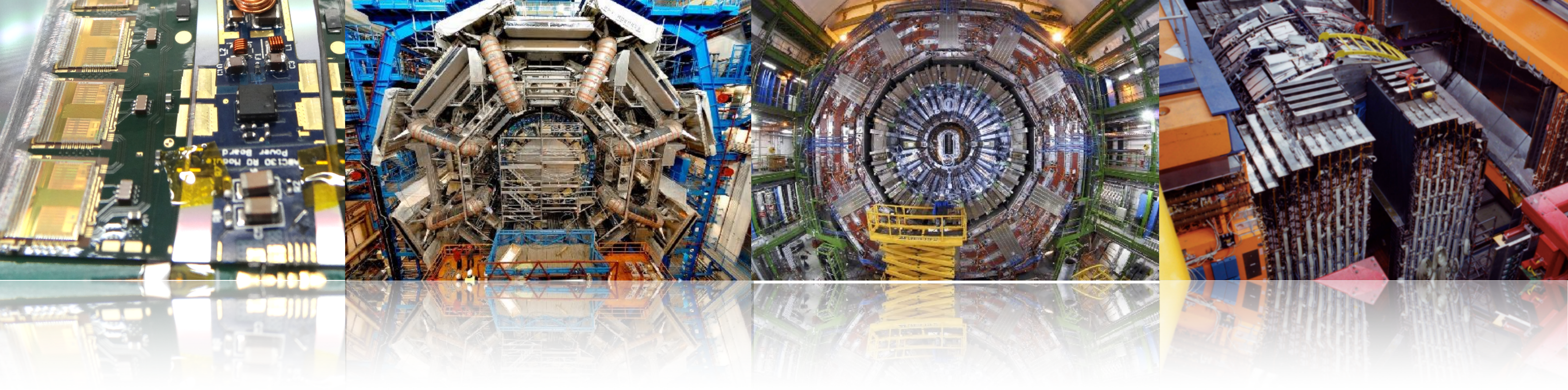


What you always wanted to know about Silicon Detectors

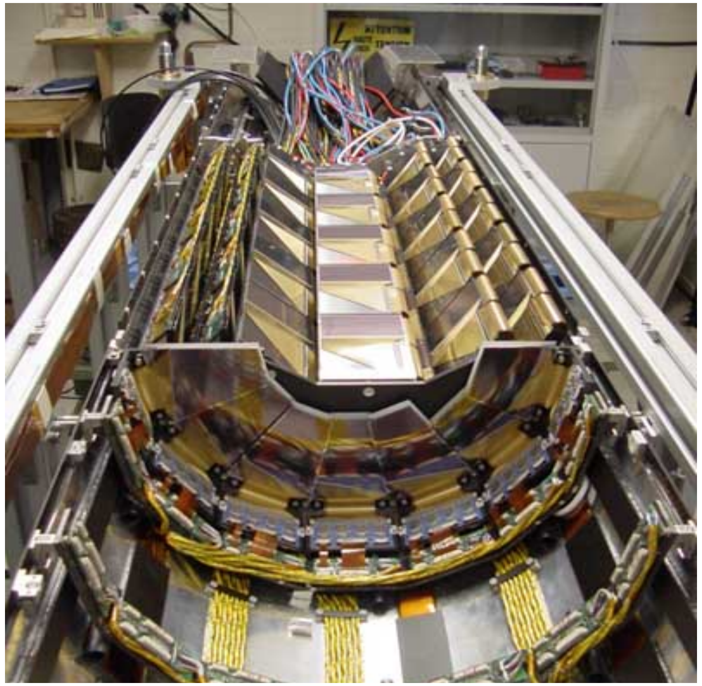
…. and never dared to ask

RADHARD2024 Bonn
2. October 2024

Ingrid Maria Gregor
DESY/Universität Bonn

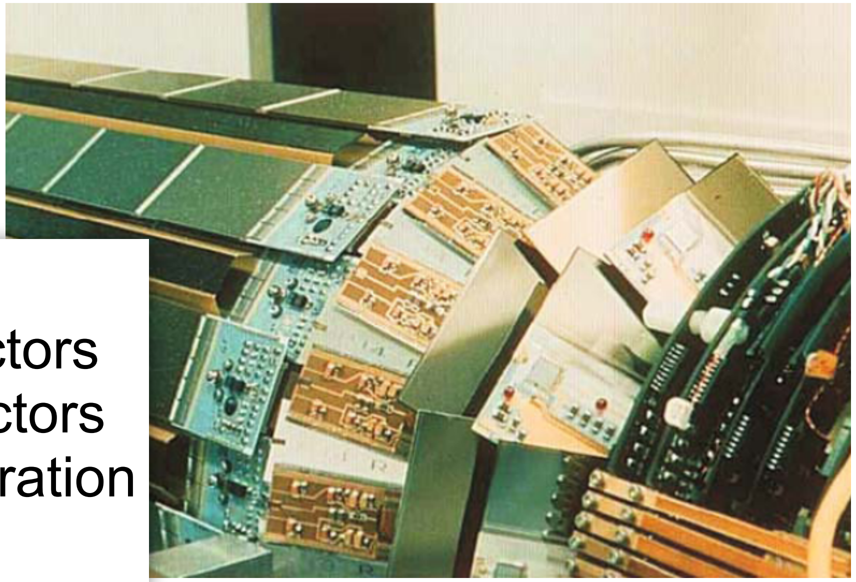
Motivation

- Semiconductors have been used in particle identification for many years:
  - ~1950: Discovery that pn-Junctions can be used to detect particles.
- Semiconductor detectors used for energy measurements (Germanium).



ZEUS MVD 2000

- Since ~50 years: Semiconductor detectors for precise position measurements
  - precise position measurements possible through fine segmentation (10-100µm)
  - multiplicities can be kept small (goal:<1%)
- Technological advancements in production t
  - developments for micro electronics



DELPHI VFT 1996

Outline
- Strip Detectors
- Pixel Detectors
- Next Generation
- Problems

Ionisation and dE/dx

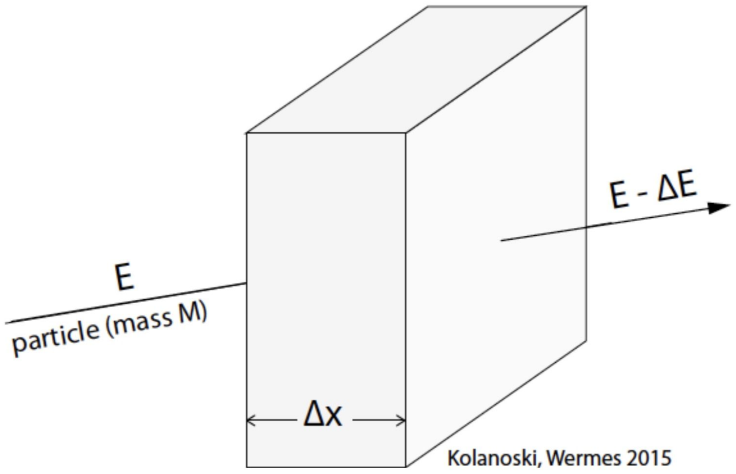
How exactly does a charged particle cause a signal?

JUMP

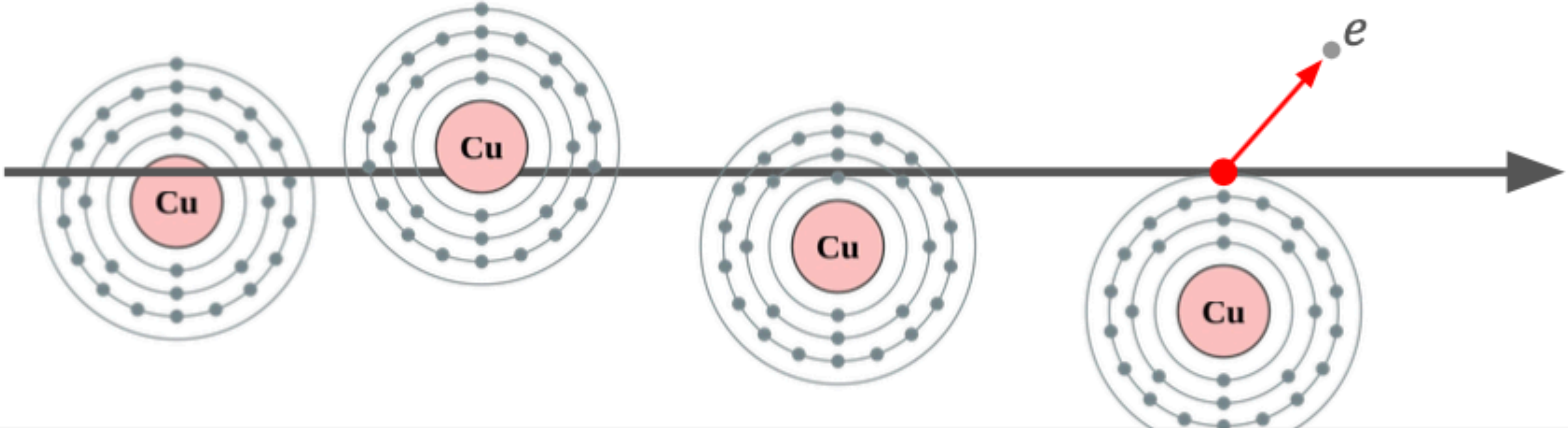
IONISATION

The primary contributor to dE/dx at typical energies

- Particle can collide with **atomic electron** (*EM* interaction)
- If enough energy is transferred, the electron escapes, **ionising** the atom and causing small $-dE$
  - can also excite the atom, if transferred energy is small
- In general, this happens frequently, with small energy transfers (<100eV), so energy loss is ~continuous



Kolanoski, Wermes 2015



INTERACTIONS OF "HEAVY" PARTICLES WITH MATTER

- Mean energy loss is described by the **Bethe-Bloch** formula

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

W_{max} Maximum kinetic energy which can be transferred to the electron in a single collision

I^2 Excitation energy

$\frac{\delta}{2}$ Density term due to polarisation: leads to saturation at higher energies

$\frac{C}{Z}$ Shell correction term, only relevant at lower energies

$$2\pi N_A r_e^2 m_e c^2 = 0.1535\,\mathrm{MeV cm^2/g}$$

r_e : classical electron radius =
m_e : electron mass
N_A : Avogadro's number
I : mean excitation potential
Z : atomic number of absorbing material

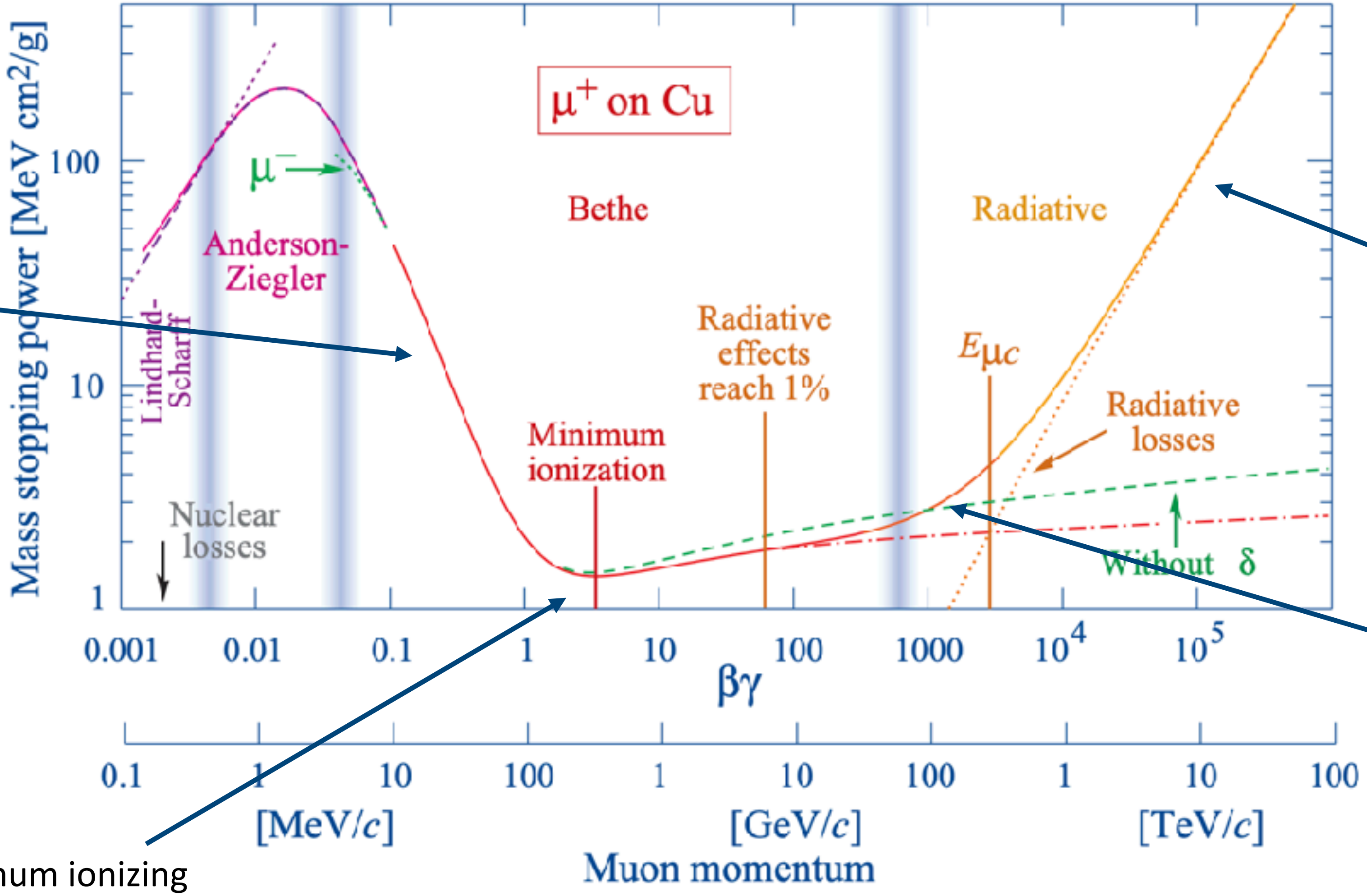
A : atomic weight of absorbing material
ρ : density of absorbing material
z : charge of incident particle in units of e
β : v/c of the incident particle
γ : $1/\sqrt{1-\beta^2}$

https://pdg.lbl.gov/2024/reviews/contents_sports.html

BETHE BLOCH IN A NUTSHELL

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

“kinematic term”



Bremsstrahlung

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$$

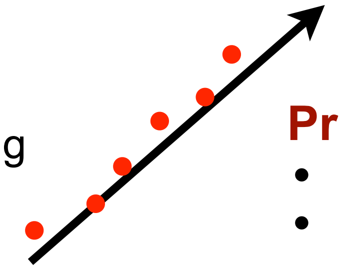
“relativistic rise”

“minimum ionizing particles” $\beta\gamma \approx 3\text{-}4$

Plot: PDG, May 2024

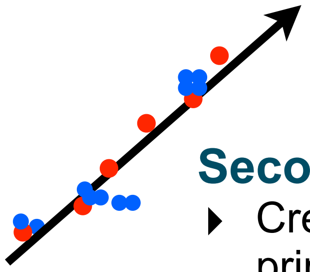
A Closer Account of Energy Loss

- Bethe-Bloch displays only the average
  - energy loss is a statistical process
  - discrete scattering with different results depending on strength of scattering
  - primary and secondary ionisation



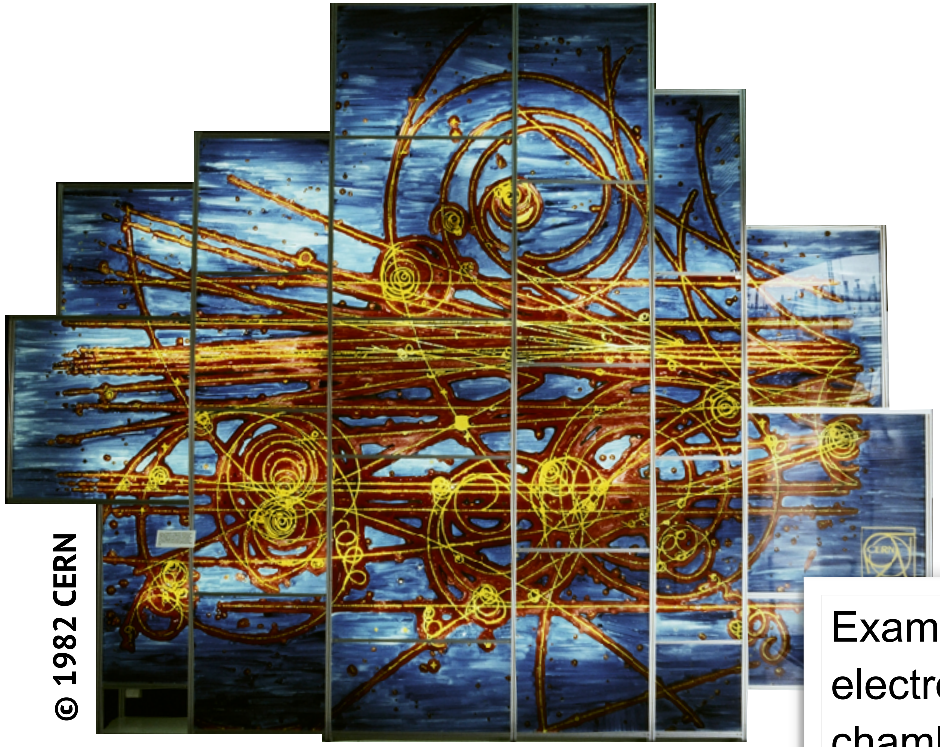
Primary ionisation

- Poisson distributed
- Large fluctuations per reaction



Secondary ionisation

- Created by high energetic primary electrons
- sometime the energy is sufficient for a clear secondary track: δ-Electron



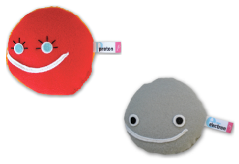
© 1982 CERN

Example of a delta electron in a bubble chamber: visible path

Liquid hydrogen bubble chamber 1960 (~15cm).

Total ionisation = **primary ionisation**
+ **secondary ionisation**

ENERGY LOSS IN THIN LAYERS



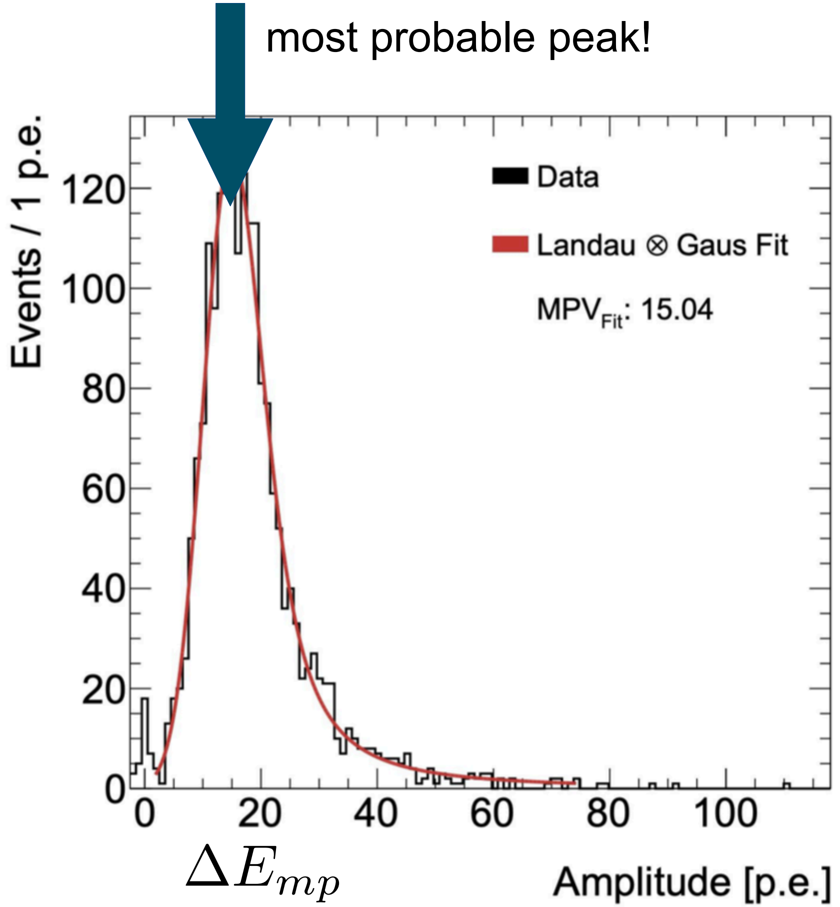
- Bethe Bloch formula describes average energy loss
- Fluctuations about the mean value are significant and non-Gaussian
  - A broad maximum: collisions with little energy loss (more probable)
  - A long tail towards higher energy loss: few collisions with large energy loss T_{max}, δ-electrons.
    -> Most probable energy loss shifted to lowed values

The Landau distribution is used in physics to describe the fluctuations in the energy loss of a charged particle passing through a thin layer of matter

$$P(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\lambda + e^{-\lambda}) \right]$$

$$\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$$

ξ is a material constant



most probable peak!

RADIATION LENGTH X_0

- Bremsstrahlung is dominating at high energies
- At low energies: ionisation, additional scattering

dE/dx for an **electron**

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^{\,2} E \ln\frac{183}{Z^{1/3}}$$

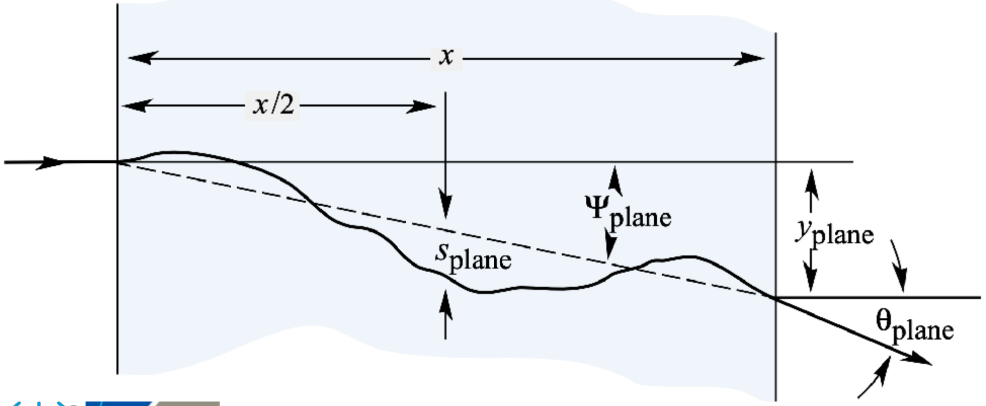
$$-\frac{dE}{dx} = \frac{E}{X_0} \longrightarrow \boxed{E = E_0\, e^{-x/X_0}}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^{\,2} \ln\frac{183}{Z^{1/3}}}$$

Parameters only depending on material the electron is passing through.

Thickness of material an electron travels through until the energy is reduced by Bremsstrahlung to 1/e of its original energy

- The radiation length is also an important quantity in multiple scattering
- A very important number when building detectors, one always has to keep in mind how much material is within the detector volume



- Usually quoted in [g/cm²], typical values are:
  - Air: 36.66 g/cm² ->~ 300 m
  - Silicon: 21.82 g/cm² -> 9.4 cm
  - Aluminium: 24.01 g/cm² -> 8.9 cm
  - Tungsten: 6.76 g/cm² -> 0.35 cm

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$$

$$\theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

Semiconductors

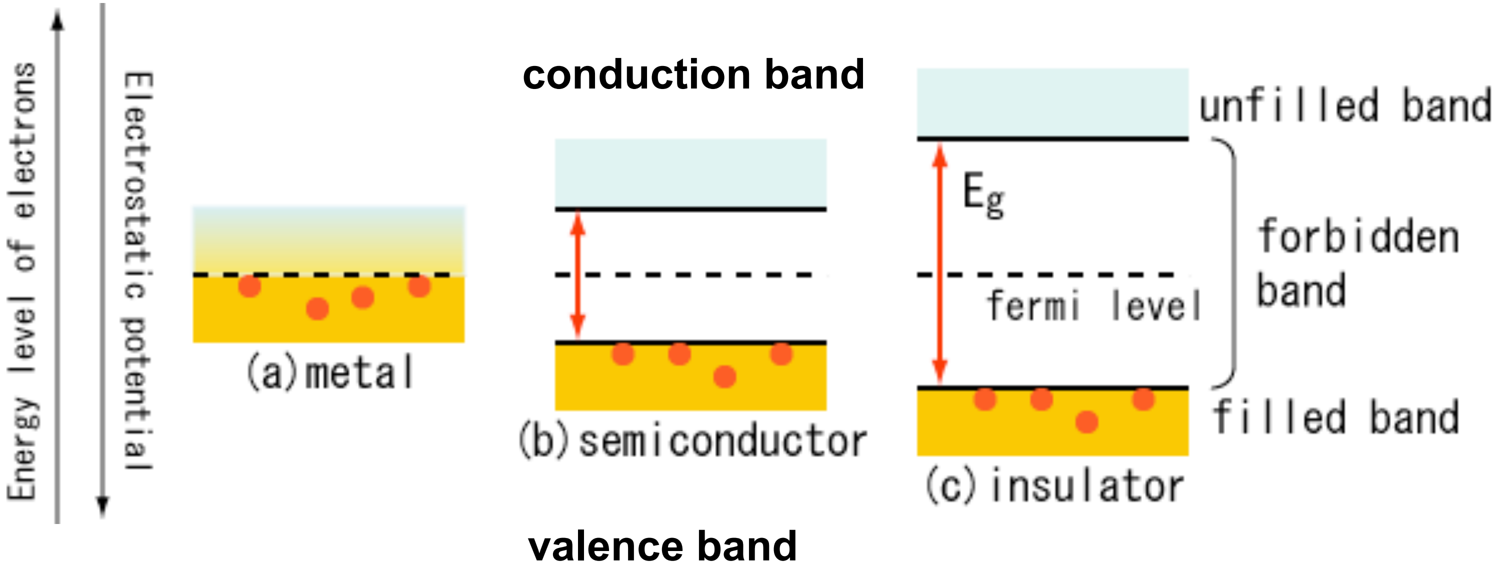
How does a pn junction work?

How do you choose the bias voltage?

JUMP

SEMICONDUCTOR BASICS

- In free atoms electron energy levels are discrete.
- In a solid, energy levels split and form a nearly-continuous band.



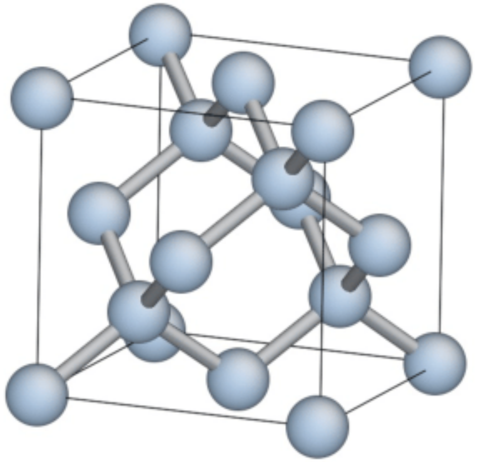
- Large gap: the solid is an insulator.
- No gap: it is a conductor.
- Small band gap: semiconductor

- For silicon, the band gap is 1.1 eV, but it takes **3.62 eV** to ionise an atom
  - Remaining energy goes to phonon excitations (heat).

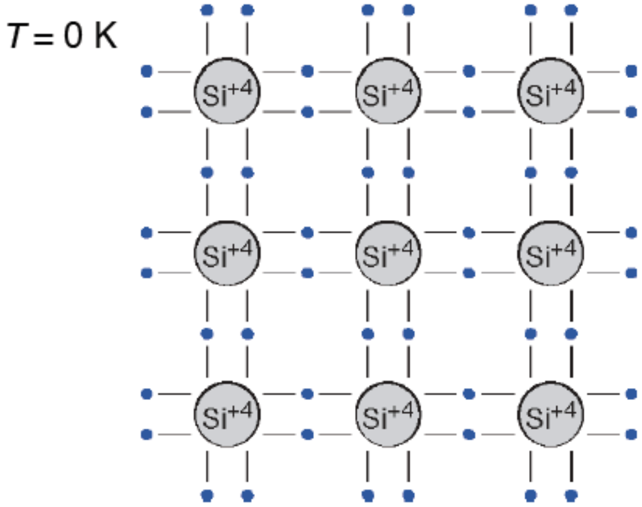
BAND MODEL FOR ELEMENTS IV (EXAMPLE FOR SI)

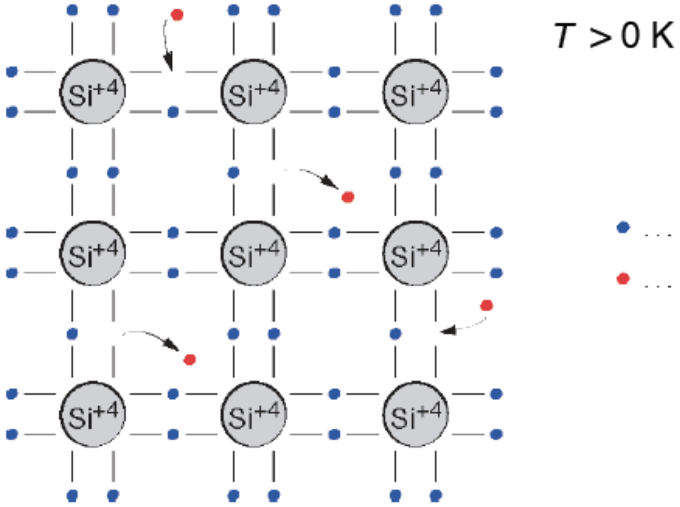
Each atom has 4 closest neighbours, the 4 electrons in the outer shell are shared and form covalent bonds.

- At low temperature all electrons are bound
- At higher temperature, thermal vibrations break some of the bonds
- Free electrons cause conductivity (electron conduction)
- The remaining open bonds attract other e- ➔ the “holes” change position (hole conduction)



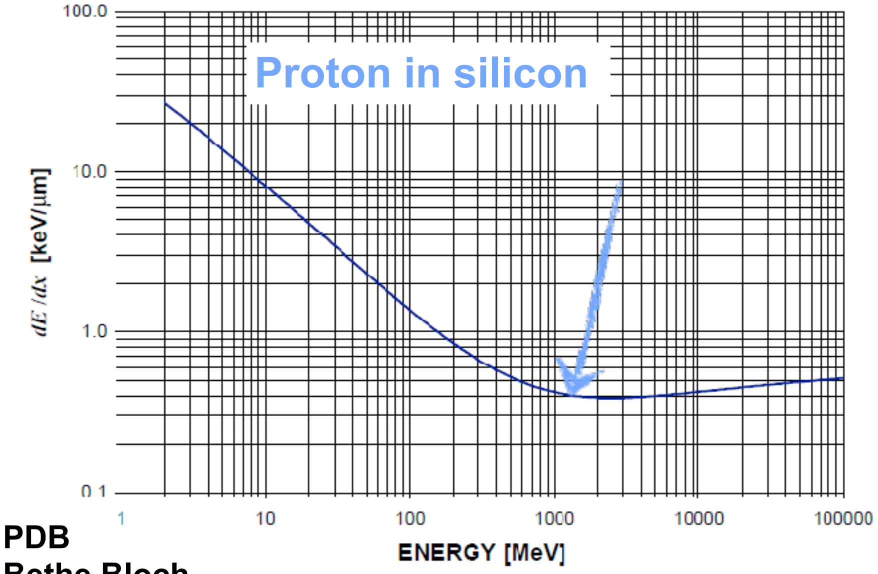
Crystal structure





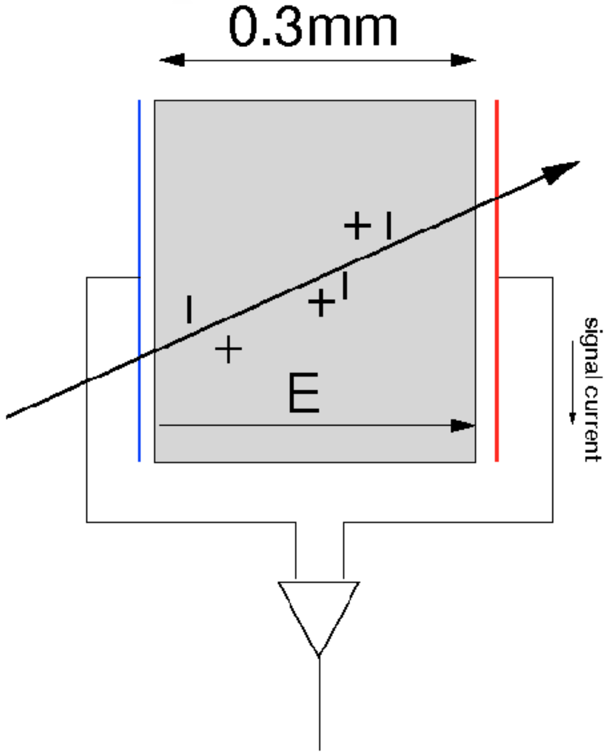
In ultra-pure silicon the intrinsic carrier concentration is $1.45 \cdot 10^{10}$ cm^{-3} at room temperature.

CONSTRUCTING A DETECTOR



PDB
Bethe Bloch

Si detector:
Thickness: 0.3 mm
Area: 1 cm^2



- Mean ionisation energy $\boldsymbol{I_0 = 3.62}$ **eV**
- Mean energy loss per flight path of a mip ***dE/dx*** **= 3.87 MeV/cm**

Signal of a mip in detector:

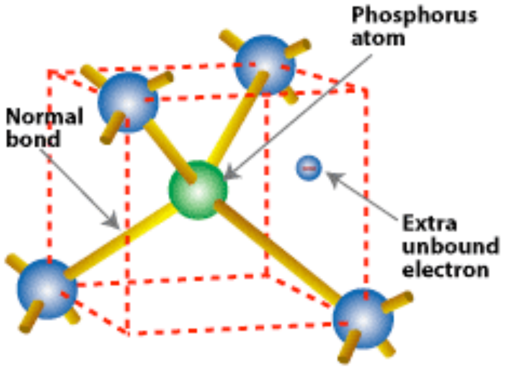
$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \, \mathrm{eV/cm} \cdot 0.03 \, \mathrm{cm}}{3.62 \, \mathrm{eV}} \approx 3.2 \cdot 10^4 \, \mathrm{e^- h^+ - pairs}$$

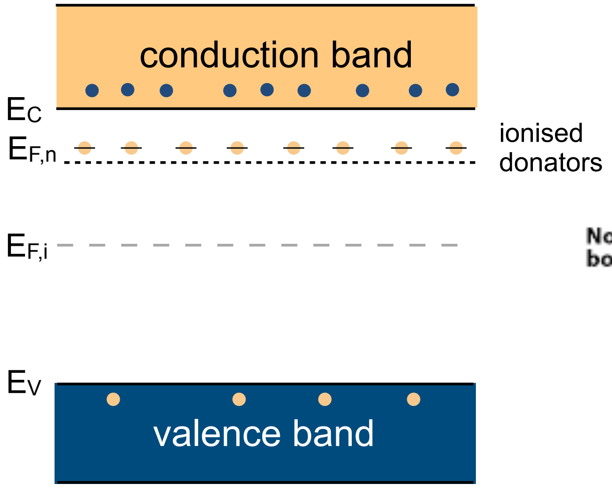
Intrinsic charge carrier in a volume of same thickness and A=1cm^2 (*T* = 300 K):

$$n_i \, d \, A = 1.45 \cdot 10^{10} \, \mathrm{cm^{-3}} \cdot 0.03 \, \mathrm{cm} \cdot 1 \, \mathrm{cm^2} \approx 4.35 \cdot 10^8 \, \mathrm{e^- h^+ - pairs}$$

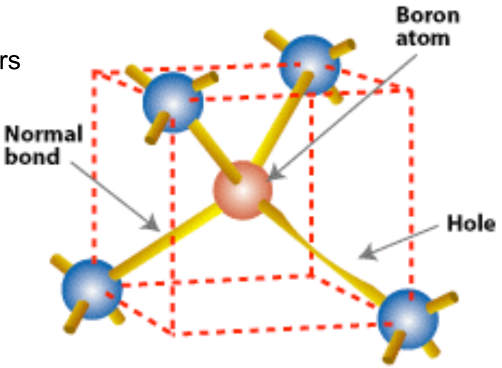
Result: The number of thermal created e–h+-pairs (noise) is four orders of magnitude larger than the signal

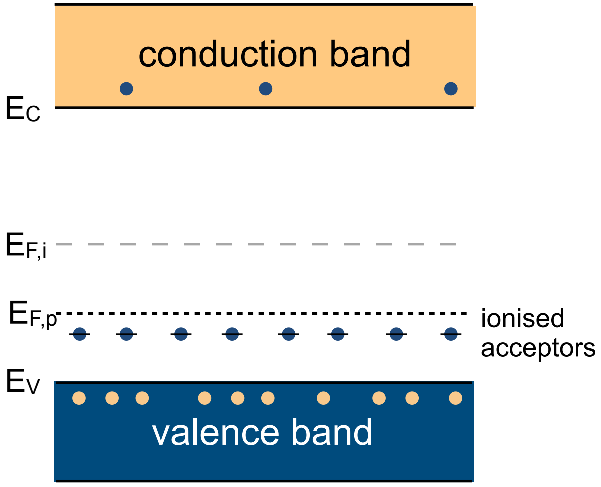
DOPING SILICON





- ● single occupied level (electron)
- ● single empty level (hole)





- ● single occupied level (electron)
- ● single empty level (hole)

n type semiconductor:

- ◎ **N**egative charge carriers (electrons) by adding impurities of donor ions (e.g. Phosphorus (type V))
- ◎ **Donors** introduce energy levels close to conduction band thus almost fully ionised (E_F closest to CB)

Electrons are the majority carriers.

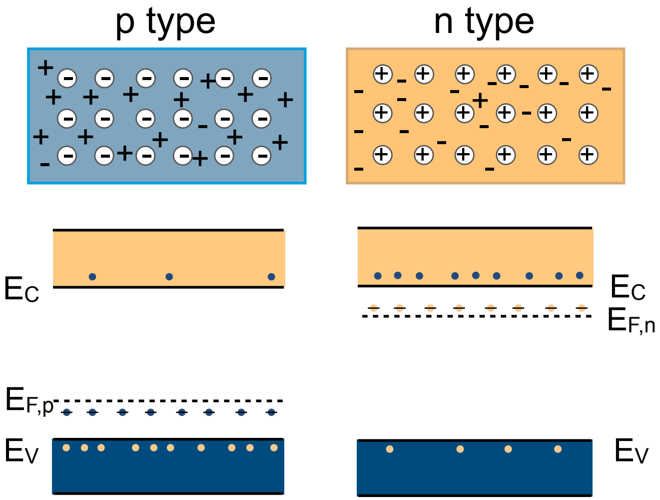
p type semiconductor:

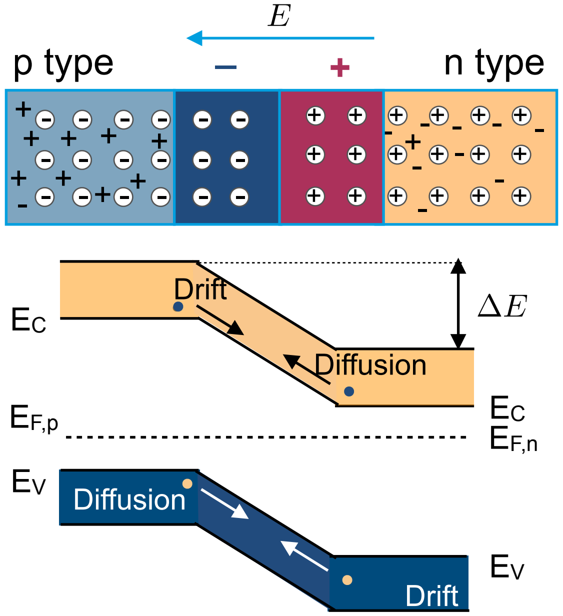
- ◎ Positive charge carriers (holes) by adding impurities of acceptor ions (e.g. Boron (type III)).
- ◎ Acceptors introduce energy levels close to valence band thus 'absorb' electrons from VB, creating holes (E_F closest to VB).

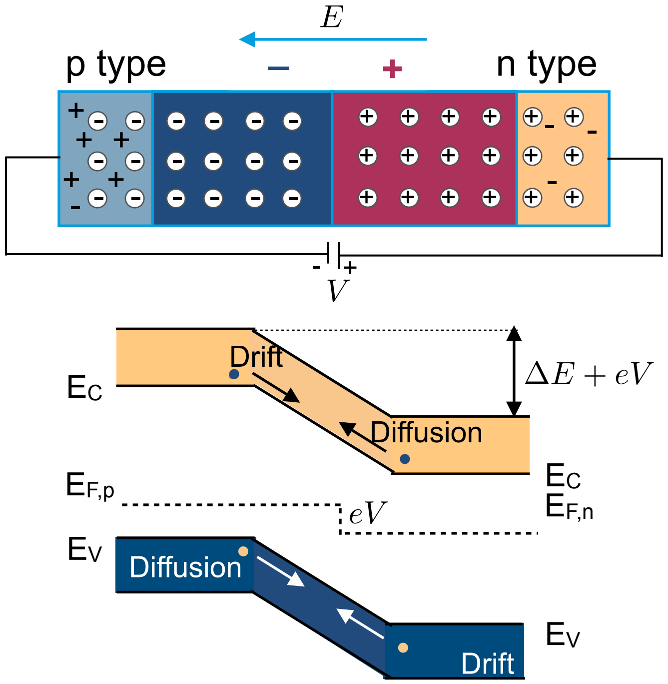
Holes are the majority carriers.

BASIS OF SILICON DETECTOR: PN JUNCTION

- At interface of p type and n type semiconductor diffusion of excessive carriers to the other material until thermal equilibrium
- Stable space charge region free of charge carriers: **depletion zone**.



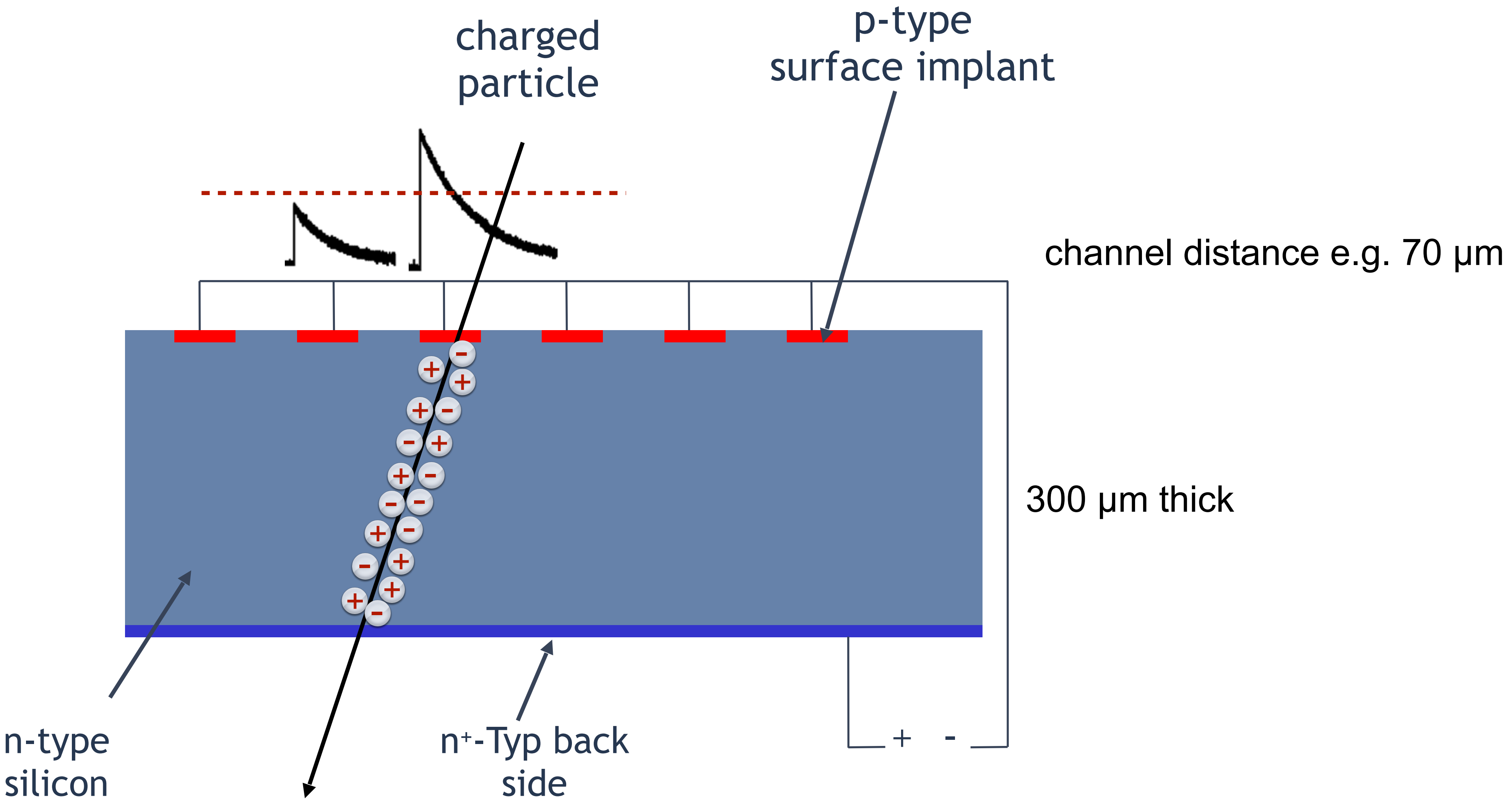




pn-junction with reverse bias

Applying an external voltage V with the cathode to p and the anode to n (reverse biasing), e-h pairs are pulled out of the depletion zone. ➔ **larger depletion zone** ➔ suppress current across the junction

SILIZIUM DETEKTOR IN A NUTSHELL



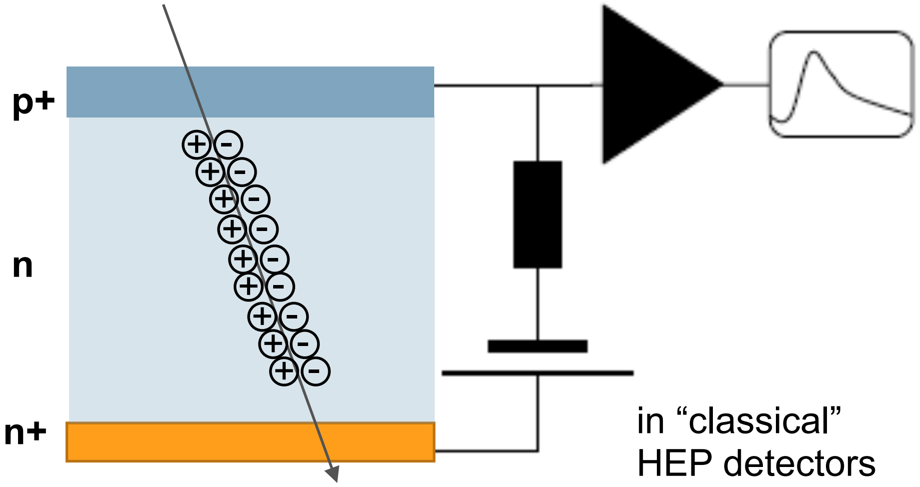
PRINCIPLE OF SEMICONDUCTOR DETECTORS

- Creation of electric field: voltage to deplete thickness d

$$d = \sqrt{\frac{2\epsilon\epsilon_0 V}{e}\left(\frac{1}{n_D} + \frac{1}{n_A}\right)}$$

with $n_A >> n_D$ $$d = \sqrt{\frac{2\epsilon\epsilon_0 V_{dep}}{e n_D}}$$

for $d = 300\mu m$: $V_{dep} \approx 160V$



in “classical” HEP detectors d=100-300 µm

Typical numbers

Doping concentration

$n_A \approx 10^{19} cm^{-3}$	Acceptors
$n_D \approx 2 \cdot 10^{12} cm^{-3}$	Donators

- Passage of a charged particle: Electron-hole pairs formed in the depletion zone
  - Drift under the influence of the electric field
  - Signal depends on width of depletion zone

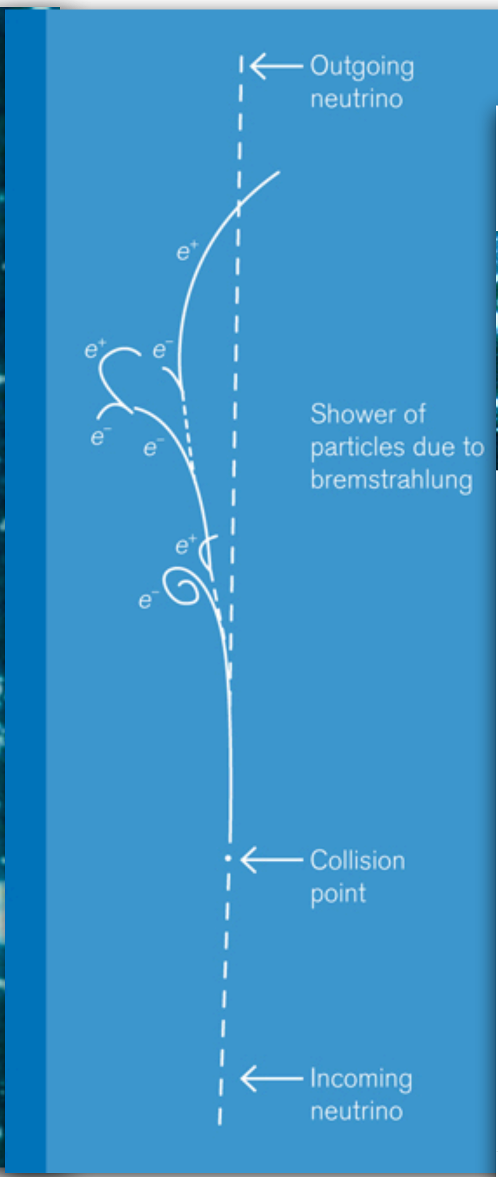
> The signal is induced by the motion of charge after incident radiation (not when the charge reaches the electrodes).

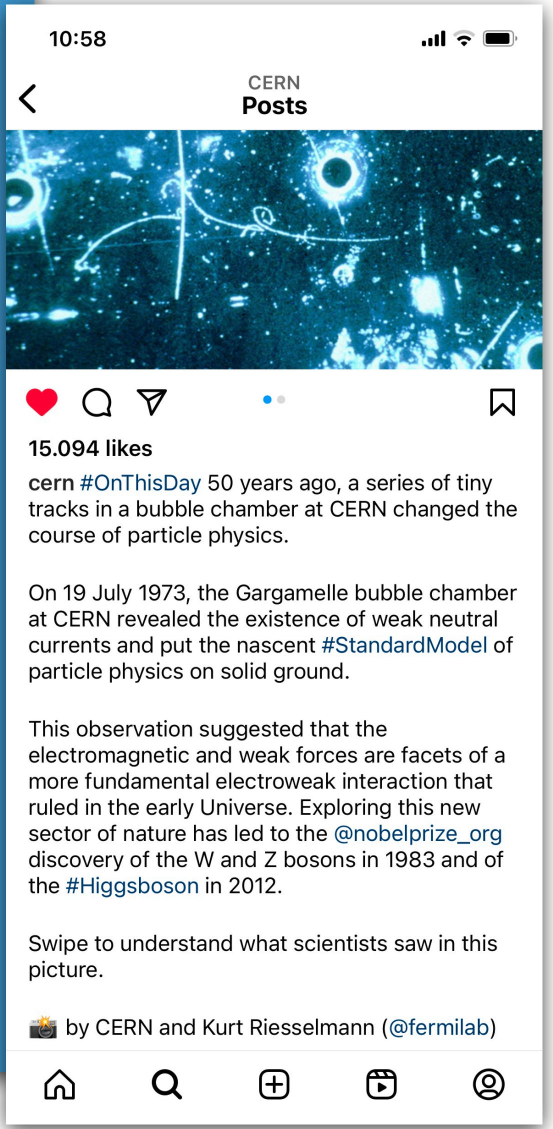
SILICON TRACKING DETECTORS

DISCOVERY OF NEUTRAL CURRENTS

Gargamelle, 19.7. 1973

© Gargamelle/CERN





15.094 likes

cern #OnThisDay 50 years ago, a series of tiny tracks in a bubble chamber at CERN changed the course of particle physics.

On 19 July 1973, the Gargamelle bubble chamber at CERN revealed the existence of weak neutral currents and put the nascent #StandardModel of particle physics on solid ground.

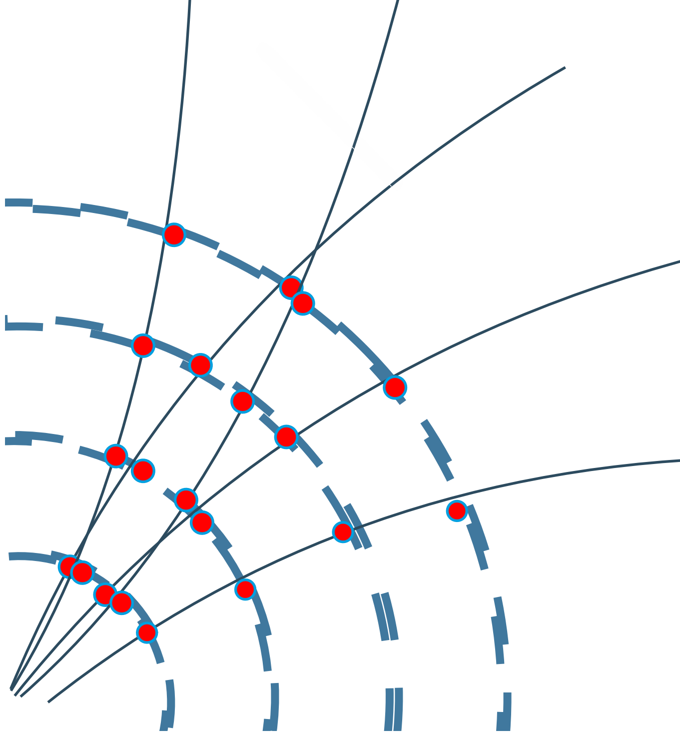
This observation suggested that the electromagnetic and weak forces are facets of a more fundamental electroweak interaction that ruled in the early Universe. Exploring this new sector of nature has led to the @nobelprize_org discovery of the W and Z bosons in 1983 and of the #Higgsboson in 2012.

Swipe to understand what scientists saw in this picture.

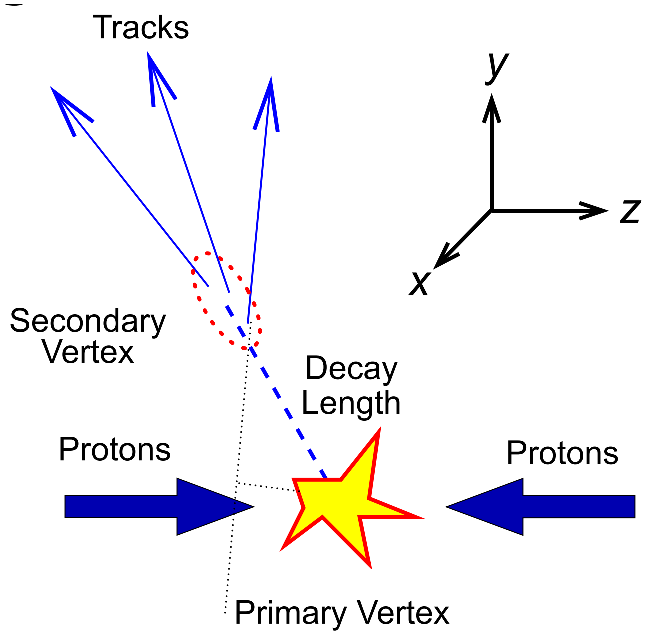
📸 by CERN and Kurt Riesselmann (@fermilab)

TRACKING DETECTORS

- Precise measurement of track and momentum of charged particles due to magnetic field.
- The trajectory should be minimally disturbed by this process (reduced material)

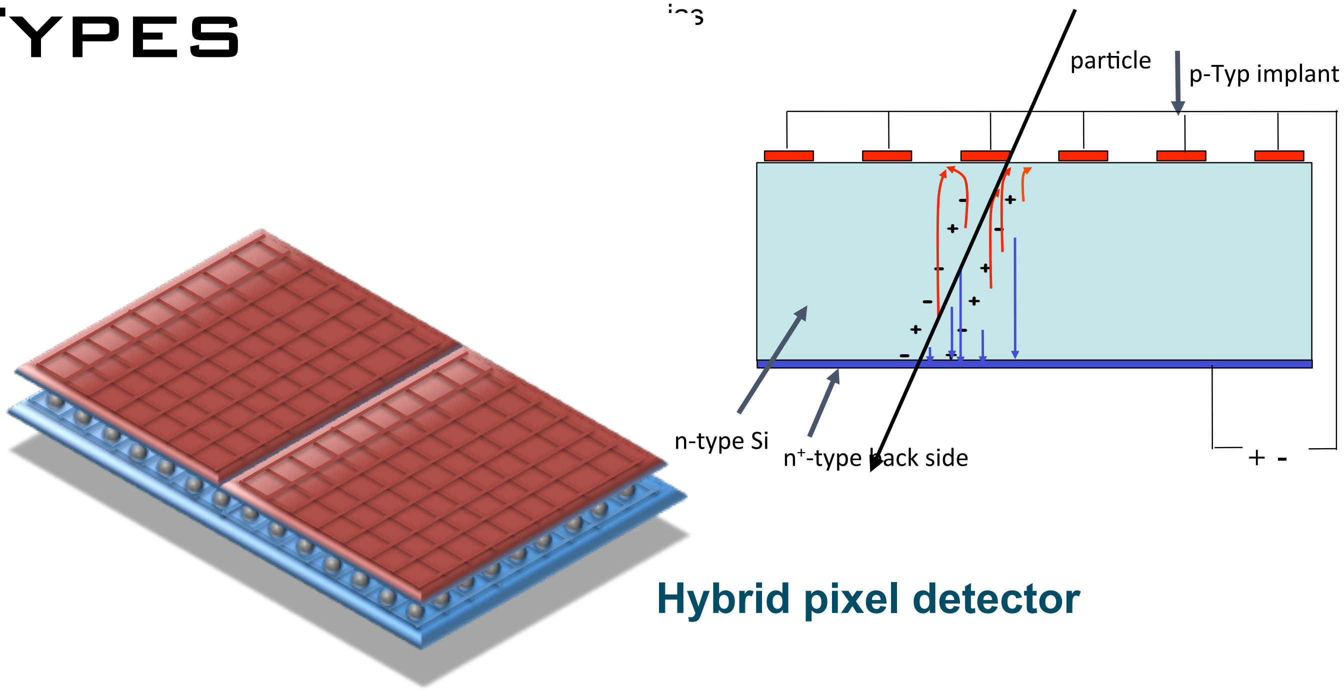


- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionisation trails.
  - An “image” of the charged particles in the event



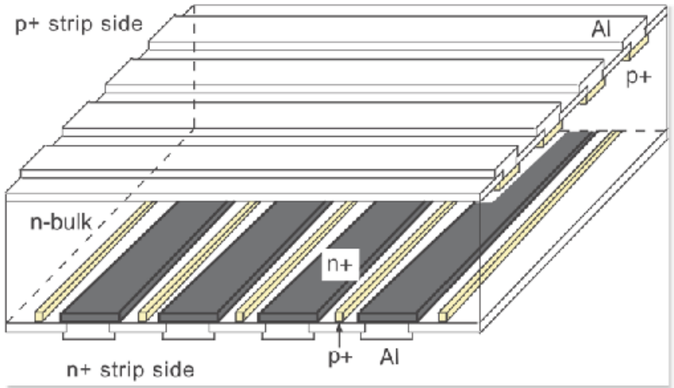
SILICON DETECTOR TYPES

- Pixel detector: deposited charge sensed by small pixels on one side of sensor
  - many channels
  - relatively expensive
  - more material (in case of hybrid pixels)
  - easy pattern recognition



Hybrid pixel detector

- Strip detector: deposited charge sensed by long narrow strips
  - fewer channels
  - less expensive
  - less material
  - pattern recognition difficult!



Double sided strip sensor

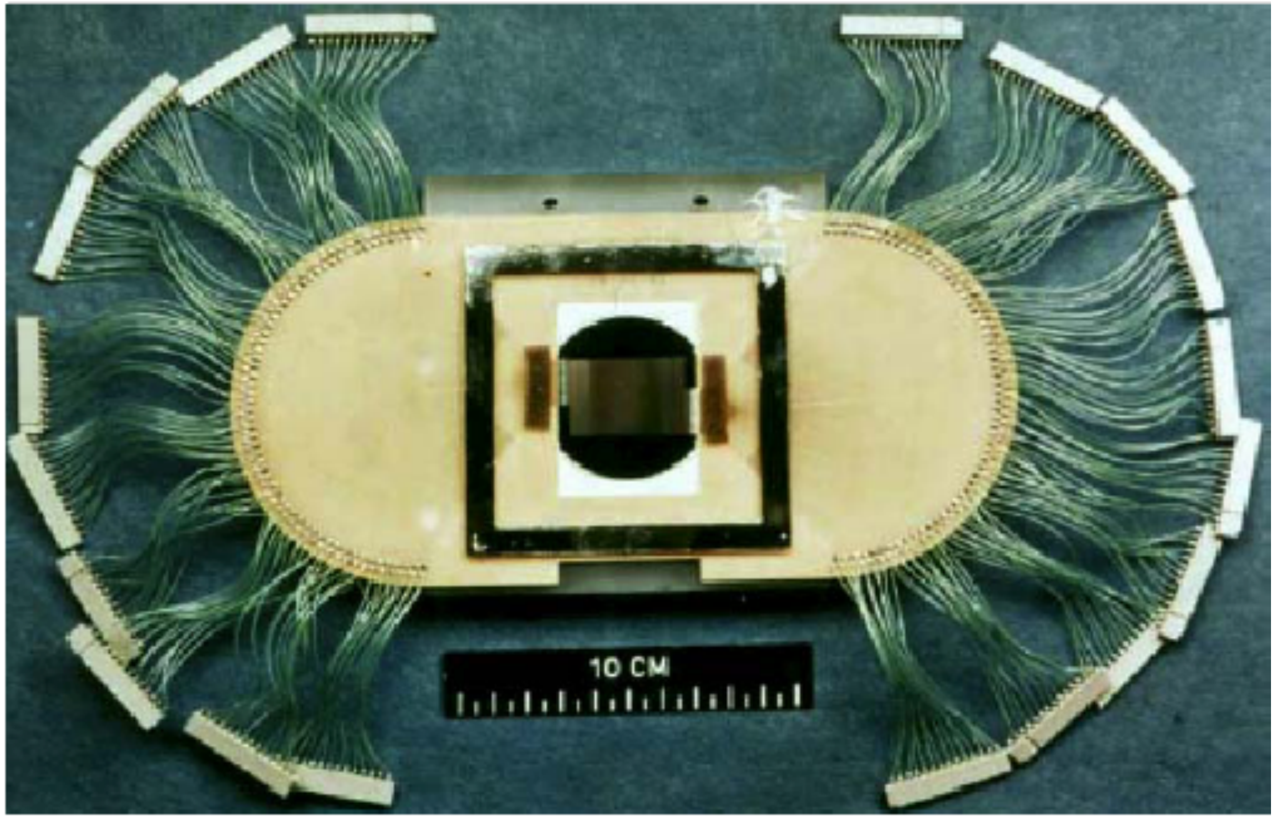
FIRST HEP APPLICATION: NA11

- After discovery of charm (1974), τ-lepton (1975) and beauty (1977) with lifetimes cτ ~100 µm: need fast (ns), and precise (µm) electronic tracking detectors

- Strip detector for NA11 in 1981
  - 1200 strip-diodes
  - 20 µm pitch
  - 60 µm readout pitch
  - 24 x 36 mm^2 active area ~0.01m^2
  - position resolution ~5.4 µm
  - 8 layer at the start

➔ precise track reconstruction

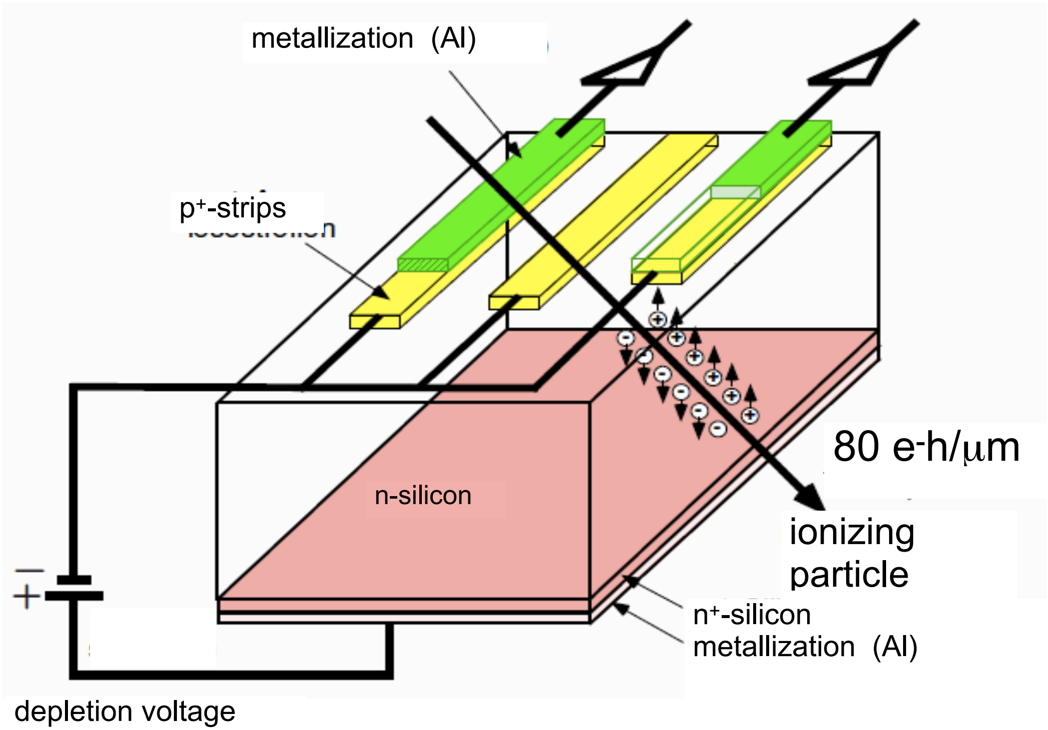
- readout electronic: ~1m^2!



STRIP DETECTORS

Recap

- First detector devices using the lithographic capabilities of microelectronics
- First Silicon detectors -> strip detectors

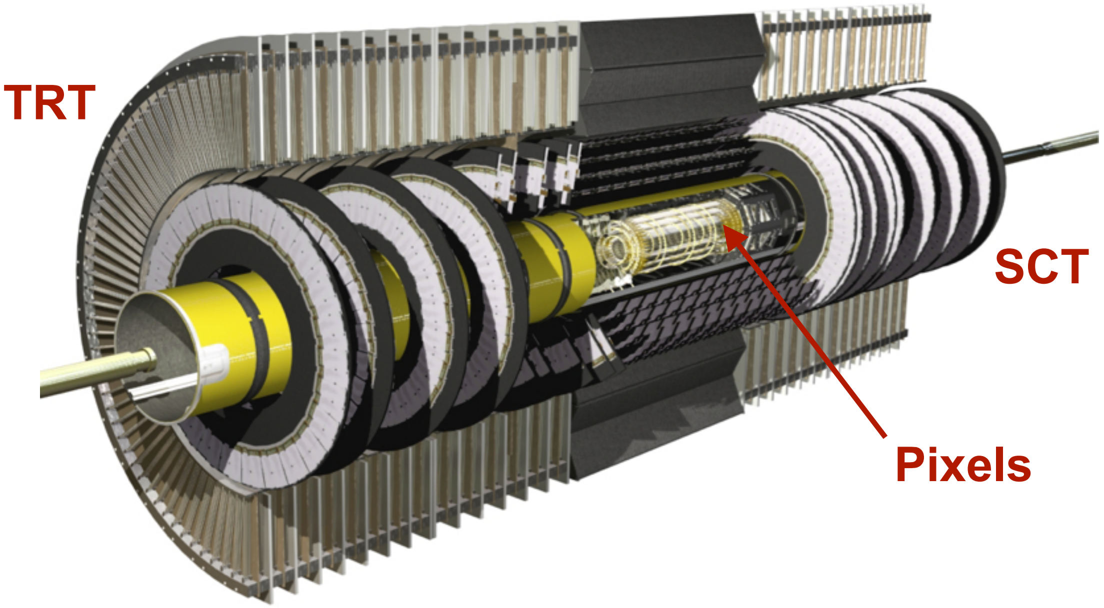


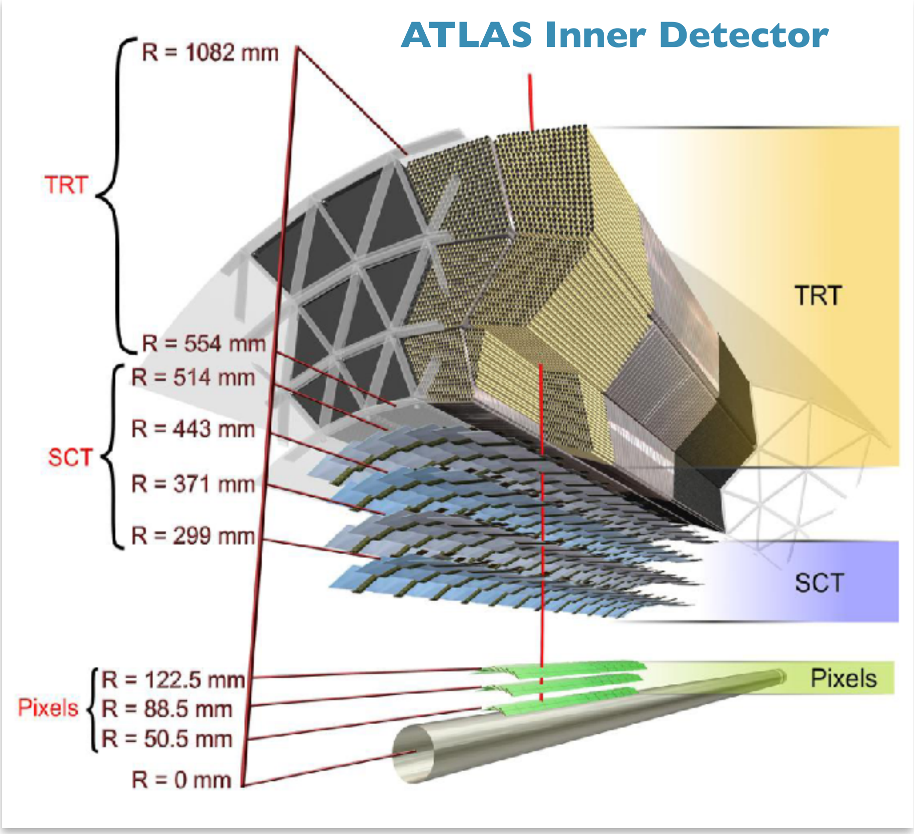
Principal: Silicon strip detector

- Arrangement of strip implants acting as charge collecting electrodes.
- Low doped fully depleted silicon wafer with implants form a one-dimensional array of diodes
- By connecting each of the metalised strips to a charge sensitive amplifier a position sensitive detector is built.
- Two dimensional: can be achieved by applying an additional strip like doping on the wafer backside (double sided technology)

EXAMPLE: CURRENT ATLAS SILICON DETECTOR

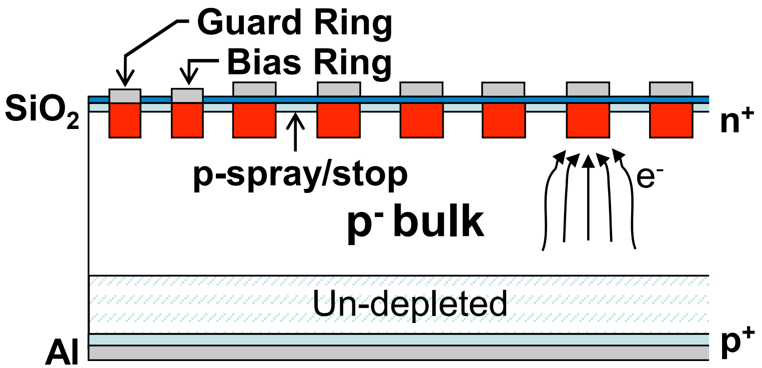
- Current tracking detector “the first meter”:
  - Silicon pixel detector
    - 4 layers, 8 disks
    - Pixel size: 50 x 400µm^2 (IBL: 50 x 250µm^2)
    - 2000 modules with 140M channels
  - SemiConductor Tracker (SCT)
    - Strips width: 70µm
    - 4088 modules with 6.3M channels, 62m^2



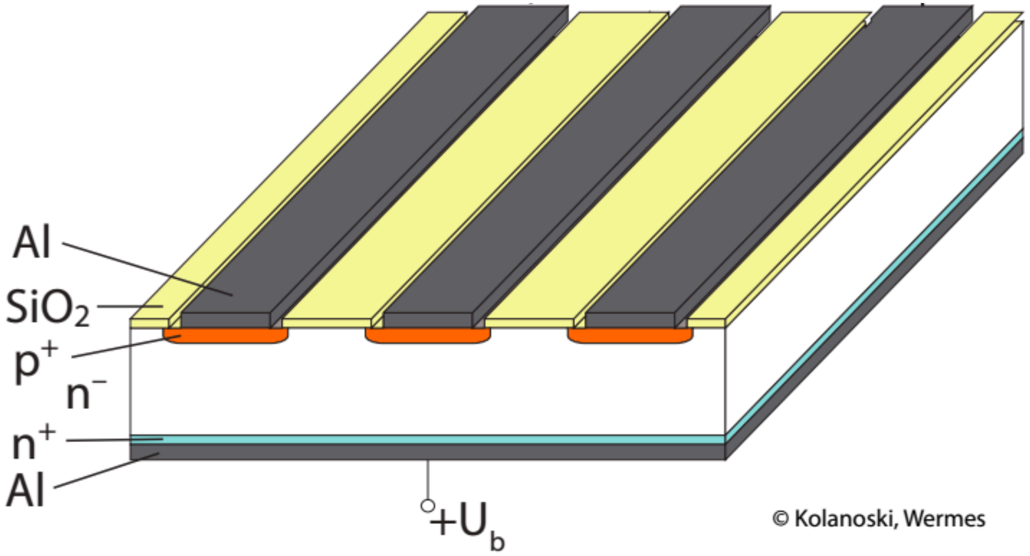


SILICON STRIP DETECTOR

- Segmented p-n diode with applied bias voltage
- Particle creates charges
    - 81 e- per um.
- Charges drift to contacts
- Signal is read out - typically connected with wire-bonds



Cross-section through sensor



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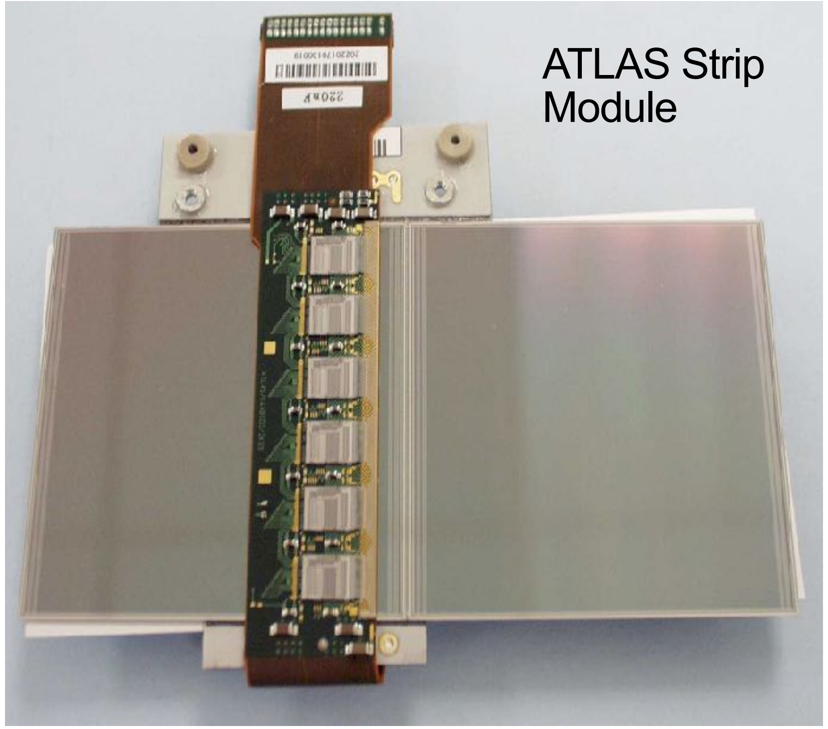
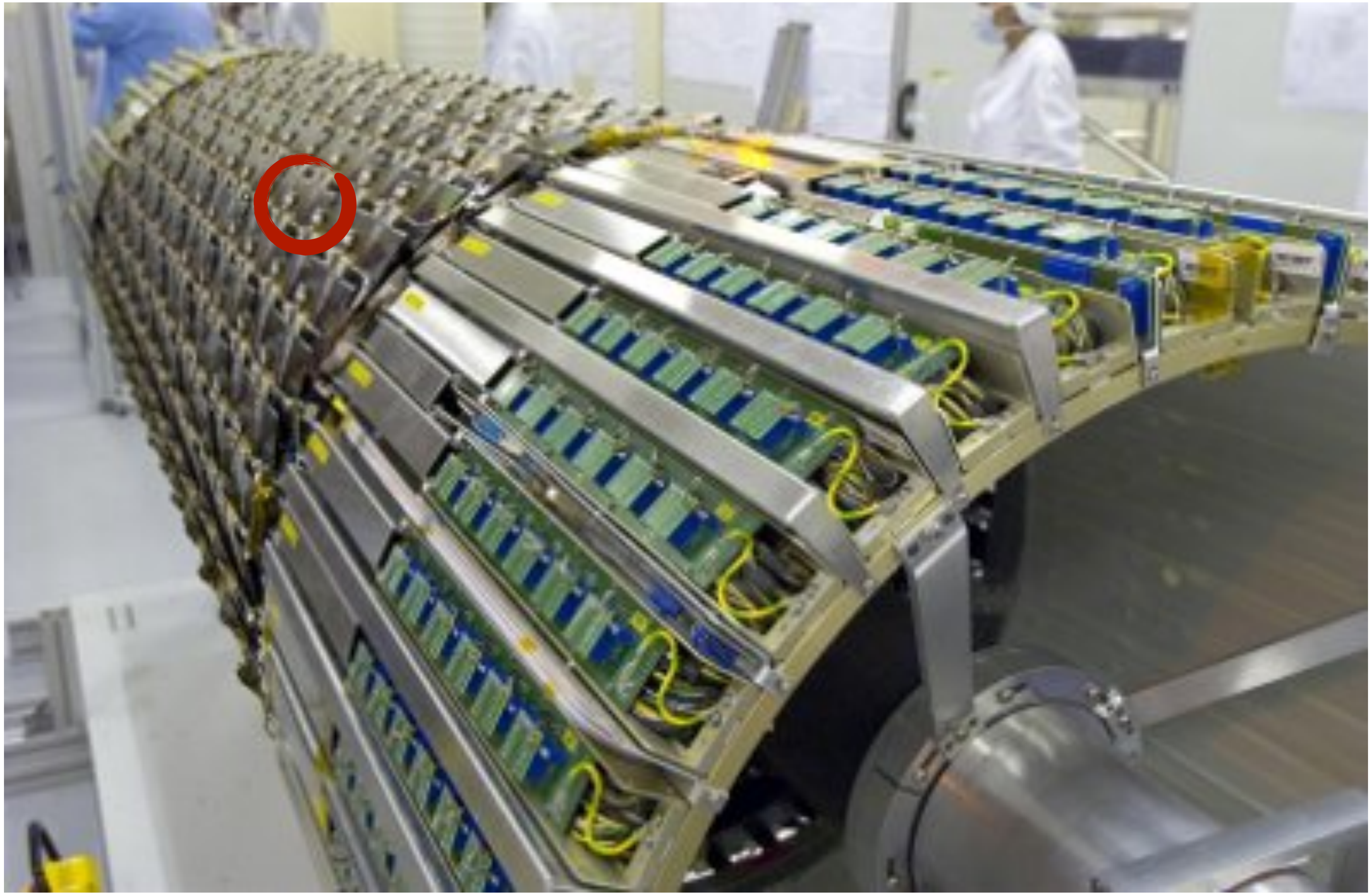
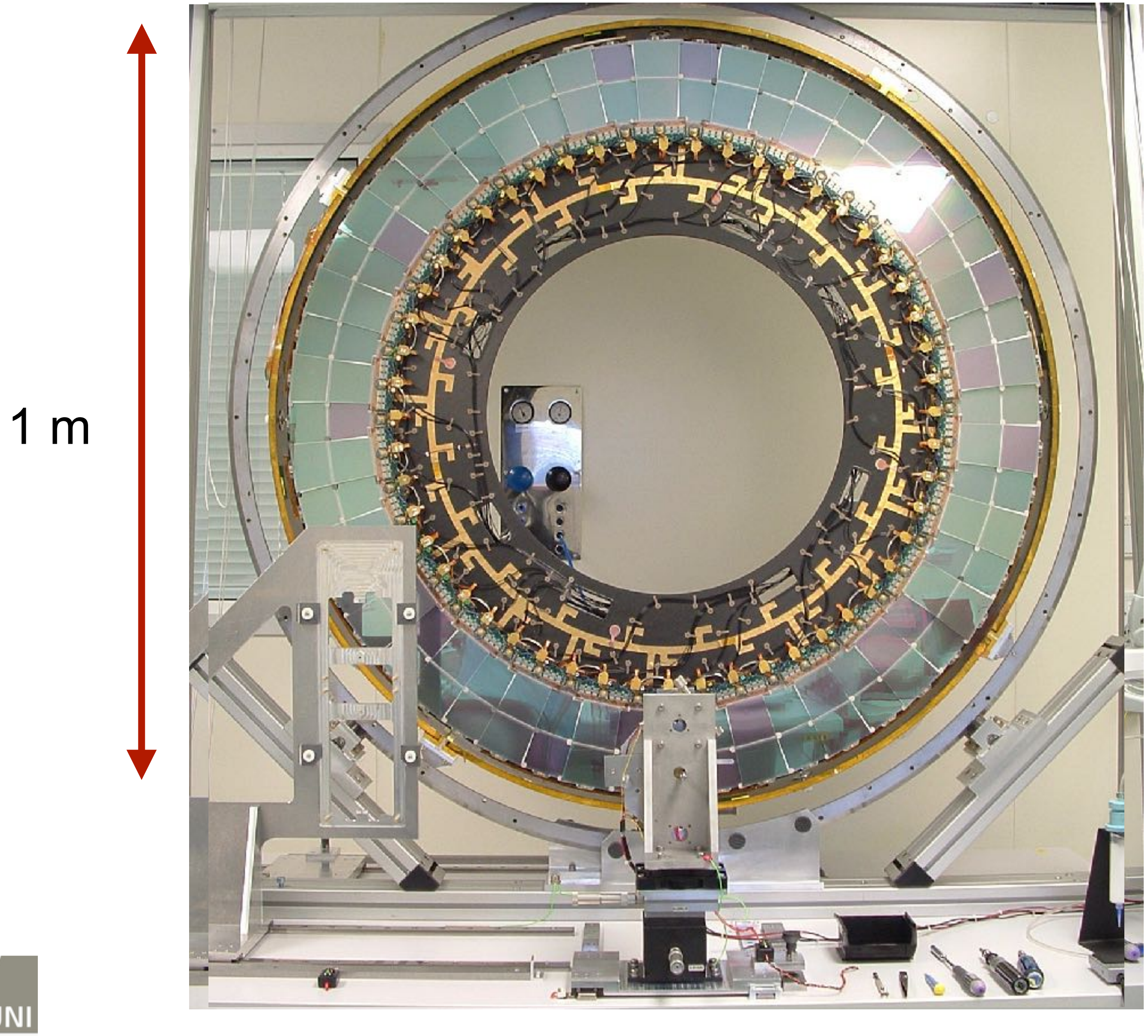
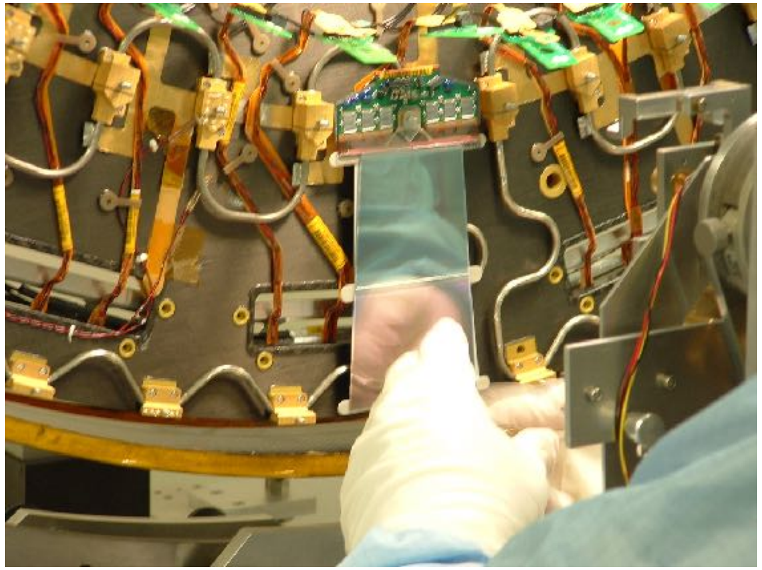


ATLAS SCT Barrel Section

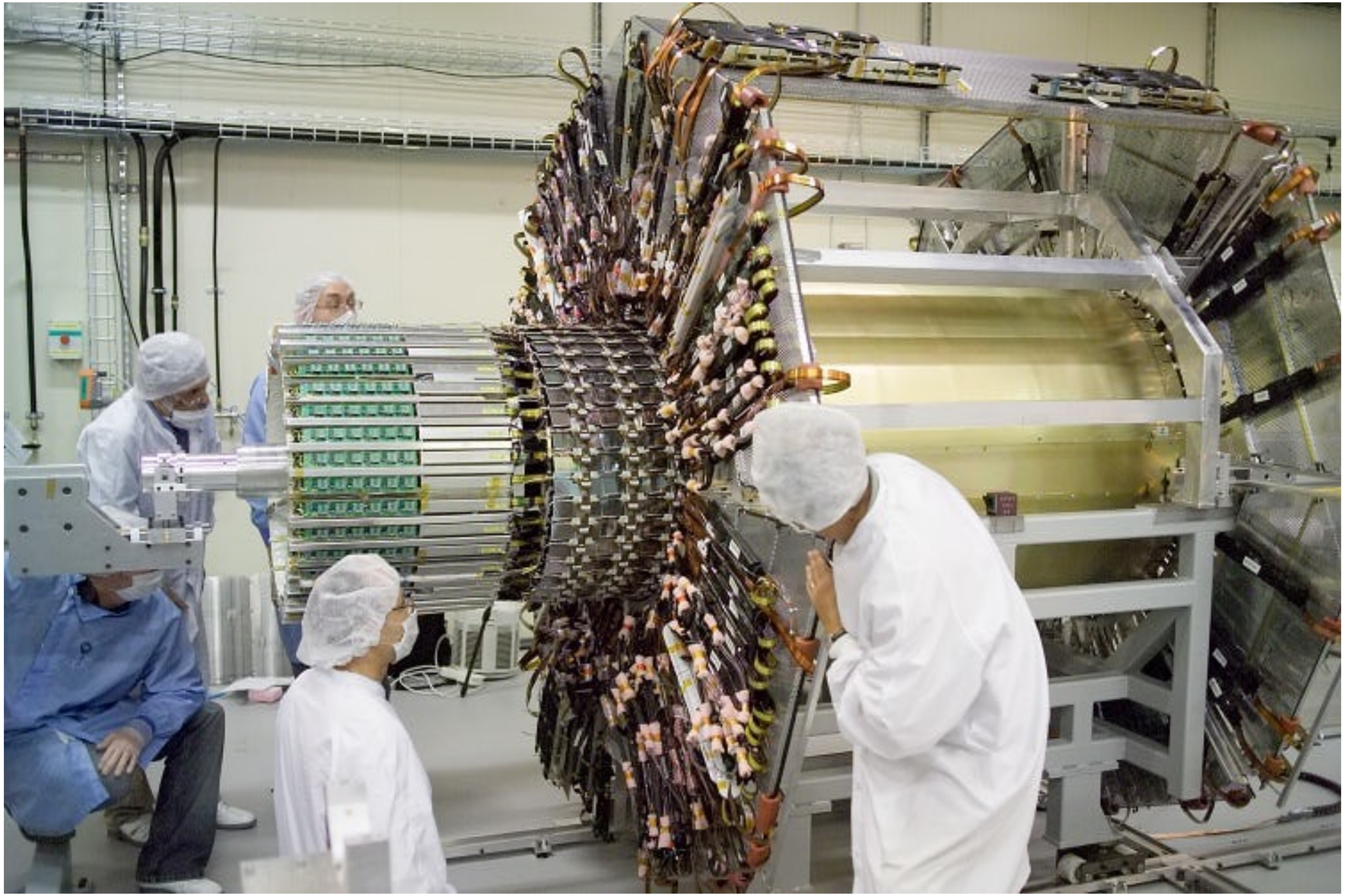


ATLAS SCT ENDCAP - BEAUTY SHOT



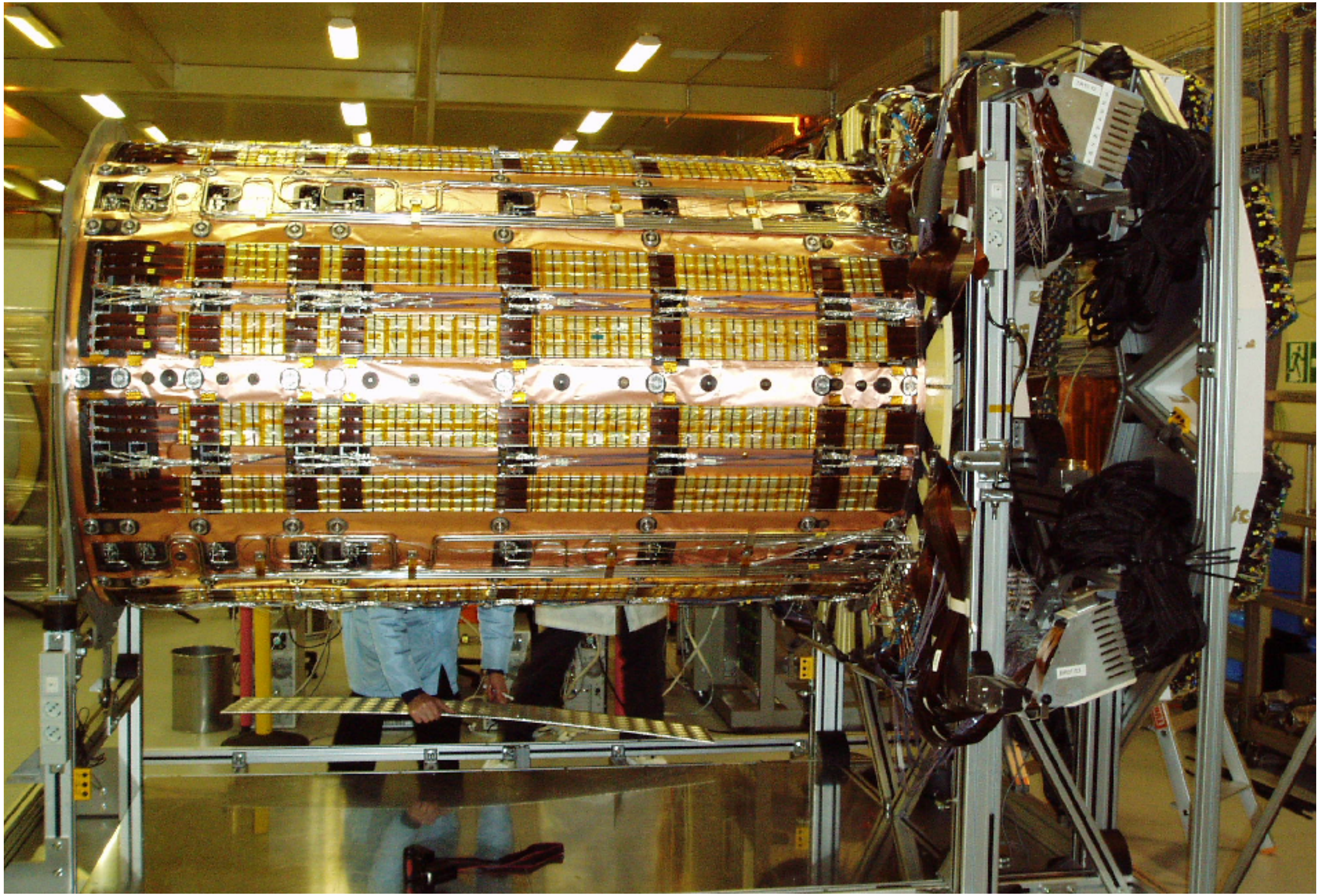


SILICON TRACKER (SCT)

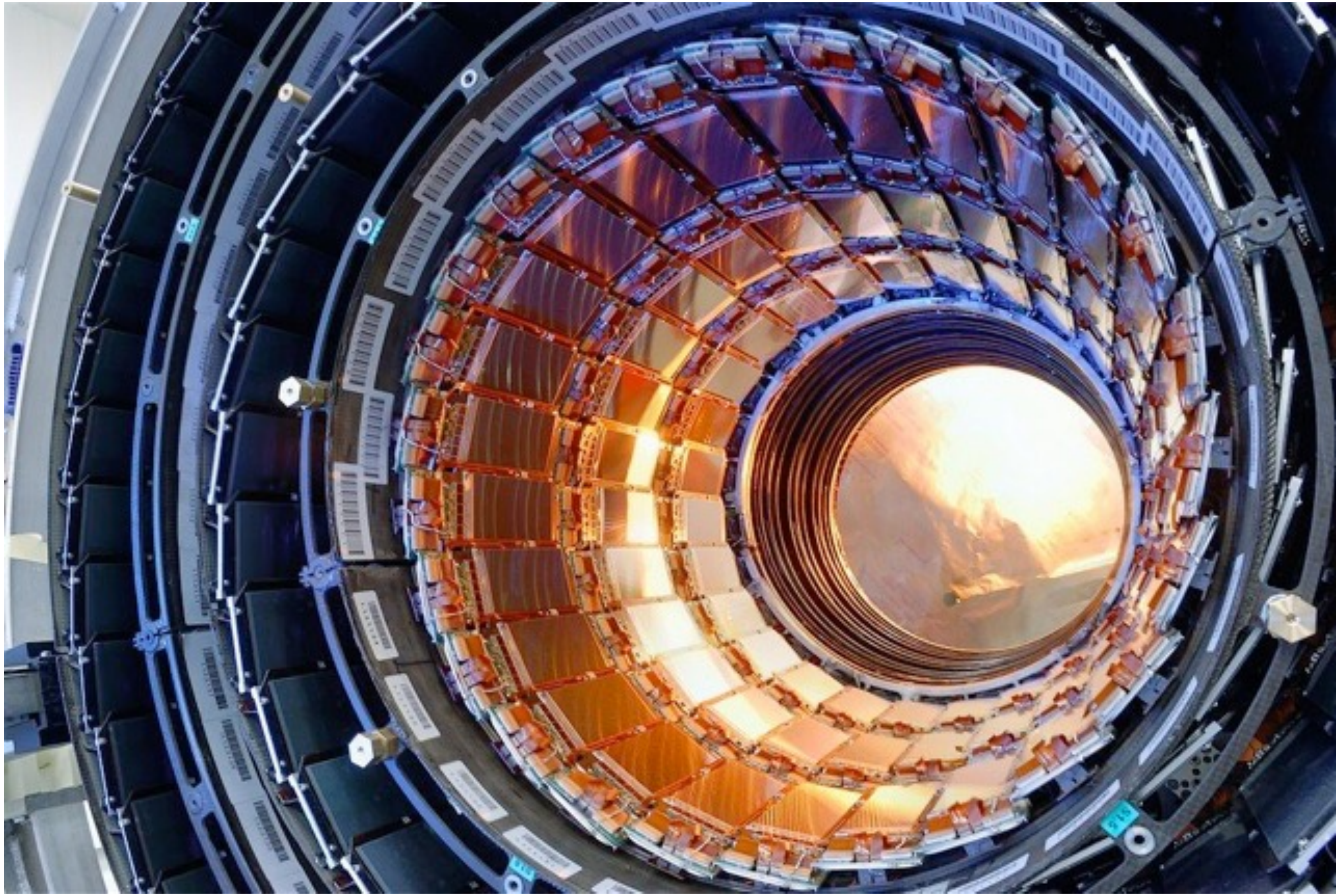


Insertion of the 3rd cylinder (out of the four) into the barrel SCT

SCT BARREL

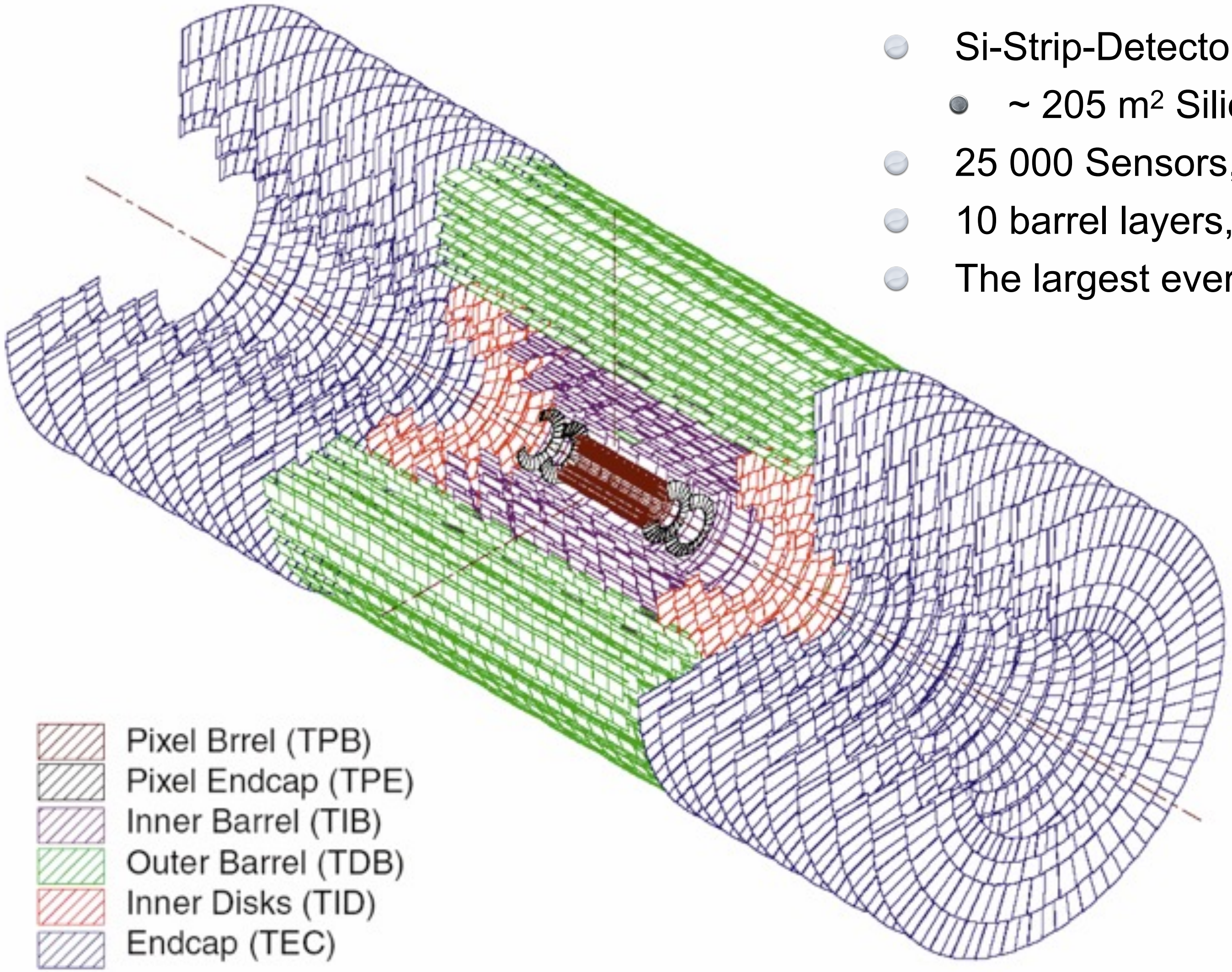


CMS TRACKER - BEAUTY SHOT

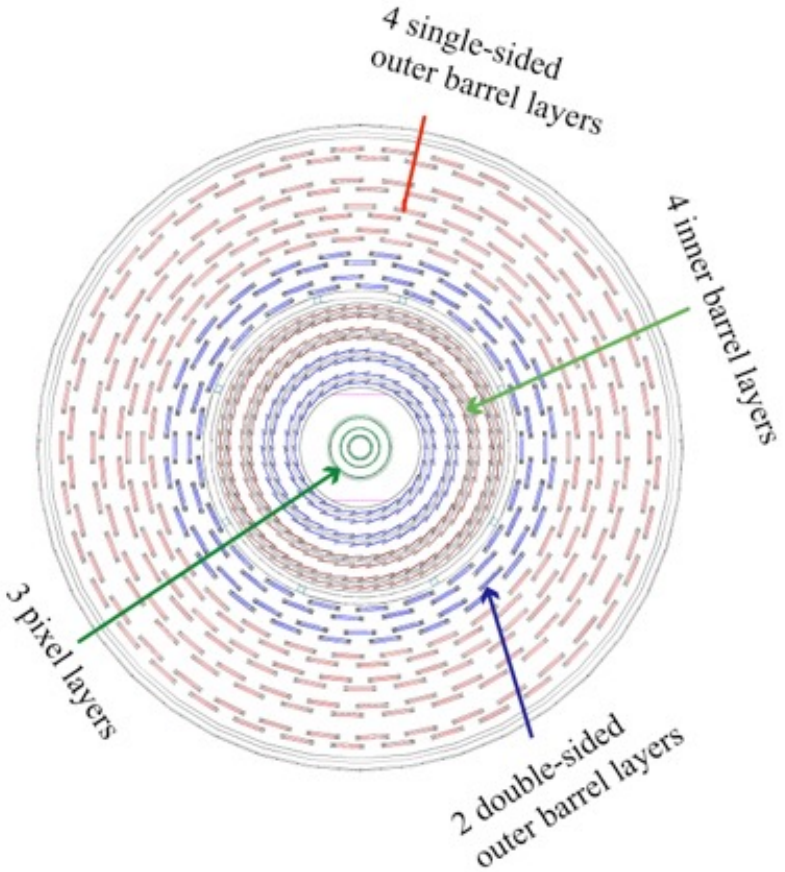


Pic: CERN

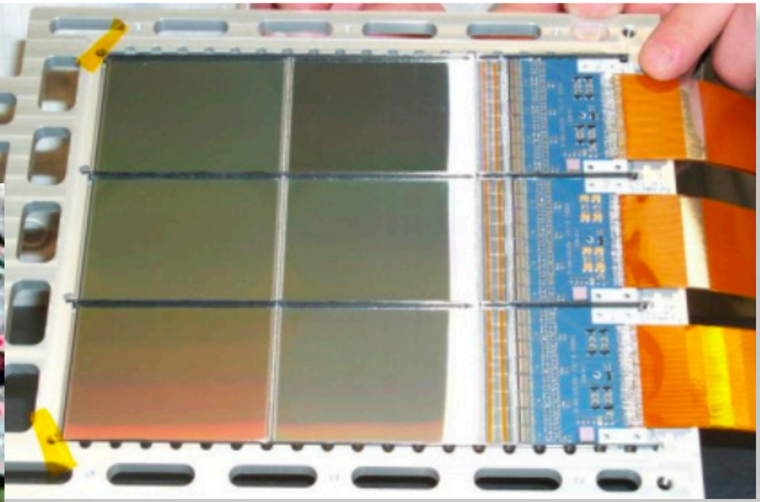
CMS SI-TRACKER



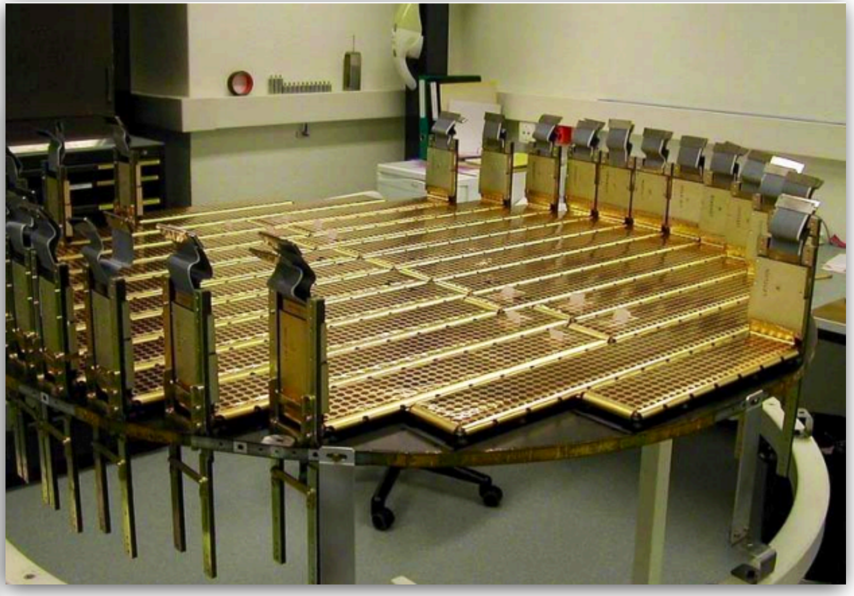
- Si-Strip-Detector:
  - ~ 205 m^2 Silicon
- 25 000 Sensors, 9.6 M channels
- 10 barrel layers, 2x 9 discs
- The largest ever built silicon tracker



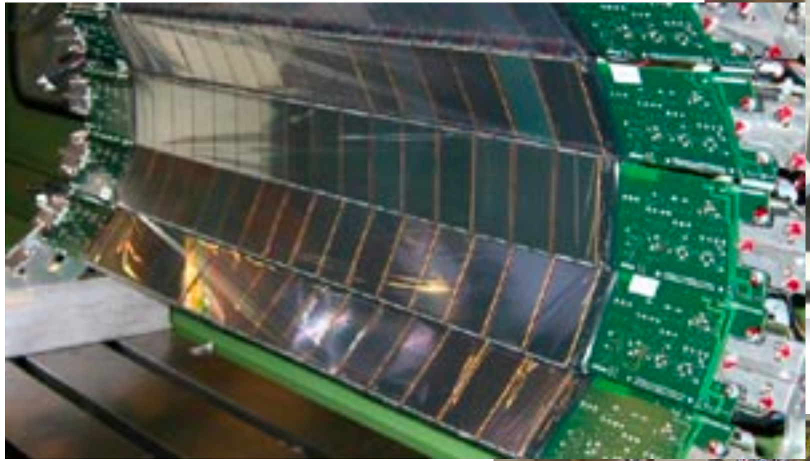
STRIP DETECTORS



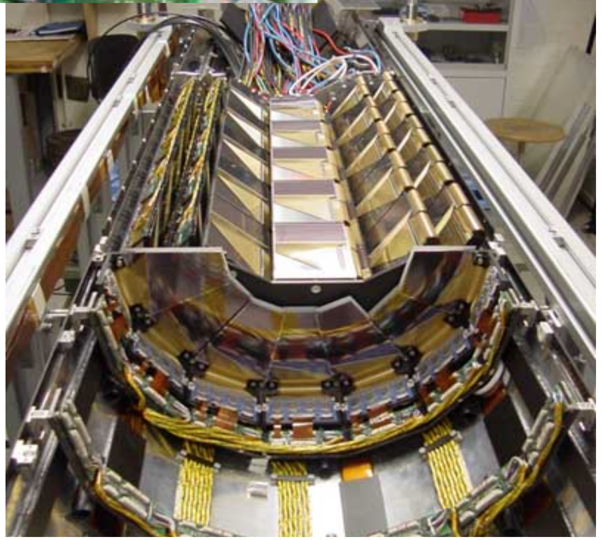
PAMELA satellite experiment



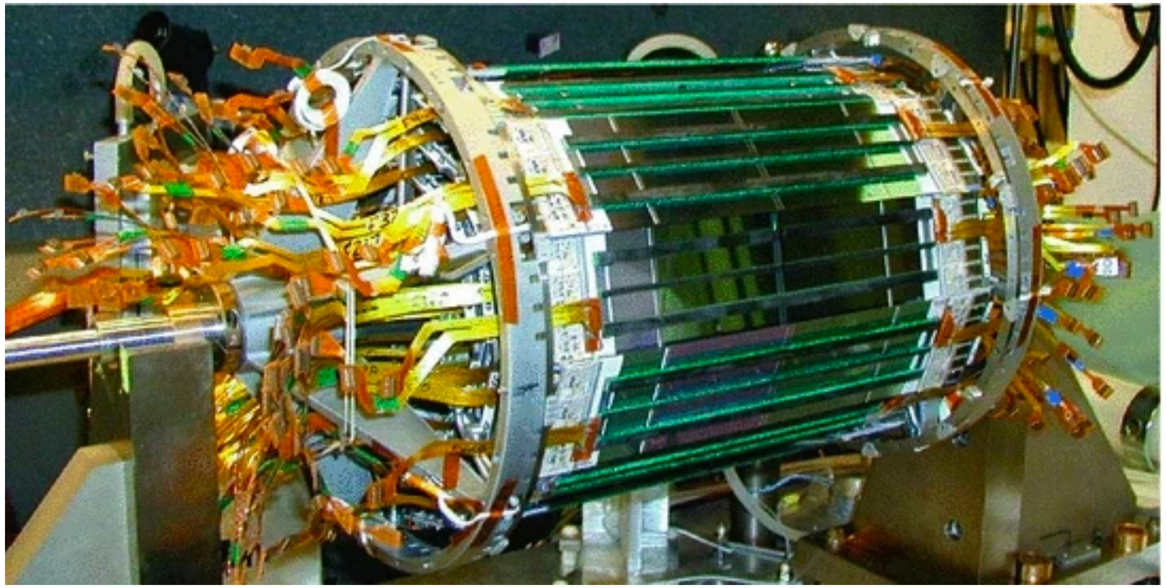
AMS-02 silicon strip tracking detector



STAR Strip Tracker



ZEUS MVD 2000

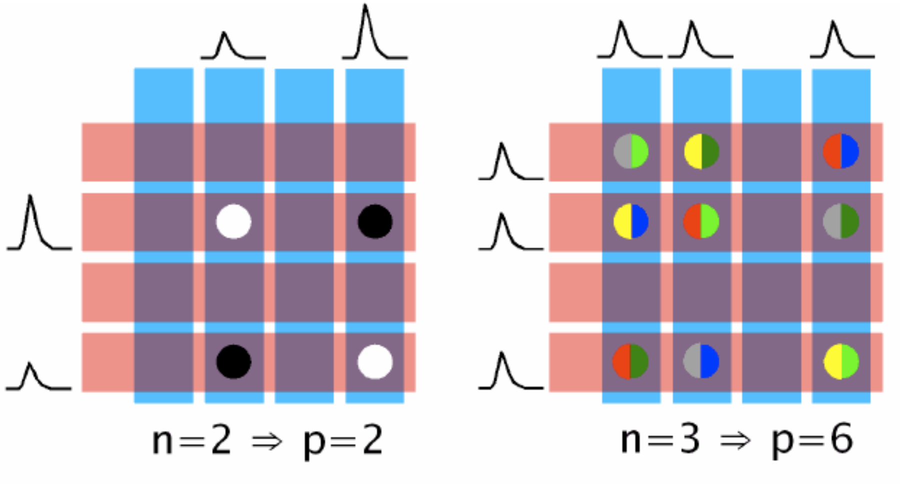


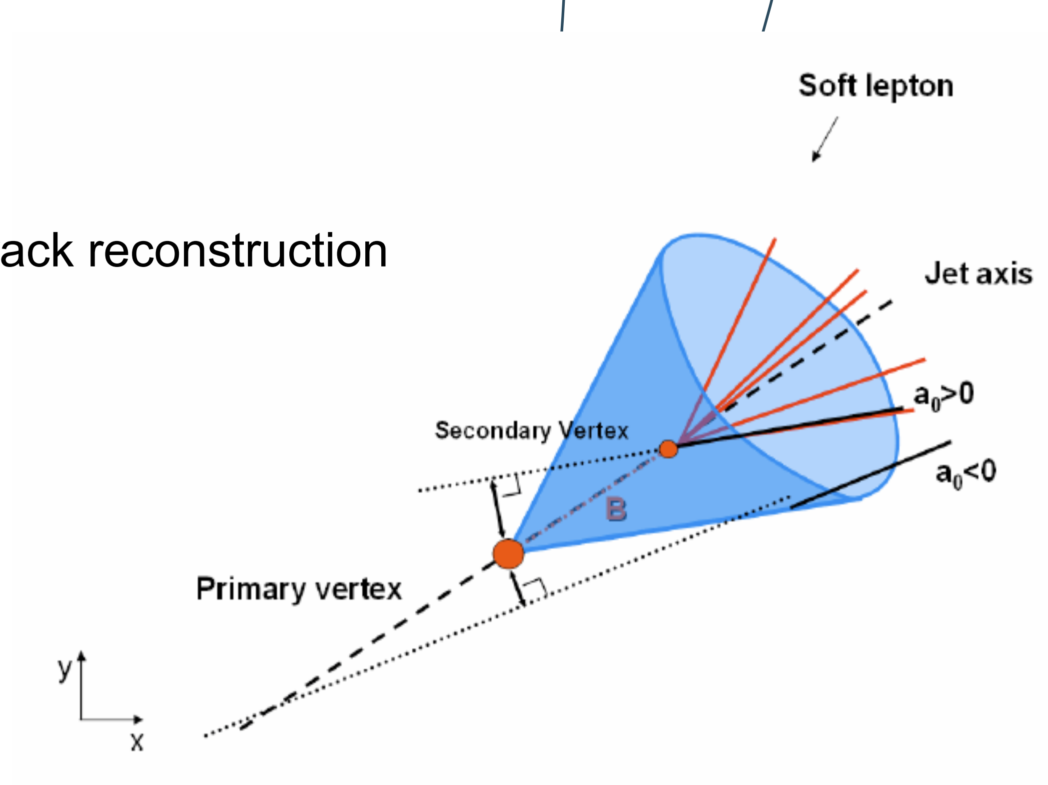
SVX-2 CDF Strip Detector

SILICON PIXEL DETECTORS

LIMITS OF STRIP DETECTORS

- In case of high hit density ambiguities give difficulties for the track reconstruction





- Deriving the point resolution from just one coordinate is not enough information to reconstruct a secondary vertex
  - Pixel detectors allow track reconstruction at high particle rate without ambiguities
  - Good resolution with two coordinates (depending on pixel size and charge sharing between pixels)
  - Very high channel number: complex read-out
  - Readout in active area a detector

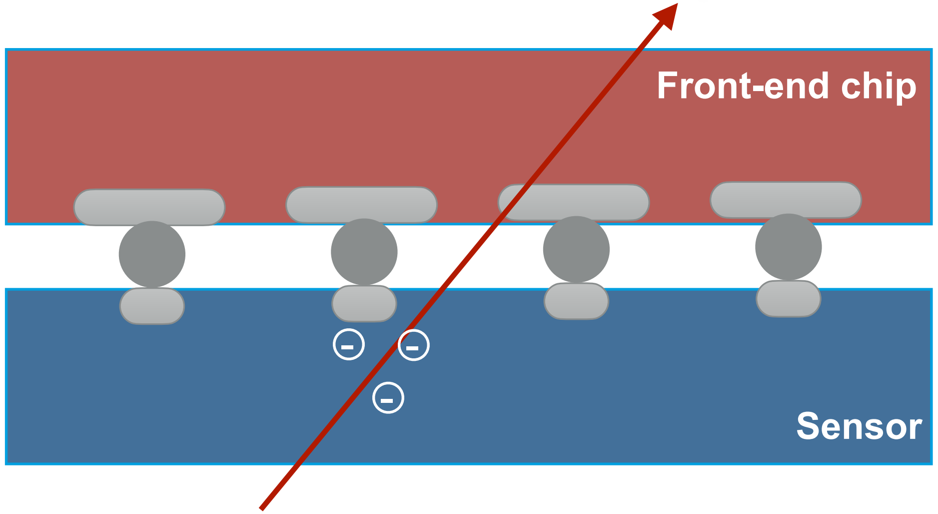
First pixels (CCDs) in NA11/NA32: ~1983

HYBRID PIXELS – "CLASSICAL" CHOICE HEP

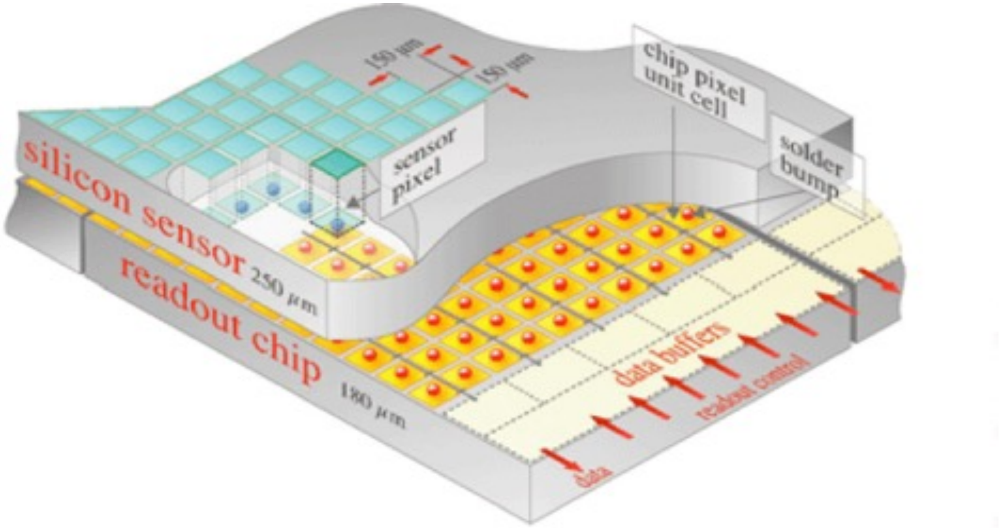
- The read-out chip is mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Can choose proper process for sensor and read-out separately
- Fast read-out and radiation-tolerant

… but:

- Pixel area defined by the size of the read-out chip
- High material budget and high power dissipation

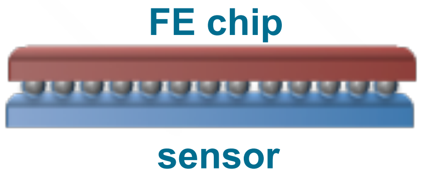


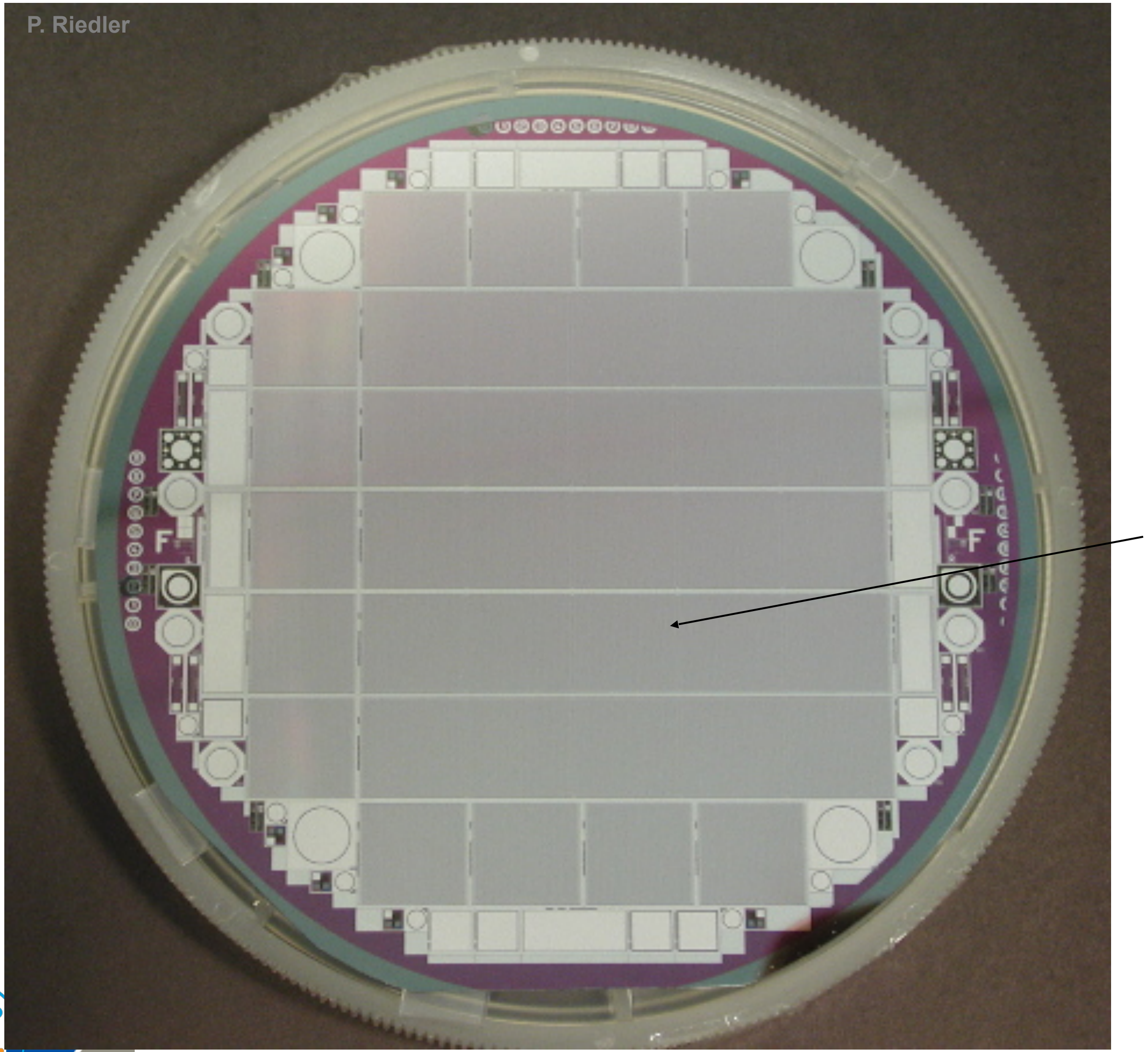
Hybrid Pixel (CMS)



- CMS Pixels: ~65 M channels
  150 µm x 150 µm
- ATLAS Pixels: ~80 M channels
  50 µm x 400 µm (long in z or r)
- Alice: 50 µm x 425 µm
- LHCb
- Phenix@RHIC
- ….

PIXEL SENSOR



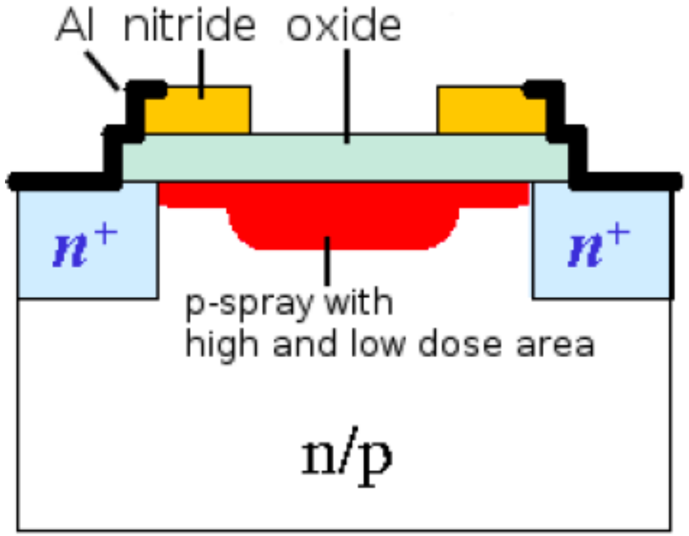


Different sensor materials can be used: Si, CdTe, GaAs, …

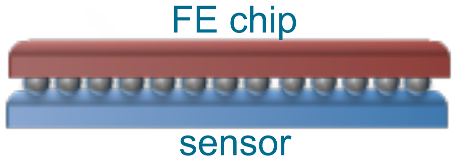
Depending on application (tracking, single photon counting, ..)

Usually several readout chips are connected to one sensor.

Pixel cell (50µm x 425µm)

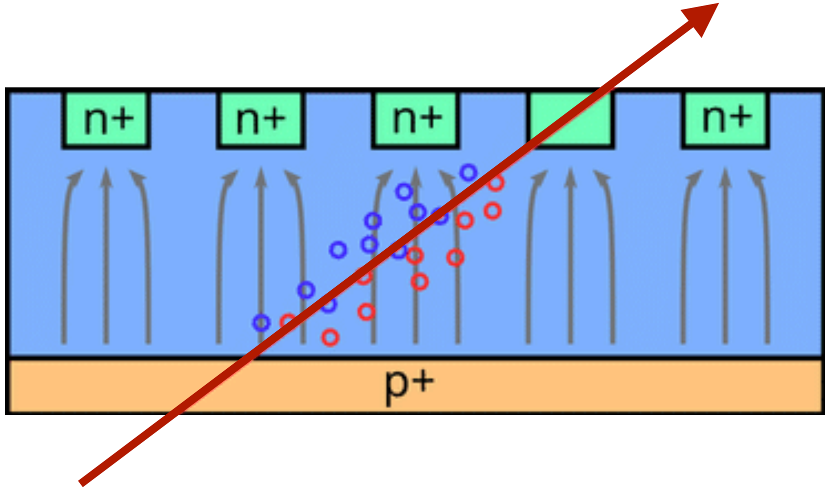


Typical Sensors for Hybrid Pixels



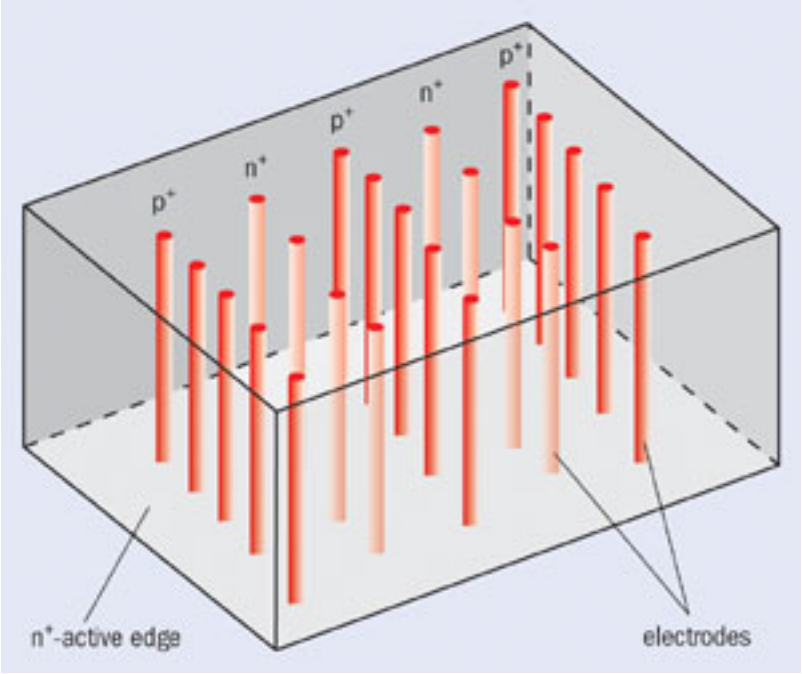
Planar Sensor

- Silicon diode (on-junction)
- Current LHC sensors mostly **n-in-n** planar sensor
- For HL-LHC different concepts were studied (n-in-n; n-in-p ….)
- Radiation hardness proven up to 5 x10^{16} p/cm^2
- Problem: HV might need to exceed 1000V



3D Silicon

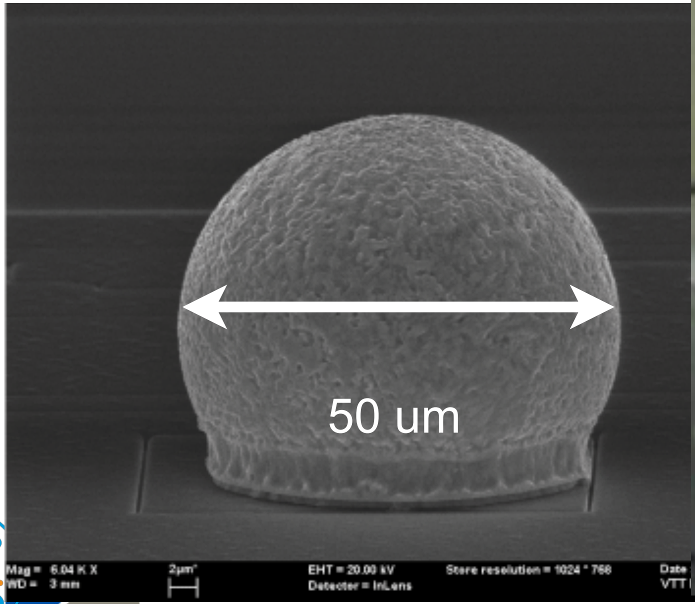
- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Intrinsically higher radiation tolerance
- Low charge sharing
- In current detectors only in ATLAS IBL @high eta



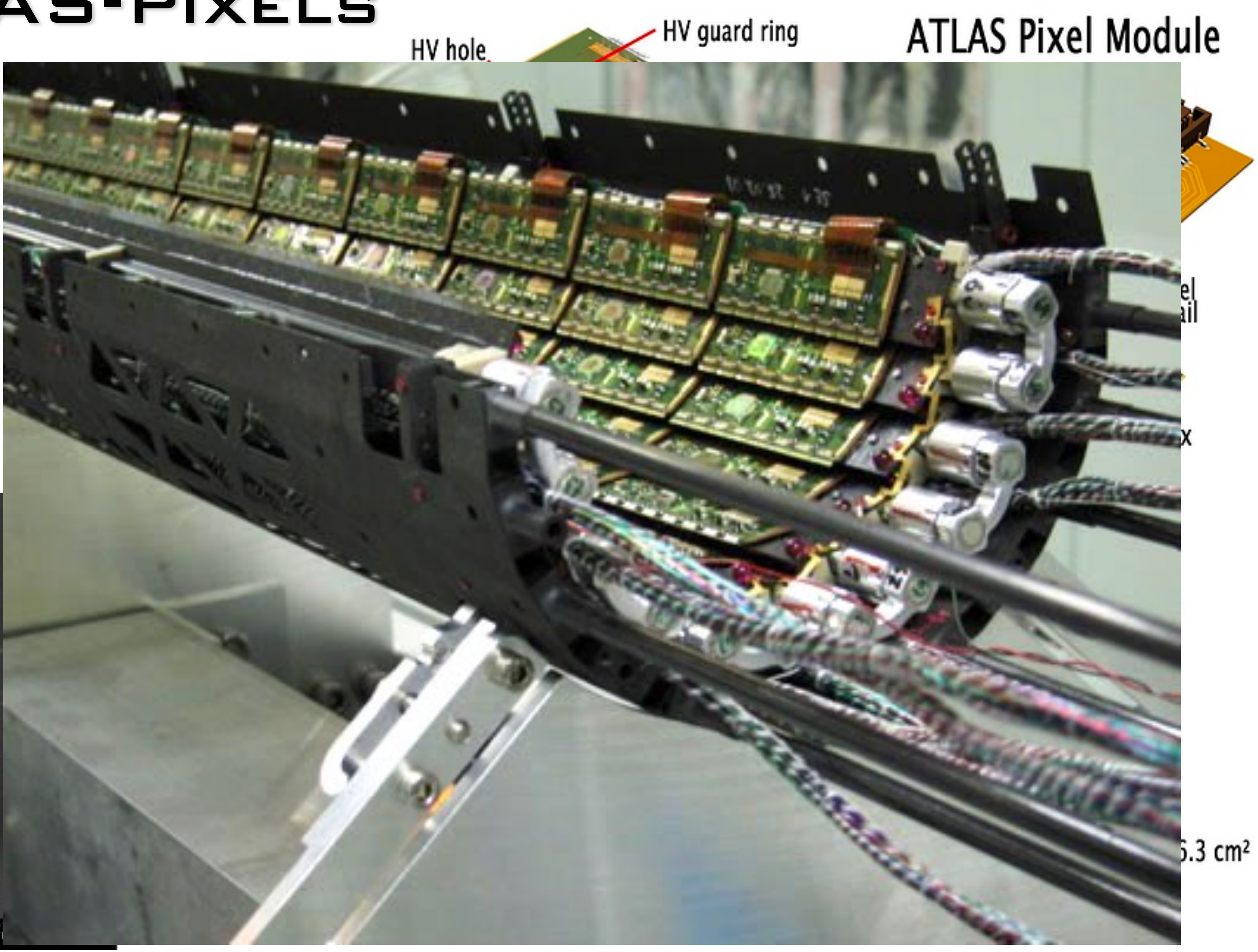
EXAMPLE: ATLAS-PIXELS

A pixel module contains:

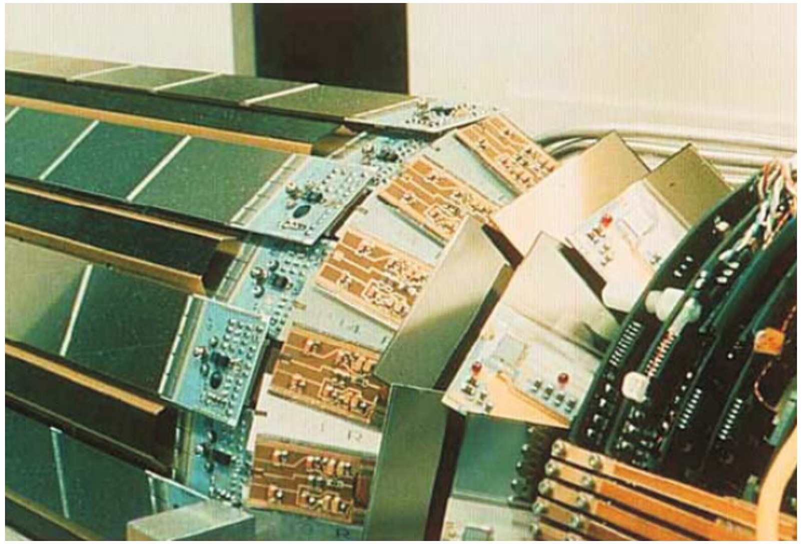
- 1 sensor (2x6cm)
  - ~40000 pixels (50x500 mm)
- 16 front end (FE) chips
  - 2x8 array
  - bump bonded to sensor
- Flex-hybrid
- 1 module control chip (MCC)
- There are ~1700 modules

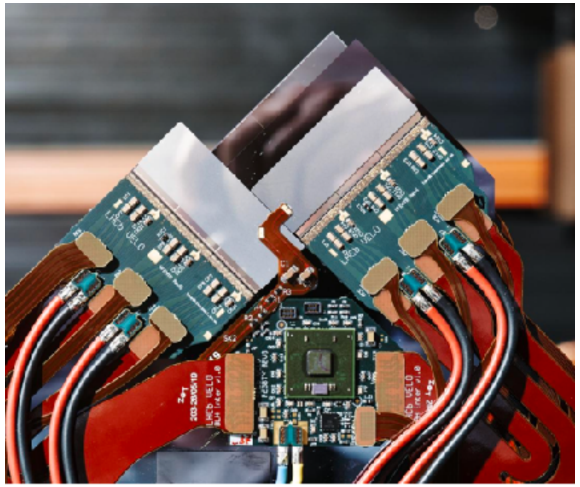


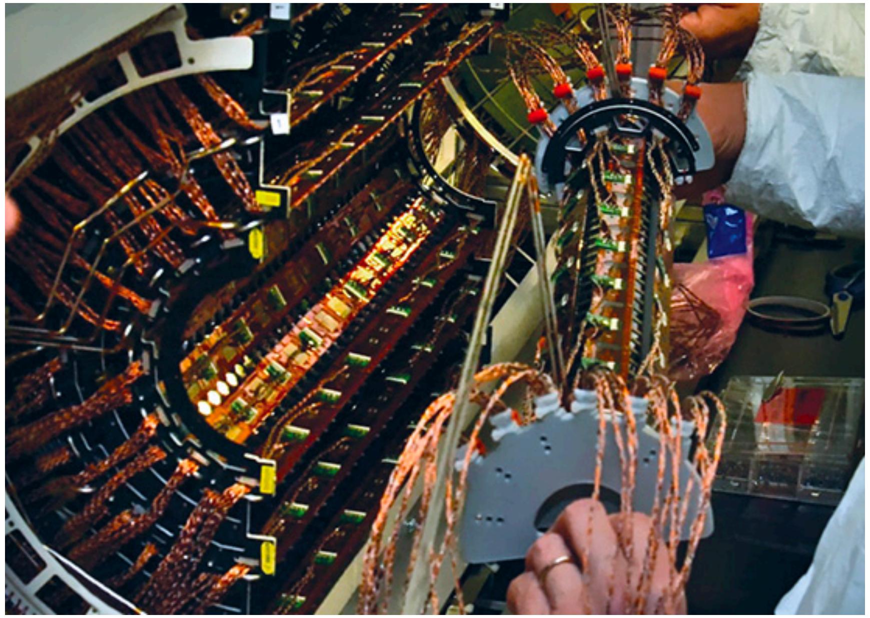
Picture: VTT



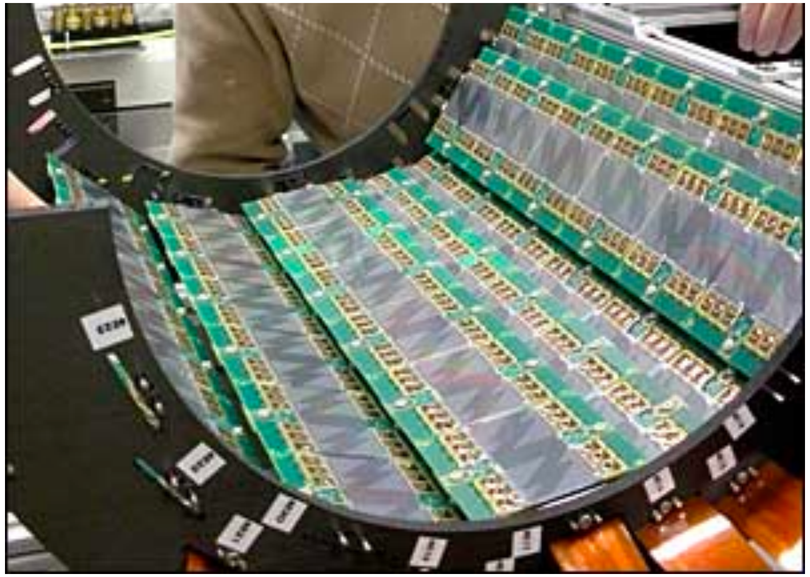
HYBRID PIXEL DETECTORS

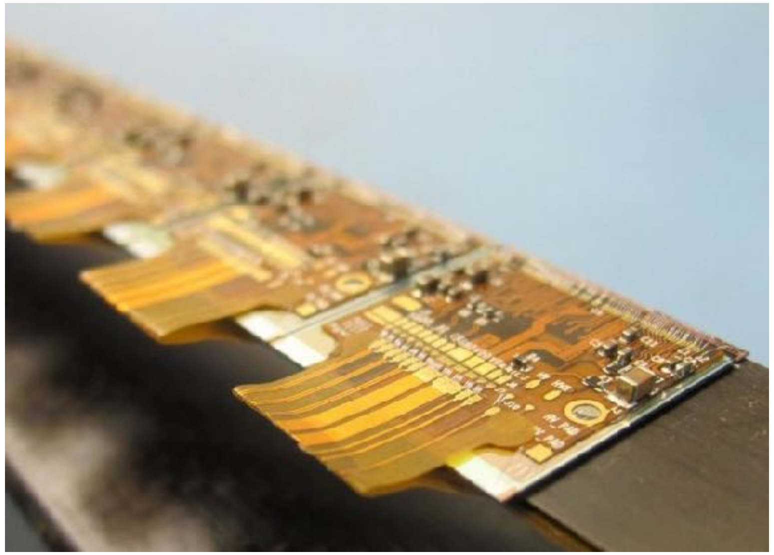

DELPHI VFT 1996


LHCb Velo


CMS Phase1 Pixel Detector

ALICE ITS


PHENIX pixel detector


ATLAS Insertable B-Layer

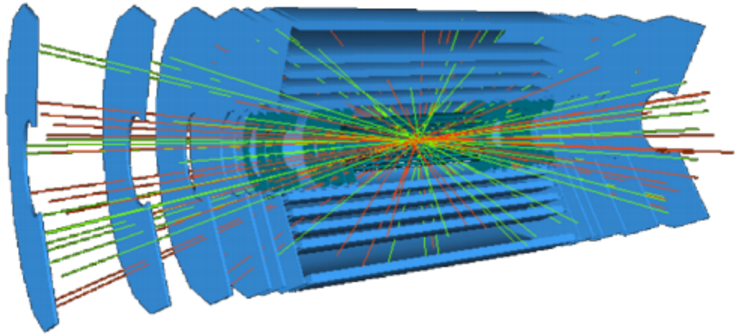
Next Generation Silicon-Detectors

A NEW INNER TRACKER IS NEEDED … WHY ?

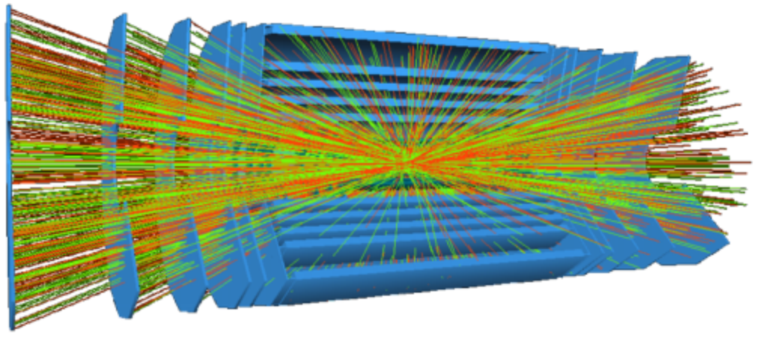
Exploit full potential of LHC

- Upgrades of accelerator and detectors are necessary to reach this ambitious goal.
- Primary motivation of all upgrades is to maximise the understanding of particle physics and searches for new phenomena beyond the known processes

- **HL-LHC implies significant scaling of design parameters:**
  - Peak luminosity: 5-7 x 10^{34} 1/cm^{2}s ➡ **x 5-7**
  - Integrated luminosity: 4000 fb-1 ➡ **x10**
  - Fluences up to 2×10^{16}MeV n_{eq} /cm^2 ➡ **x10**
  - Average pile-up: up to ~200 ➡ **x 8**



LHC, 20 - 55 pile-up events



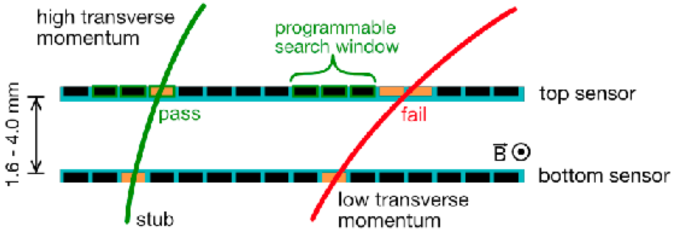
HL-LHC, 140 - 200 pile-up events

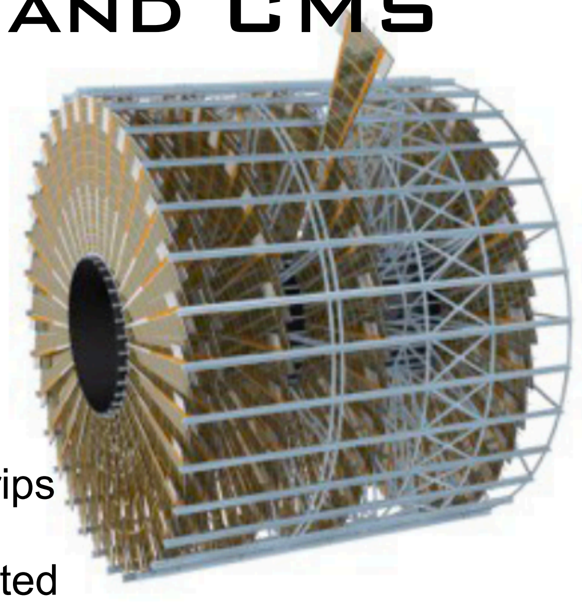
New sensor & readout require more radiation hardness

Si-Strips for ATLAS (HL-LHC)

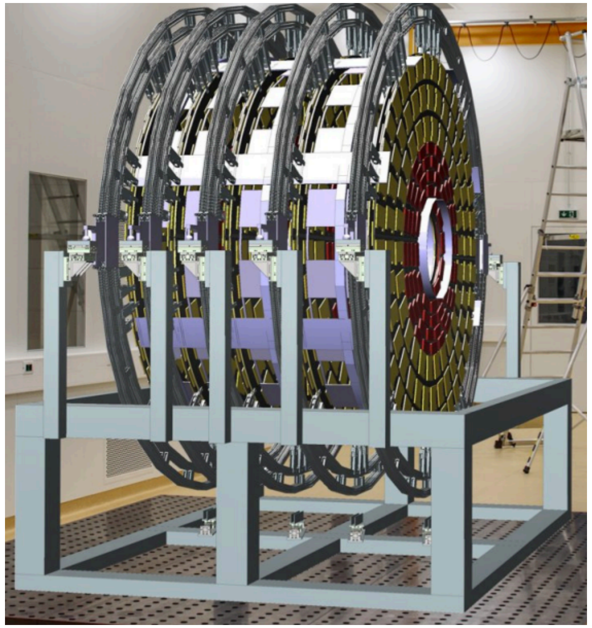
LARGE AREA SILICON TRACKERS - ATLAS AND CMS

- ATLAS&CMS each plan for ~150 m^2 silicon strip detector
- Commonalities:
  - **20000** modules to be produced
  - choice of sensor technology (n-in-p)
  - radiation level (10^{15} n$_{eq}$/cm^2)

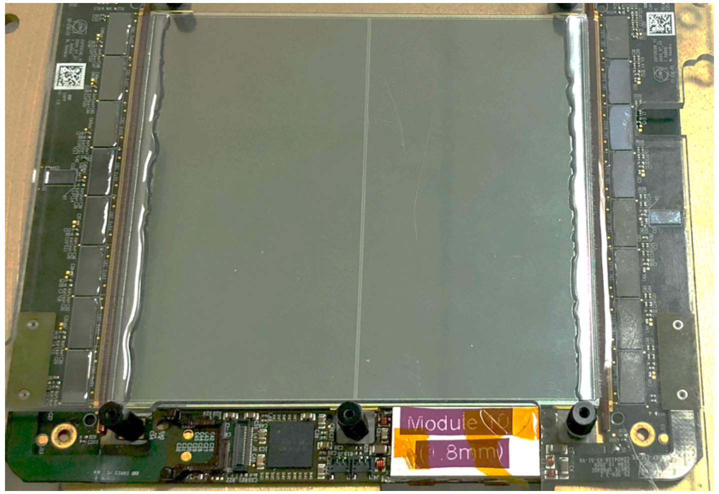




ATLAS ITk Strips end-cap to be constructed in Germany



CMS Outer Tracker end-cap to be constructed in Germany

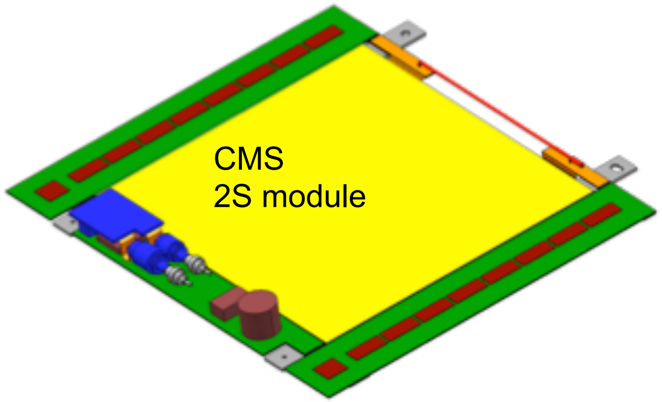


CMS 2S Module

ATLAS End-cap strips module

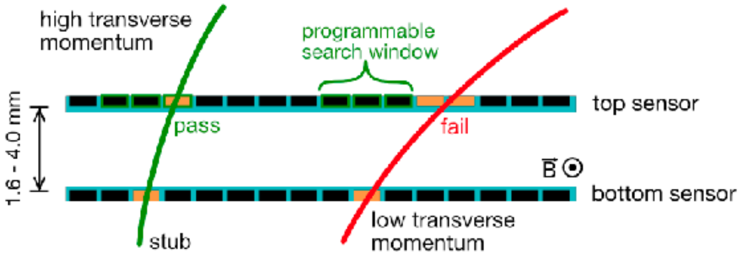
“Outer” Tracker for ATLAS&CMS

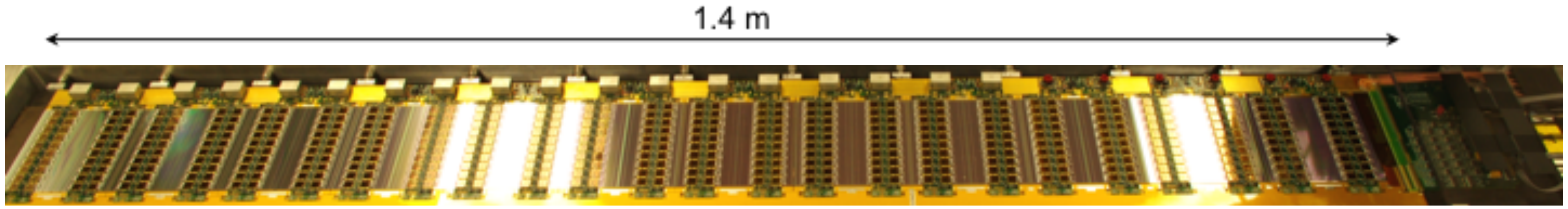
- ATLAS&CMS each plan for ~150 m^2 silicon strip detector
- Commonalities:
    - **20000** modules to be produced
    - choice of sensor technology (n-in-p)
    - radiation level (10^{15} n_{eq}/cm^2)



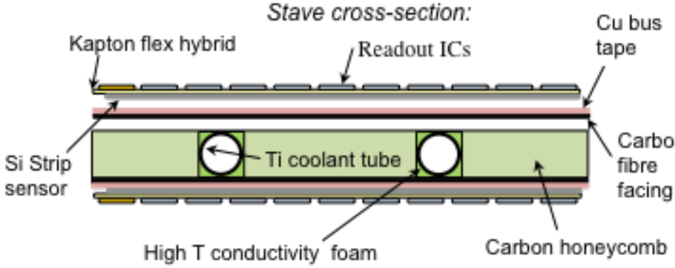
End-cap strips module

- CMS:
    - modules discriminate low-p_T tracks in the FE electronics
    - hybrid is key element: Wire-bonds from the sensors to the hybrid on the two sides
- ATLAS:
    - stave concept where silicon is directly glued onto carbon fibre

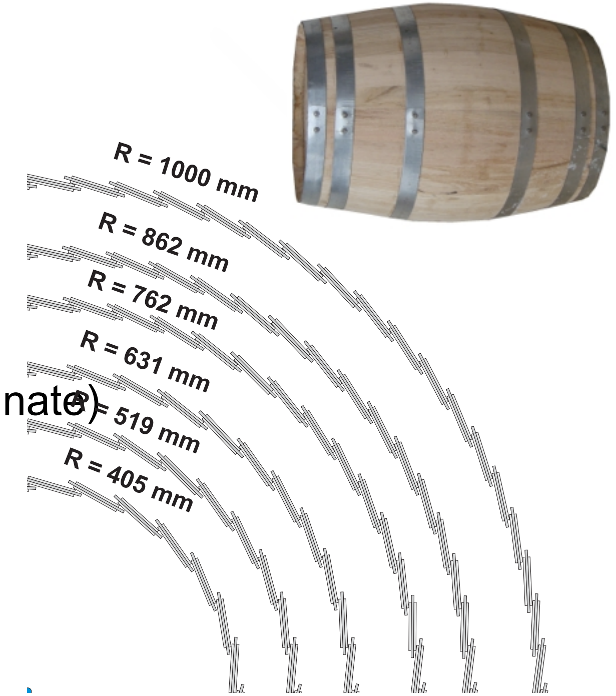




ATLAS Prototype for barrel strip stave

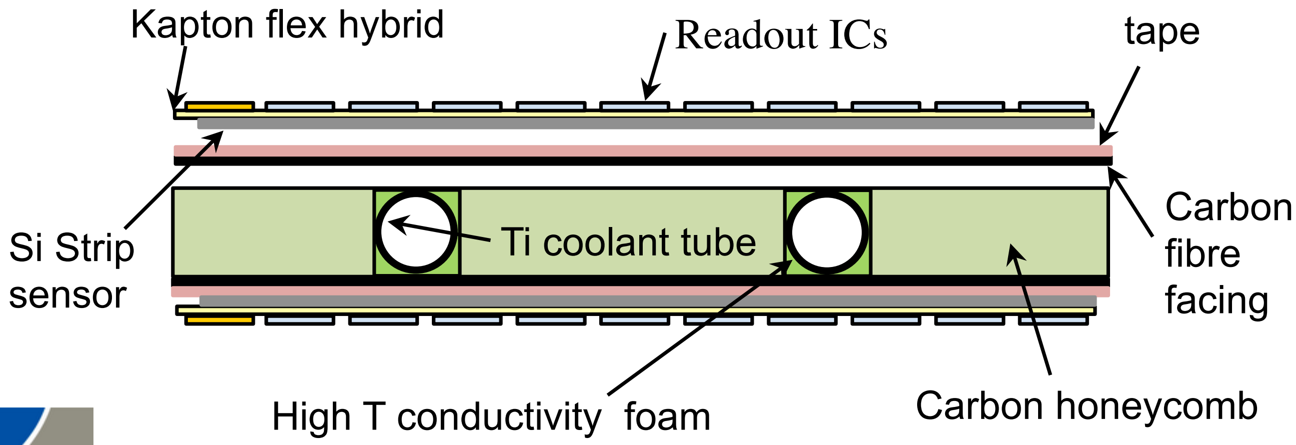


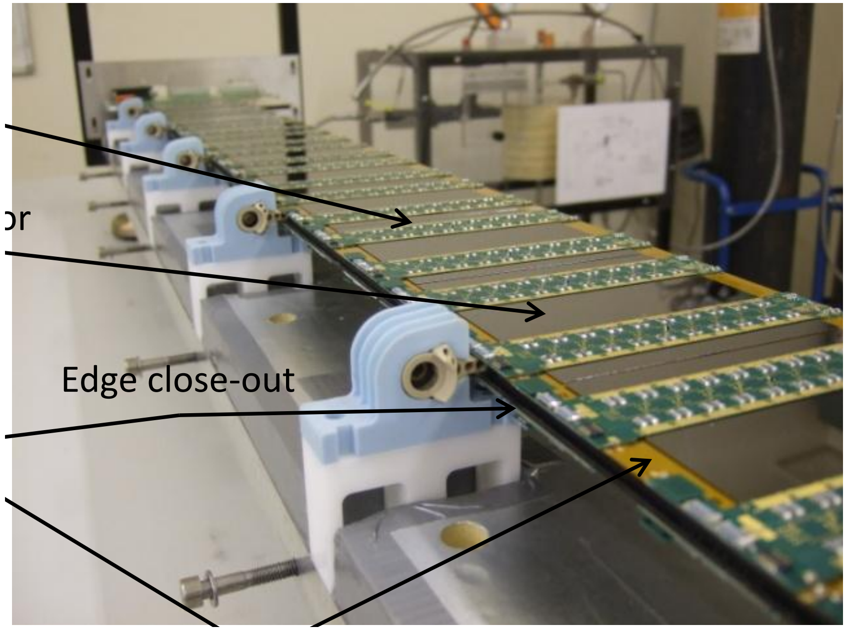
ATLAS Barrel Strip Detector



- Staves are arranged in concentric cylinders centred around the beam-line
  - overlap is arranged to make the layer hermetic down to 1 GeV/c tracks
- Double-sided layers with axial strip orientation and rotated by 26 mrad on other side (z-coordinate)
  - A sandwich construction for high structural rigidity with low mass.
  - End insertable (in z) to allow repairs up to the very last moment
  - Silicon Modules directly bonded to a cooled carbon fibre plate.

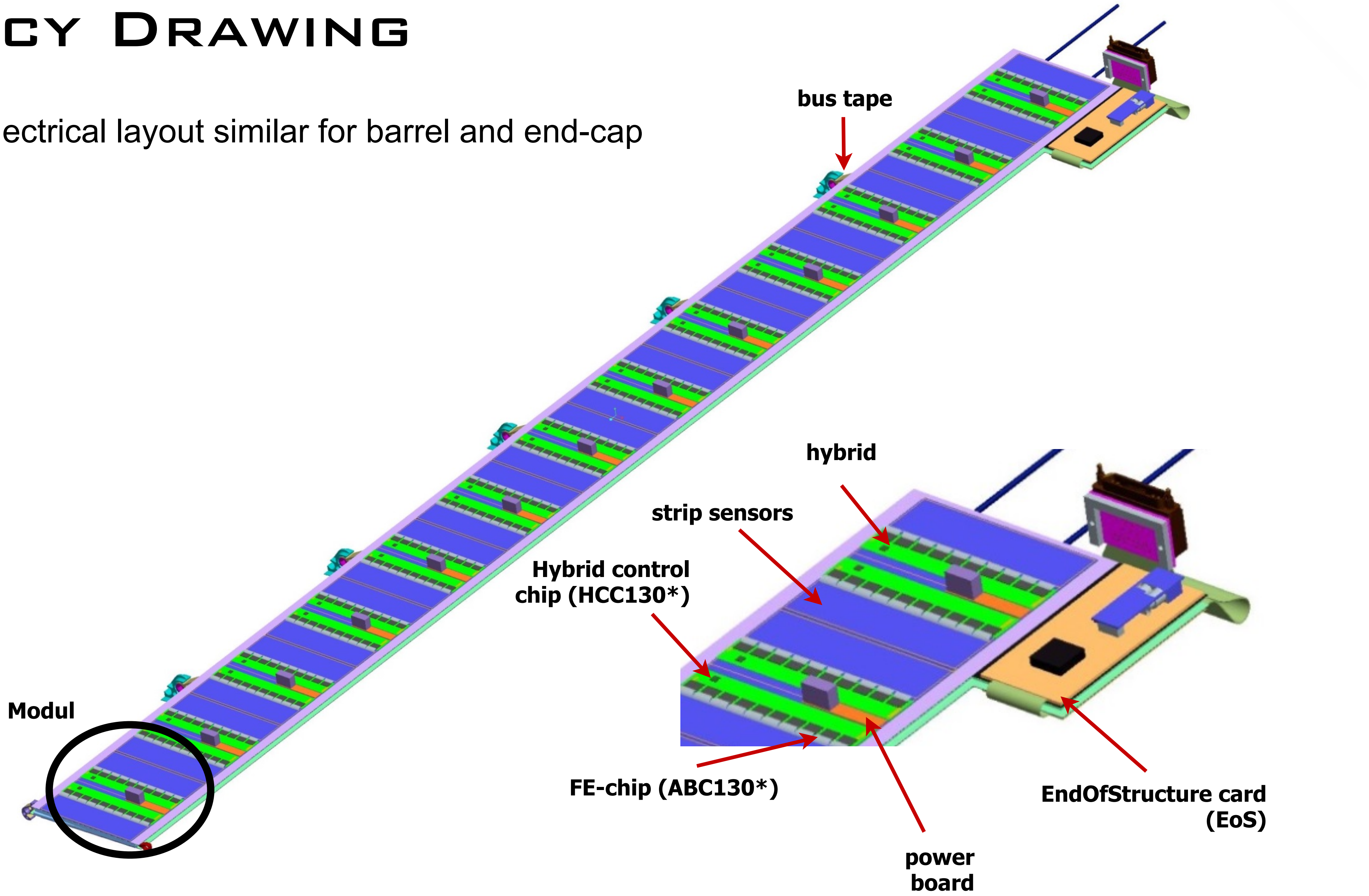
Stave cross-section:



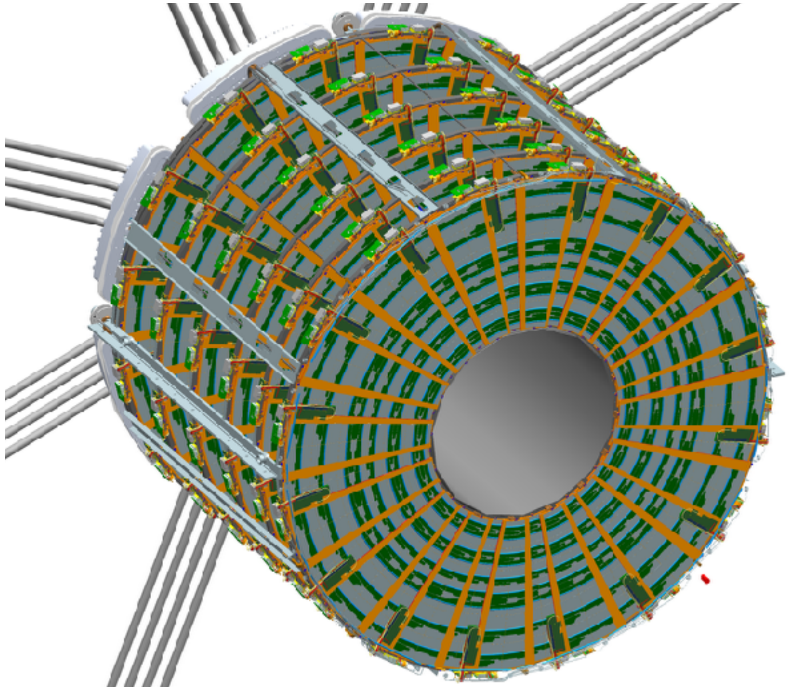


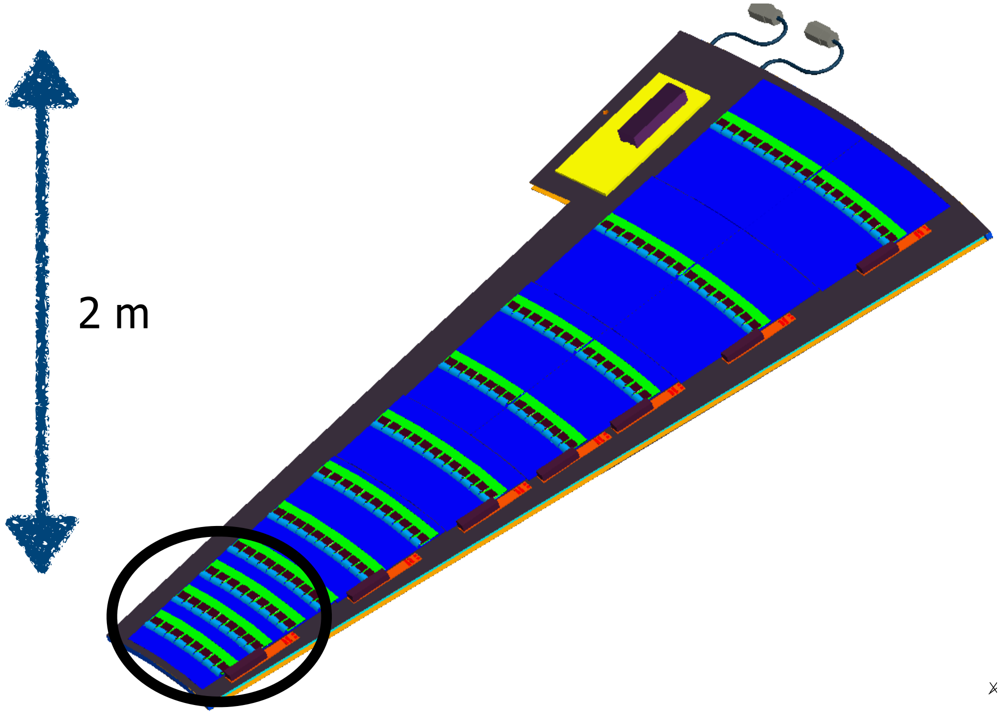
Fancy Drawing

- Electrical layout similar for barrel and end-cap



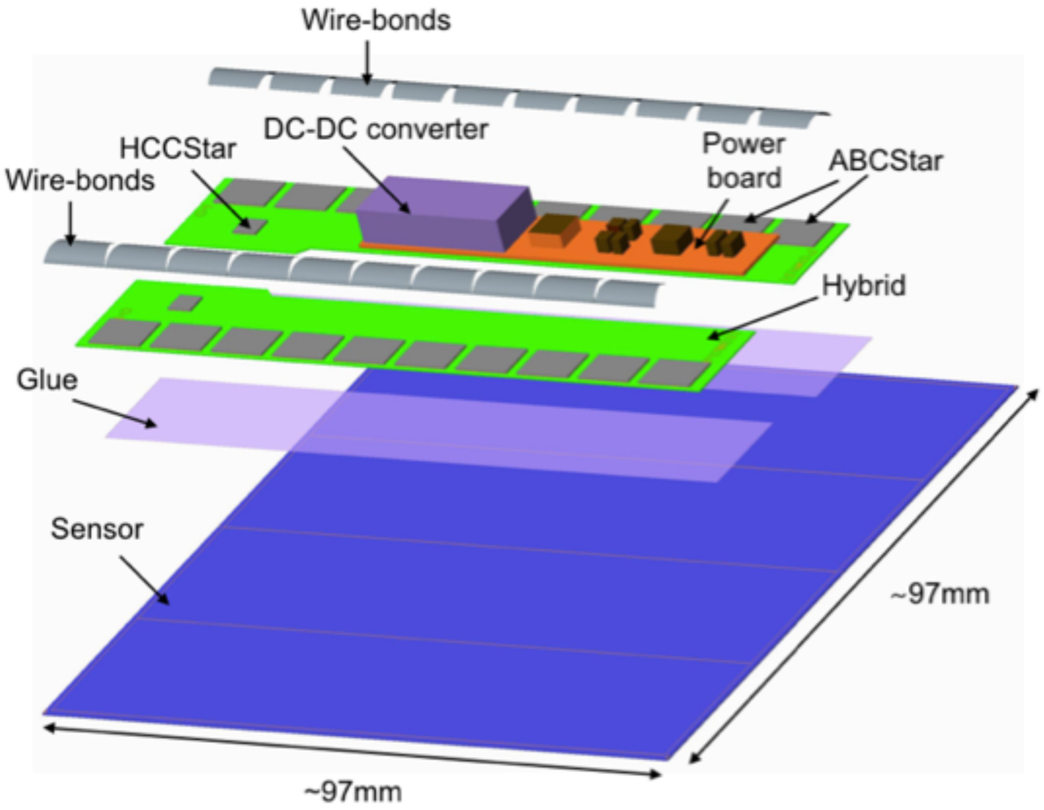
END-CAPS - COMPLICATED GEOMETRY





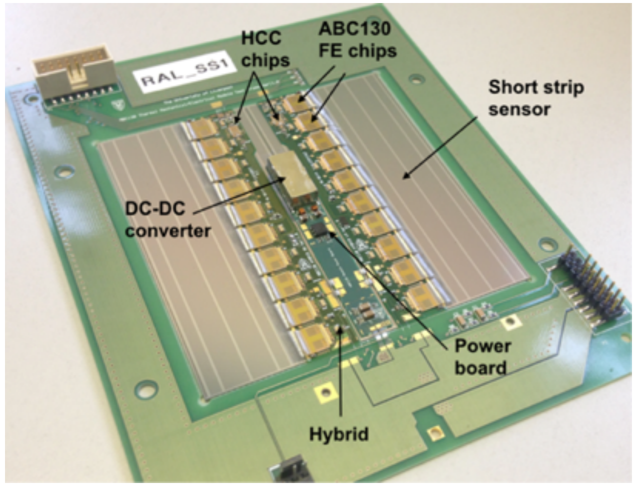
- End-caps are a problem due to their geometrical constraints
  - following stave concept -> build disks out of wedge shaped petals covered by **six** (!) different sensor shapes
  - more complicated layout for the electronics as we have two modules besides each other

Strips Module Components example ATLAS ITk



Exploded view of barrel short strips module

- Silicon strips sensor
  - Square for barrel, trapezoidal for end-cap
- Hybrids glued directly onto sensor
  - Contains up to 12 front-end chips ABC130 (UV glue)
  - One hybrid control chip (HCC) per hybrid
- Power board
  - Providing LV, HV and monitoring chip
- O(7k) wire-bonds



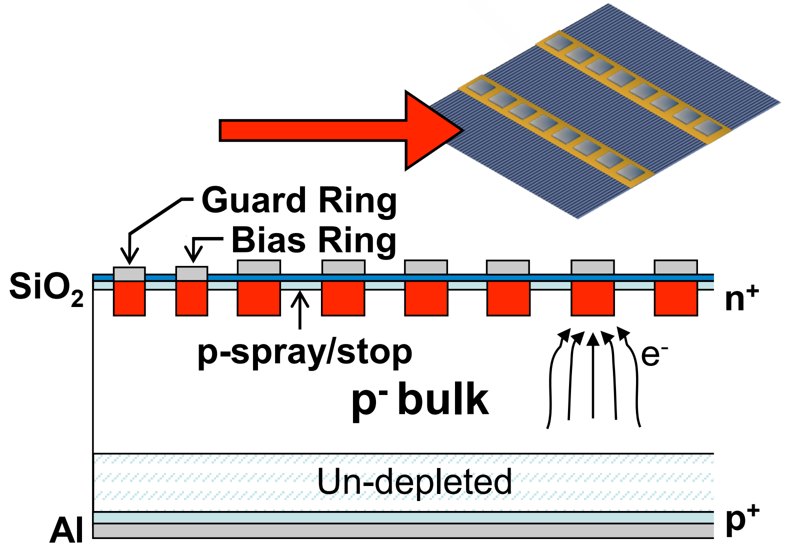
Barrel short strips module

End-cap innermost strips module

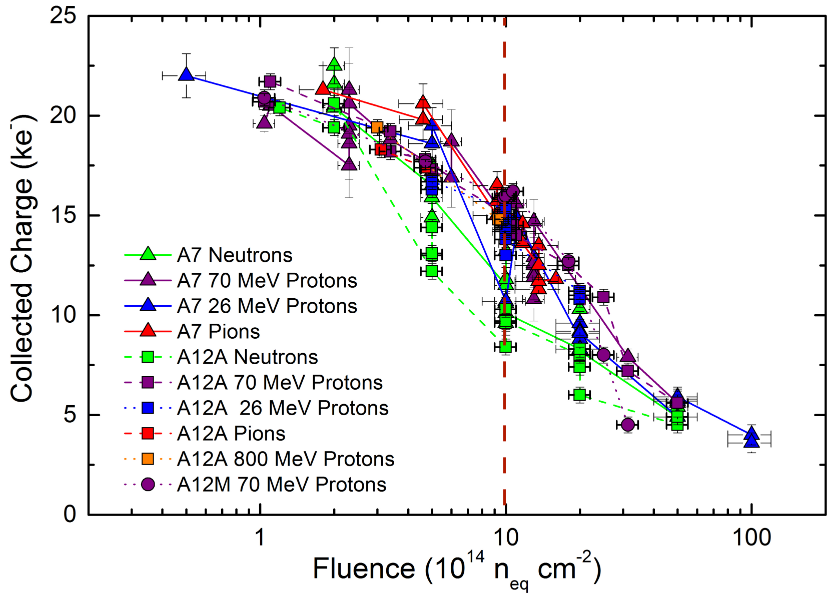
SILICON STRIPS SENSORS

- Sensor parameters defined: **n-in-p with p-stop isolation**
  - Collects electrons
    -> faster signal, reduced charge trapping
  - Always depletes from the segmented side:
    good signal even under-depleted
- Single-sided process
  - Cheaper than n-in-n
  - More foundries and available capacity world-wide
- Radiation damage most important issue

Sensor	
Substrate material	p type FZ
Thickness	300-320 µm
Resistance	> 3kΩcm
Collected charge after 1×10^{15} n_{eq} /	> 7500 e^- per MIP



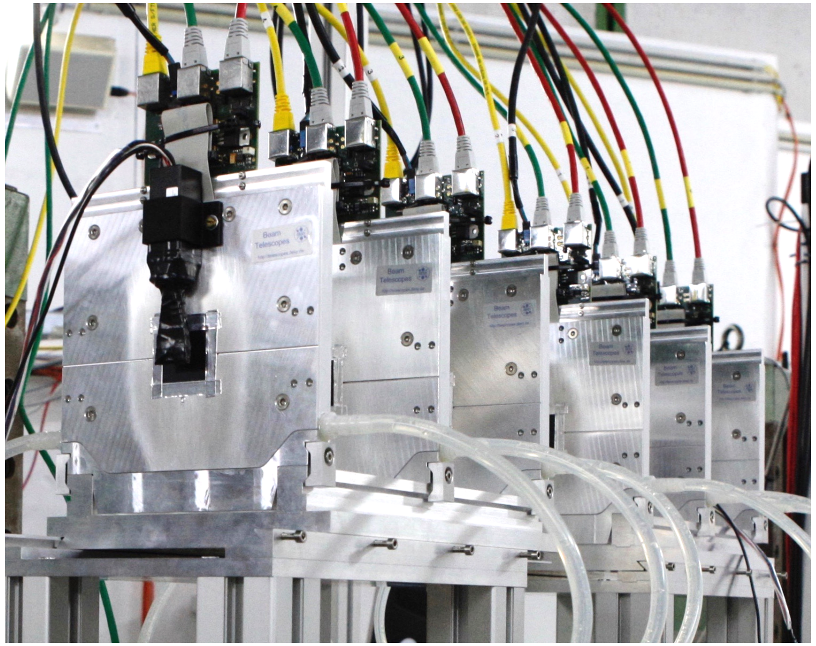
Cross-section through sensor

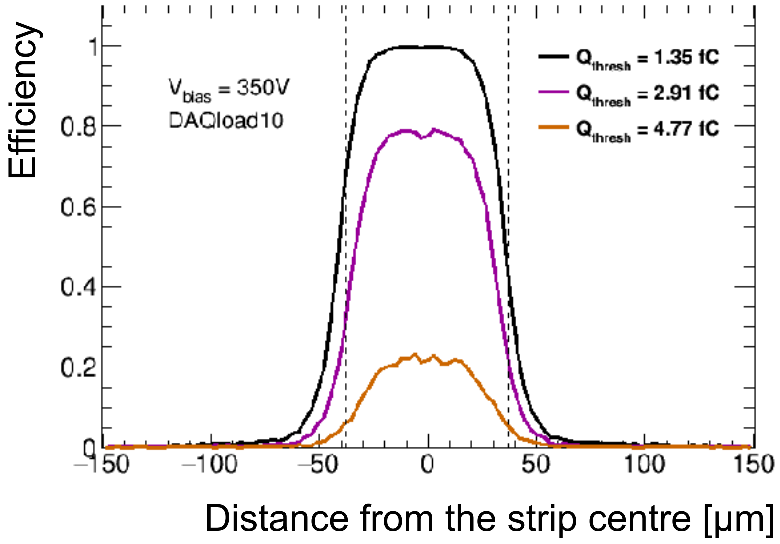


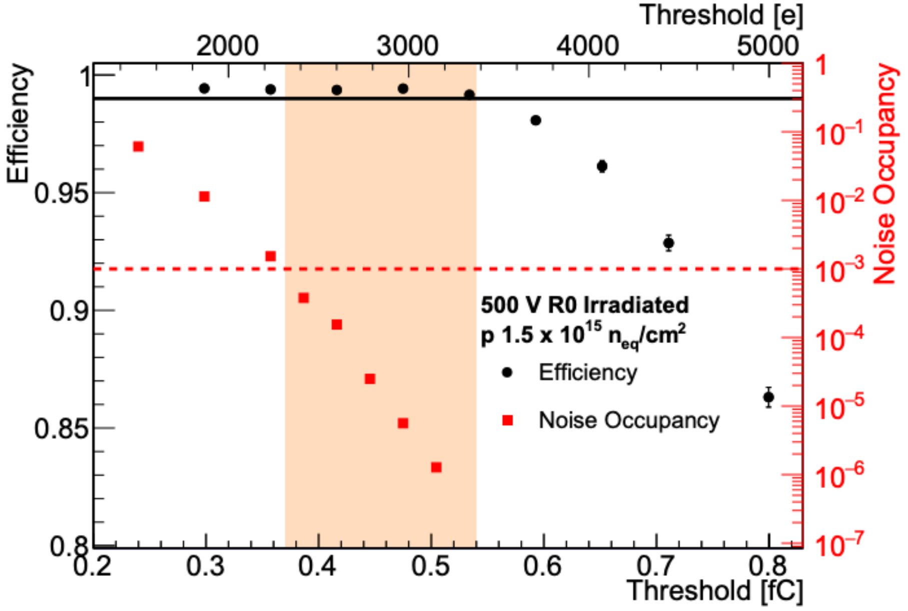
Collected charge versus irradiation

MODULE PERFORMANCE

- Modules should still be operational at the end of HL-LHC
  - Highest expected fluence in ITk Strips: 1.2 $10^{15} n_{eq}/cm^2$
- Benchmark for module performance
  - >99% detection efficiency
  - $<10^{-3}$ noise occupancy
- Best demonstrated at a test beam (DESY, CERN)
- Compared module results (binary) with analogue sensor results
  - Consistent within uncertainties







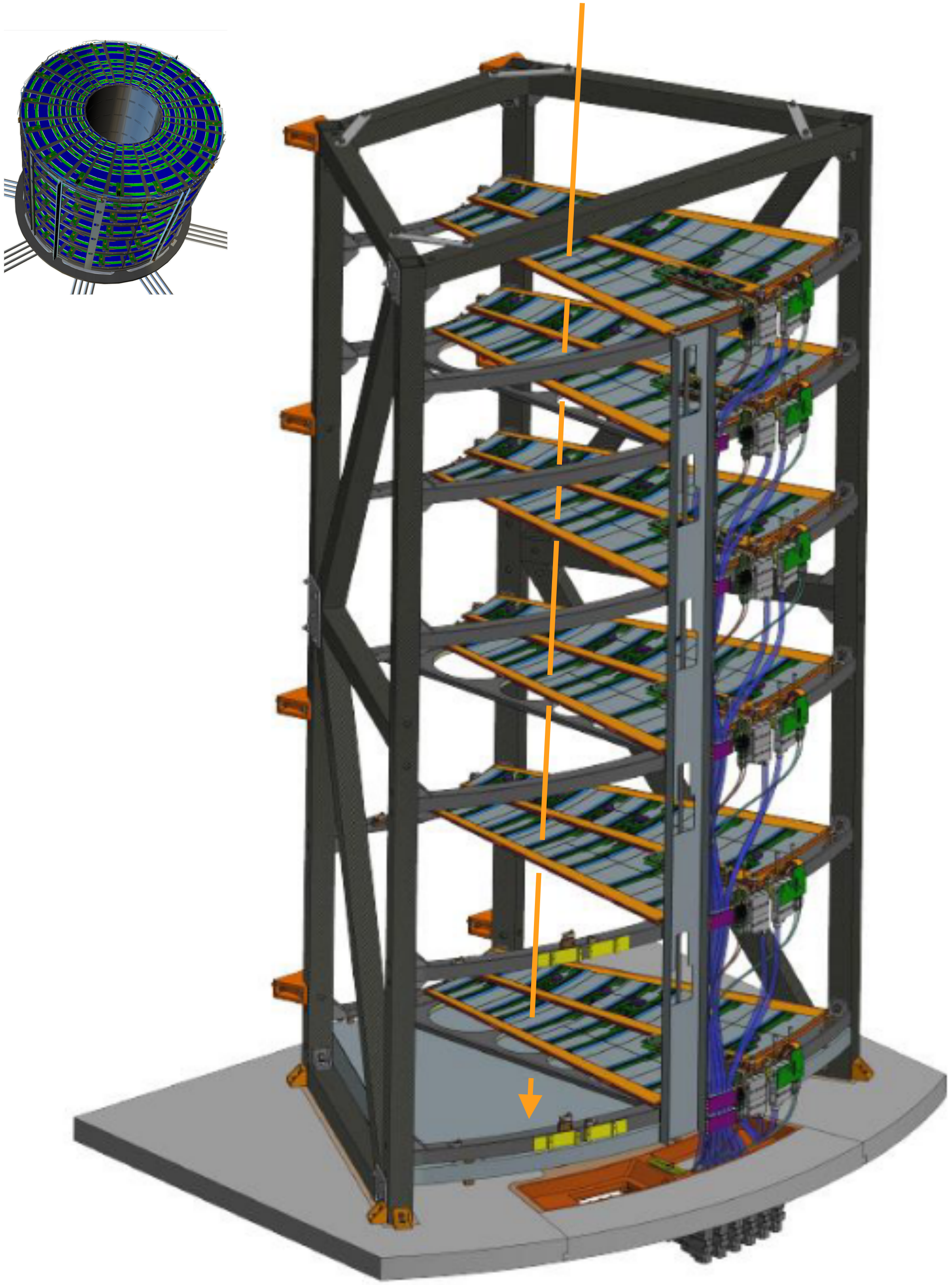
E. Rossi, CERN-THESIS-2020-177

END-CAP SYSTEM TEST

- Plan: built 1/8th slice of the EC populated with 12 petals
  - Test different permutations of petals in the structure to study electrical noise behaviour
  - First located at DESY, afterwards move to CERN for full strips system test

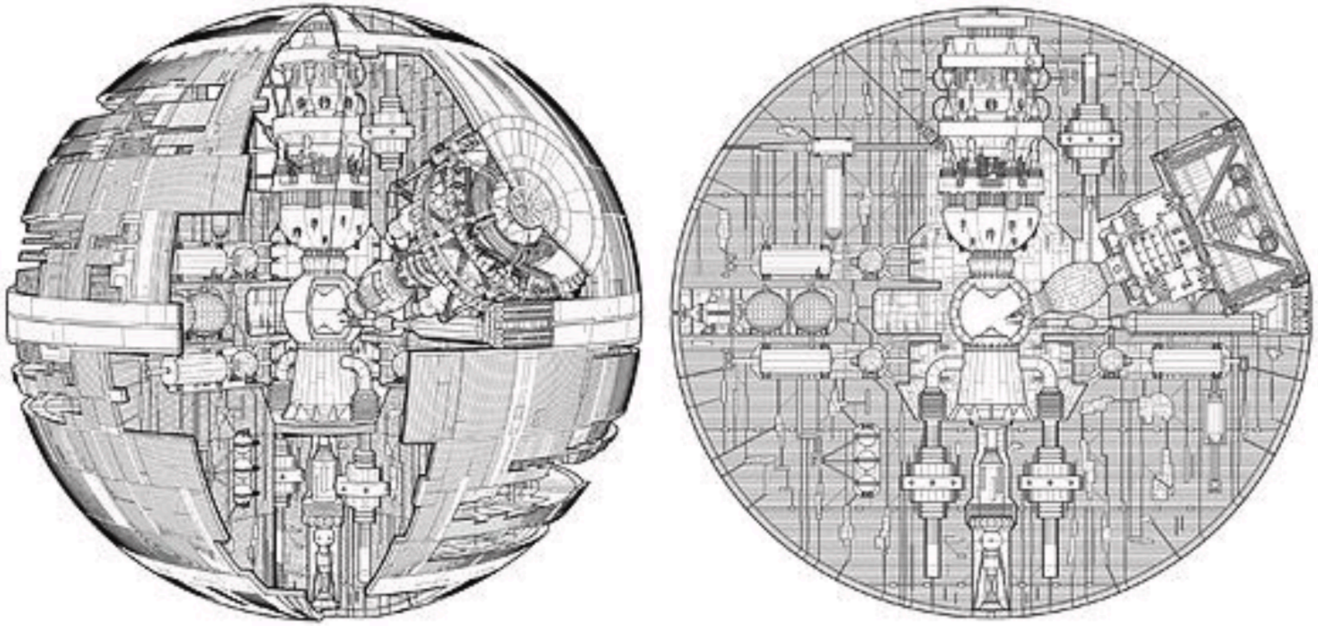
- Need realistic mechanical structure with electrical services and cooling infrastructure
  - real mechanical CF disk structure with bulkhead and additional lateral support structure with CF service tray and prototype electrical cables for powering and readout
  - CO2 cooling lines with temporary connections

- Under construction now: hope to take first **cosmic muon** runs end of the year



Building these Beasts

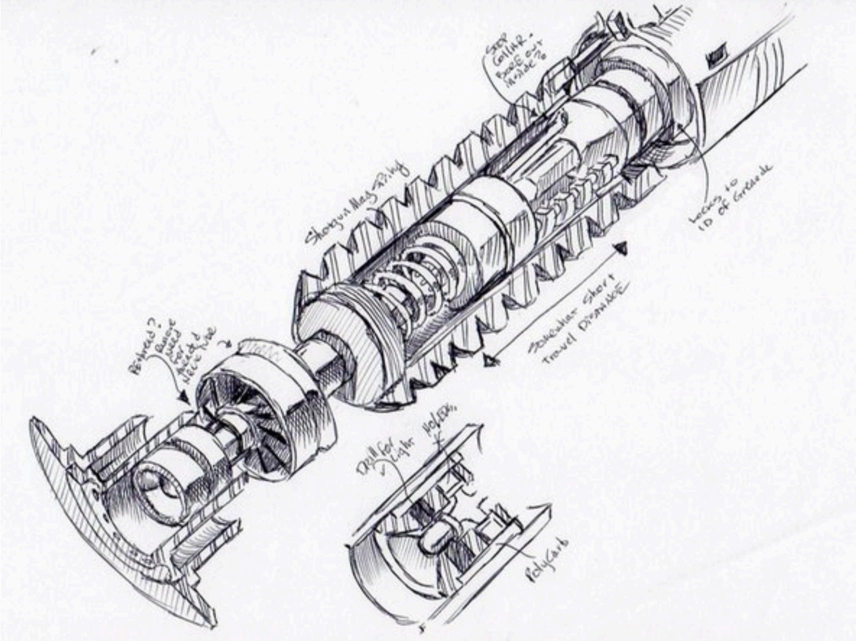
INTRODUCTION



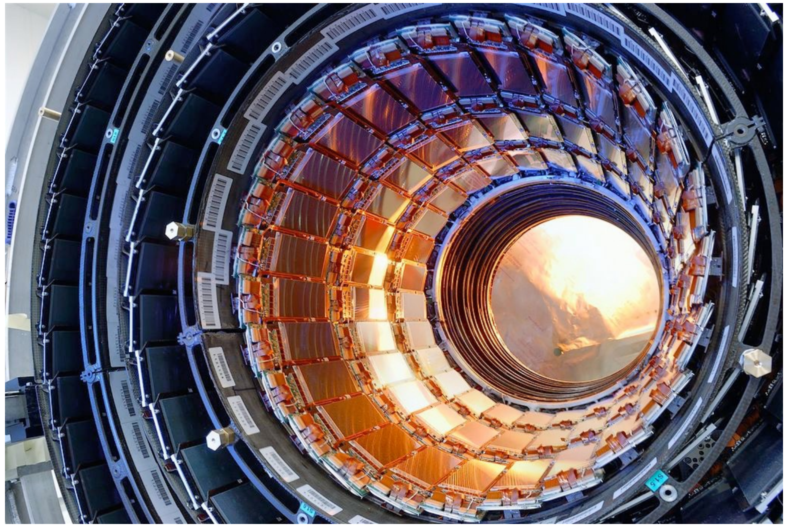
- Designing a particle physics (tracking) detector is a very complex business
- Many very nice examples exist
- Also some examples of failures

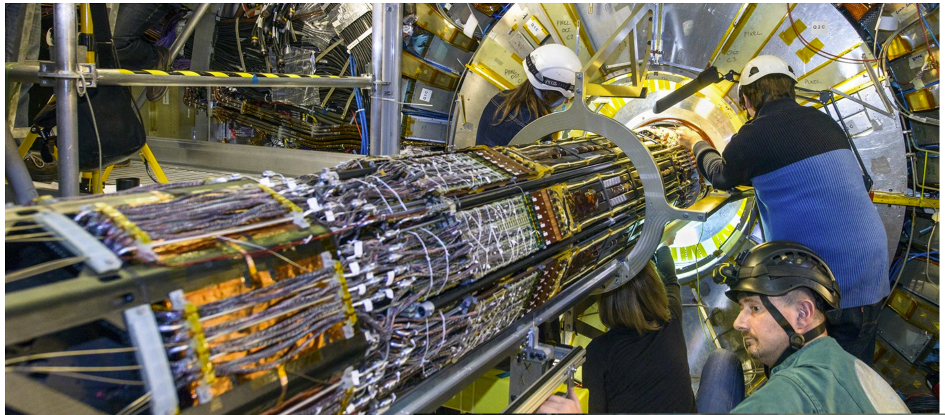
- Today: overview of main steps to get from sensor to detector
- Some examples where problems appeared

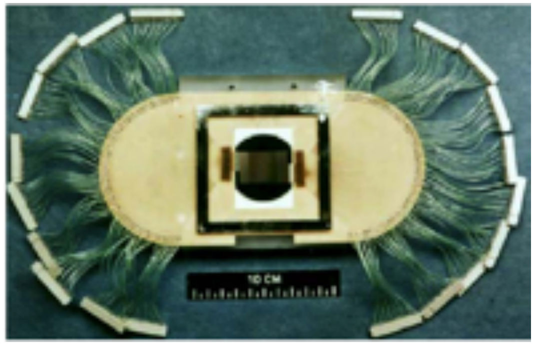
A topic to talk hours about.
Some bias in the selection of detectors and examples based on my experience, my friends and other factors …

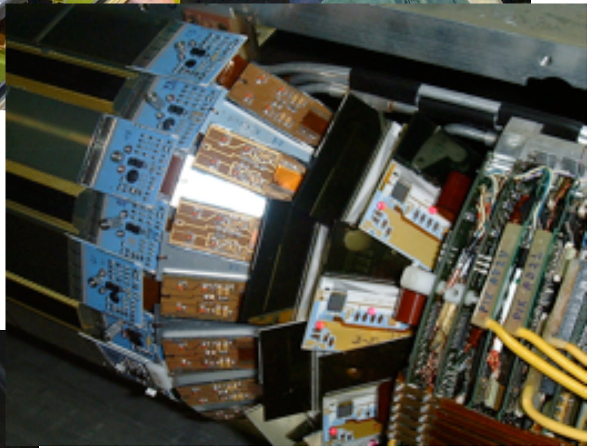


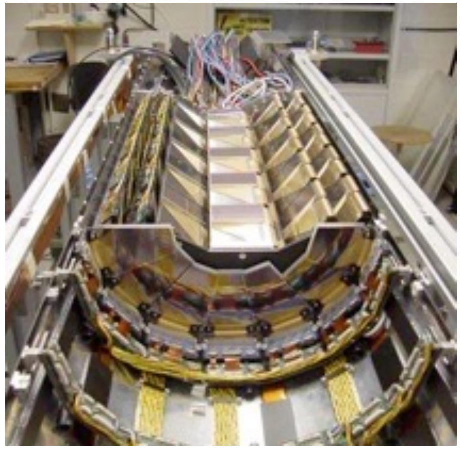
What we want ...


CMS Strip Detector, 2007

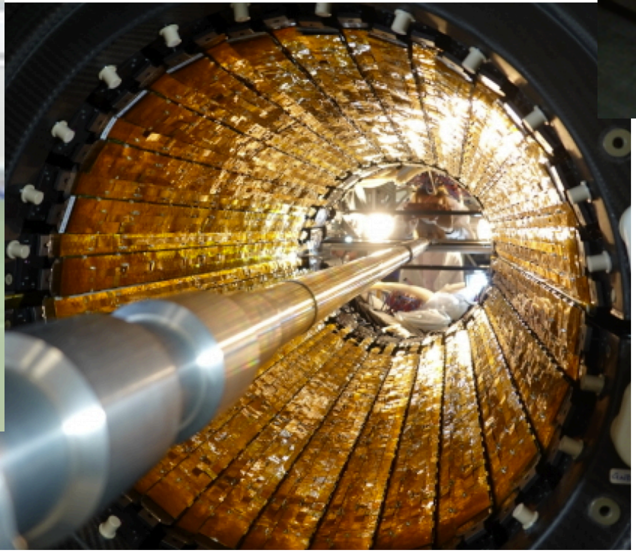

ATLAS Pixel Detector 2007


NA11 1981


DELPHI VFT 1996


ZEUS MVD 2000

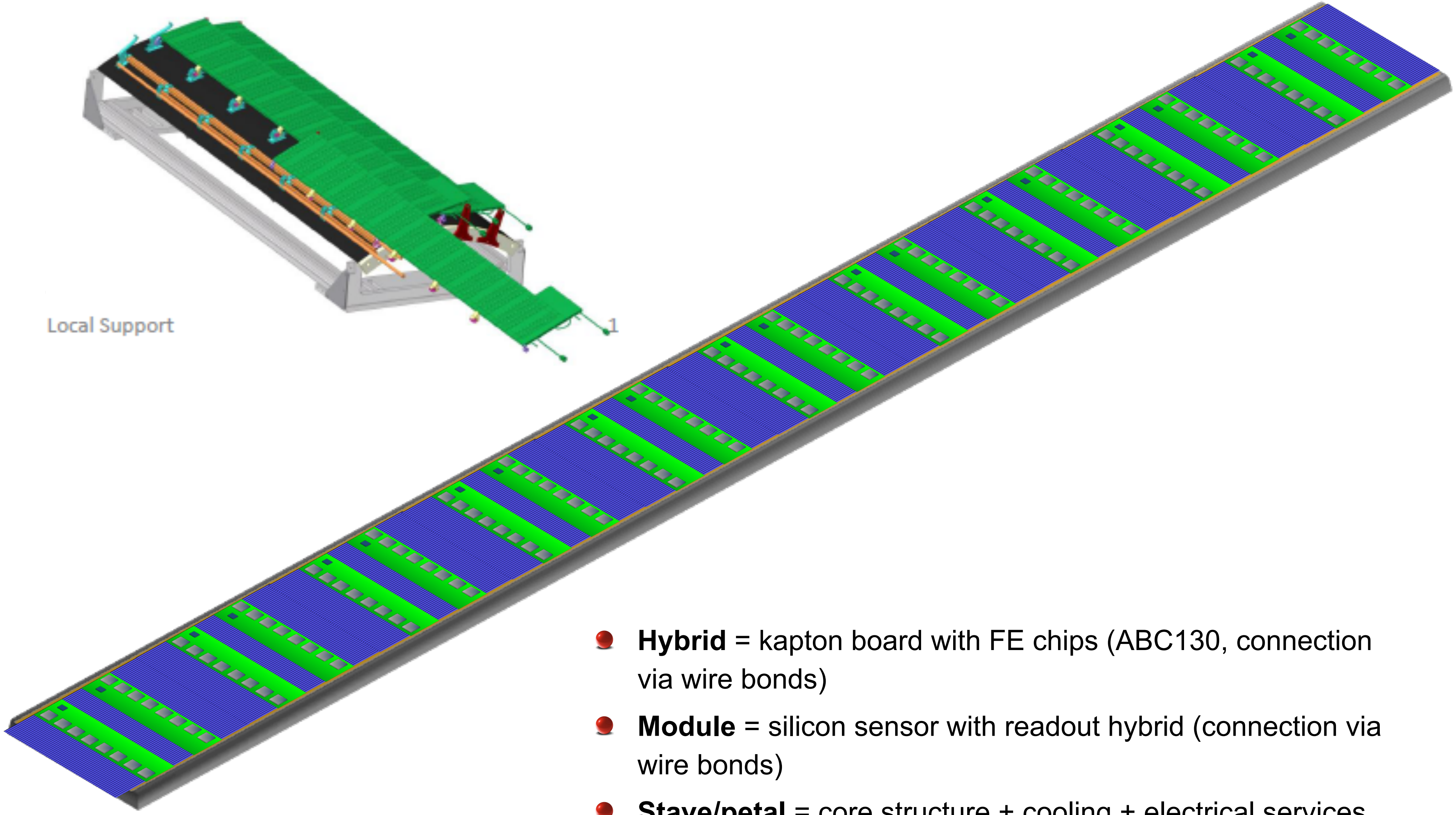

Belle II PXX, 2022


ALICE ITS


AMS Strip Detector,

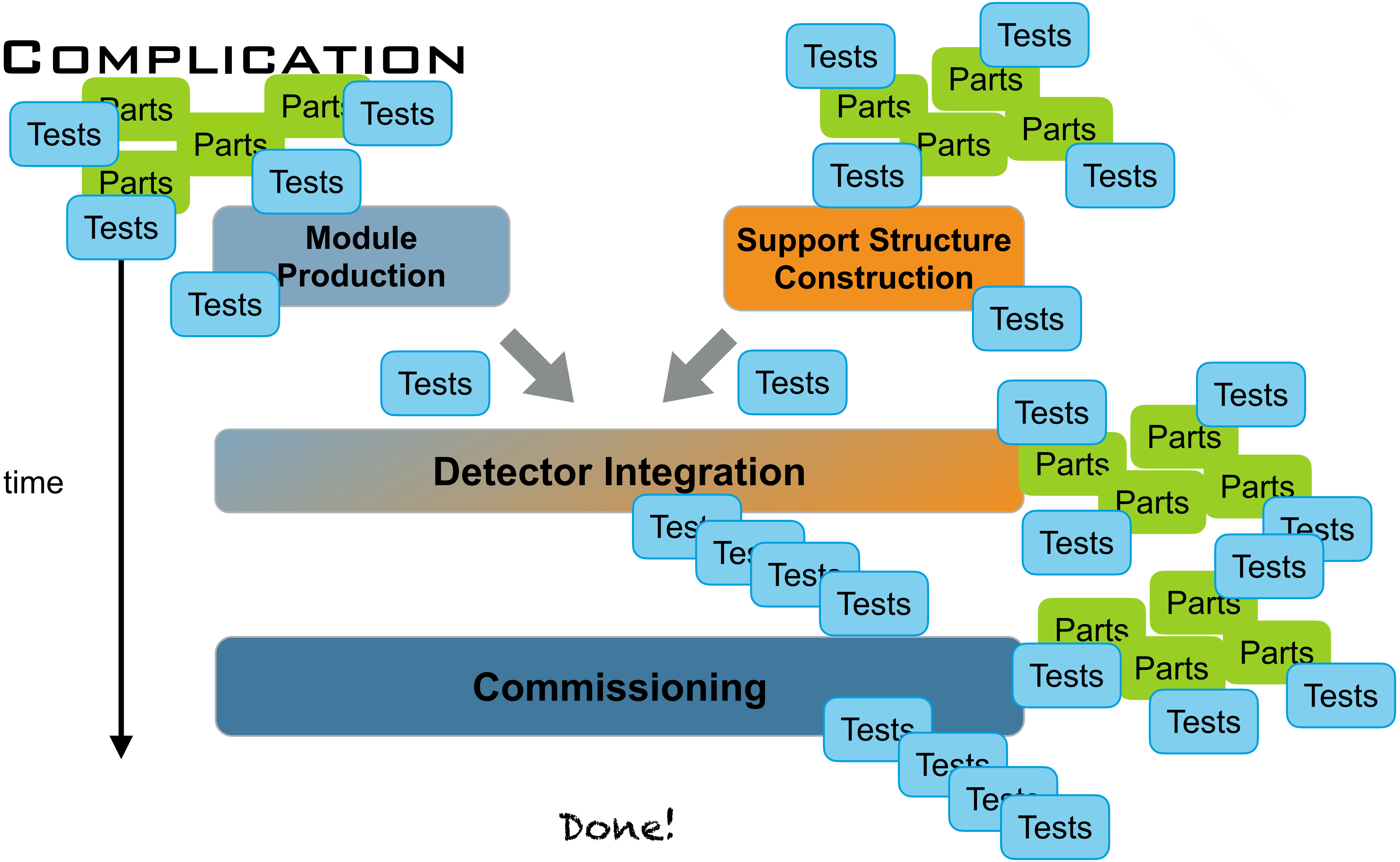
Pictures: CERN, KEK

ATLAS STRIPS: STAVE/PETAL CONCEPT



- **Hybrid** = kapton board with FE chips (ABC130, connection via wire bonds)
- **Module** = silicon sensor with readout hybrid (connection via wire bonds)
- **Stave/petal** = core structure + cooling + electrical services (power, data, TTC) + modules

THE COMPLICATION



Tests
Parts
Parts
Parts
Tests
Parts
Tests
Tests

Module Production

Tests

Tests
Tests
Parts
Parts
Parts
Parts
Tests
Tests

Support Structure Construction

Tests

Tests
Tests

time

Detector Integration

Tests
Tests
Tests
Tests

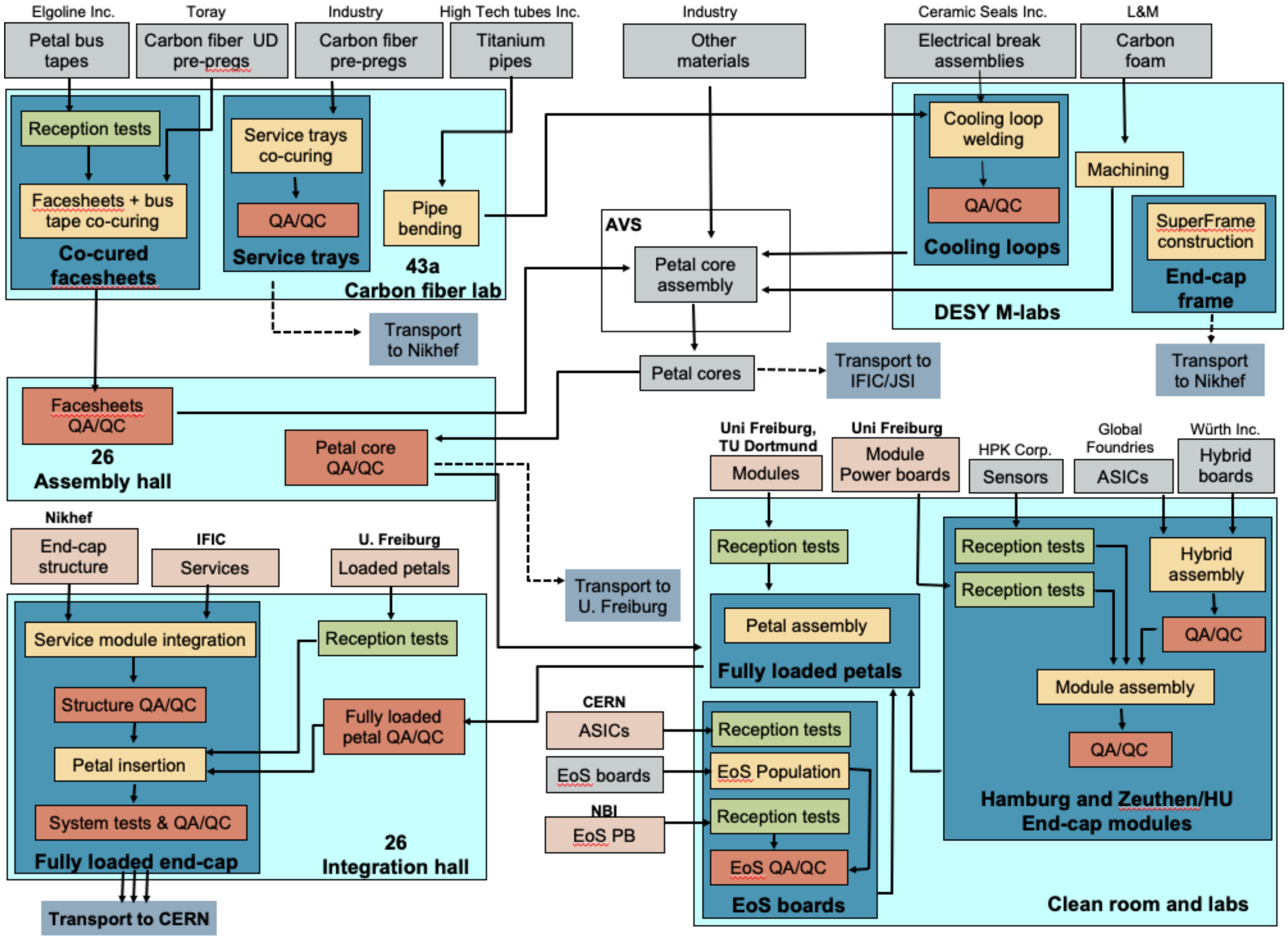
Tests
Tests
Parts
Parts
Parts
Parts
Tests
Tests
Tests
Parts
Parts
Parts
Parts
Tests
Tests
Tests

Commissioning

Tests
Tests
Tests
Tests

Done!

ATLAS End-cap Workflow at DESY



Elgoline Inc.
Petal bus tapes

Toray
Carbon fiber UD pre-pregs

Industry
Carbon fiber pre-pregs

High Tech tubes Inc.
Titanium pipes

Industry
Other materials

Ceramic Seals Inc.
Electrical break assemblies

L&M
Carbon foam

Reception tests
Facesheets + bus tape co-curing
Co-cured facesheets

Service trays co-curing
QA/QC
Service trays

Pipe bending

43a
Carbon fiber lab

Transport to Nikhef

AVS
Petal core assembly

Petal cores

Transport to IFIC/JSI

Cooling loop welding
QA/QC
Cooling loops

Machining

SuperFrame construction
End-cap frame

DESY M-labs

Transport to Nikhef

Facesheets QA/QC
Petal core QA/QC
26
Assembly hall

Transport to U. Freiburg

Nikhef
End-cap structure

IFIC
Services

U. Freiburg
Loaded petals

Service module integration
Structure QA/QC
Petal insertion
System tests & QA/QC
Fully loaded end-cap

Reception tests
Fully loaded petal QA/QC

26
Integration hall

Transport to CERN

Uni Freiburg, TU Dortmund
Modules

Uni Freiburg
Module Power boards

HPK Corp.
Sensors

Global Foundries
ASICs

Würth Inc.
Hybrid boards

Reception tests
Petal assembly
Fully loaded petals

Reception tests
Reception tests
Hybrid assembly
QA/QC
Module assembly
QA/QC
Hamburg and Zeuthen/HU End-cap modules

CERN
ASICs

EoS boards

NBI
EoS PB

Reception tests
EoS Population
Reception tests
EoS QA/QC
EoS boards

Clean room and labs

DESY facility

Reception test at DESY facilities

Activity at DESY facility

QA/QC evaluation at DESY facility

DESY deliverable

Transport to another ITk institute

Name of the company if known
Industry Deliverable

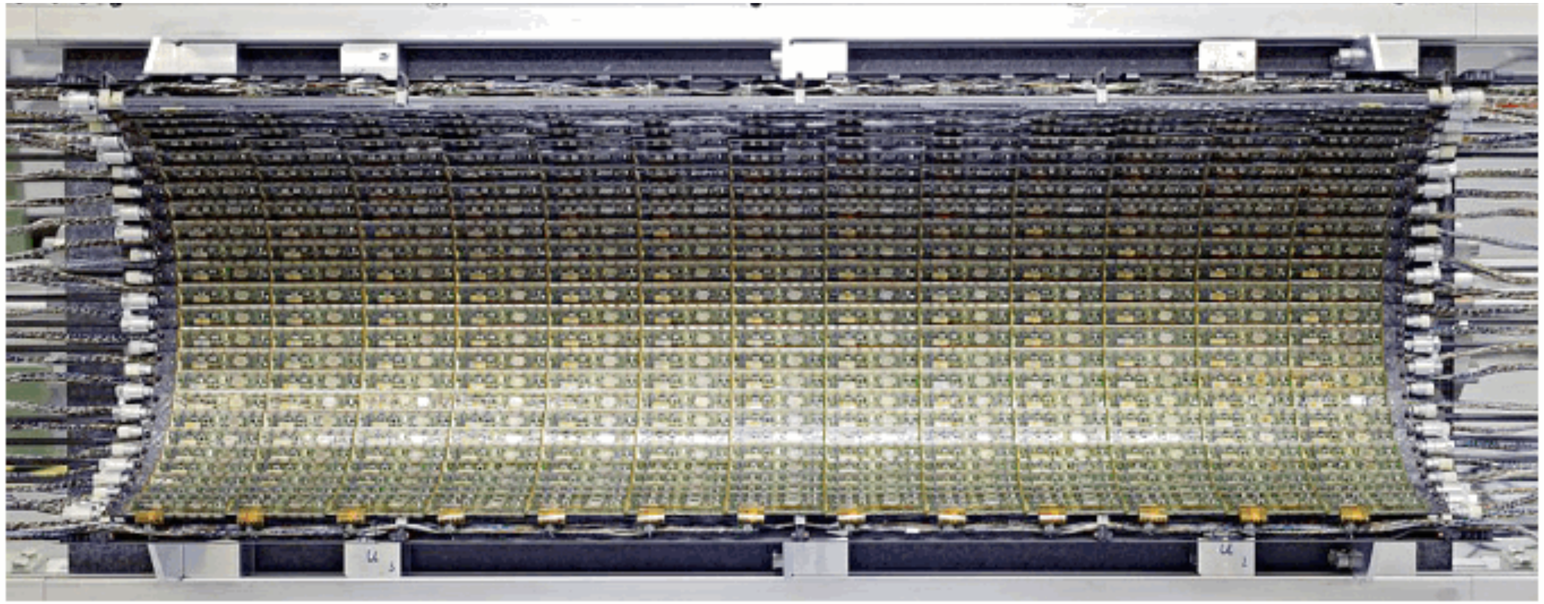
Name of the institute
Deliverable from another ITk institute

MODULE PRODUCTION

THE MODULE

- Module
  - Smallest building block to be mounted to support structure
  - Sensor plus readout electronics
  - Maybe some powering electronics and interfaces
- The detector can only be as good as its smallest parts
- Module quality defines detector quality (to some extent)
- Large share of production time is dedicated to module production

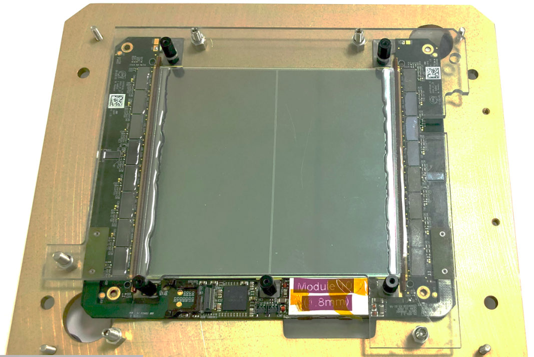
Project	**CMS Pixel Phase I**	**LHCb Velo**	**DØ Microstrip Tracker**	**ATLAS ITk Strips**	**Belle II**
#	1 856	42	672	17 888	40



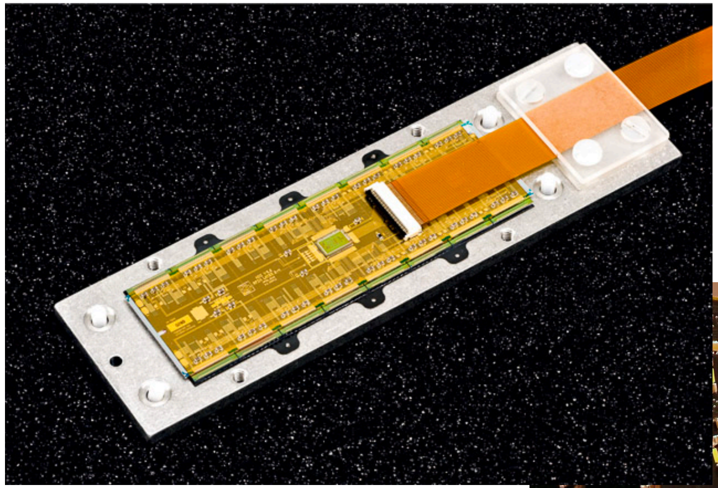
ATLAS Pixel Detector

THE MODULE

- Module
  - Smallest building block to be mounted to support structure
  - Sensor plus readout electronics
  - Maybe some powering electronics and interfaces

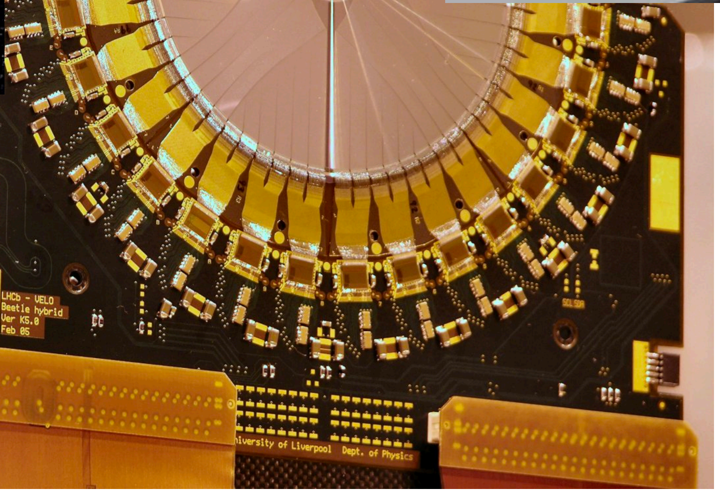


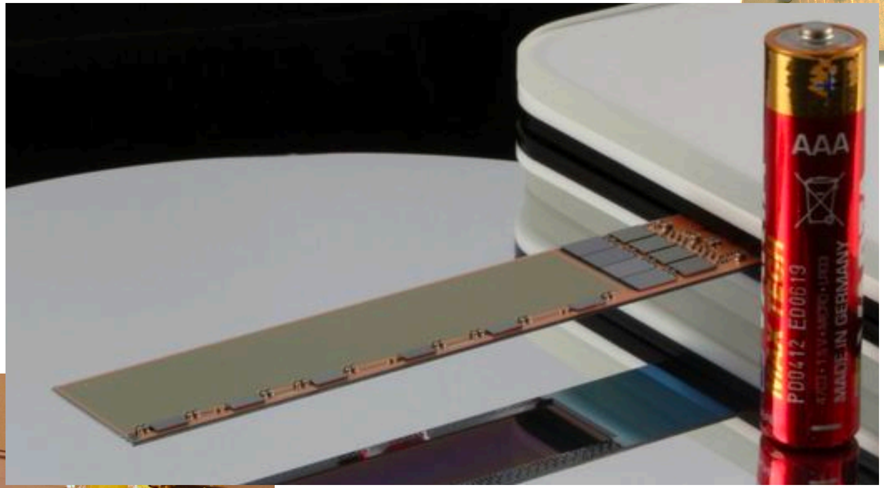
CMS Phase II 2S



CMS Phase I Pixel

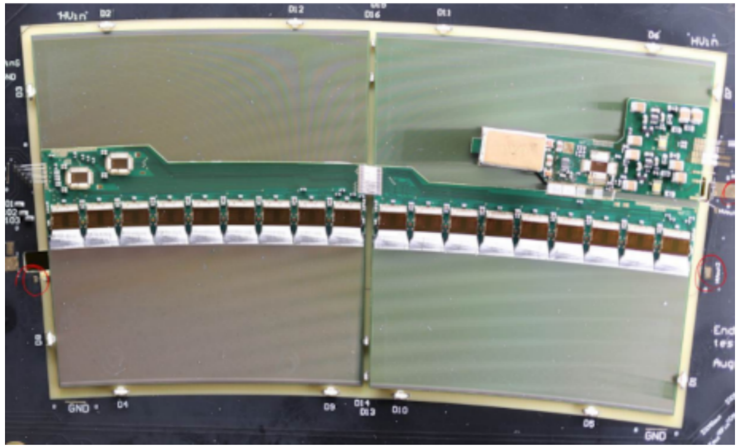
LHCb Velo





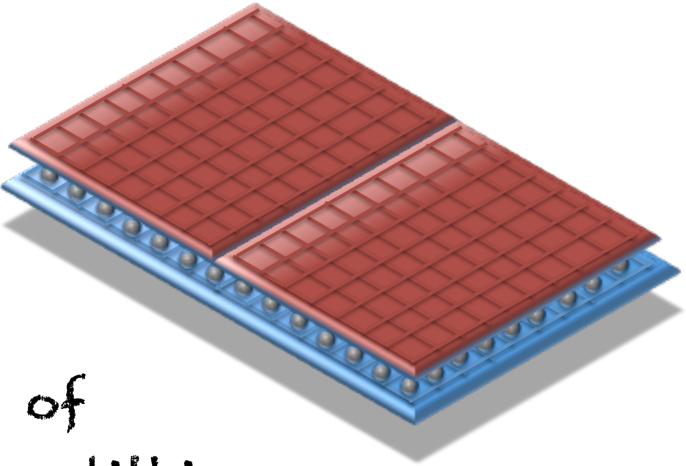
Belle II Pixel

ATLAS ITk Strip R5

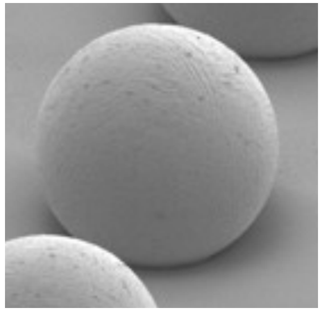


MODULE CONCEPTS

- Pixel
  - Hybrid with
    - **Bump bonds**
    - Wafer to wafer
    - Capacitive coupling
  - Monolithic

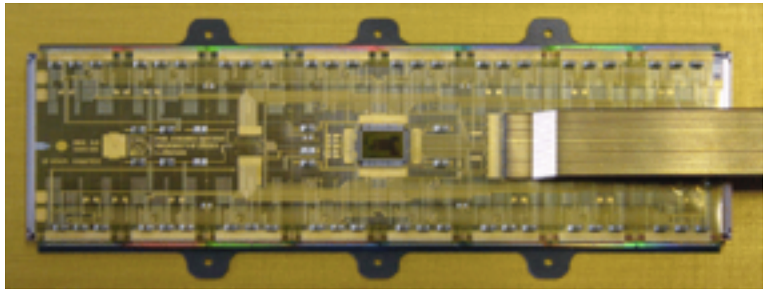


Independent of hybrid or monolithic: Need connection to outside world!

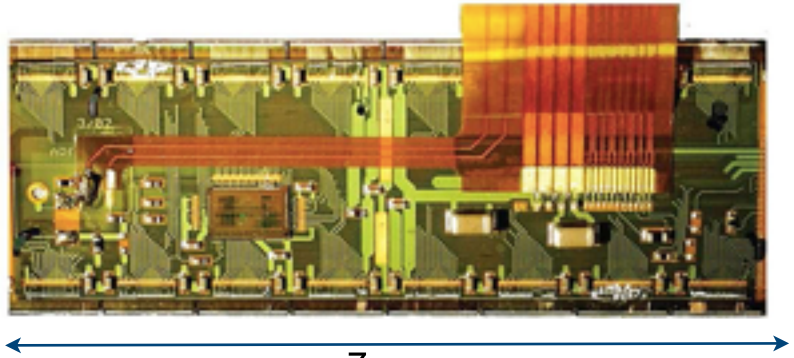


Bump-bonds
-> see backup

Typically flexible circuit board placed on top or below and connected via wire-bonds

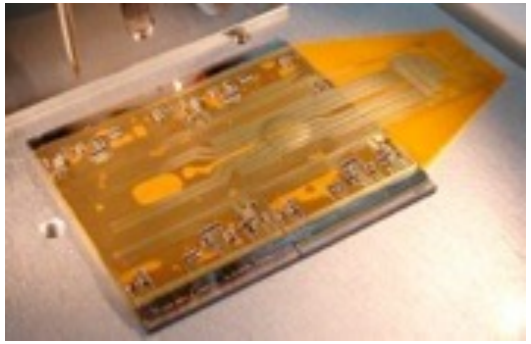


CMS pixel module



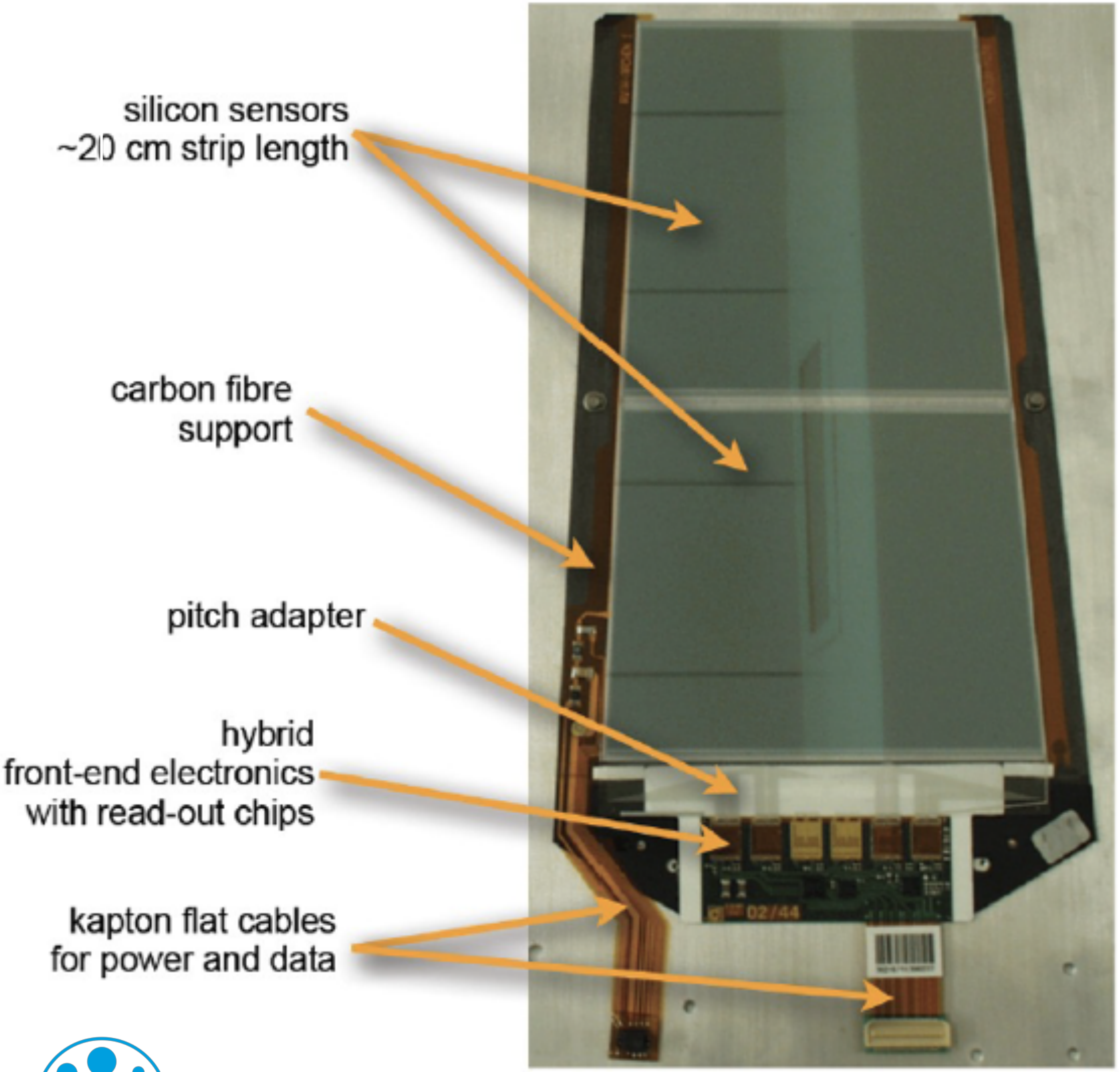
7 cm

ATLAS pixel module

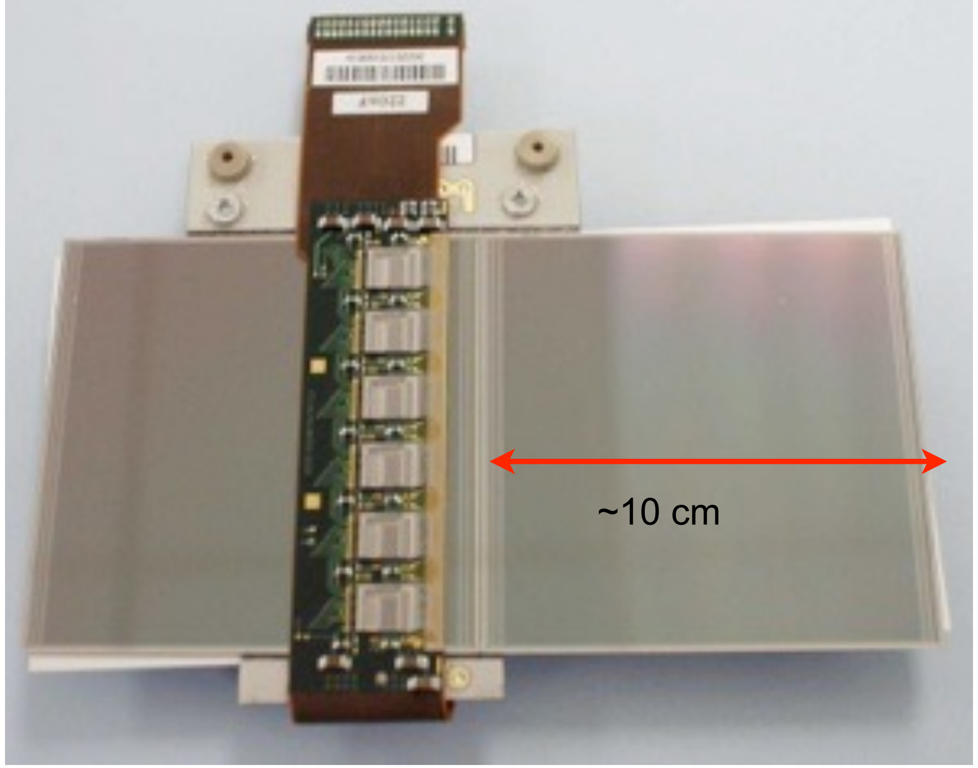


ATLAS quad module (early version)

MODULE CONCEPTS



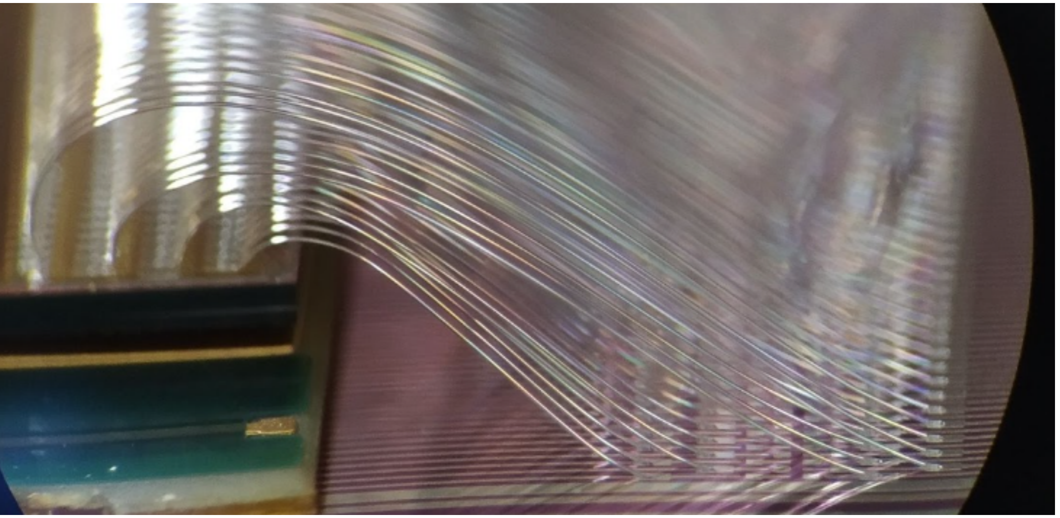
- Strips
  - Classic hybrid with wire-bonds
  - Monolithic - future dream
- FE chips wire bonded to large strip sensor

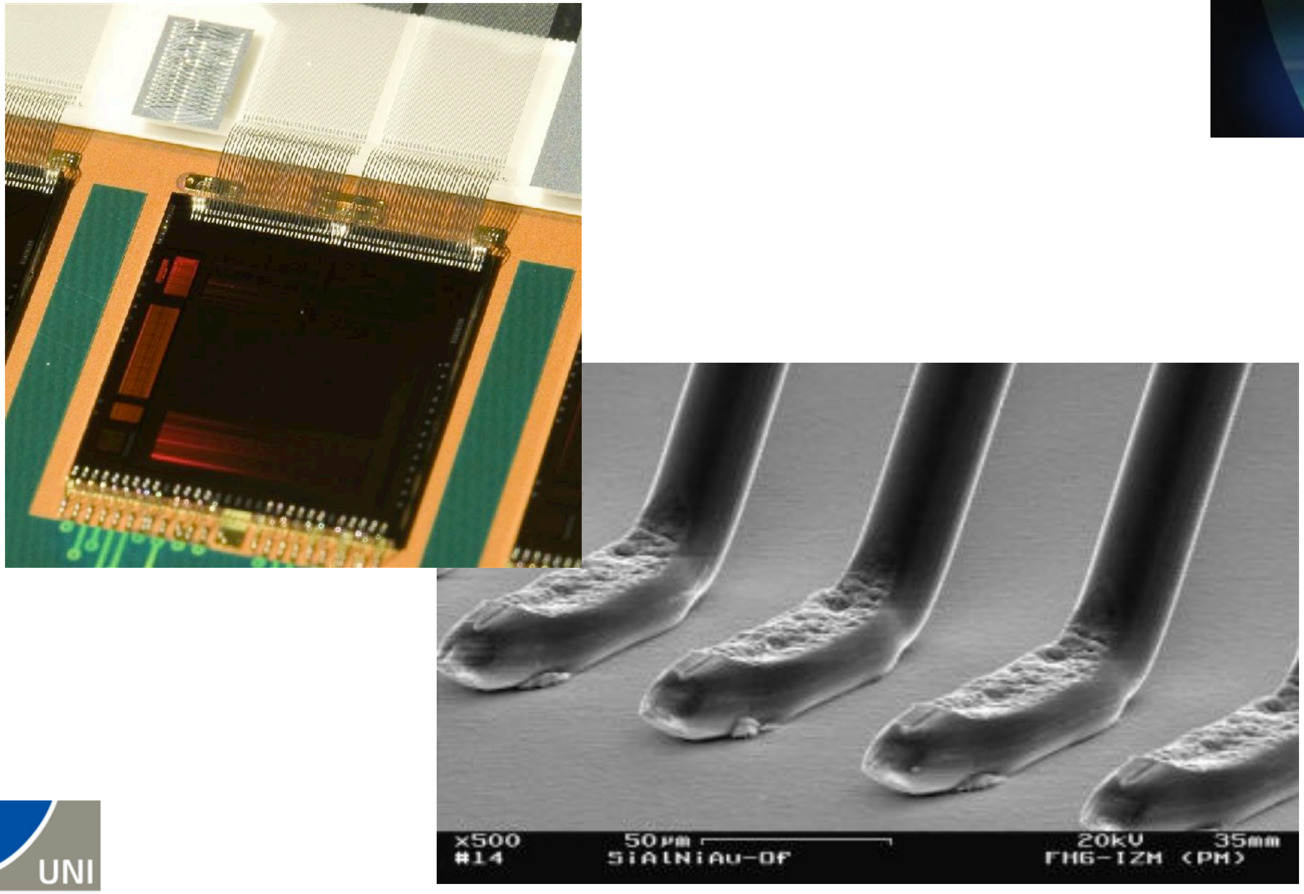


ATLAS strip barrel module

WIRE BOND CONNECTION

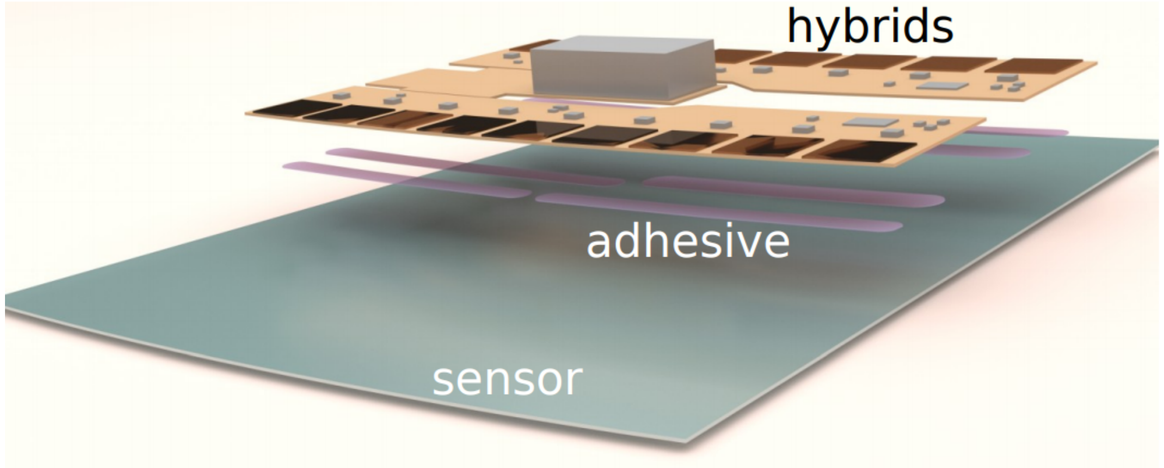
- Ultrasonic welding technique
  - typically 25 micron bond wire of Al-Si-alloy
- Nowadays: Fully-automatised system with automatic pattern recognition





BUILDING MODULES (EXAMPLE STRIPS)

- **Before production:**
  - define specifications for module (quality)

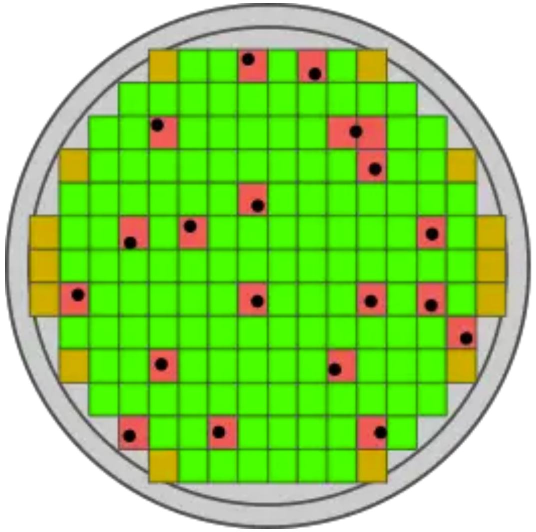


Exploded view ATLAS ITk Strips module

To be defined:
- Sensor IV, CV, etc
- Sensor bow
- Chip on wafer tests
- Hybrid noise performance
- Wire bonds strength
- Electrical performance
- Full module: metrology
- ….

based on many years of R&D

- **Understanding the yield:**
  - yield: the (expected) fraction of parts surviving tests during production
  - relying on very high yield
  - example: 20 steps with yield of 98% -> only 66% of sensors go into experiment

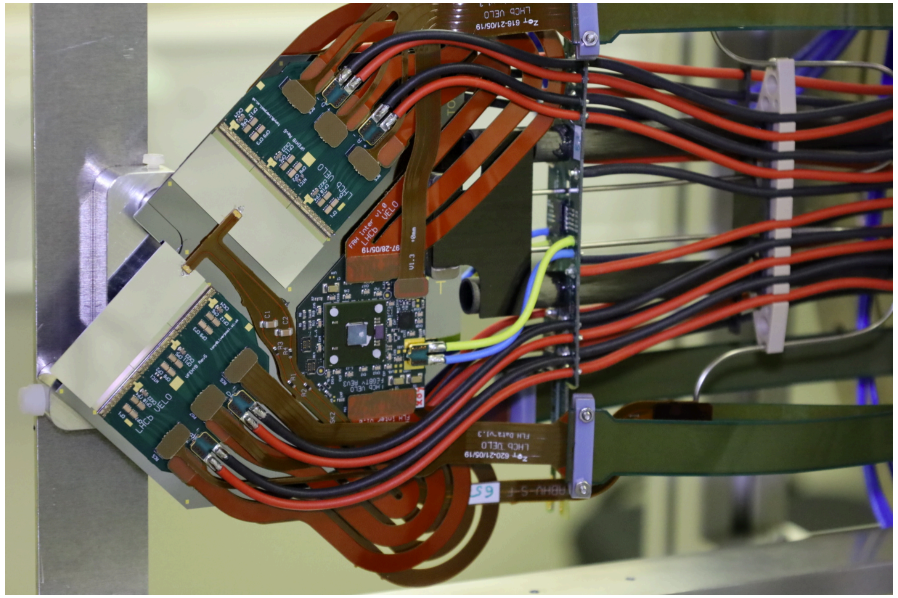


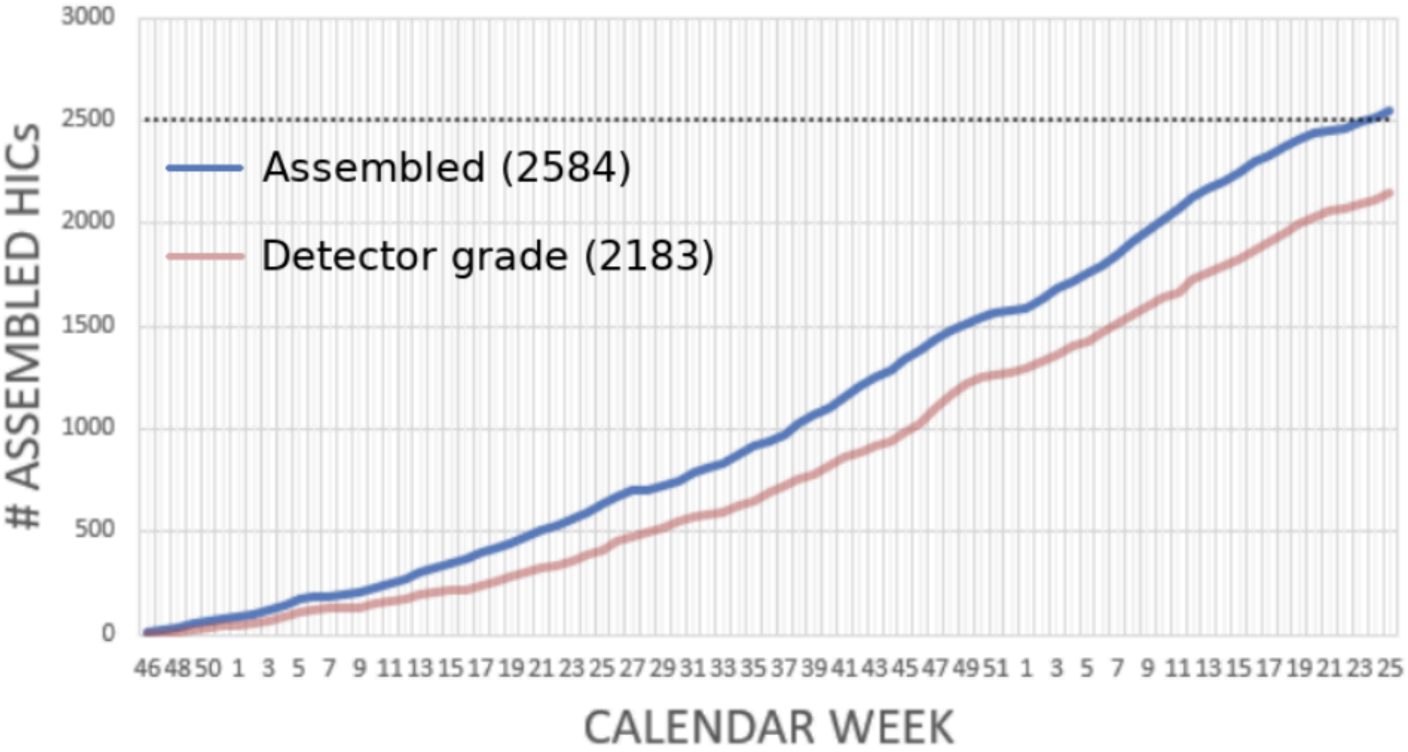
● - defect
🟥 - defective die
🟩 - good die
🟨 - partial edge die

BUILDING MODULES

Nice videos:
https://www.youtube.com/watch?v=Vo4tvenA4rQ (Belle II)
https://www.youtube.com/watch?v=fV5SiKzZ8M8 (ATLAS)

- For large detectors many things to be taken into account to set up module
  - Avoid single vendors!!!
  - Try to have as many parts as possible “off the shelf”
  - Where possible stay within industry standards
  - Reduce manual steps and make every thing as simple as possible


LHCb Velo Pixel



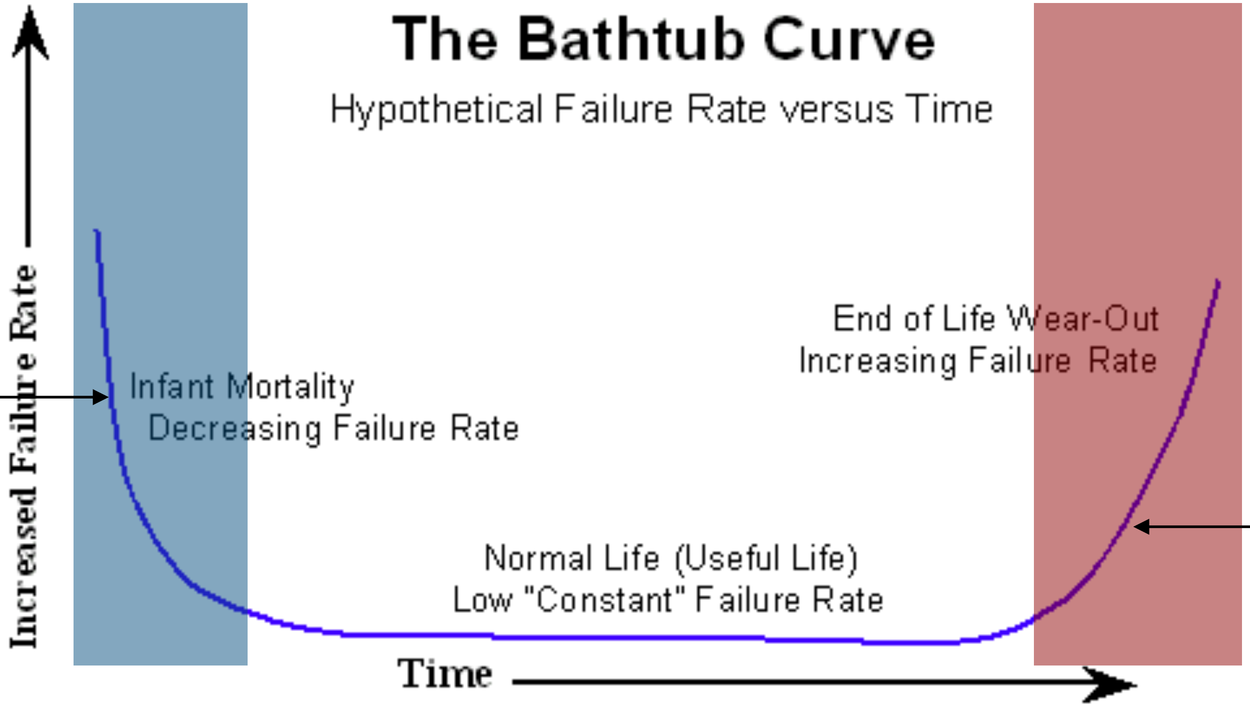
Alice ITS production progress

BUILDING MODULES

- **During production:**
  - Perform fast checks on every single module – automation
  - Provide feedback for construction
  - Classify & reject modules
  - Store results - data base

Fun fact!

	ATLAS	**CMS**
R&D parts and samples during production - possibly up to destruction	QA Quality assurance	QC Quality control
Checks of every single production part	QC Quality control	QA Quality assurance



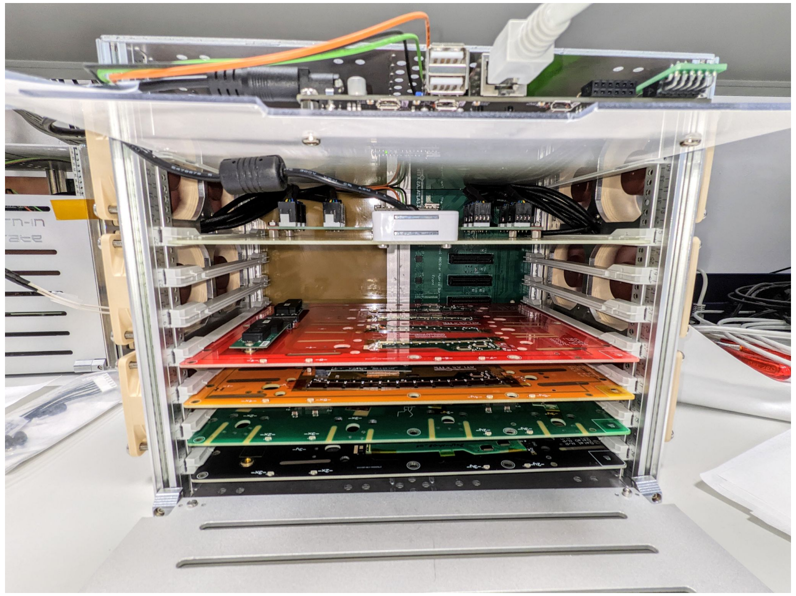
get rid of before installation in experiment

be done with experiment before this starts

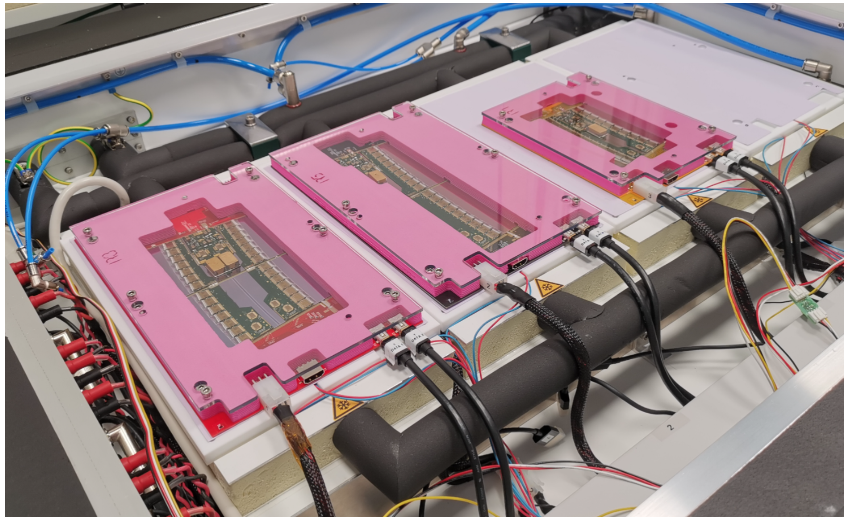
CHECKS DURING PRODUCTION

- Most checks during production are performed at room temperature
- Detectors are often operated at low temperatures (down to -45C)

- Test detectors at high and low temperatures
  - Test response to thermal cycling
- Burn-In: thermal cycling with tests at extreme temperatures
  - Trigger & identify thermal stress
  - Overcome infant mortality
  - Calibration



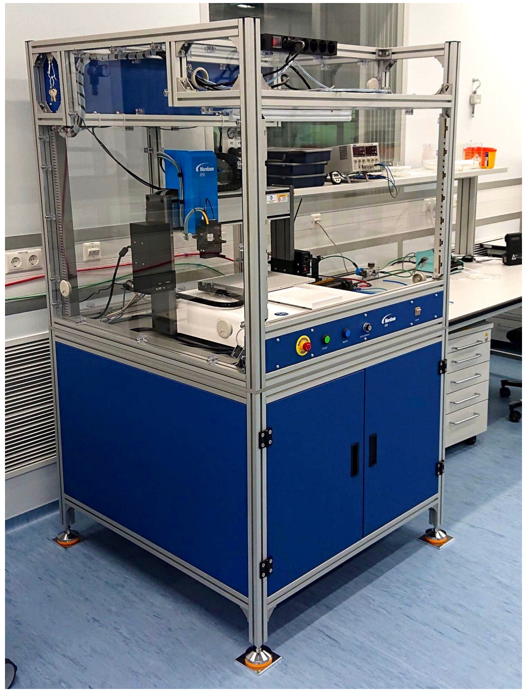
Hybrid burn-in test



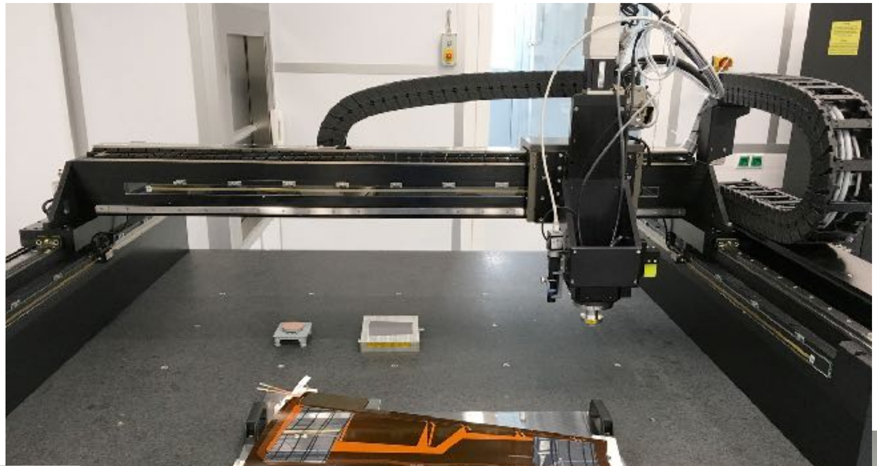
Setup for module thermal cycling - 3 modules simultaneously tested

ROBOTS

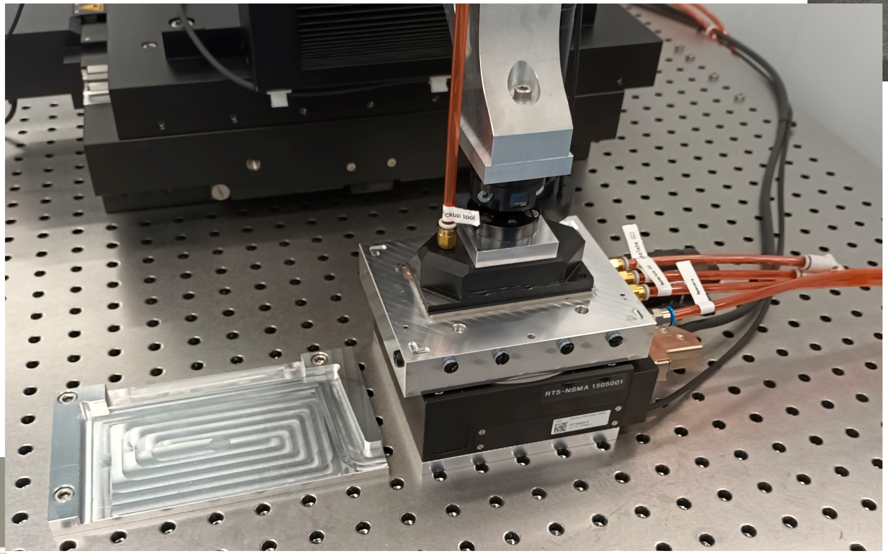
- During production need to limit manual steps
- By now all automated machines are available
- Industrial solutions
  - Wire-bonder
  - Gluing robot
- Home-made developments
  - Module loading (based on gantry)
  - Bustape testing
- Very attractive tasks for detector R&D newcomers



Gluing robots



Module gluing and placing tool (ATLAS)



Module construction robot (CMS)

Testing robot (ATLAS)

Pictures: DESY

Semi-electrical petal @ DESY

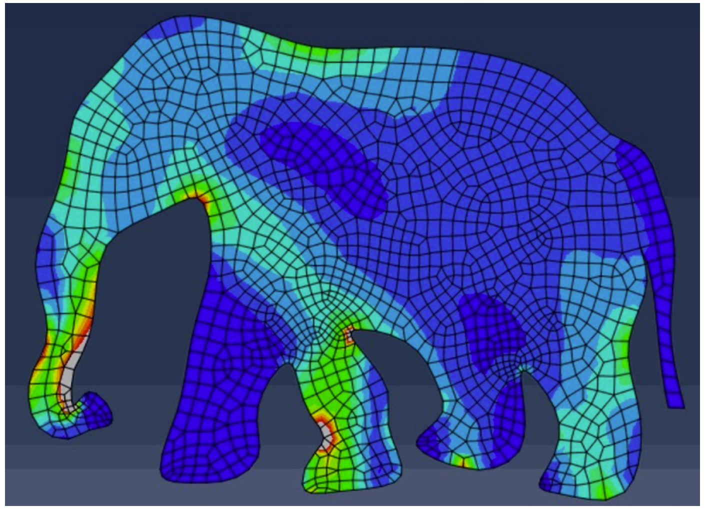
Loading of petal core 07 - back side

Video: Othmane Rifki, 2017

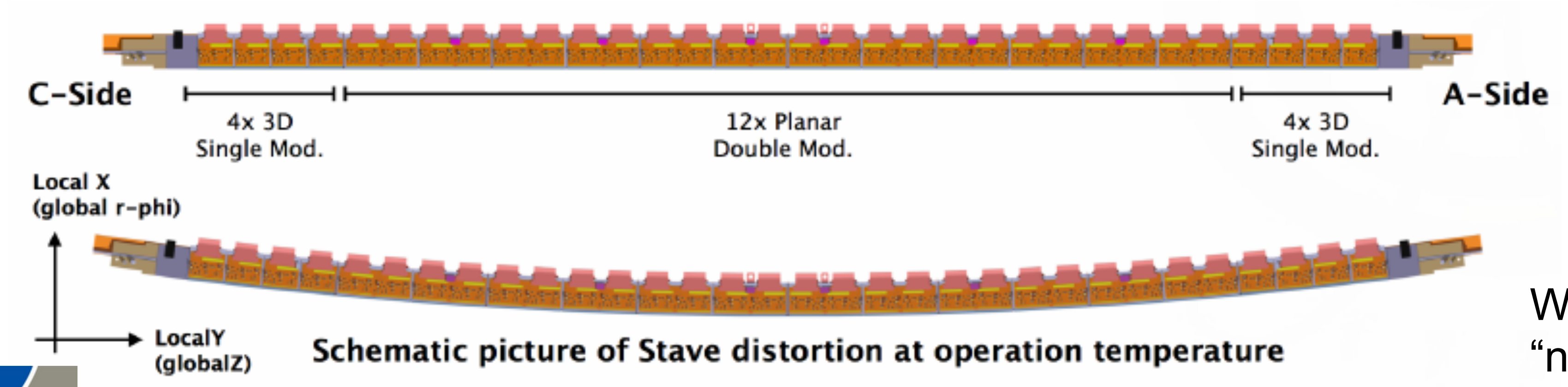
(LOCAL) SUPPORT PRODUCTION AND TESTING

SUPPORT STRUCTURE

- Sounds simple:
  - Something to put modules and cables on that keeps the active components cold and in position
- Years of engineering and design effort, because they require …
  - Incredibly high precision over large areas
  - Stability (mechanical, thermal & thermo-mechanical)
  - To be customised to module design
  - Best made without material
  - Radiation tolerance (if needed)
- To be *transportable*



Finite element analysis (FEA) vital for a good detector.



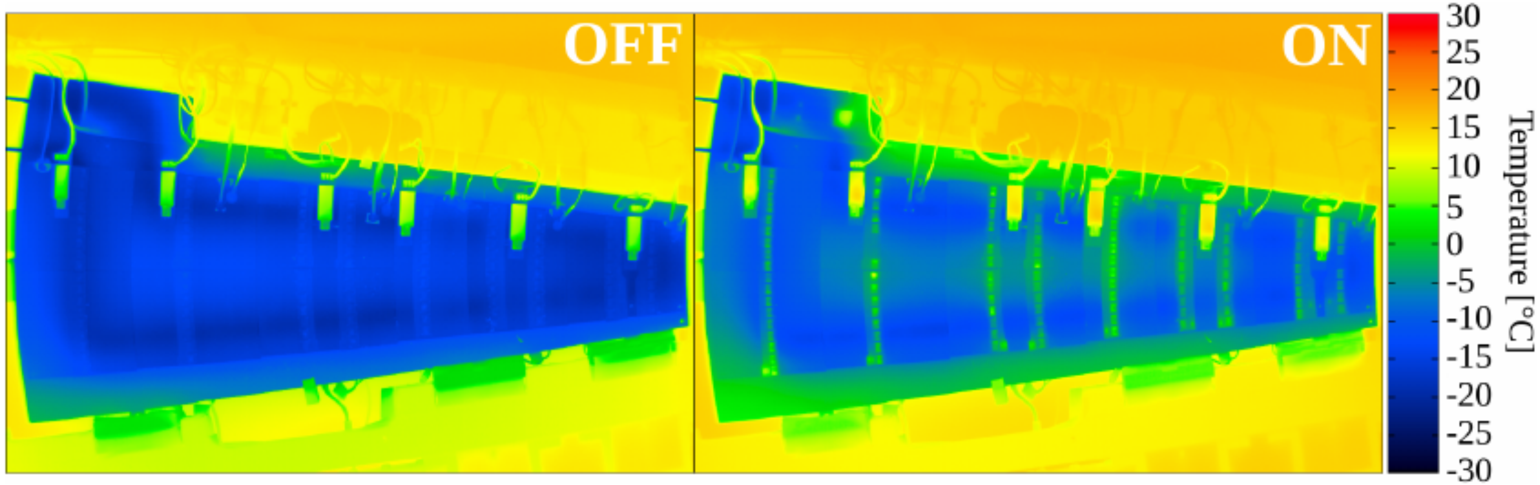
Schematic picture of Stave distortion at operation temperature

Work very often seen as "non-scientific"
- which is certainly NOT true

MORE QUALITY TESTS NEEDED

- One of the main challenges for large systems: maintain good flatness over large areas
- Measurement: e.g. via metrology arm
- Well define and design construction processes

  - QA of cooling performance: coping with heat dissipation of modules & temperature stability/homogeneity
  - Typical method: Infrared thermography



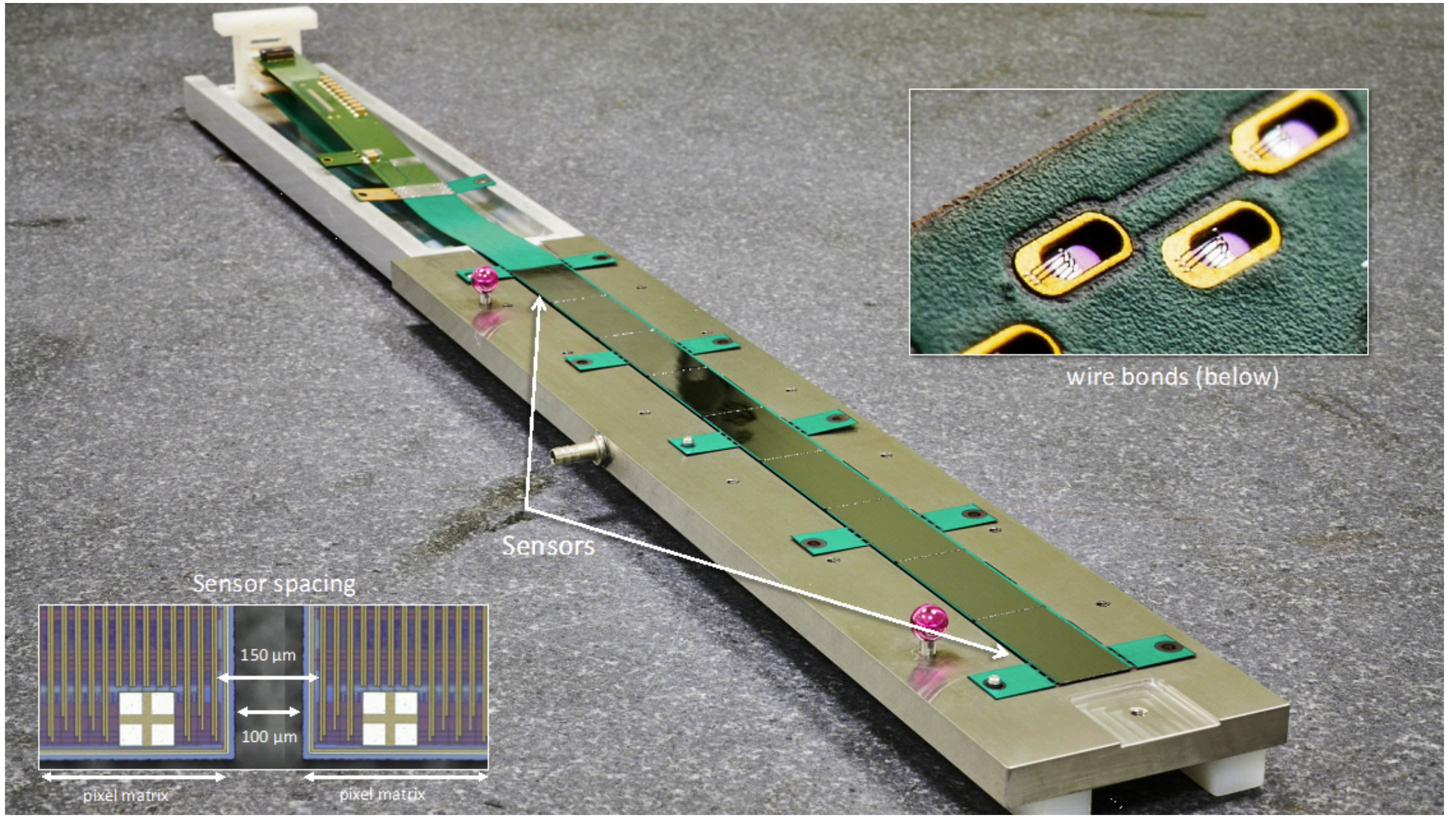
CMS Outer Tracker

“INTEGRATION”

Maybe most used word for different steps

MODULE ONTO LOCAL SUPPORT

- Depending on size and amount of modules, a manual approach is probably not recommendable
- Many tools to be designed
- Precision placement needed
- Modules need to be attached (glue)
- Possibly use of robots!

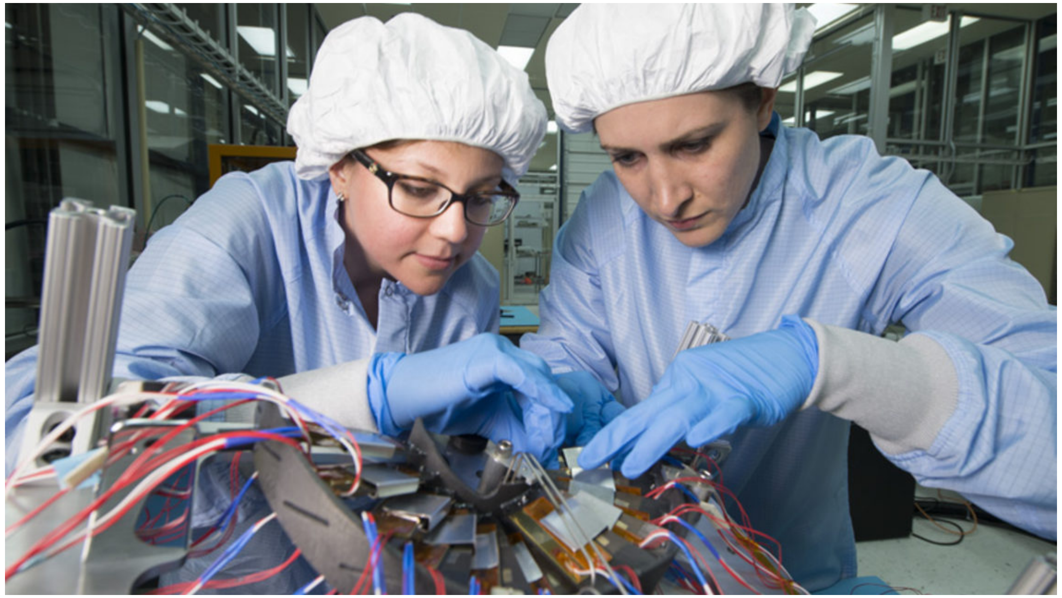


Ladder of ALICE ITS Pixel

DETECTOR INTEGRATION

- Integration of detector modules & support structure
  - Extremely delicate task
  - Handling many certified functional components at the same time
  - Unwieldy in case of small or large systems (either delicate and compact or hard to reach)

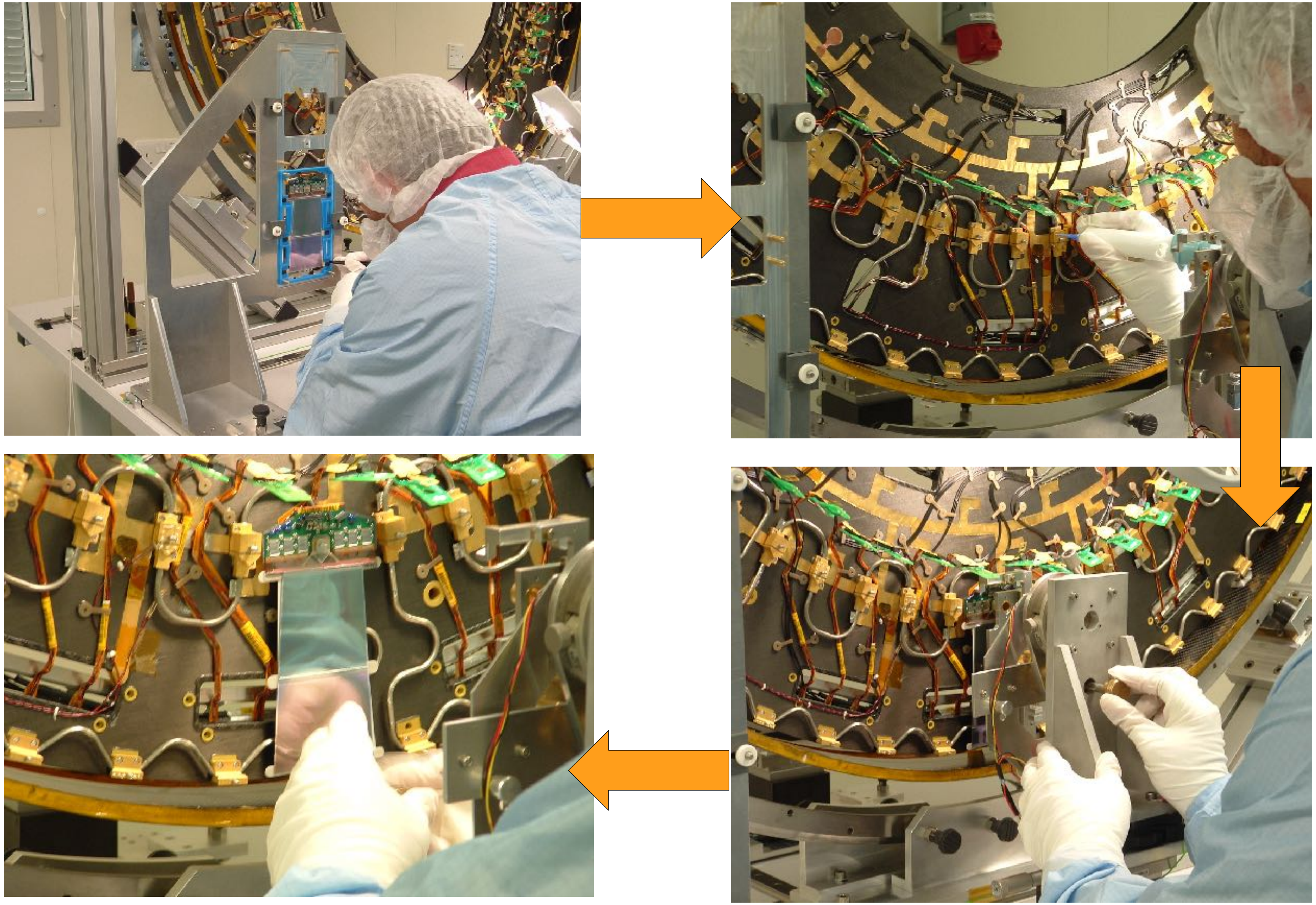
➔ Proper tooling required!



CMS Pixel Phase I

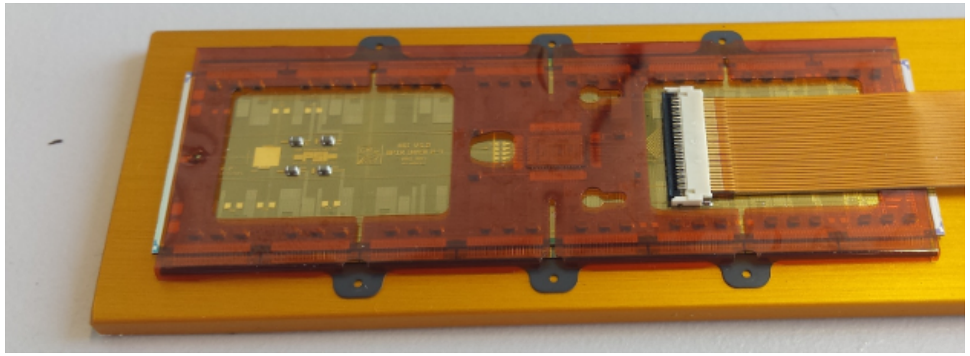
LHCb Velo

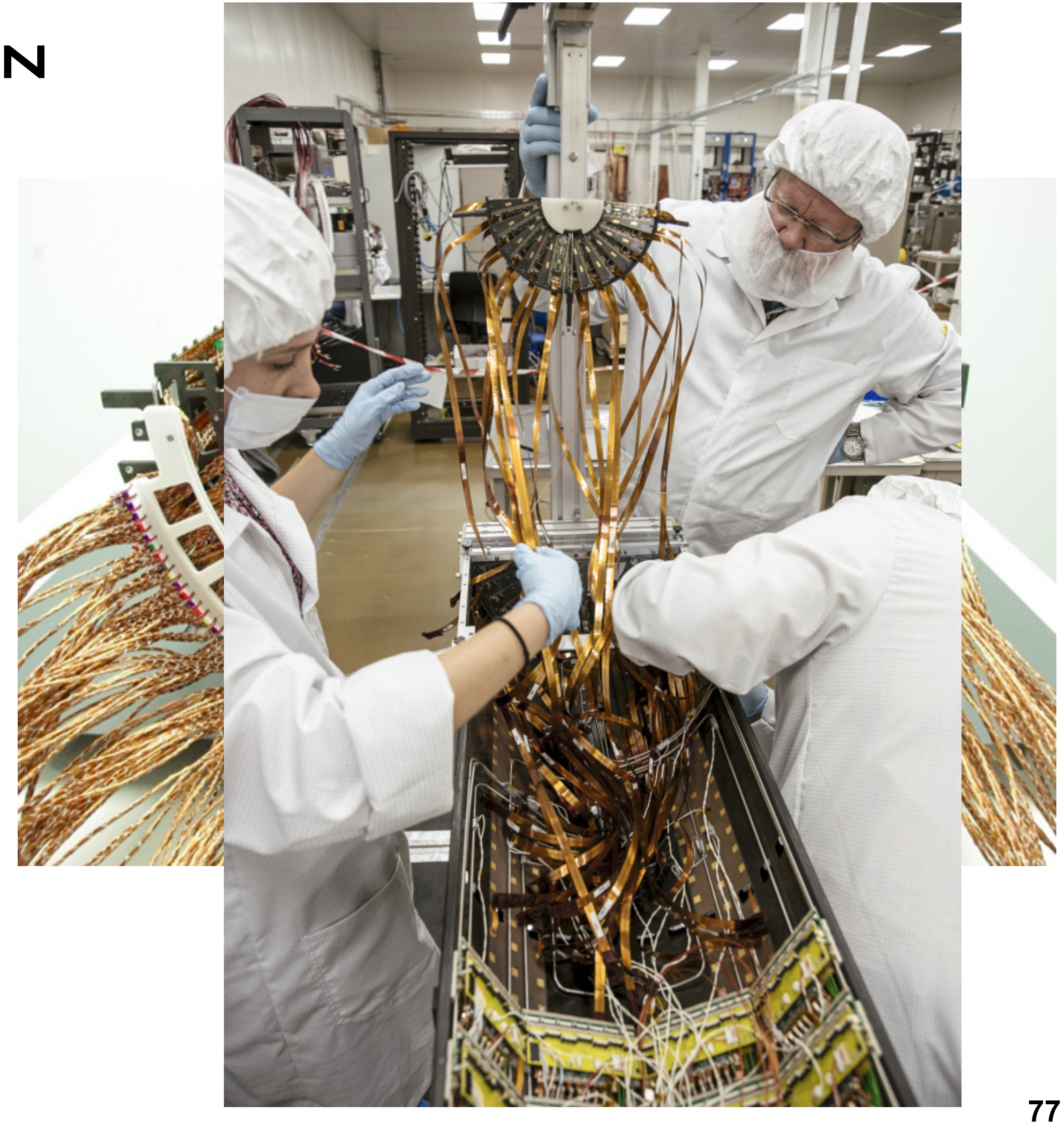
FROM MODULE TO DETECTOR



DETECTOR INTEGRATION

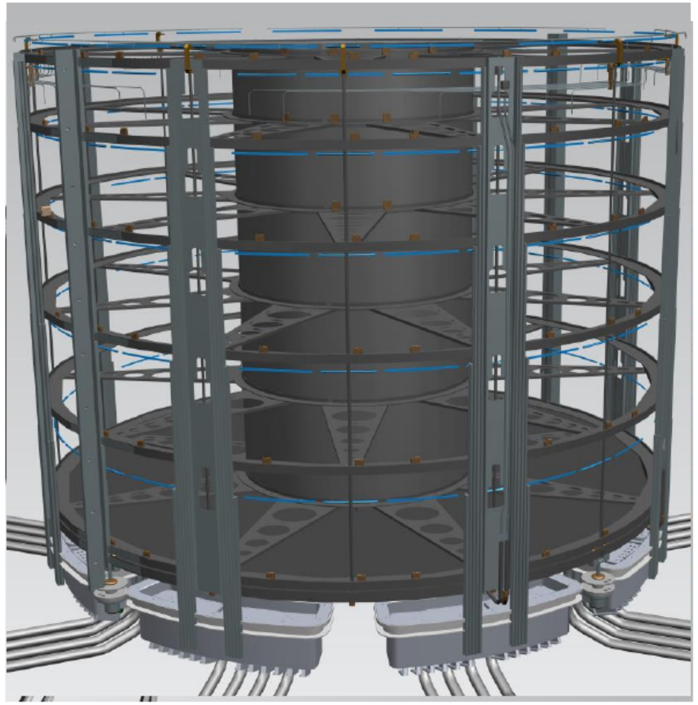
- **CMS Phase I Pixel Barrel**
- Half barrel: 592 modules,
  ~ 1 year of module production
- Delicate placing & mounting of modules
- Always label your cables …

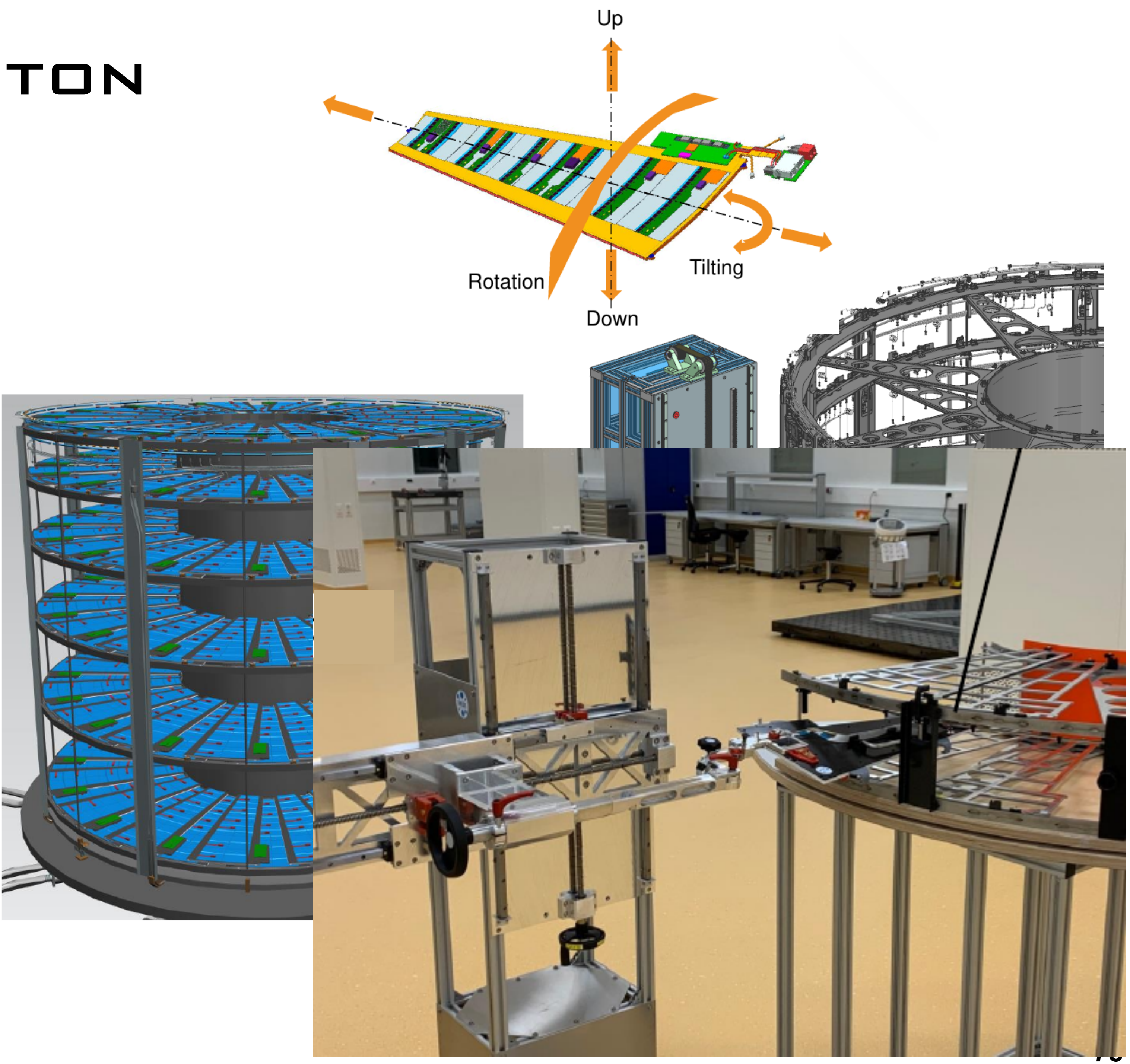




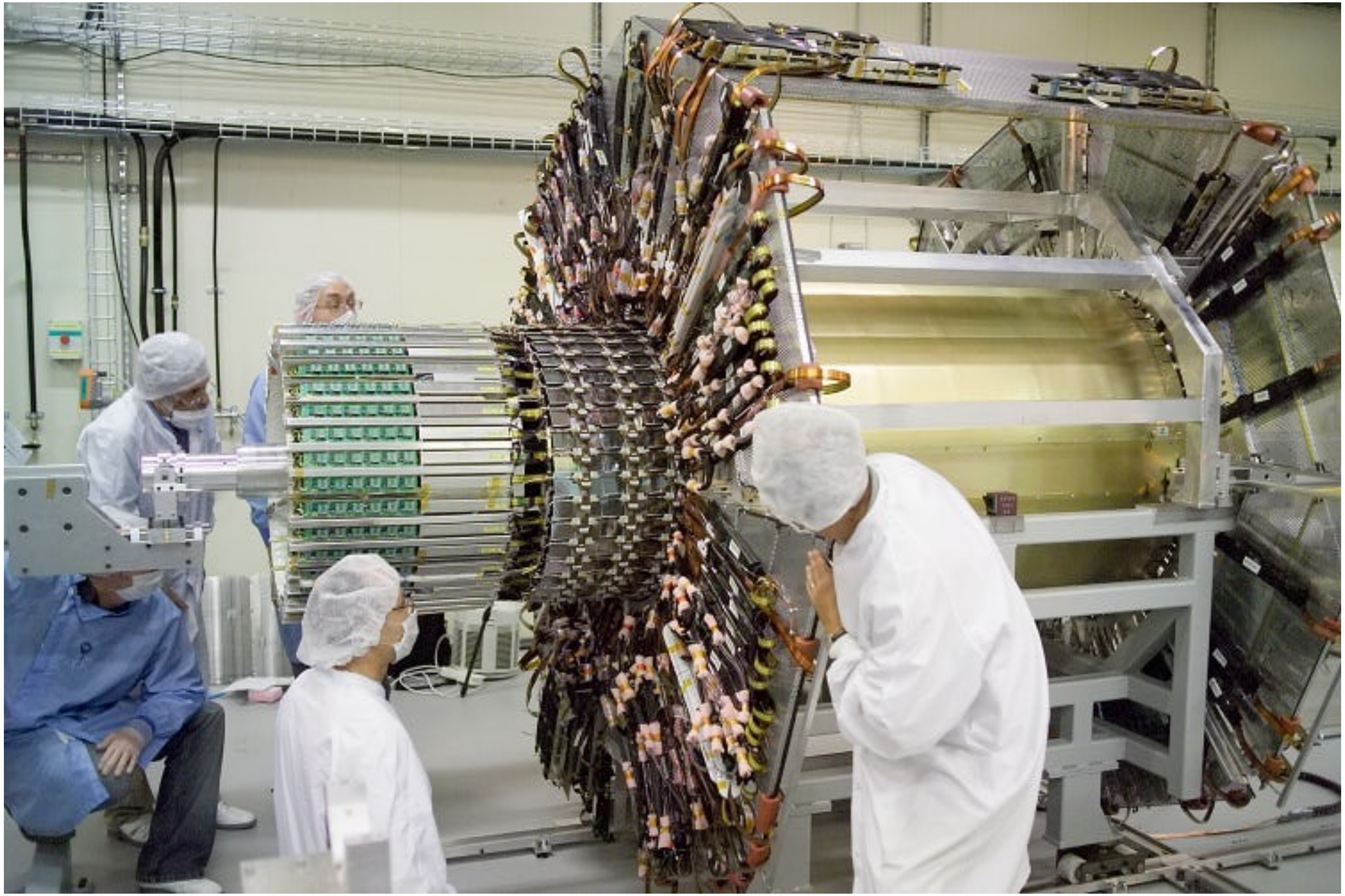
FILLING THE SKELETON

- Example: ATLAS ITk Strips
- Tools designed to do all steps
- Here: tool to insert petals into skeleton





SILICON TRACKER (SCT)



Insertion of the 3rd cylinder (out of the four) into the barrel SCT

TRANSPORTATION

GETTING (LARGER) PARTS TO DESTINATION

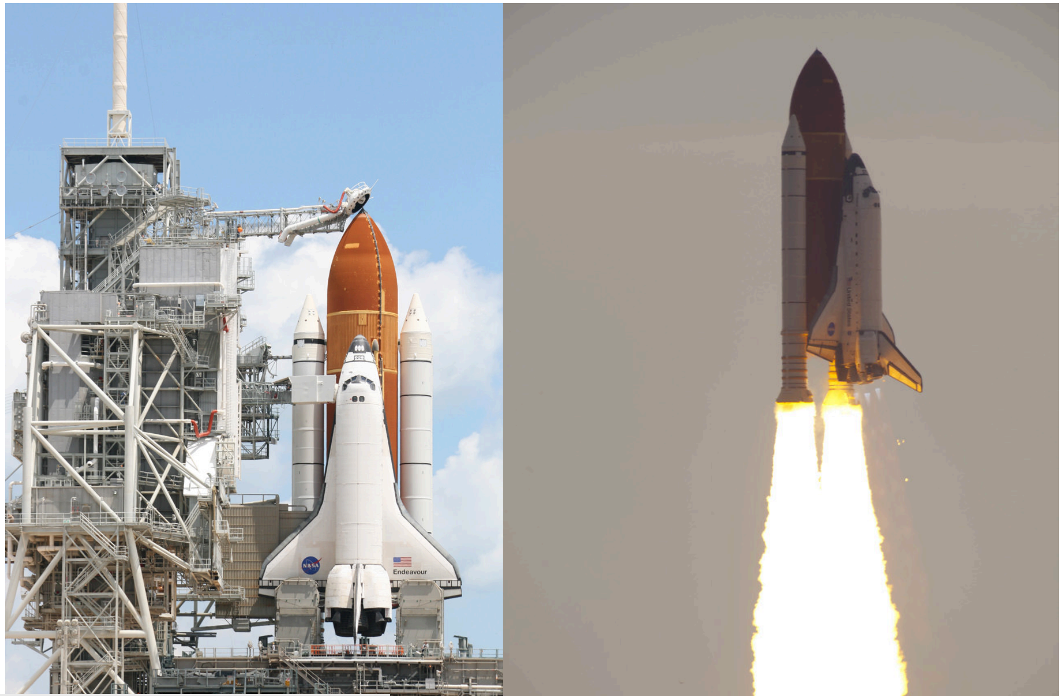
- Distributed construction of modules, detectors & components requires transportation
- Sensors, Chips, Cables, Connectors, ….: parcel shipment
- Modules: parcel shipment or custom transportation
  - Mounted on carriers
- Full detectors: very special needs ….

Paul Schütze with 300 CMS Phase I Pixel Detector Modules (selfie)

Belle II PXD2 flying business class

Completely Different Requirements ....

- AMS experiment needed a rocket to get inserted
- Acceleration during start/ landing up to 9g



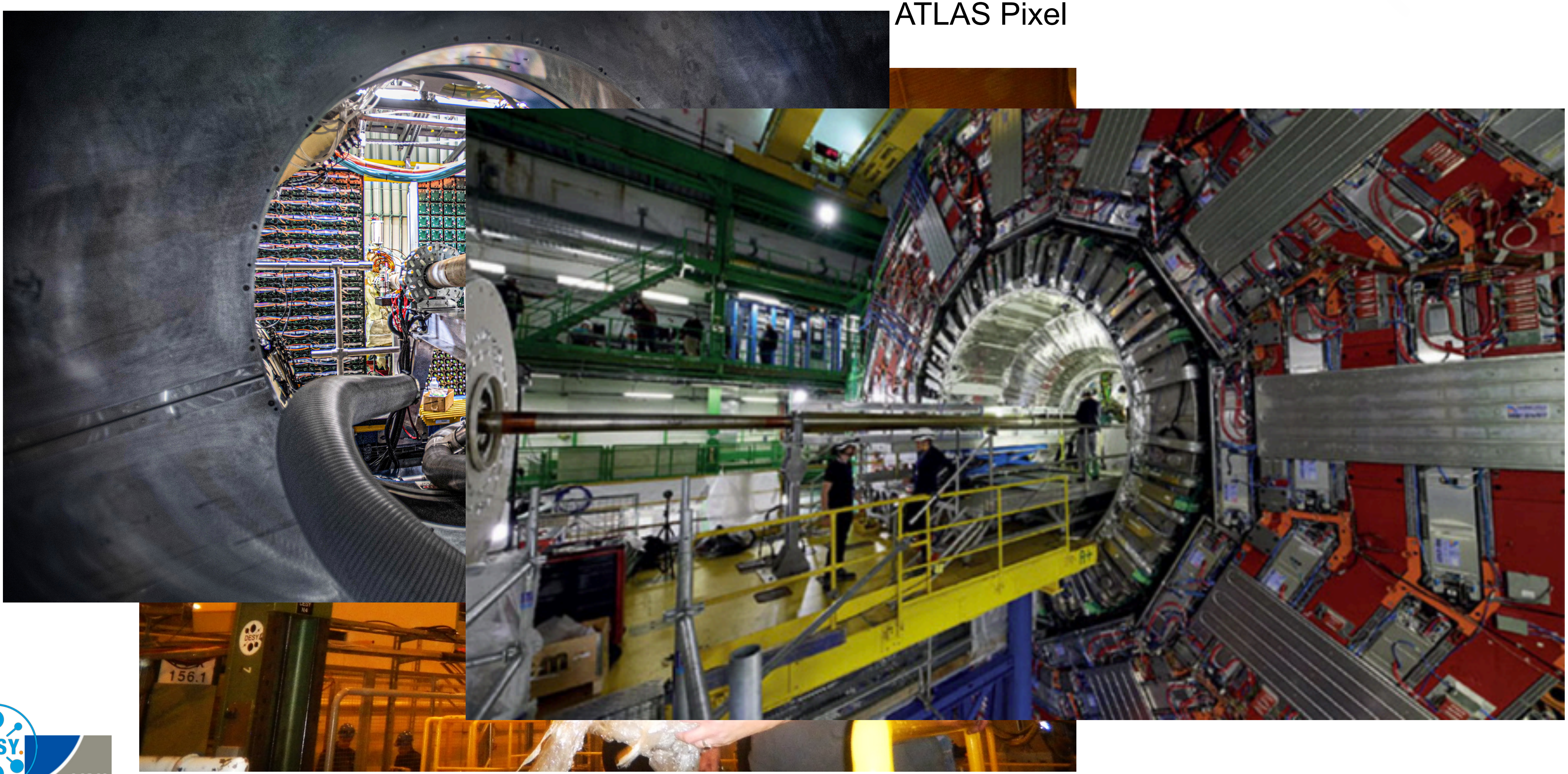
On ground transport requirements <2g due to ramped-up magnet

GETTING THE DETECTOR SAFELY TO EXPERIMENT

INSTALLATION

Big Tools are needed!!

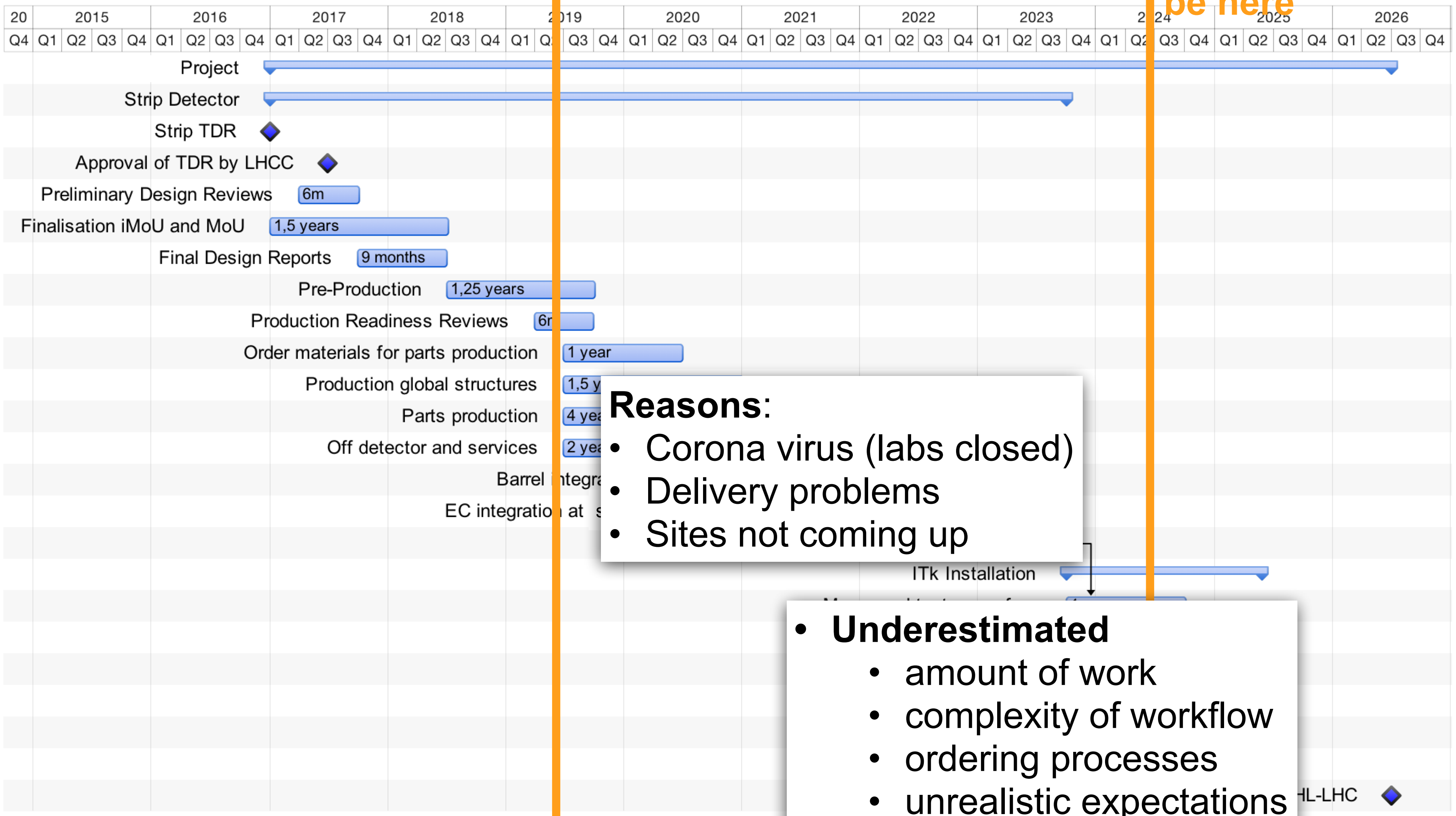
Nice video:
https://www.youtube.com/watch?v=NEpfljUk9sk
ATLAS Pixel



THE SCHEDULE ….

An Example - Unknown Experiment

Schedule Fall 2016



are somewhere here

should be here

Reasons:
- Corona virus (labs closed)
- Delivery problems
- Sites not coming up

- **Underestimated**
  - amount of work
  - complexity of workflow
  - ordering processes
  - unrealistic expectations
  - technical problems ..

THE PROBLEMS ....

UNEXPECTED IRRADIATION FAILURE

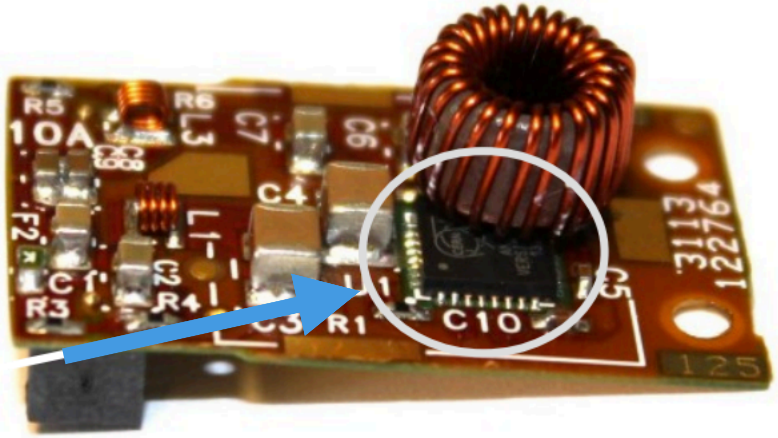
CMS DC-DC CONVERTER

during running

- During 2017 new pixel detector installed in CMS with DC-DC converter for powering
  - After few months: ~5% of deployed converters failed.
  - During winter shutdown: another ~35% of converters were found partially damaged

DC-DC in a nutshell:
transfer energy into detector with higher voltage/lower current and transform just before the load to operation voltage

- Extremely difficult to identify problem - over months multiple tests conducted
- Found strong correlation between radiation background and failures, as well as the functional sequence necessary for the damage to happen.
  - Damage caused by TID radiation damage opening a source-drain leakage current in **one** transistor in Feast2.1 chip
  - High-voltage transistors can not be designed in an enclosed layout to prevent this problem



Feast2

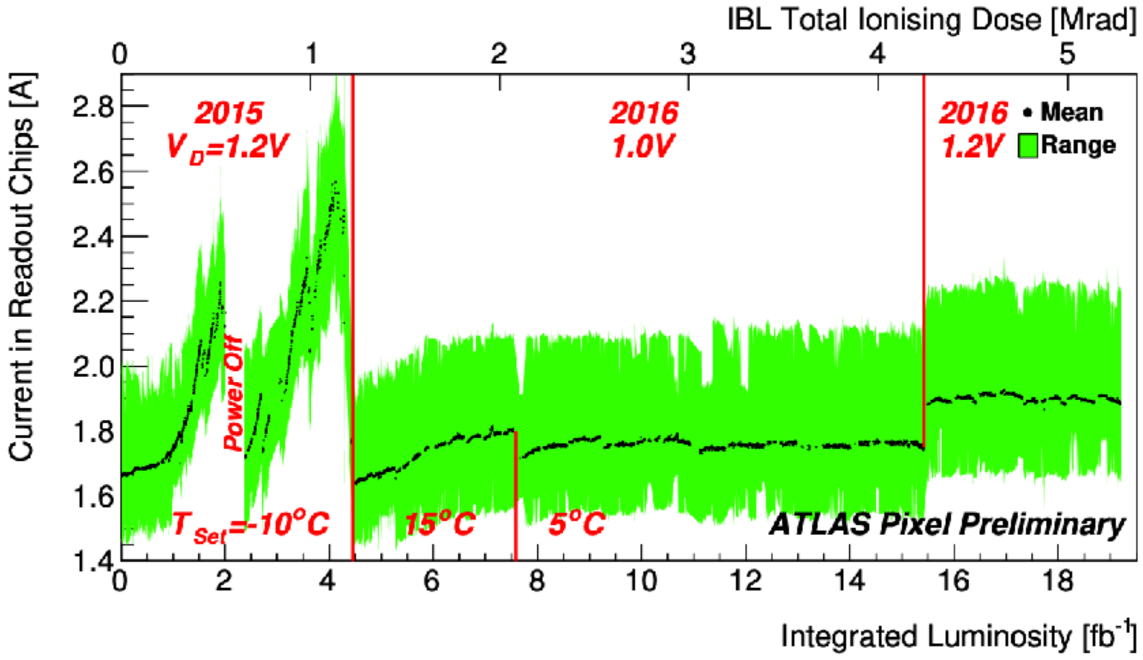
Consequences for operation
- lower input voltage helps
- stop disabling the output

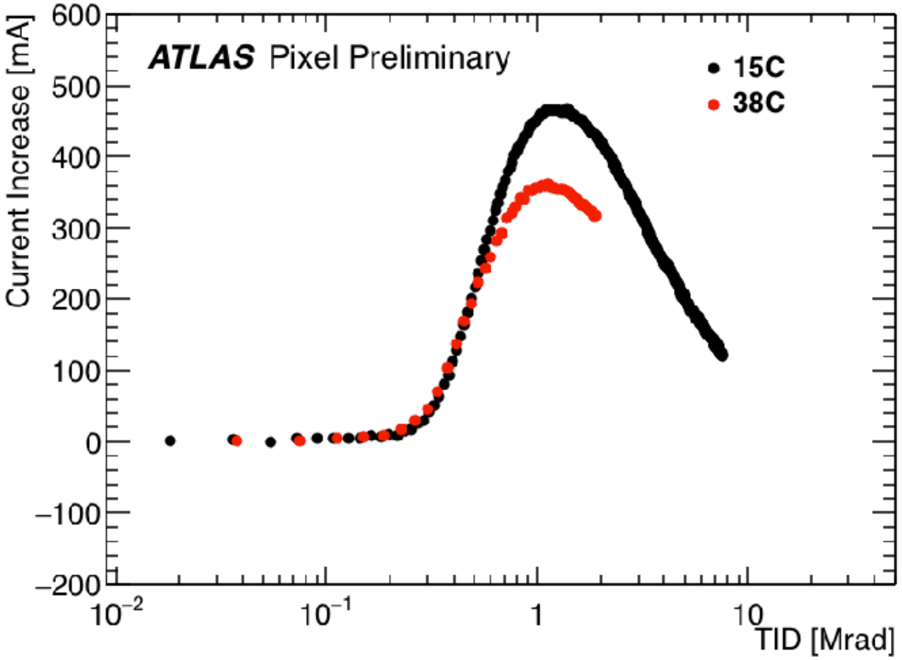
https://project-dcdc.web.cern.ch/project-dcdc/public/Documents/ExecutiveSummary2018.pdf
https://instrumentationseminar.desy.de/sites2009/site_instrumentationseminar/content/e70397/e282395/e287407/20190614_pixelphase1JIS.pdf

ATLAS IBL TID Bump

during running

- Steep increase in power consumption of IBL during operation increasing the temperature
- Effect of total ionising dose on front-end chip FE-I4B
- Caused by the effect of TID on NMOS transistors:
  - Leakage current was induced by positive charge trapped in the bulk of the shallow trench isolation (STI)
  - Temperature and voltage depending





Mitigation plan:

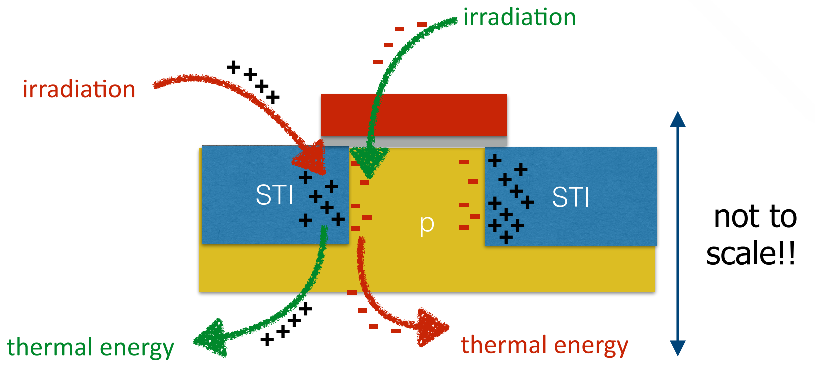
- Operating temperature was increased from −10 ◦C to and 10 ◦C then decreased to 5 ◦C.
- Digital supply-voltage was decreased to from 1.2 V 1.0 V until TID approached more than 4 MRad.

TID BUMP

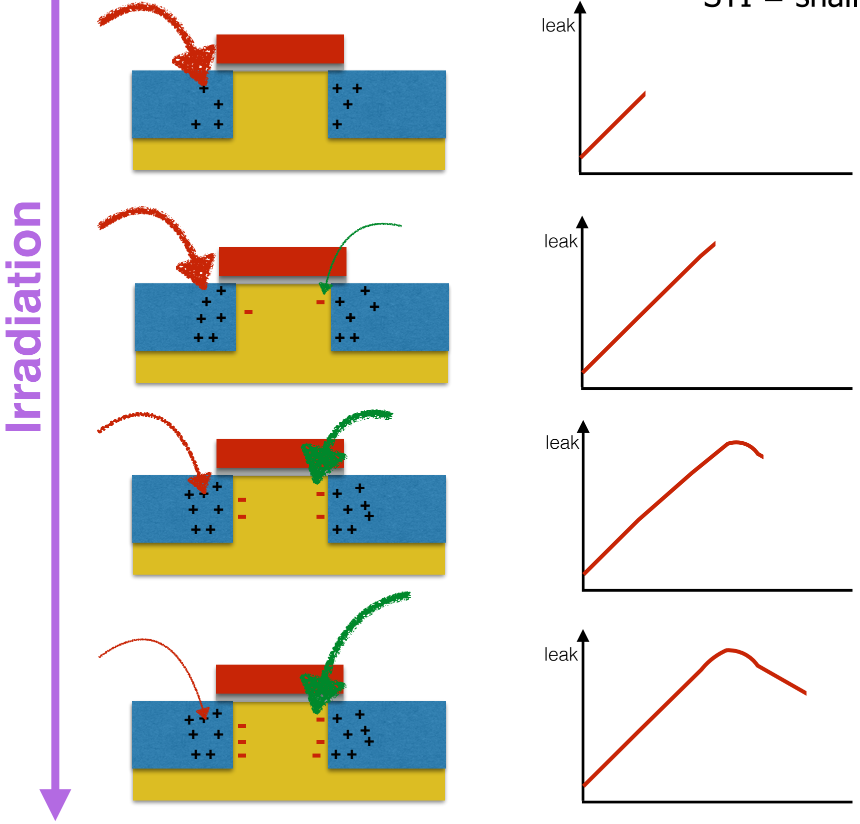
Surface effects: Generation of charge traps due to ionizing energy loss (Total ionising dose, TID) **(main problem for electronics).**

- The leakage current is the sum of different mechanisms involving:
  - the creation/trapping of charge (by radiation)
  - its passivation/de-trapping (by thermal excitation)
- These phenomena are dose rate and temperature dependent!

- Charge trapped in the STI oxide
  - +Q charge
  - Fast creation
  - Annealing already at T_{amb}
- Interface states at STI-Silicon interface
  - -Q for NMOS, +Q for PMOS
  - Slow creation
  - Annealing starts at 80-100C



STI = shallow trench interface

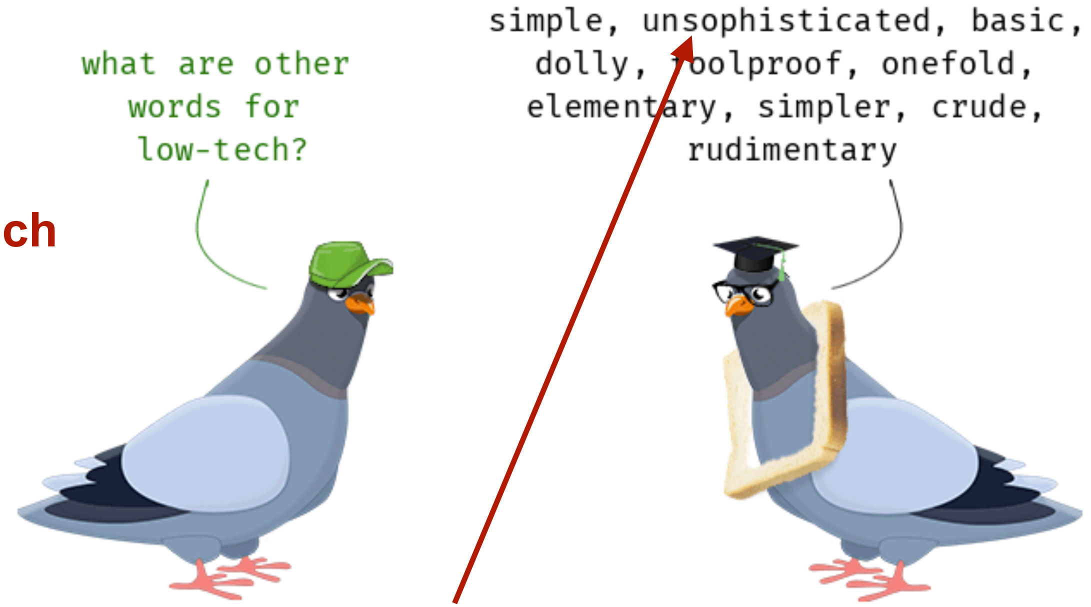


“LOW TECH” FAILURES

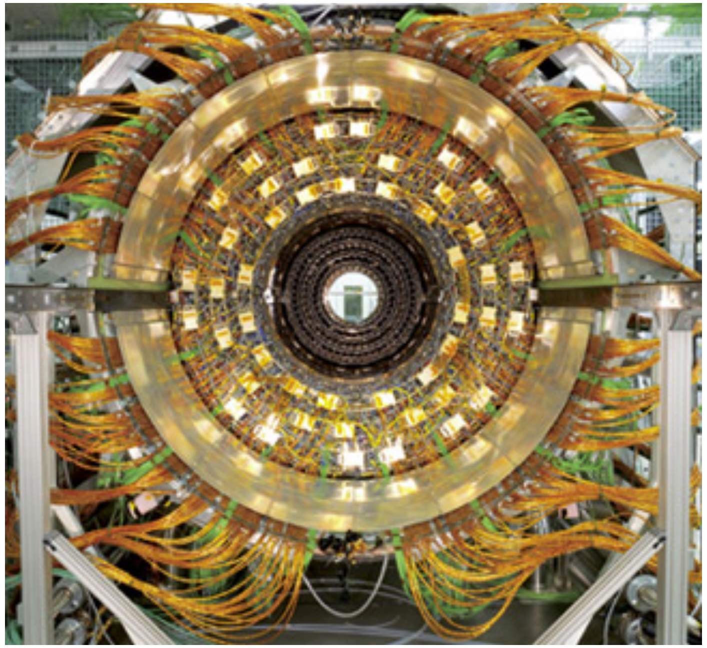
WHAT IS “LOW” TECH ?

- In particle physics experiments almost everything is **high tech**
  - Need extreme reliability
  - Radiation tolerance
  - Precision
  - Mostly running longer than originally planned

- However - some areas considered as “low tech” and people (and funding agencies) don’t like to invest research money into those areas
  - Cables for powering
  - Power plants
  - Cooling
  - Data transfer (optical and electrical)
  - Non sensitive materials (mechanics)
  - Glues
  - …..



For particle physics experiments this is not true !

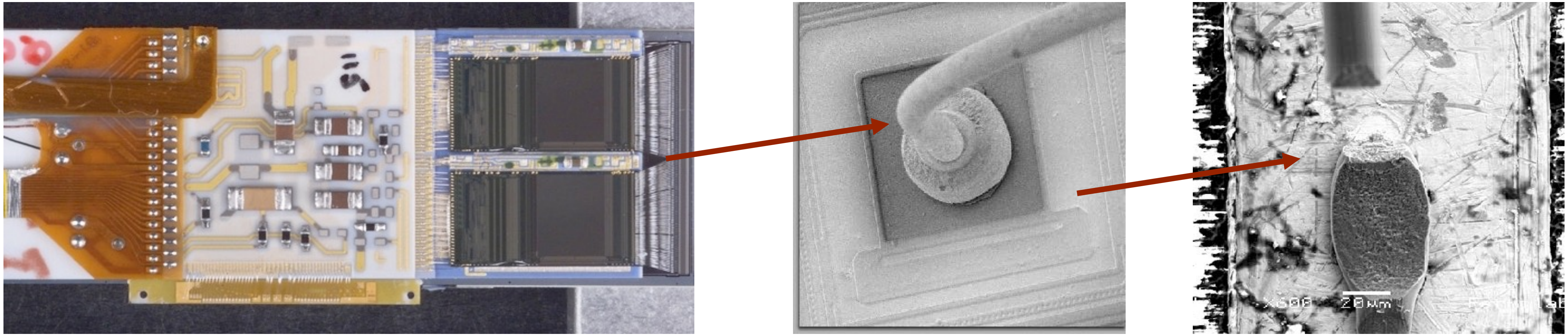


WIRE-BONDS AND WIRE BREAKAGE

Problems with Wire Bonds (CDF,

during running

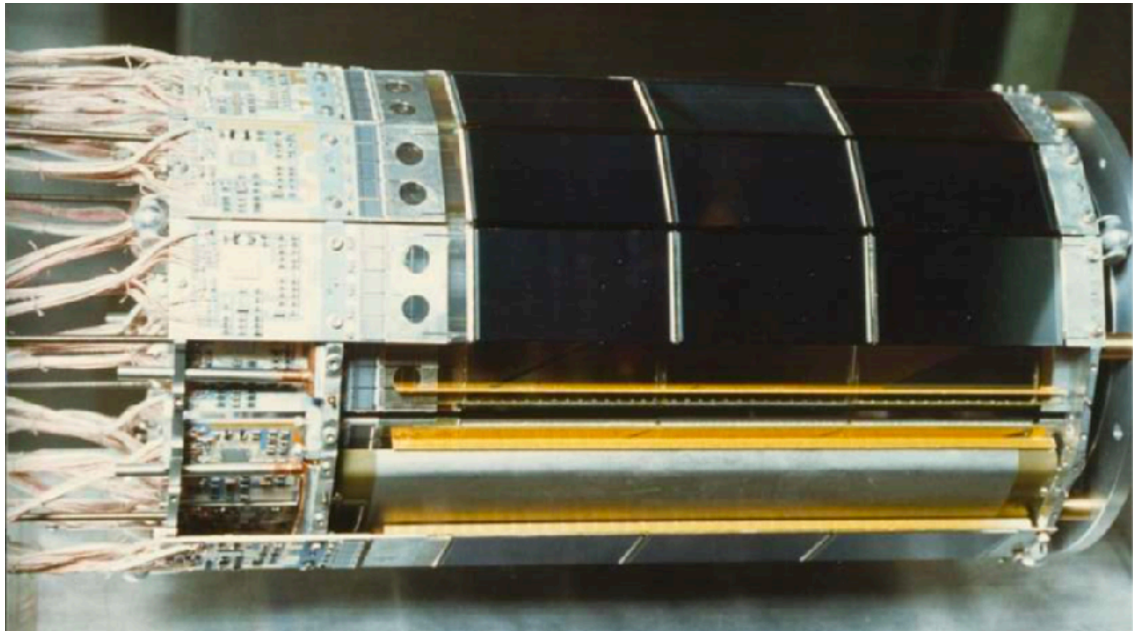
- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- Observation: During synchronous readout conditions, loss of modules (no data, Drop in current)



- Tests revealed:
  - Bonds start moving due to Lorentz Force in magnetic field
  - Wire resonance in the 20 kHz range
  - Current is highest during data readout
  - Already a few kicks are enough to get the bond excited

Implemented “Ghostbuster” system which avoids long phases with same readout frequency

OPAL MVD 1994



- OPAL MVD ran for a short while without cooling water flow.
- Temperature of the detector rose to **over 100°C.**
  - Most of the modules to fail or to be partially damaged.

- Chain of problem causing damage:
  - MVD expert modified the control/monitoring software between consecutive data taking runs.
  - Inserted bug which stopped software in a state with cooling water off but with the low voltage power on.
  - Stopped software also prevented the monitoring of the temperature from functioning
  - Should have been prevented by additional interlock but that was also disabled….

Lucky outcome:

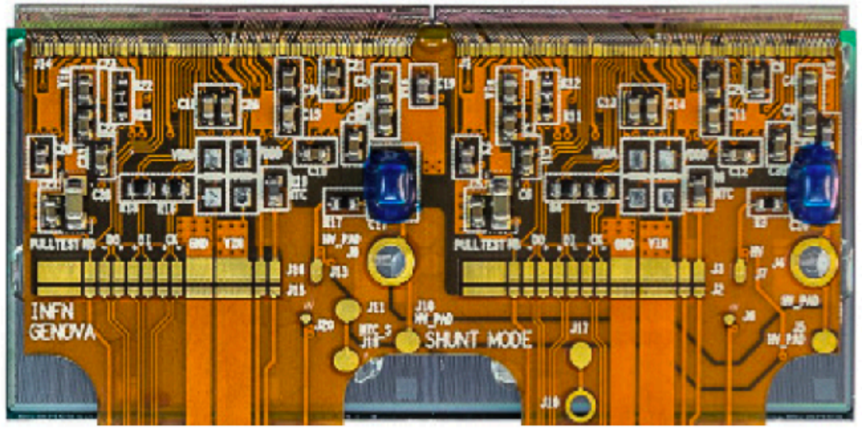
- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

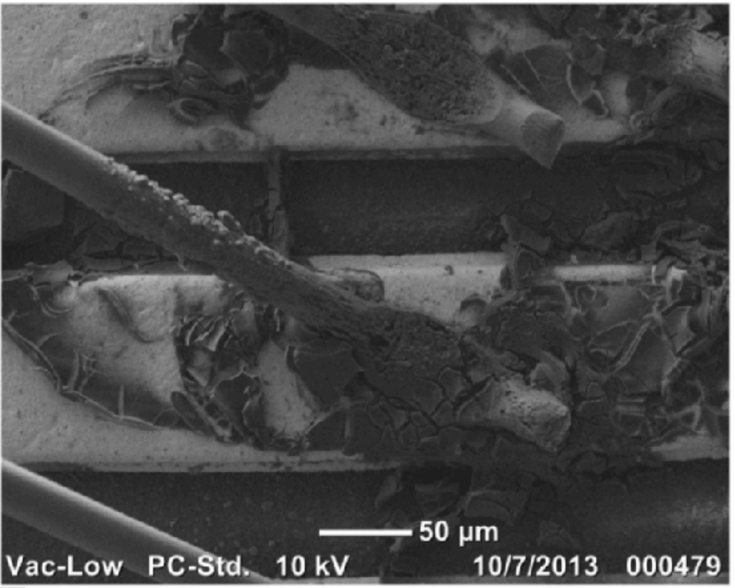
Mitigation plan:

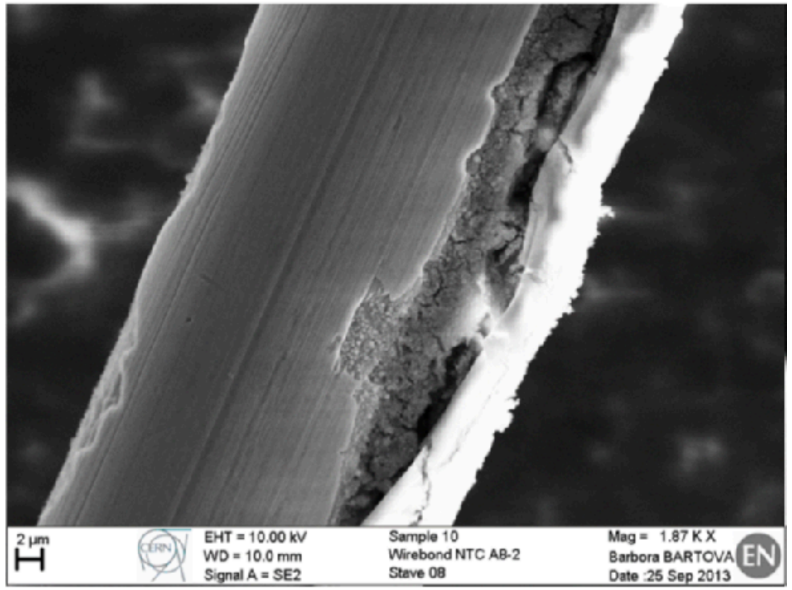
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

ATLAS IBL - Wire Bond Corrosion

- Additional pixel layer for ATLAS installed in 2015
- Five months **before** installation: corrosion residues observed at wire-bonds after cold tests (-25 C)
  - Severe damage of many wire-bonds
- Residue showed traces of chlorine: catalyst of a reaction between Aluminium (wire-bonds) and H_2O (in air)
- Origin of chlorine in system never fully understood







- Emergency repair and additional staves from spare parts

during production

https://indico.cern.ch/event/435798/contributions/1074098/attachments/1134177/1622192/encapsulation_study_-_Oxford.pdf

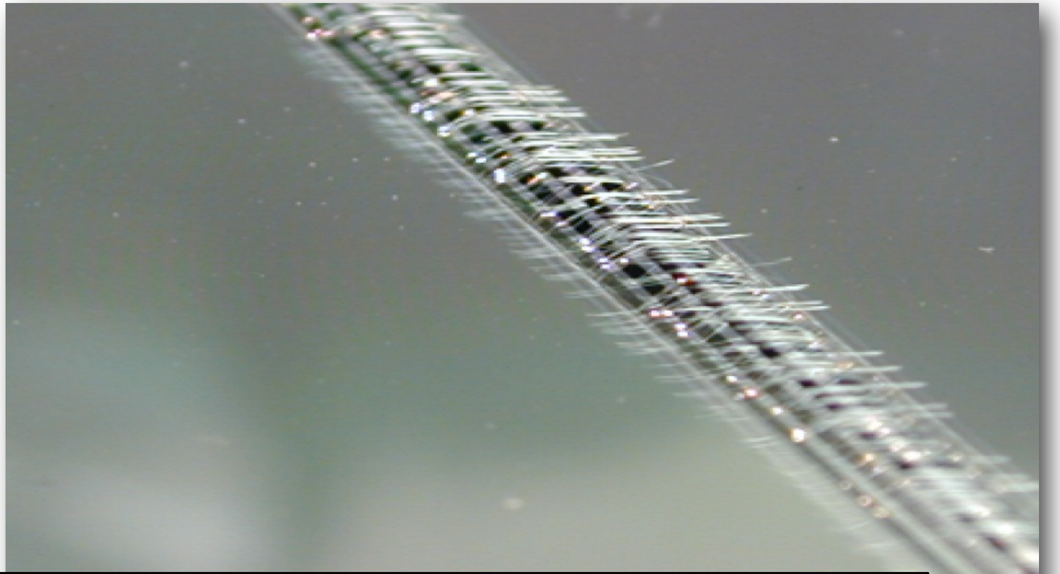
MORE WIRE BOND WRECKAGE

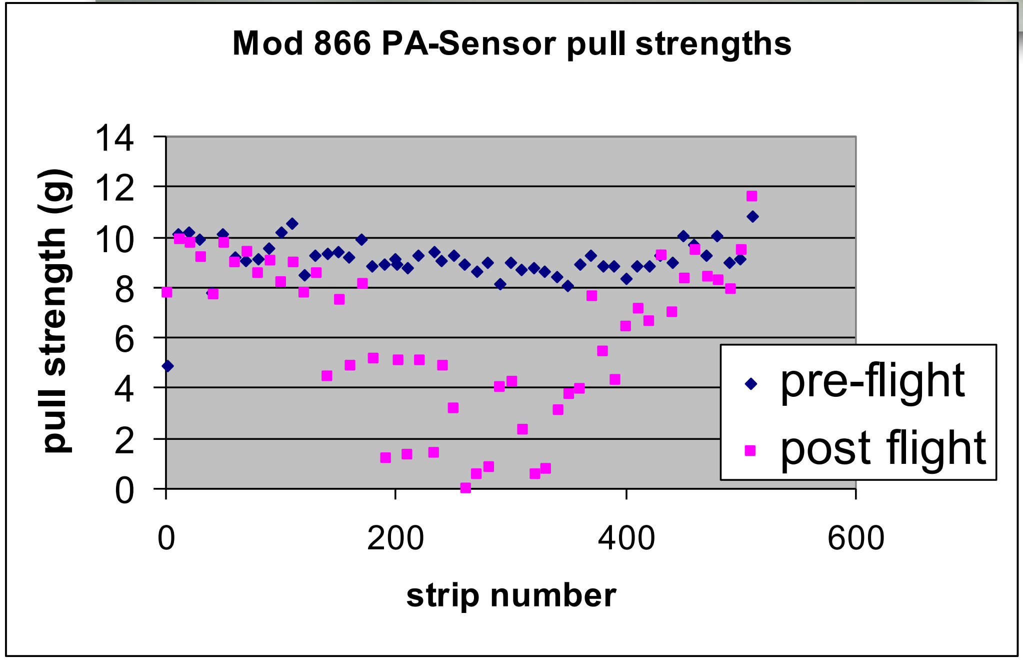
- During CMS strip tracker production quality assurance applied before and after transport
  - Quality of wires is tested by pull tests (measured in g)

- Wire bonds were weaker after transport with plane
- Random 3.4 g NASA vibration test could reproduce same problem

- Problem observed during production -> improved by adding a glue layer
- No further problems during production

during production

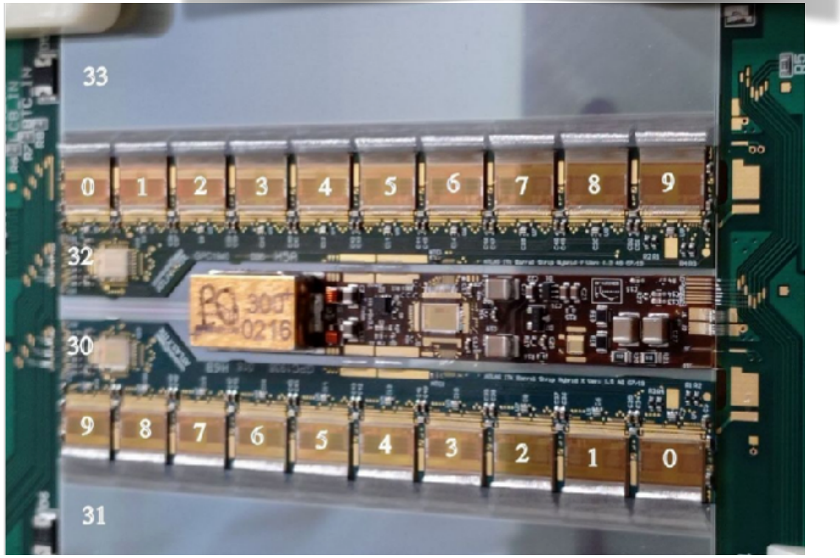




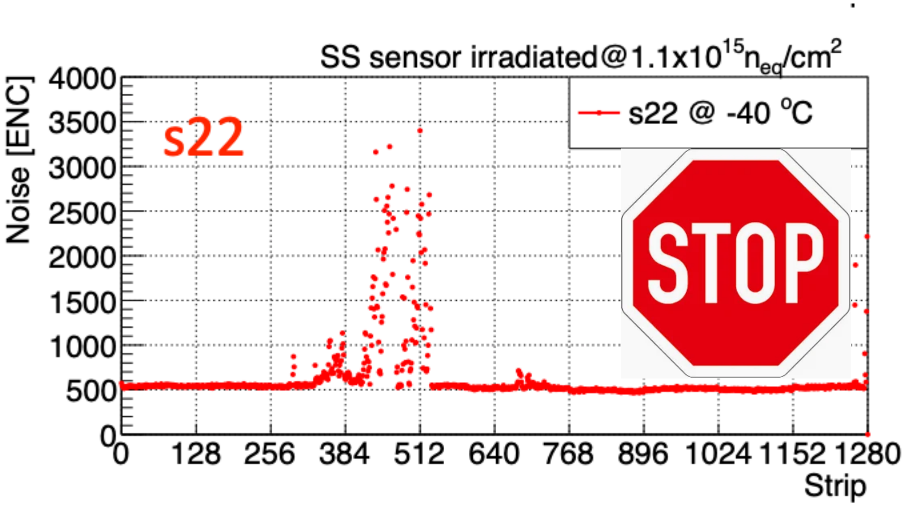
CURRENT (UNSOLVED) ONES

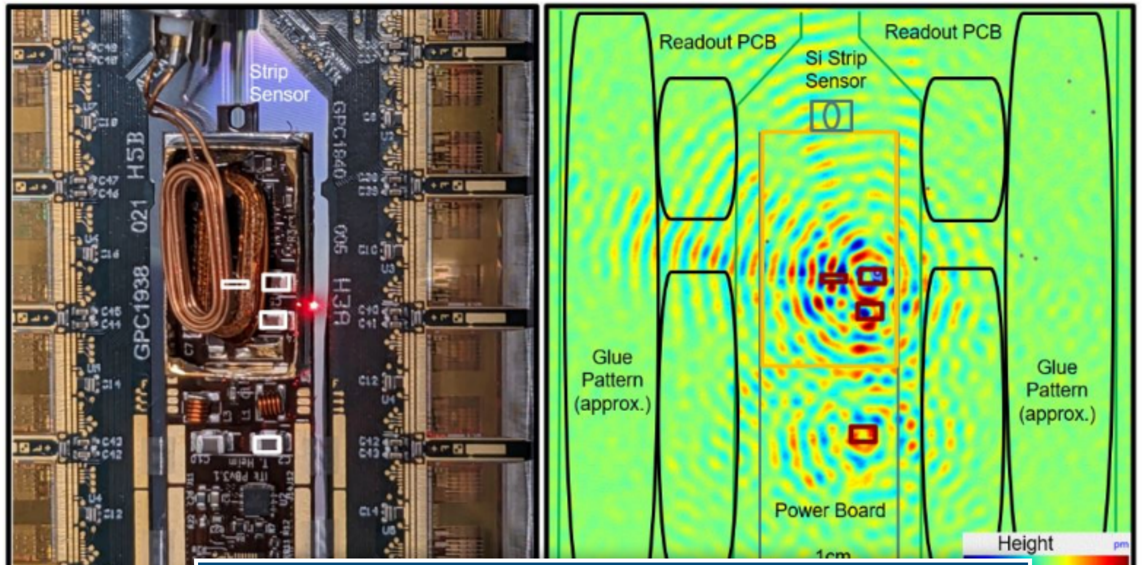
ATLAS ITk Strips: Cold Noise

shortly before production



- Hybrids for readout and power board directly on silicon strip sensors
- Clusters of very noisy channels observed at operating temperatures of around -35 ºC
- Caused by mechanical vibrations from capacitors of powerboard inducing electrical noise
  - Not observed in EC modules
- Studies on new module-building glue show no cold noise for long-strip barrel modules

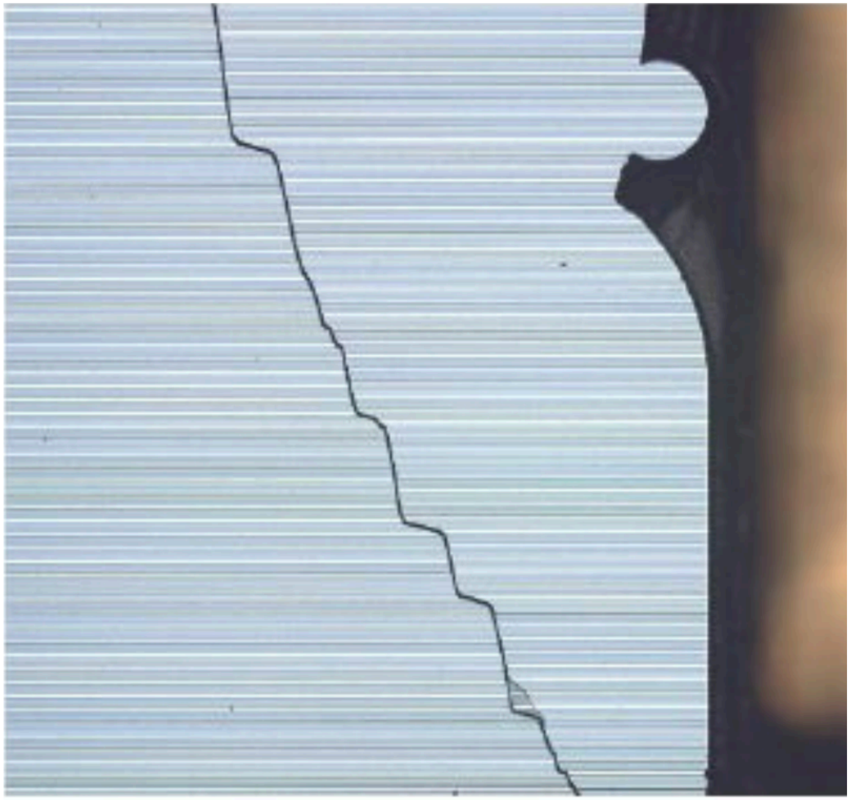




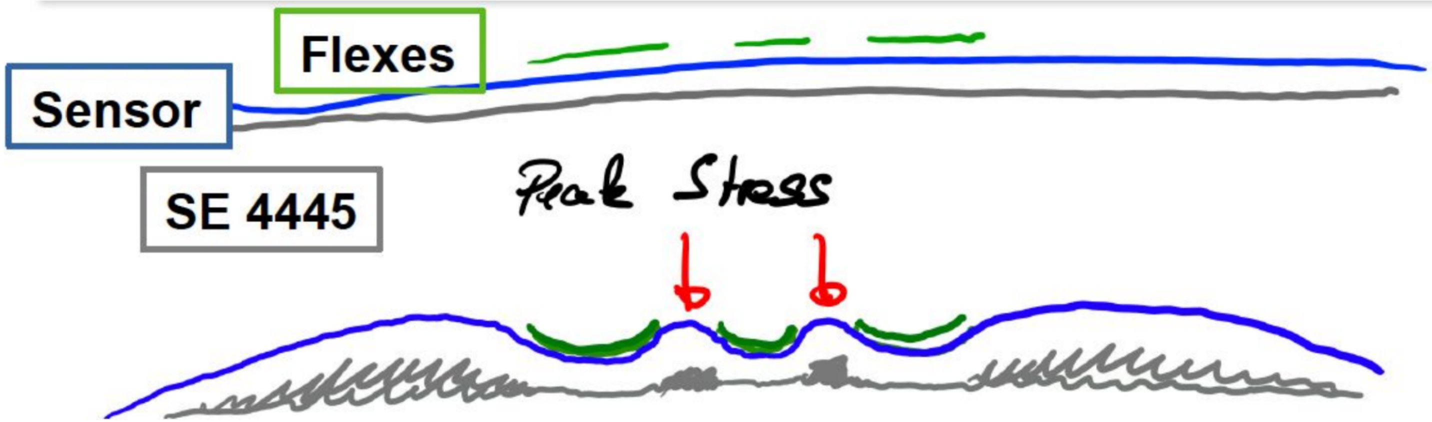
Exact effect not yet understood

SAME DETECTOR: MODULE CRACKING

shortly before production



- Fraction of modules loaded on support structures show early breakdown (< 500 V), and show fractures when cycled to very cold temperatures
- Explained as peak stress, induced by CTE mismatching
- Investigated solutions (guided by simulations):
  - Change of loading glue
  - Increase of gap width between flexes
  - Addition of “interposer” layer



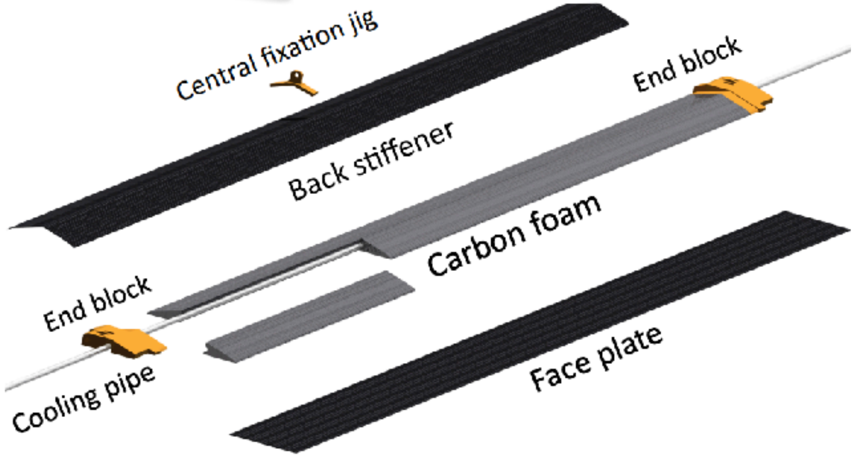
Qualitative understanding of origin of module cracking

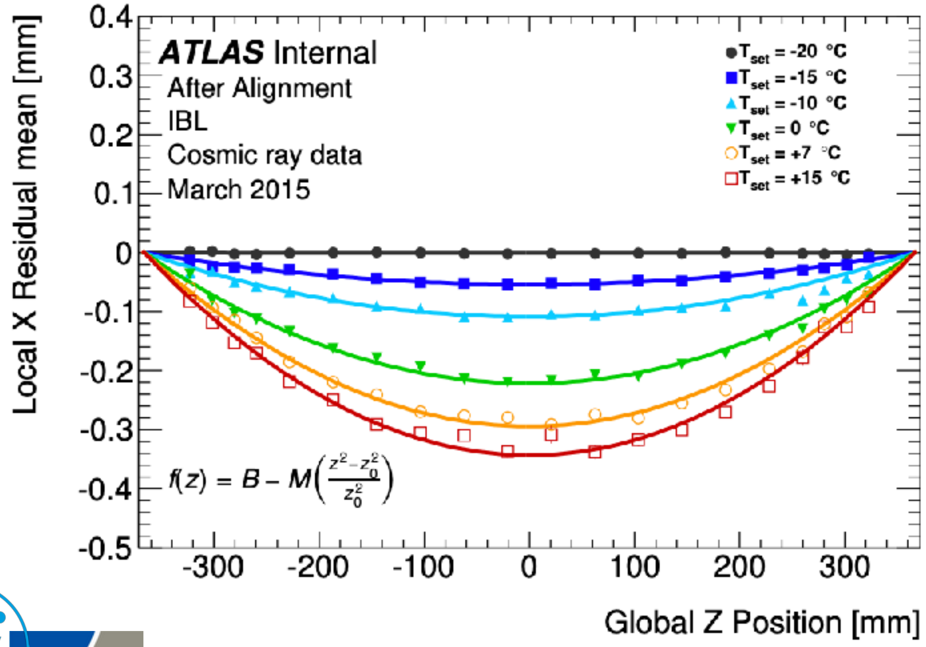
Other Problems and Famous Problems

ATLAS IBL STAVE BOW

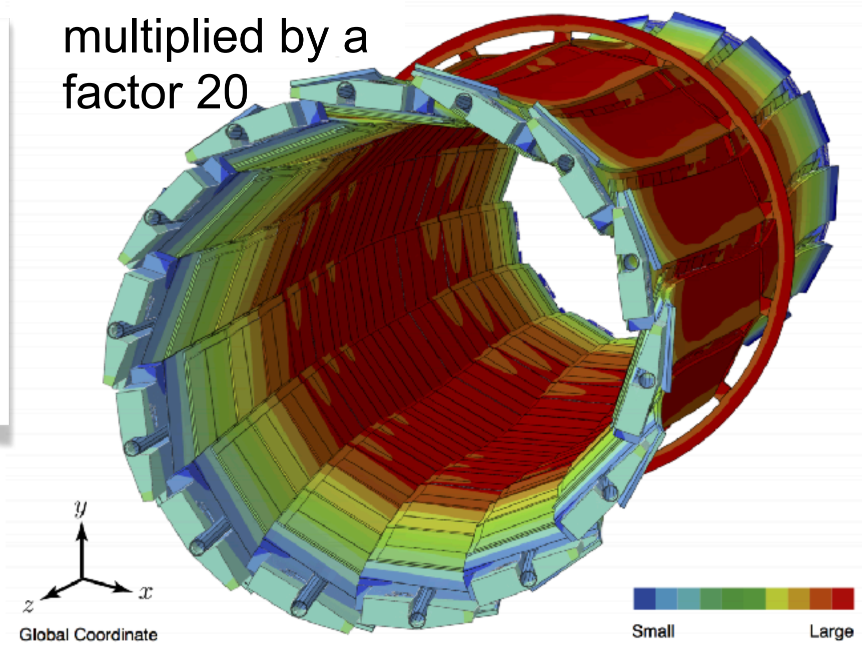
during commissioning

- Distortion depending on the operating temperature was observed.
- Caused by a mismatch between the coefficients of thermal expansion (CTE) of a bare stave made with the carbon foam and the flex attached on the bare stave.
- Maximum more than 300 μm at -20 ◦C with respect to the nominal position at the room temperature.





Mitigated by temperature control at the level of 0.2 K and the regular alignment correction in the offline reconstruction

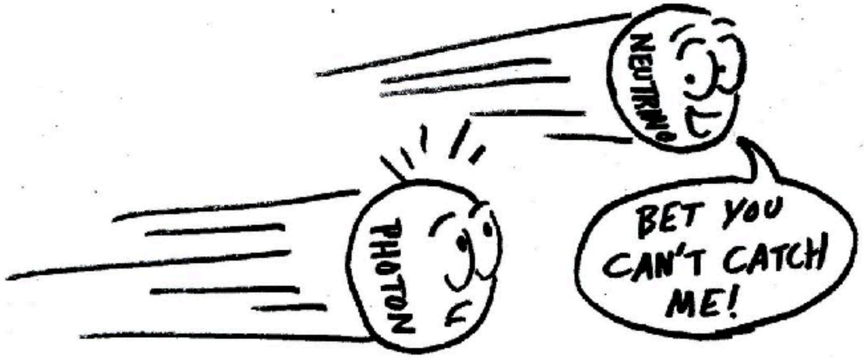


multiplied by a factor 20

http://cds.cern.ch/record/2022587/files/ATL-INDET-PUB-2015-001.pdf

CABLE PROBLEM WITH PRESS COVERAGE

- Oscillation Project with Emulsion-tRacking Apparatus — **OPERA:** instrument for detecting tau neutrinos from muon neutrino oscillations
- In 2011 they observed neutrinos appearing to travel faster than light.
  - Very controversial paper also within collaboration



The top 10 biggest science stories of the decade

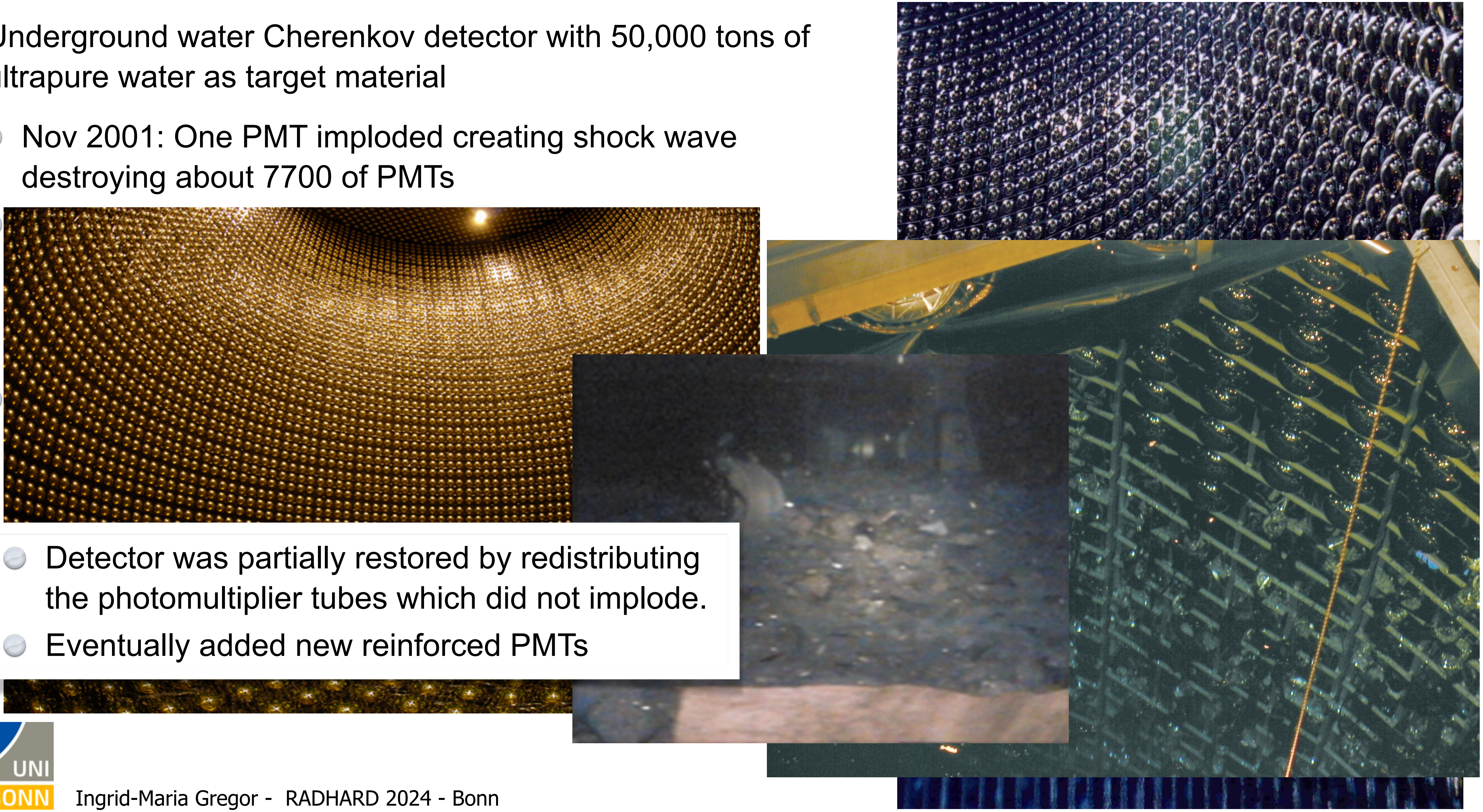
- Kink from a GPS receiver to OPERA master clock was loose
  - Increased the delay through the fibre resulting in decreasing the reported flight time of the neutrinos by 73 ns,
  - making them seem faster than light.

After finding the problem, the difference between the measured and expected arrival time of neutrinos was approximately 6.5 ± 15 ns.

MAYBE MOST FAMOUS DAMAGE ....

during commissioning

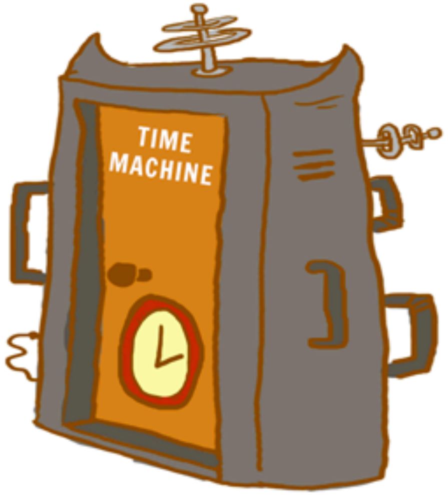
- Underground water Cherenkov detector with 50,000 tons of ultrapure water as target material
  - Nov 2001: One PMT imploded creating shock wave destroying about 7700 of PMTs



- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.
- Eventually added new reinforced PMTs

Pic: unknown source....

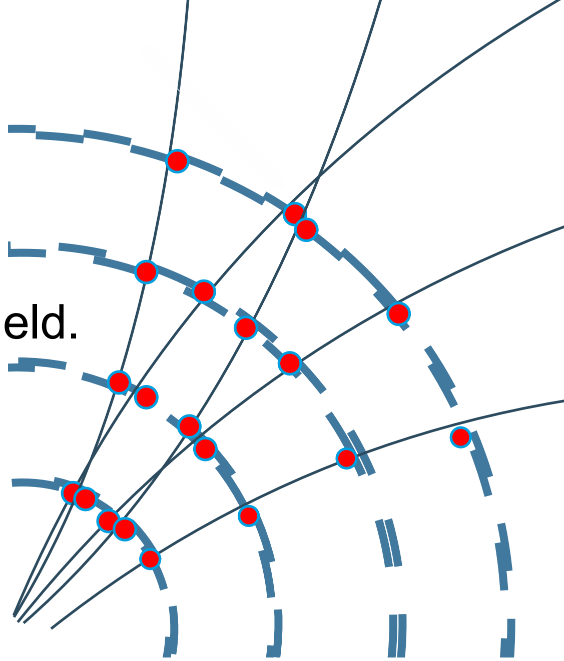
LESSONS LEARNED ?



- Spend enough time on simulating all aspects of your detector with ALL materials implemented
- Don't underestimate the "low tech"
  - Cables
  - Cooling
  - Mechanics including FEA
  - Radiation damage of non-sensitive materials
  - …..
- Make sure the overall timeline is not completely crazy (tough job)
- When mixing materials — ask a chemist once in a while
- Better is the enemy of good enough (Marty Breidenbach)
- …..

Solving and preventing theses kind of problems is also part of the fascination of detector physics!!

SUMMARY



Tracking Detectors

- Precise measurement of track and momentum of charged particles due to magnetic field.
- Mostly based on ionisation

Semiconductor Detectors

- In particle physics mostly based on silicon
- Pixel and strip detectors for innermost regions of experiments