Tracking detectors in High Energy Physics (HEP)

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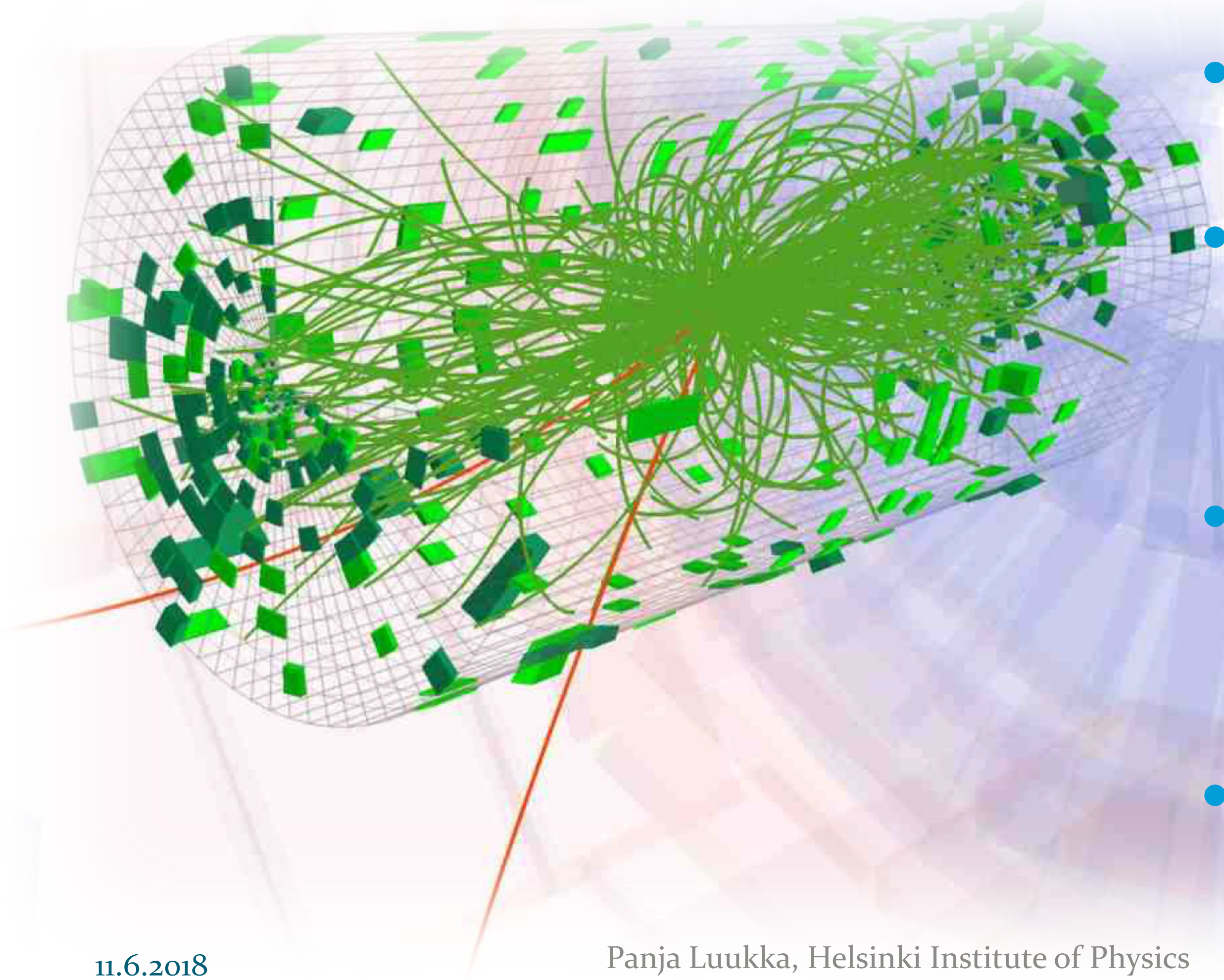
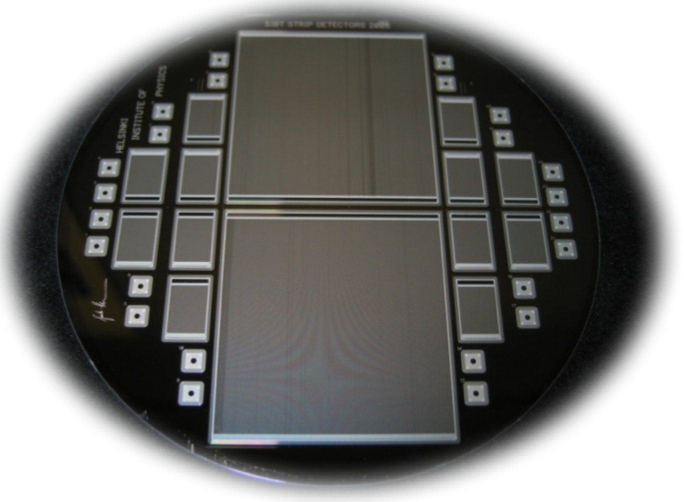
Common requirements for tracking detectors



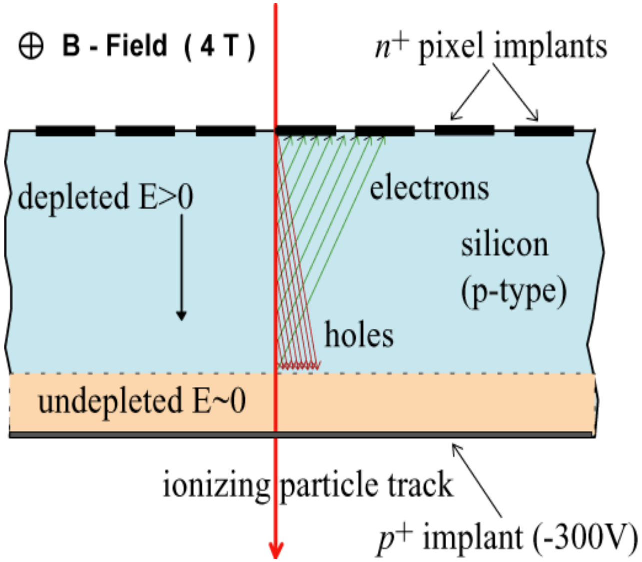
- Track particles without disturbing them.
- Excellent position resolution.
  - Highly segmented ⇒ high resolution.
- Large signal.
  - Small amount of energy to create sufficient signal.
- Small material budget.
  - Minimize multiple scattering.

Why silicon is most practical as tracking detector material?

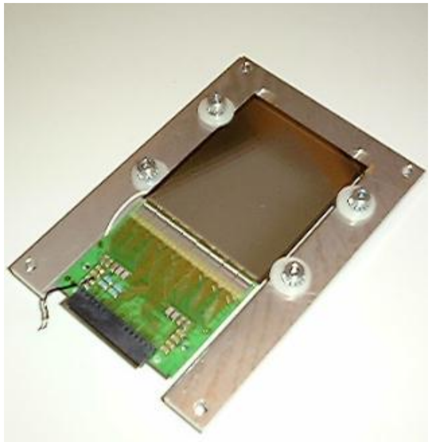
- Silicon detectors have very good intrinsic energy resolution: for every 3.6 eV released by a particle crossing the medium, one electron-hole pair is produced.
  - Compared to about 30 eV required to ionize a gas molecule in a gaseous detector, one gets 10 times the number of particles in silicon.
- 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.



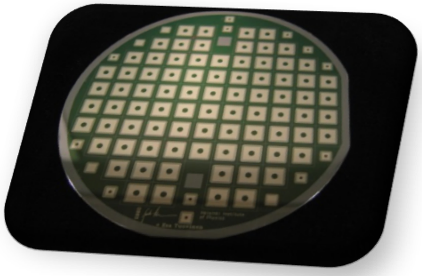
Silicon detector basics



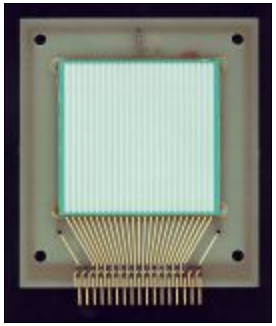
- Traversing particle creates electron-hole pairs in silicon.
- Even intrinsic silicon contains much more free charge carriers than those produced by a charged particle.
- These free carriers can be removed by applying an electric field over the entire device bulk → full depletion.
- The particle induced current can be sensed and amplified.

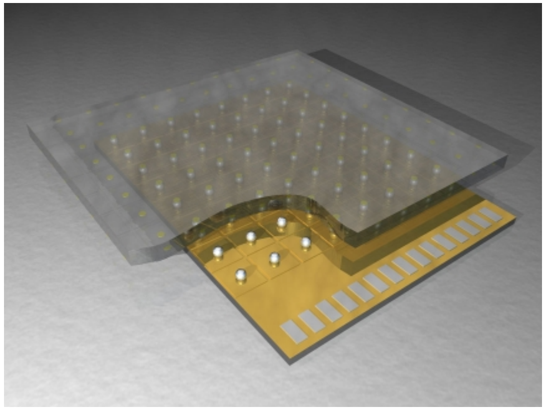


Types of silicon detectors



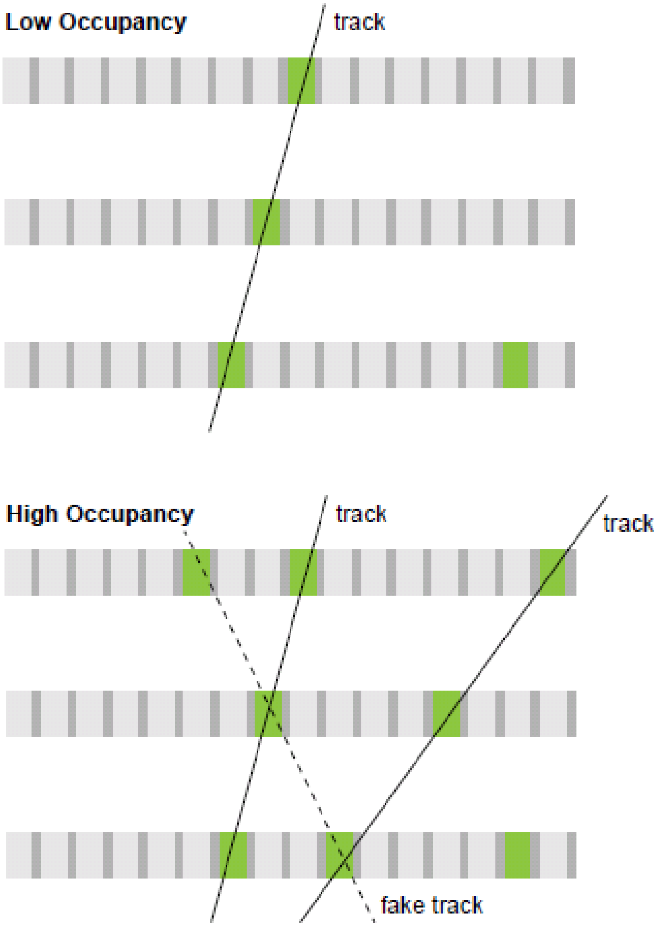
- Pad devices
  - Pre-shower and calorimeters (charge measurement)
- Strip devices
  - High precision (< 5μm) 1-D coordinate measurement
  - Large active area (up to 10cm x 10cm from 6” wafers)
  - Inexpensive processing (single-sided devices)
  - 2nd coordinate possible *(double-sided devices)*
  - 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





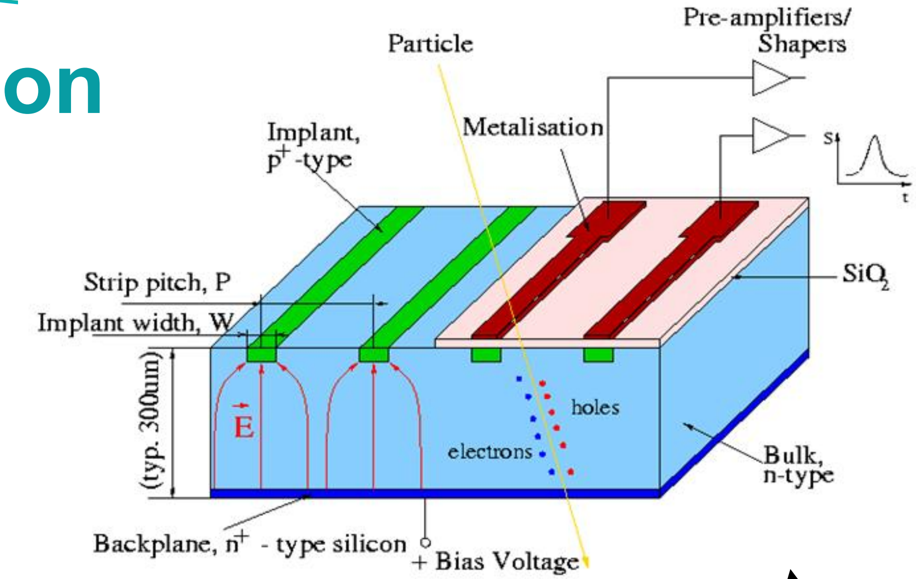
Why the innermost detectors are nowadays always pixel detectors?

- 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..

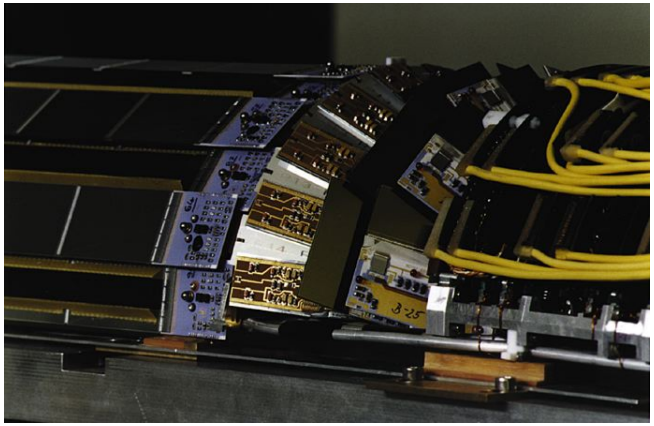
Silicon crystal growth by Float Zone or Czochralski methods

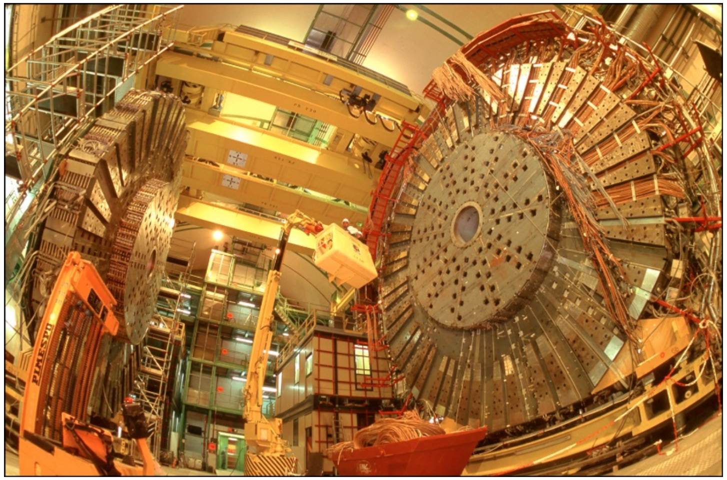
LEP Detectors at CERN

- Large Electron–Positron Collider (LEP) was used from 1989 until 2000.
- It was located at CERN (Geneva, Switzerland), in the same tunnel that Large Hadron Collider currently uses.
- To date, LEP is the most powerful collider of leptons ever built.
- LEP had four detectors, built around the four collision points:
  - ALEPH (Apparatus for LEP PHysics at CERN)
  - DELPHI (DEtector with Lepton, Photon and Hadron Identification.)
  - OPAL (Omni-Purpose Apparatus for LEP)
  - L3

DELPHI Microvertex detector

- 2 silicon layers, 40cm long, inner radius 7.8 cm, outer radius 12 cm
- 300 µm thick double-sided silicon strip detectors.
- Mass and distance between the interaction point and detectors was minimized.
- As well as the mass inside the tracking volume.
- Readout chips were located at the end of ladders.





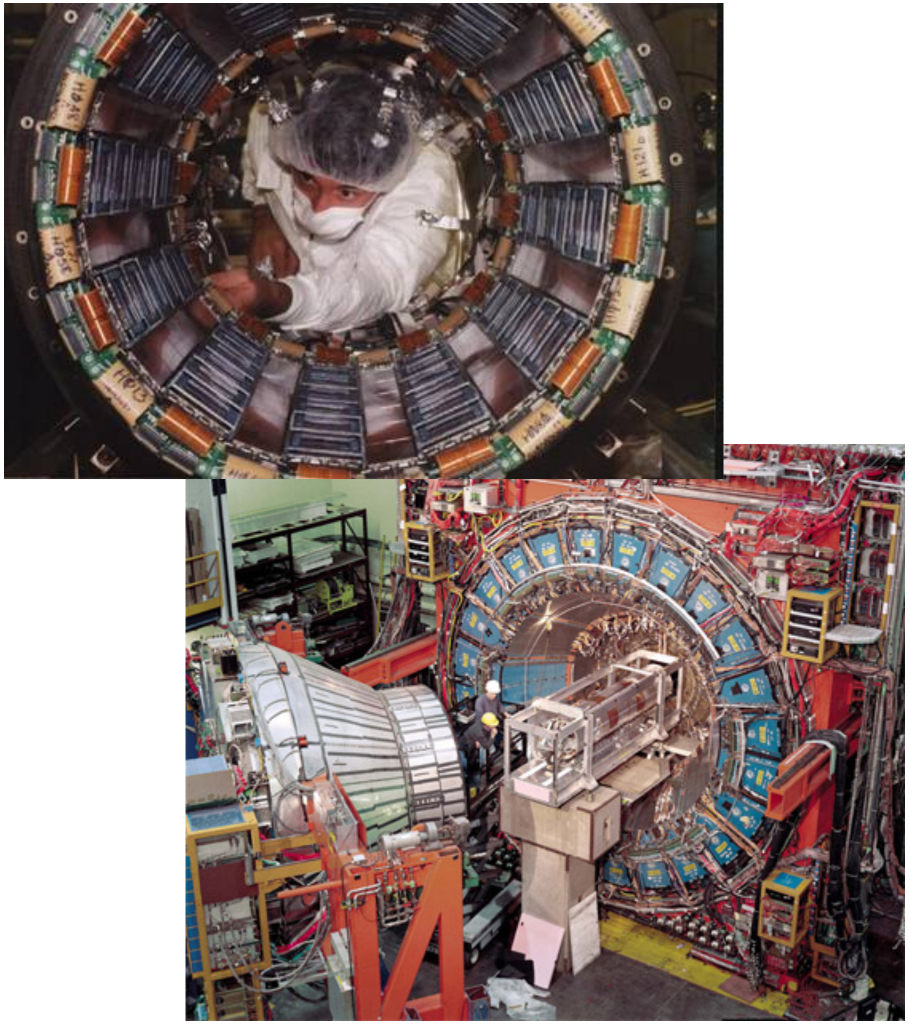
Tevatron detectors

- Tevatron was a circular particle accelerator at the Fermi National Accelerator Laboratory (Fermilab) in the United States.
- The main achievement of the Tevatron was the discovery of the top quark in 1995 - the last fundamental fermion predicted by the standard model of the particle physics.
- The two main experiments at Tevatron were CDF and DØ.

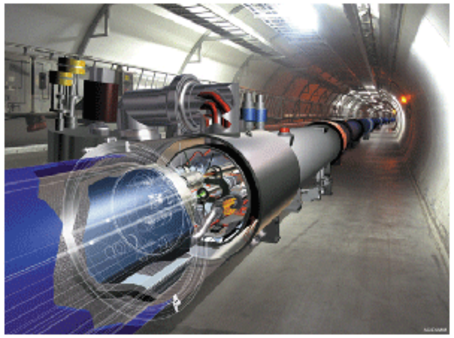
CDF

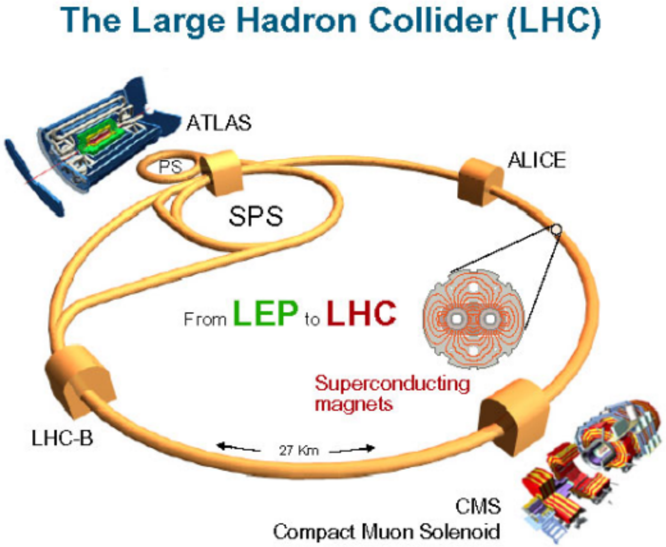
Tracker:

- Barrel with 3 different silicon layers:
  - L00 (single-sided strip detectors, r~ 1.5 cm, l=94cm)
  - SVX (r = 5-10 cm)
  - ISL (double-sided strip detectors, r = 20-29cm)
- Total active area: approx. 10 m^2



Detectors at Large Hadron Collider (LHC)

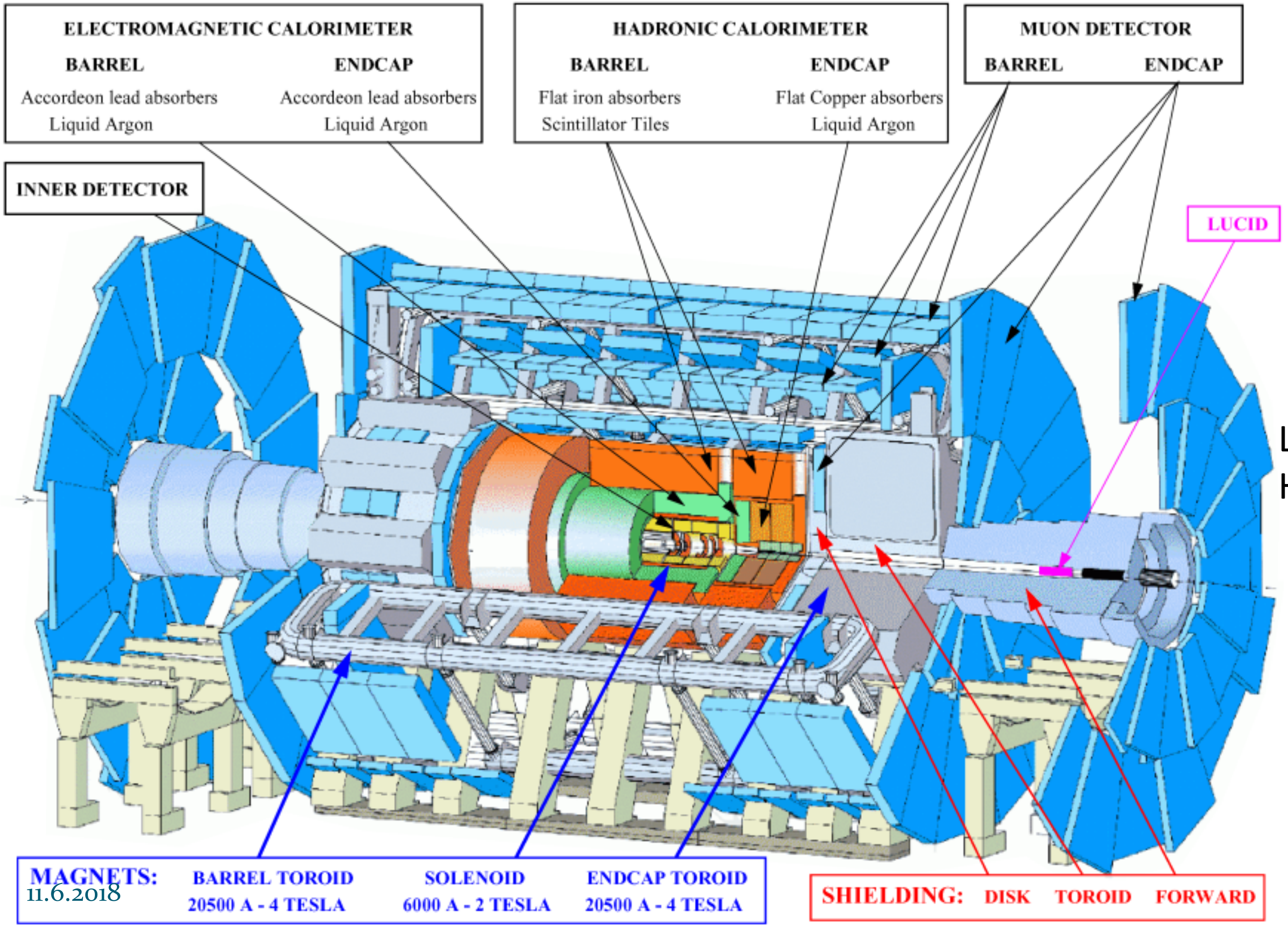




	Beams	Energy	Luminosity
LEP	e^+ e^-	200 GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14 TeV	10^{34}
	Pb Pb	1312 TeV	10^{27}

- Large Hadron Collider (LHC) is the world's largest and most powerful particle collider located at CERN.
- The accelerator complex is about 100 m underground and has a circumference of ~27 km.
- The first particle collisions took place in March 2010, and in 2013 the discovery of the Higgs particle was confirmed.
- There are 4 main experiments:
  - ATLAS (A Toroidal LHC Apparatus)
  - CMS (Compact Muon Solenoid)
  - LHCb (LHC-beauty)
  - ALICE (A Large Ion Collider experiment).

ATLAS, the largest detector in LHC



ELECTROMAGNETIC CALORIMETER

BARREL	ENDCAP
Accordeon lead absorbers	Accordeon lead absorbers
Liquid Argon	Liquid Argon

HADRONIC CALORIMETER

BARREL	ENDCAP
Flat iron absorbers	Flat Copper absorbers
Scintillator Tiles	Liquid Argon

MUON DETECTOR

BARREL ENDCAP

INNER DETECTOR

LUCID

MAGNETS:

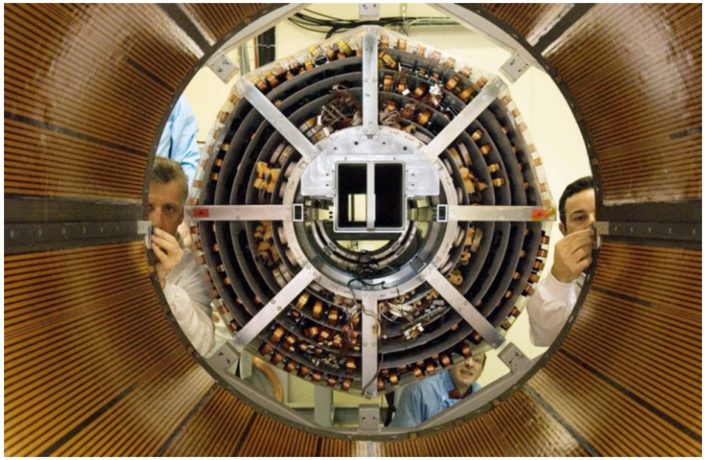
BARREL TOROID	SOLENOID	ENDCAP TOROID
20500 A - 4 TESLA	6000 A - 2 TESLA	20500 A - 4 TESLA

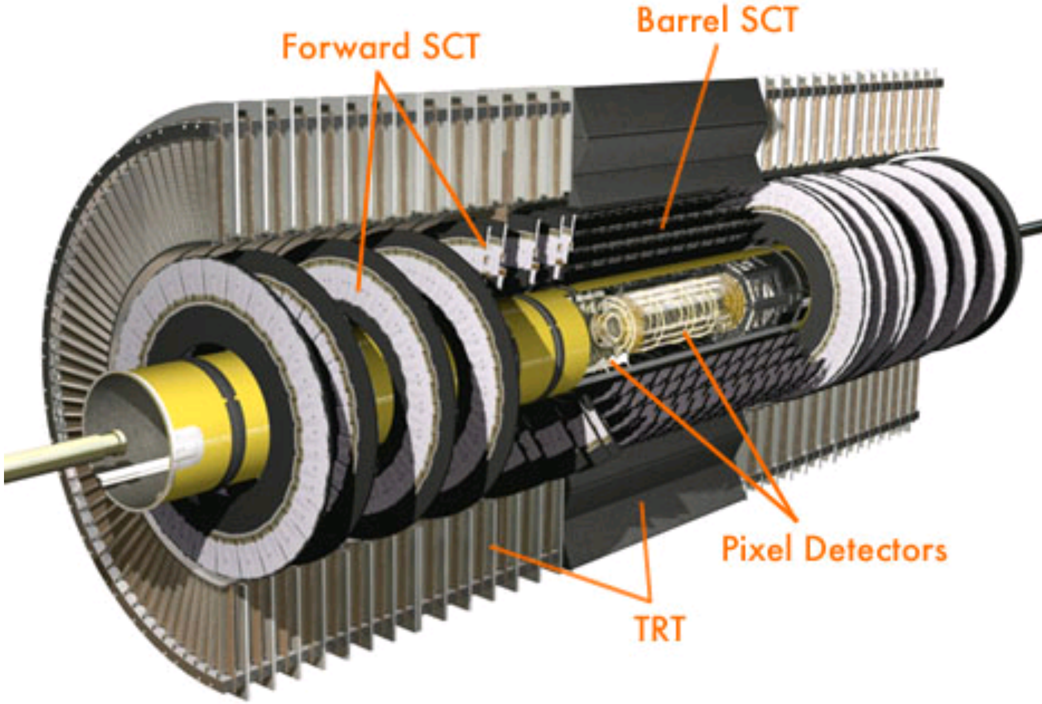
SHIELDING: DISK TOROID FORWARD

Length 46 m
Height 22 m

Atlas Semiconductor Tracker

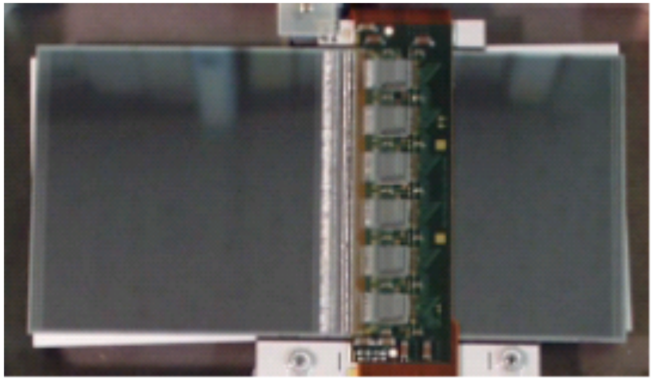
- The highest granularity is achieved around the vertex region using semiconductor pixel detectors (2.3 m^2).
- These are followed by layers of silicon microstrip detectors in the barrel and the forward region (61.1 m^2).

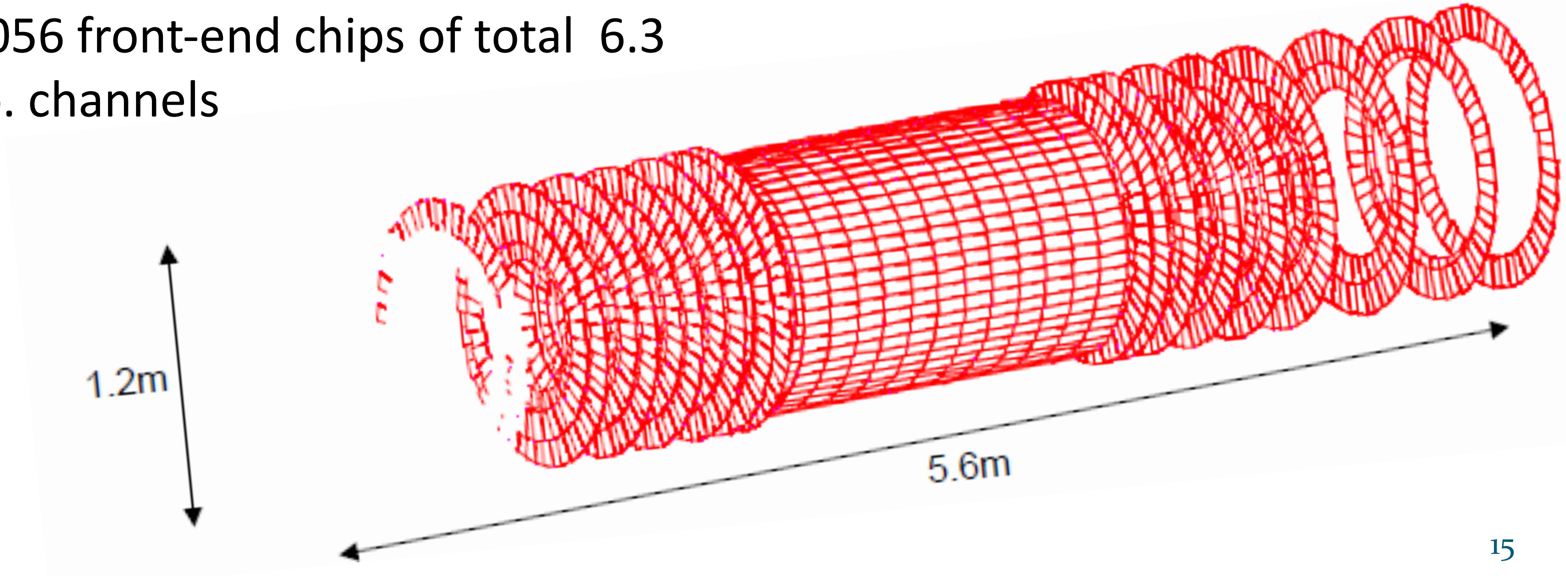




ATLAS Silicon Microstrip Tracker

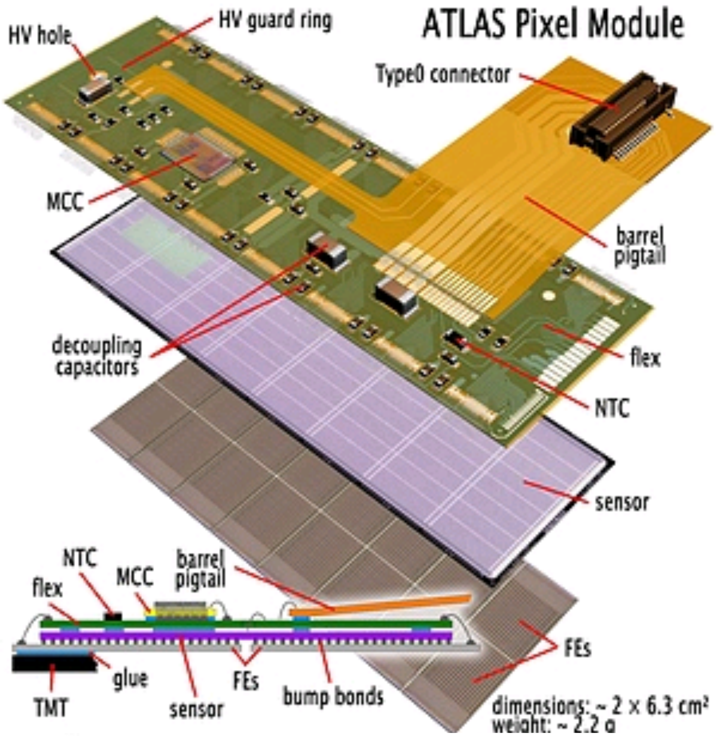
- 4 barrel layers
  - in total 2112 modules
- 2 x 9 forward disks
  - in total 1976 modules
- all 4088 modules double side
- 15,392 sensors of total 61.1m²
- 49,056 front-end chips of total 6.3 Mio. channels

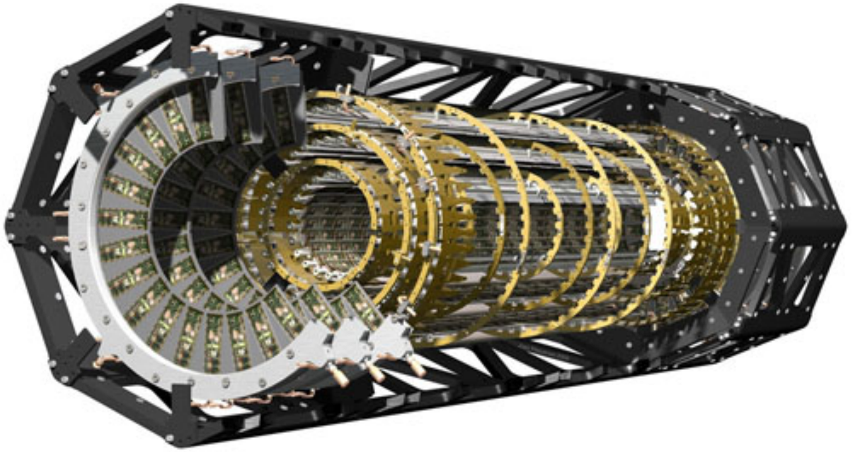




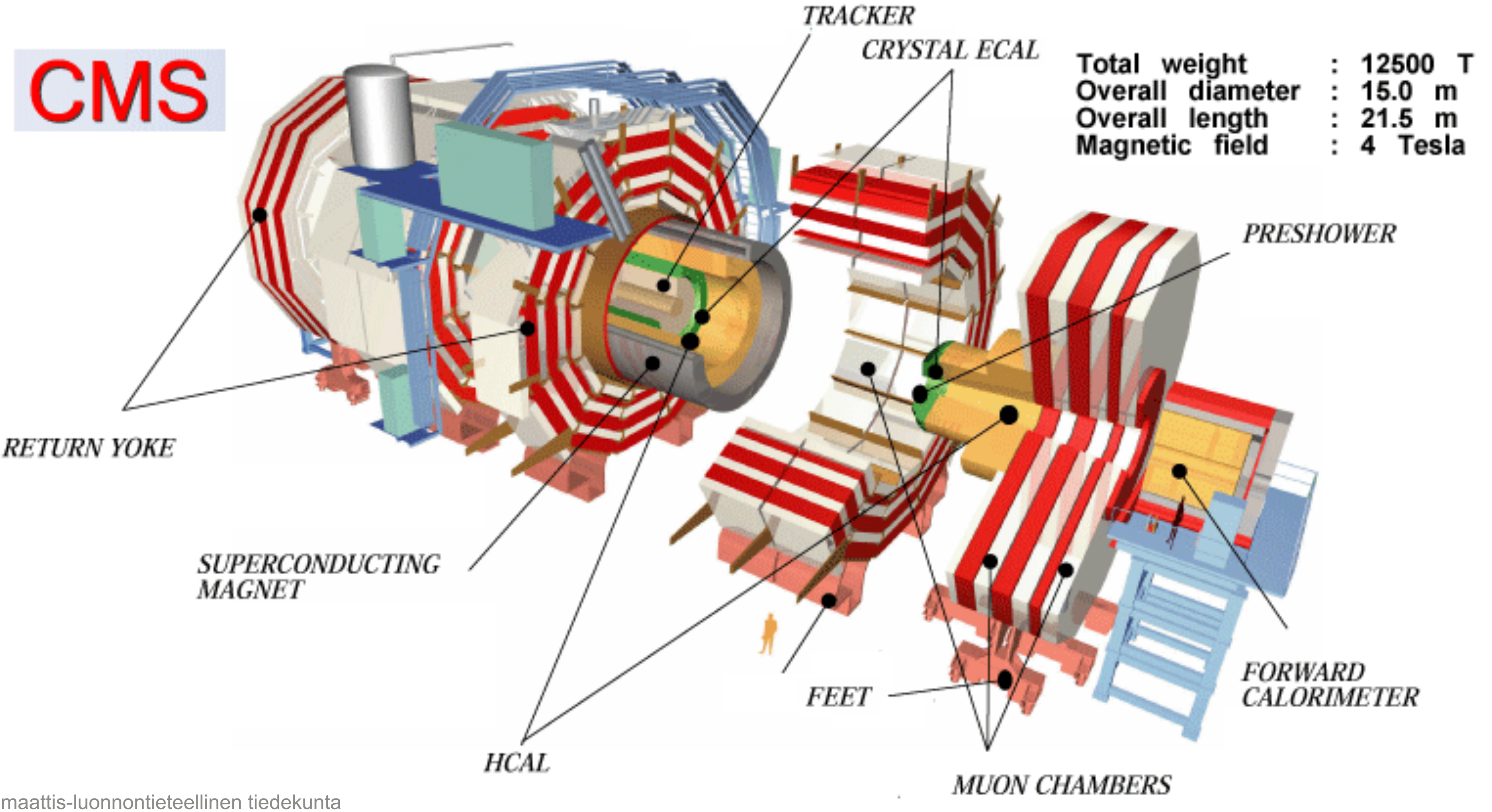
ATLAS pixel detector

- The system consists of:
    - three barrels at average radii of ~ 5 cm, 9 cm, and 12 cm (1456 modules)
    - three disks on each side, between radii of 9 and 15 cm (288 modules).
- Each detector module is 62.4 mm long and 21.4 mm wide, with 46080 pixel elements read out by 16 chips, each serving an array of 18 by 160 pixels.
- The thickness of each layer is expected to be about 2.5% of a radiation length at normal incidence.



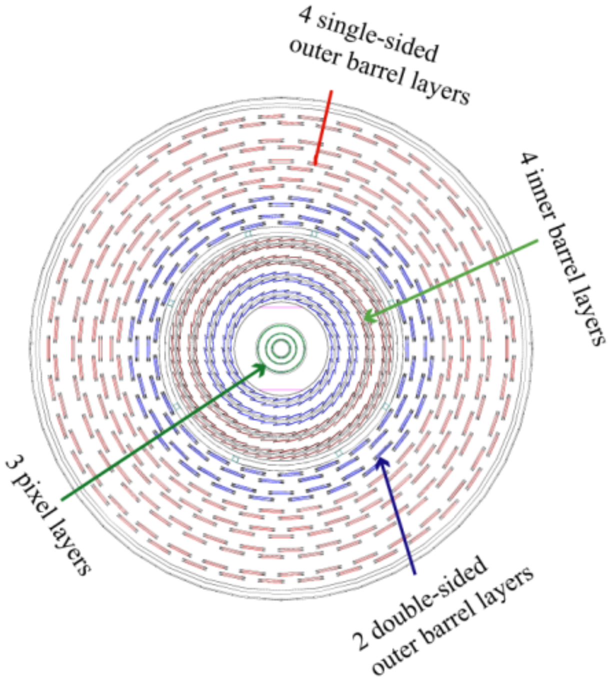


Compact Muon Solenoid (CMS) experiment

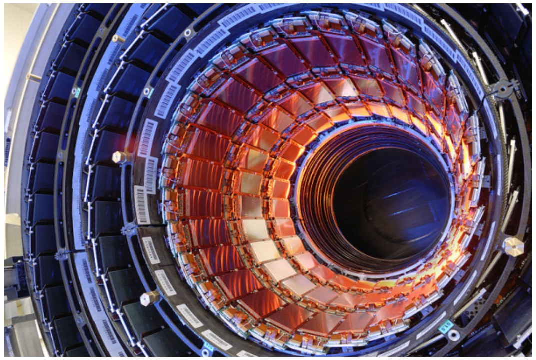


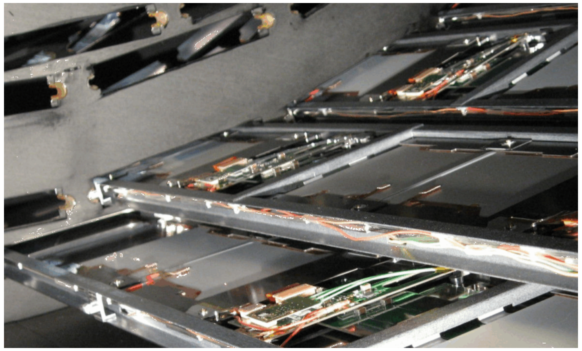
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

CMS Tracker

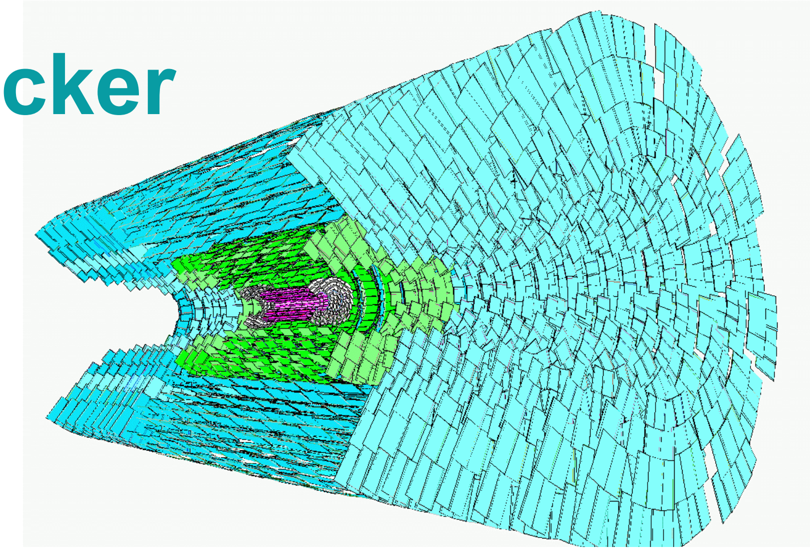


- Tracker is the innermost detector of the CMS experiment.
- In total the CMS tracker implements silicon sensors with an area of 210 m^2.
- At the smallest radii the interaction region is surrounded by pixel detectors
- Further from the interaction point the detector consists of silicon strip sensors.

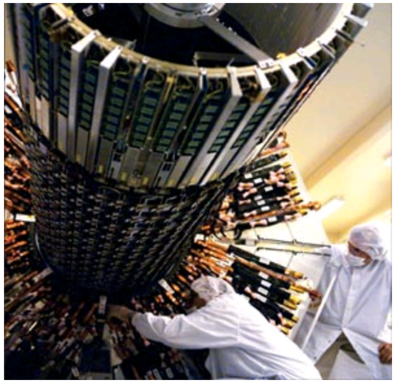


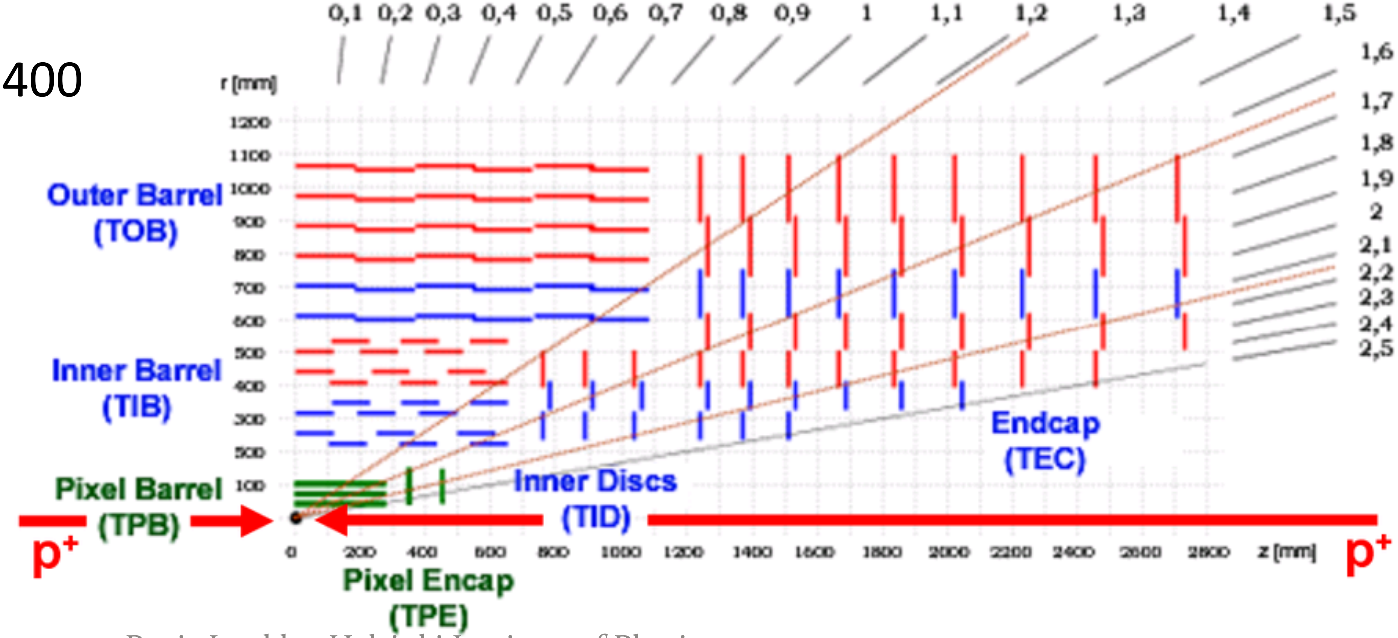


CMS strip tracker



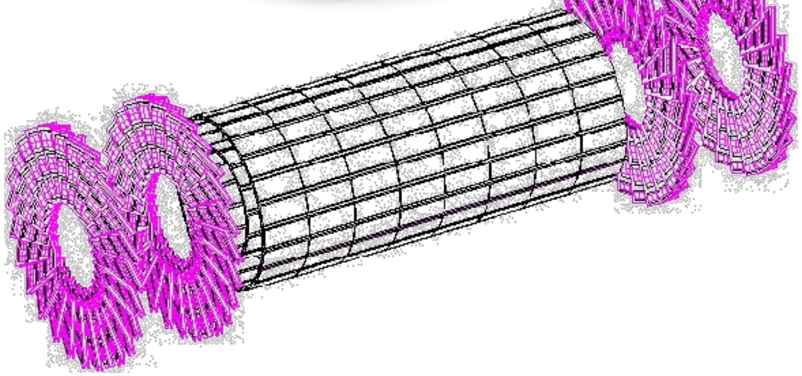
- TOB: 6 layers, 5208 modules
- TIB:4 layers, 2724 modules
- TID: 2x3 disks, 816 modules
- TEC: 2x9 disks, 6400 modules



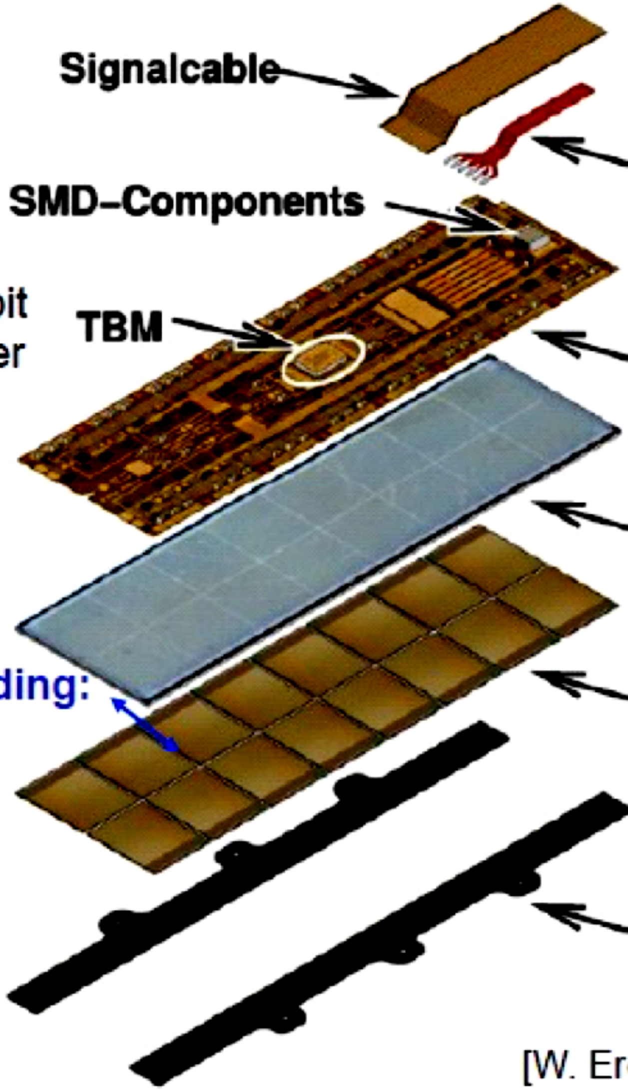


CMS pixel detector

- The pixel detector is the closest detector to the beam pipe, with cylindrical layers at 4cm, 7cm and 11cm and disks at either end.
  - Barrel Pixels (Bpix): 48M pixels, 11520 ROCs
  - Forward Pixels (Fpix): 18M pixels, 4320 ROCs.
    - All together 66 million 100µm x 150µm pixels covering an area of 1.06 m^2.



CMS Barrel Pixel Module



Signalcable

Powercable

SMD–Components

Token bit manager **TBM**

HDI High density interconnect

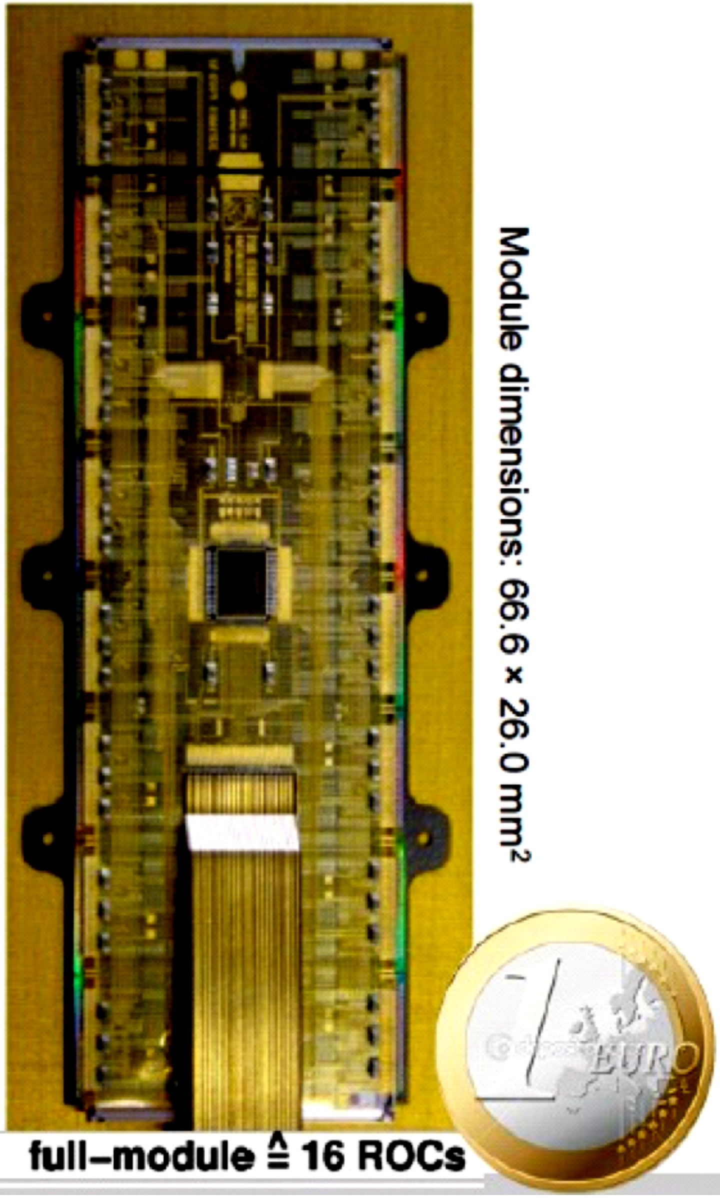
Sensor 16×62 mm² 66,560 pixels

bump bonding:

ROCs Read-out chips

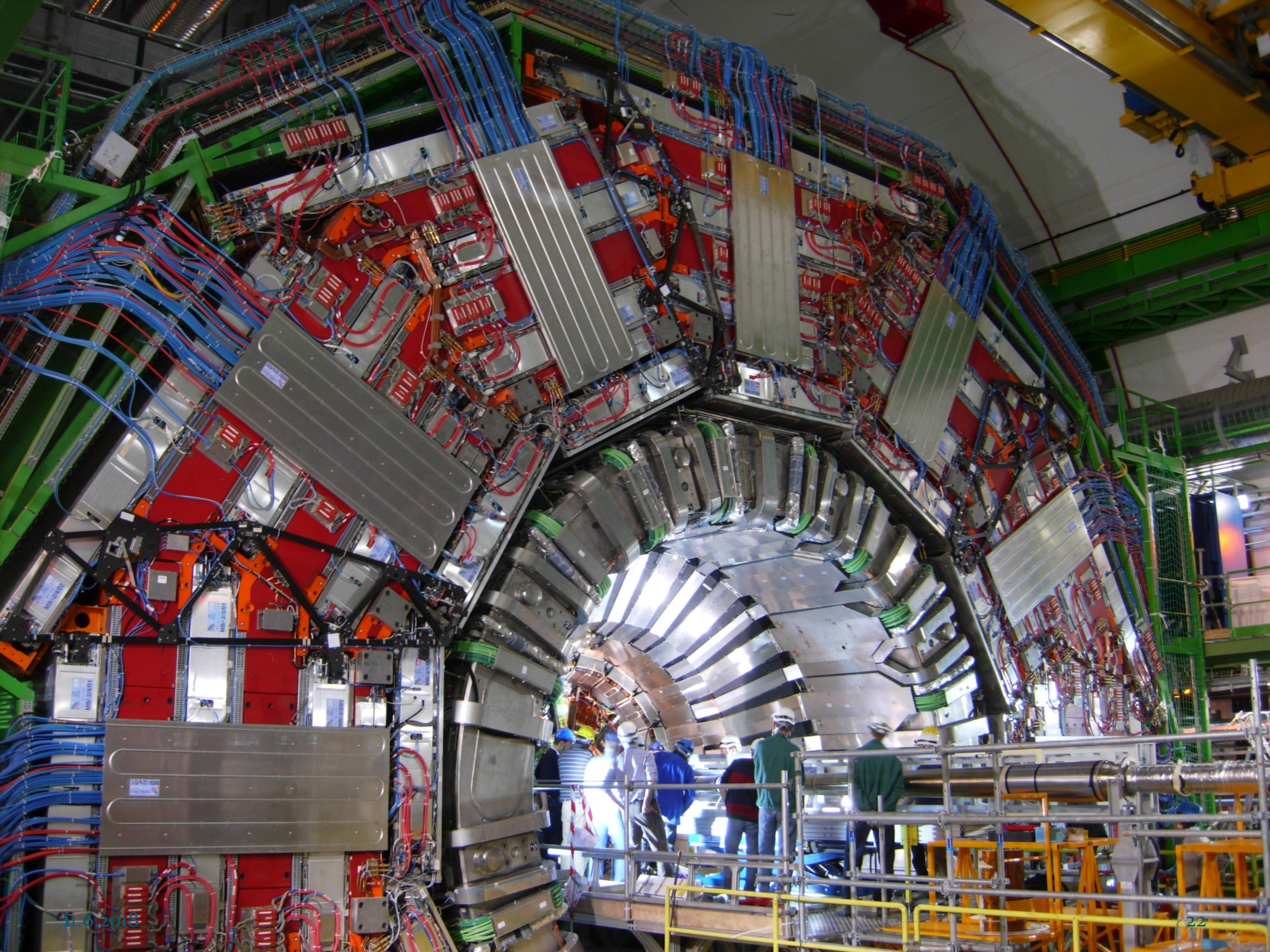
SiN Basestrips

[W. Erdmann]



Module dimensions: 66.6 × 26.0 mm²

full–module ≙ 16 ROCs



Radiation environment

- Promising new physical results are related to some very rarely produced particles → high event rate needed.
- However, this also means harsh radiation environment for the detectors (!).
- Already in Tevatron some effects of radiation damage were observed, but in the LHC era they have become
  one of the most challenging issues in the detector development.

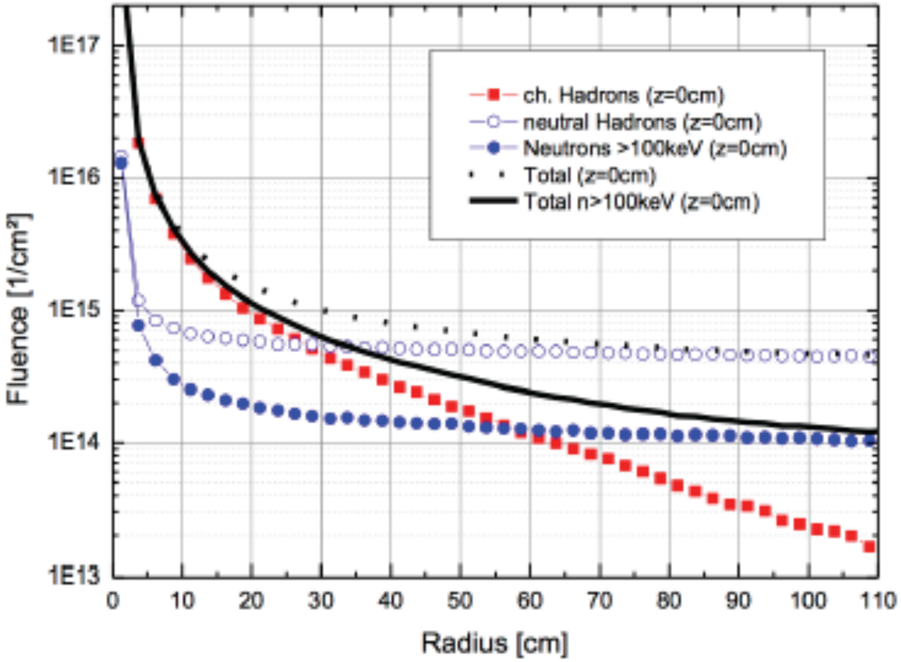
High Luminosity LHC (HL-LHC)

LHC upgrade to High Luminosity LHC:

Luminosity of LHC: L ~ 10^{34} $cm^{-2}s^{-1}$ and fluence of fast hadrons at r=4cm ~ $3\cdot10^{15}cm^{-2}$

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

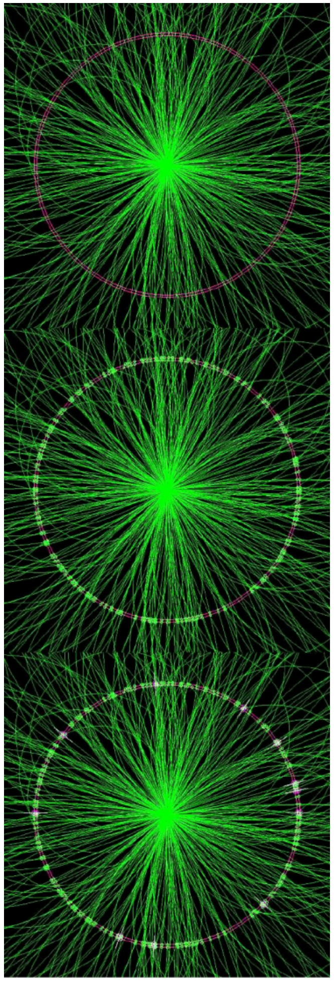
→ E.g. in the upgraded CMS Tracker the sensors need to withstand fluences up to 1.5×10^{15} 1 MeV neutrons cm^{-2}.



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: *granularity, powering, cooling, connectivity, triggering, low mass, low cost !*

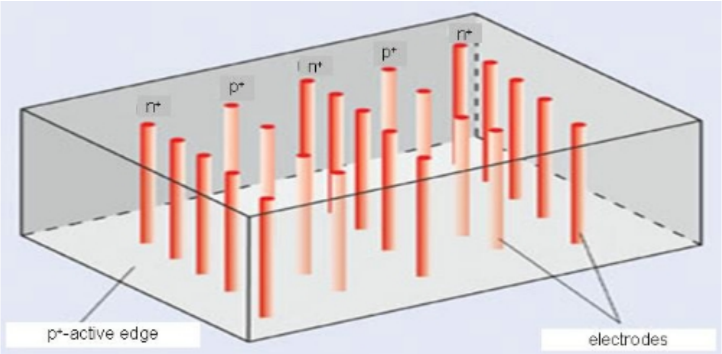
Future tracking devices

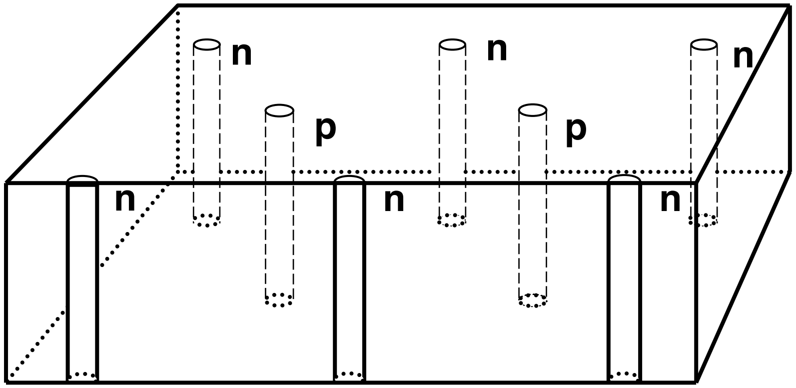
- For the high-luminosity experiments new solutions have to be developed.
- This can be achieved by:
  - Material and defect engineering of silicon.
    - Understanding the radiation damage and influence of processing technology, e.g. oxygen enriched material
  - Looking for new promising materials.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



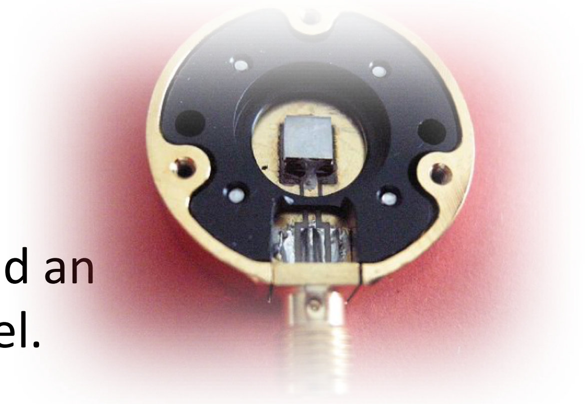
3D detectors

- 3D detectors have doped electrodes penetrating through the entire substrate.
- The generated carriers are collected on the electrodes.
- Compared to the microstrip and pixel detectors, 3D detectors have the advantages of fast collection time, active edge (no dead area at the edges) and low depletion voltage.
- However, the processing of 3D detectors is very complex.





Diamond detectors



- Large band gap and high binding energy make diamond an ideal material for particle detectors on theoretical level.
- However, the availability of natural single crystal silicon or high pressure high temperature (HPHT) synthetic material is poor.
- Diamonds are, however, used already e.g. In beam monitoring applications (beam luminosity monitors) that require extreme radiation hardness.