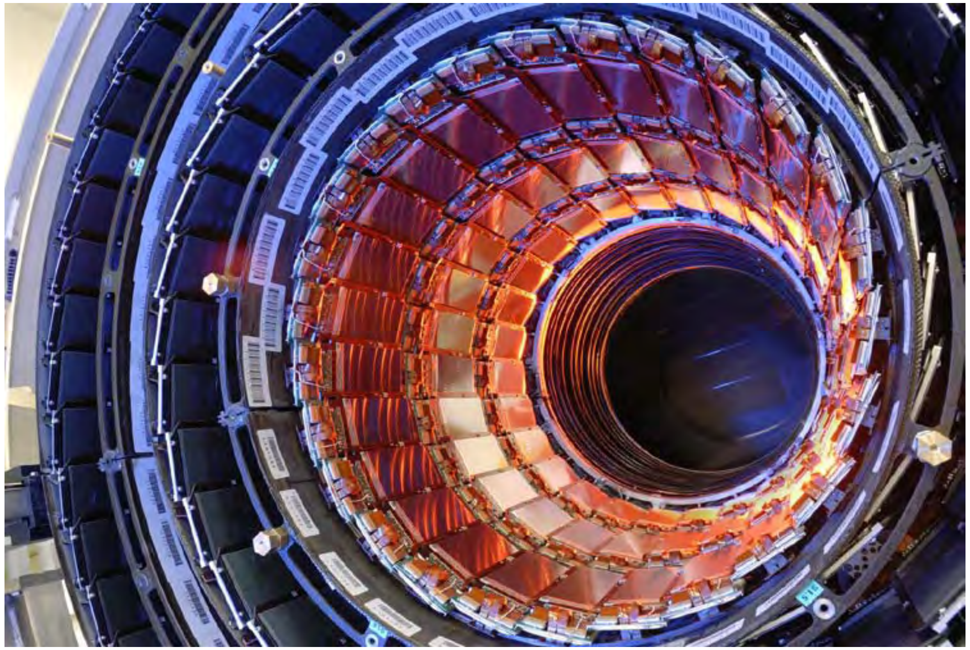
HEPHY
Institute of High Energy Physics

ÖAW
Österreichische Akademie der Wissenschaften



Silicon Detectors in CMS

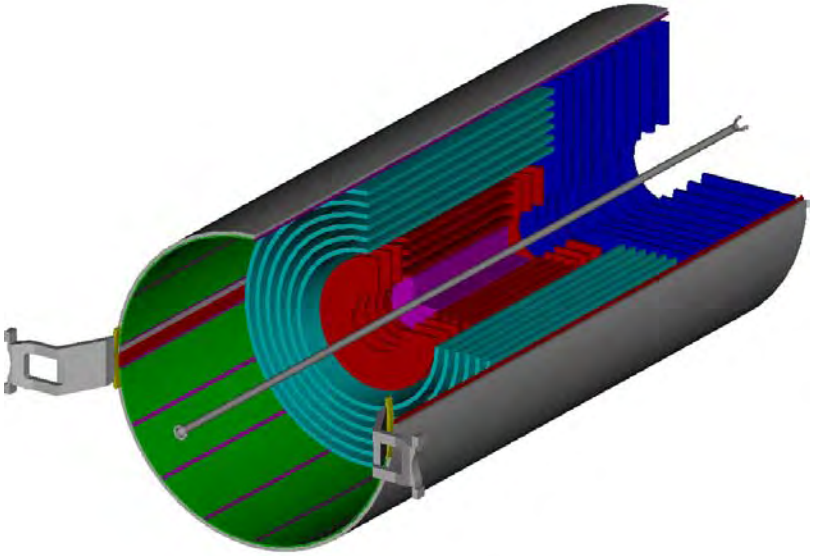
Thomas Bergauer (HEPHY Vienna)

IPM Teheran

8 October 2013

Content

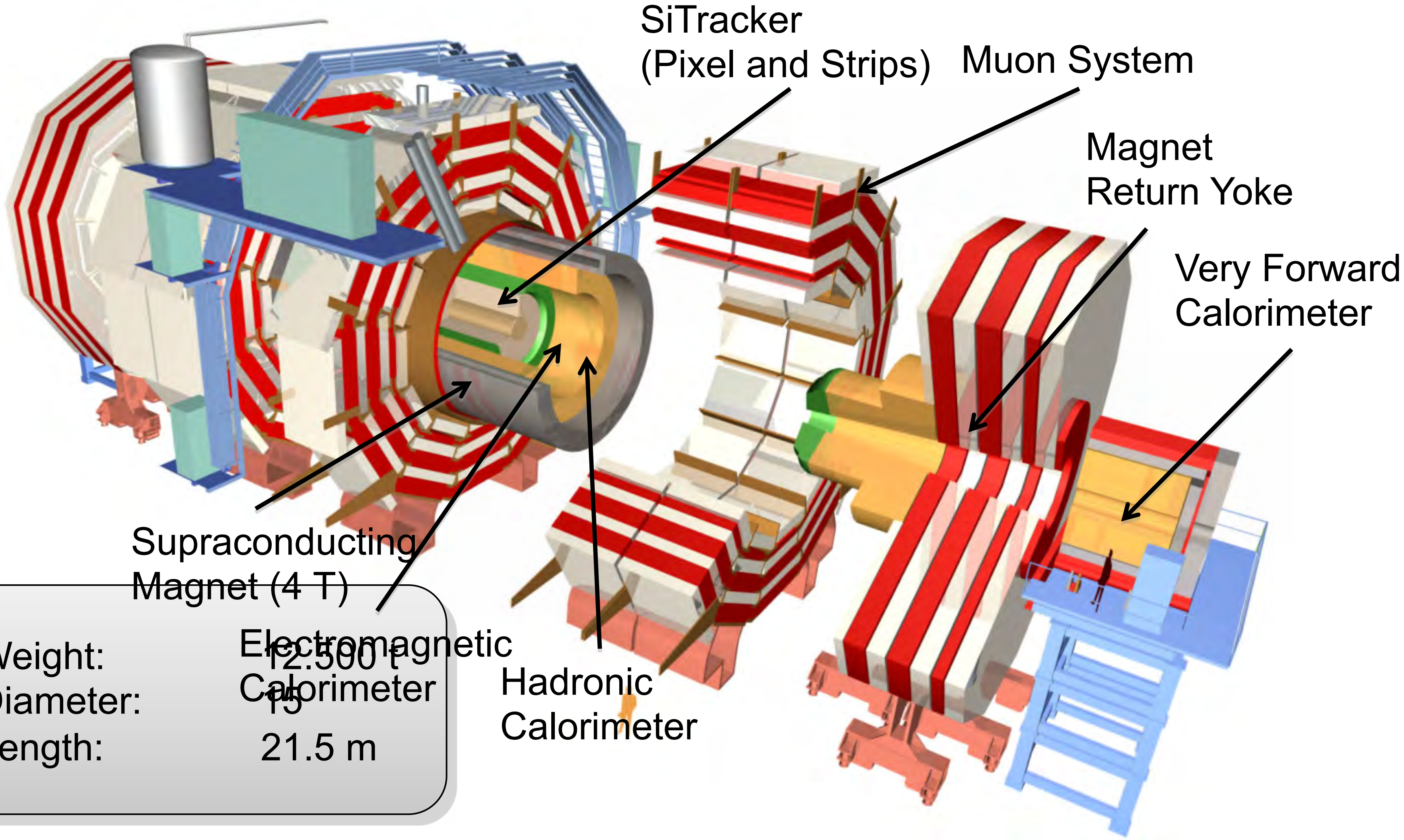
- CMS Tracker Layout and Elements
  - Readout electronics
- Brief Physics of silicon strip detectors
  - more details in 1st IPM Detector school http://particles.ipm.ir/conferences/DetectorSchool2011/
- Silicon Sensor Fabrication Technologies
- Radiation Damage in Silicon



Layout and Elements

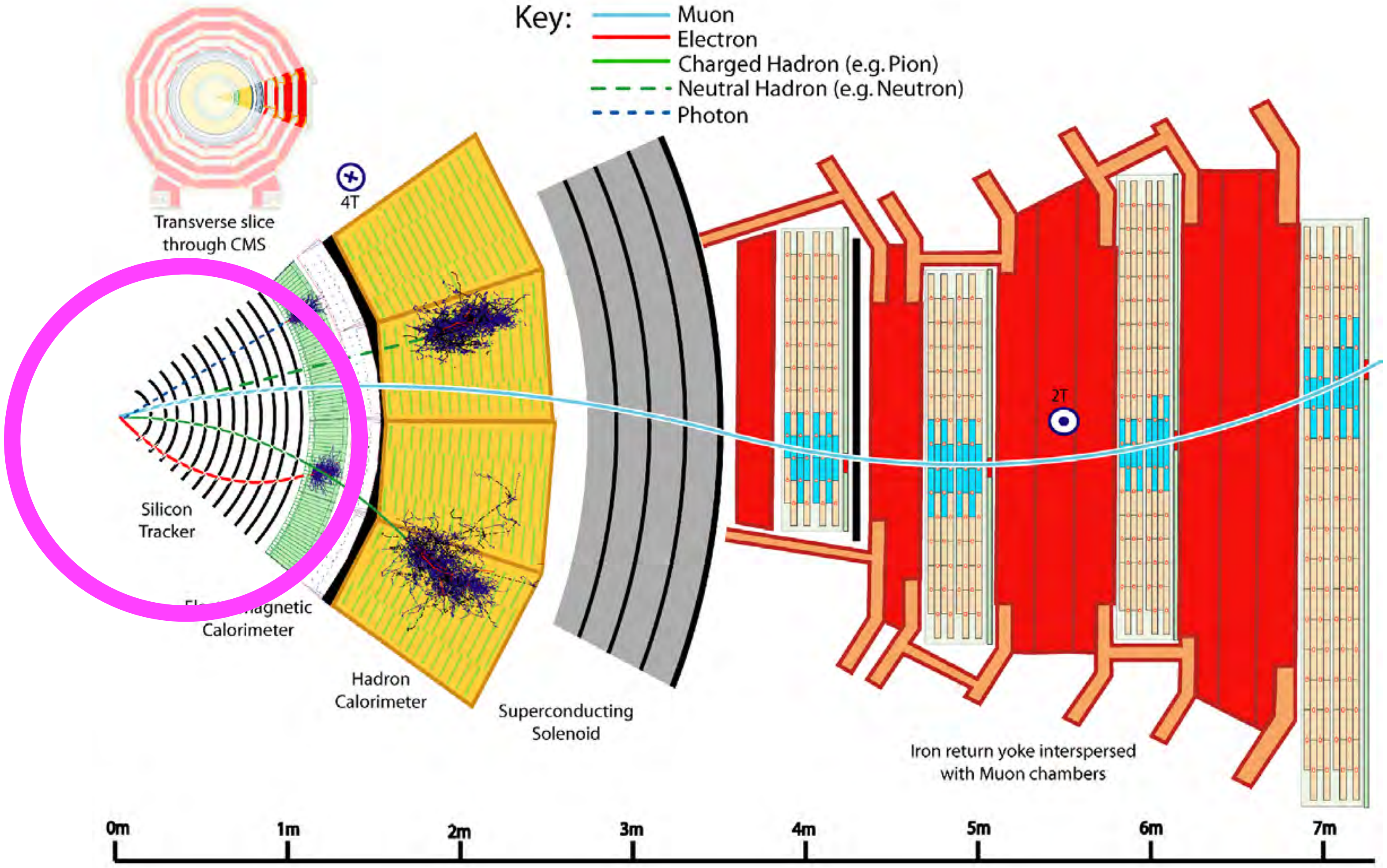
CMS TRACKER

CMS: Compact Muon Solenoid

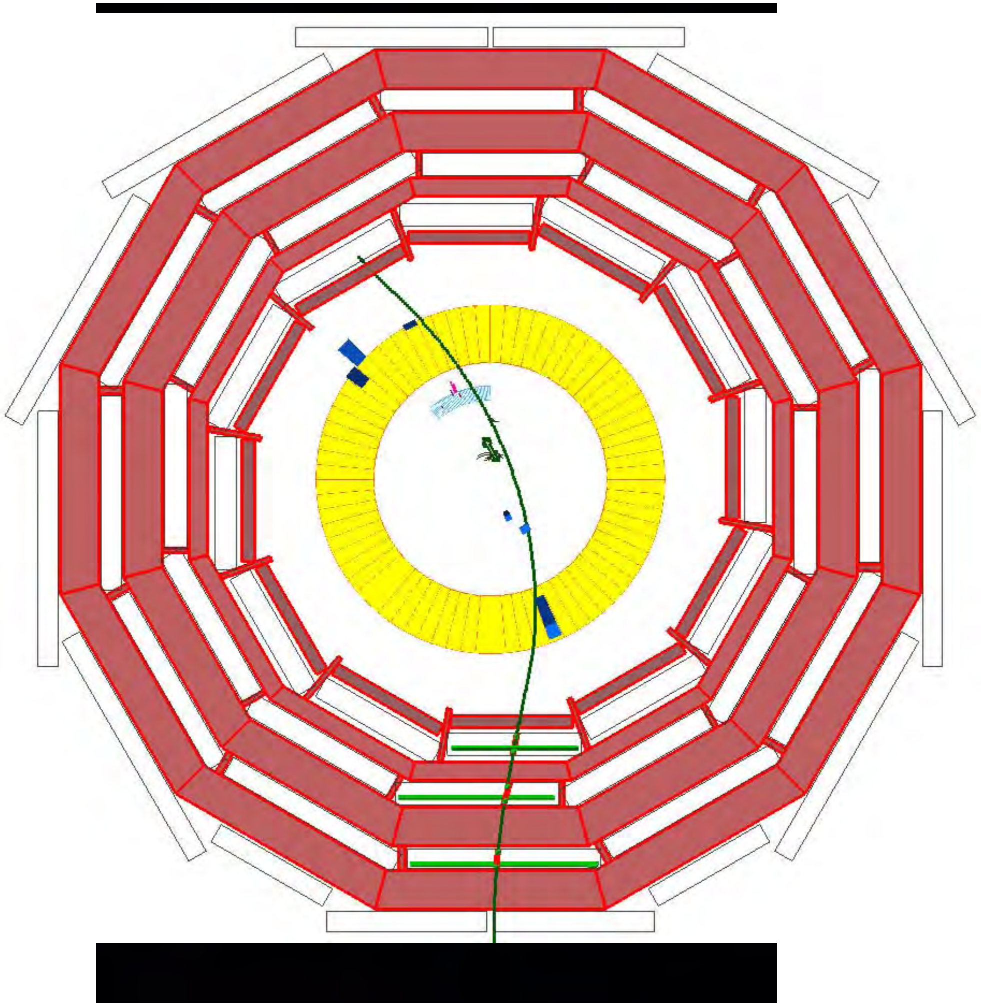


Weight: 12.500 t
Diameter: 15
Length: 21.5 m

Compact Myon Solenoid



Why “Tracker”?



Measure: space points

Reproduce: particle tracks

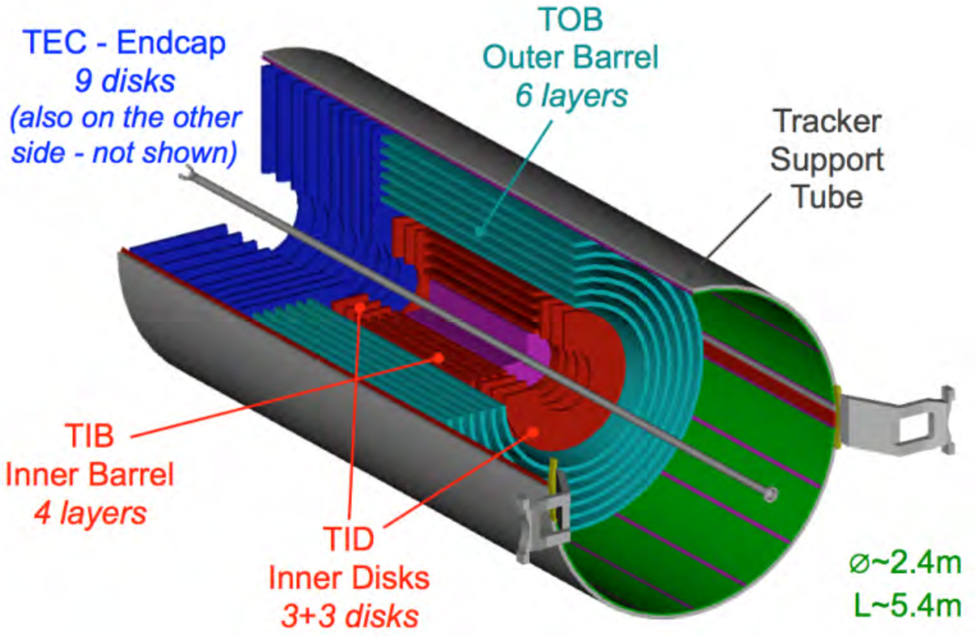
Deduce:

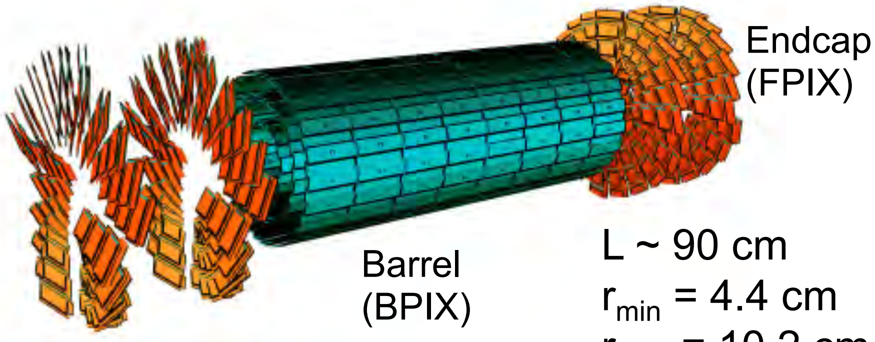
- vertex location
- decay length
- impact parameter
- Particle momentum via curvature of track

CMS Silicon Tracker

Silicon pixel + strip detector with optical analog readout

- Pixel :
  - N+ in n sensors : 100 µm x 150 µm
  - Barrel: 3 layers (56cm long) at r= 4.3,7.2, 11.0 cm ➔ 48M pixels, 11520 ROCs, 1120 RO links
  - Endcap (FPix) : 4 disks inner (outer) radius=6 (15) cm at z= ±34.5, ±46.5 cm
  - ➔ 18M pixels, 4320 ROCs, 192 RO links
- Strip :
  - 9.3M strips in 15148 modules :
  - Inner: 4 layers barrel (TIB), 3 disks (TID) cap
  - Outer:6 layers barrel (TOB), 9 disks (TEC)cap 200m2 silicon sensor (p-in-n) :
  - Pitch from 80 to 205 µm 20<r<55 cm thin (d=320 µm) r>55 cm thick (d=500 µm)
  - Generally measure rΦ direction
  - Some radii (’Stereo’): additional 2nd modules rotated by 100 mrad





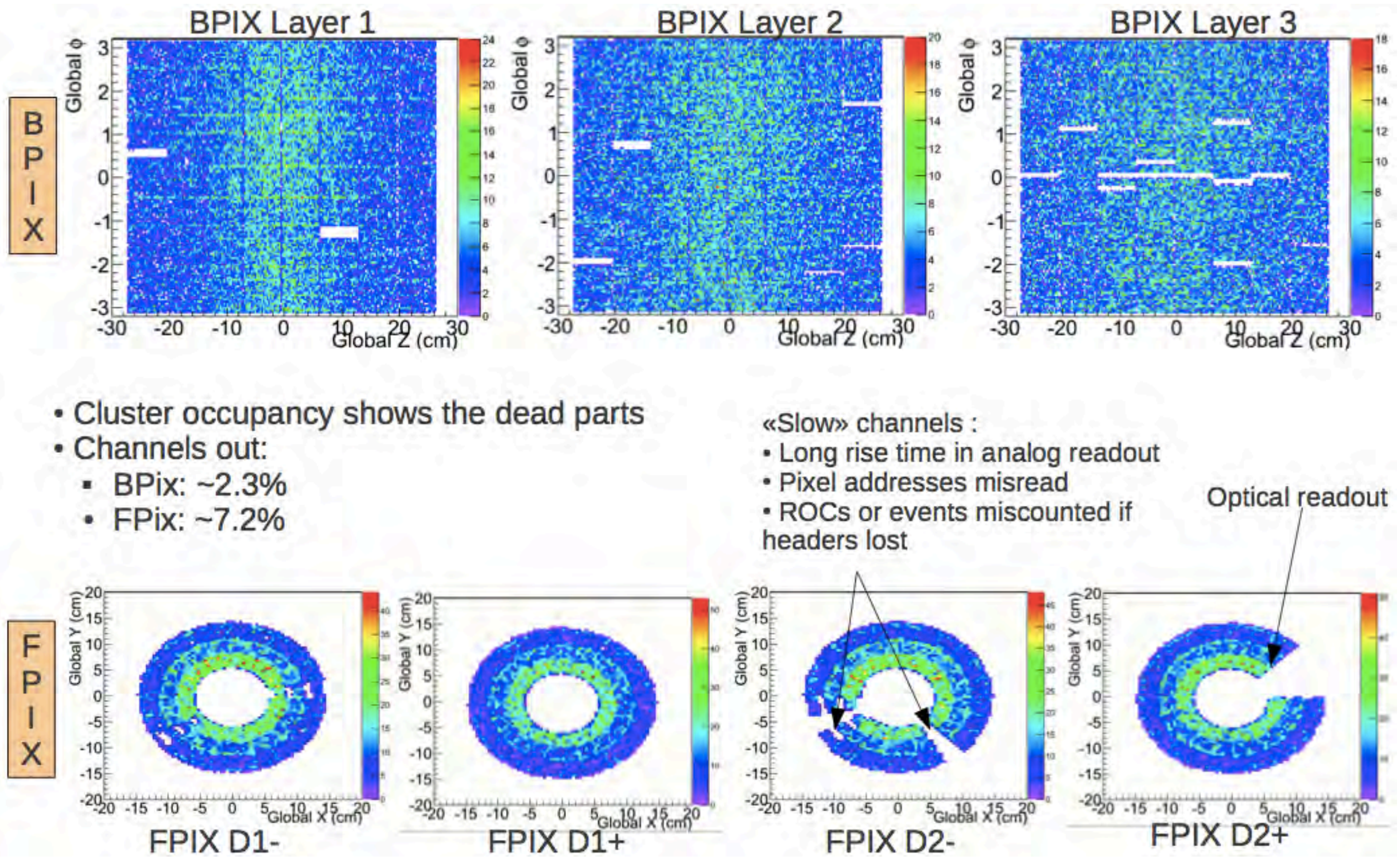
L ~ 90 cm

r_{min} = 4.4 cm

r_{max} = 10.2 cm

Pixel Sensor Operation Status

at end of run 1

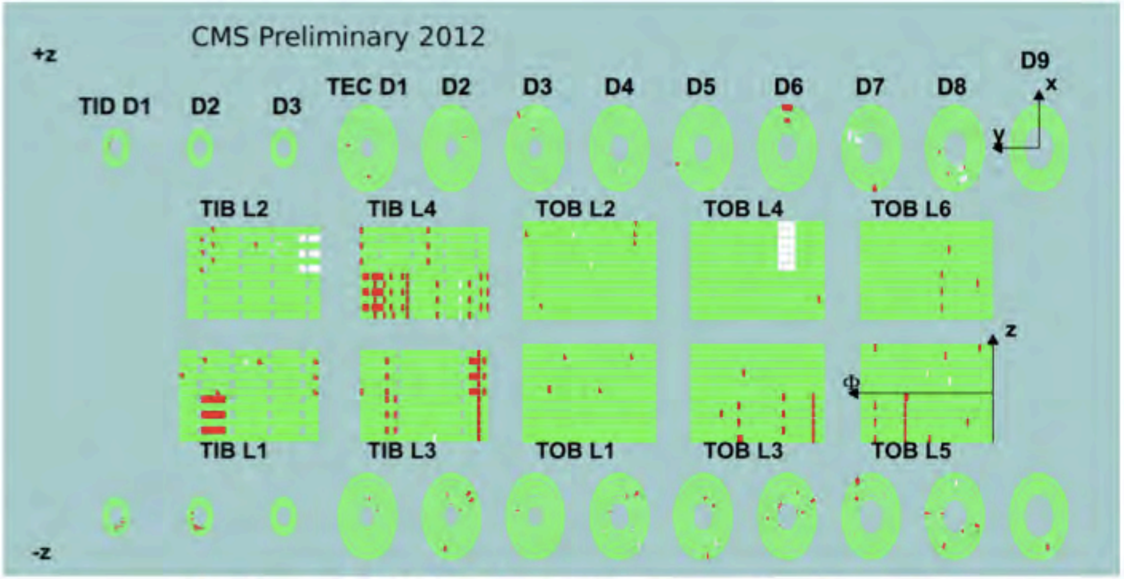


- Cluster occupancy shows the dead parts
- Channels out:
  - BPix: ~2.3%
  - FPix: ~7.2%

«Slow» channels :

- Long rise time in analog readout
- Pixel addresses misread
- ROCs or events miscounted if headers lost

Strip Tracker Operation Status at end of run 1



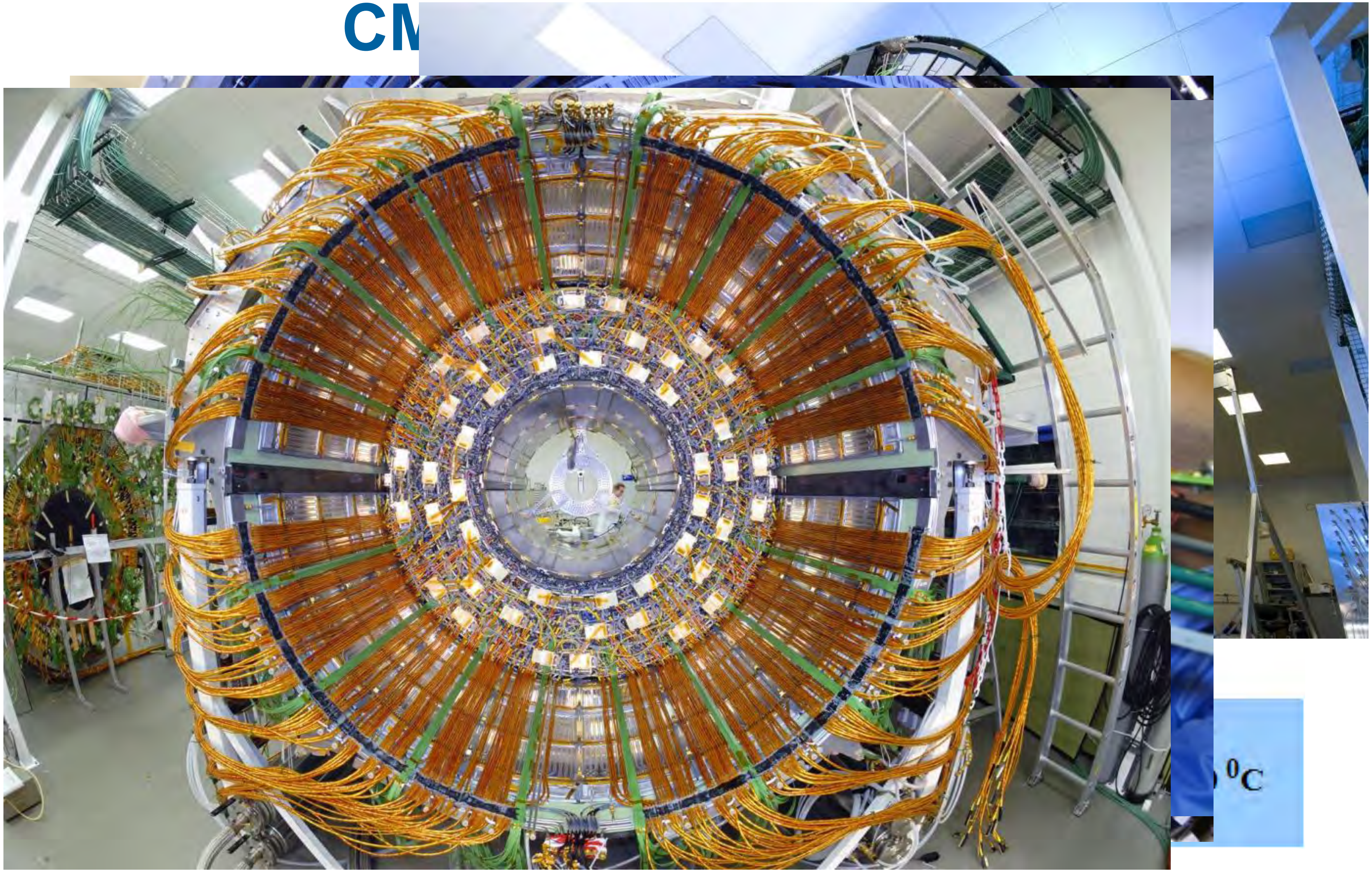
Active, Masked, Not Commissioned

- Active fraction > 97.5%
    - No/low impact on track reconstruction as many layers
- Stable :
    - 98.5% (2008) ->97.75 % (2011)
- Can't be removed for recovery (as pixel)

Reasons for masking :

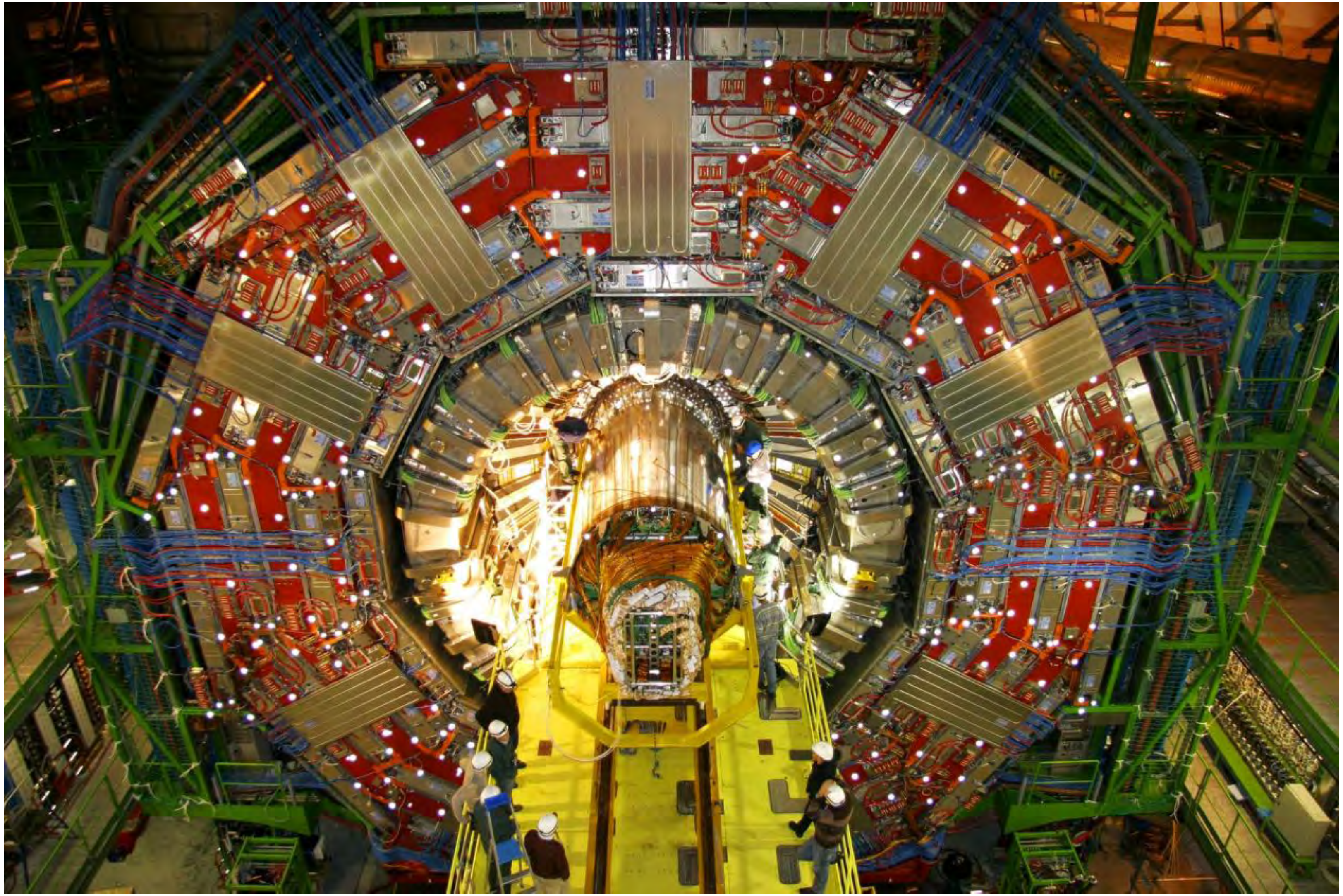
- Control ring shorts
- Control rings not functioning
- HV line shorts
- HV lines open
- Fibres, Communication and Control Units (CCU)

CM

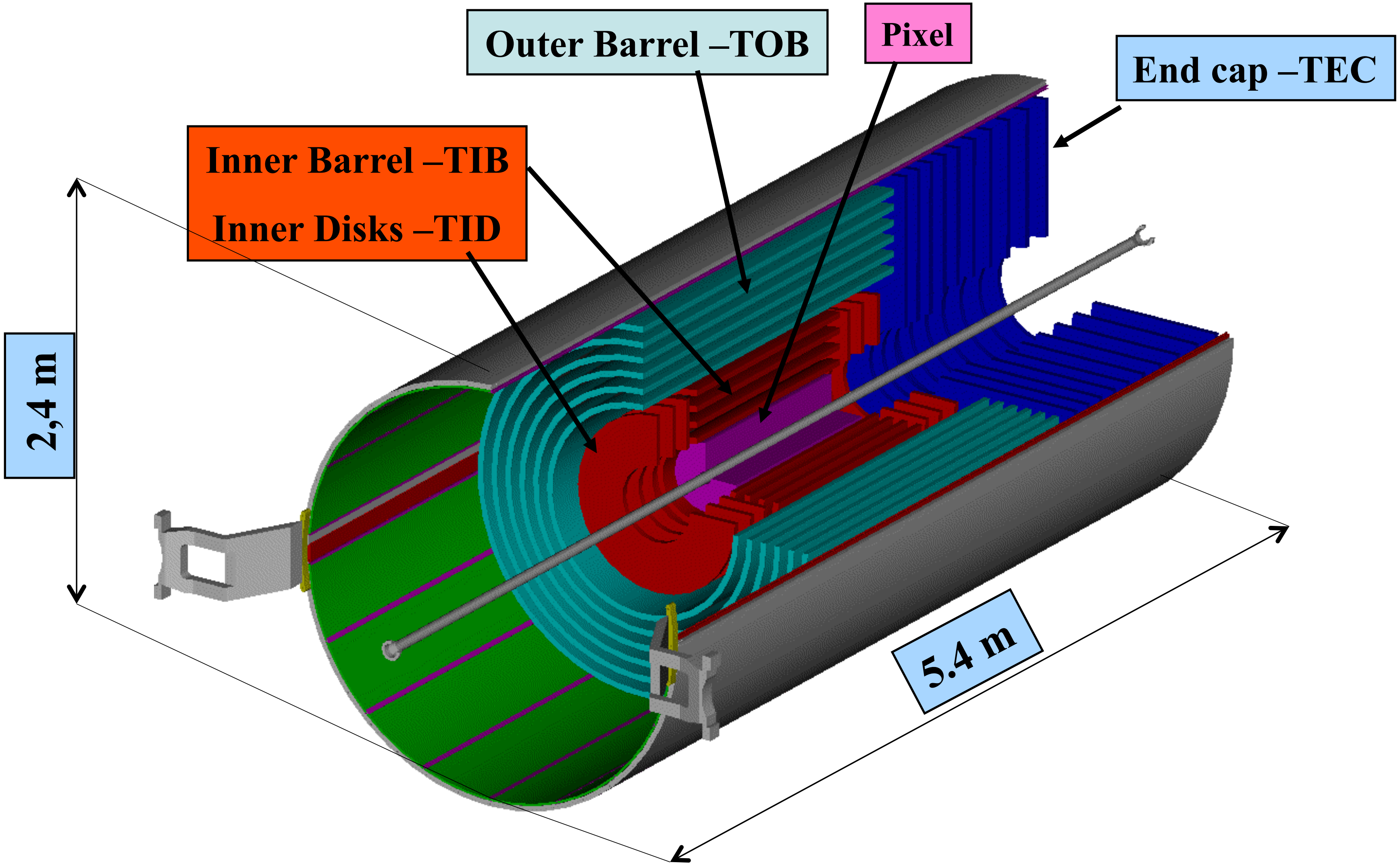


^{0}C

CMS Tracker Installation December 2007



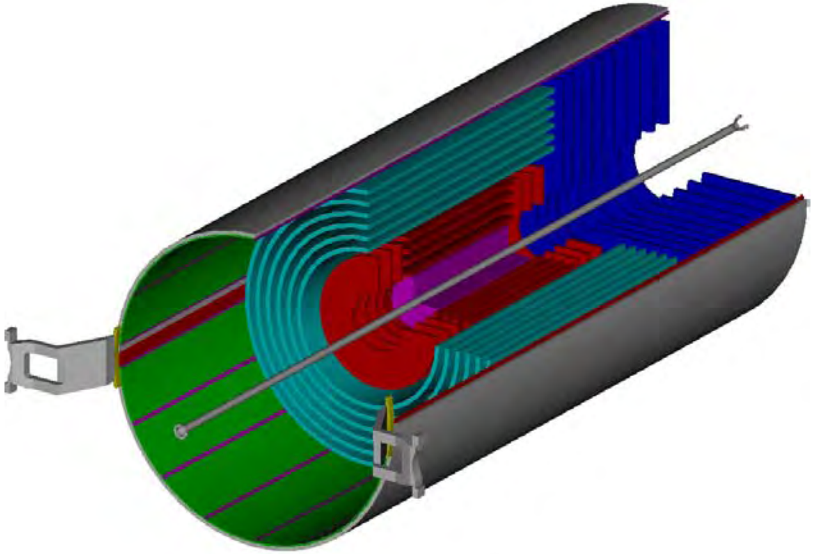
CMS Tracker


Outer Barrel –TOB
Pixel
End cap –TEC
Inner Barrel –TIB
Inner Disks –TID
2,4 m
5.4 m

CMS Tracker Numbers

- 6.136 thin detectors with one thin sensor (TIB, TID, inner TEC)
- 9.096 modules with two thick sensors (TOB, outer TEC)
- 29 module designs
- 16 sensor designs
- 12 hybrid designs
- 9.648.128 Strips (electronics channels)
- 75.376 readout chips (APV25)
- 26.000.000 Bond wires
- 37.000 optical links
- 3000 km optical fibres

- Diameter: 2,4 m
- Length: 5,4 m
- Operating T: -10°C
- Dry atmosphere for 10 years
- Radiation Levels
  > $1.6*10^{14}$ 1MeV Neq./cm²

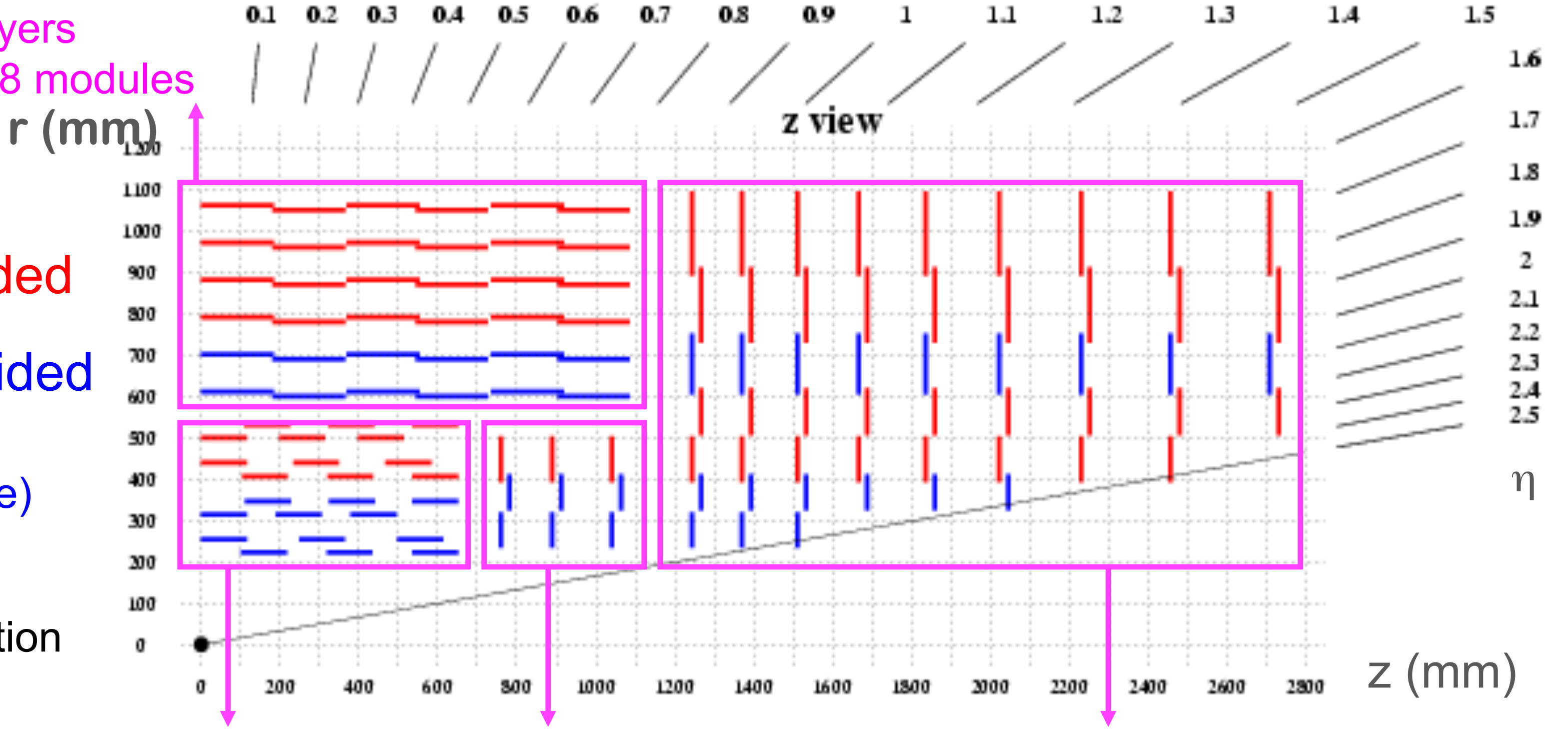


CMS Tracker layout

TOB
6 layers
5208 modules

Single sided

Double sided
(100 mrad stereo angle)



Interaction point

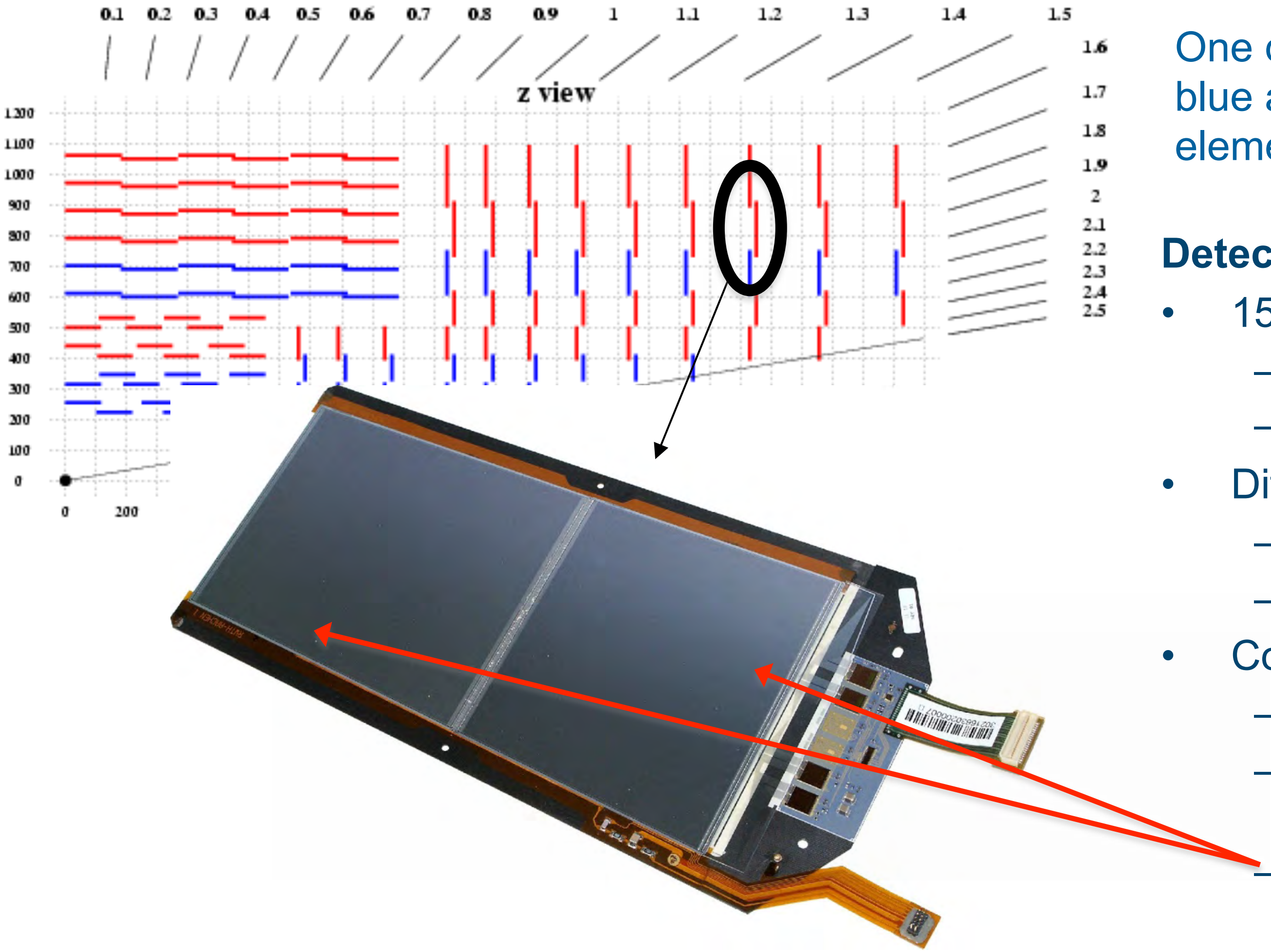
TIB
4 layers
2724 modules

TID
2x3 disks
816 modules

TEC
2x9 disks
6400 modules

Barrel: strips parallel to beam
End cap: strips in radial direction

CMS Strip Tracker: Elementary Parts

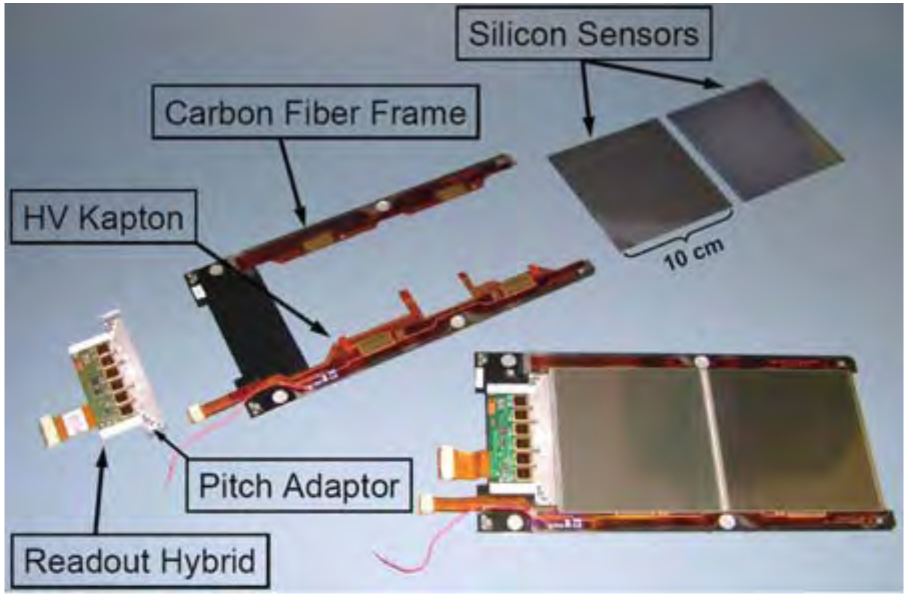


One quarter of silicon strip tracker: blue and red lines represent each elementary component:

Detector Module

- 15.148 pieces in total
  - Red: single sided modules
  - Blue: double sided modules
- Different Geometries
  - 4 rectangular (TIB und TOB)
  - 11 trapezoid (TID und TEC)
- Components
  - Carbon fiber/graphite frame
  - Front End Hybrid housing readout chip
  - One or two silicon sensors

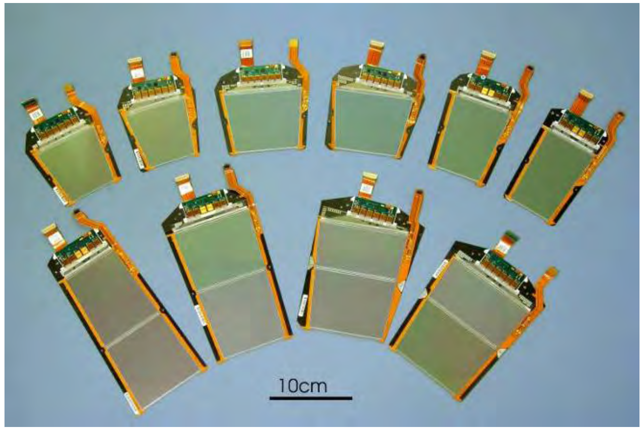
Basic Element of the Tracker: Module

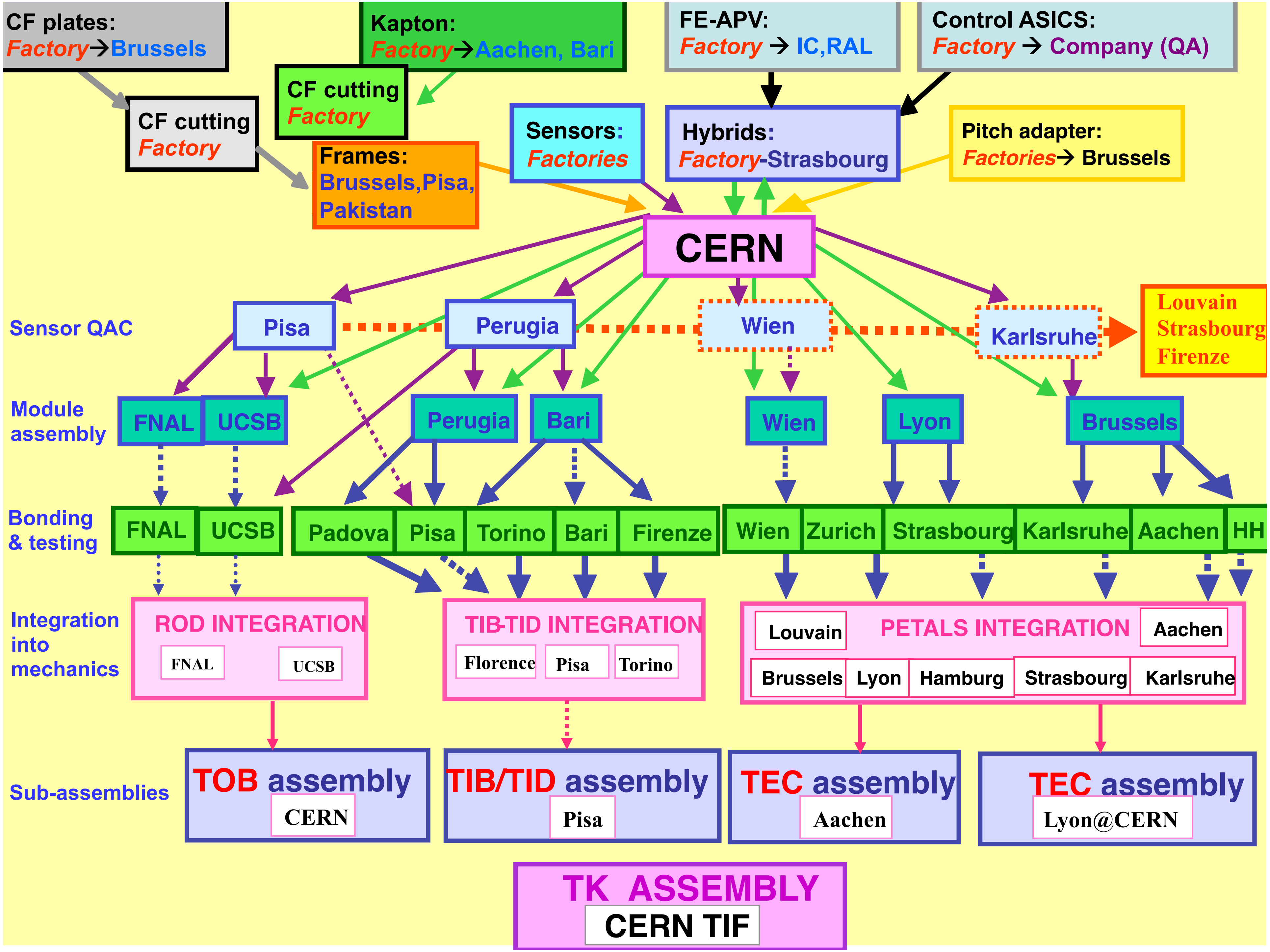


Components:

- Carbon fiber/graphite frame
- Kapton flex circuit for HV supply
- Front End Hybrid housing readout chip
- Pitch Adaptor
- One or two silicon sensors

Total:
- 29 module designs
- 16 sensor designs
- 12 hybrid designs





CF plates:
Factory→Brussels

Kapton:
Factory→Aachen, Bari

FE-APV:
Factory → IC,RAL

Control ASICS:
Factory → Company (QA)

CF cutting
Factory

CF cutting
Factory

Frames:
Brussels,Pisa,
Pakistan

Sensors:
Factories

Hybrids:
Factory-Strasbourg

Pitch adapter:
Factories→ Brussels

CERN

Sensor QAC: Pisa, Perugia, Wien, Karlsruhe → Louvain, Strasbourg, Firenze

Module assembly: FNAL, UCSB, Perugia, Bari, Wien, Lyon, Brussels

Bonding & testing: FNAL, UCSB, Padova, Pisa, Torino, Bari, Firenze, Wien, Zurich, Strasbourg, Karlsruhe, Aachen, HH

Integration into mechanics:

ROD INTEGRATION: FNAL, UCSB

TIB-TID INTEGRATION: Florence, Pisa, Torino

PETALS INTEGRATION: Louvain, Aachen, Brussels, Lyon, Hamburg, Strasbourg, Karlsruhe

Sub-assemblies:

TOB assembly: CERN

TIB/TID assembly: Pisa

TEC assembly: Aachen

TEC assembly: Lyon@CERN

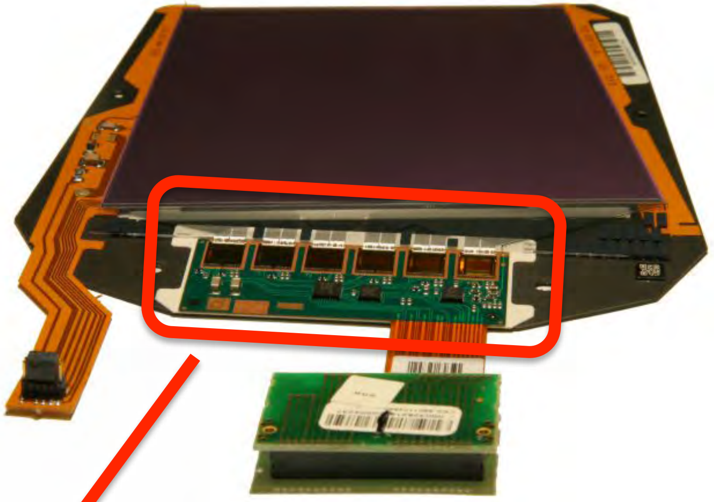
TK ASSEMBLY
CERN TIF

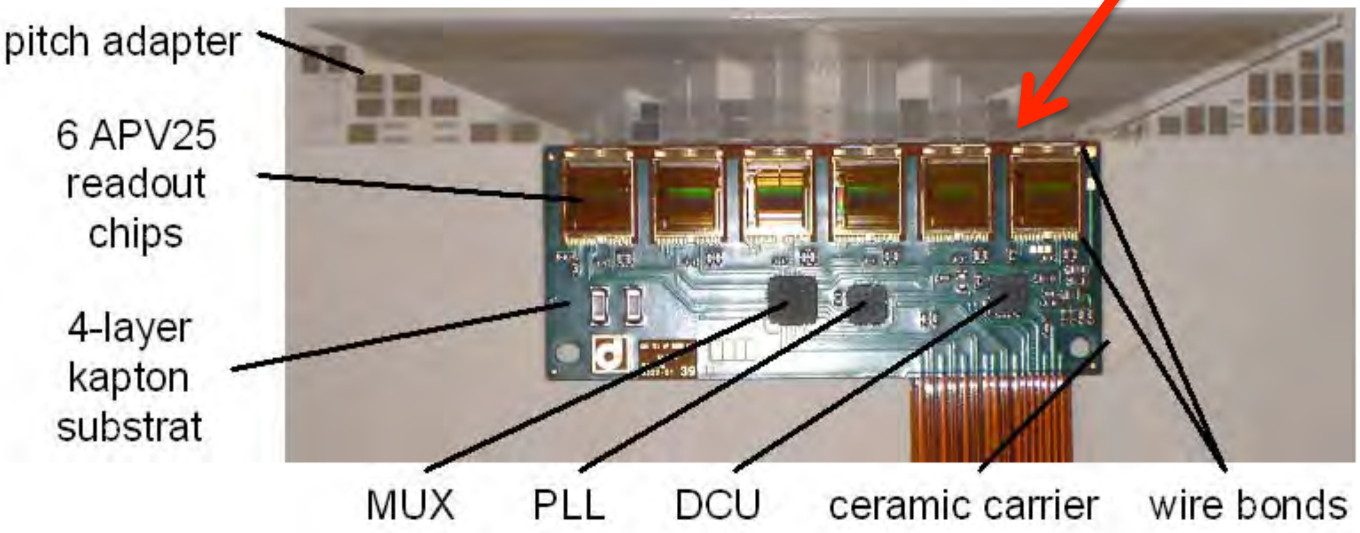
From Modules to Tracks

READOUT ELECTRONICS

Frontend (FE) Hybrid

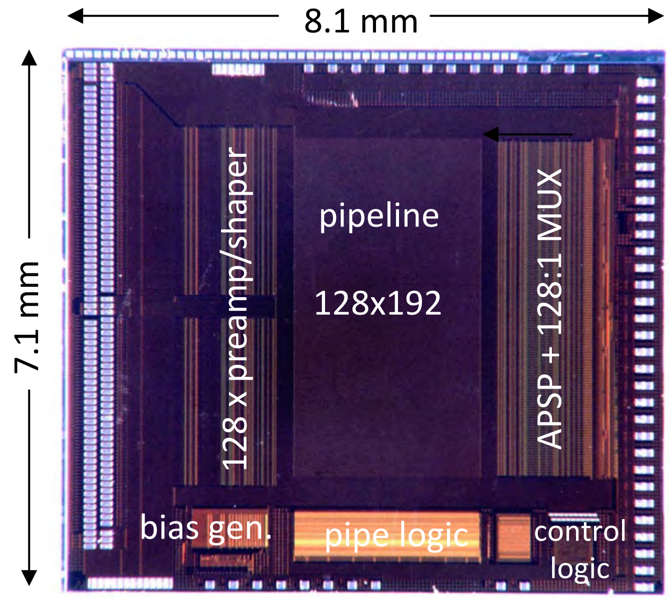
- “Hybrid” is a sandwich of
  - Several layers of Kapton (Polyiimide)
  - ceramic carrier
- Hybrids equipped with
  - 4 or 6 APV25 readout chips (custom made ASIC chip for CMS)
  - Several other helper chips
  - Wire bonds to pitch adapter

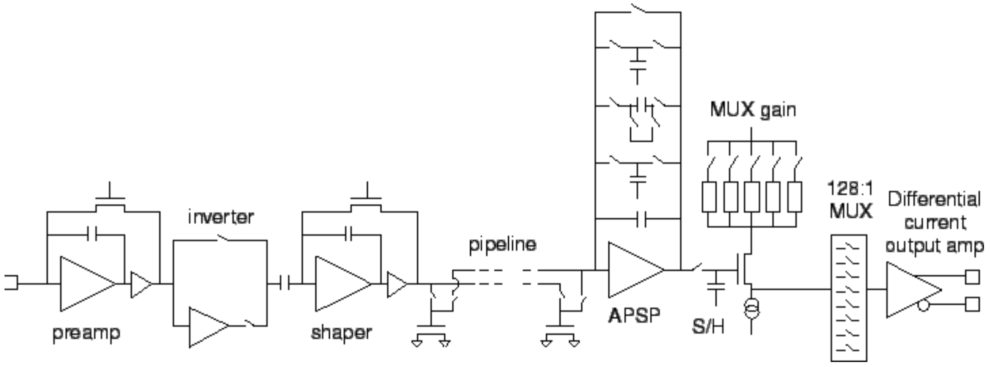




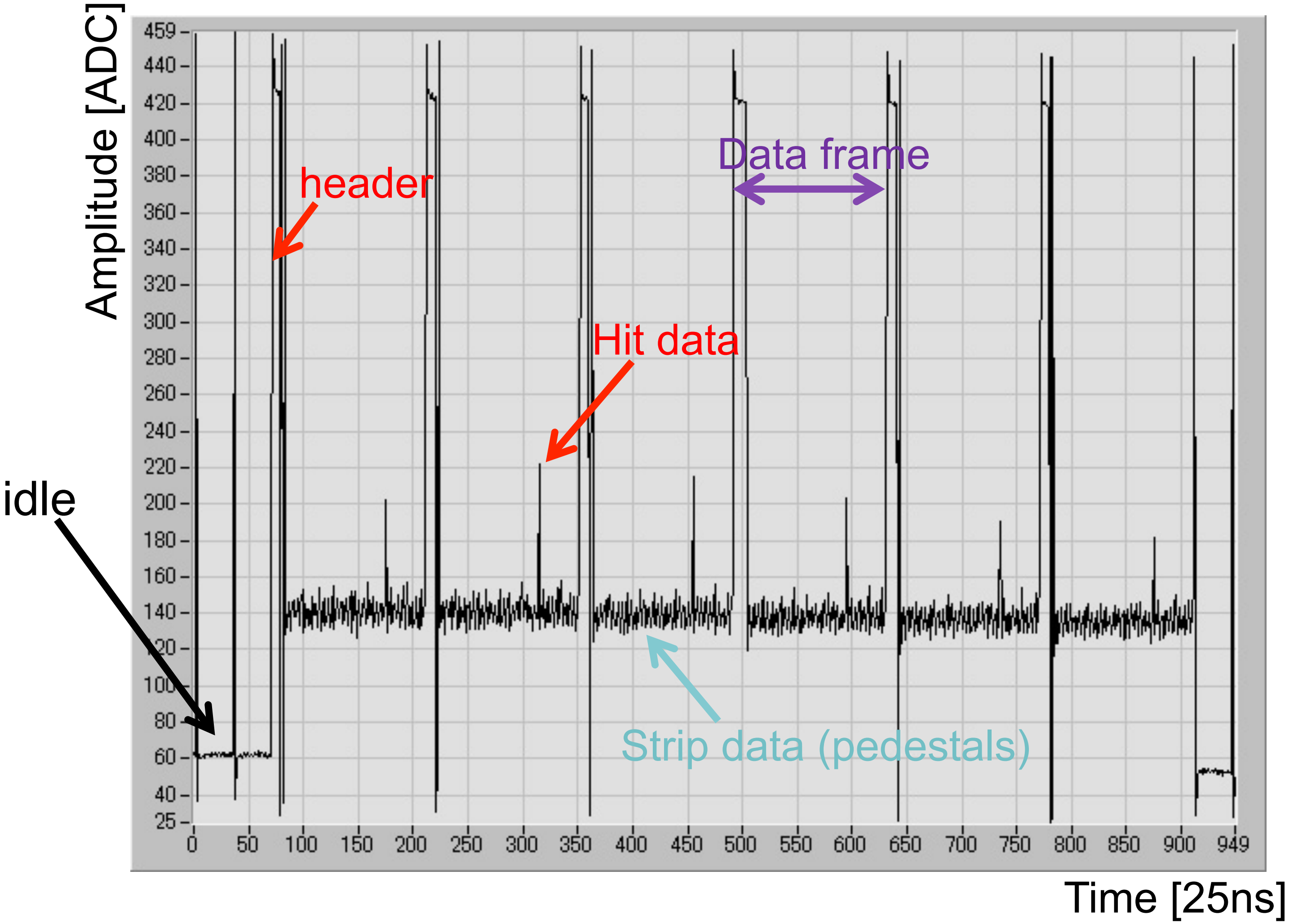
APV 25 Frontend (FE) Readout Chip

- 0.25 µm CMOS process (**>100 MRad tolerant**)
- 128 channels
- **192 cell analog pipeline**
- **50 ns shaping time**
- **Different operation modes:**
  - **Peak**
  - **Deconvolution Mode**
  - **Multi-peak mode** (read out several samples along shaping curve)
- **Noise:** 250 e + 36 e/pF (peak), 400 e + 60 e/pF (decon)

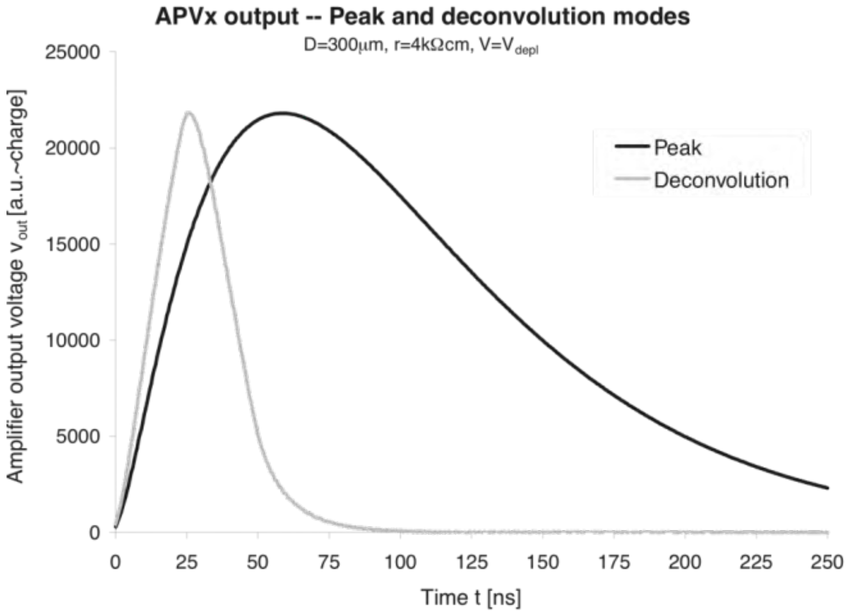




Example: APV25 Output Data Stream



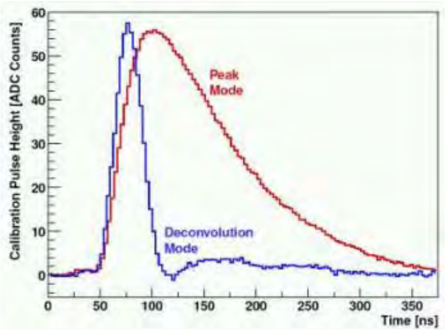
APV25 Peak vs. Deconvolution mode

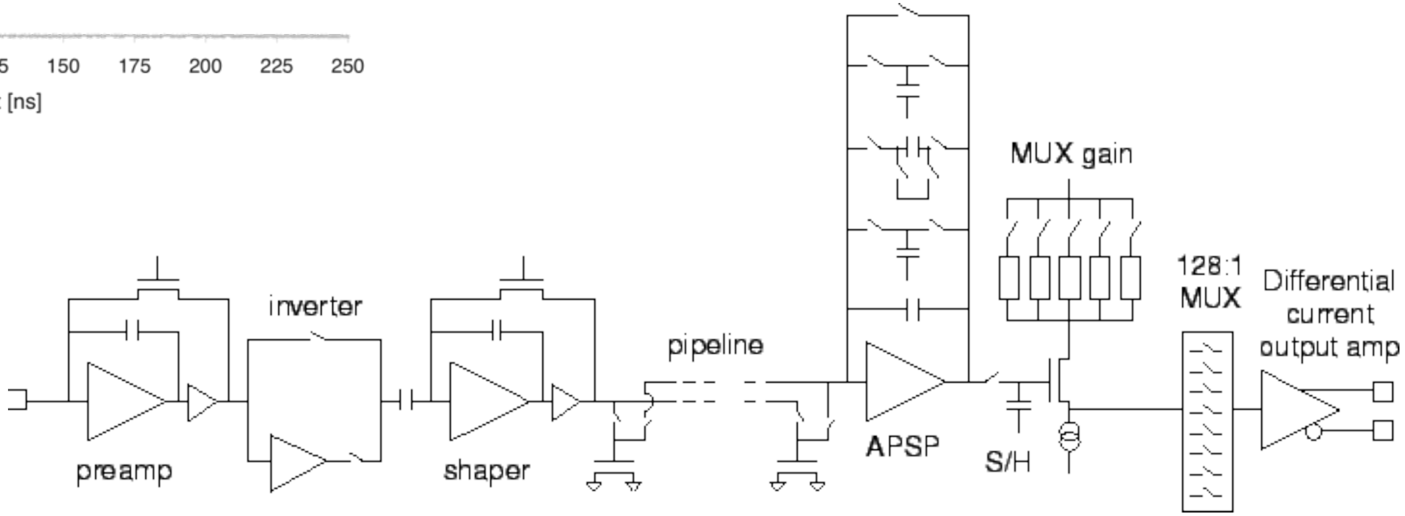


Deconvolution mode

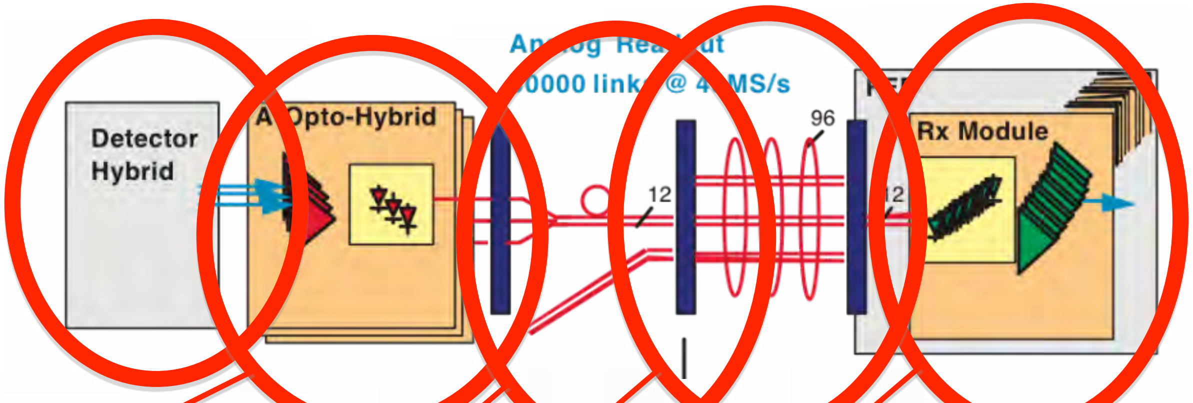
- output charge for each strip represents a weighted sum of three consecutive pipeline cells (APSP)
- designed to avoid signal pile-up in high luminosity operations
- necessary whenever bunch separation is less than a few hundred nanoseconds

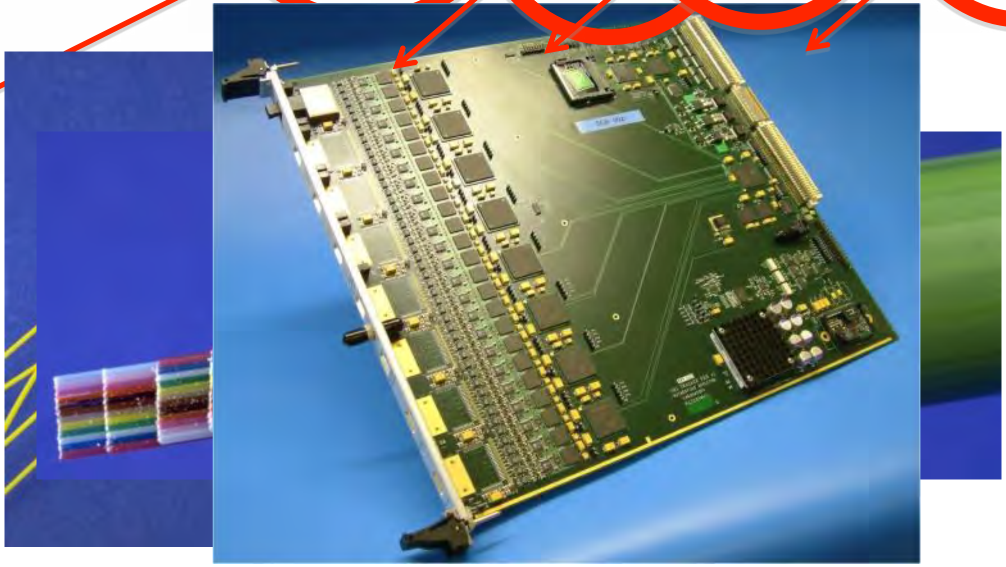
$$d_k = w_3 p_{k-2} + w_2 p_{k-1} + w_1 p_k$$





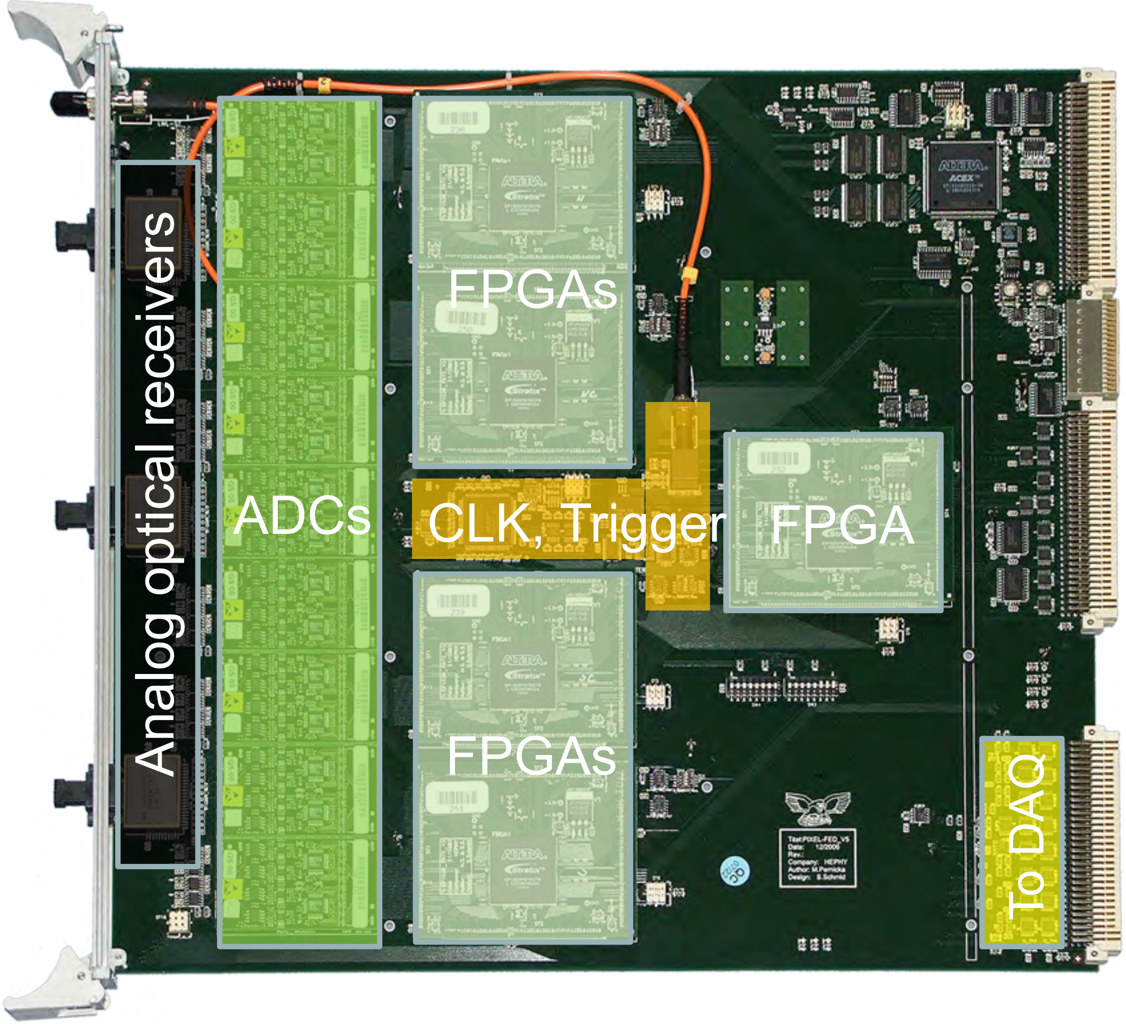
Readout Chain: Data Path





FED Board

- FED means “Front End Driver” (misleading)
- 9U VME Board
- Contains
  - analog optical receivers,
  - ADCs,
  - Clock and Trigger processors
  - Reads out 96 channels



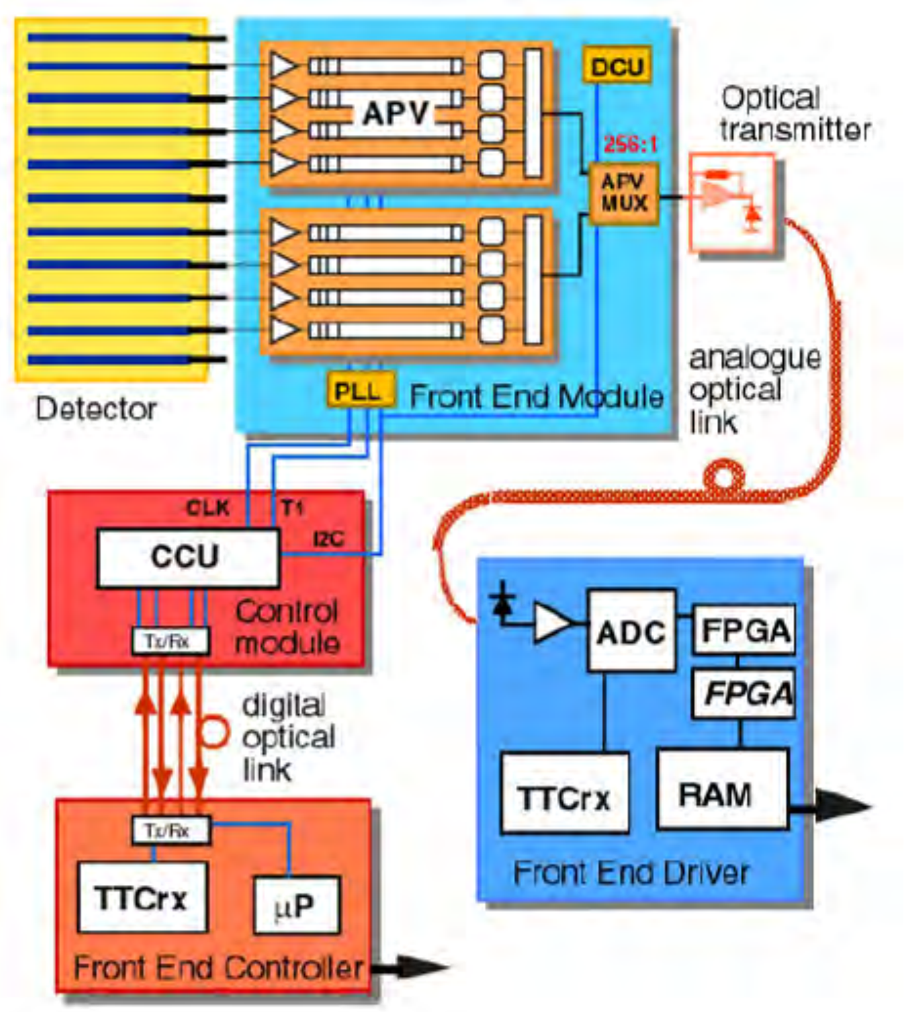
Readout Chain: Control Path

Data Flow:

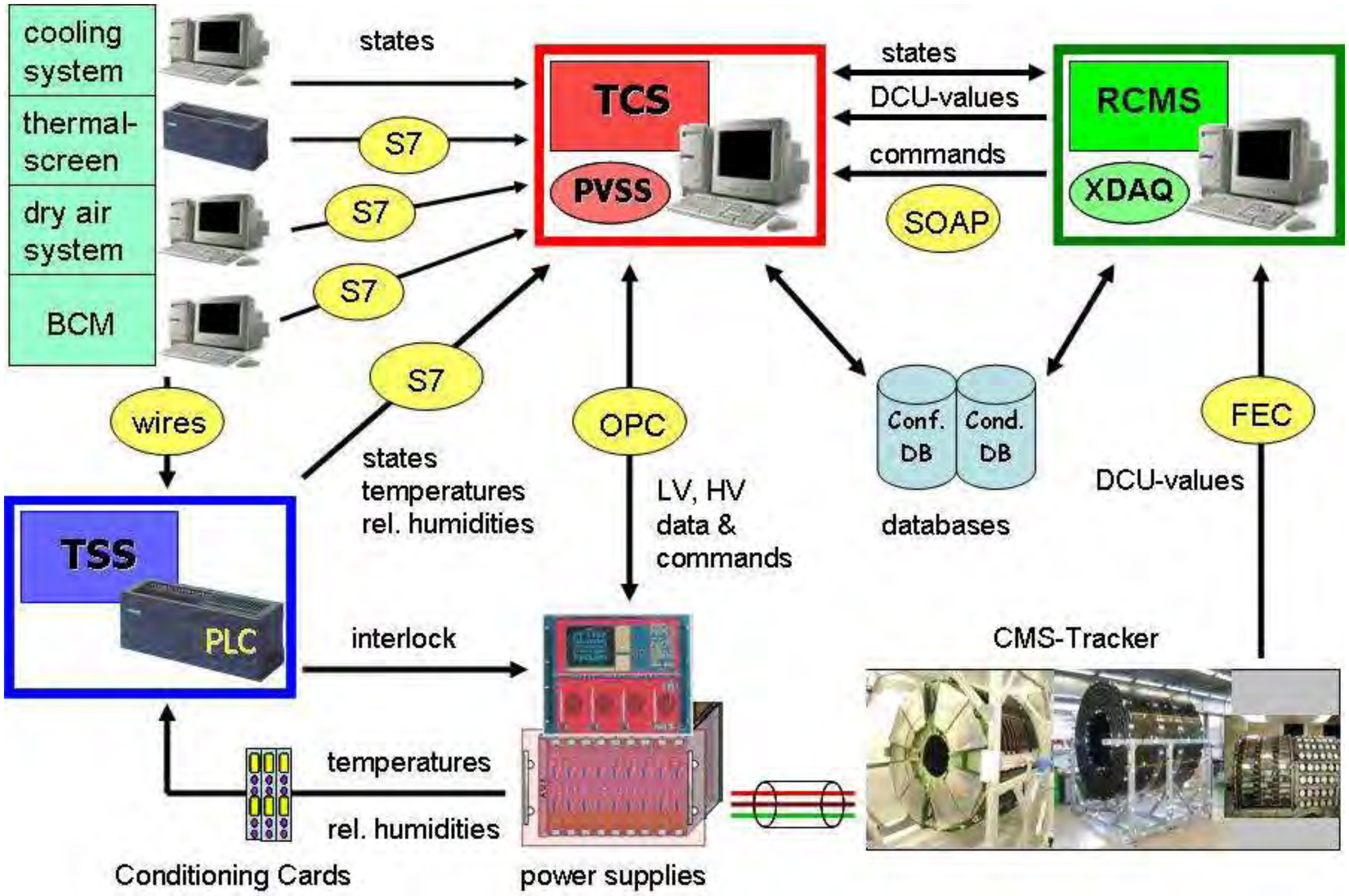
- Silicon Sensor
- FE Hybrid with APV chip
- AOH (optical transmitter)
- FED (Front End Driver) with ADCs

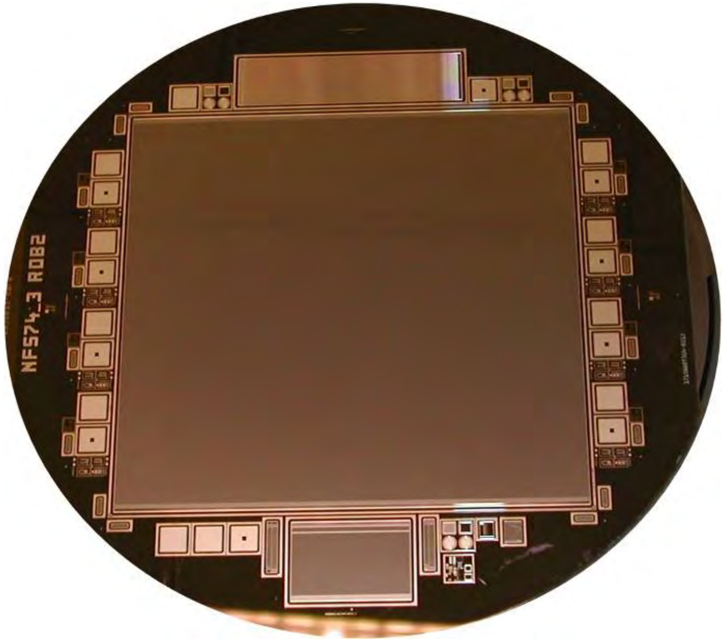
Control Path:

- FEC (Front End Controller)
- DOH (optical transmitter)
- CCU provides Clock, Trigger and I^{2}C communication



Slow Control: Schematics





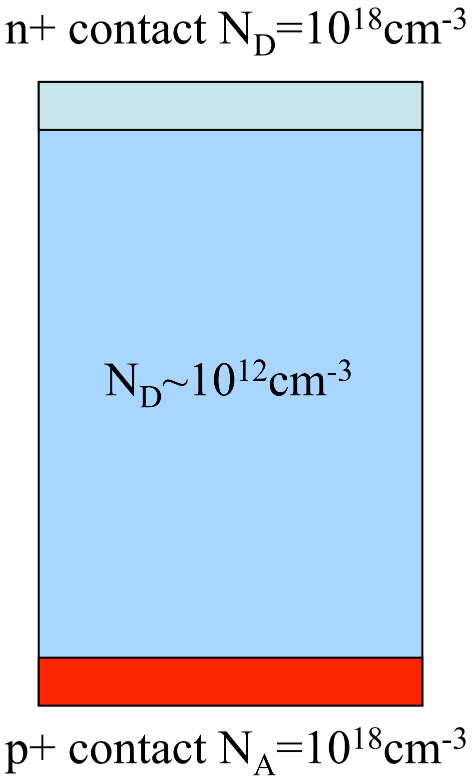
Very brief

PHYSICS OF SILICON DETECTORS

more details in 1st IPM Detector school
http://particles.ipm.ir/conferences/DetectorSchool2011/

Detector = p-i-n diode

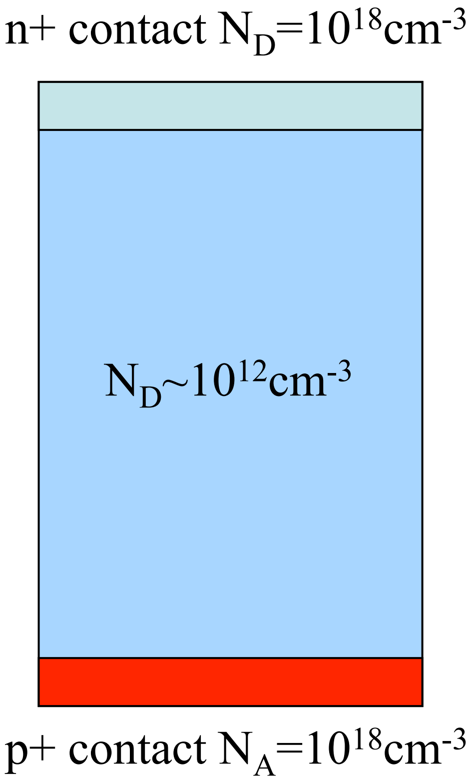
- Almost intrinsic bulk
- Highly doped contacts
- Apply bias voltage
  (-V on p^+ contact)
  - Deplete bulk
  - High electric field
- Radiation creates carriers
  - signal quanta
- Carriers swept out by field
  - Induce current in external circuit
    ⇒ signal



Is a p-i-n diode really working?

- traversing particle generates signal = 23.000 electron/hole pairs (for 300 μm thick sensor)
- Intrinsic carrier concentration
  - $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$
  - Si area = 1cm^2, thickness=300 μm $\Rightarrow 4.5\text{x}10^8$ electrons
  - 4 orders of magnitude larger than signal
- Need to deplete device of free carriers
- Use reversely biased pn-junction (diode) to create depleted space-charge region

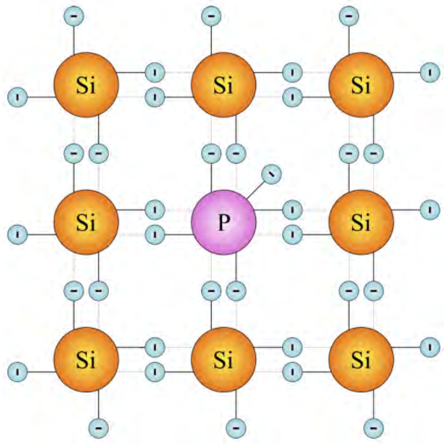
p-i-n diode:

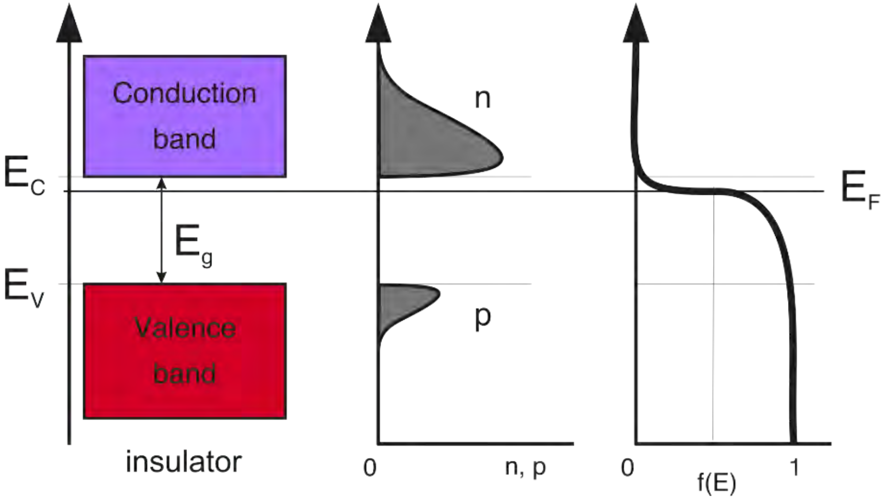


Doping: n- and p-type Silicon

n-type:

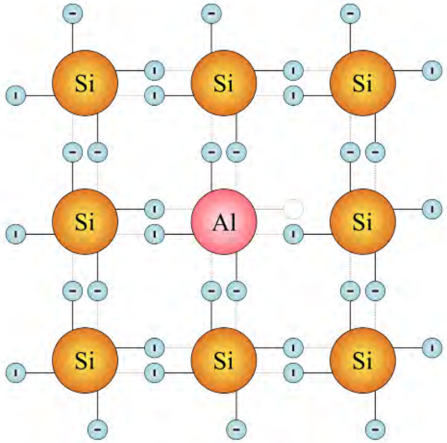
- Donor (electron abundance)
- Dopants: Elements with 5 valence electrons, e.g. Phosphorus

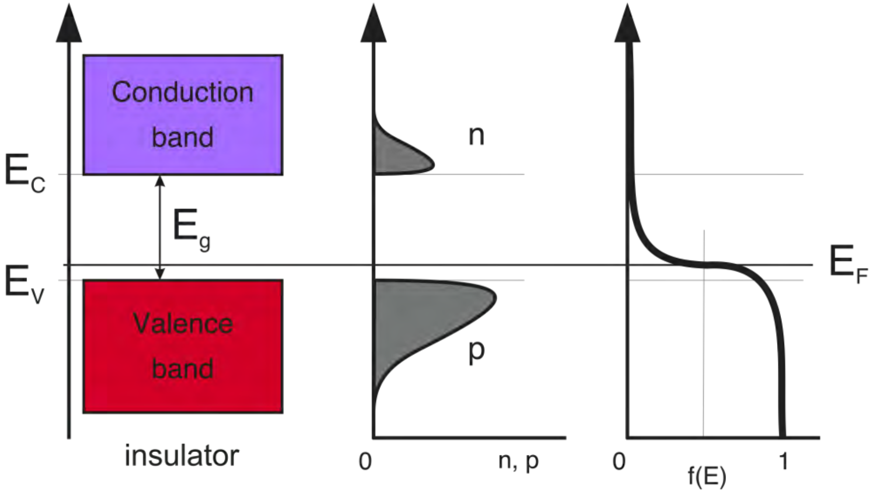




p-type:

- Acceptor (electron shortage)
- Dopants: Elements with 3 valence electrons, e.g. Aluminum





pn-Junction

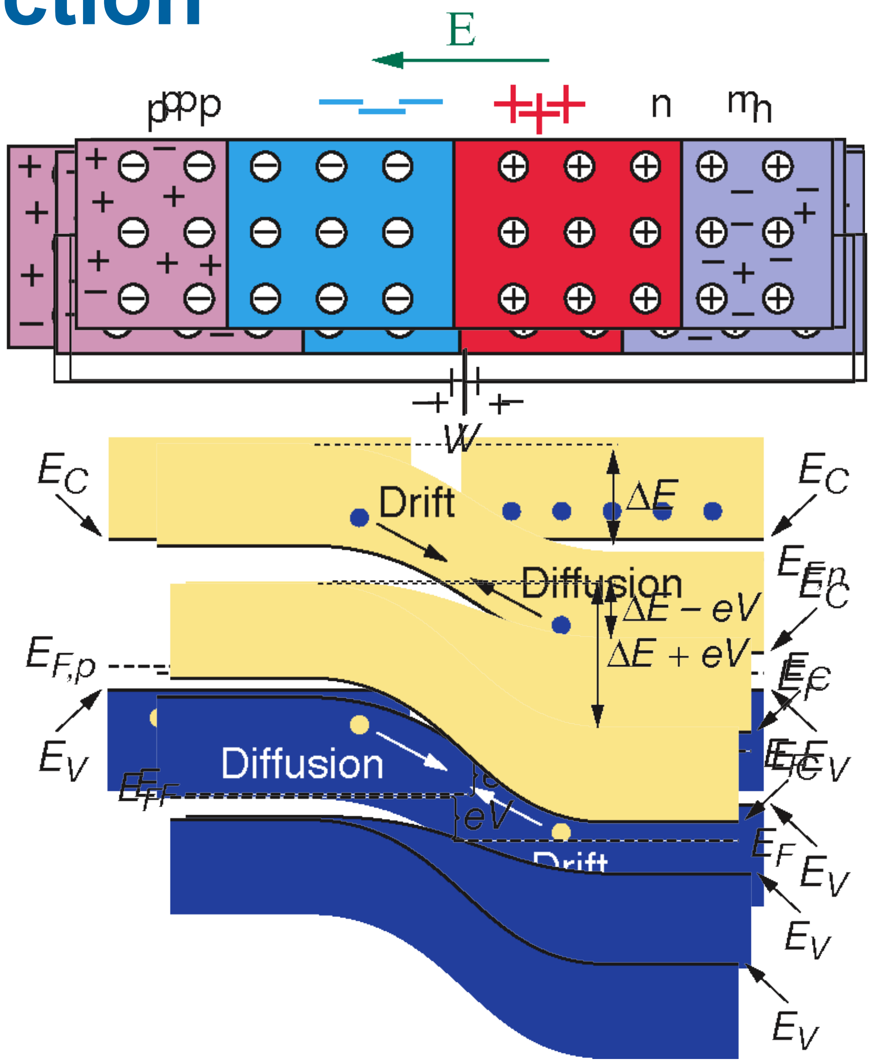
1) take your neutral but doped samples
2) bring together – free carriers move
   - two forces drift and diffusion
   - In stable state: $J_{diffusion} = J_{drift}$
3) Space charge region emerges
   - Also called depletion region

External positive voltage:

- Called “forward bias”
- Space charge region small
- Device conducts

External negative voltage:

- Called “reverse bias”
- Space charge region grows
- Device does not conduct



Width of depletion region

in p-region:

$$W_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0(V_0 - V)}{eN_a(1 + N_a/N_d)}}$$

in n-region:

$$W_n = \sqrt{\frac{2\varepsilon_r\varepsilon_0(V_0 - V)}{eN_d(1 + N_d/N_a)}}$$

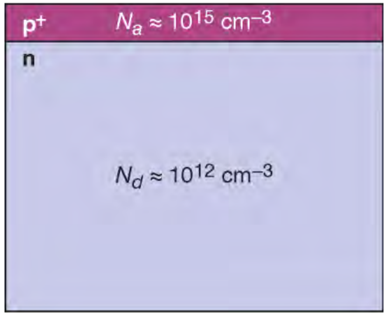
V_0 … built-in voltage (diffusion)
V … external voltage

Total width of depletion region equals to:

$$W = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{e} \cdot (V_0 - V) \cdot \left(\frac{1}{N_d} + \frac{1}{N_a}\right)}$$

$$\boxed{W \approx \sqrt{2\varepsilon_0\,\varepsilon_r\,\mu\,\rho\,|V|}}$$

e.g. V=100 V:
W_p = 0.4 µm
W_n = 363 µm



with: $\rho = \frac{1}{e\mu N_{eff}}$

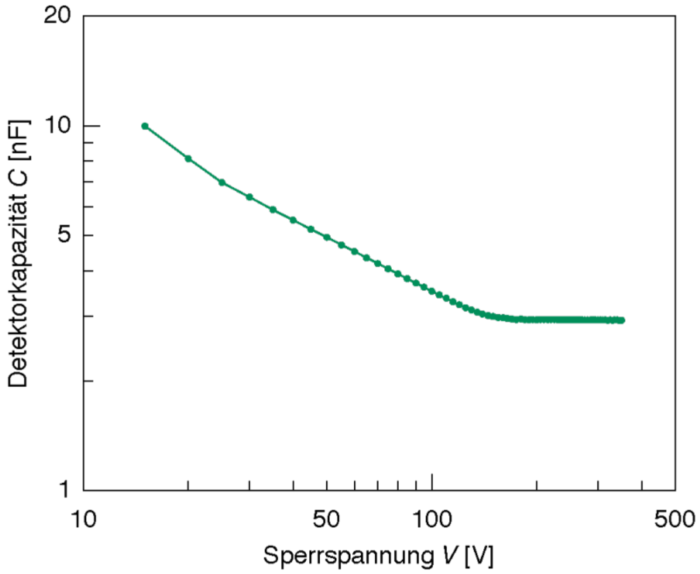
V … external voltage
ρ … resistivity of bulk material
μ … Charge mobility
ε_0, ε_r permittivity
N_{eff} … effective doping concentration in bulk material

Detector Capacitance

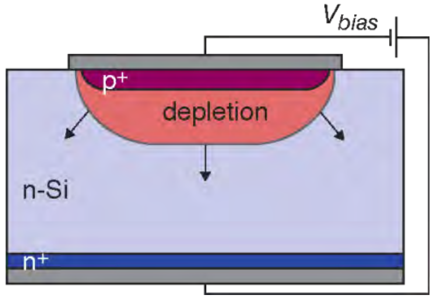
- Capacitance is due to movement of charge in the junction
- Fully depleted detector capacitance defined by geometric capacitance

$$C = \frac{\varepsilon_0\varepsilon_r \cdot A}{W} = \sqrt{\frac{e\varepsilon_0\varepsilon_r N_a N_d}{2(N_a + N_d)\cdot|V|}}\cdot A$$

$$\boxed{C = \sqrt{\frac{\varepsilon_0\varepsilon_r}{2\mu\rho|V|}}\cdot A}$$



ρ … bulk resistivity
μ … charge mobility
V … voltage
A … junction area

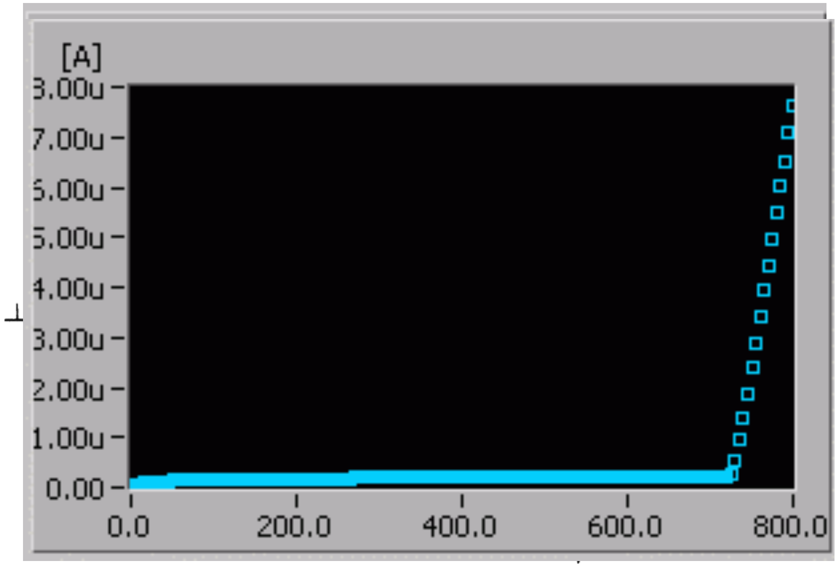


Reverse current

- Diffusion current
  - From generation at edge of depletion region
  - Negligible for a fully depleted detector

- Generation current
  - From generation in the depletion region
  - Reduced by using material pure and defect free
    - high carrier lifetime
  - Must keep temperature low & controlled

- Breakthrough

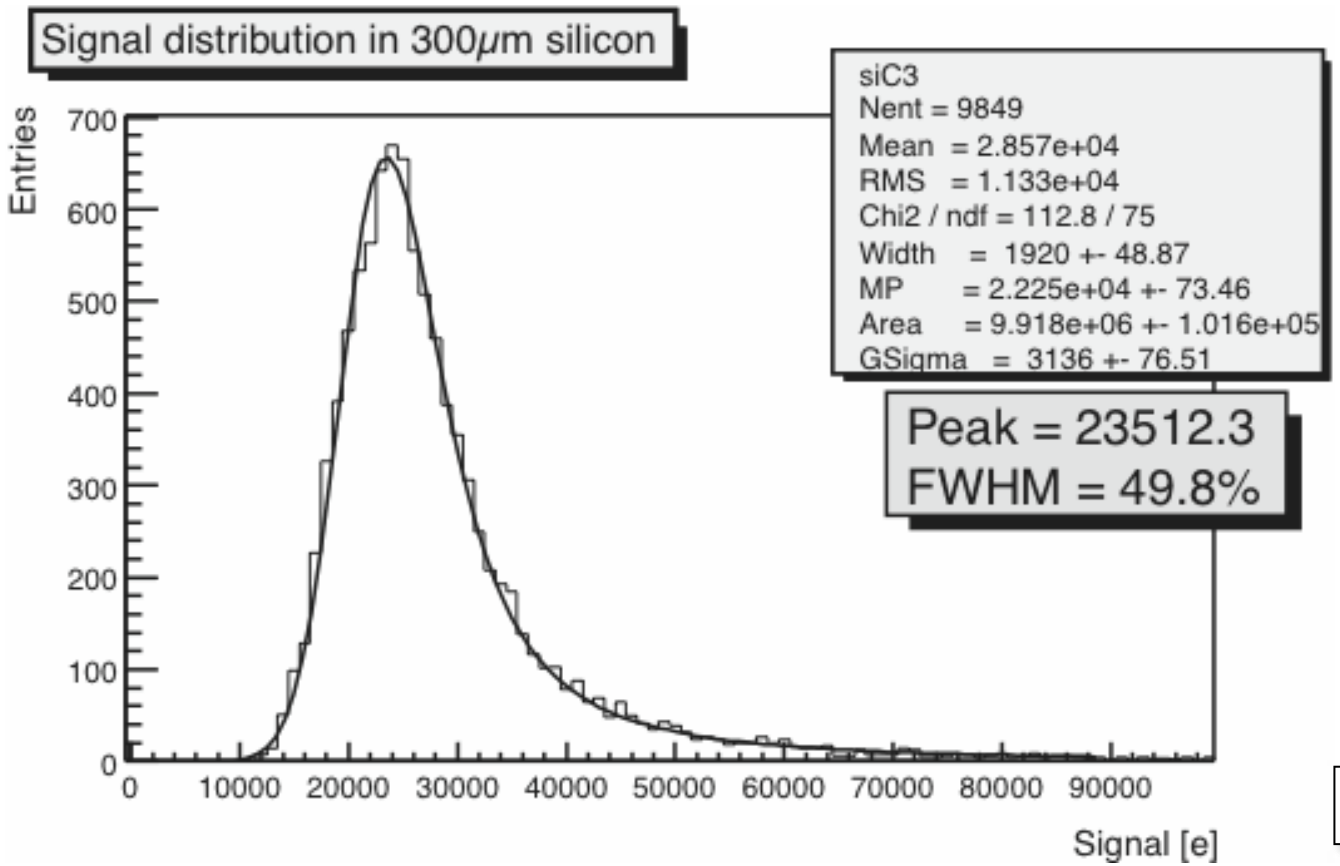


$$j_{gen} = \frac{1}{2} q \frac{n_i}{\tau_0} W \qquad j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$

$$j_{gen} \times 2 \;\; for \;\; \Delta T = 8K$$

Signal Generation: dE/dx and Landau Distribution

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\cdot\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$



Valid only for thick absorber

Thin absorber (silicon detectors) need cut-off parameter since delta electrons carry energy away

$$-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \approx 1,5\frac{\mathrm{MeV}}{\mathrm{g\ cm^{-2}}}$$

Landau-distribution

Landau Distribution in thin layers

Energy Loss in Silicon Sensors:

- $(dE/dx)_{Si}$ = 3.88 MeV/cm

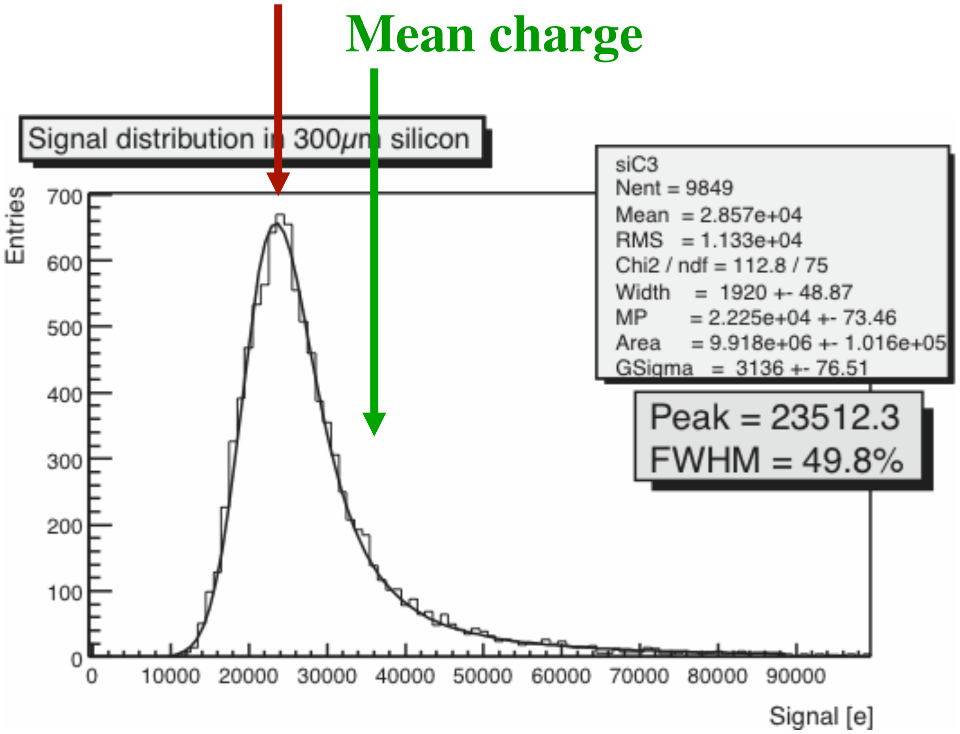
3.6eV needed to make e-h pair:

- **72 e$^-$h / µm (most probable)**
- **108 e$^-$h / µm (mean)**

Typical sensor thickness (300 µm):

- 21600 e$^-$ (most probable)
- 32400 e$^-$ (mean)

Most probable charge ≈ 0.7× mean



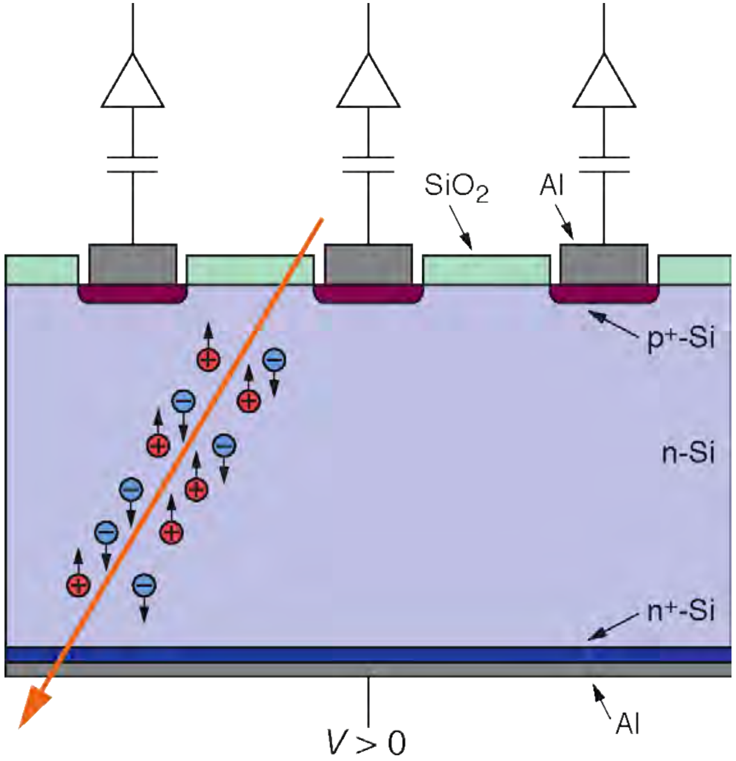
Mean charge

Landau distribution, convoluted with a narrow Gaussian distribution due to electronic noise and intrinsic detector fluctuations

Position-sensitive Strip Detectors

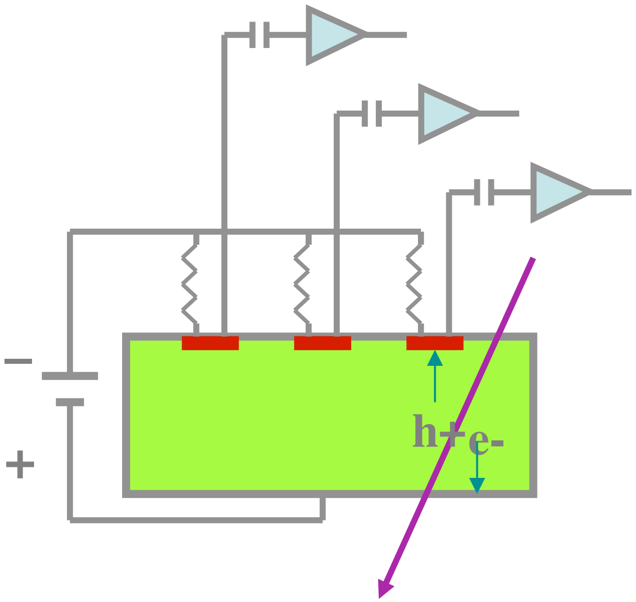
- Patterned implants as strips
- Connect readout electronics to strips
- Determine position from strip hit info
- Charge sharing between several strips improves position resolution (enter of gravity calculation)

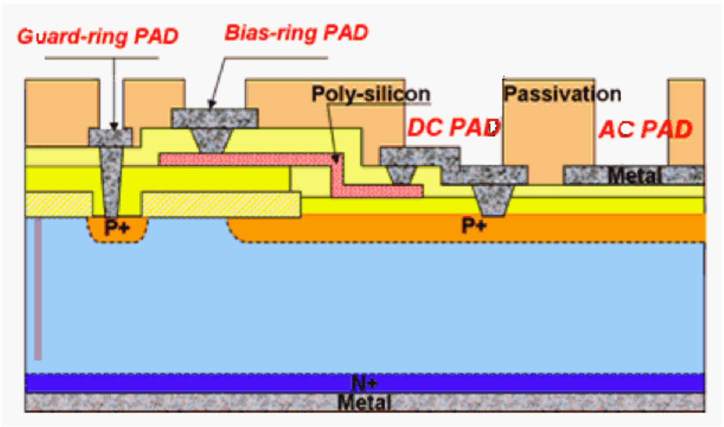
- Very often, capacitors are included in sensor ⇒ AC-coupled strip sensor



Biasing Methods

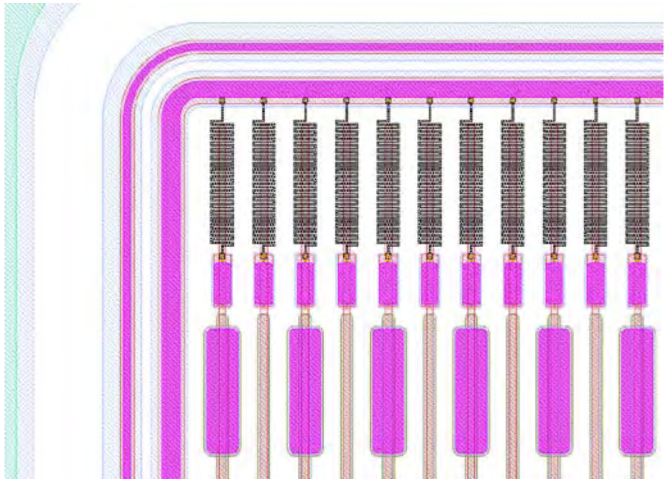
- AC-coupled sensors create two electrical circuits on the sensor:
  - Readout circuit into amplifier (AC current)
  - Biasing circuit (DC current)
- Method to connect readout strips to bias voltage source:
  - **Poly-silicon resistor**
  - (Punch-through)
  - (FOXFET)
- Typical sheet resistance of up to $R_s \approx 4\ \mathrm{k\Omega}$/square. Depending on width and length a resistor of up to $R \approx 20\ \mathrm{M\Omega}$ is achieved ($R = R_s \cdot \mathit{length}/\mathit{width}$)

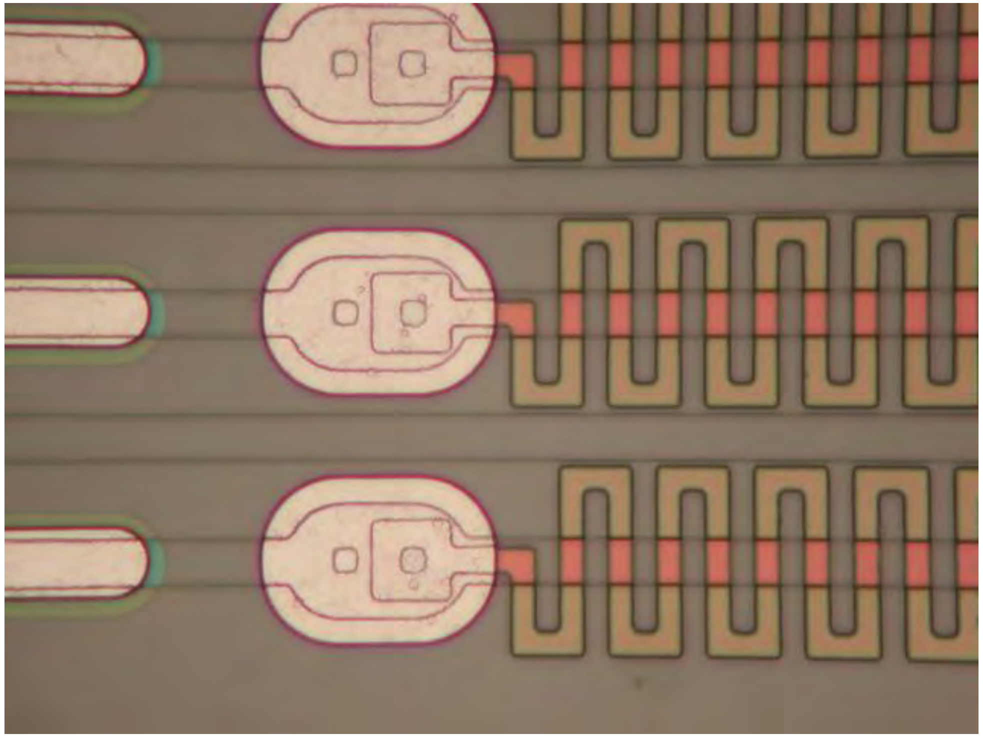


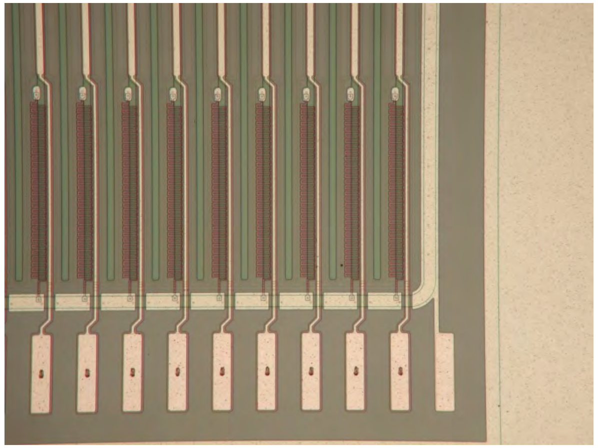


Biasing Methods: Poly-Silicon

Top view of a strip detector with poly-silicon resistors:

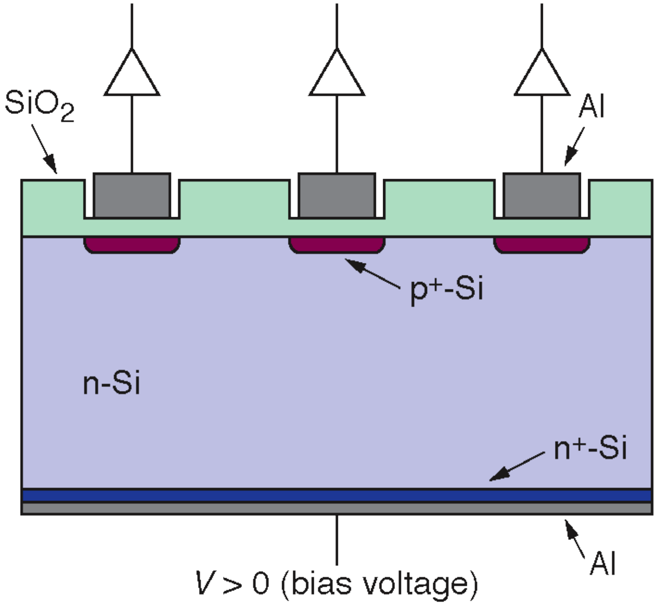






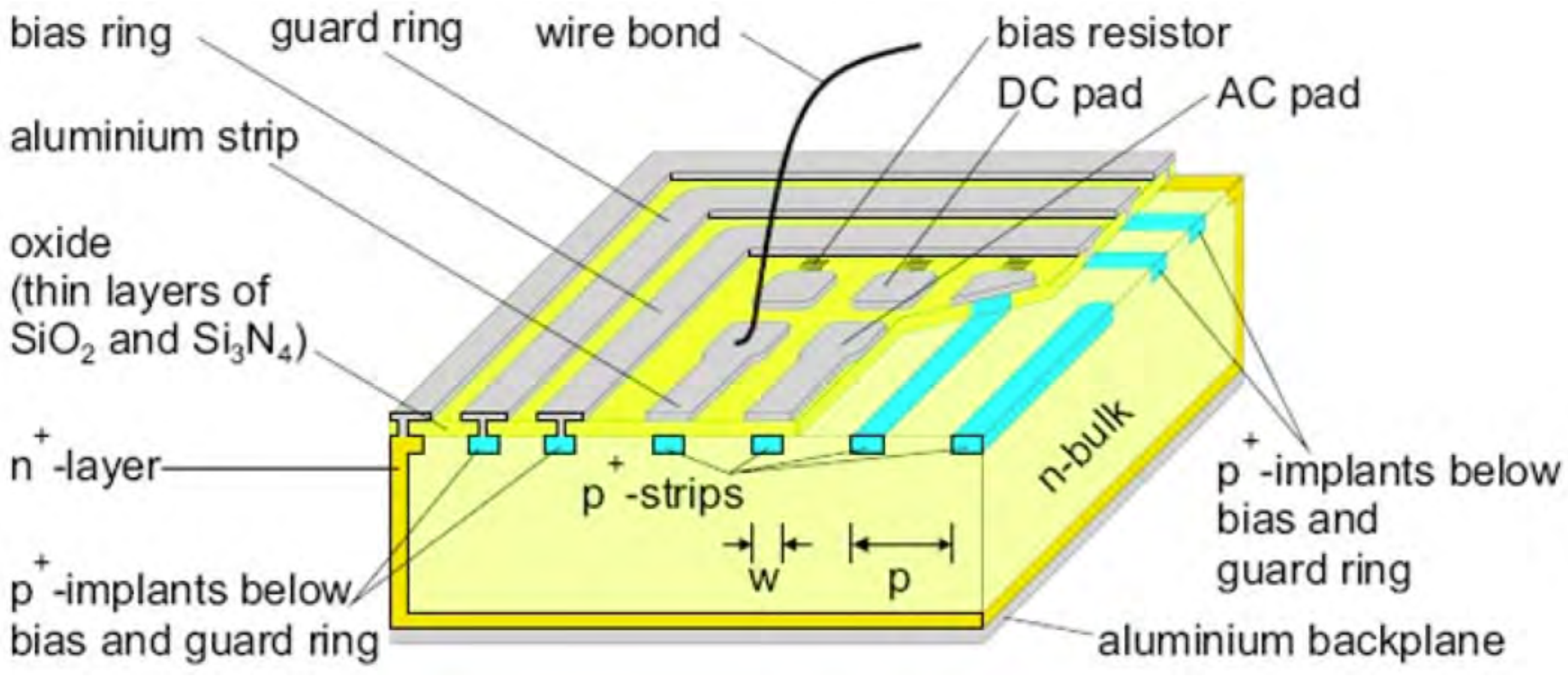
AC Coupled Strip Detectors (1)

- Capacitor is implemented into sensor
- Insulation layer between p^+-Silicon (implant)-strip and Al-(readout)-strip
- Insulation layer acts as dielectric ⇒ capacitor
- Insulation Materials:
  - Pure SiO_2,
  - Sandwich using SiO_2 together with Si_3N_4 (Silicon-Nitride)
- HV is applied between Al-backplane and bias line
- Strips needs to be connected from bias line via poly-silicon resistor (usually 1-100 MΩ)

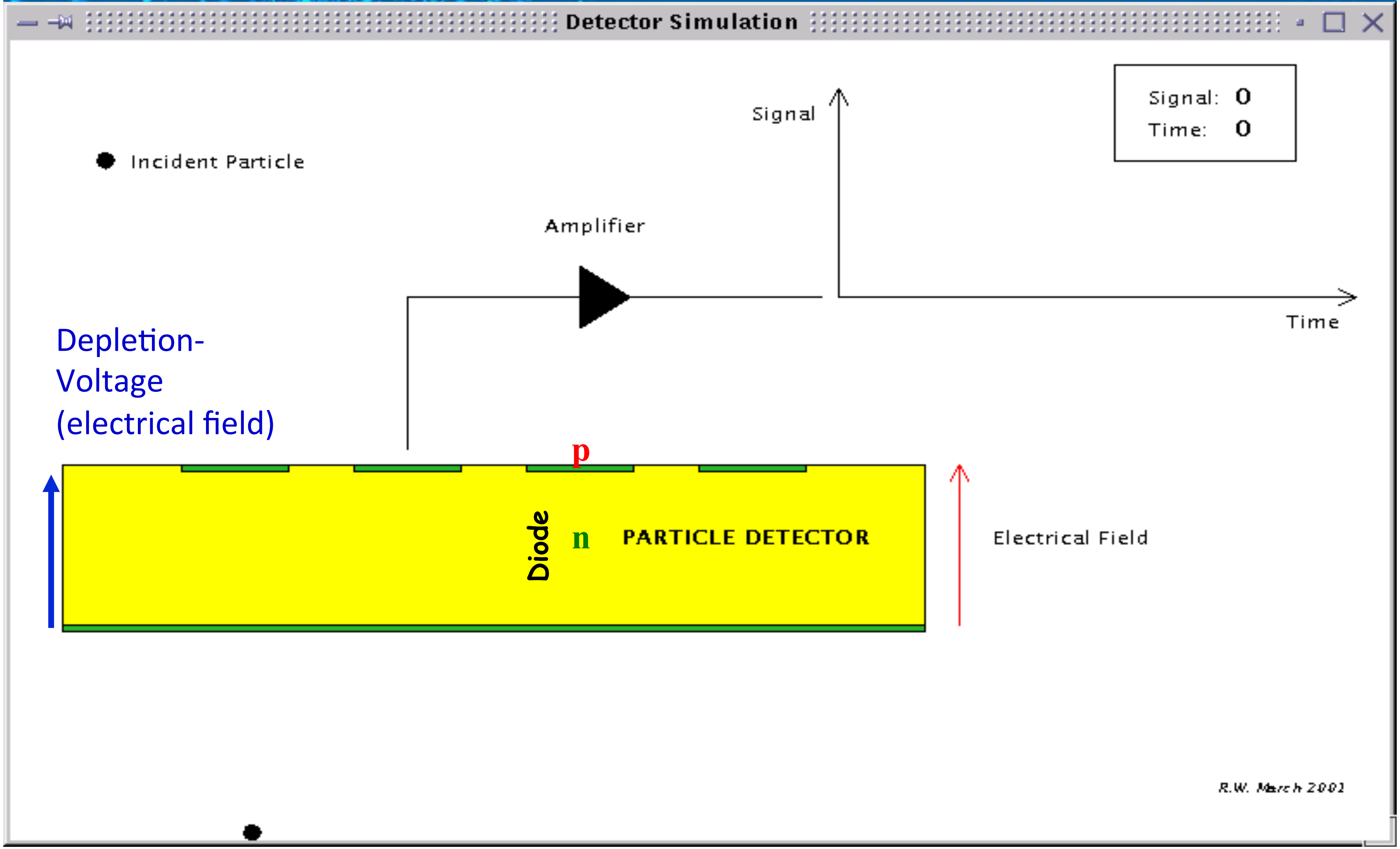


Summary: Typical AC-coupled Sensor

Most commonly used scheme using poly-Si bias resistor



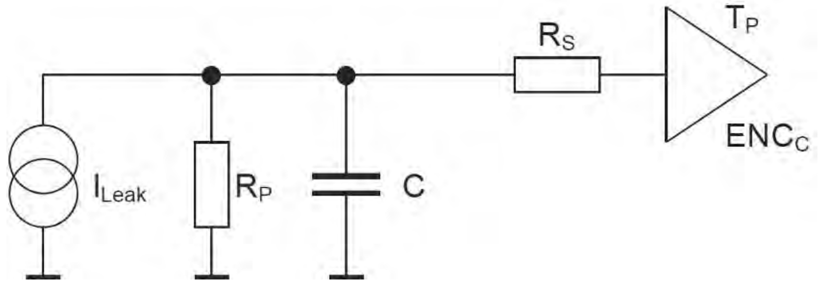
Silicon Strip Detectors in CMS



Depletion-Voltage (electrical field)

Noise Sources in Silicon Strip Sensors

- Depends upon detector capacitance and reverse current
- Depends upon electronics design
- Function of signal shaping time t_p
- Lower capacitance ⇒ lower noise
- Faster electronics ⇒ more noise



$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

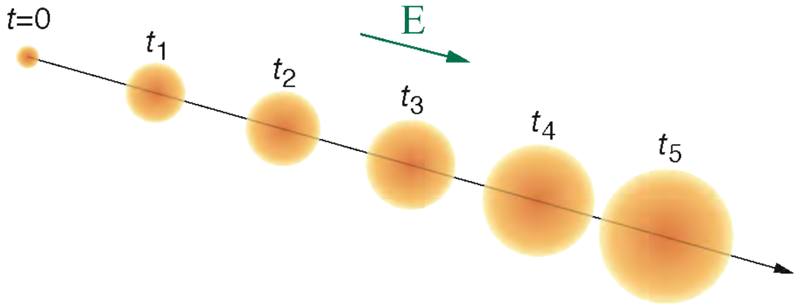
$$ENC_C = a + b \cdot C$$

$$ENC_I = \frac{\mathbf{e}}{2}\sqrt{\frac{It_p}{e}}$$

- Signal-to-Noise ratio (SNR) important quality parameter of full readout system (must be >10, good if >20)
- Signal: scales with thickness of detector

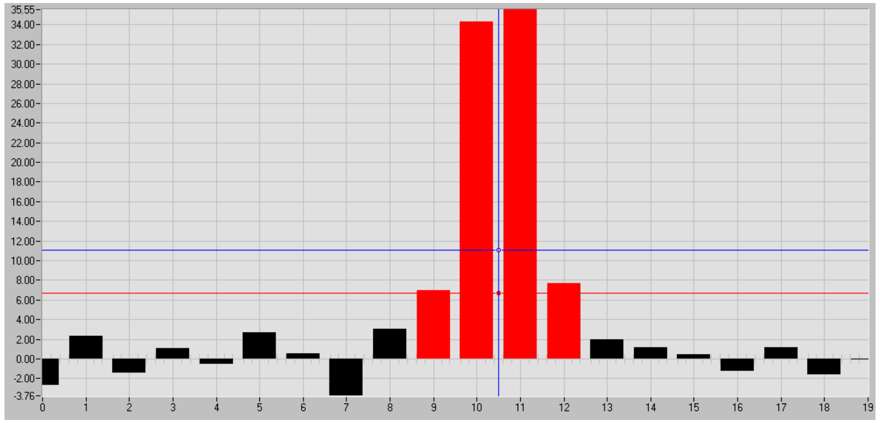
$$\boxed{SNR = \frac{Signal}{ENC}}$$

Position resolution



- Charge generation within 1 µm
- Diffusion effects during drift in electrical field to electrodes:

$$\sigma_D = \sqrt{2Dt} \qquad \text{with:} \qquad D = \frac{kT}{e}\mu$$



- Resolution, if one strip is hit:

$$\boxed{\sigma_x \approx \frac{p}{\sqrt{12}}}$$

- Resolution, if multiple strips are hit:

$$\boxed{\sigma_x \approx \frac{p}{SNR}}$$

TWO-DIMENSIONAL-READOUT

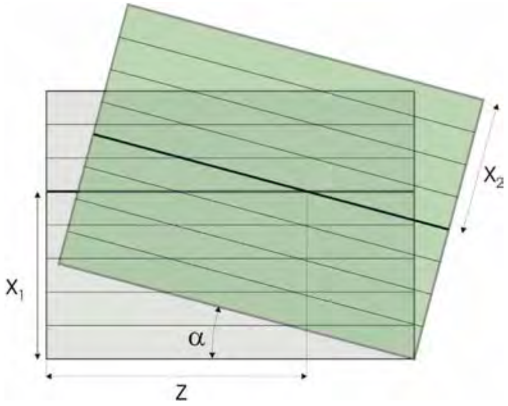
Stereo Modules

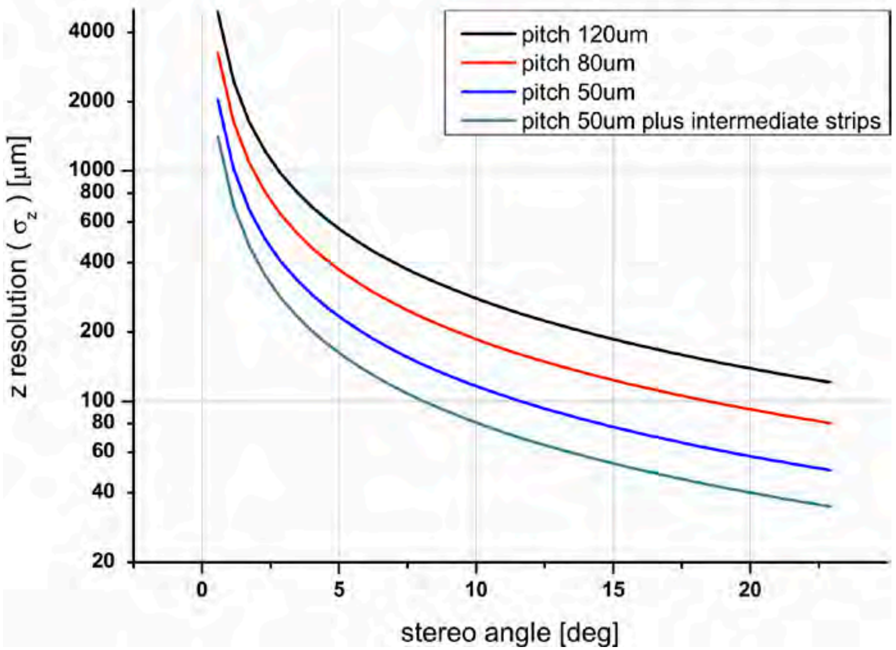
2nd coordinate requires second detector underneath
⇒ double the material

- Acceptable for hadron colliders like LHC
- Not acceptable for e+/e- colliders with tighter material budget

Tilt angle defines z-resolutions (usually along beam axis)

- CMS uses 100 mrad





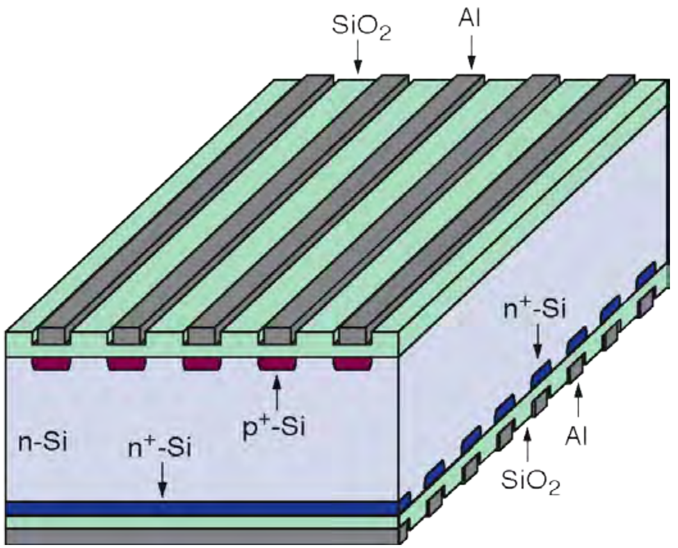
Double Sided Silicon Detectors (DSSDs)

Advantages:

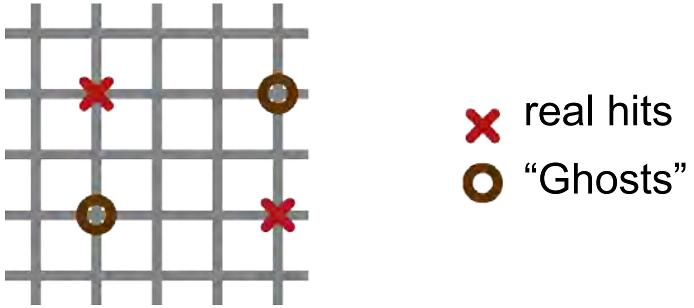
- More elegant way for measuring 2 coordinates
- Saves material

Disadvantages:

- Needs special strip insulation of n-side (p-stop, p-spray techniques)
- Very complicated manufacturing and handling procedures ⇒ expensive
- Ghost hits at high occupancy



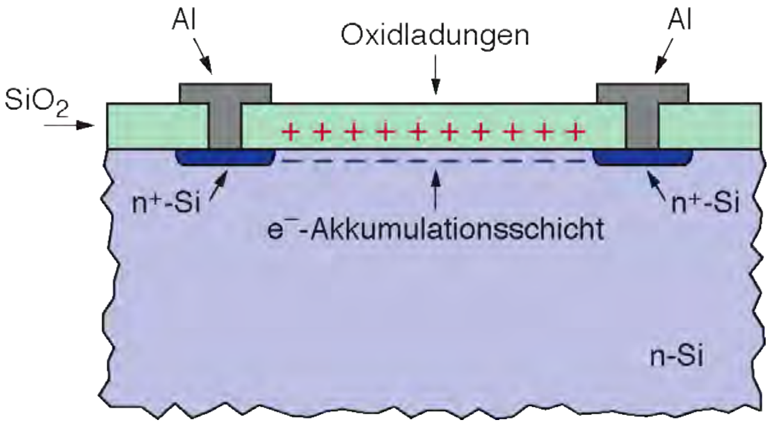
Scheme of a double sided strip detector (biasing structures not shown)



Strip Isolation on n-Side

- Problem with n$^+$ segmentation: Static, positive oxide charges in the Si-SiO$_2$ interface.
- These positive charges attract electrons. The electrons form an accumulation layer underneath the oxide.
- n+ strips are no longer isolated from each other (resistance ≈ kΩ).

- Charges generated by through going particle spread over many strips.
- No position measurement possible.
- Solution: Interrupt accumulation layer using p$^+$-stops, p$^+$-spray or field plates.

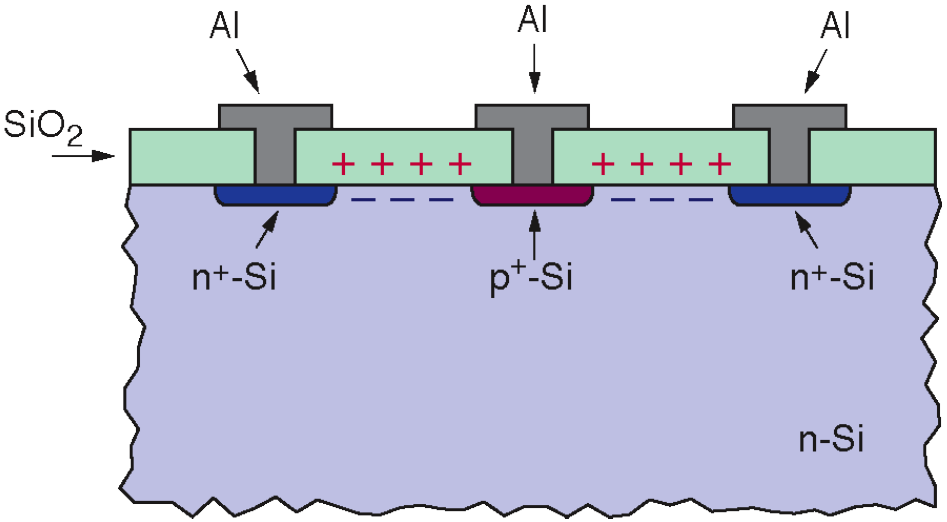


Positive oxide charges cause electron accumulation layer.

Strip Isolation using p-stop

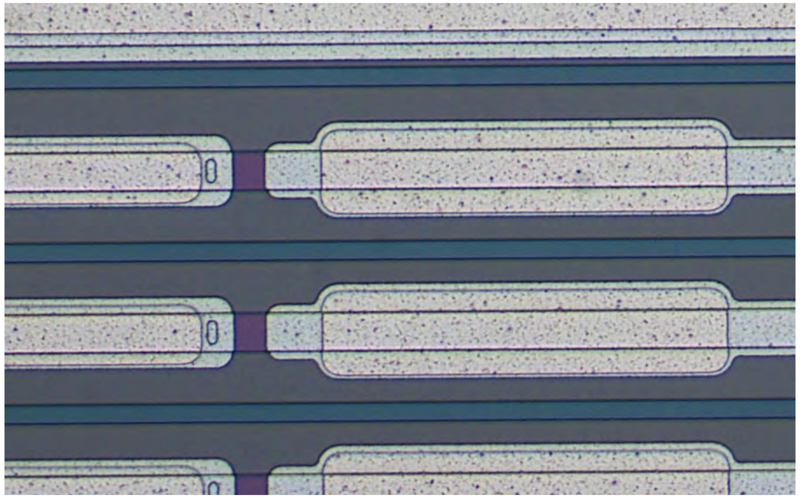
- p^+-implants (p^+-stops, blocking electrodes) between n^+-strips interrupt the electron accumulation layer.

➢ Inter-strip resistance reach again O(GΩ).



A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

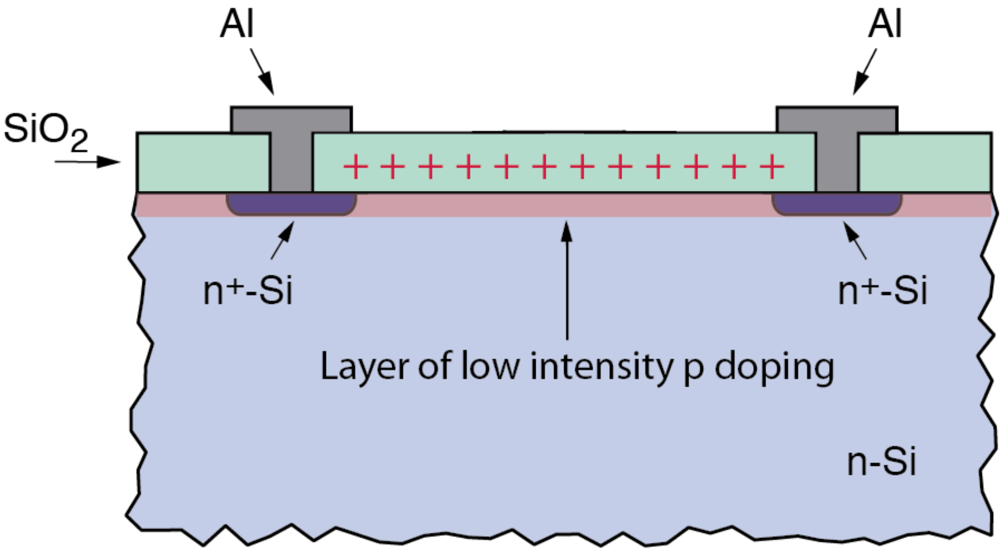
Picture showing the n^+-strips and the p^+-stop structure:



Prototype sensors for Belle II SVD

Strip Isolation using p-spray

- p doping as a layer over the whole surface.
- disrupts the e^- accumulation layer.

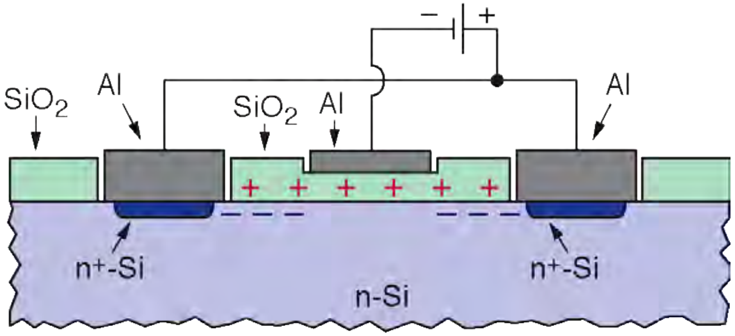


- Often, a combination of p^+ stops and p spray is being used

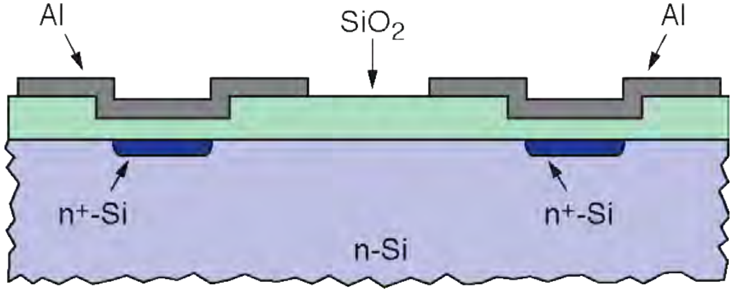
Strip Isolation using Field plates

- Metal of MOS structure at negative potential compared to the n+-strips displace electrons below Si-SiO$_2$-interface.
- Above a threshold voltage n+-strips become isolated.
- Simple realization of AC coupled sensors: Wide metal lines with overhang in the inter-strip region serve as field plates.

A field plate at negative potential interrupts accumulation layer:



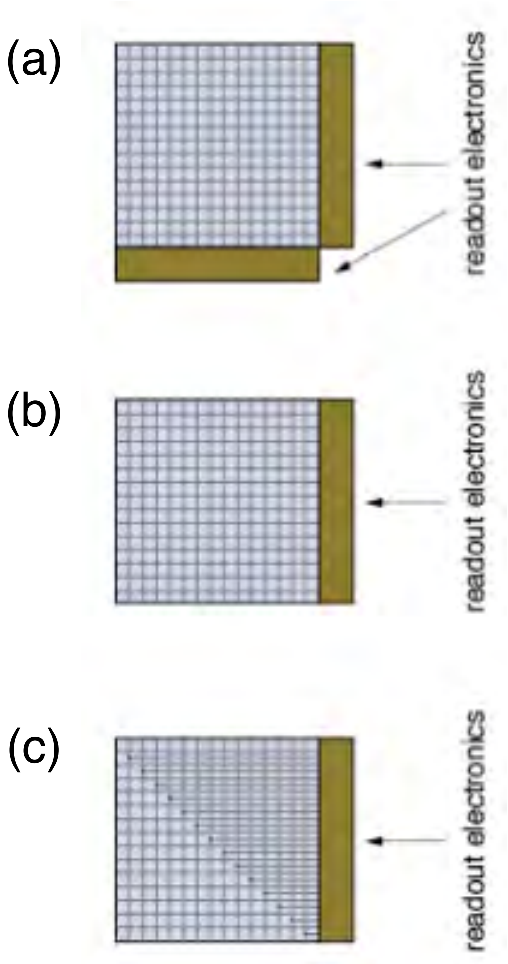
n+-strips of an AC coupled detector. The alumimnum readout lines act as field plates:



A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

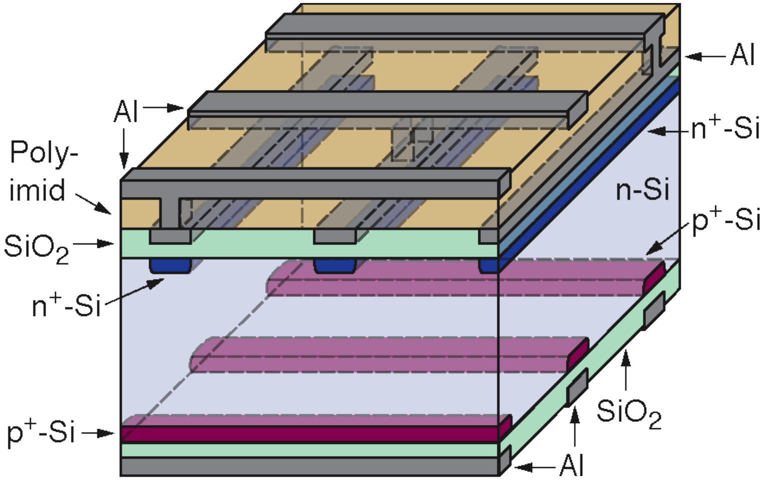
Routing using 2nd metal layer

- In the case of double sided strip detectors with orthogonal strips the readout electronics is located on at least two sides (fig. a).
- Many drawbacks for construction and material distribution, especially in collider experiments.
- Electronics only on one side is a preferred configuration (fig. b).
- Possible by introducing a second metal layer. Lines in this layer are orthogonal to strips and connect each strips with the electronics (fig. c). The second metal layer can be realized by an external printed circuit board, or better integrated into the detector.



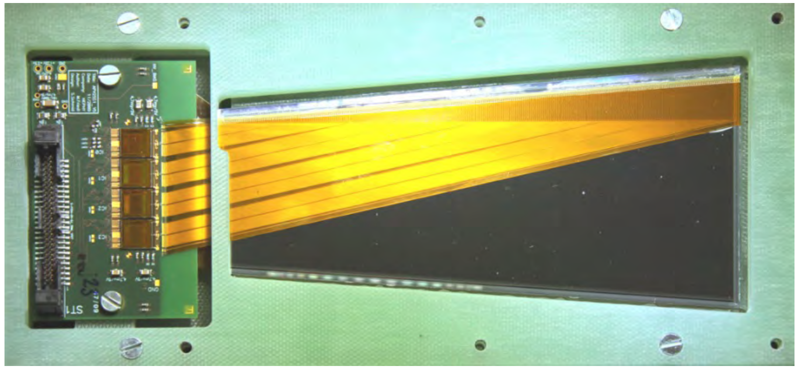
Routing using 2nd metal layer

- DSSD with double metal
  - Most complex detector
  - 16 layers
  - The isolation between the two metal layers is either SiO_2 or polyimide (common name Kapton)
  - Has been used by DELPHI experiment at LEP

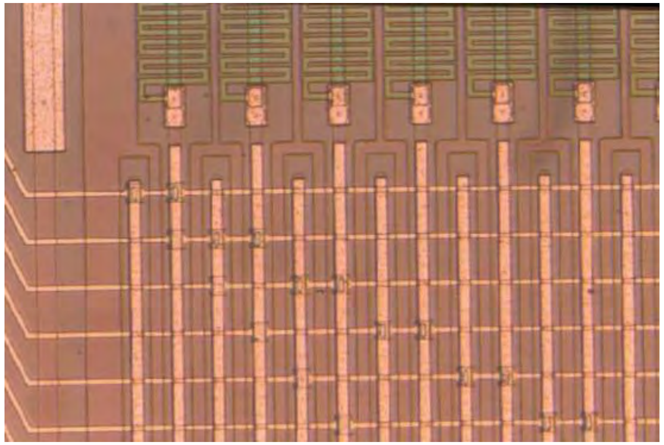


3D scheme of an AC coupled double sided strip detector with 2nd metal readout lines (bias structure not shown).

- Alternative
  - Discrete pitch adapter using Kapton flex circuit



Double Metal Layer

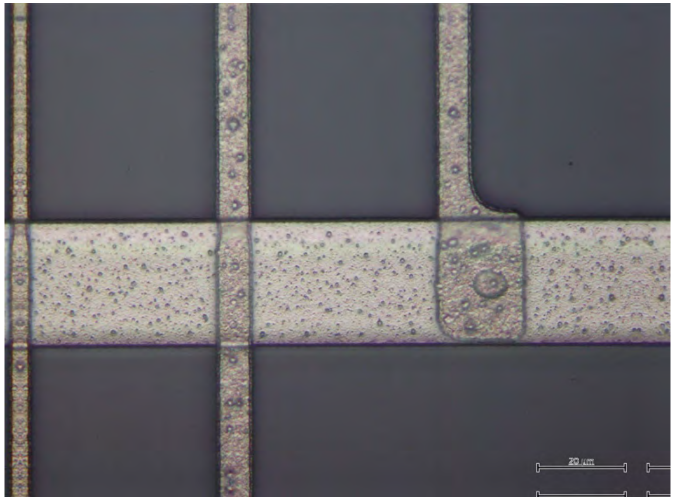


Advantages:

- routing integrated into sensor

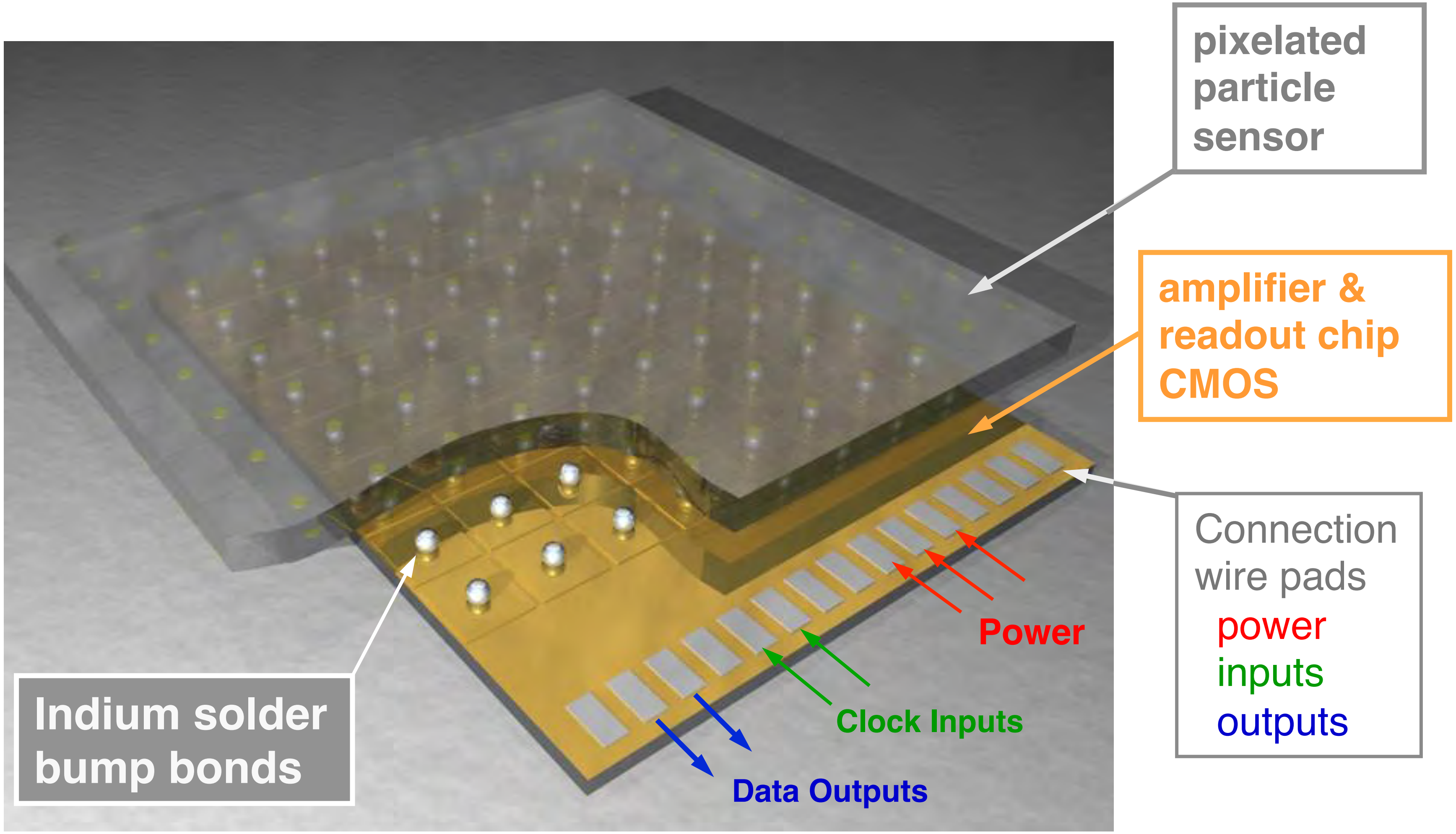
Disadvantages:

- Two more layers on wafer increase complexity
  - Via's
  - Metal
- Increased coupling and crosstalk between readout and routing lines
  - Thickness of isolation between metal layers is crucial



HYBRID PIXEL DETECTORS

Hybrid Pixel Detectors Principle



pixelated particle sensor

amplifier & readout chip CMOS

Connection wire pads
power
inputs
outputs

Indium solder bump bonds

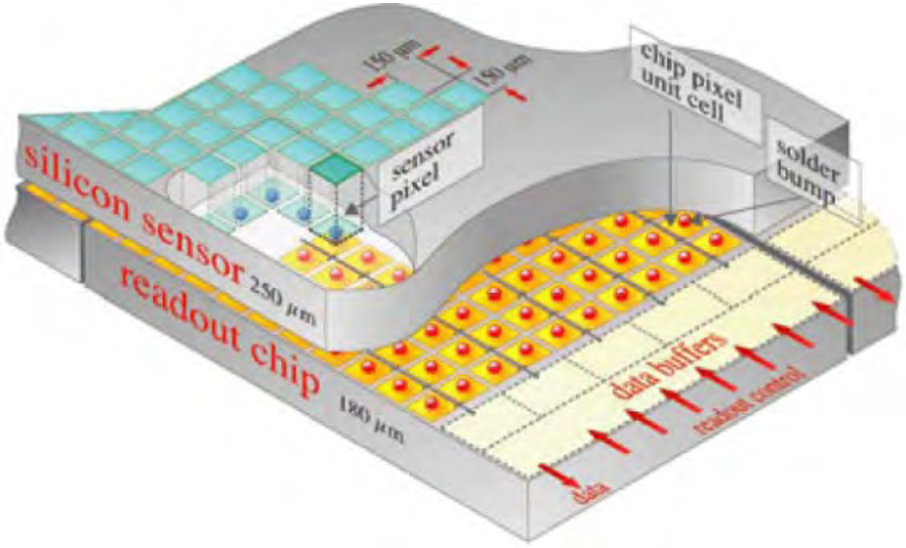
Power

Clock Inputs

Data Outputs

Pixel Detectors

- Real 2-dimensional device
- Typical pixel sizes: 50 x 50 µm
- Digital readout results in resolution of ~ 14 µm (at 50 µm pixel size)



Typical values:

- Pixel current ≈1 pA/Pixel
- Pixel capacitance ≈1 fF/Pixel
  ⇒ very low noise

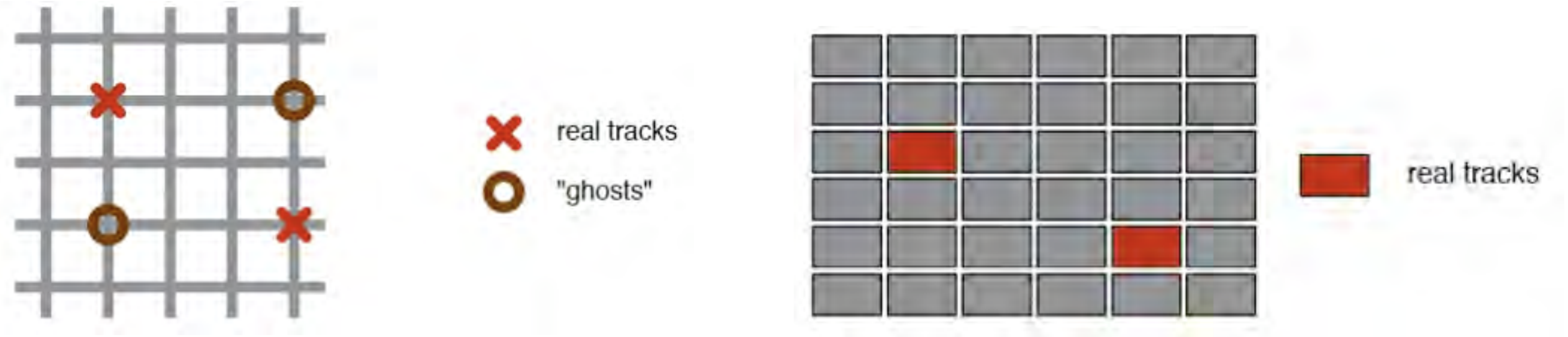
- To reach S/N-ratio between 10-20 very thin detectors are sufficient: 30-100 µm thickness

This results in main application: vertex detector in innermost region because of:

- Very fast
- Very little material (low multiple scattering)
- Can cope high occupancy (no ghost hits)

Pixel Detectors Advantages

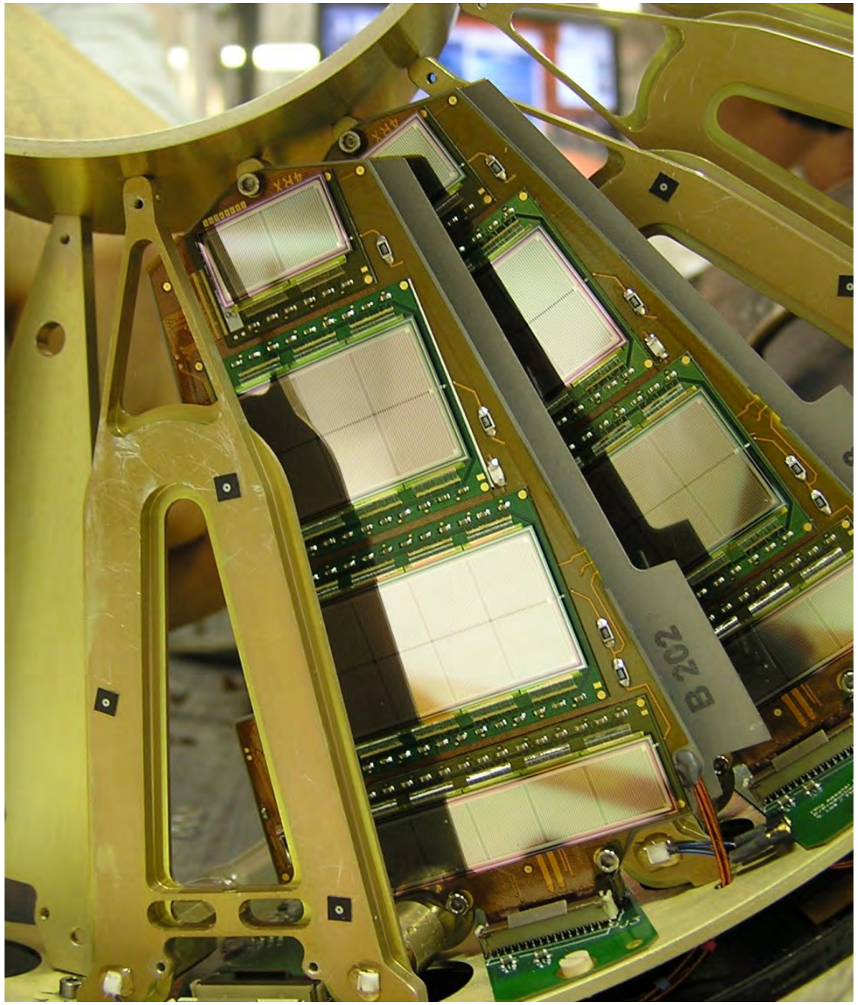
- Double sided strip sensors produce ghost hits
  - Problematic for high occupancies
- Pixel detectors produce unambiguous hits



- Small pixel area → low detector capacitance (≈1 fF/Pixel) → large signal-to-noise ratio (e.g. 150:1).
- Small pixel volume → low leakage current (≈1 pA/Pixel)

Disadvantages of pixel detectors

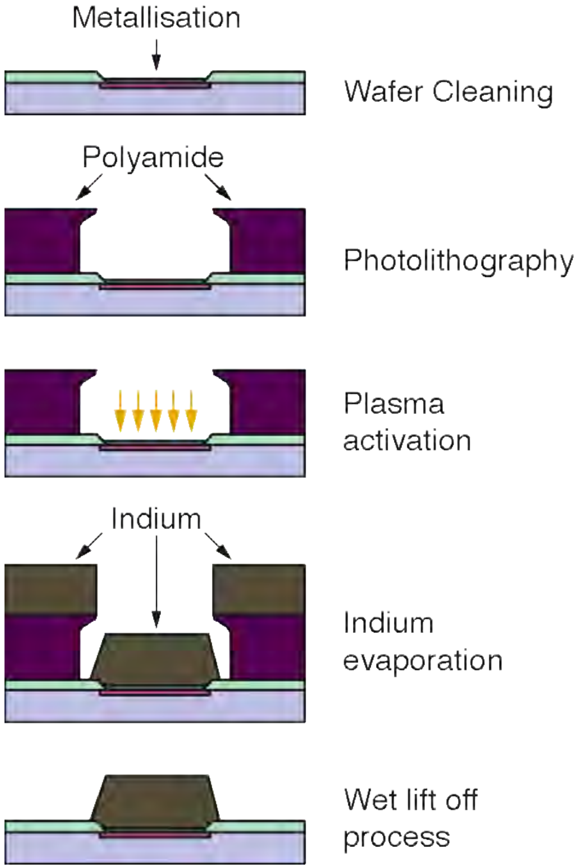
- Large number of readout channels
  - Large number of electrical connections in case of hybrid pixel detectors.
  - Large power consumption of electronics
- Expensive to cover large areas
  - Suitable for innermost region near collision region



Bump bonding process

A typical bump bonding process (array bump bonding) is the following:

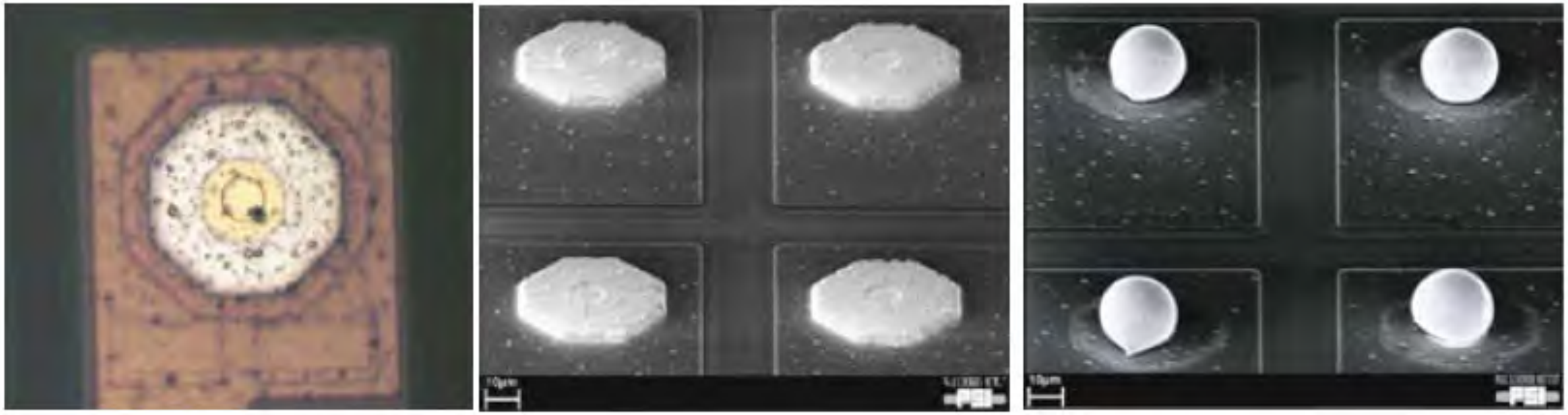
1. Deposition of an "under-bump metal layer", plasma activated, for a better adhesion of the bump material.
2. Photolithography to precisely define areas for the deposition of the bond material.
3. Deposition, by evaporation, of the bond material (e.g. In or SnPb) producing little "bumps" (≈ 10 μm height).
4. Edging of photolithography mask leaves surplus of bump metal on pads.
5. Reflow to form balls.



L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Bump bonding process

Electron microscope pictures before and after the reflow production step.
In bump, The distance between bumps is 100 µm, the deposited indium is 50 µm wide while the reflowed bump is only 20 µm wide.



C. Broennimann, F. Glaus, J. Gobrecht, S. Heising, M. Horisberger, R. Horisberger, H. Kästli,J. Lehmann, T. Rohe, and S. Streuli, *Development of an Indium bump bond process for silicon pixel detectors at PSI, Nucl. Inst. Met. Phys, Res. A565(1) (2006) 303–308 82*

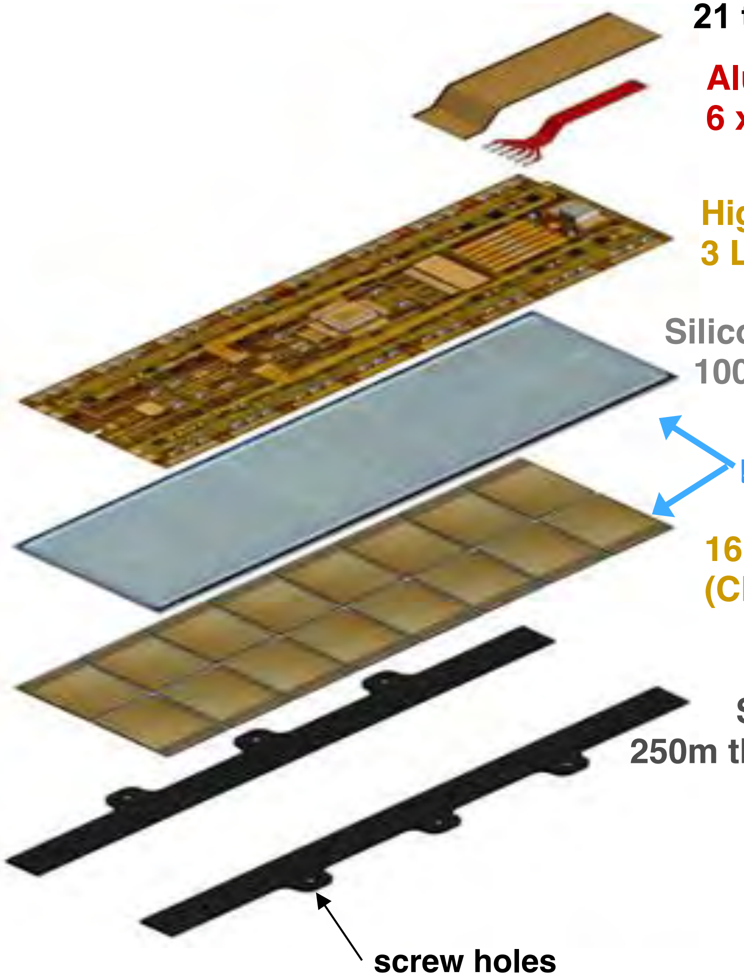
Hybrid Pixel Module for CMS

Sensor:

- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r\text{-}\varphi}$ ~ 15μm
  - Resolution σ_{z} ~ 20μm
- n+-pixel on n-silicon design
  - Moderated p-spray → HV robustness

Readout Chip:

- Thinned to 175μm
- 250nm CMOS IBM Process
- 8” Wafer



Kapton signal cable
21 traces, 300μ pitch

Alu-power cable
6 x 250μ ribbon

High Density Print
3 Layers, 48μ thick

Silicon Sensor t=285μ
100μ x 150μ pixels

μ-bump bonding

16 x Readout Chips
(CMOS) 175μ thick

SiN base strips
250m thick, screw holes

screw holes

R. Horisberger

The Planar Process

FABRICATION TECHNOLOGIES

Ingot production

Properties of Si bulk required for detectors:

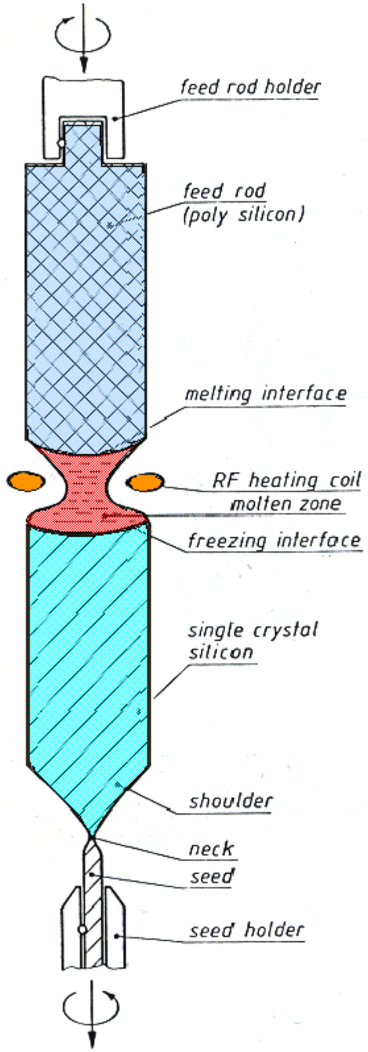
- Diameter: 4, 6 or 8 inches
- Lattice orientation <111> or <100>
- Resistivity 1–10 kΩcm

Therefore, **float-zone technique** for ingot production is used

  – technique moves a liquid zone through the mater

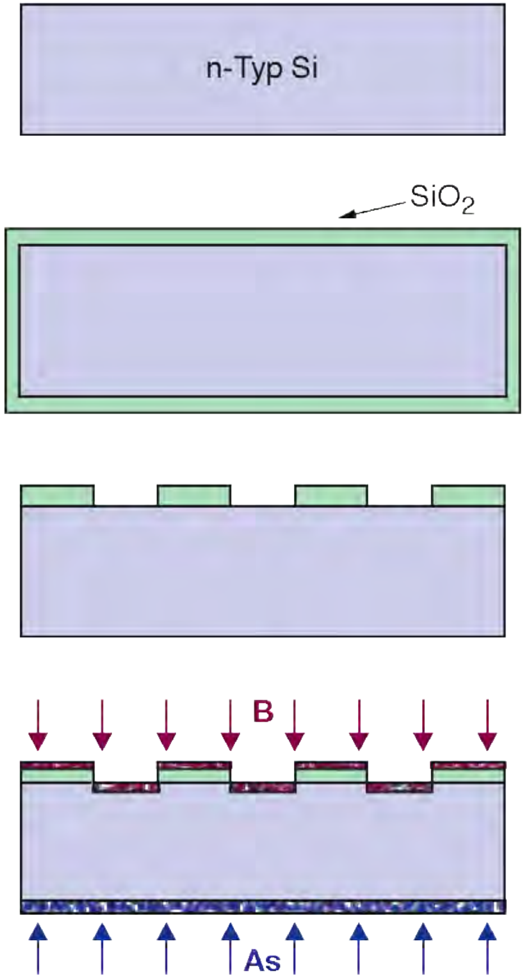
- Result: **single-crystal ingot**

Chip industry: Czochralski process (less purity)



Planar process

1. Starting Point: single-crystal n-doped wafer ($N_D \approx 1–5 \cdot 10^{12}$ cm^{-3})
2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at 1030 °C.
3. Window opening using **photolithography technique** with etching, e.g. for strips
4. Doping using either
   - **Thermal diffusion** (furnace)
   - **Ion implantation**
     - p⁺-strip: Boron, 15 keV, $N_A \approx 5 \cdot 10^{16}$ cm^{-2}
     - Ohmic backplane: Arsenic, 30 keV, $N_D \approx 5 \cdot 10^{15}$ cm^{-2}



Planar process

5. After ion implantation: **Curing** of damage via thermal annealing at approx. 600°C, (activation of dopant atoms by incorporation into silicon lattice)
6. **Metallization** of front side: sputtering or CVD
7. Removing of excess metal by photolithography: **etching** of non-covered areas
8. Full-area metallization of backplane with annealing at approx. 450°C for better adherence between metal and silicon

Last step: wafer **dicing** (cutting)

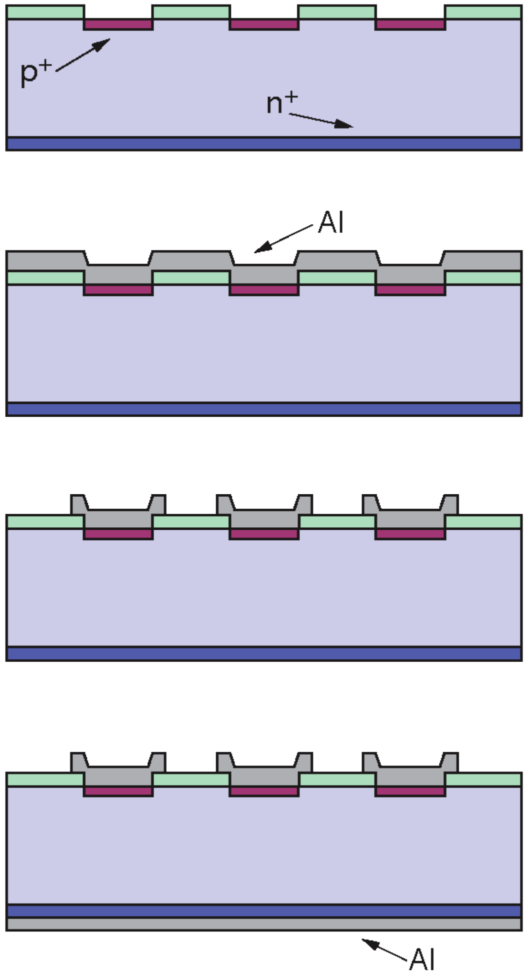
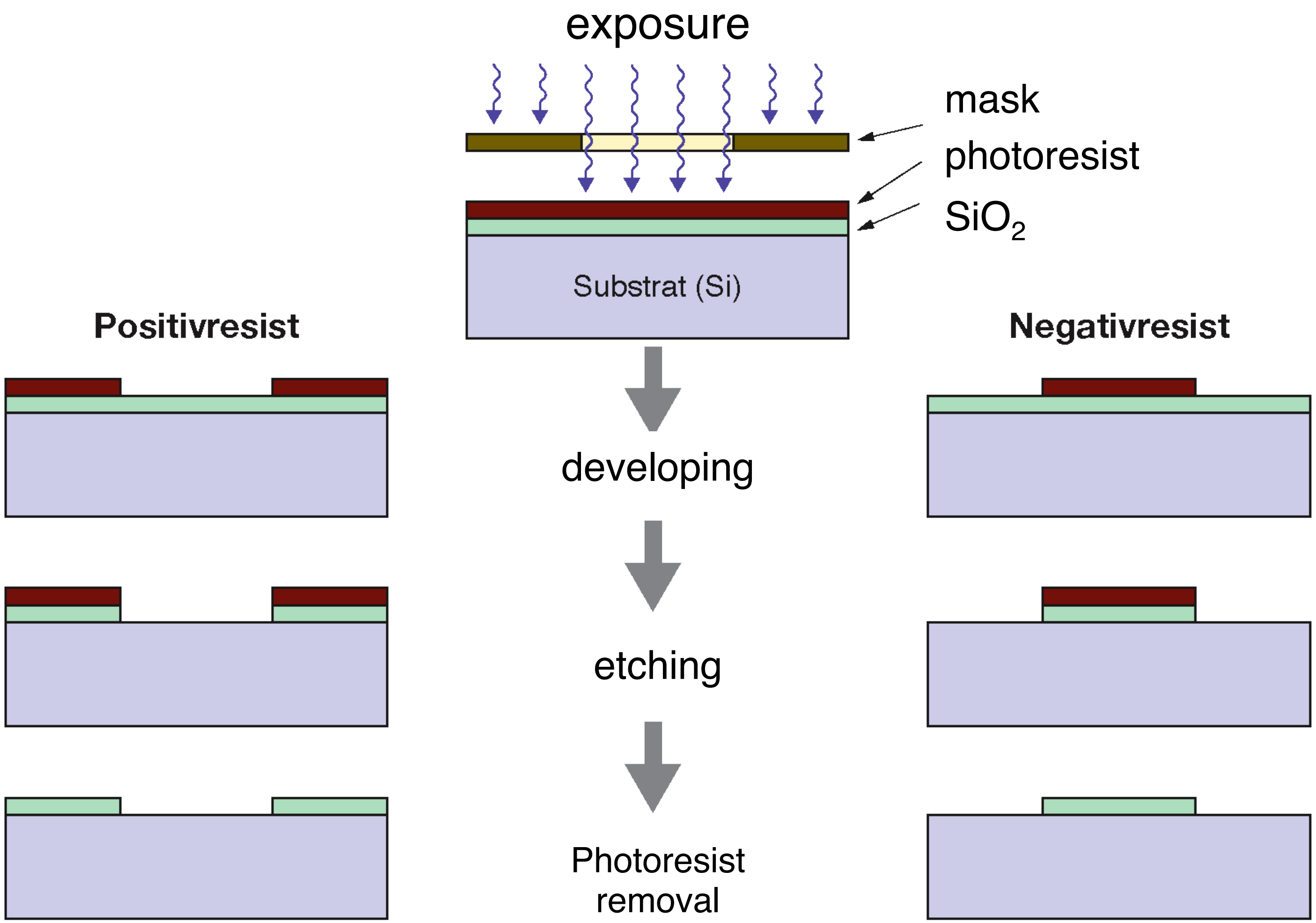


Photo-Lithography

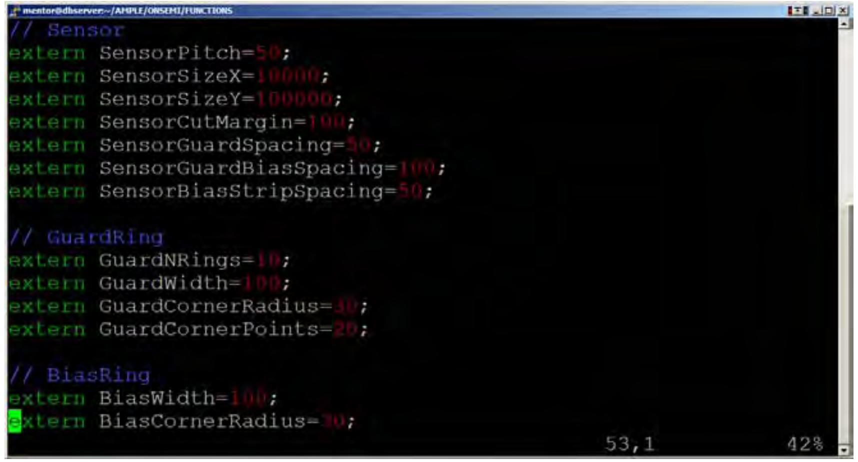


Sensor mask design

- Design tools like in commercial chip industry
  - ICStation from Mentor Graphics
  - Cadence
  - Klayout (open source)

- Design is not drawn but actually “programmed”
  - using simple programming language (C like)

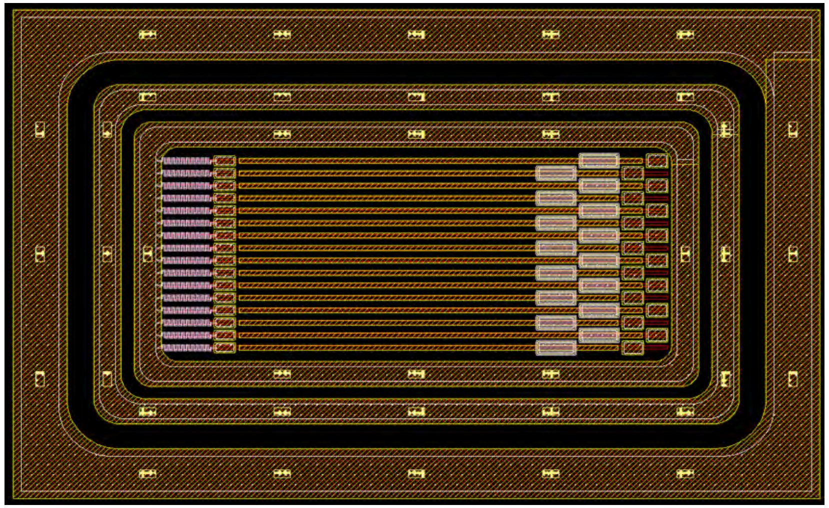
- Therefore, it is easy to change any parameter and re-create the full sensor within minutes
  - e.g. width of strips

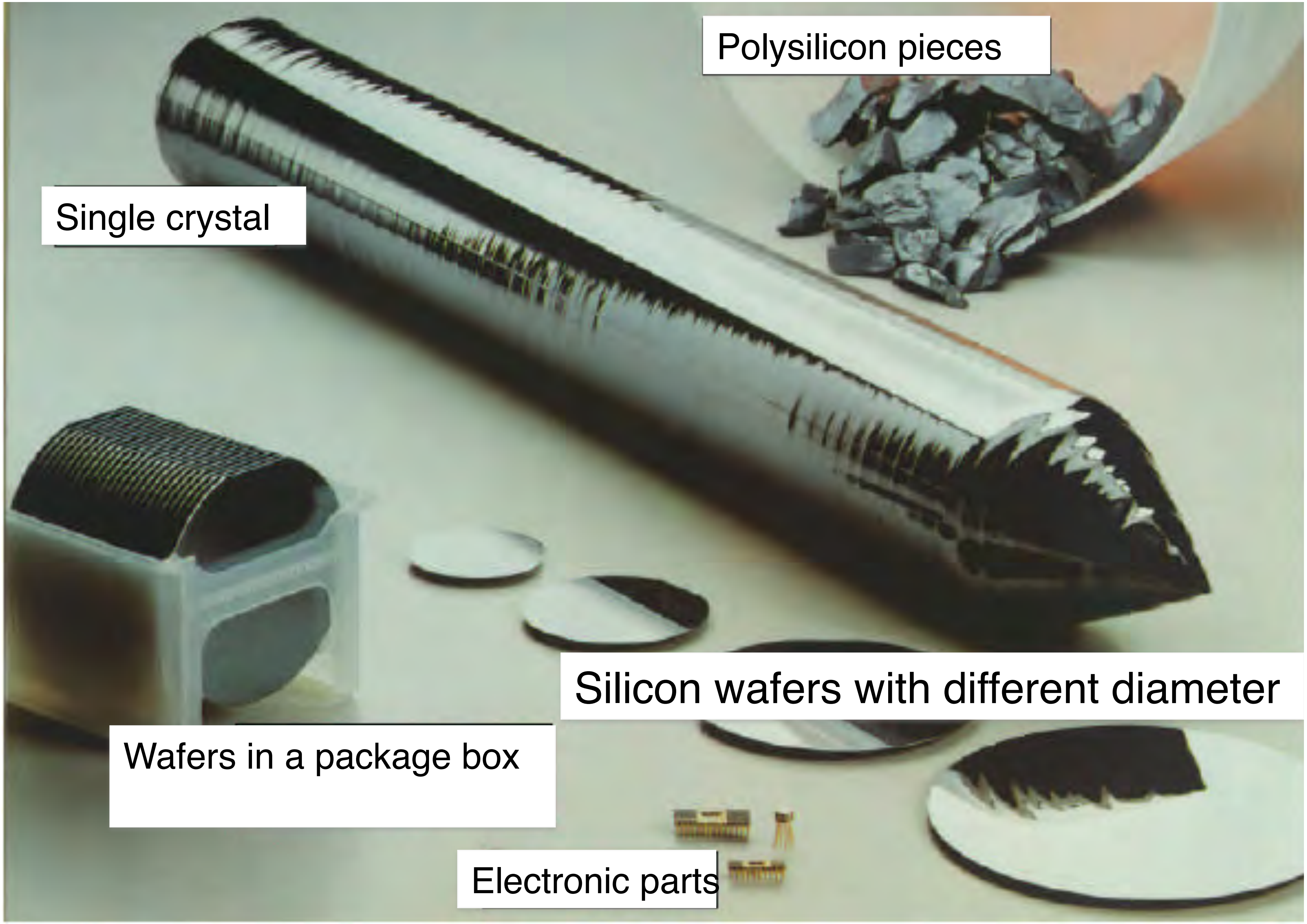

mentor@dbserver:~/AMPLE/ONSEMI/FUNCTIONS

```
// Sensor
extern SensorPitch=50;
extern SensorSizeX=10000;
extern SensorSizeY=100000;
extern SensorCutMargin=100;
extern SensorGuardSpacing=50;
extern SensorGuardBiasSpacing=100;
extern SensorBiasStripSpacing=50;

// GuardRing
extern GuardNRings=10;
extern GuardWidth=100;
extern GuardCornerRadius=30;
extern GuardCornerPoints=20;

// BiasRing
extern BiasWidth=100;
extern BiasCornerRadius=30;
                                                  53,1          42%
```





Polysilicon pieces

Single crystal

Silicon wafers with different diameter

Wafers in a package box

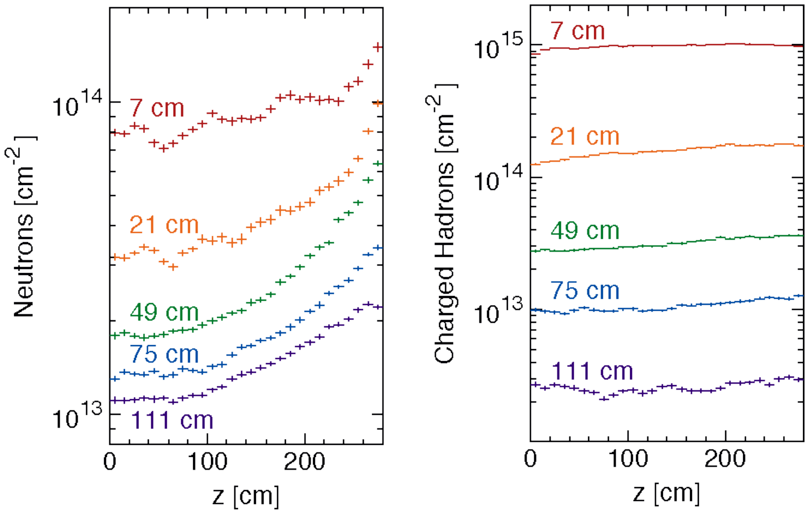
Electronic parts

How does the detector behave in the experiment?

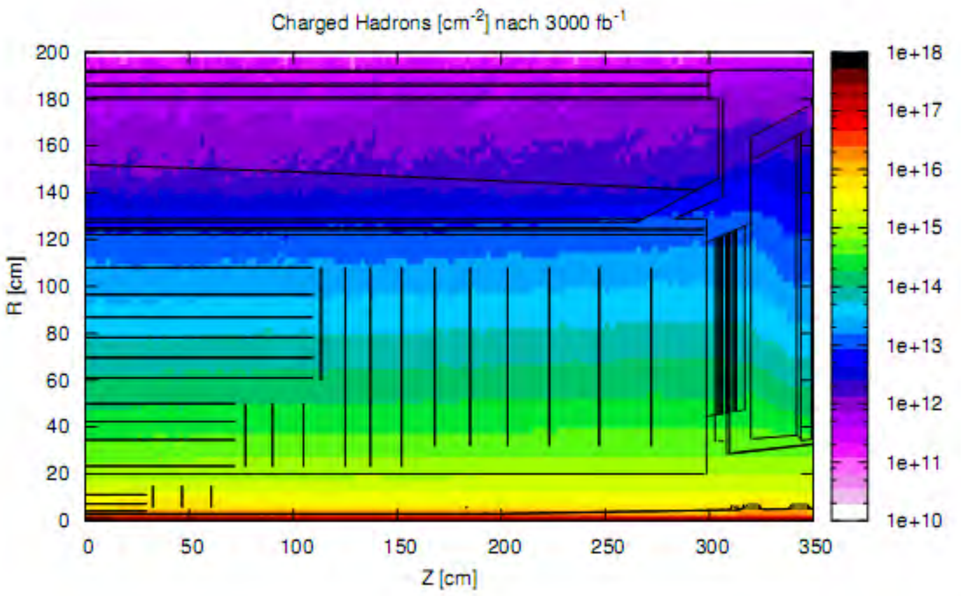
RADIATION DAMAGE

Motivation

- The event rate and as a consequence the irradiation load in experiments at hadron colliders is extreme (e.g. the pp collider LHC, collision energy 14 TeV, event rate 10^9 s^{-1}).
- Understanding radiation damage in silicon detectors is vital for the experiments at LHC and future applications.



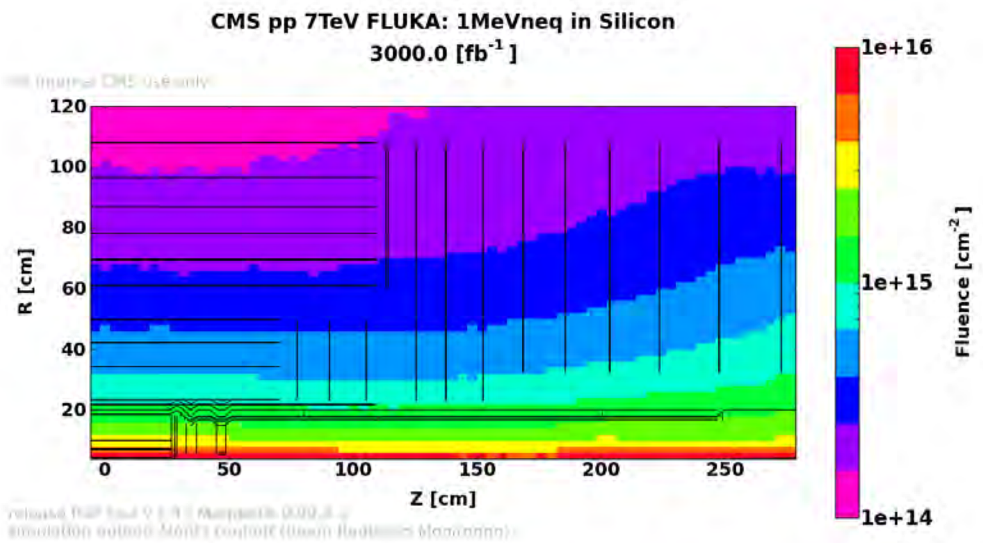
CERN/LHCC 98-6, CMS TDR 5, 20 April 1998



HL-LHC environment

- HL-LHC: Upgrade of LHC and its experiments
- Detector R&D focused on
  - Phase 1 upgrades, e.g. pixel detector replacement, replacement of LHCb VELO …
  - Phase 2 upgrades: major changes expected to modules and electronics

HL-LHC fluences



Effects of Radiation Damage to Silicon

Macroscopic Effects:

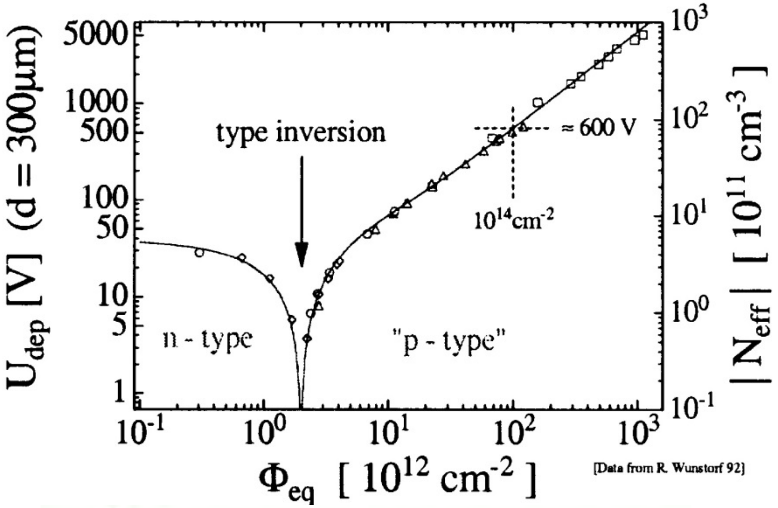
1. Change of the full depletion voltage
2. Increase of leakage current

Microscopic Effects:

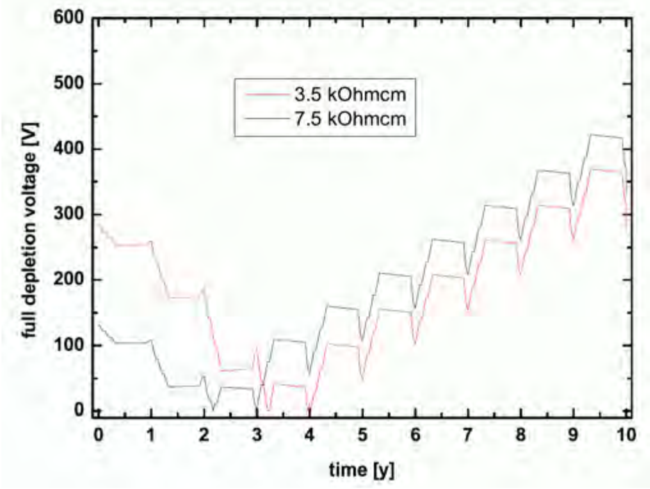
- **Change of effective doping concentration of bulk material including type inversion**
- Increase of resistivity of undepleted material
- Charge trapping and thus reduction of signal

Surface Effects:

- Change of oxide charges
- Change of flat band voltage, surface current, inter-strip capacitance
- Inter-strip capacitance increases
- Inter-strip resistance drops

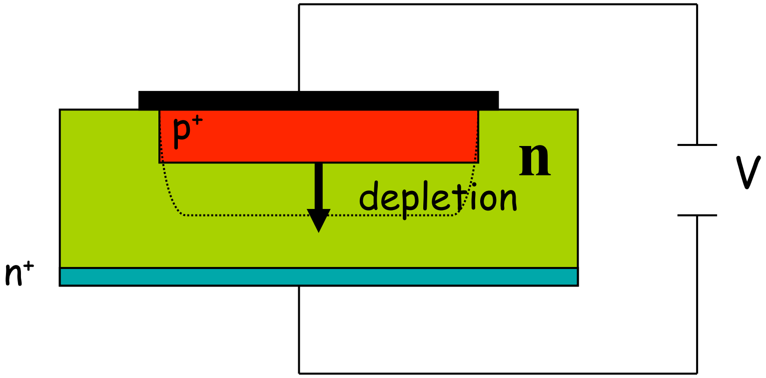


[Data from R. Wunstorf 92]

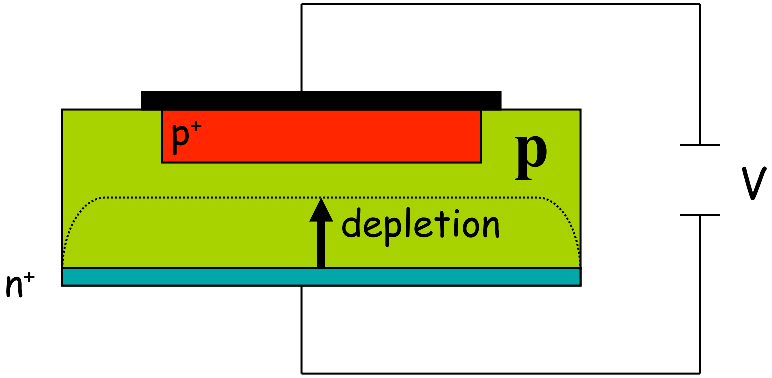


Depletion Voltage and Type Inversion

Before Inversion:

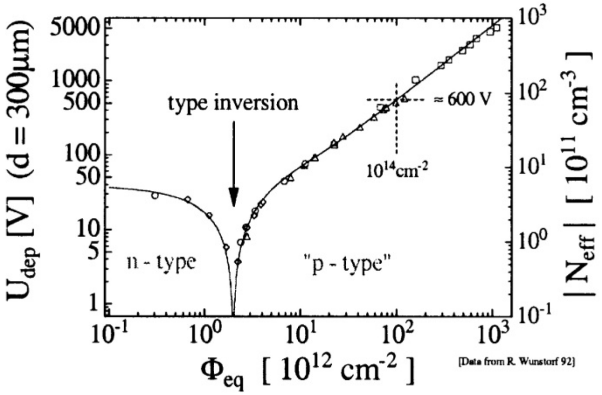


After Inversion:



After “inversion” of bulk-type n ➔ p:
The depletion region grows from the back

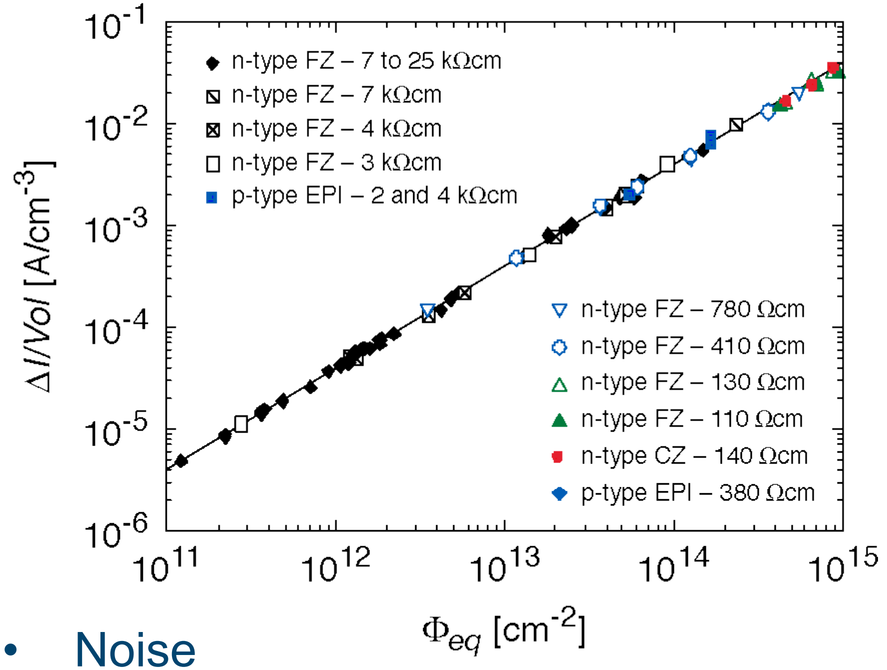
➔ Sensor does not work under-depleted anymore



[Data from R. Wunstorf 92]

Dark Current Increase

During irradiation current increases linearly with fluence:



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

V = volume of sensor
ΔI = increase of total leakage current
Φ_{eq}= equivalent fluence
α = Current related damage rate

Current related damage rate is temperature dependent ➔ α(T)

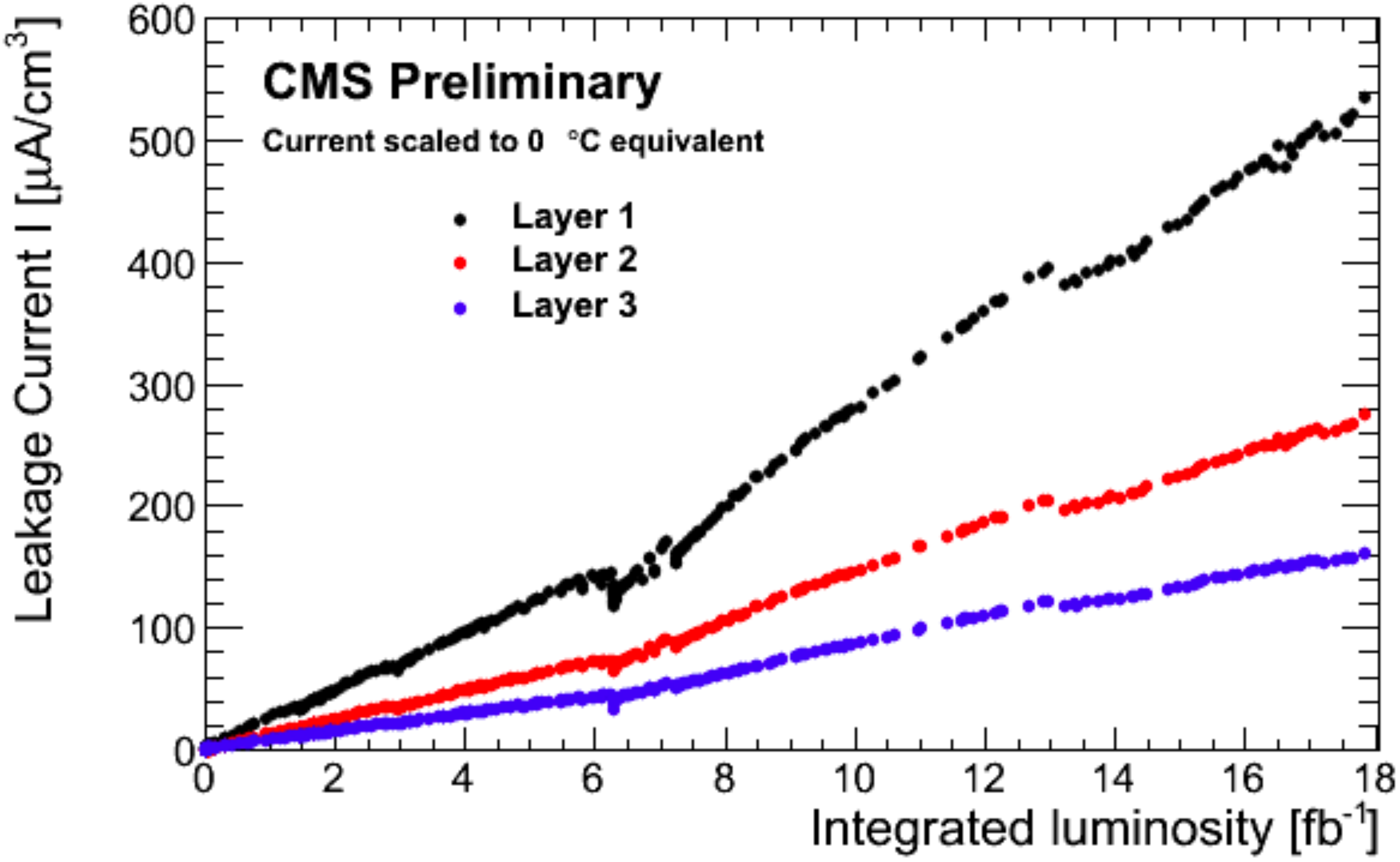
20°C: α = 4,00 ·10-17 A/m

-10°C: α = 1.86 ·10-18 A/m

- Noise
- Hard to bias
- strong temperature dependence

⇒ **cooling essential!**

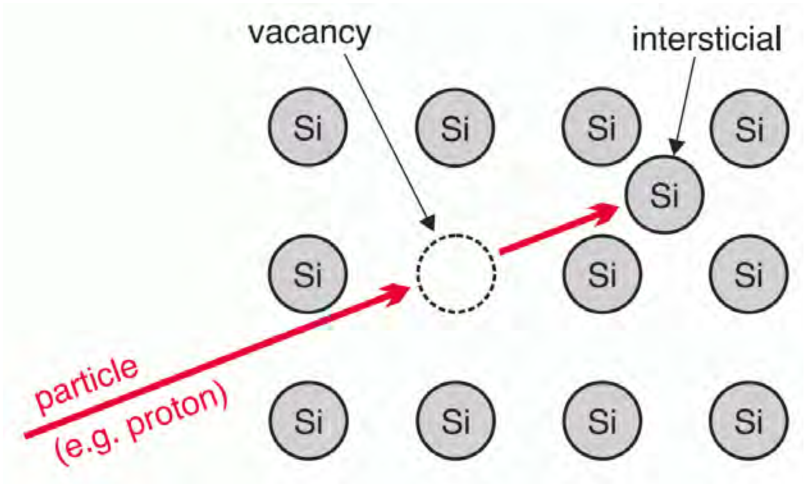
Dark current increase in CMS



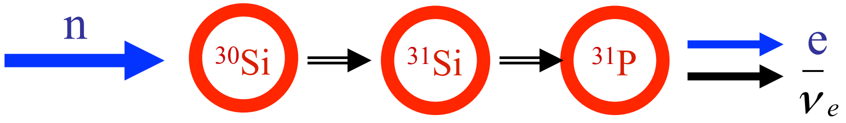
What happens exactly in the silicon?

Particles traversing silicon sensors create damage in the silicon lattice

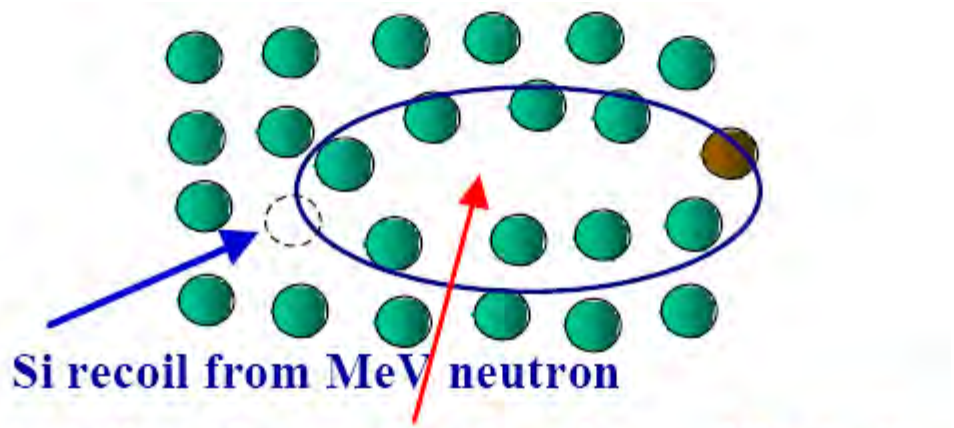
- displacements via em-force (compton scattering):
  - point defects (Frenkel Pairs)
    - interstitials (I)
    - vacancies (V)



- nuclei reactions, e.g. (point defects



- Clusters created by Primary Knock On Atoms (PKA)

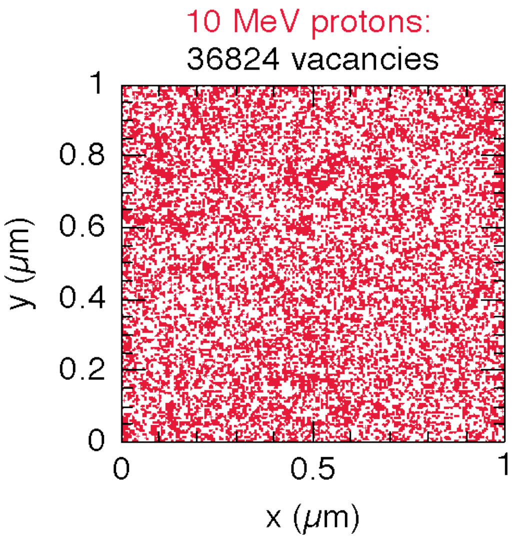


Si recoil from MeV neutron

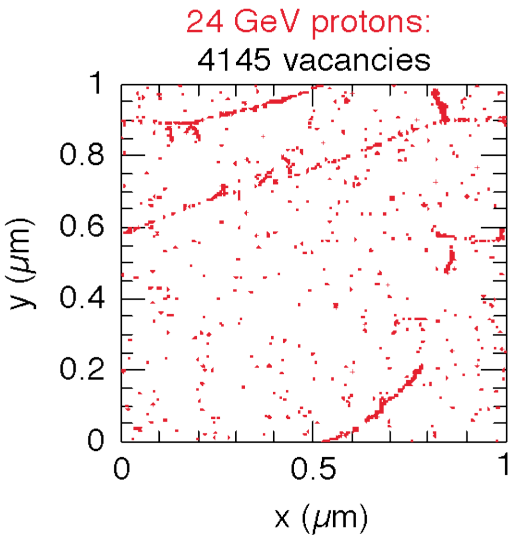
creation of disordered regions, „Cluster“

Dependence on type and energy of radiation

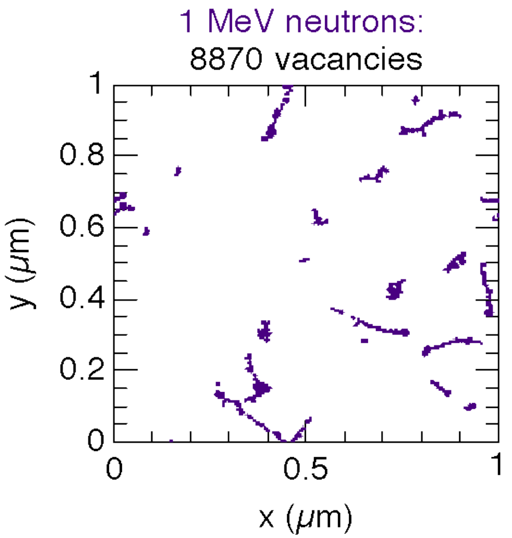
Type and frequency of defects depends on the particle type and the energy. Plots below show a simulation of vacancies in 1 μm thick material after an integrated flux of 10^{14} particles per cm^2:


10 MeV protons:
36824 vacancies

Many vacancies produced


24 GeV protons:
4145 vacancies

Less vacancies, a significant part of the energy is consumed to produce cluster defects

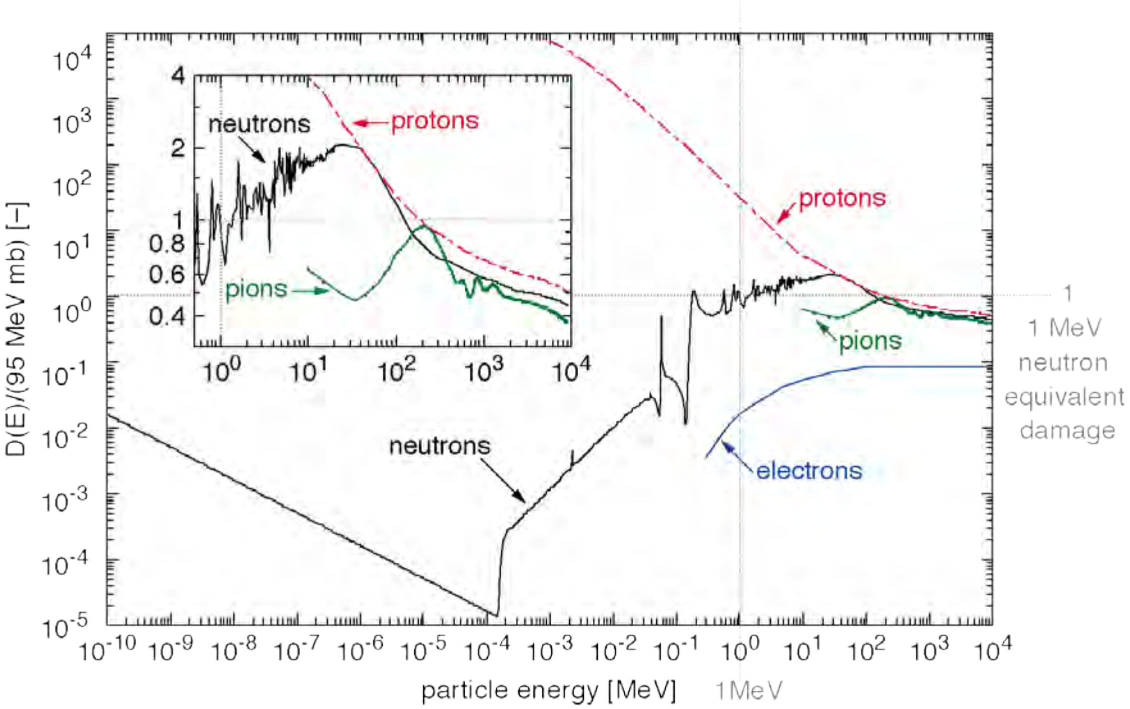

1 MeV neutrons:
8870 vacancies

Very few vacancies, energy of the neutrons is used up to produce cluster defects.

M. Huhtinen, *Simulation of Non-Ionising Energy Loss and Defect Formation in Silicon*, Nucl. Instr. Meth. A **491**, 194 (2002)

NIEL hypothesis — p,n comparison possible

<u>N</u>on <u>I</u>onising <u>E</u>nergy <u>L</u>oss
Particles of different types and energies have different cross sections
→ Neutrons of 1MeV as reference particles „**equivalent fluence Φ_{eq}**“



Comparison between fluences with hardness factor:

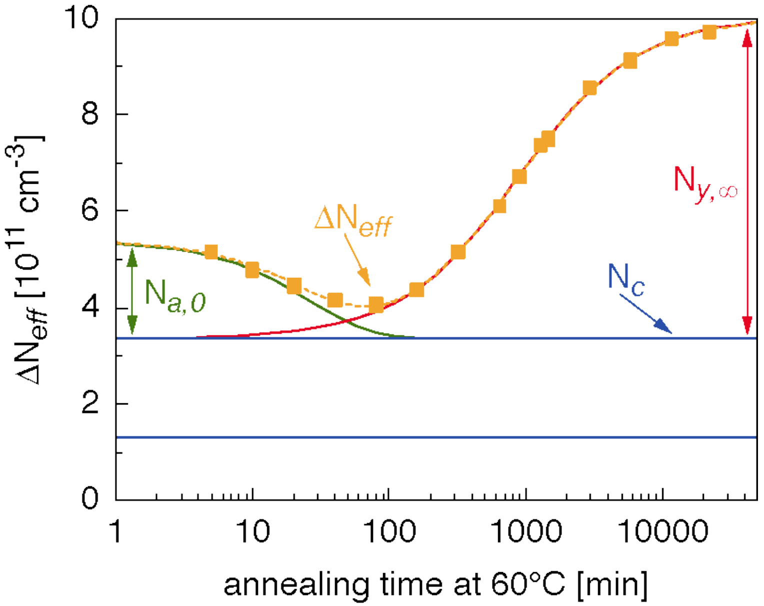
$$\Phi_{eq} = \kappa \cdot \Phi$$

A common language: “1 MeV neutron equivalent”

Time Dependence of Radiation Damage

- Defects diffuse with time
- N_{eff} changes:

$$\Delta N_{eff}(\Phi_{eq},t) = stable\ damage\ (N_c(\Phi_{eq})) + annealing\ (N_b(\Phi_{eq},t), N_r(\Phi_{eq},t))$$



G. Lindström, *Radiation Damage in Silicon Detectors*, NIM A **512**, 30 (2003)

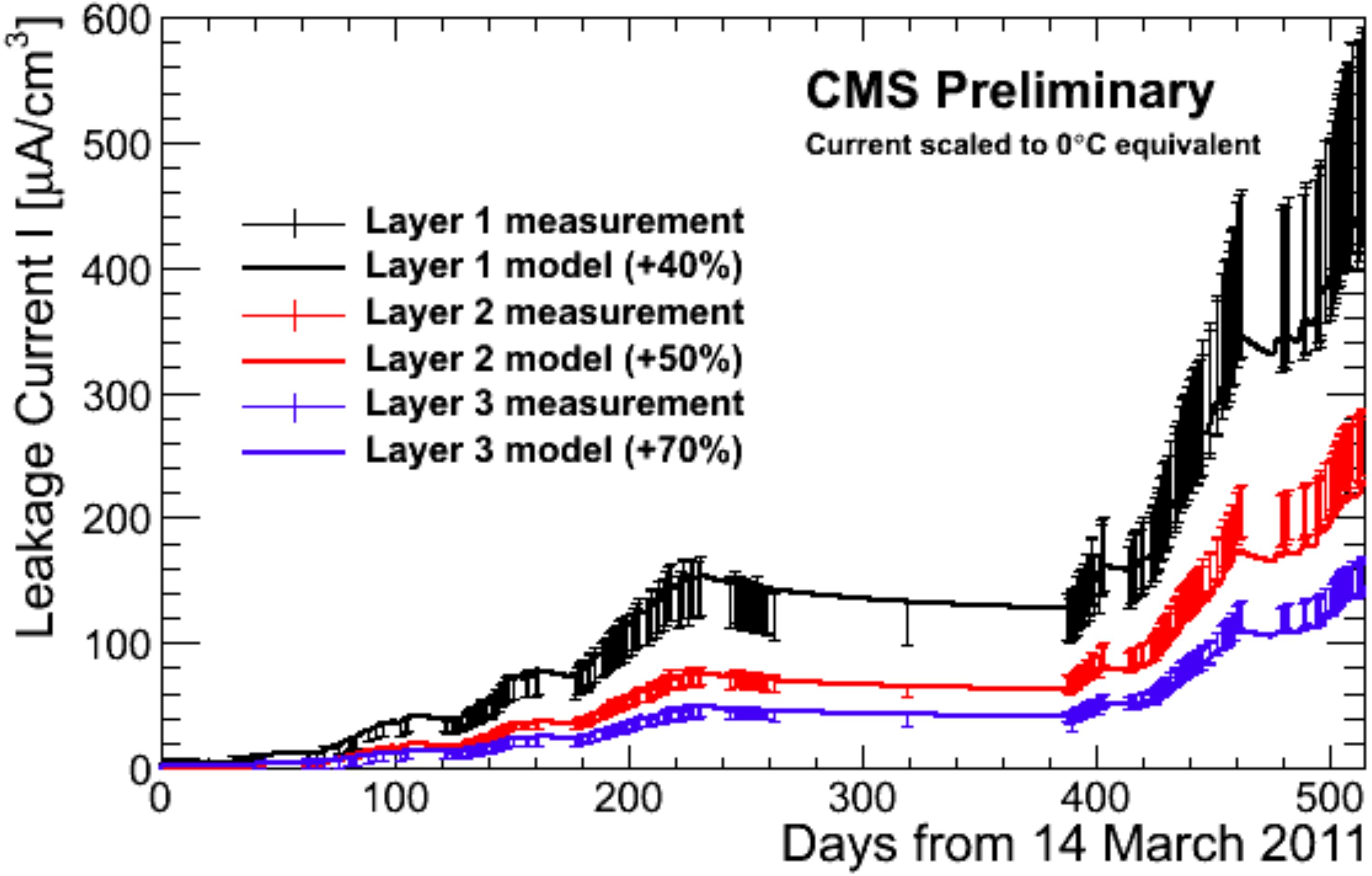
Three Terms:

- constant damage N_c
- Two kinds of Annealing:
  - **beneficial annealing**: N_b (short-term)
  - **reverse annealing** N_r (long-term)
- Different time-scales:

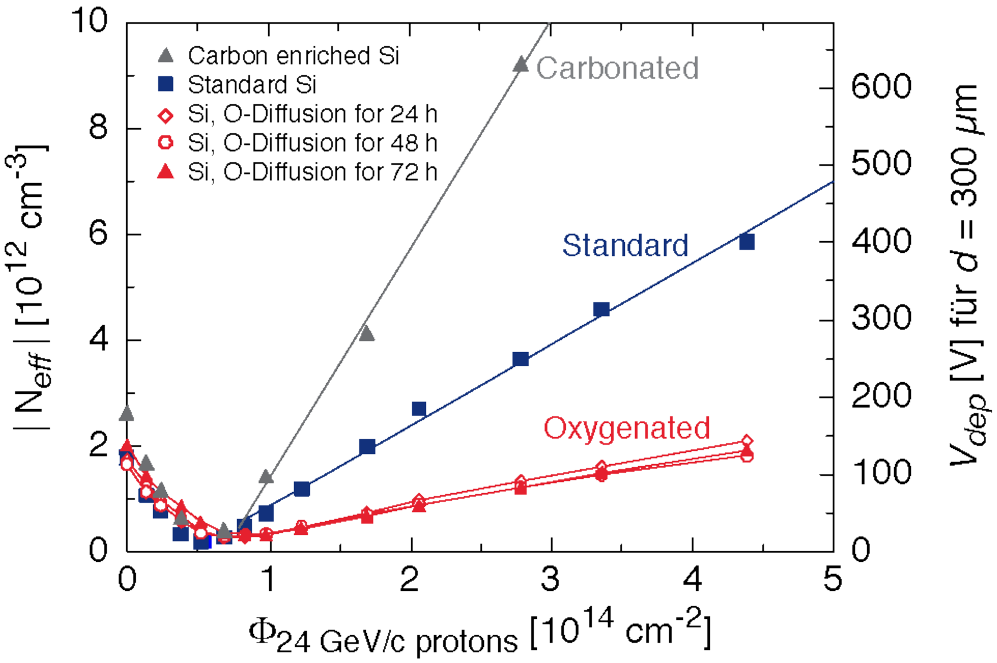
T[°C]	-10	-7	0	10	20	40	60	80
τ_b	306d	180d	53d	10d	55h	4h	19min	2min

T[°C]	-10	0	10	20	40	60	80	100
τ_r	516y	61y	8y	475d	17d	1260min	92min	9min

Annealing in CMS



Radiation Hard Silicon (1)



- Oxygen concentration in typical floatzone (FZ) material <10^{16} cm^{-3}
- DOFZ (diffusion-oxygenated FZ): 10^{17} cm^{-3}

Try materials naturally rich in Oxygen:

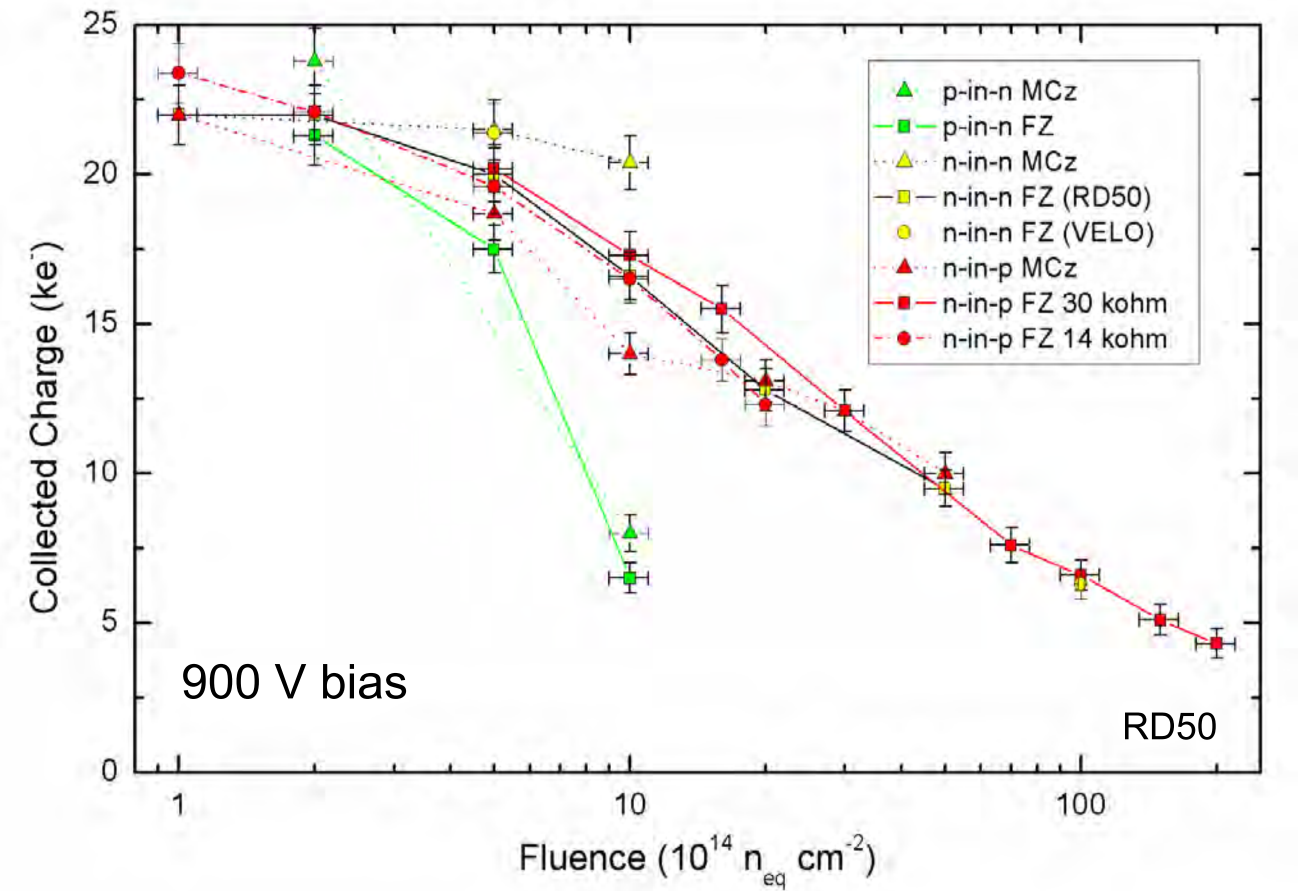
Czochralski silicon

- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap), now available in high purity for use as particle detector (MCz)

Epitaxial silicon

- Chemical-Vapour Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ diffusion of oxygen
- Excellent homogeneity of resistivity
- 150 µm thick layers produced (thicker is possible)

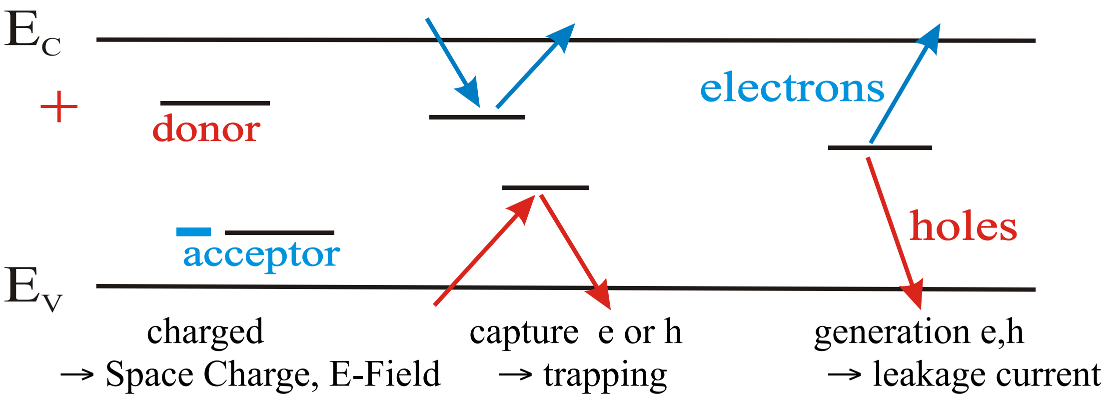
Radiation Hard Silicon (2)



- Irradiation Studies show p-in-n FZ Silicon not very radiation hard
- Better: magnetic Czrochalski (mCz) or n-in-p FZ
- Needs much higher bias voltages than currently used

Defects

- Defect generation can depend on material (remember: oxygenated silicon)
- Electronic defect properties rule the impact on the device
- Different consequence depending on position within band gap:
  - **e or holes capturing**: Trapping -> signal loss -> lower CCE
  - **Generation of e,h pairs**: increased leakage current



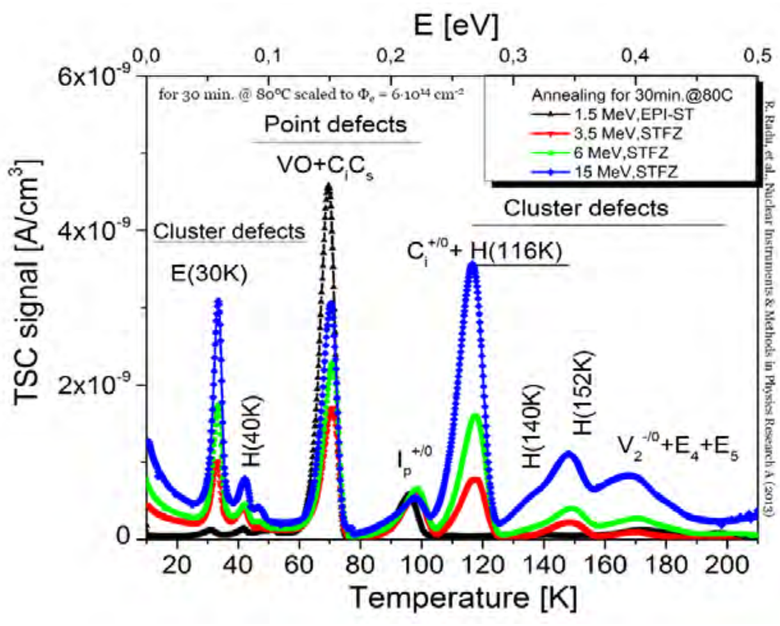
Defect parameters:

$\sigma_{n,p}$: cross sections
ΔE : ionization energy
N_t : concentration
type : acceptor, donor,…

Defect Characterization

- Aim:
  - Identify defects responsible for Trapping, Leakage Current, Change of N_{eff} , Change of E-Field
  - Understand if this knowledge can be used to mitigate radiation damage (e.g. defect engineering)
  - Deliver input for device simulations to predict detector performance under various conditions
- Method: Defect Analysis on identical samples performed with various tools inside RD50:
  - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
  - **I-DLTS** (Current Deep Level Transient Spectroscopy)
  - **TSC** (Thermally Stimulated Currents)
  - **PITS** (Photo Induced Transient Spectroscopy)
  - **FTIR** (Fourier Transform Infrared Spectroscopy)
  - **RL** (Recombination Lifetime Measurements)
  - **PC** (Photo Conductivity Measurements)
  - **EPR** (Electron Paramagnetic Resonance)
  - **TCT** (Transient Current Technique)
  - **CV/IV** (Capacitance/Current-Voltage Measurement)
- RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ

… significant progress on identifying defects responsible for sensor degradation over last 5 years!

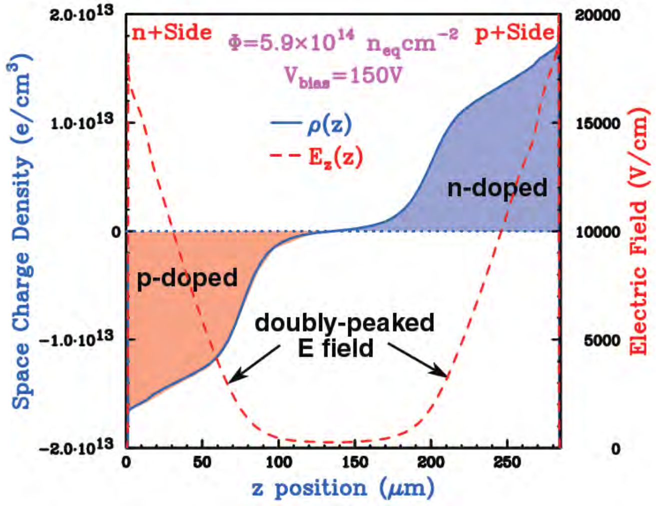


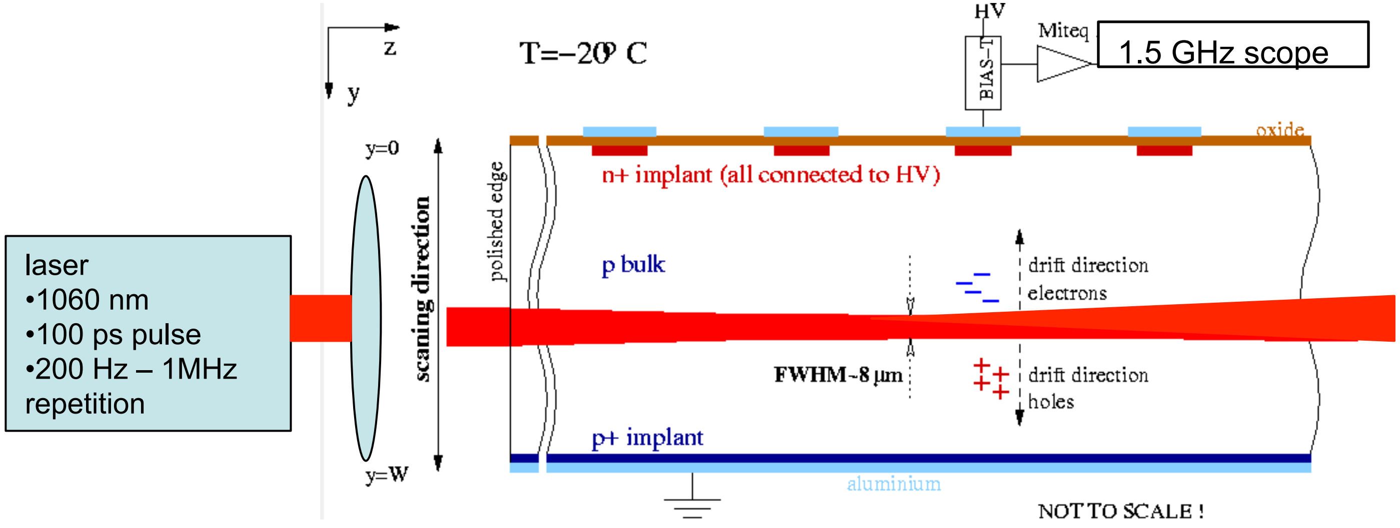
[R.Radu, 22nd RD50 Workshop, 3-5 June

Example: TSC measurement on defects produced by electron irradiation (1.5 to 15 MeV)

Edge-TCT to Study Electric Fields

- Edge-TCT: Illuminate sensor from the side
- Scan across detector thickness
- Measure charge and induced current as function of depth
- Reconstruct electric field





[G. Kramberger, 17th RD50 Workshop, Nov. 2010]

The RD50 Collaboration

- RD50: *48 institutes and 270 members*

40 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Glasgow, Liverpool)

6 North-American institutes

Canada (Montreal), USA (BNL, Fermilab, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

Detailed member list: http://cern.ch/rd50

RD50 Collaboration

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

(Liverpool University) (CERN PH-DT)

Defect / Material Characterization

Mara Bruzzi
(INFN & Uni Florence)

- **Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation**
- **DLTS, TSC, ….**
- **SIMS, SR, …**
- **NIEL (calculations)**
- WODEAN: Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem & M.Bruzzi)

Detector Characterization

Eckhart Fretwurst
(Hamburg University)

- **Characterization of test structures (IV, CV, CCE, TCT,.)**
- **Development and testing of defect engineered silicon devices**
- **EPI, MCZ and other materials**
- **NIEL (experimental)**
- **Device modeling**
- **Operational conditions**
- **Common irradiations**
- Wafer procurement (M.Moll)
- Device Simulations (Eremin)

New Structures

Giulio Pellegrini
(CNM Barcelona)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- **Other new structures**
- **Detectors with internal gain (avalanche detectors)**
- **Slim Edges**

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Slim Edges (H.Sadrozinski)

Full Detector Systems

Gregor Kramberger
(Ljubljana University)

- **LHC-like tests**
- **Links to HEP**
- **Links electronics R&D**
- **Low rho strips**
- **Sensor readout (Alibava)**
- **Comparison:**
  - **- pad-mini-full detectors**
  - **- different producers**
- **Radiation Damage in HEP detectors**

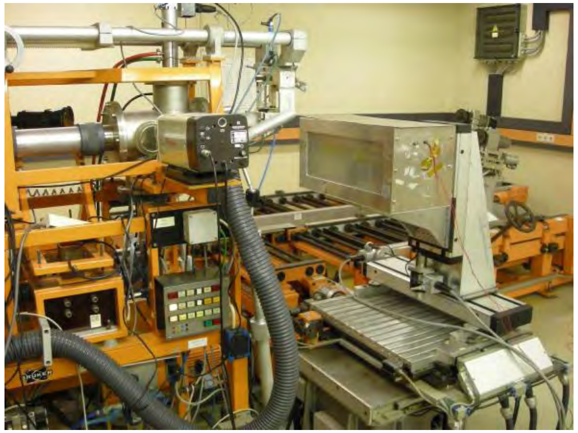
- Test beams (G.Casse)

Backup slides follow

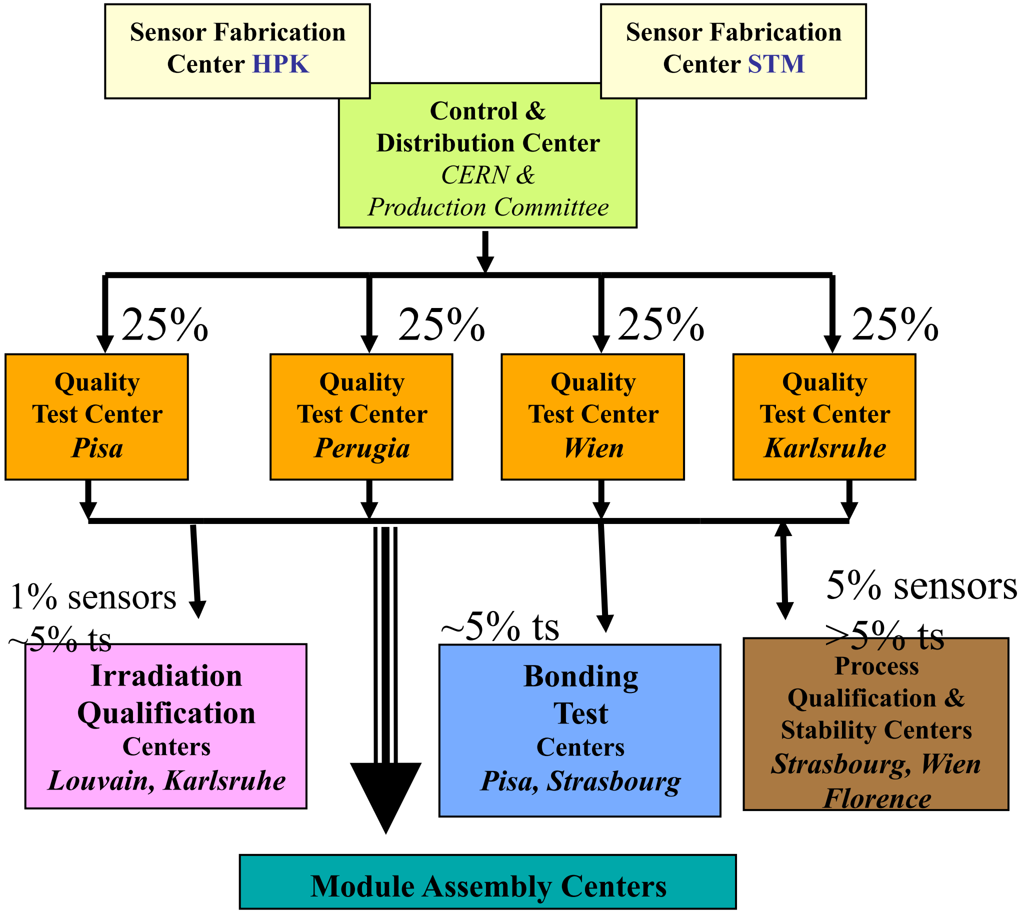
THE END

Silicon Sensors

- Two producers:
  - Hamamatsu Photonics (Japan)
  - ST Microelectronics (Italy)
- Four main Test centers
  - Supported by smaller tests in different locations
  - Irradiation
  - Bonding tests
  - Process Qualification & Longterm stability



Complex logistics



Sensor Fabrication Center HPK

Sensor Fabrication Center STM

Control & Distribution Center
CERN & Production Committee

25% 25% 25% 25%

Quality Test Center *Pisa*

Quality Test Center *Perugia*

Quality Test Center *Wien*

Quality Test Center *Karlsruhe*

1% sensors
~5% ts

Irradiation Qualification Centers *Louvain, Karlsruhe*

~5% ts

Bonding Test Centers *Pisa, Strasbourg*

5% sensors
>5% ts

Process Qualification & Stability Centers *Strasbourg, Wien Florence*

Module Assembly Centers

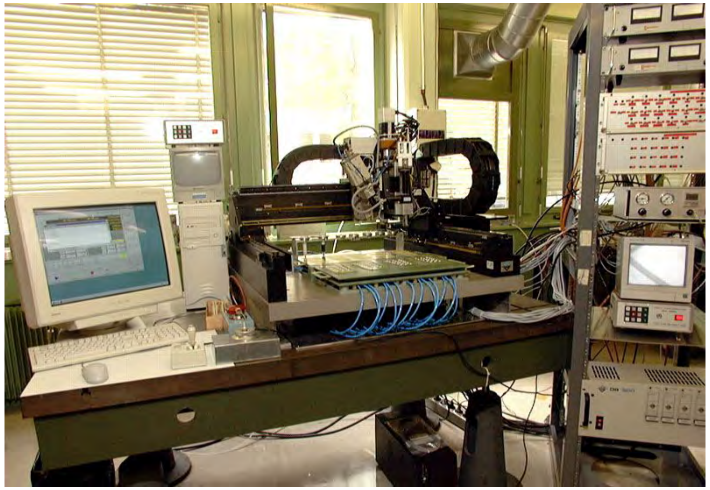
Module Assembly

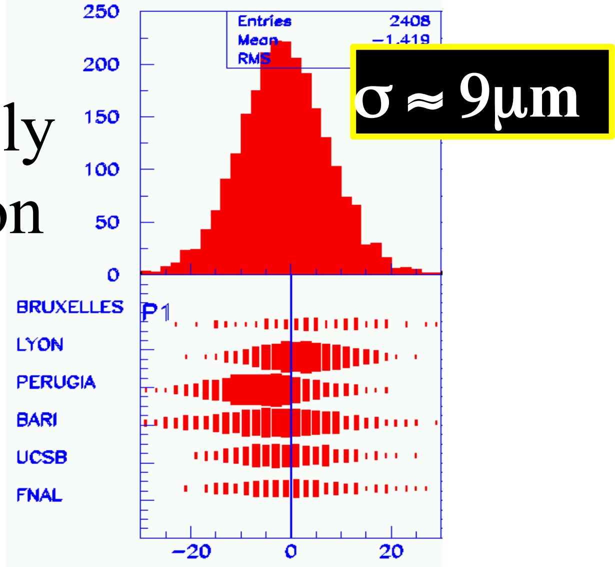
Robotic assembly system which:

1. Apply glue on frame
2. Place hybrid onto frame
3. Place sensor onto frame
4. Optical measurement of placement precision
5. Glue curing
6. Second measurement of alignment precision

Displacement data entered in TrackerDB and used for correction during track reconstruction

(more precise: as starting point of track-based alignment)





Assembly precision

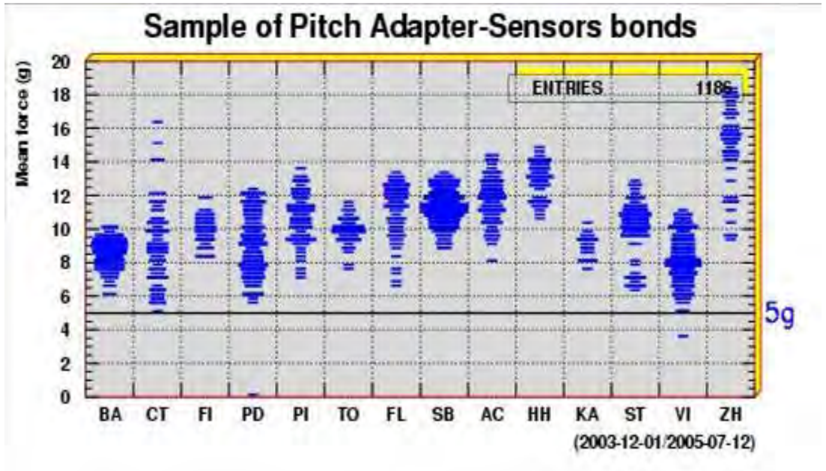
$\sigma \approx 9\mu m$

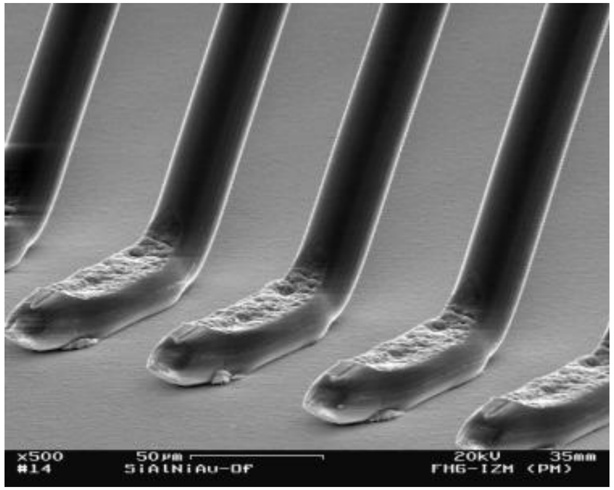
Wire Bonding

Electrical connection between strips on sensor and hybrid:

- Wire bonding with fully automatic bonding machines
- Bonding: Ultra-sonic welding
- Wire: 25 µm thin Al-Si wire
- Pull tests: Bond wires must resist pull force of 5g

14 bonding centers



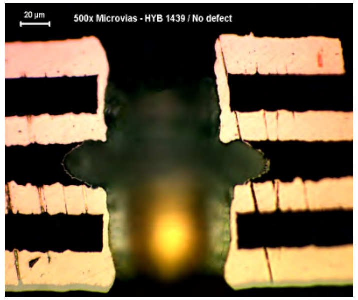


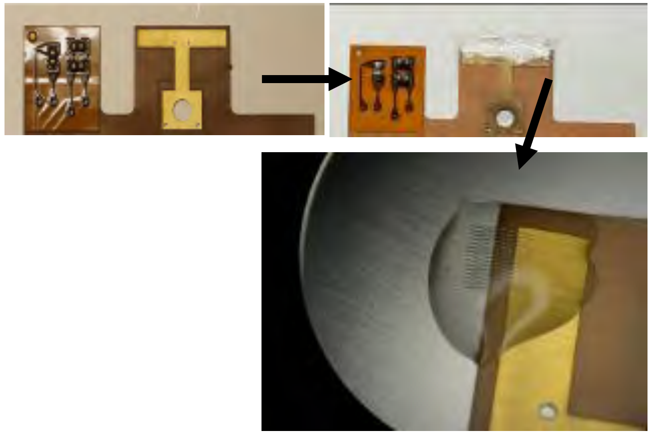
Problems During Module Production

- Resonance during shipping = bond lift off
  - ➔ add. Stiffeners on modules
- Faulty hybrids
  - – Kapton cable insufficiently (Al break)
  - – Faulty vias without conduction
  - ➔ Modules with bad hybrids: 400 dis-assembled (sensor re-used)
- Doubts on long term behavior of back plane conductive glue
  - ➔ Reinforce glue spot
  - ➔ backplane bonding with encapsulation

Bond liftoffs

Bad via

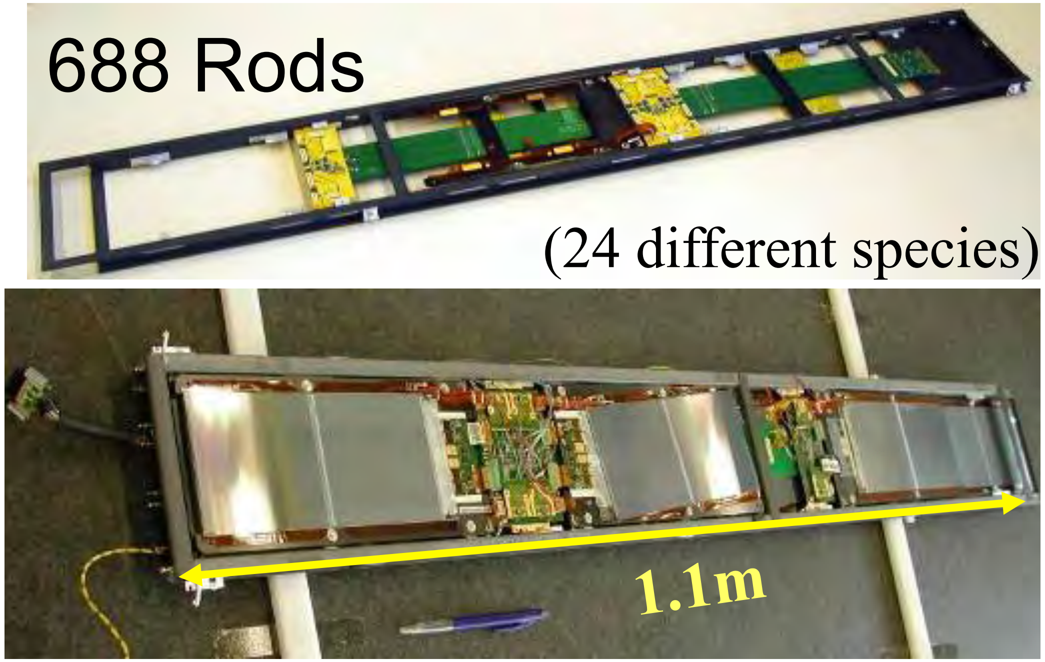




Obviously all problems were solved, since we have 100% of modules available!

Tracker Outer Barrel (TOB)

- Tracker Outer Barrel (TOB) mainly produced in US



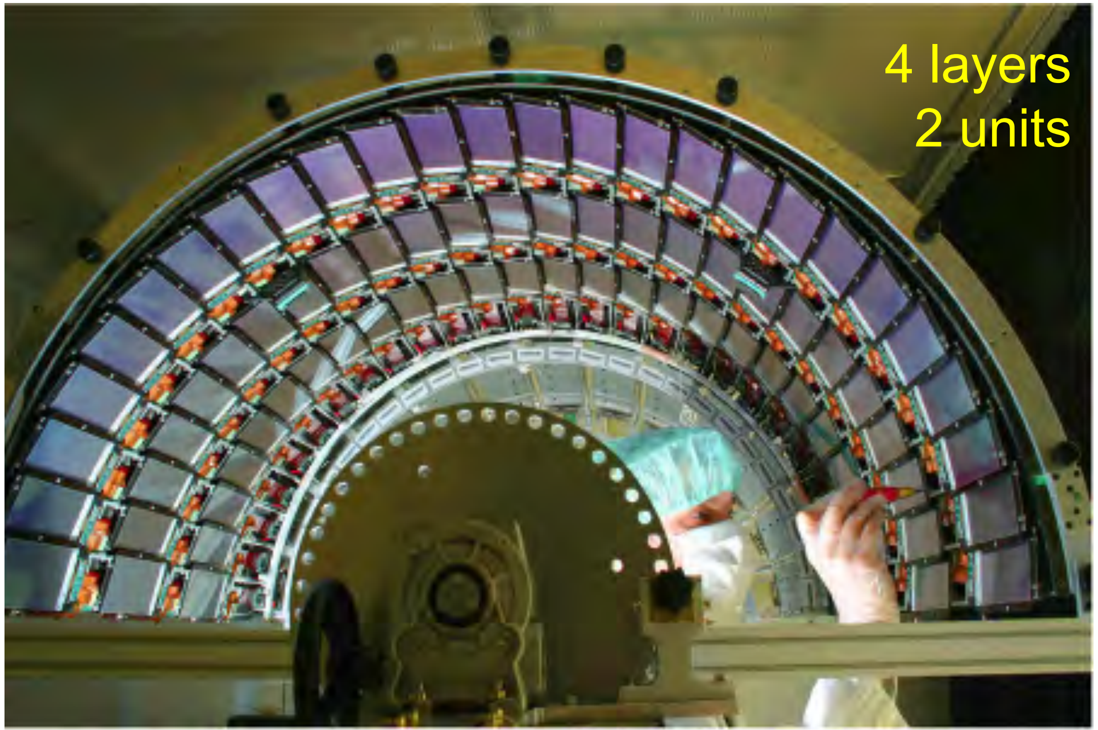
Tracker Support Tube:

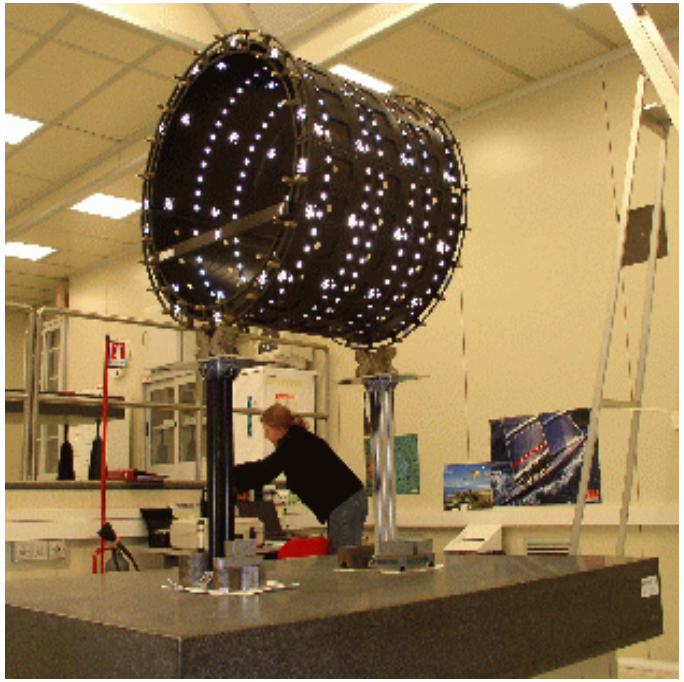
Tracker Inner Barrel (TIB)

- TIB mainly produced in Italy


3800 modules

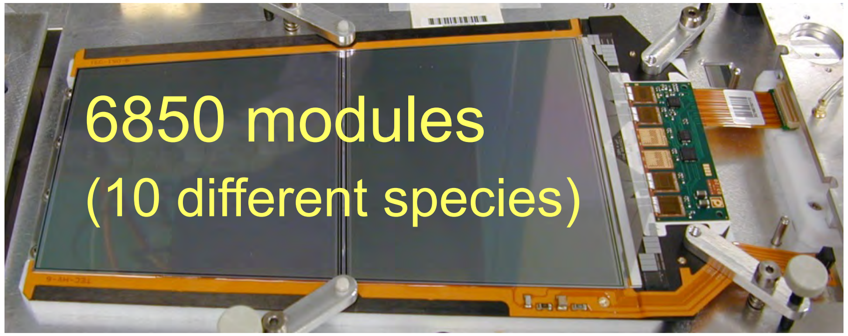
16 shells + 6 disks

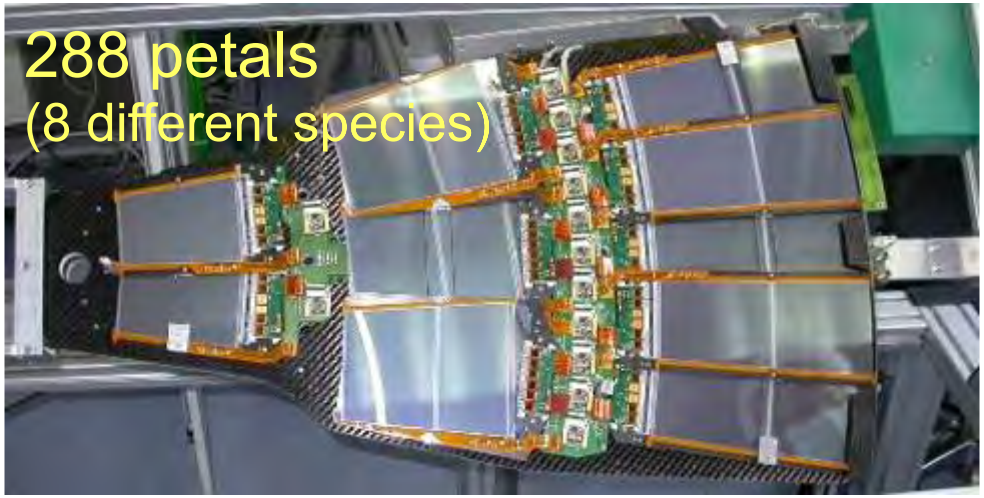

4 layers
2 units

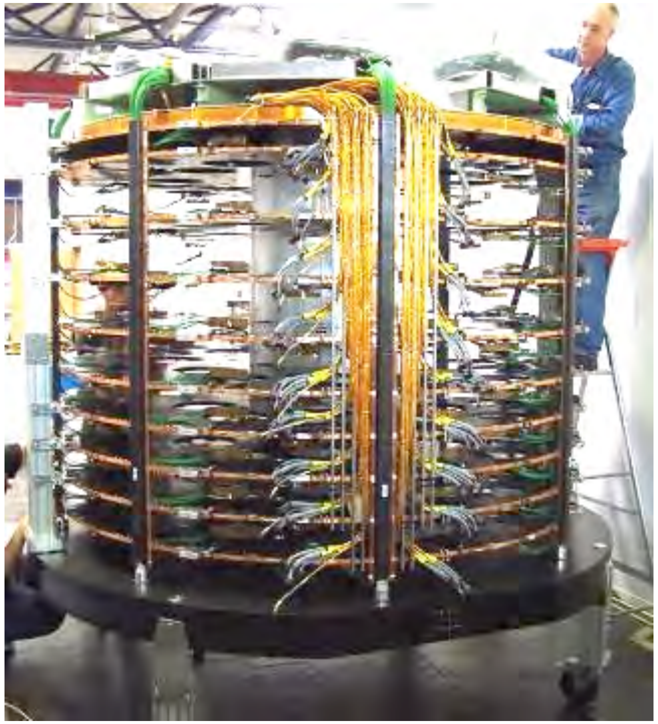


Tracker End Caps (TEC)

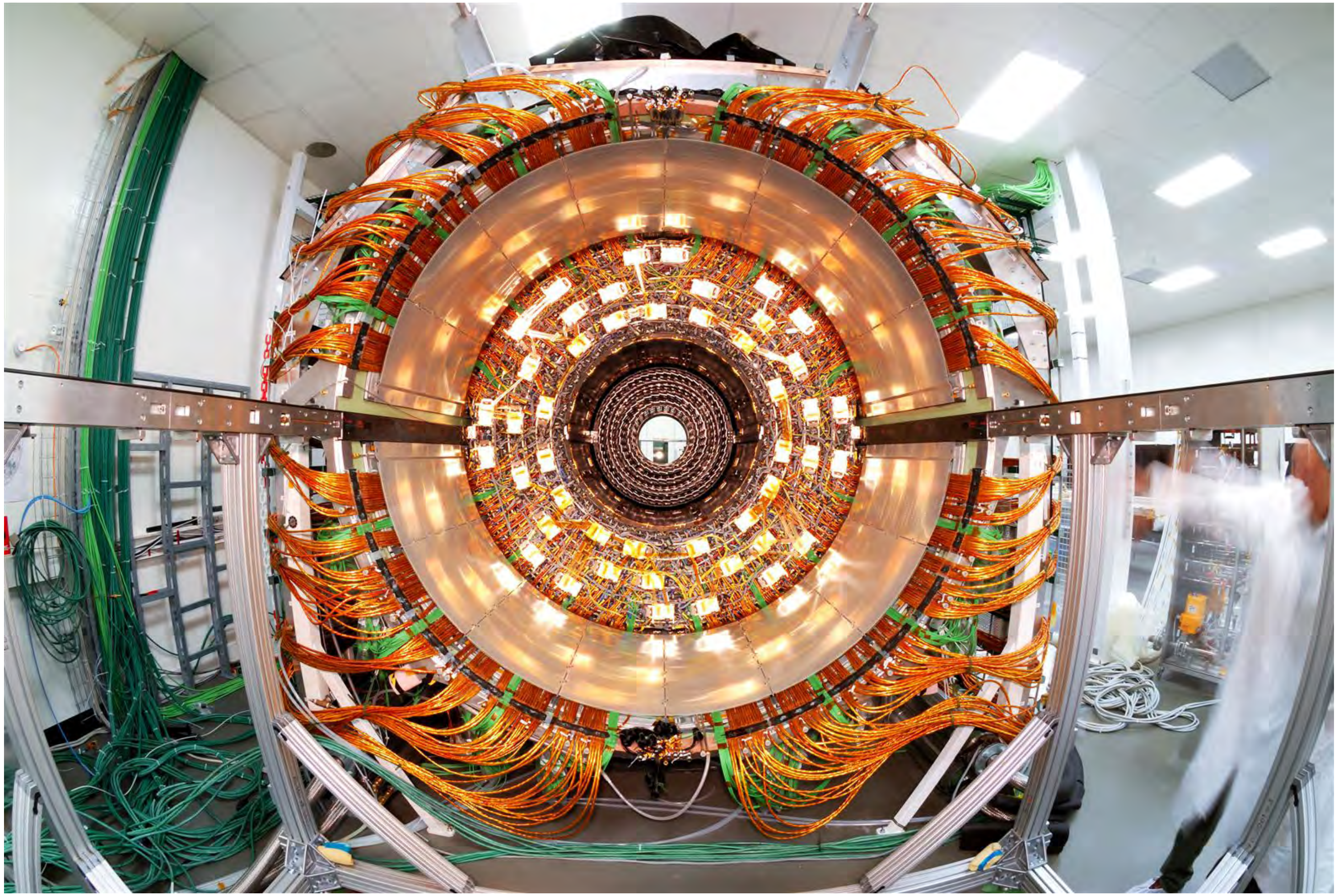
- TEC modules and petals mostly from Central Europe (Belgium, Germany, France, Austria)


6850 modules
(10 different species)

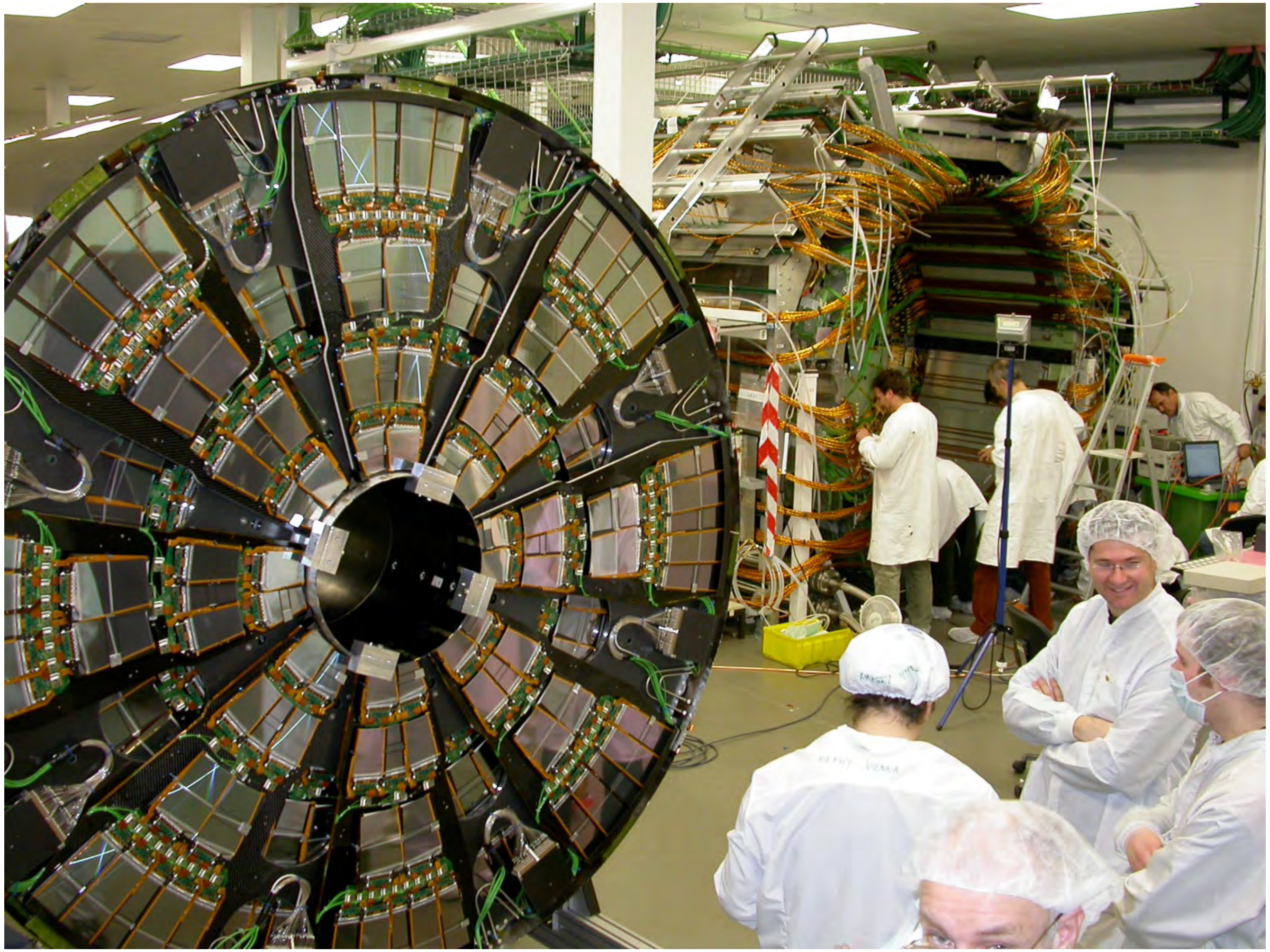

288 petals
(8 different species)



TOB plus TIB/TID



TEC Installation



CMS Tracker in pictures