Semiconductor Detectors for CERN Experiments (SeDeCE)

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Introduction

- Semiconductor detectors are widely used in high-energy physics (HEP) experiments, different space applications and medical imaging.
- Silicon pixel and micro-strip detectors provide excellent spatial resolution while being cost-effective due to well-established semiconductor manufacturing technology.
- However, the luminosity of the LHC accelerator will significantly increase in the coming years and consequently, radiation induced defects will severely affect the silicon sensor performance, especially in the innermost layers of the experiments.

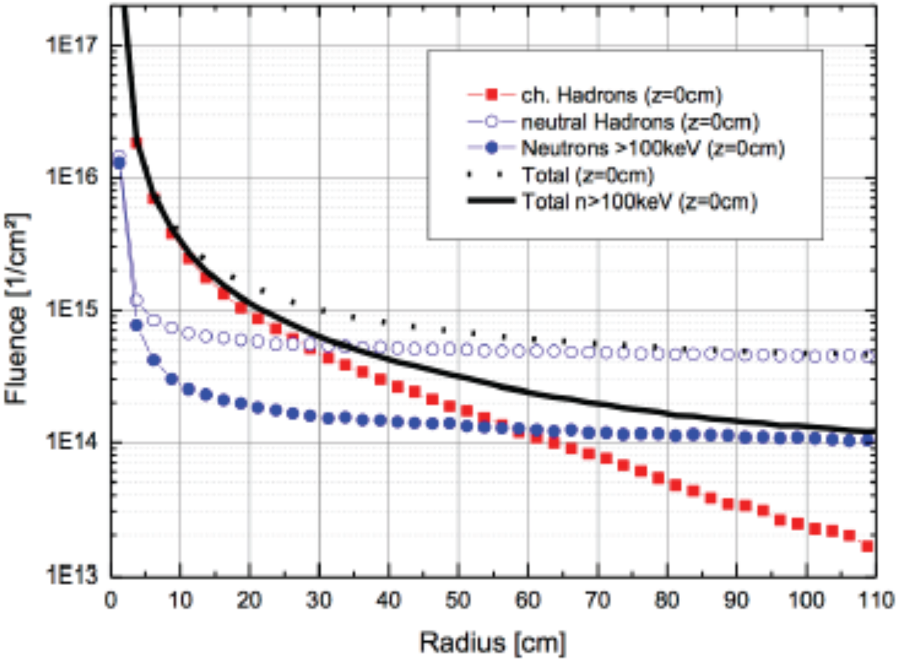
High Luminosity LHC (HL-LHC)

LHC upgrade to High Luminosity LHC:

Luminosity of LHC: $L \sim 10^{34}$ $cm^{-2}s^{-1}$
and fluence of fast hadrons
at r=4cm ~ $3 \cdot 10^{15} cm^{-2}$

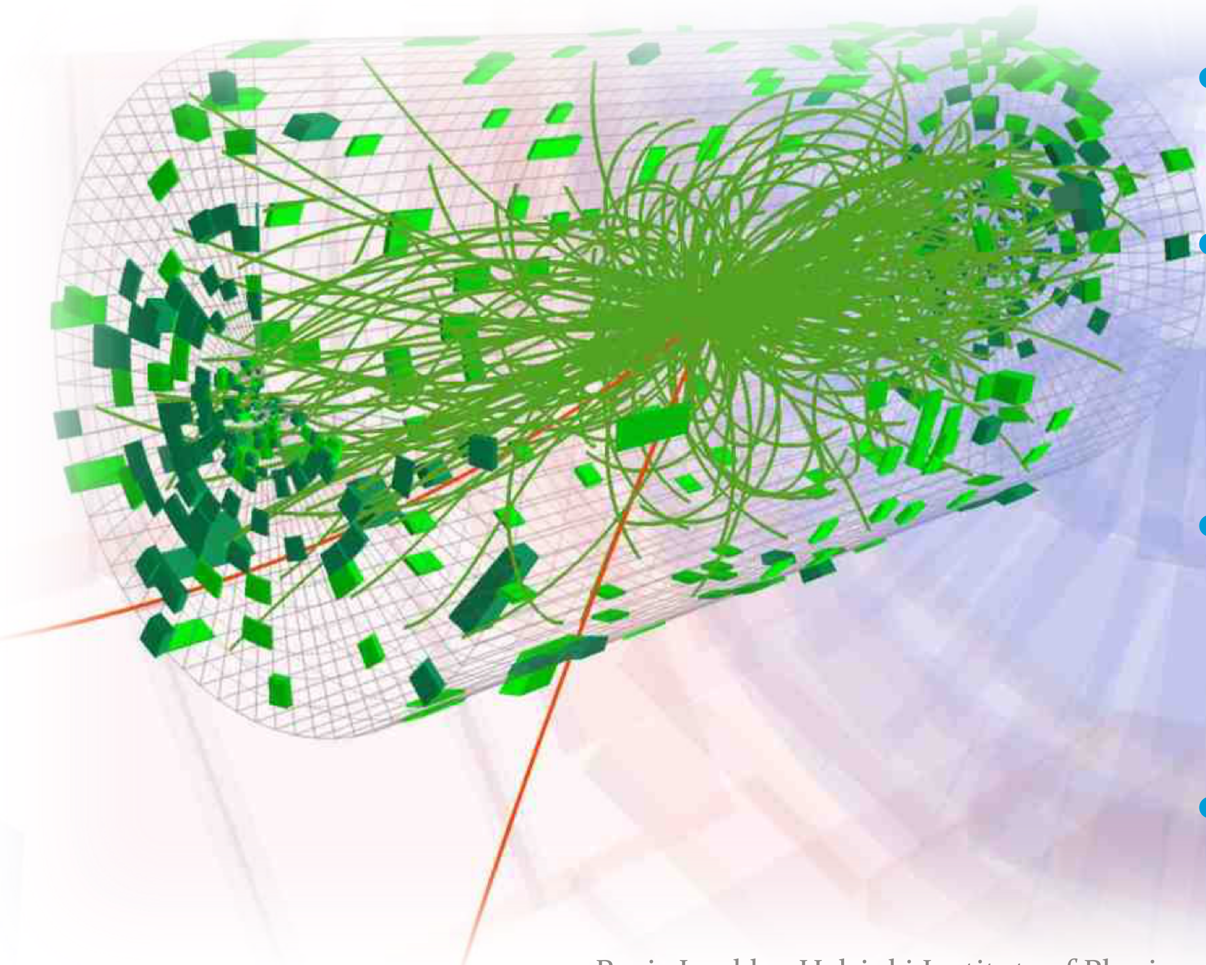
→ HL-LHC: $L \sim 10^{35}$ $cm^{-2}s^{-1}$,
expected fast hadron fluence
at r=4cm ~ 1.6×10^{16} cm^{-2}

→ E.g. in the upgraded CMS Tracker the sensors need to withstand fluences up to 1.5×10^{15} 1 MeV neutrons cm^{-2}.



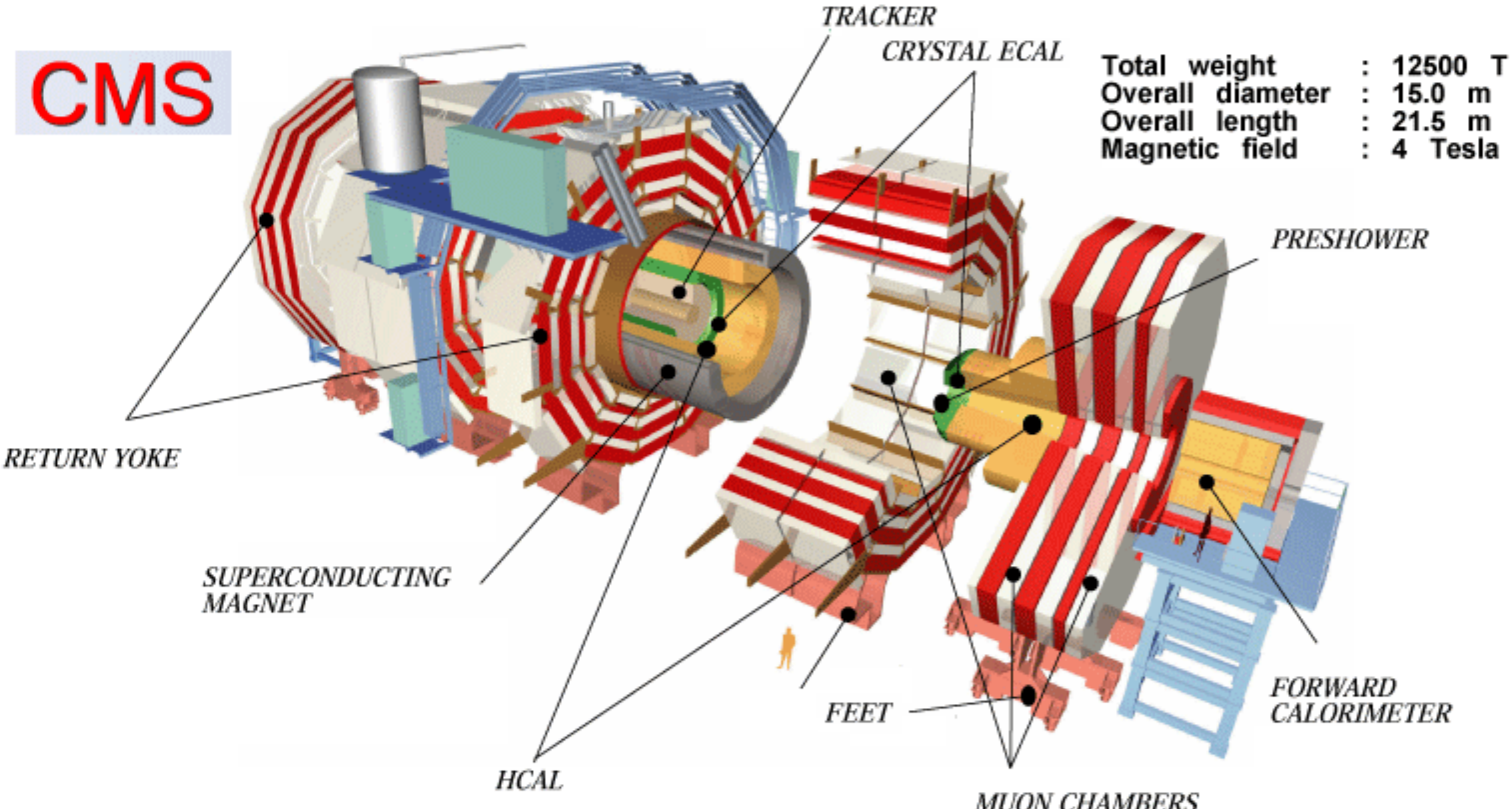
The main constraint is the survival of the silicon tracking systems in this radiation environment. Thus, HL-LHC will require even more radiation tolerant tracking detector concepts with the boundary conditions of: *fine segmentation, low power consumption, efficient cooling, highly integrated connectivity, low mass and low cost!*

Common requirements for tracking detectors

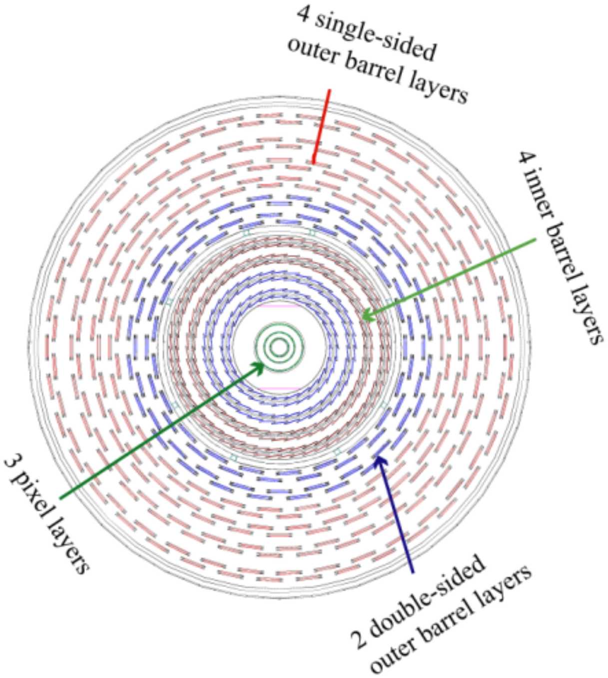


- Track particles without disturbing them.
- Excellent position resolution.
  - Highly segmented ⇒ high resolution.
- Large signal.
  - Small amount of energy to create sufficient signal.
- Small material budget.
  - Minimize multiple scattering.

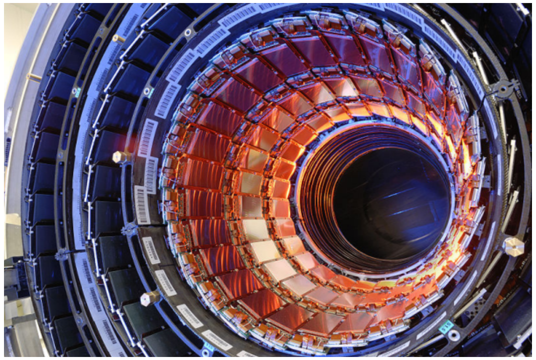
Compact Muon Solenoid (CMS) experiment

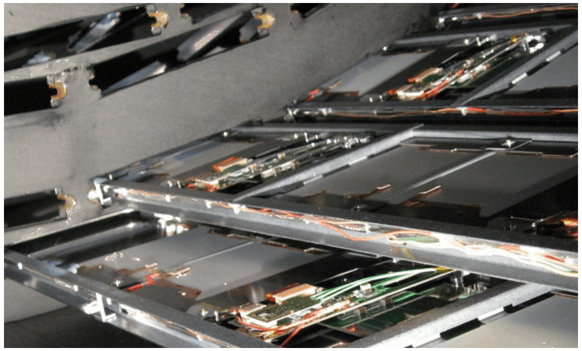


CMS Tracker



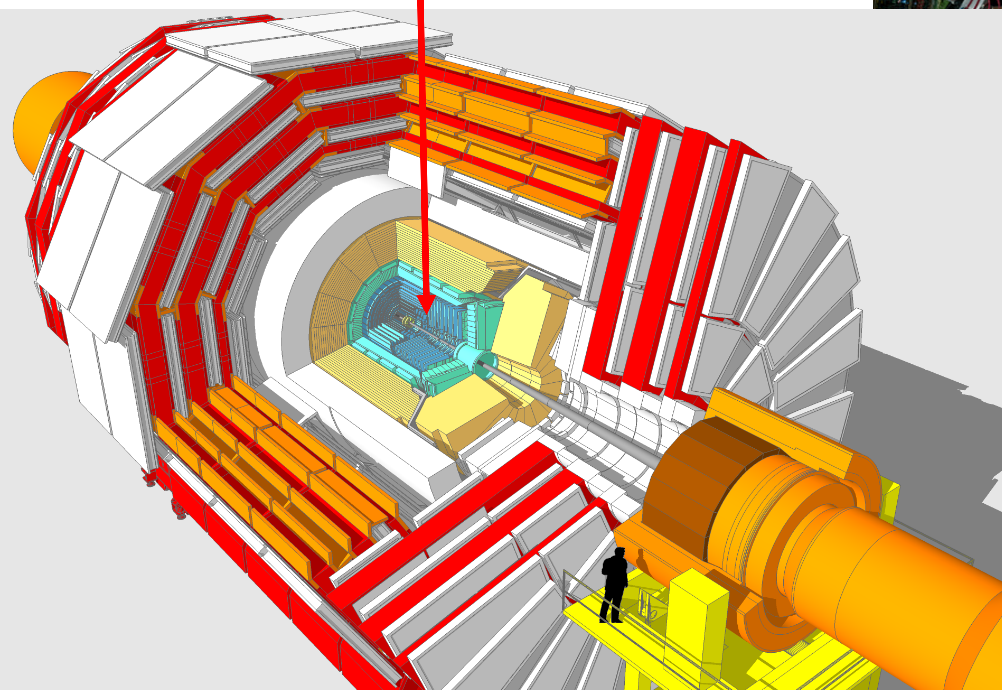
- Tracker is the innermost detector of the CMS experiment.
- In total the CMS tracker implements silicon sensors with an area of 210 m^2.
- At the smallest radii the interaction region is surrounded by pixel detectors
- Further from the interaction point the detector consists of silicon strip sensors.

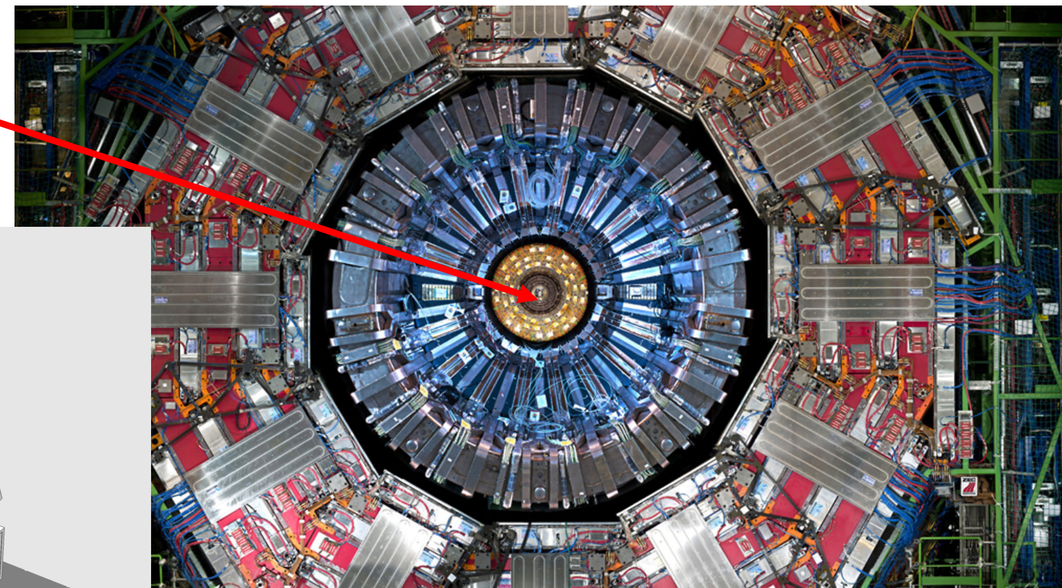


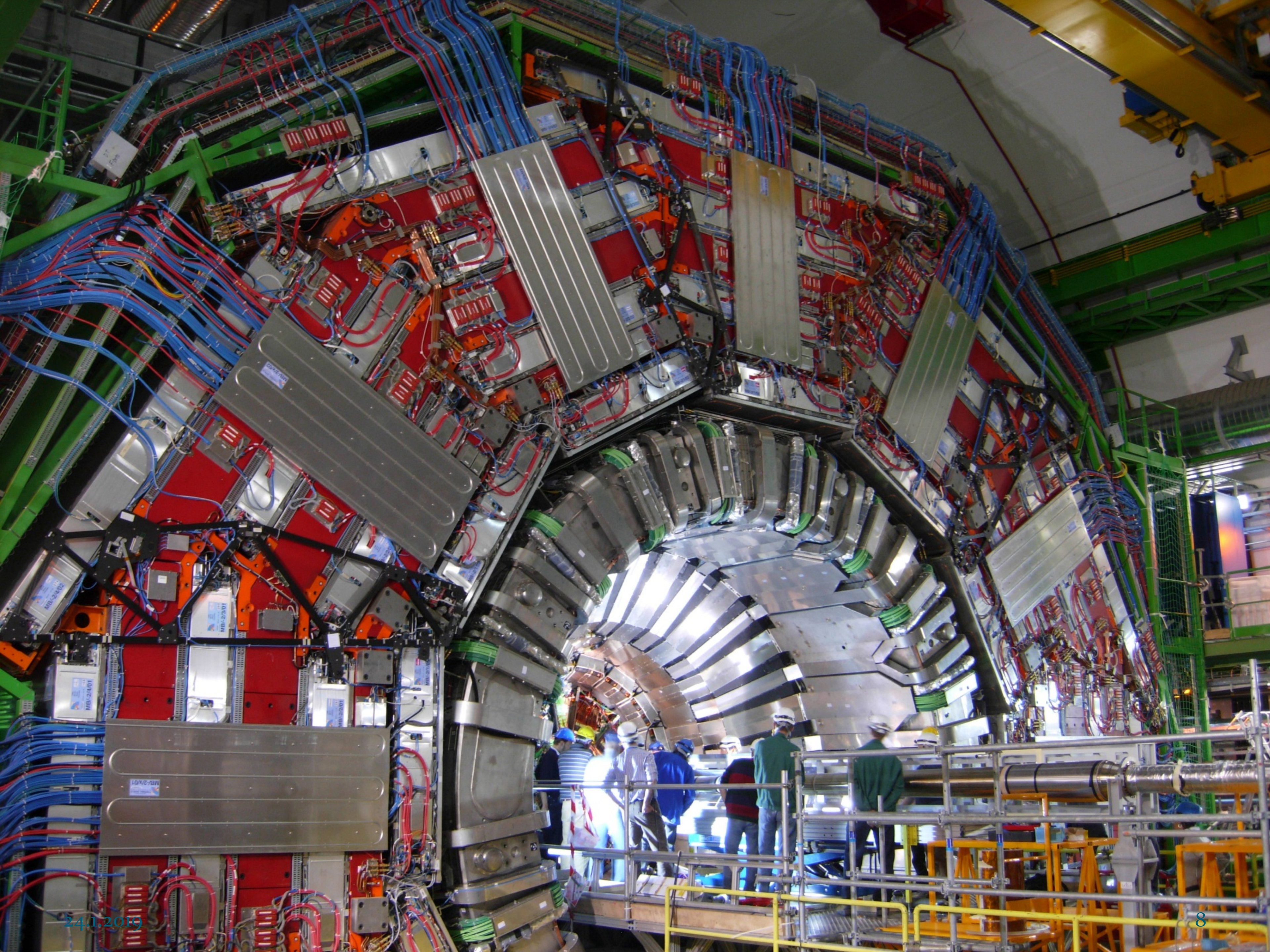


CMS Tracker and the pixel detector

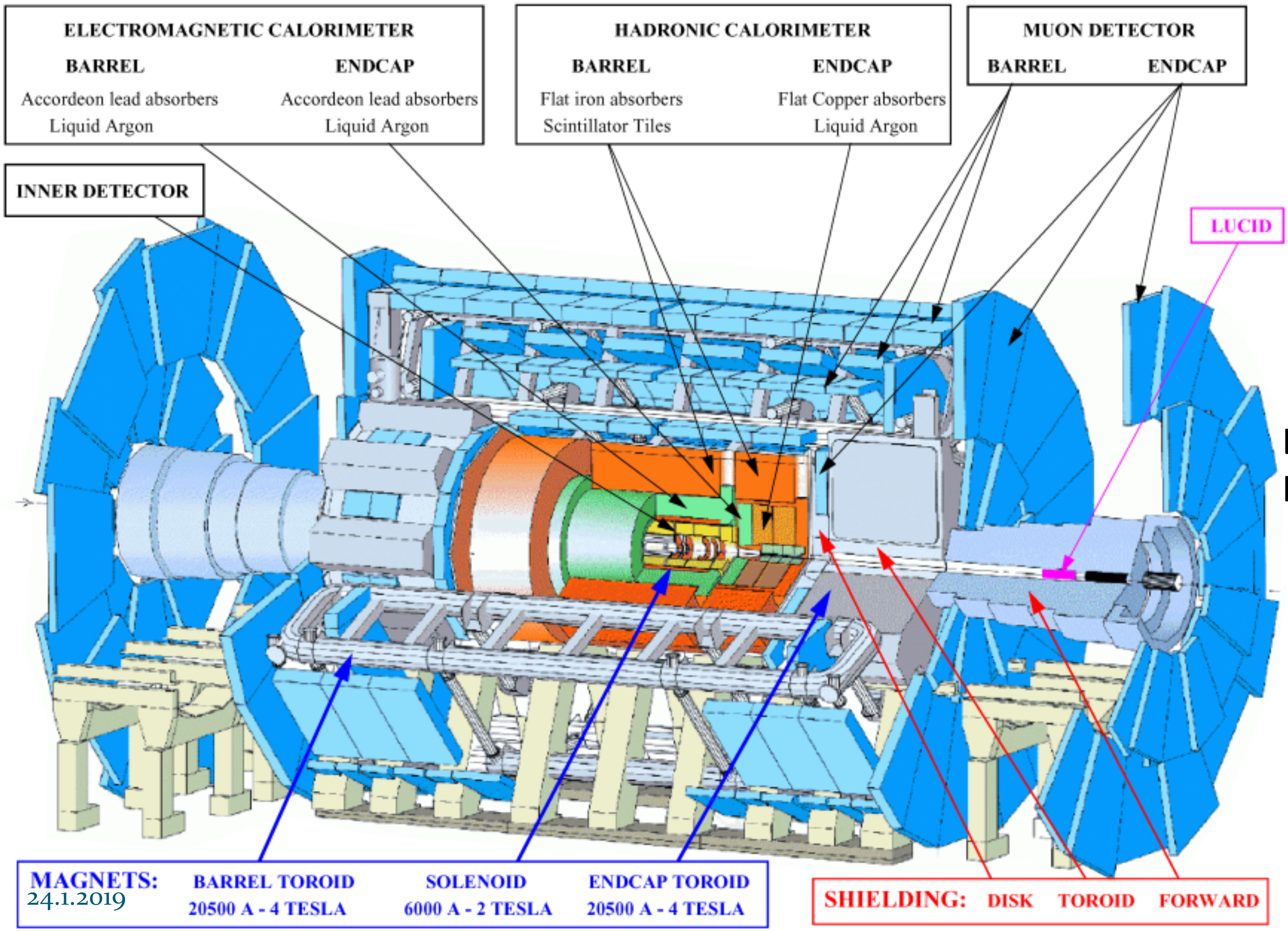
CMS Tracker and the pixel detector







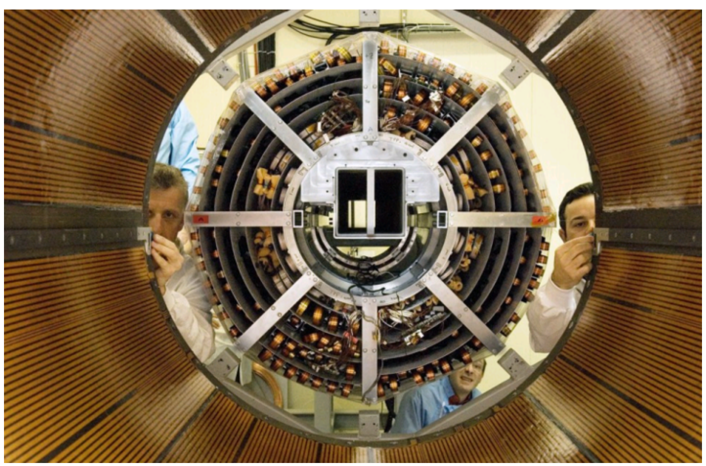
ATLAS, the largest detector in LHC

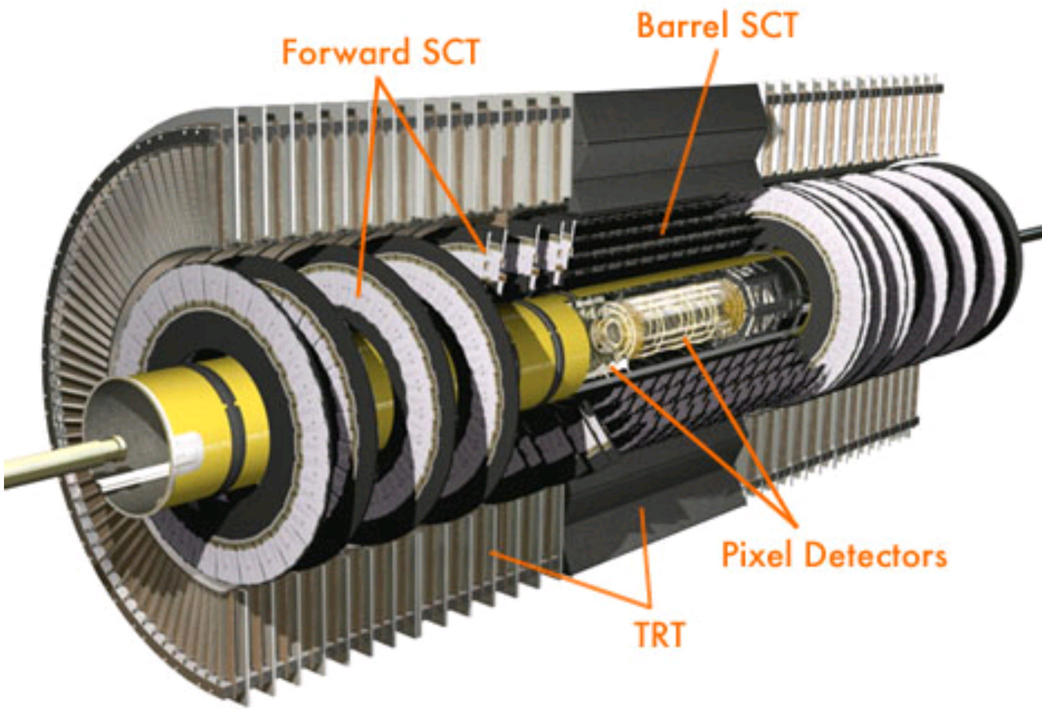


Length 46 m
Height 22 m

ATLAS Semiconductor Tracker

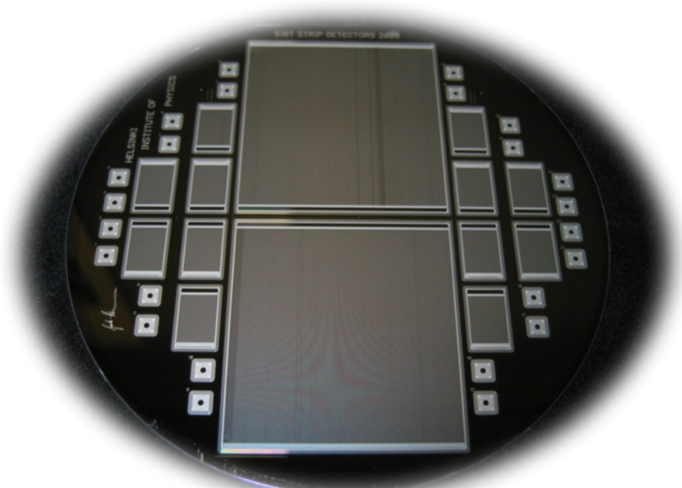
- The highest granularity is achieved around the vertex region using semiconductor pixel detectors (2.3 m^2).
- These are followed by layers of silicon microstrip detectors in the barrel and the forward region (61.1 m^2).





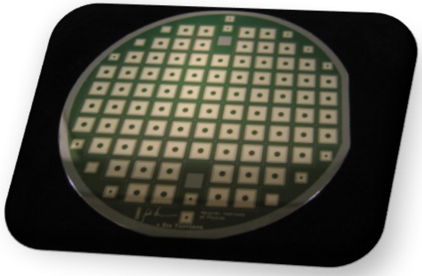
Why do we want to use silicon, if it suffers from radiation damage?

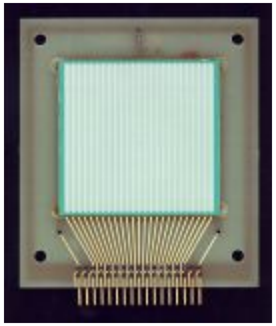
- Silicon detectors have very good intrinsic energy resolution: for every 3.6 eV released by a particle crossing the medium, one electron-hole pair is produced.
  - Compared to about 30 eV required to ionize a gas molecule in a gaseous detector, one gets 10 times the number of particles in silicon.
- High stopping power of silicon → almost all free charge is created within a few microns of the path of a charged particle.
- Long carrier lifetime.
- Mature processing technology.

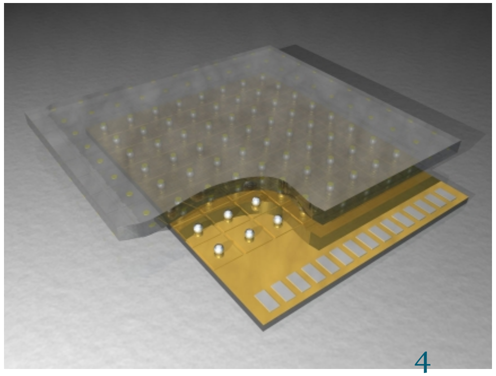


Types of silicon detectors

- Pad devices
  - Pre-shower and calorimeters (charge measurement)
- Strip devices
  - High precision (< 5μm) 1-D coordinate measurement
  - Large active area (up to 10cm x 10cm from 6” wafers)
  - Inexpensive processing (single-sided devices)
  - 2nd coordinate possible *(double-sided devices)*
  - Most widely used silicon detector in HEP
- Pixel devices
  - True 2-D measurement
  - Usually only small areas (mostly due to cost!), but best for high track density environment, like HL-LHC

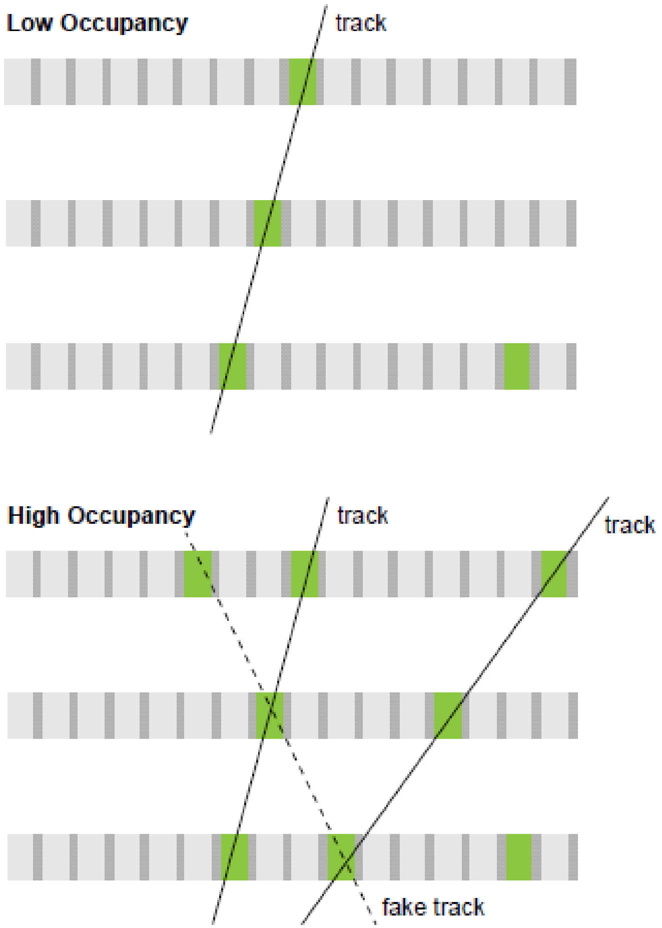






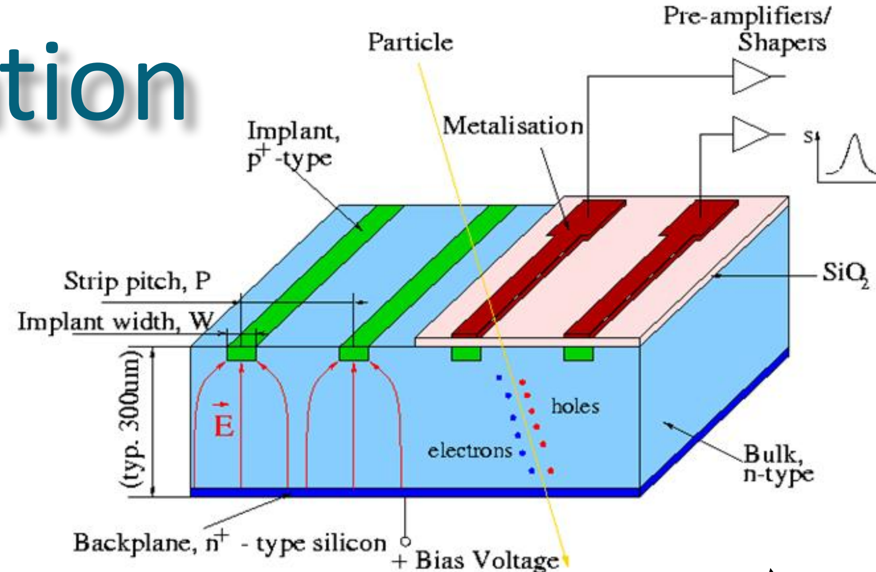
Why the innermost detectors are nowadays always pixel detectors?

- Resolution and material budget:
  - Small pixels → high hit resolution → high track and vertex resolution
  - Material budget: 3D space point with a single detector layer
- Tracking advantages of highly segmented detectors:
  - Low hit occupancy → low hit combinatorics
  - “Track seed” from region with smallest probability for wrong assignment of hits to tracks



Detector fabrication

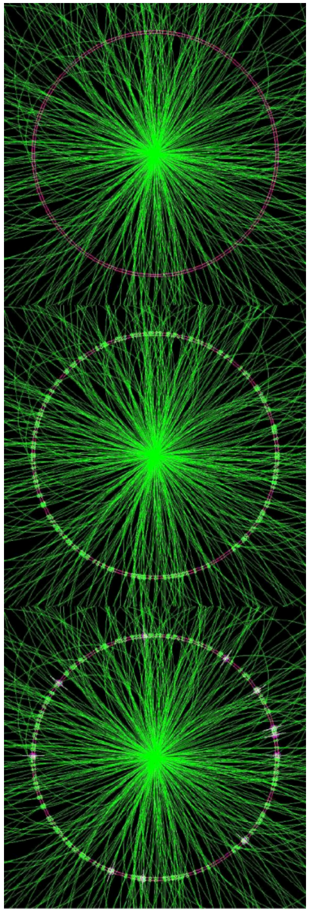
Very pure sand or quartz



Many processing steps involving several individual steps e.g. etching (photochemical, plasma etc.), ion implantation, metal deposition..

Silicon crystal growth by Float Zone or Czochralski methods

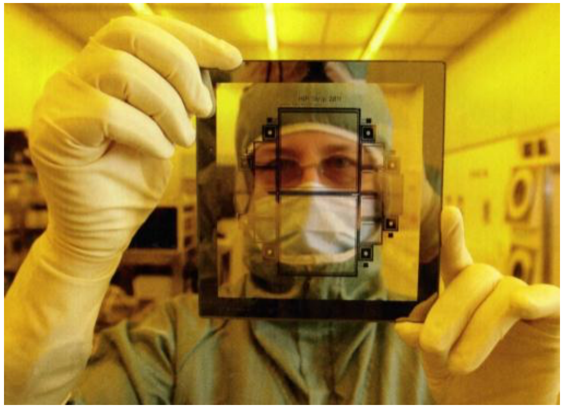
Future tracking devices for HL-LHC

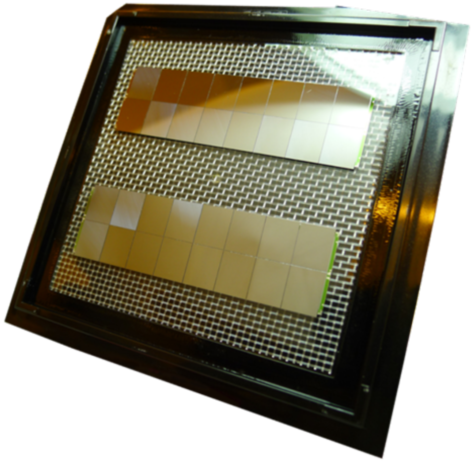


- For the high-luminosity experiments new solutions have to be developed.
- This can be achieved by:
  - Material and defect engineering of silicon.
    - Understanding the radiation damage and influence of processing technology, e.g. oxygen enriched material.
  - Looking for new promising materials.
    - E.g. diamond, germanium.
  - Device engineering i.e. developing new detector designs.
    - E.g. p-type detectors or 3D structures.

Detector R&D and Finnish companies

- Finland has several companies in the field of semiconductor processing and advanced interconnection technologies.
- There is a large cluster of such companies operating in Micronova Centre for Micro and Nanotechnology in Otaniemi.
- There is also the silicon wafer producer Okmetic in Finland.
- The most comprehensive upgrade of the CERN experiments will happen in 2024-2026.
- The R&D for the this is taking place now.
- Thus, this is the moment to introduce Finnish companies to the experiments through common R&D together with the university groups operating in these experiments.





Summary

- CERN experiments are preparing for their most comprehensive upgrade, which will take place in 2024-2026.
- The R&D for the this has already started and will continue next few years.
- Thus, this is the moment to introduce Finnish companies to the experiments through common R&D together with the companies and the university groups participating into these experiments.