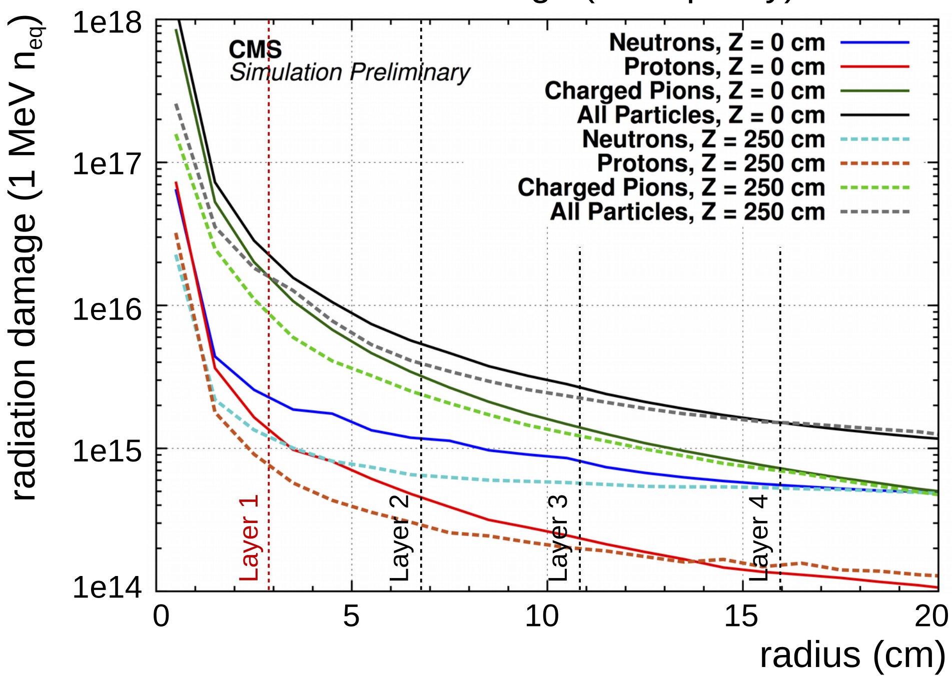


Phase I Upgrade

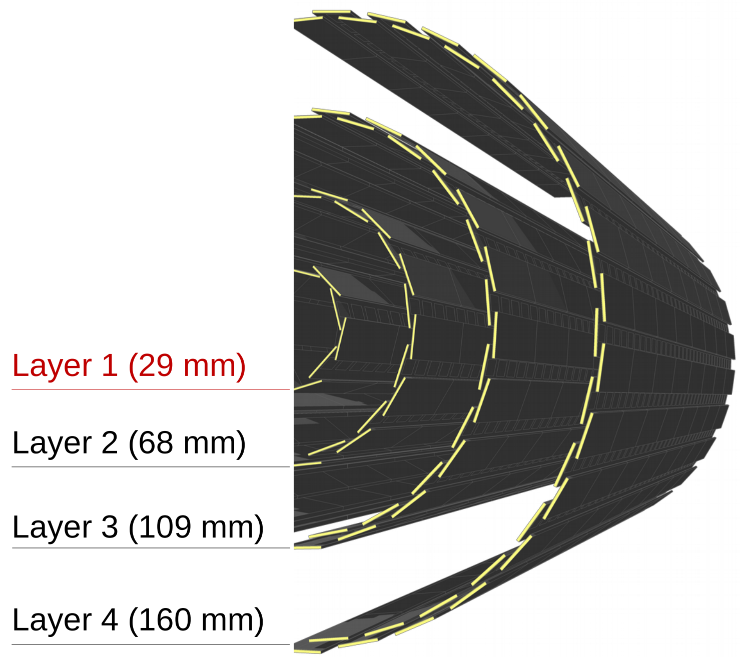
Irradiation

- Samples are irradiated (at Zyklotron AG KIT CN) to final radiation dose expected in 2022
  - Different values for each layer of the pixel detector
  - The CMS pixel detector is the subdetector which suffers most from radiation damage

radiation damage (exemplarily)

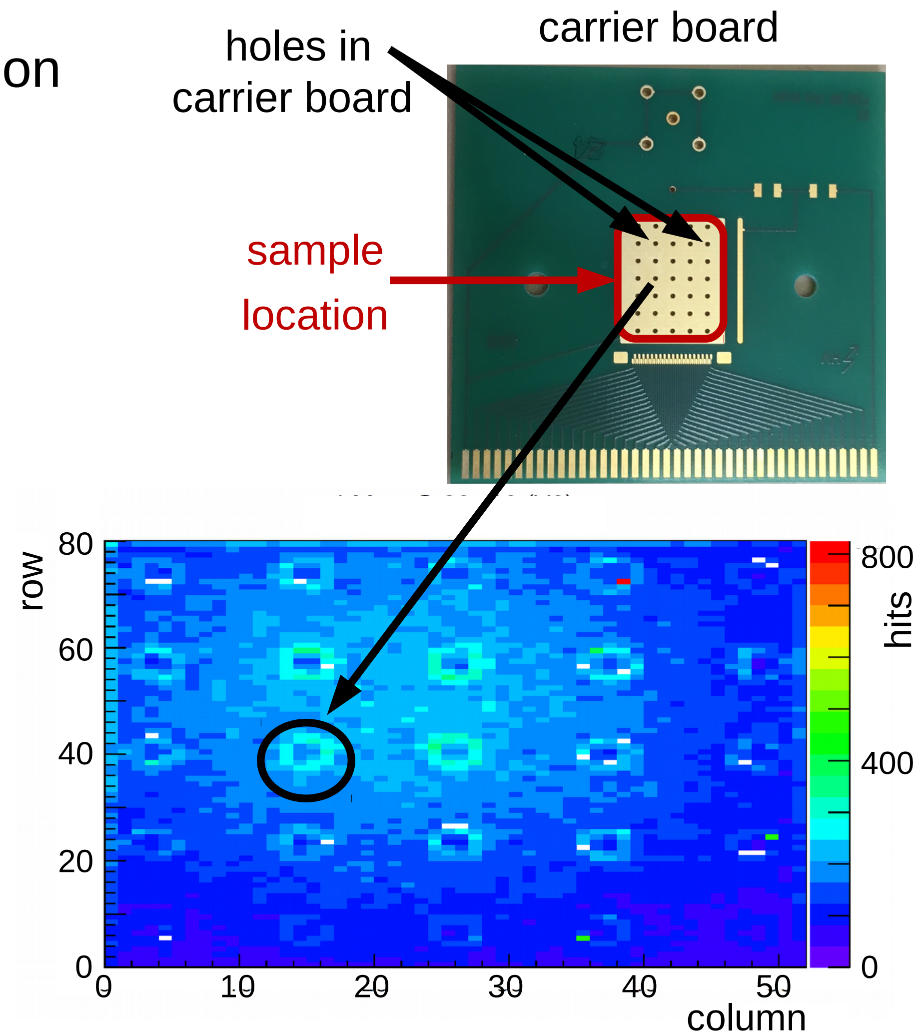


CMS Pixel Detector (barrel region)



Irradiation

- Unexpected feature due to carrier board related effect during irradiation
- Different radiation dose at areas where the carrier board has holes
- Hitmaps show more hits at holes
- Take into account for analysis
  - Analysis with and without these areas



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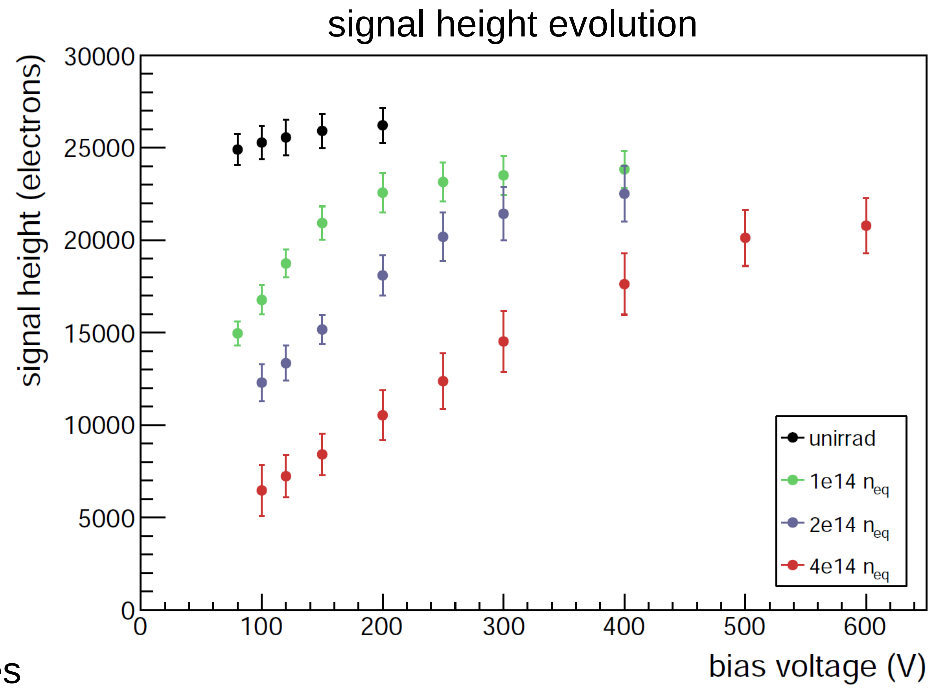
Charge Collection Efficiency

- Signal height (lab measurement) decreases due to radiation damage
  - Additional energy levels are created within the energy band structure because of radiation damage, some of them can trap electrons
  - Increasing the bias voltage recovers the signal partially

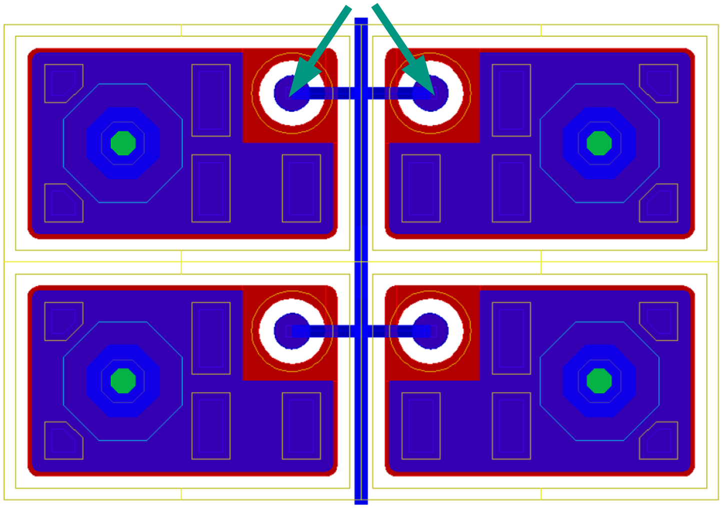


Reminder:
A charged particle creates
~70 electron-hole pairs per µm silicon

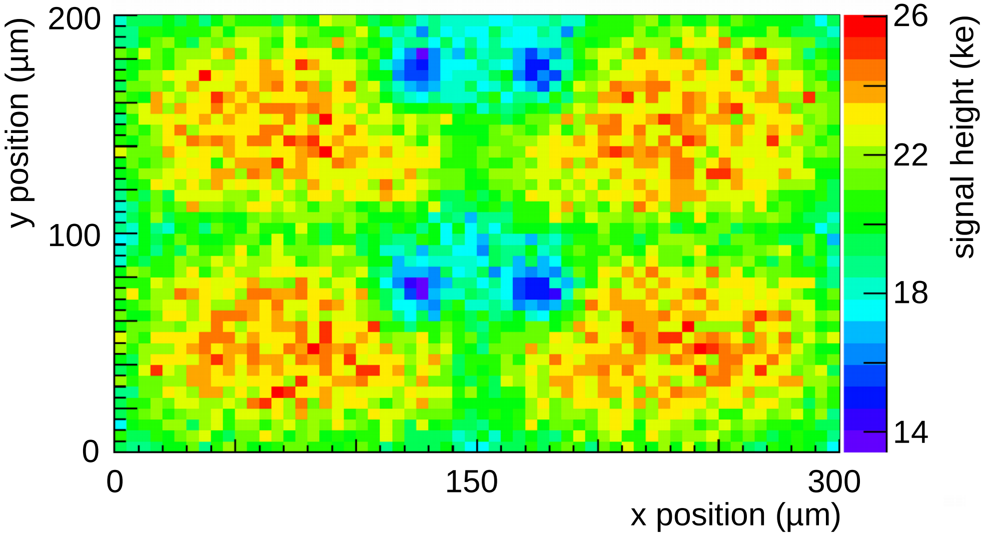
Charge Collection Efficiency

- Signal height (test beam) also depends on region where charged particles traverse the sensor
- Less efficient region due to geometry (e.g. “bias dot”)

less efficient region due to bias dot (2x2 pixel)



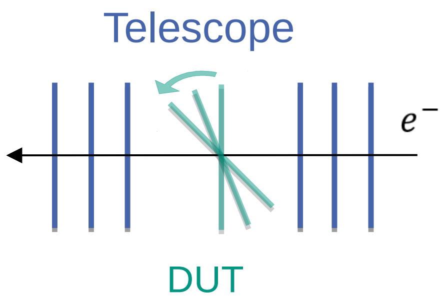
Signal height of seed pixel (2x2 pixel)

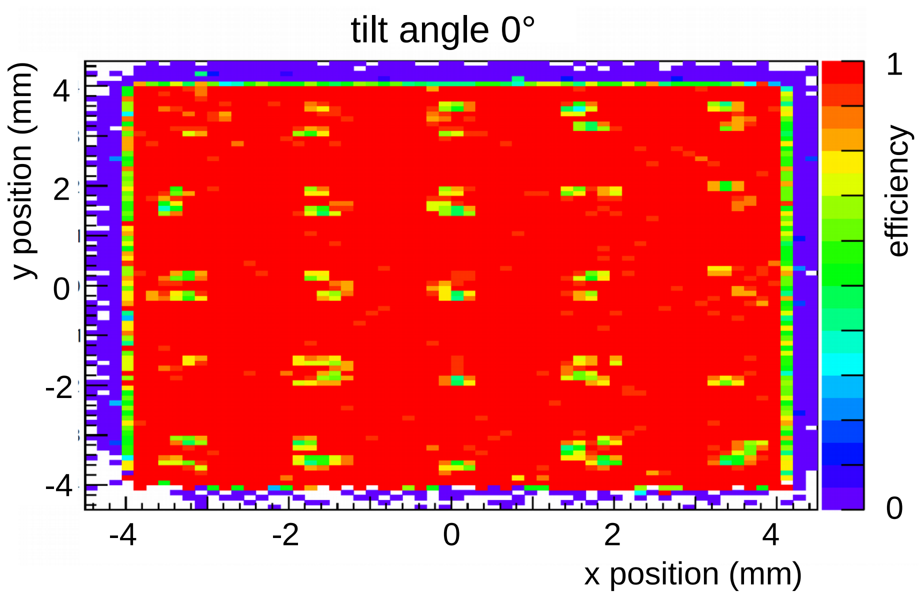


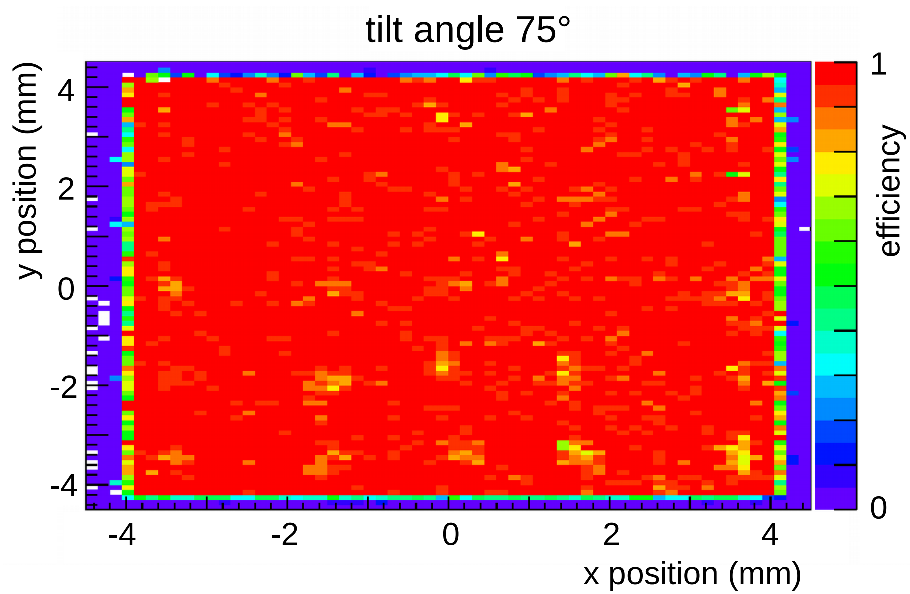
Note: If a particle deposits charge in more then one pixel, the pixel with the highest signal is the seed pixel of this cluster

Tracking Efficiency

- Tracking efficiency (test beam) drops in “hole regions”
- Impact of these regions reduced at higher tilt angles due to multiple pixel clusters
  - a single missing pixel does not cause an ineffiency







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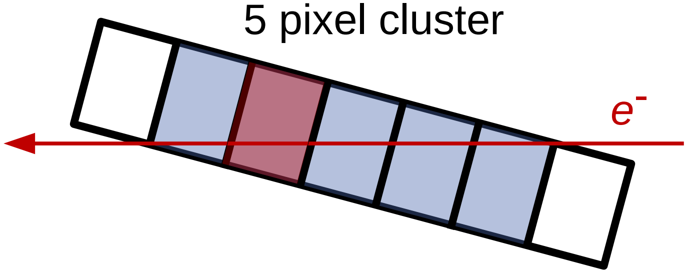

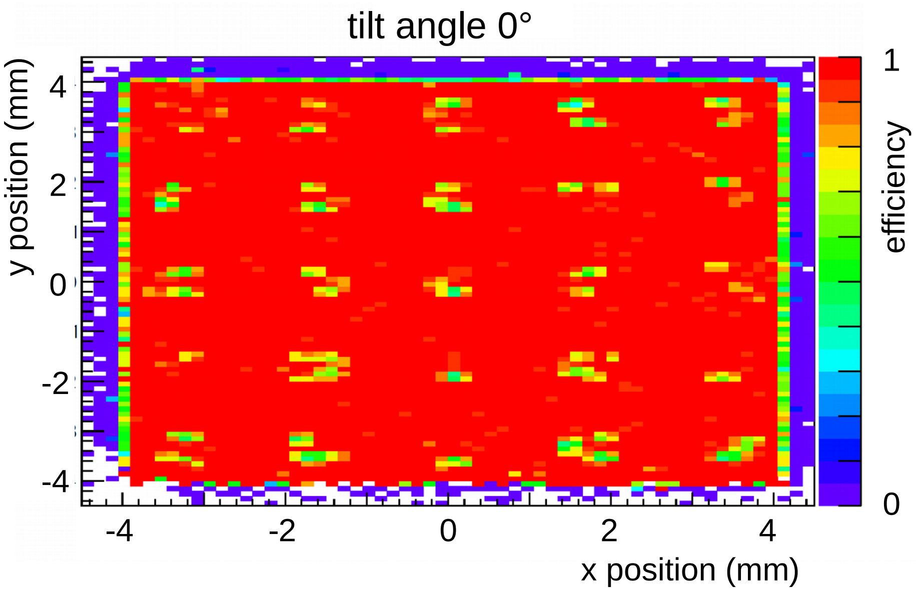

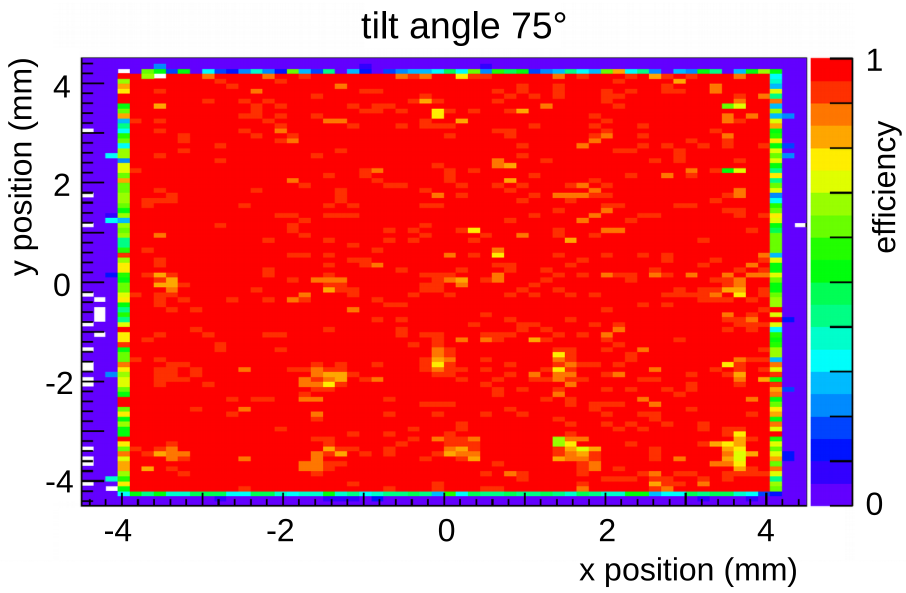

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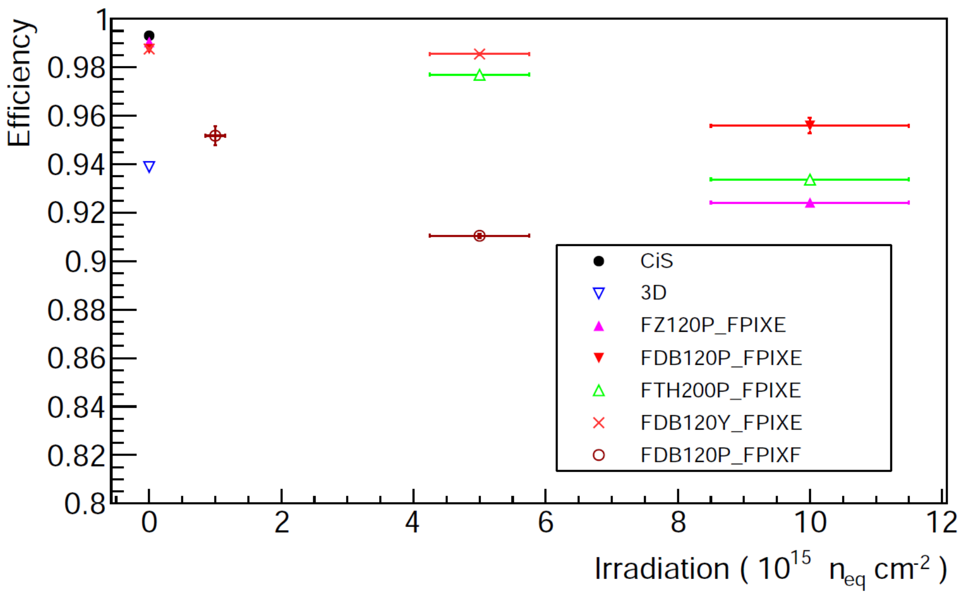
Tracking Efficiency

- Compare tracking efficiency (test beam) for different irradiation doses / angles / voltages / thresholds
  - Threshold determines the amount of electrons required to detect a hit
- Example (below): tracking efficiency over irradiation dose for different sensor technologies

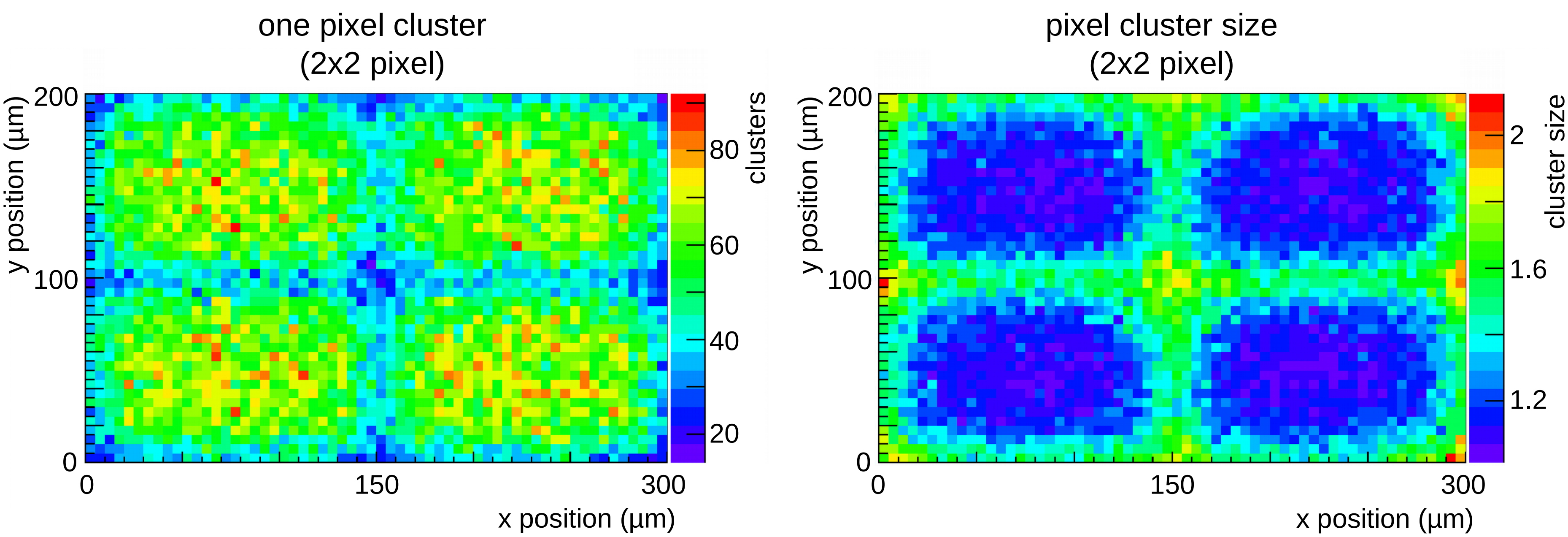
test beam results of former study



Daniel Schell (master thesis)

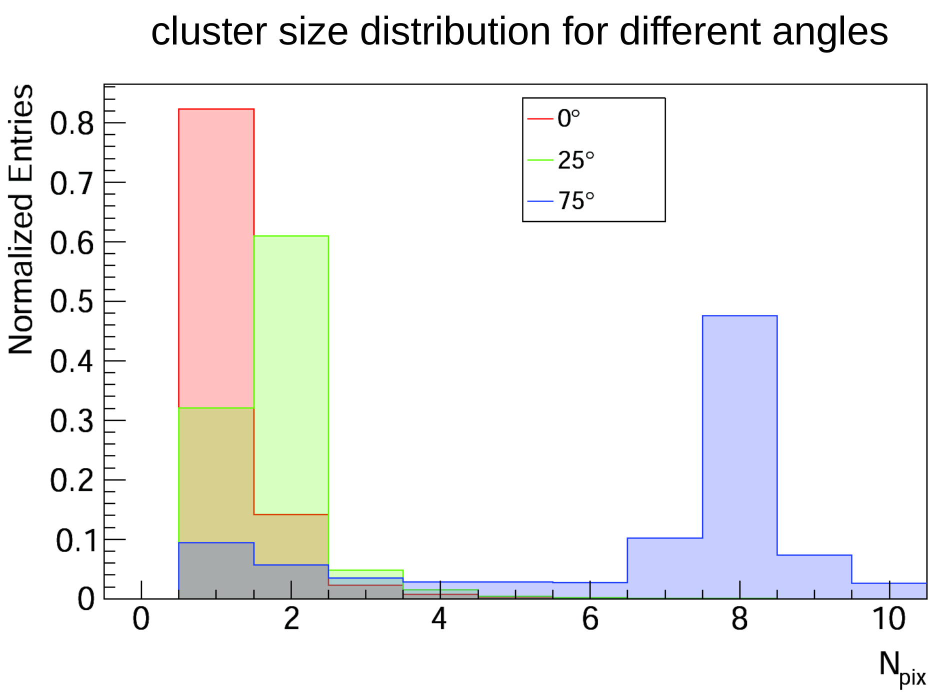
Charge Cluster Size

- Charge cluster size (test beam) depends on penetration point
  - One pixel clusters are most likely if the particle hits the sensor in the pixel center
  - Between pixels the cluster size increases, especially at pixel corners



Charge Cluster Size / Hit Resolution

- Detectors which exploit charge sharing have an improved resolution by calculating the charge center of multiple pixel clusters
- Possible drawback: bigger clusters lead to more data which needs to be processed by the readout chip



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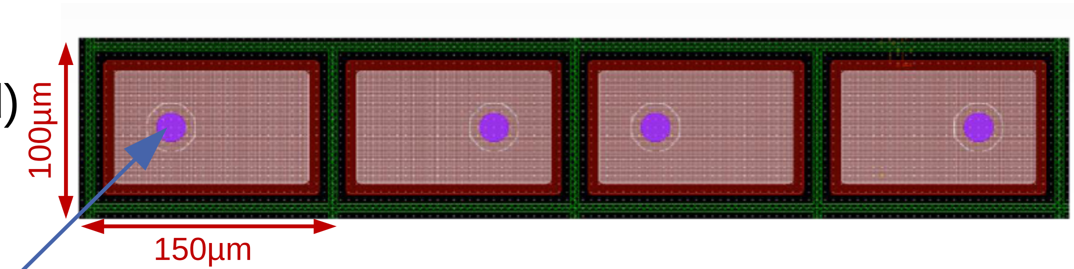
Phase II Upgrade

New Sensor Designs

- New readout chips required to investigate sensors with smaller pixels
  - New readout chips available end of this year
    - Meanwhile: use available readout chips and “intermediate” sensor designs

- “Intermediate” sensors
  - 100µm × 150µm (standard)



Bump connection
to readout chip

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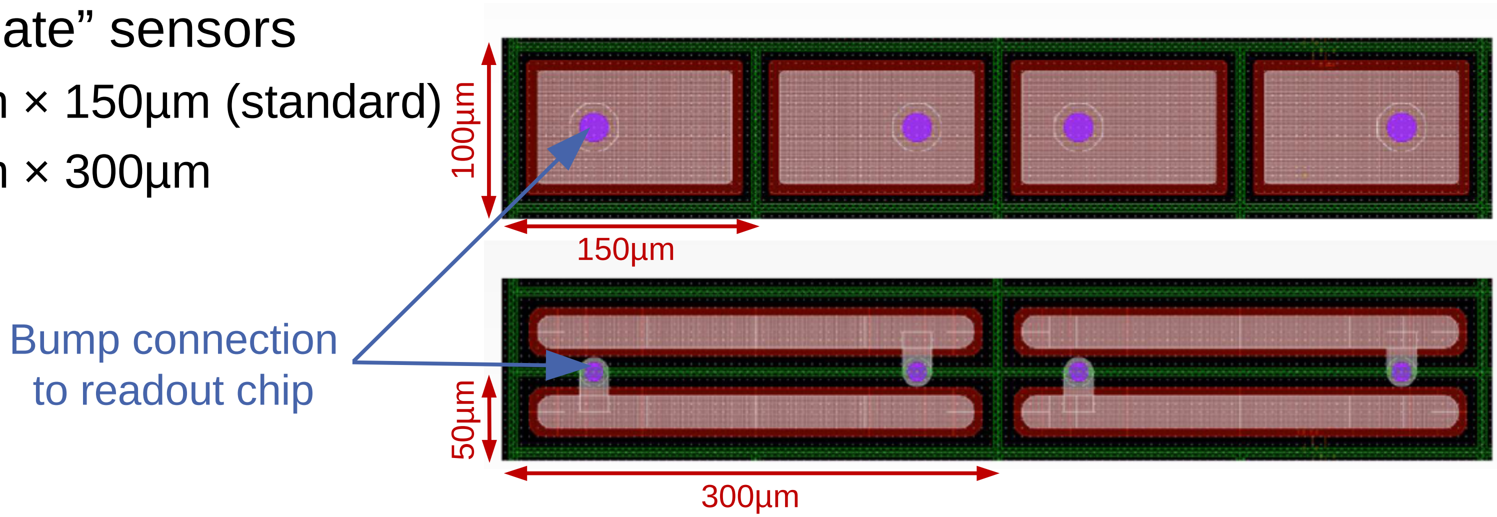
- “Intermediate” sensors
  - 100µm × 150µm (standard)
  - 50µm × 300µm



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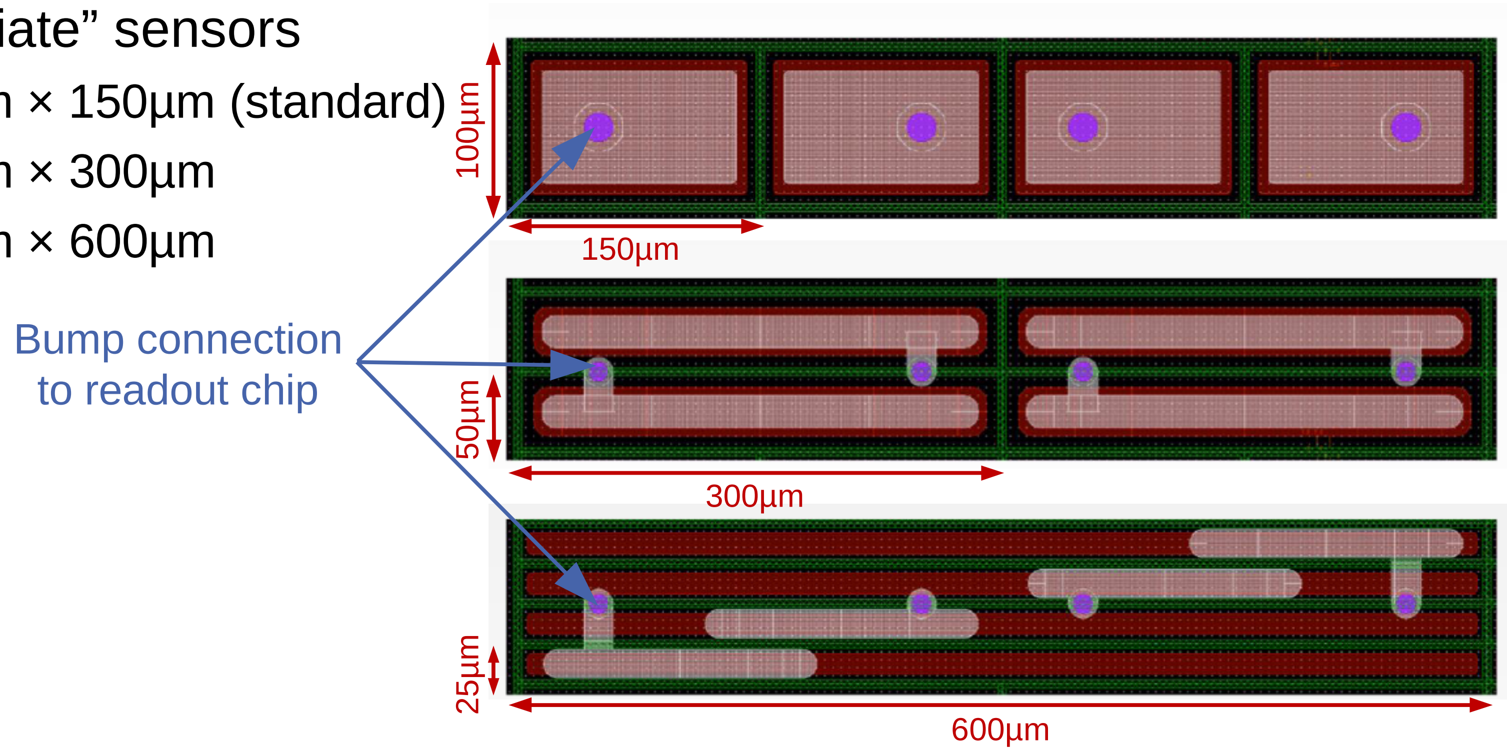

Summary

- LHC luminosity will be increasing in the coming years
  - Two upgrades for CMS to cope with harsher environment
- Phase I Upgrade
  - Test beam to investigate "lifetime-performance" of new CMS Pixel Detector done, data analysis next
    - Charge collection efficiency
    - Tracking efficiency
    - Charge cluster size
    - Hit resolution
- Phase II Upgrade
  - Additional test beam measurements to evaluate new sensor designs
    - Investigate same criteria as for Phase I Upgrade but smaller pixels

Thank you.