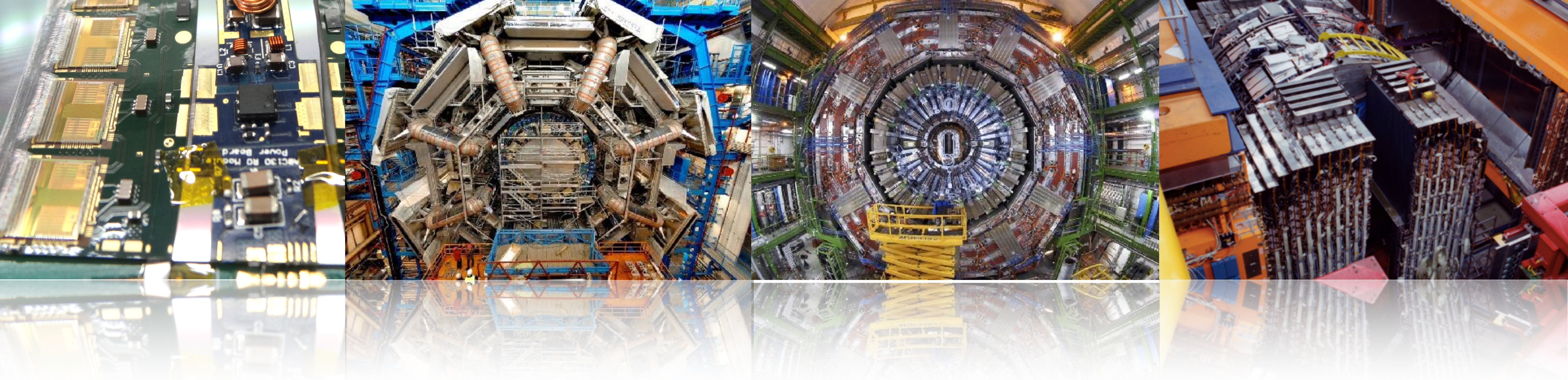


From Sensor to Detector

With some Obstacles

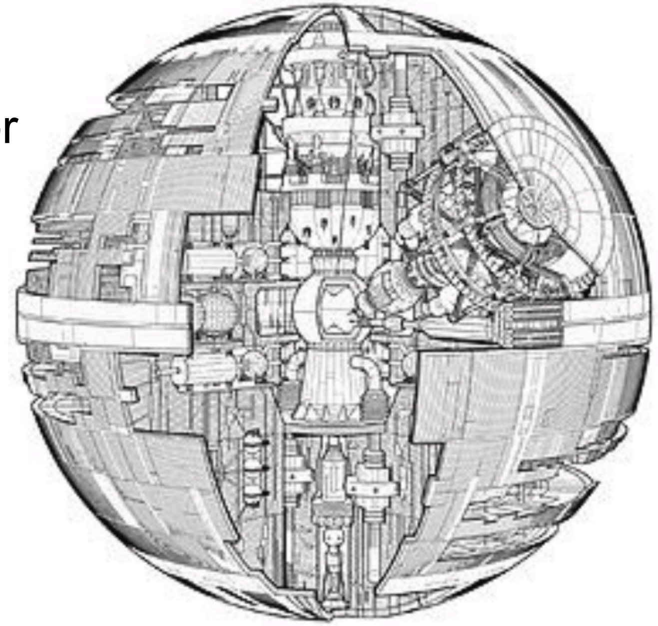
11th Beam Telescopes and Test Beams Workshop

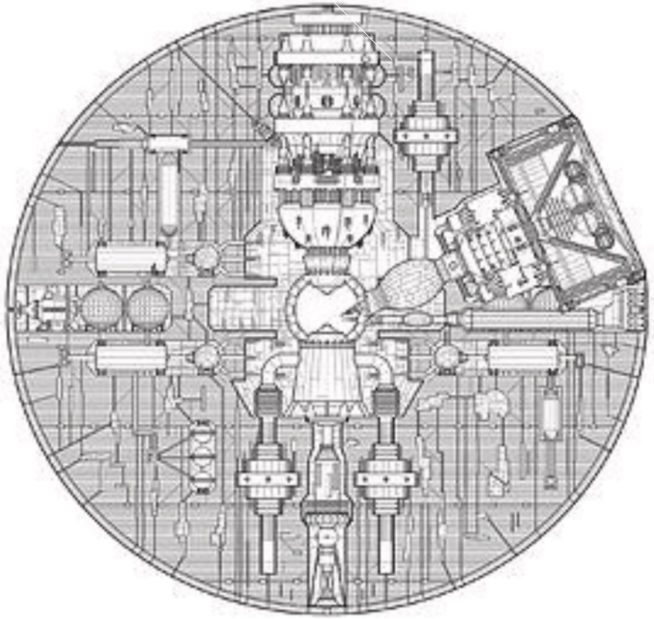
17-21 April 2023

Ingrid Maria Gregor
DESY/Universität Bonn

Introduction

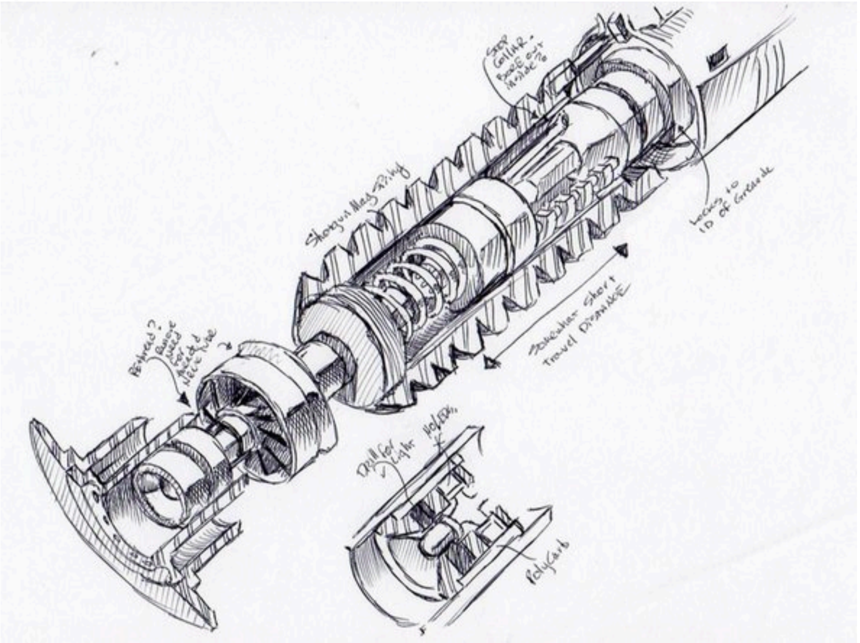
- Designing a particle physics (tracking) detector is a very complex business
- Many very nice examples exist
- Also some examples of failures





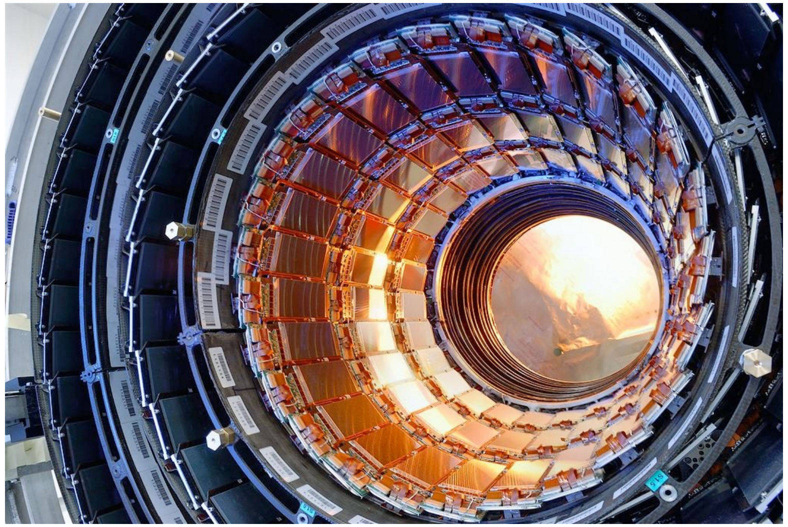
- Today: overview of main steps to get from sensor to detector
- Some examples where problems appeared

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

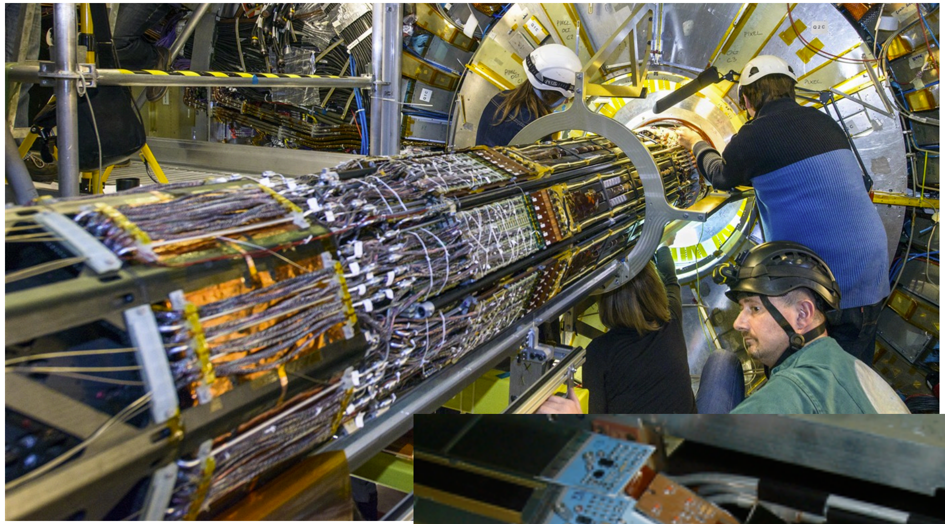


The Main Steps

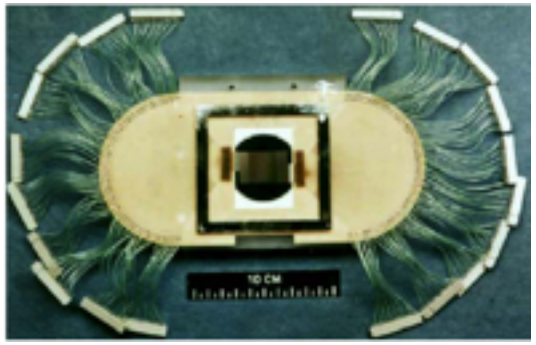
What we want ...



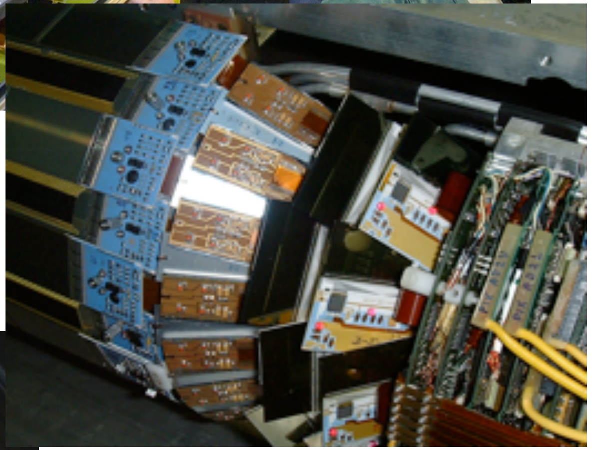
CMS Strip Detector, 2007



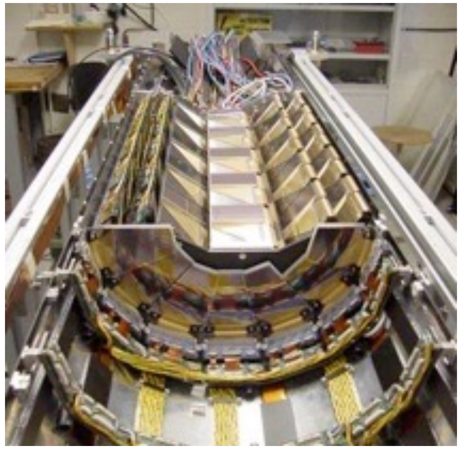
ATLAS Pixel Detector 2007



NA11 1981

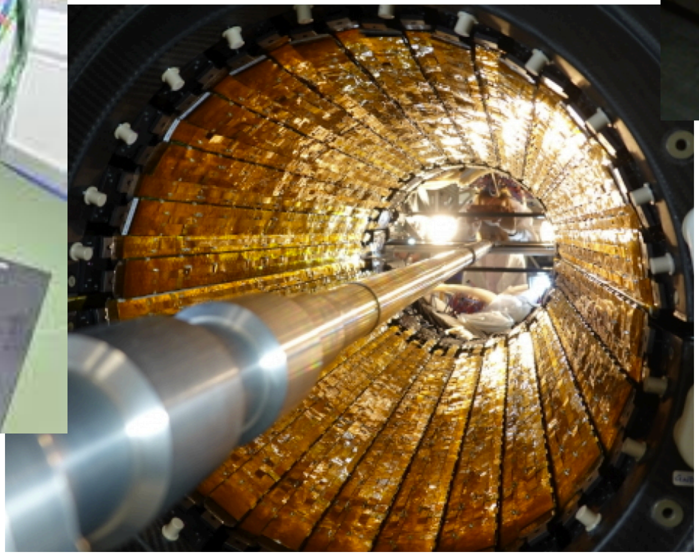


DELPHI VFT 1996



ZEUS MVD 2000

Belle II PXX, 2022

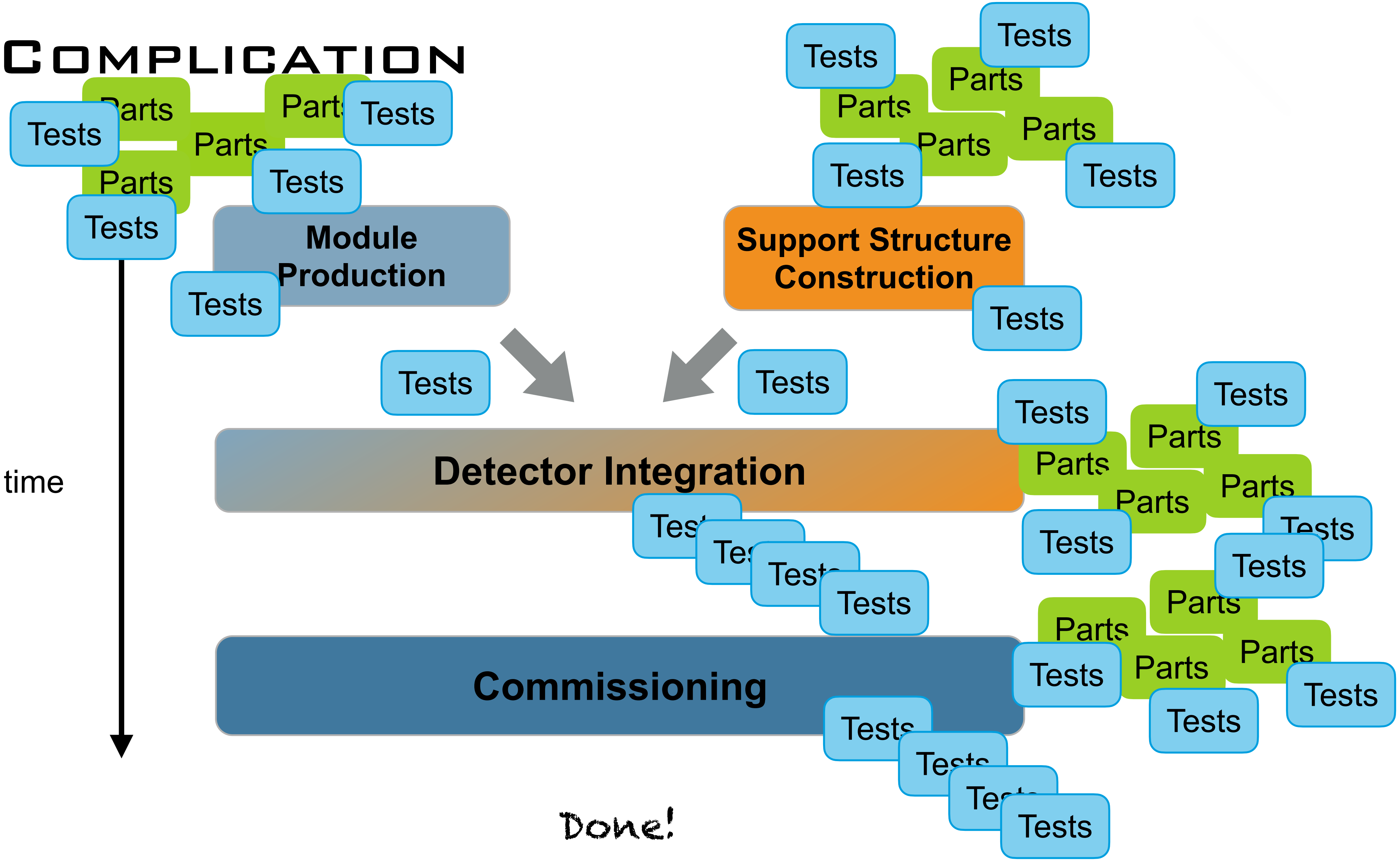


ALICE ITS

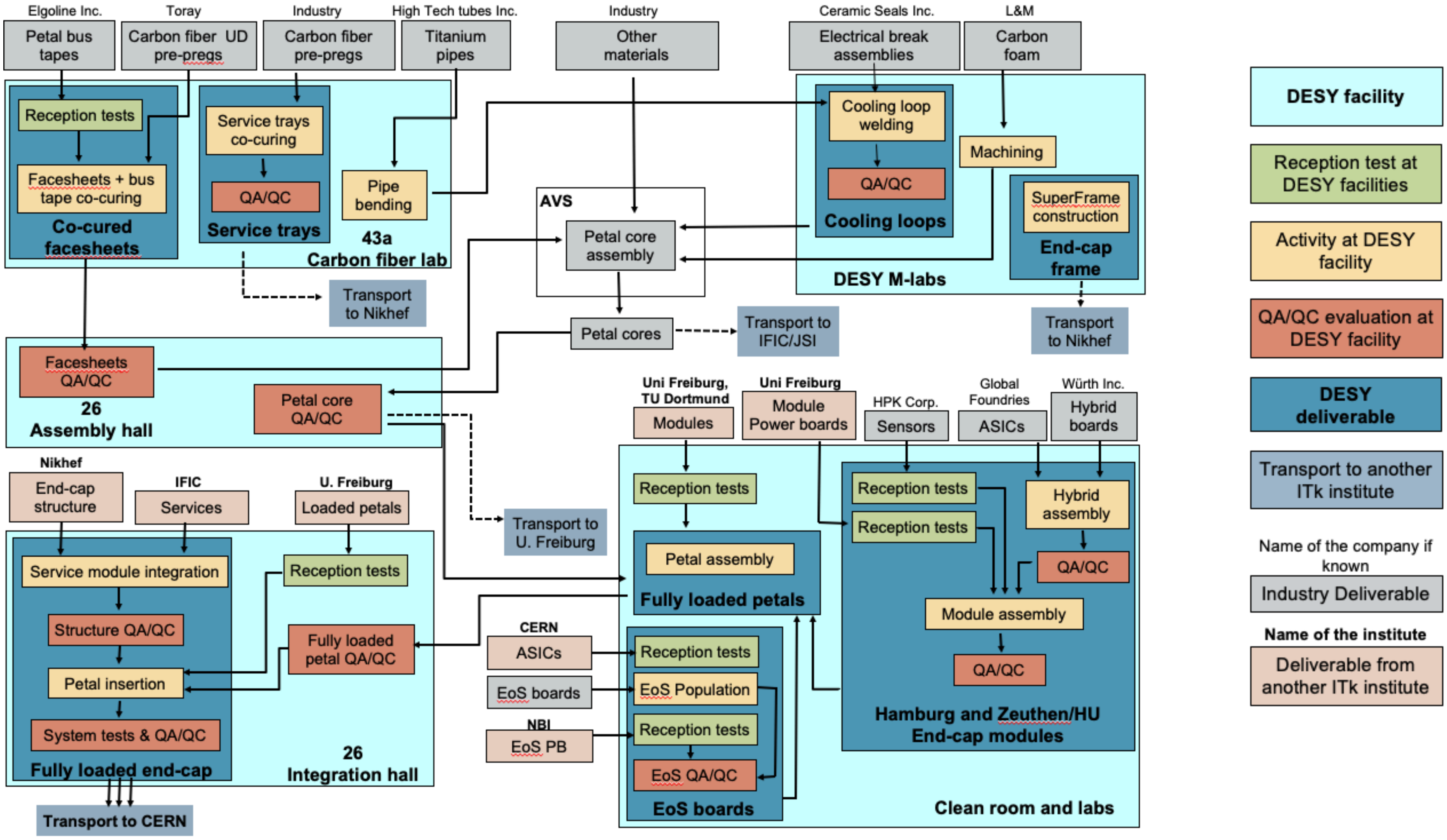
AMS Strip Detector,

Pictures: CERN, KEK

The Complication



ATLAS End-cap Workflow at DESY

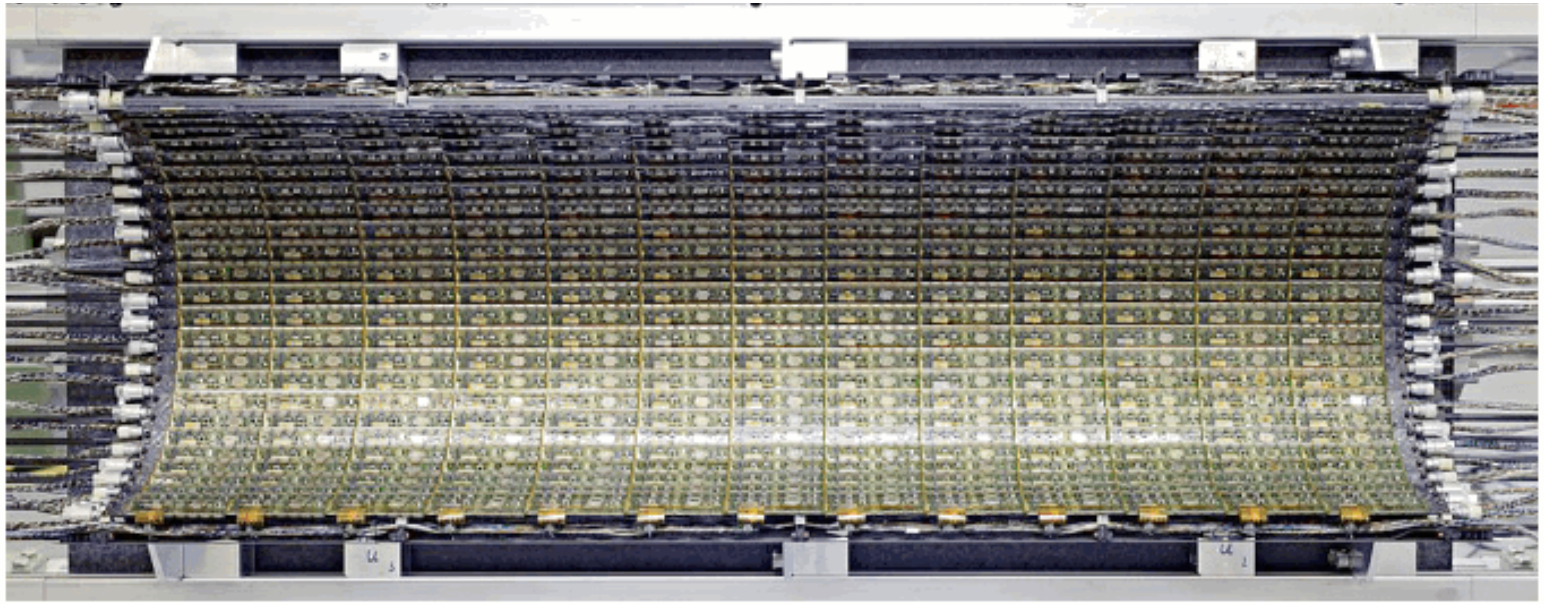


Module Production

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

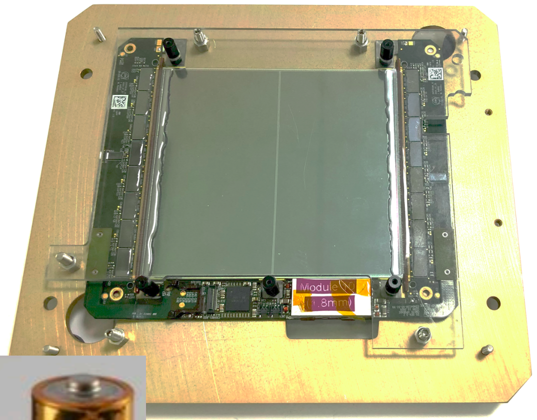
Project	CMS Pixel Phase I	LHCb Velo	DØ Microstrip Tracker	ATLAS ITk Strips	Belle II
#	1 856	42	672	17 888	40



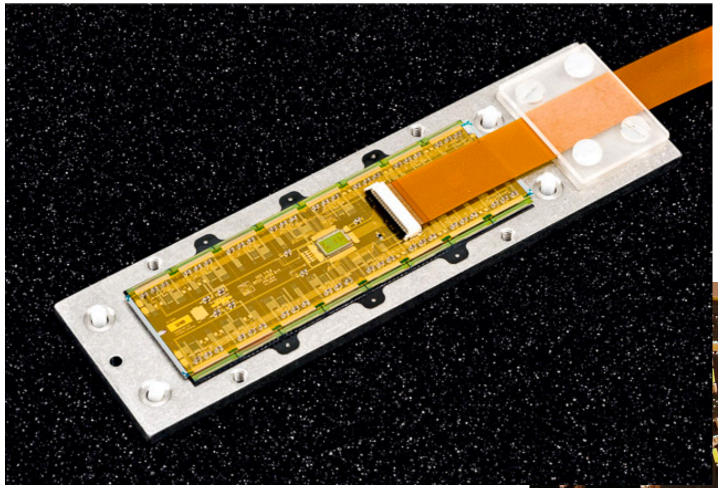
ATLAS Pixel Detector

The Module

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

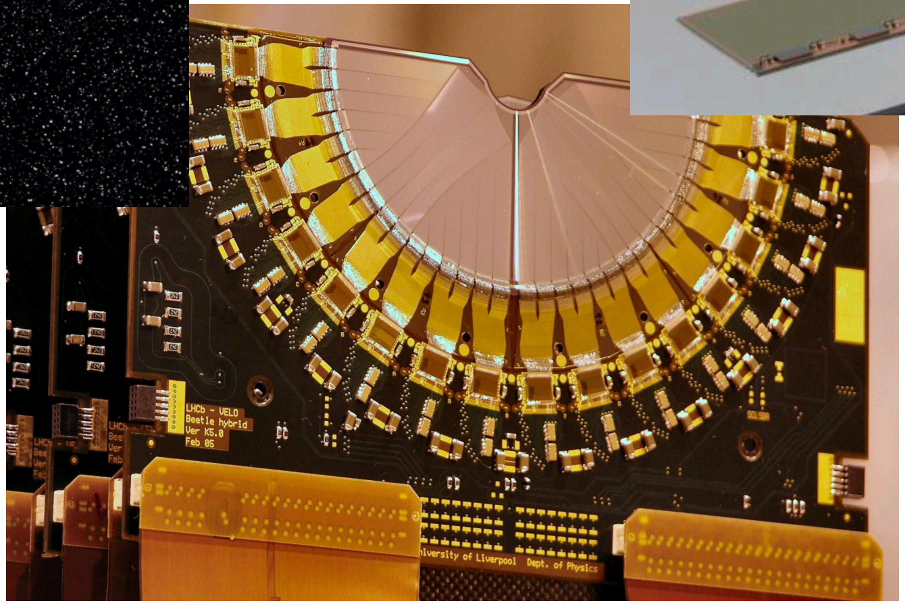


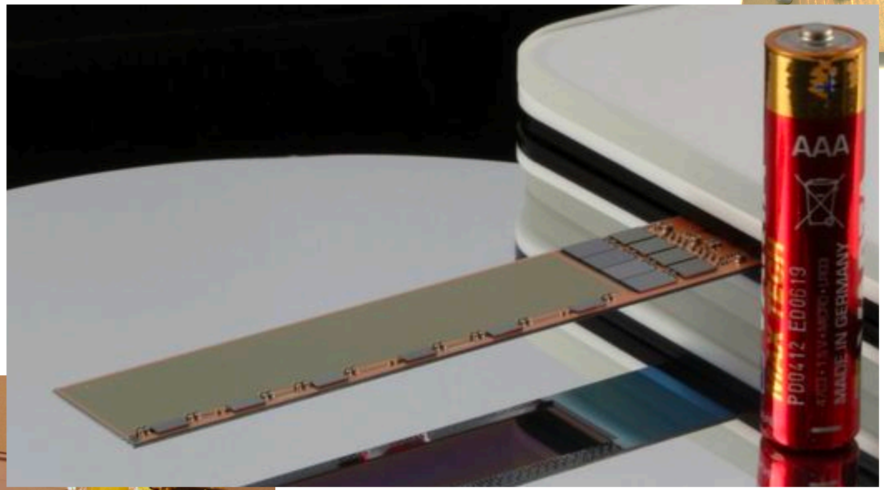
CMS Phase II 2S



CMS Phase I Pixel

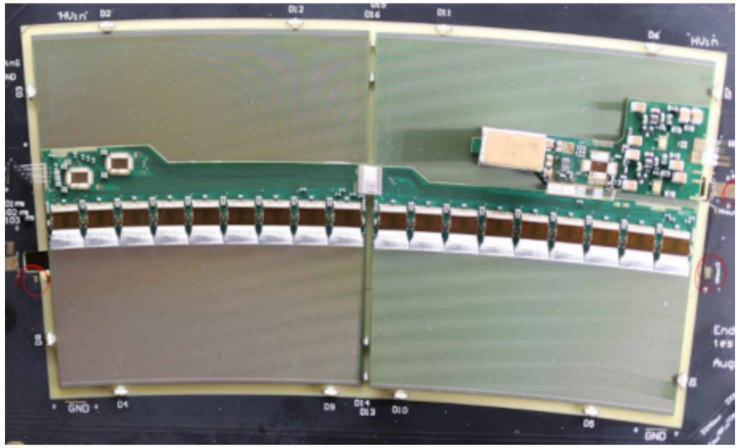
LHCb Velo





Belle II Pixel

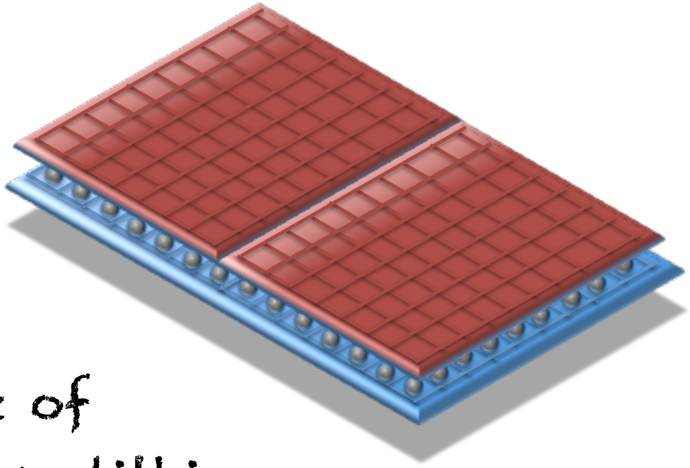
ATLAS ITk Strip R5



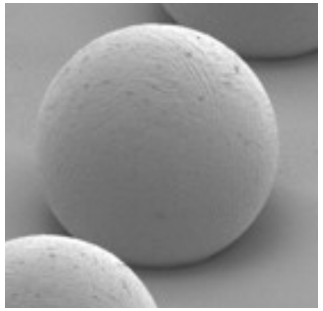
Module Concepts

see Dominik Dannheim

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

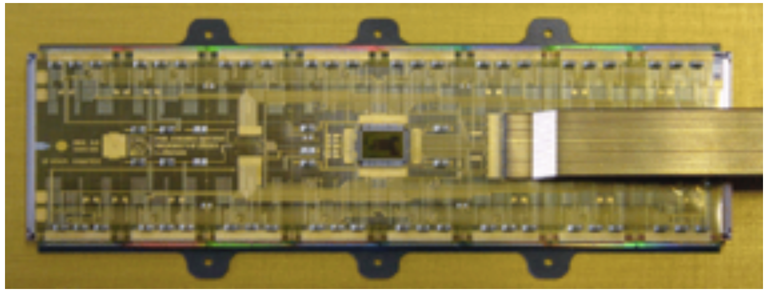


Independent of hybrid or monolithic: Need connection to outside world!

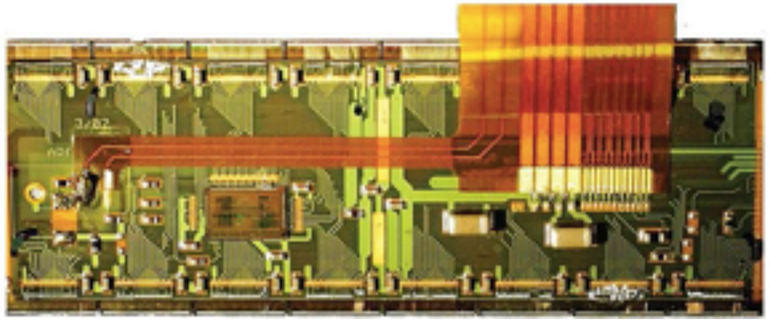


Bump-bonds -> see backup

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

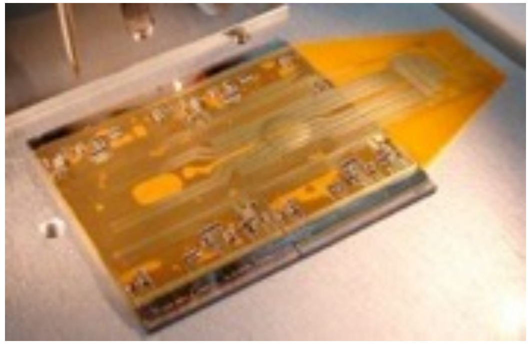


CMS pixel module



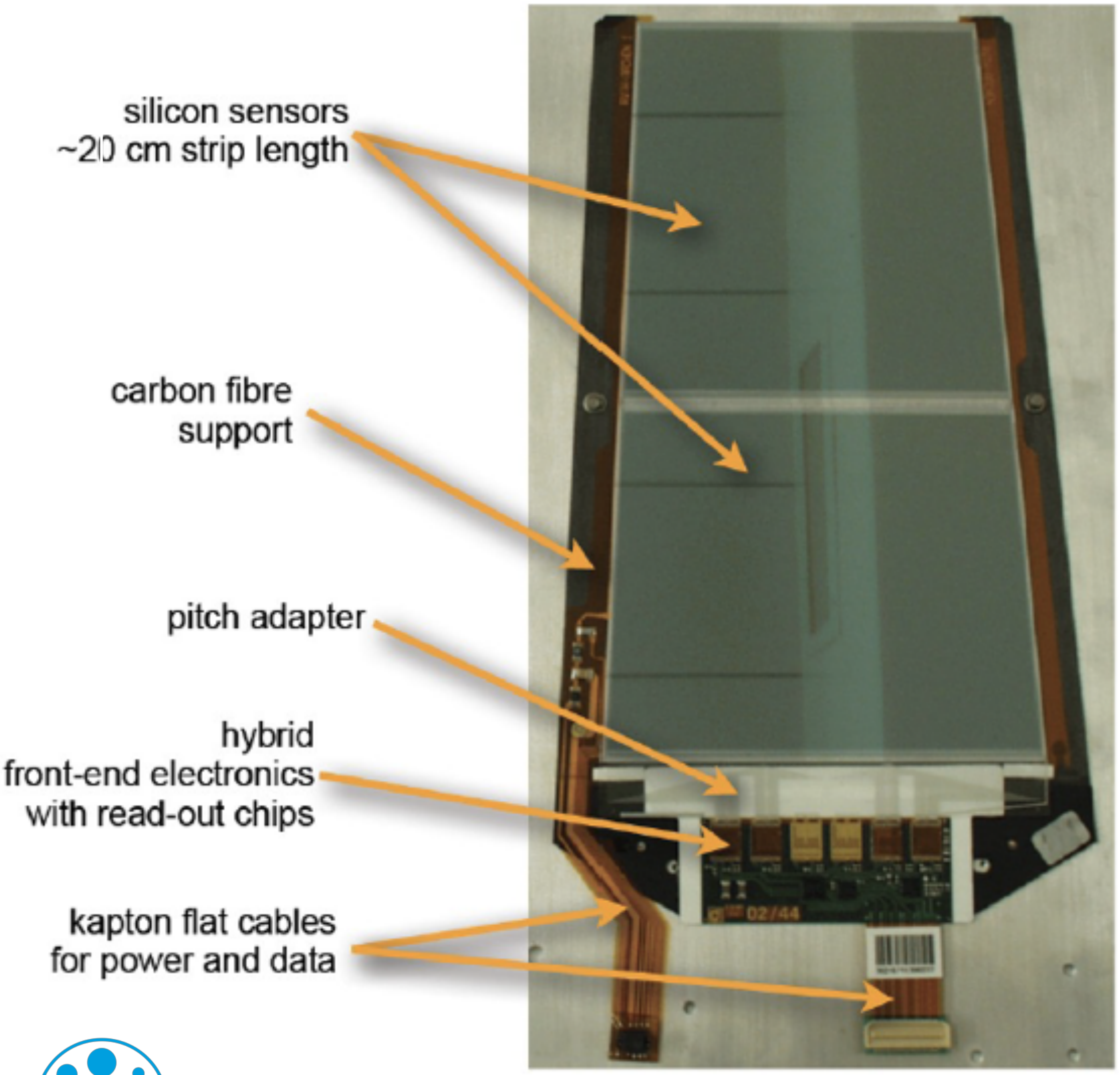
7 cm

ATLAS pixel module

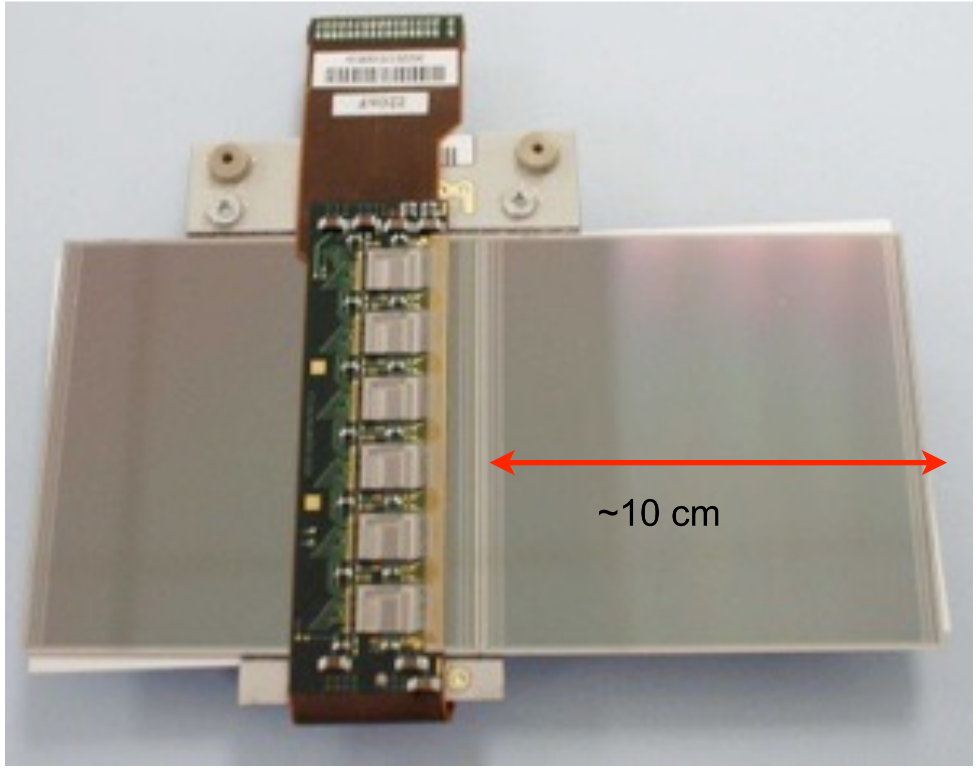


ATLAS quad module (early version)

Module Concepts



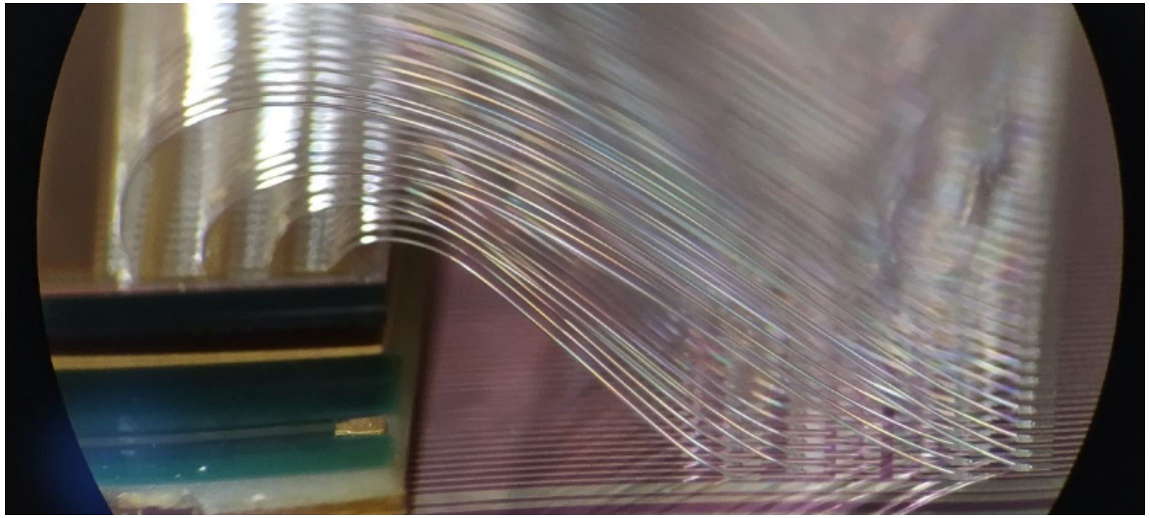
- Strips
  - Classic hybrid with wire-bonds
  - Monolithic - future dream
- FE chips wire bonded to large strip sensor

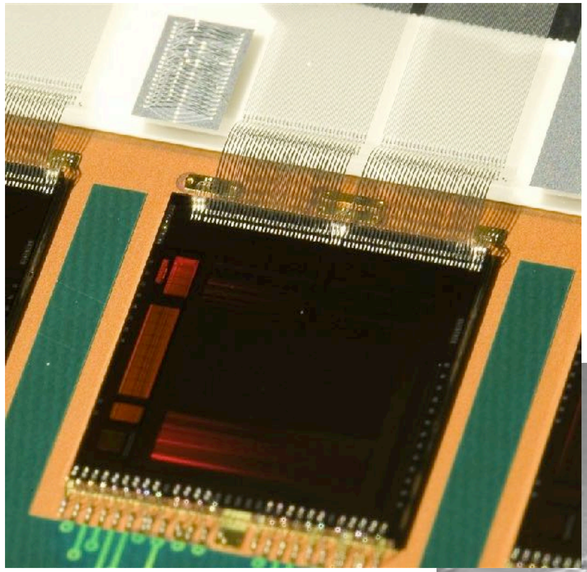


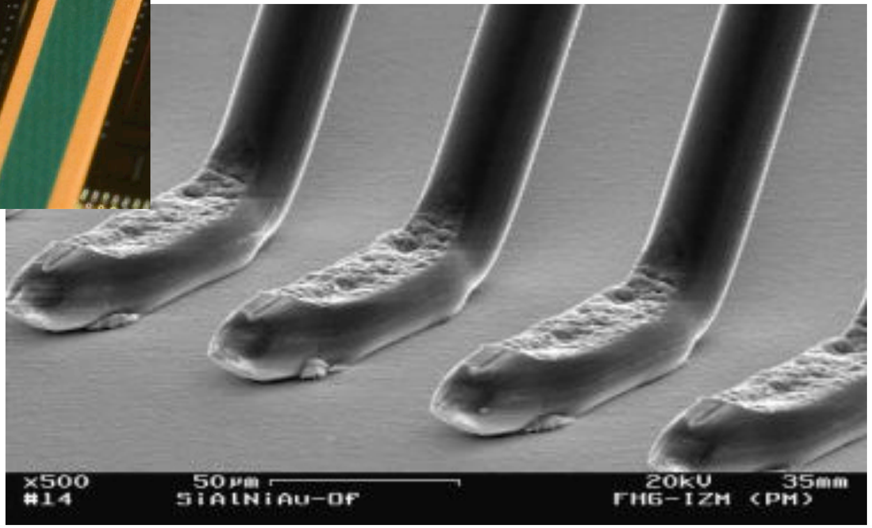
ATLAS strip barrel module

Wire Bond Connection

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





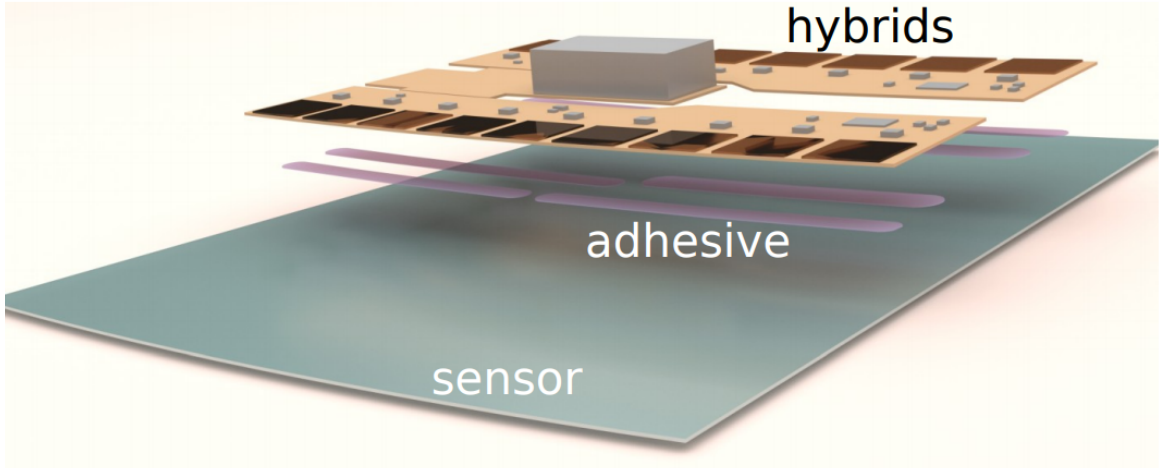


Building Modules (Example Strips)

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

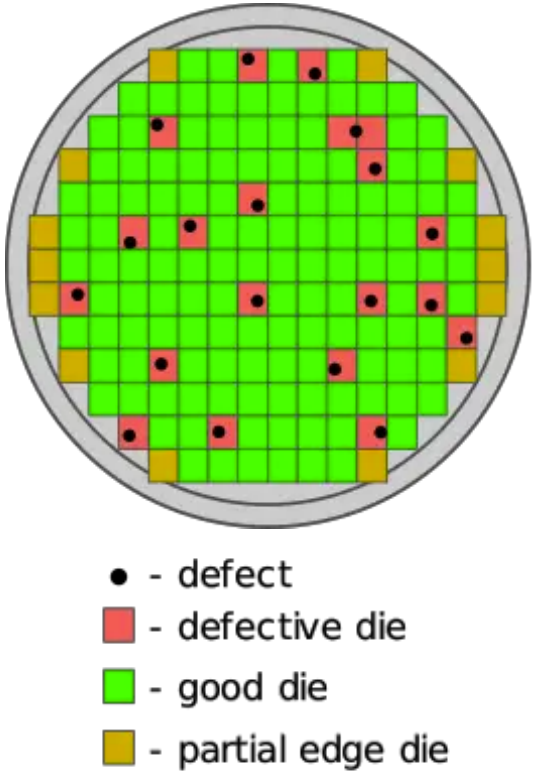
To be defined:
- Sensor IV, CV, etc
- Sensor bow
- Chip on wafer tests
- Hybrid noise performance
- Wire bonds strength
- Electrical performance
- Full module: metrology
- ….

based on many years of R&D



Exploded view ATLAS ITk Strips module

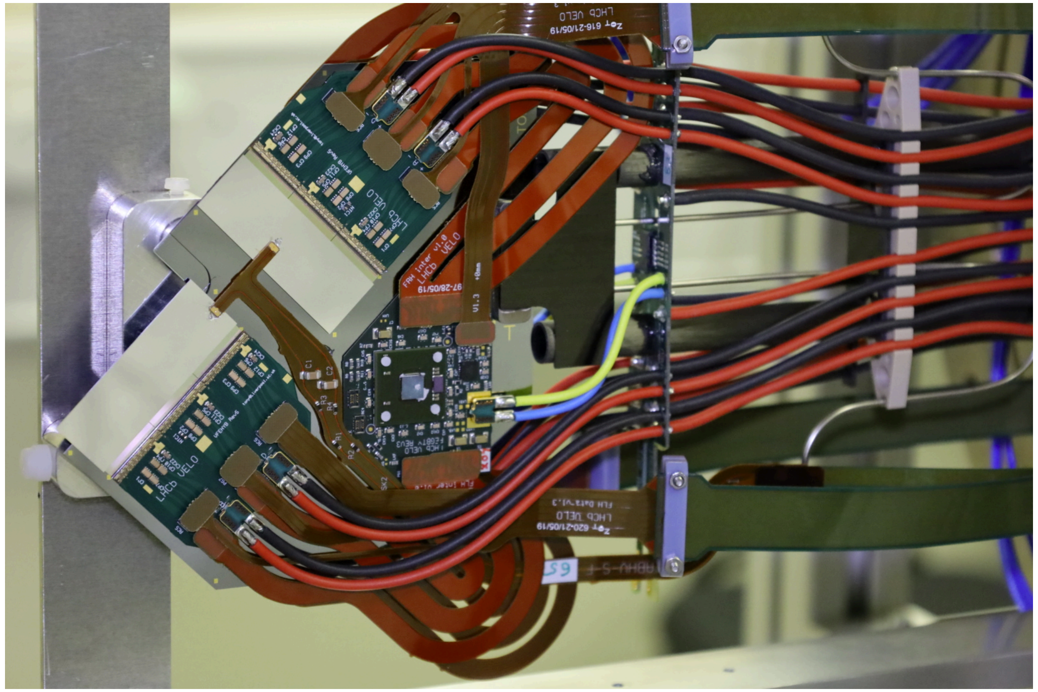
- **Understanding the yield:**
  - yield: the (expected) fraction of parts surviving tests during production
  - relying on very high yield
  - example: 20 steps with yield of 98% -> only 66% of sensors go into experiment



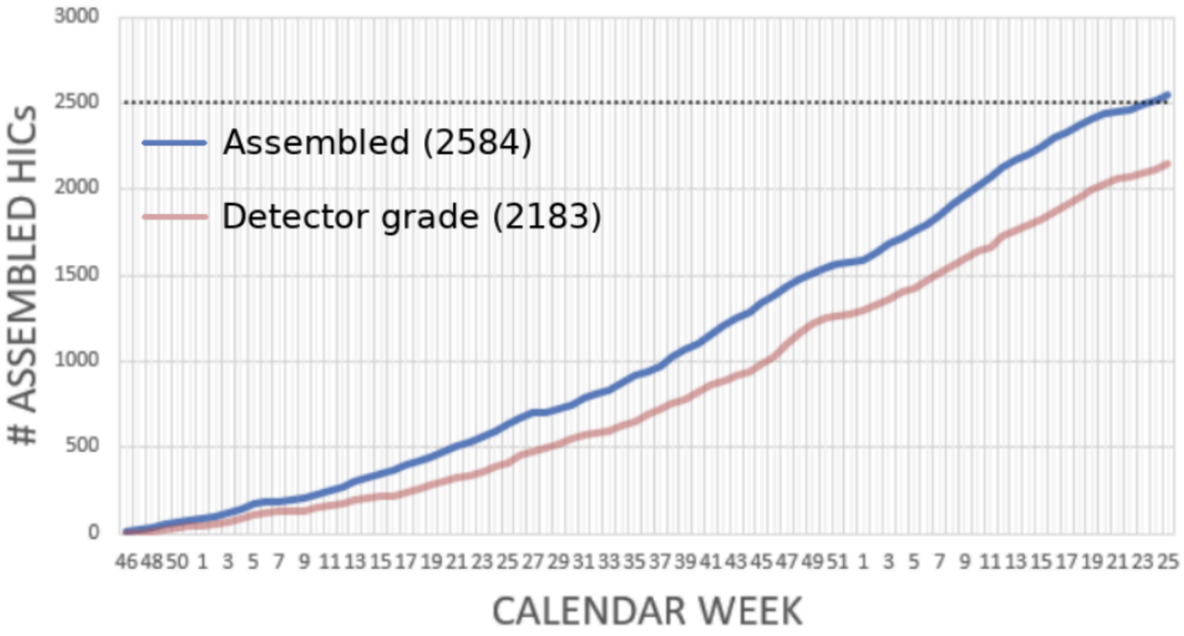
Building Modules

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

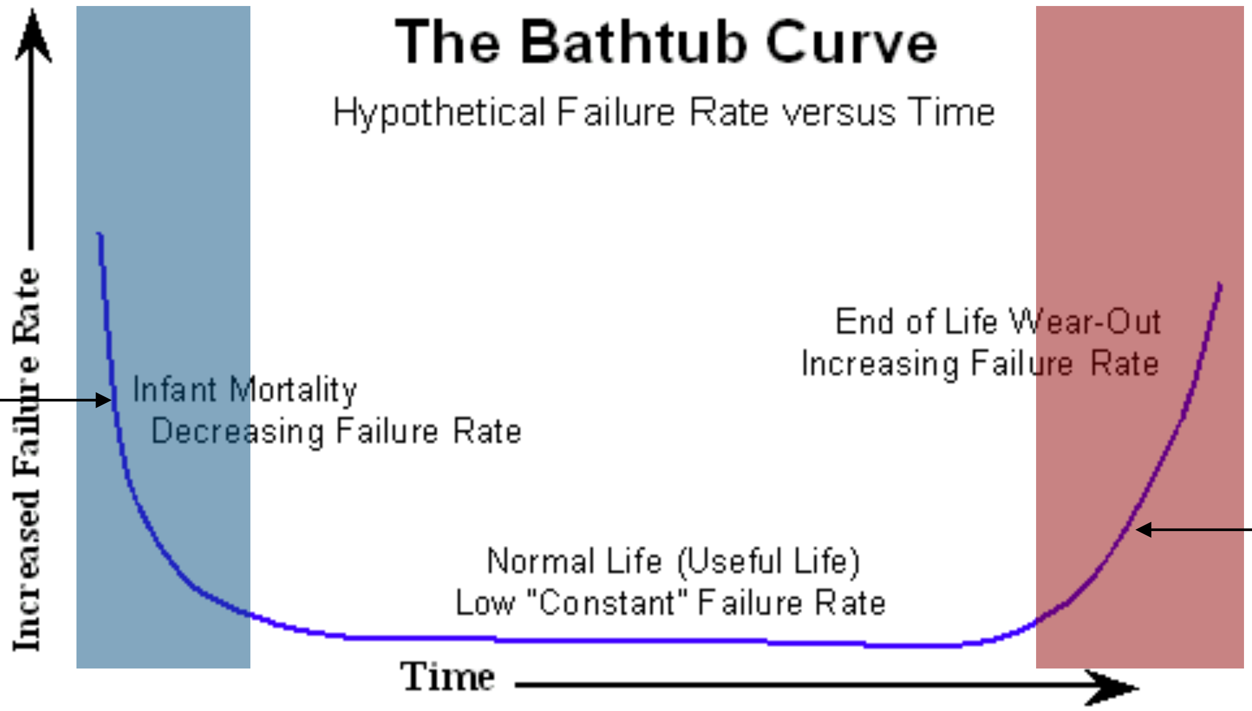
Building Modules

- **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

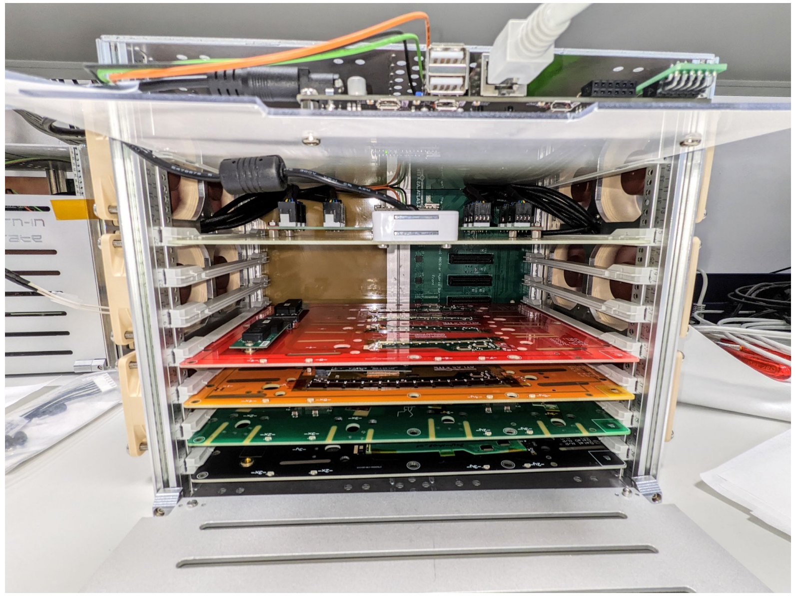


be done with experiment before this starts

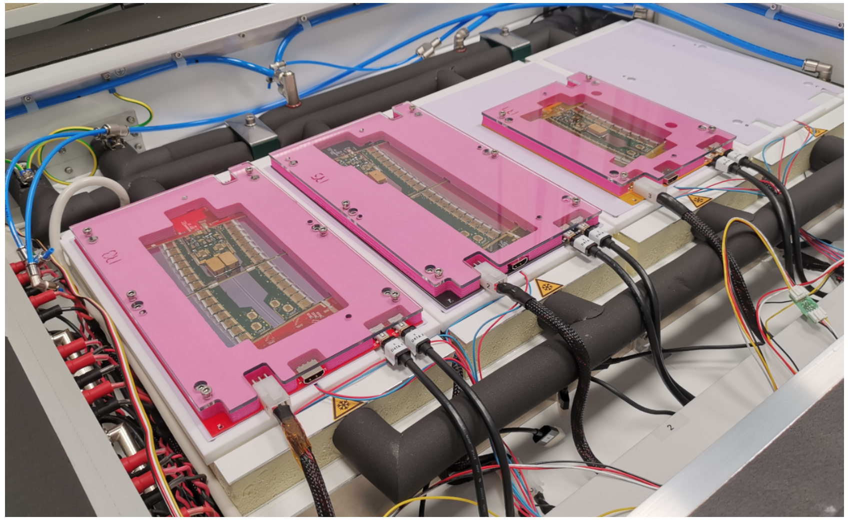
Checks During Production

- Most checks during production are performed at room temperature
- Detectors are often operated at low temperatures (down to -30C)

- 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



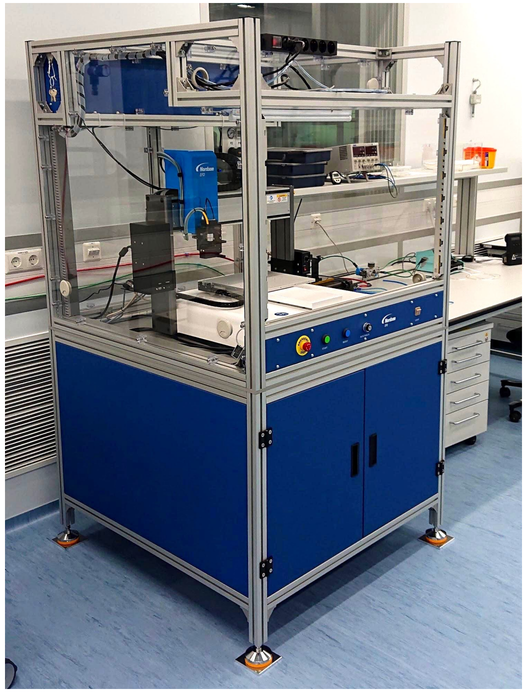
Hybrid burn-in test



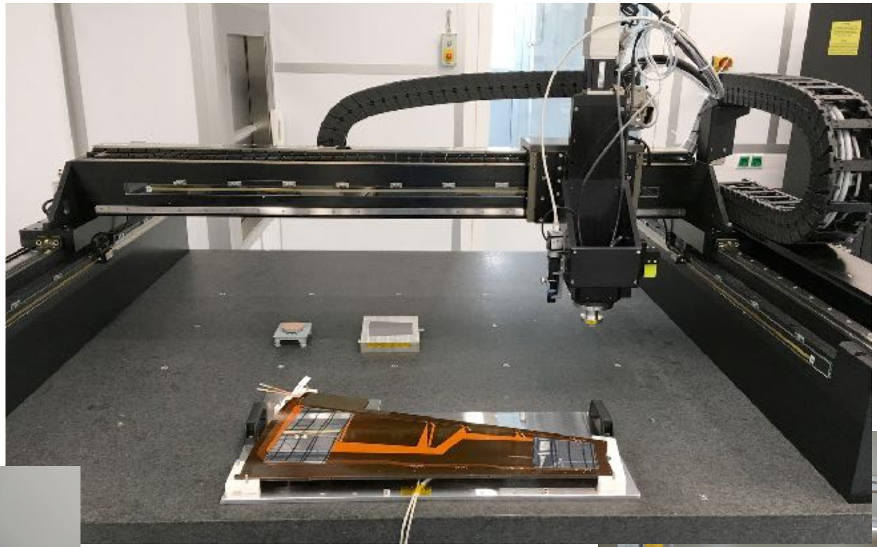
Setup for module thermal cycling - 3 modules simultaneously tested

Robots

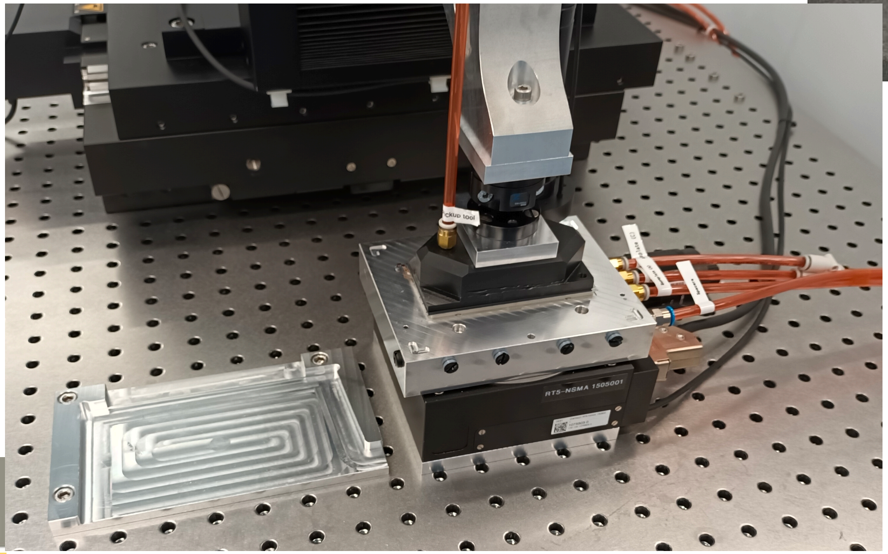
- During production need to limit manual steps
- By now all automated machines are available
- Industrial solutions
  - Wire-bonder
  - Gluing robot
- Home-made developments
  - Module loading (based on gantry)
  - Bustape testing
- Very attractive tasks for detector R&D newcomers



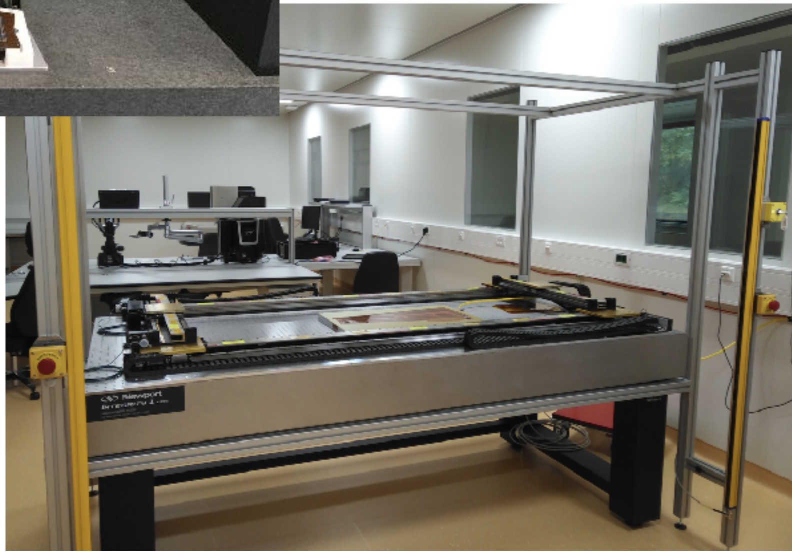
Gluing robots



Module gluing and placing tool (ATLAS)



Module construction robot (CMS)



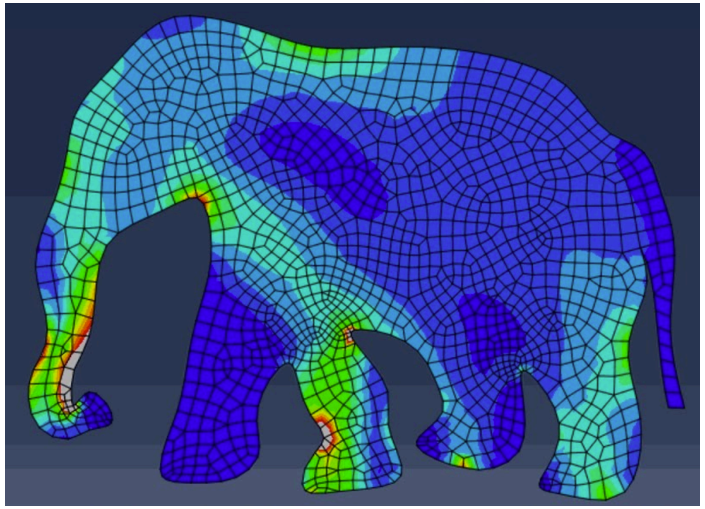
Testing robot (ATLAS)

Pictures: DESY

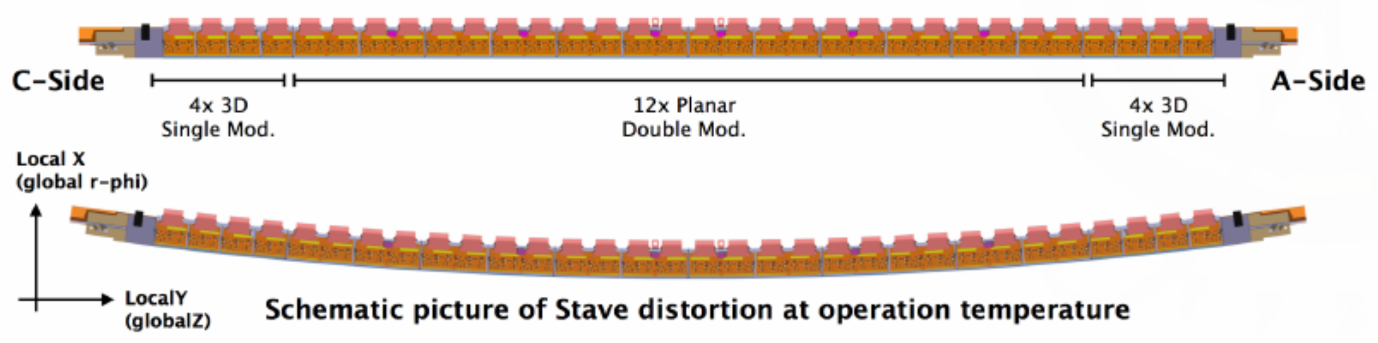
(Local) Support Production and Testing

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.



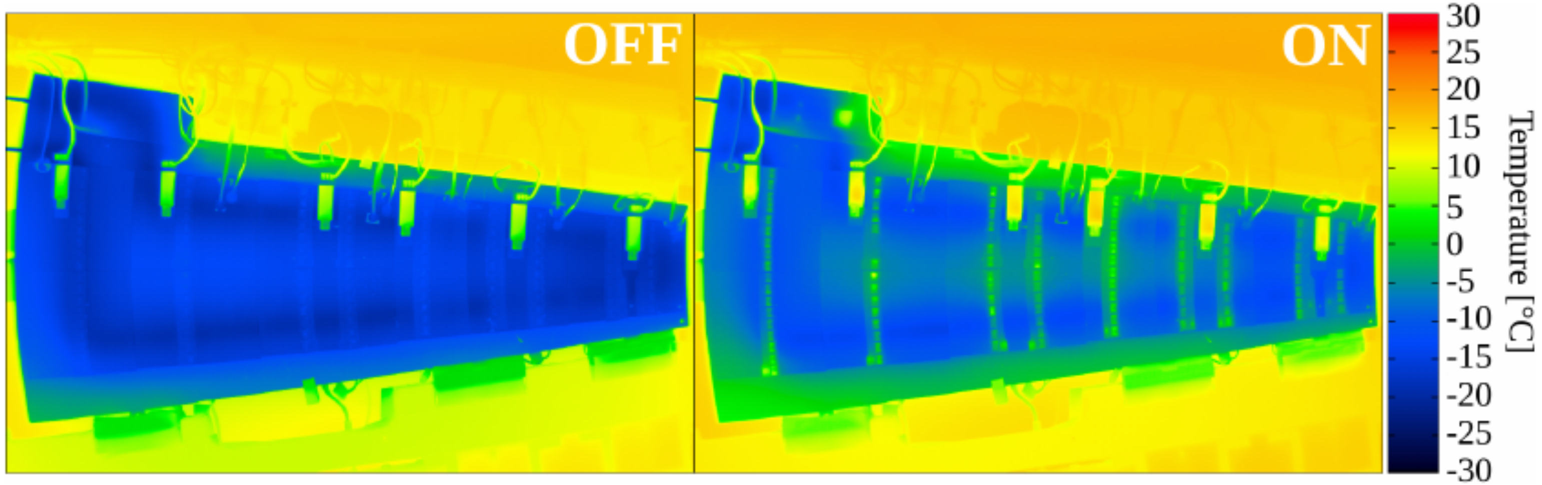
Work very often seen as "non-scientific"
- which is certainly NOT true

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



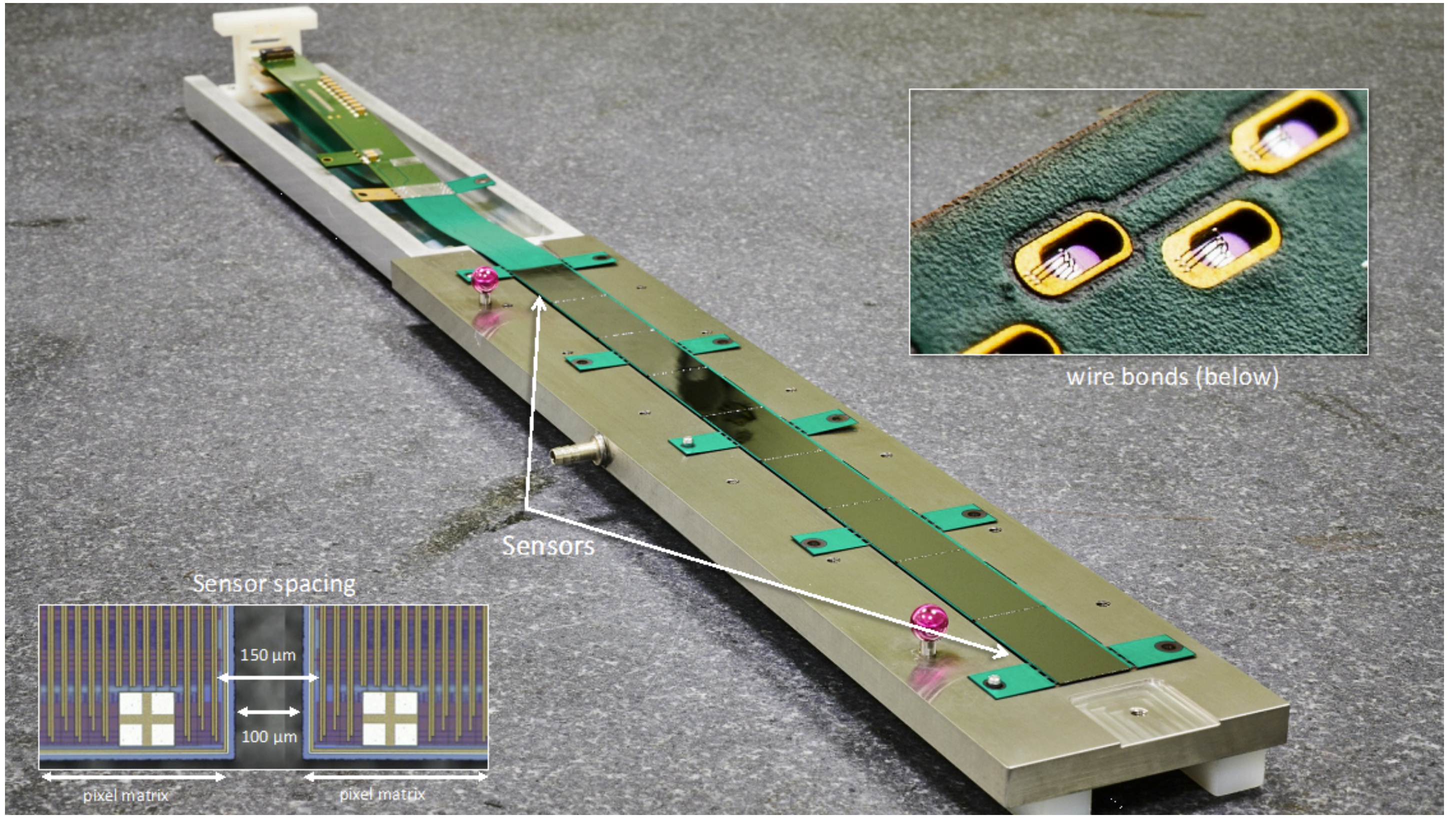
CMS Outer Tracker

"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

Semi-electrical petal @ DESY

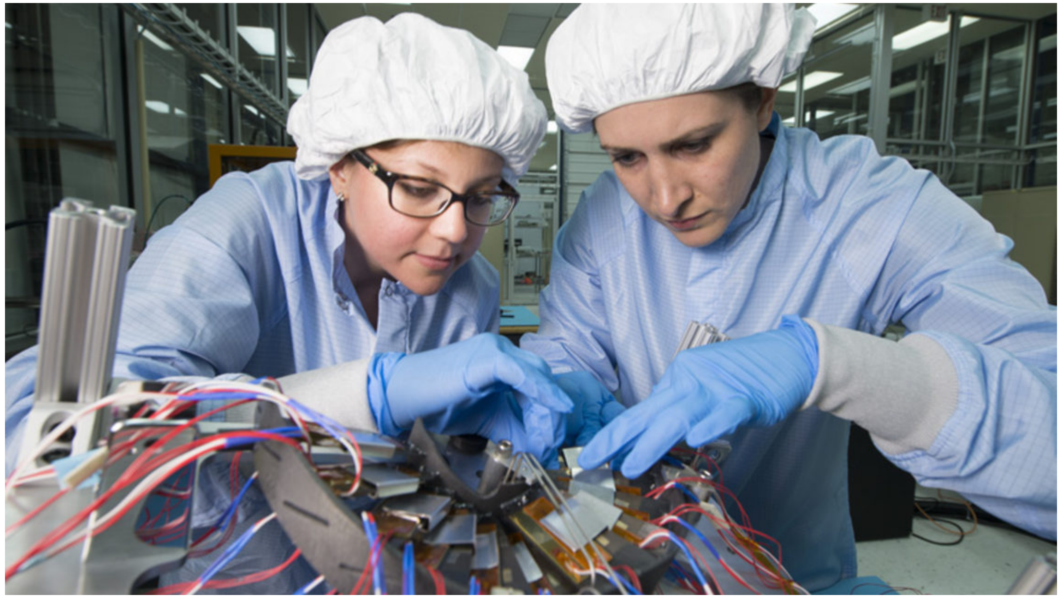
Loading of petal core 07 - back side

Video: Othmane Rifki, 2017

DESY Integration

- 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)

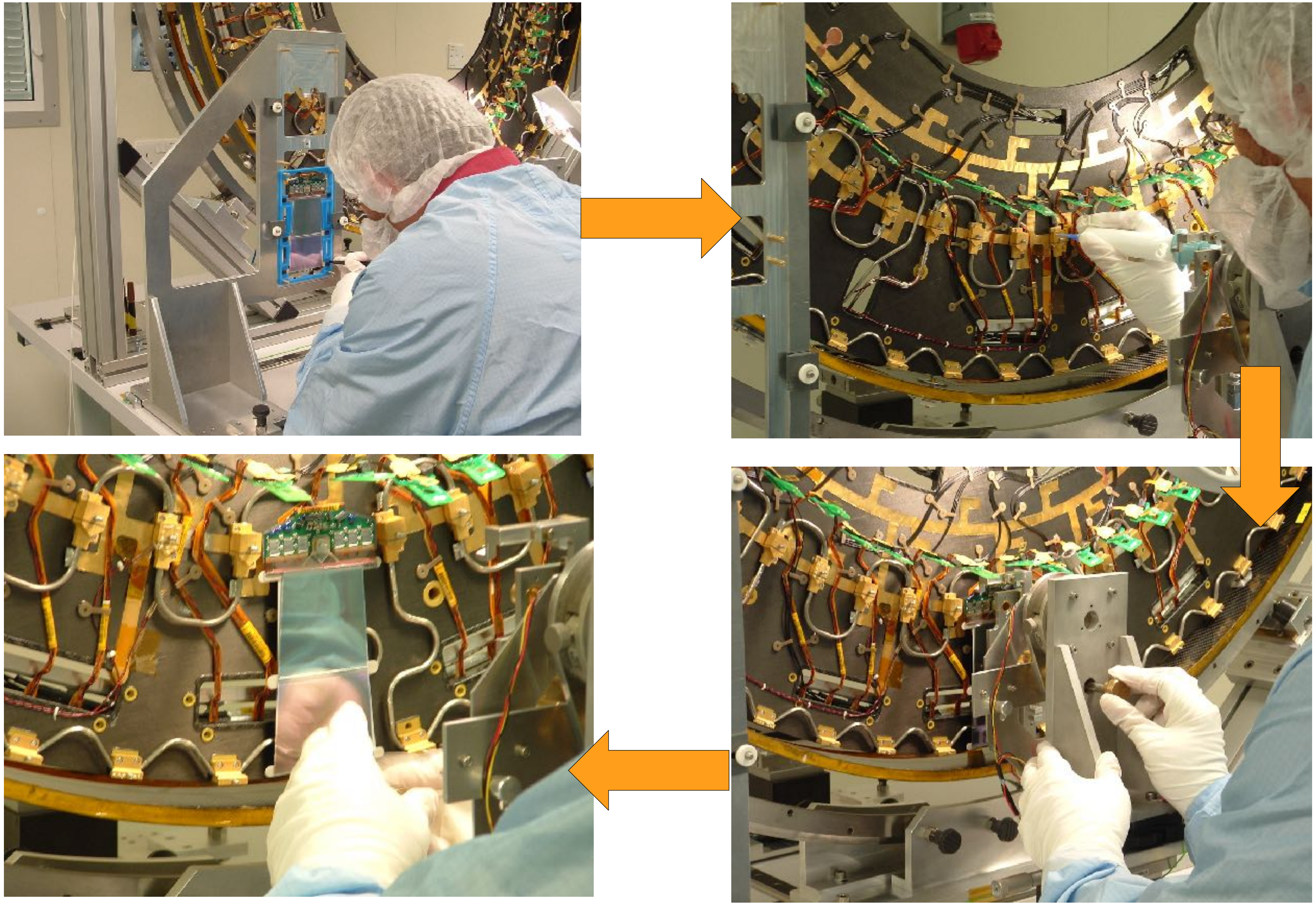
➔ Proper tooling required!



CMS Pixel Phase I

LHCb Velo

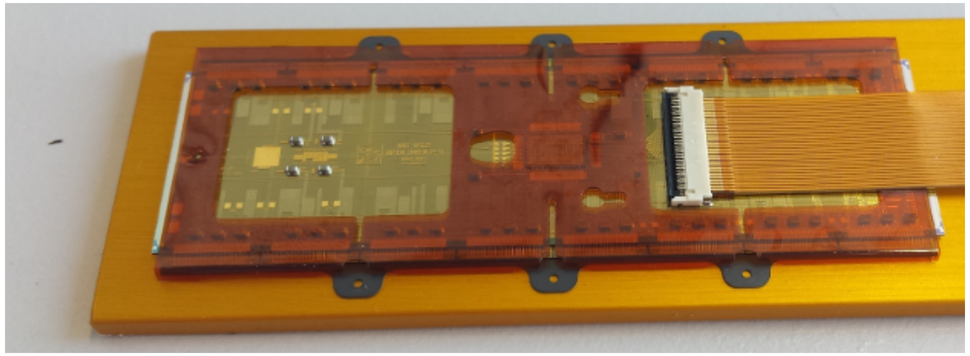
From Module to Detector

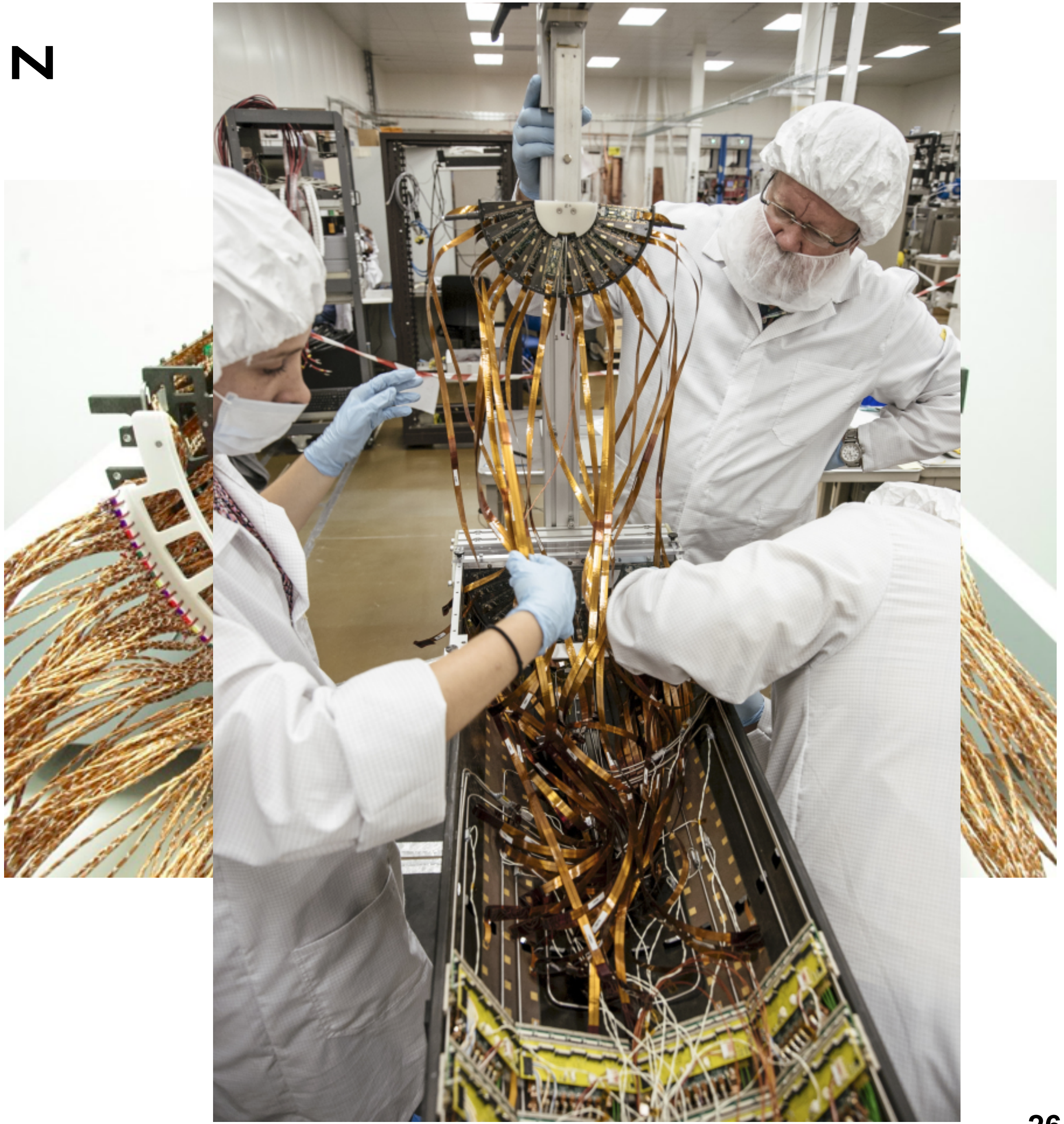


Assembly ATLAS SCT

Detector Integration

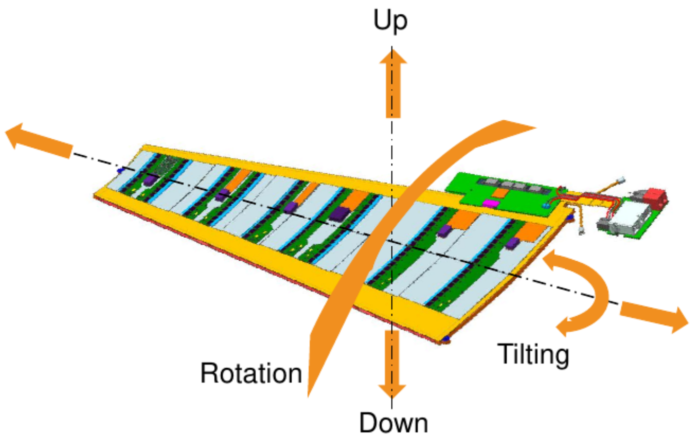
- **CMS Phase I Pixel Barrel**
- Half barrel: 592 modules,
  ~ 1 year of module production
- Delicate placing & mounting of modules
- Always label your cables …

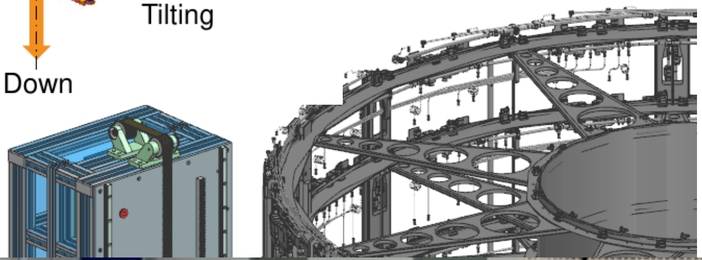


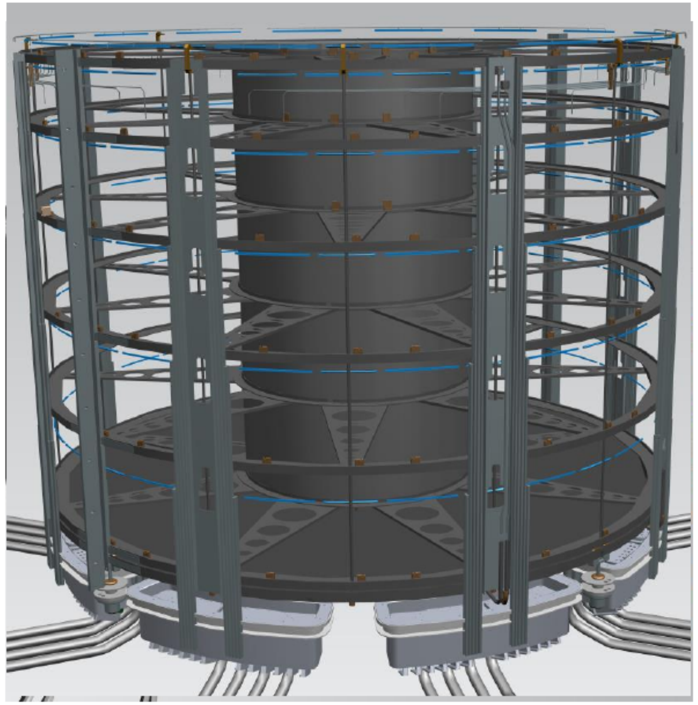


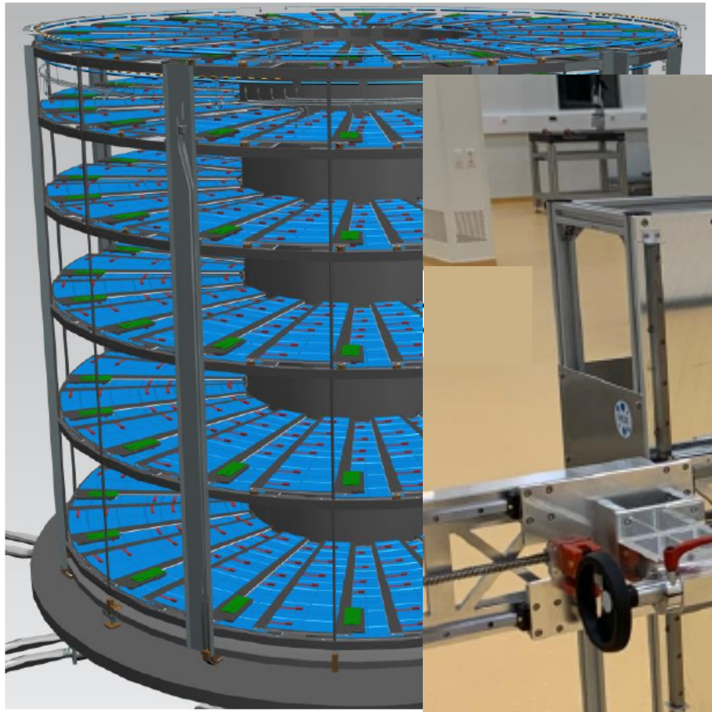
Filling the Skeleton

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

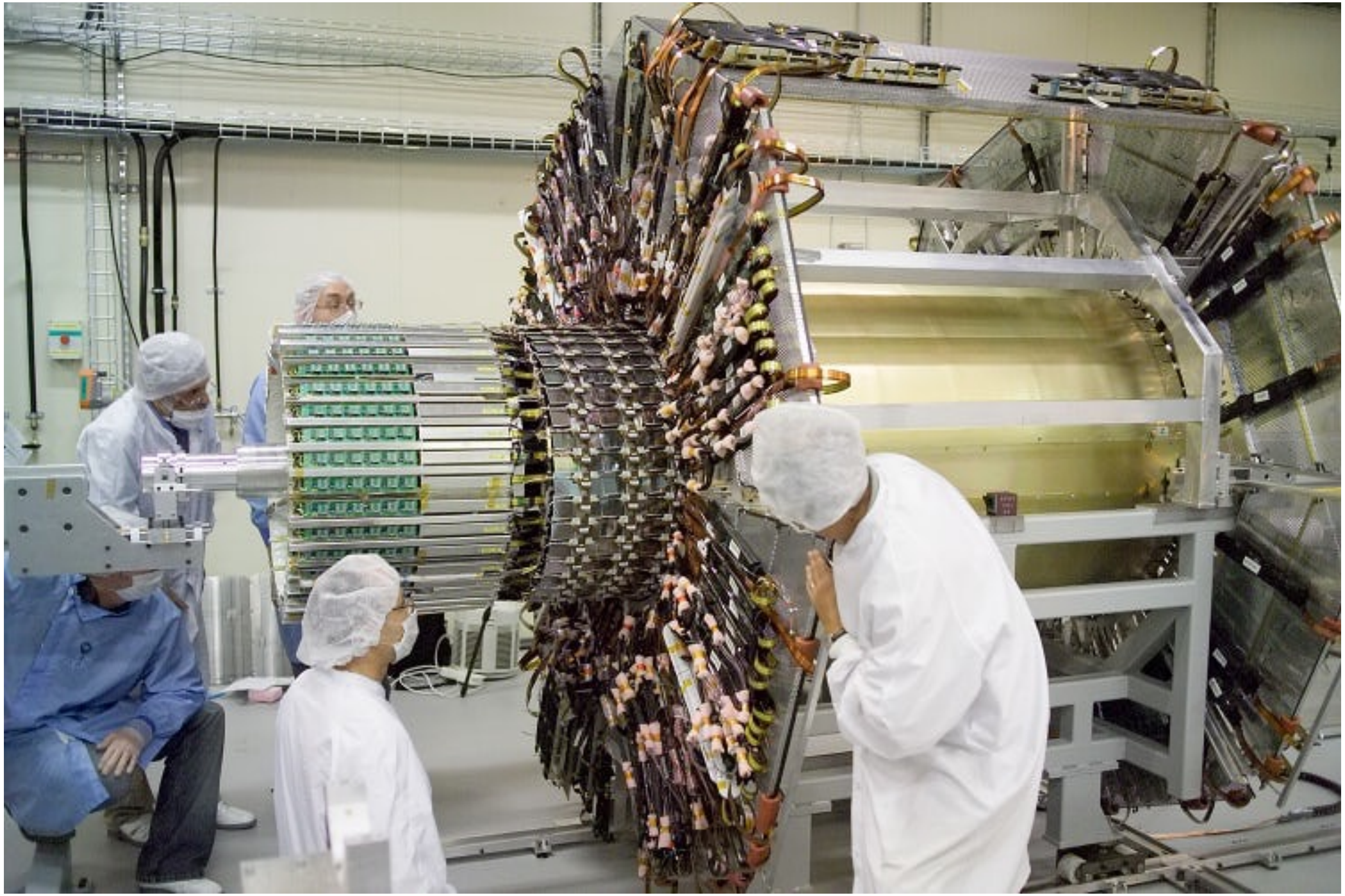








Silicon Tracker (SCT)



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

Transportation

Getting (larger) Parts to Destination

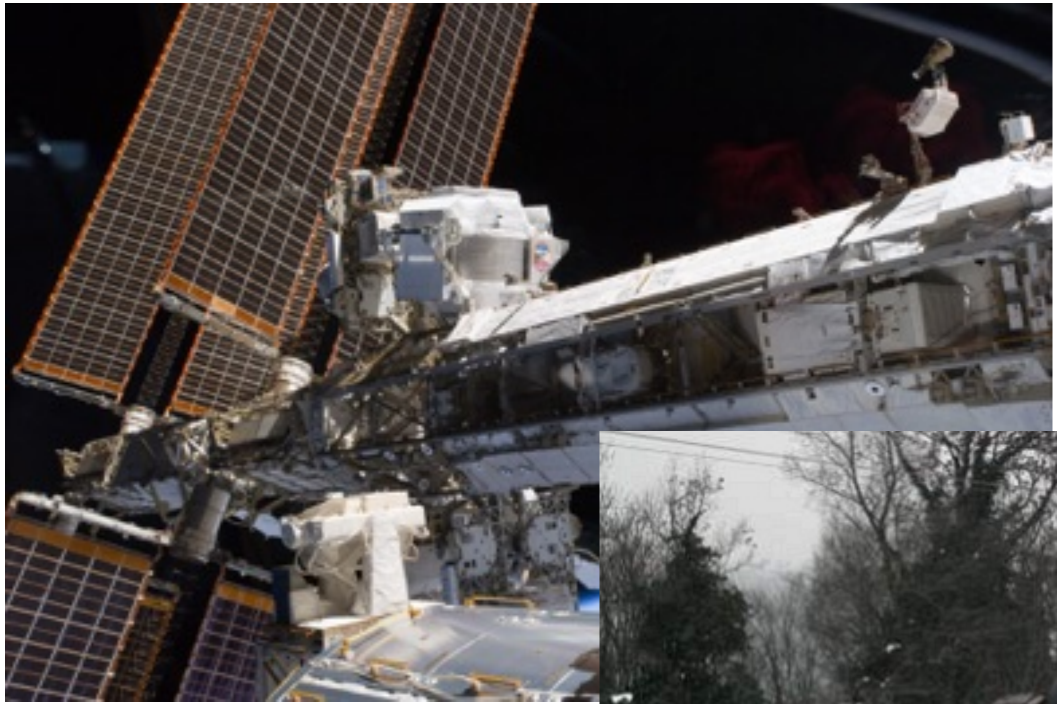
- Distributed construction of modules, detectors & components requires transportation
- Sensors, Chips, Cables, Connectors, ….: parcel shipment
- Modules: parcel shipment or custom transportation
  - Mounted on carriers
- Full detectors: very special needs ….

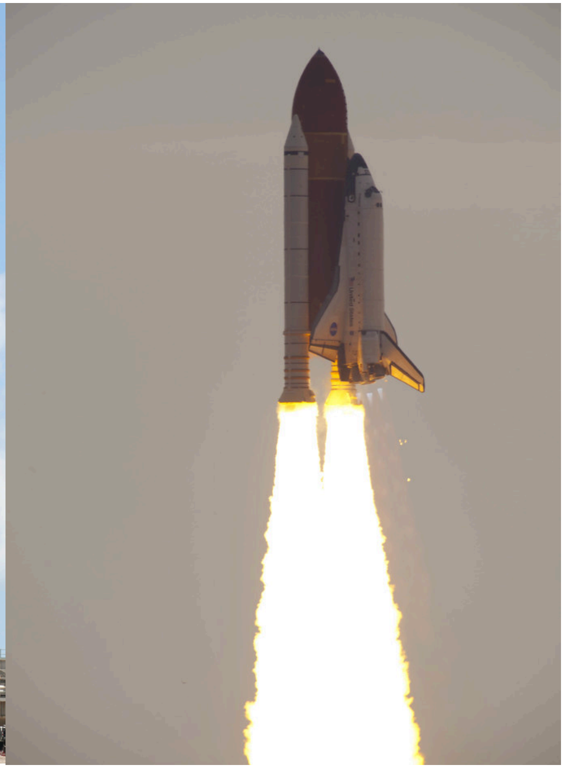
Paul Schütze with 300 CMS Phase I Pixel Detector Modules (selfie)

Belle II PXD2 flying business class

Completely Different Requirements ....

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





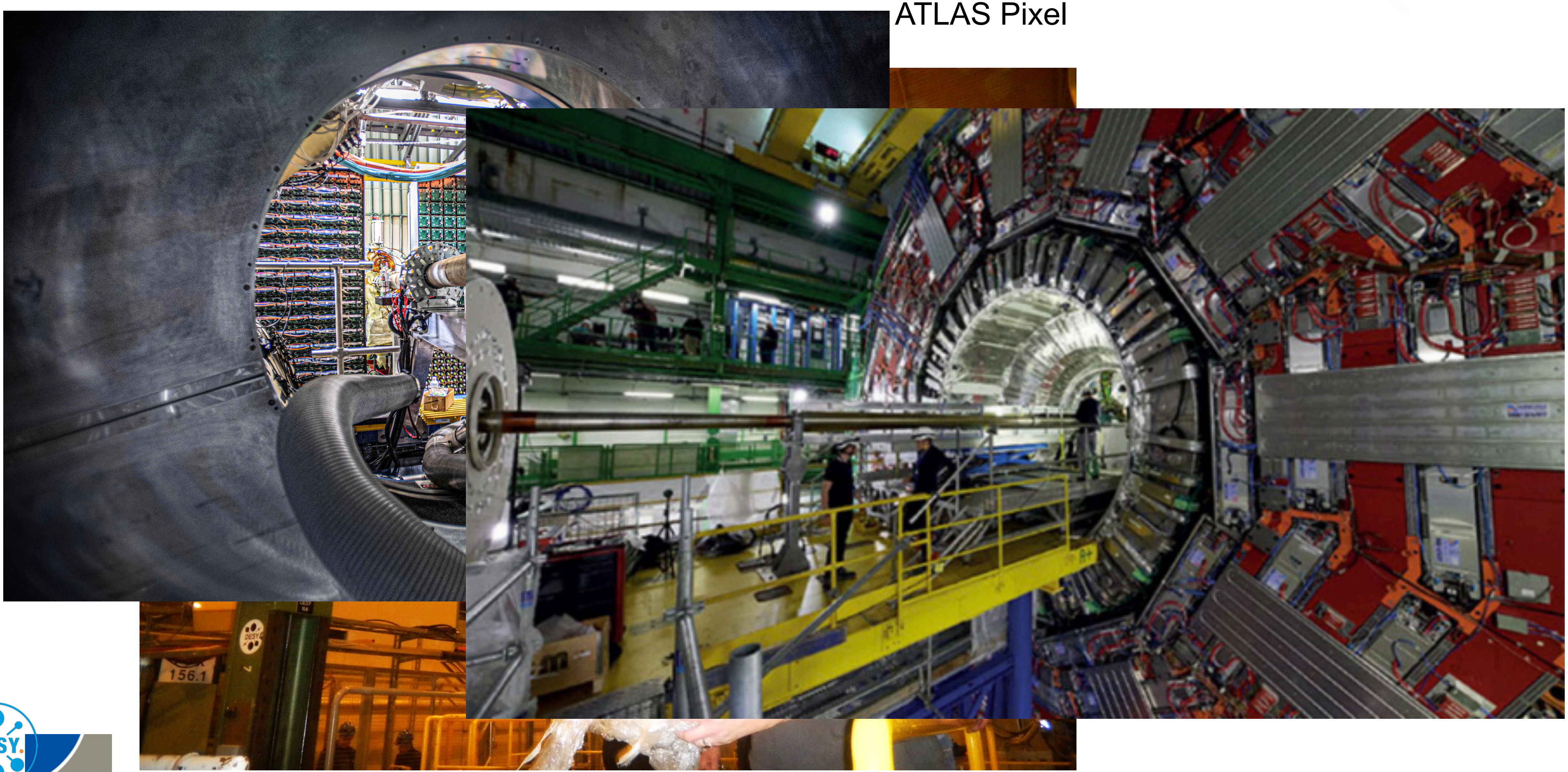
On ground transport requirements <2g due to ramped-up magnet

Getting the Detector Safely to Experiment

Installation

Big Tools are needed!!

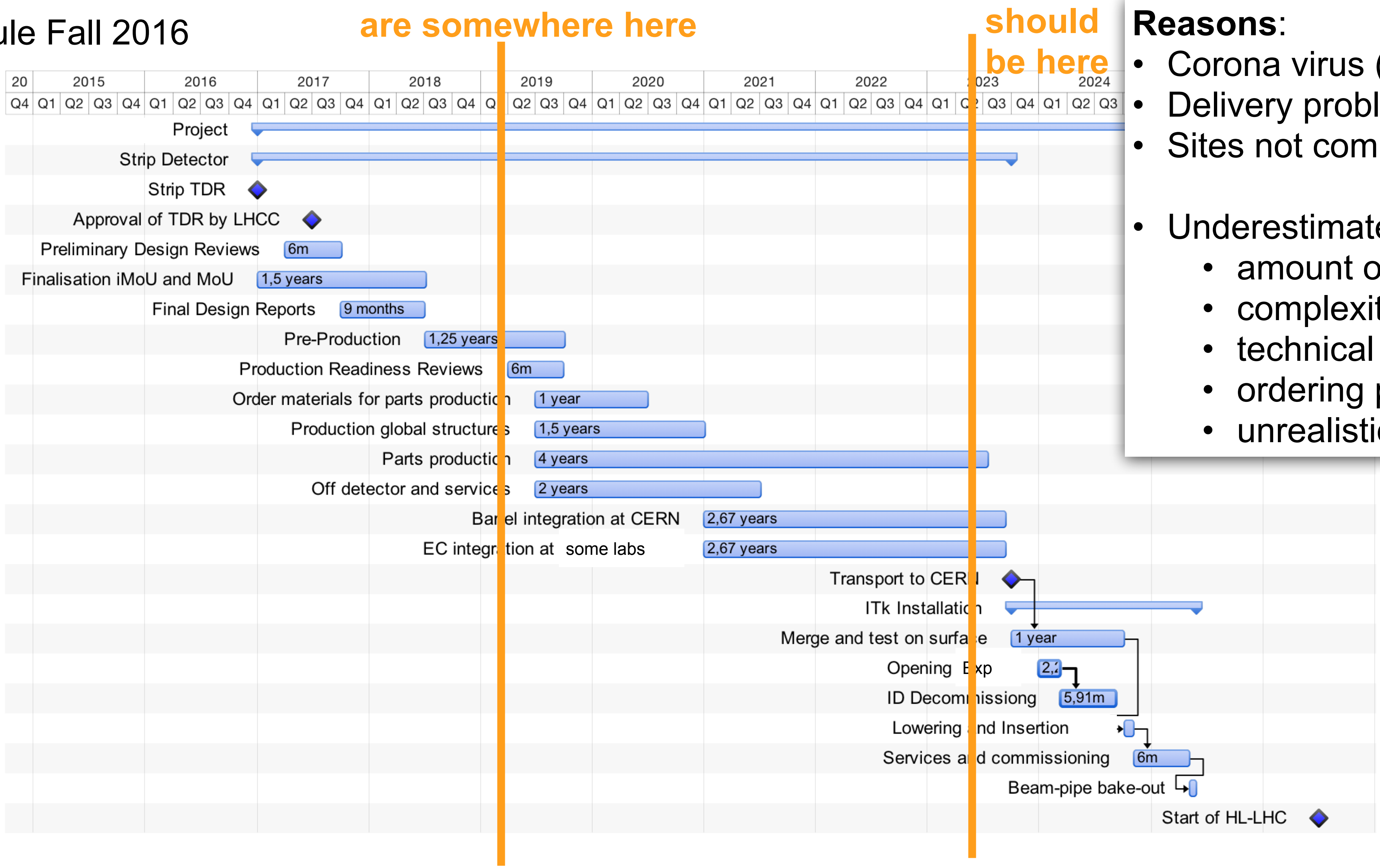
Nice video:
https://www.youtube.com/watch?v=NEpfljUk9sk
ATLAS Pixel



The Schedule ....

An Example - Unknown Experiment

Schedule Fall 2016

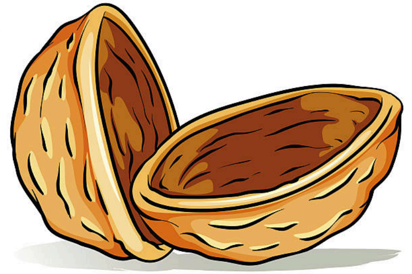


Reasons:
- Corona virus (labs closed)
- Delivery problems
- Sites not coming up

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

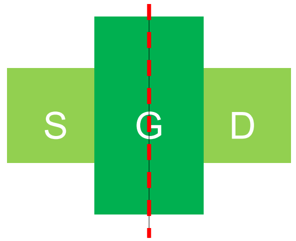
Unexpected Irradiation Failure

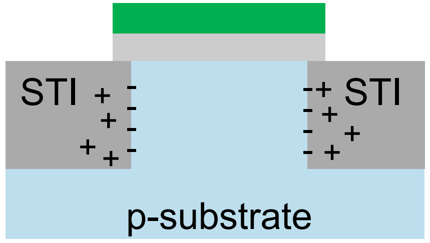
Radiation Damage in Silicon



- Radiation damages the silicon on atomic level significantly leading to macroscopic effects.

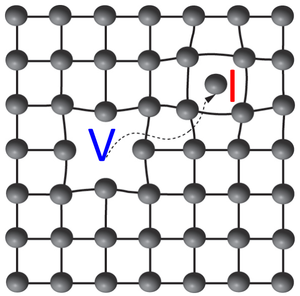
- **Surface effects:** Generation of charge traps due to ionising energy loss — Total ionising dose, TID **(problem for sensors and readout electronics).**
  - Cumulative long term trapping of positive charge
  - Increase of leakage current and oxide breakdown





STI = shallow trench interface

- **Bulk effects:** displacement damage and build up of crystal defects due to non ionising energy loss (NIEL) **(main problem for sensors).**
  - Unit: 1MeV equivalent n/cm^2



Defects composed of:
Vacancies and Interstitials

Compound defects with impuritie possible!

- **Transient effects:** Radiation induced **errors in microelectronic** circuits
  - caused by passing charged particles leaving behind a wake of electron-hole pairs
  - single event upsets, single event latch-ups, ….

Generations of scientists worked on understanding failures connected to radiation damage and how to mitigated the effects - however …

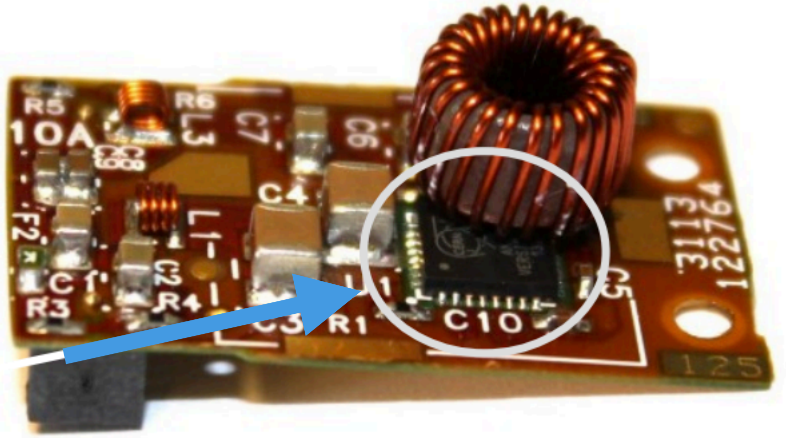
CMS DC-DC Converter

during running

- 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
- 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

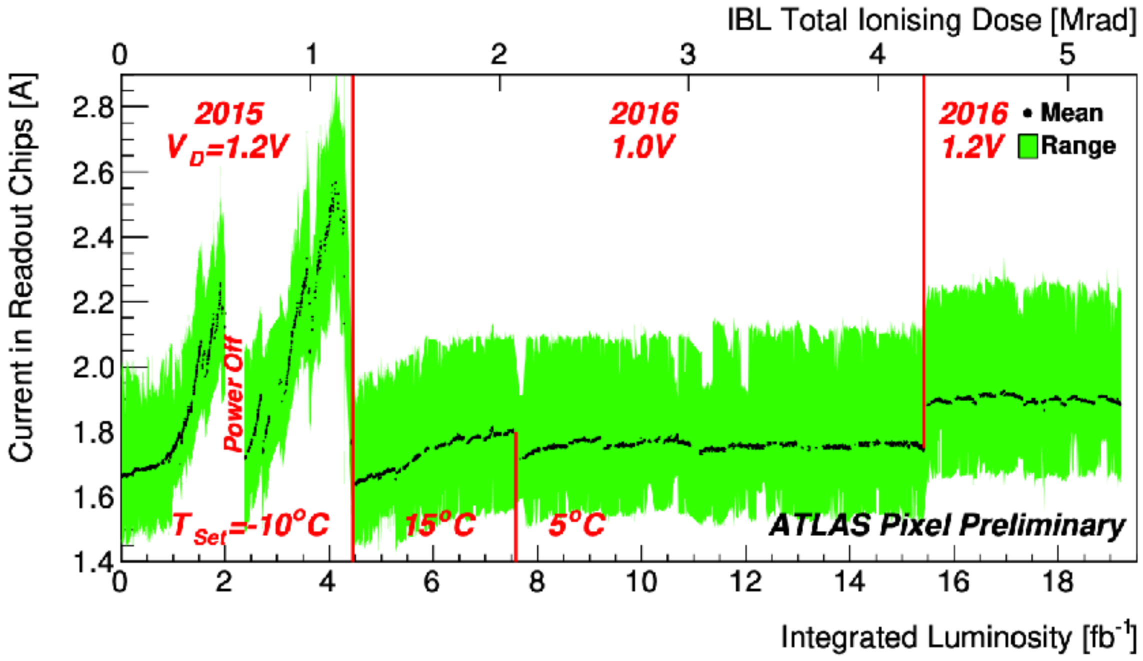
Consequences for operation
- lower input voltage helps
- stop disabling the output

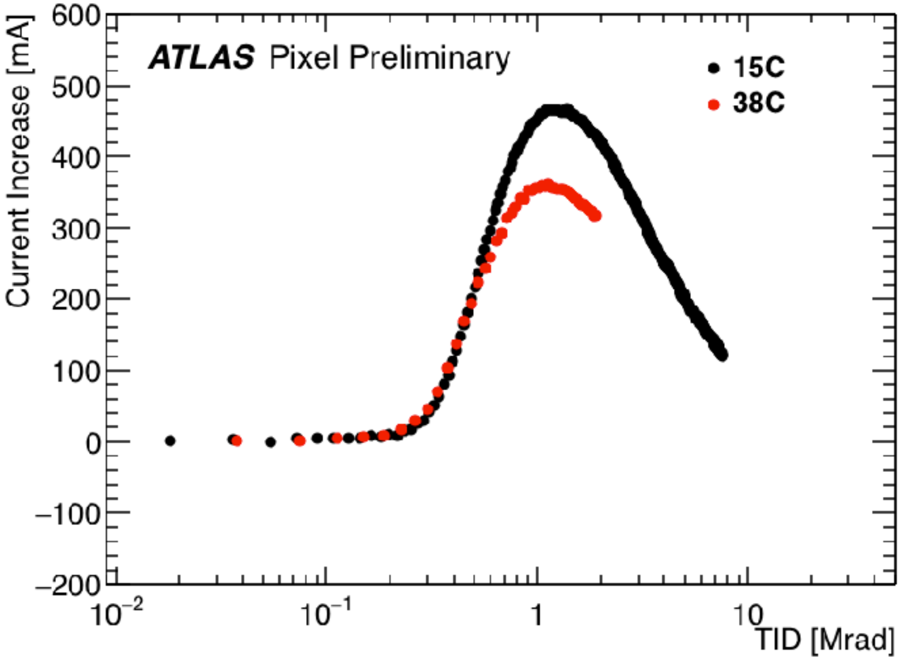
https://project-dcdc.web.cern.ch/project-dcdc/public/Documents/ExecutiveSummary2018.pdf
https://instrumentationseminar.desy.de/sites2009/site_instrumentationseminar/content/e70397/e282395/e287407/20190614_pixelphase1JIS.pdf

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:

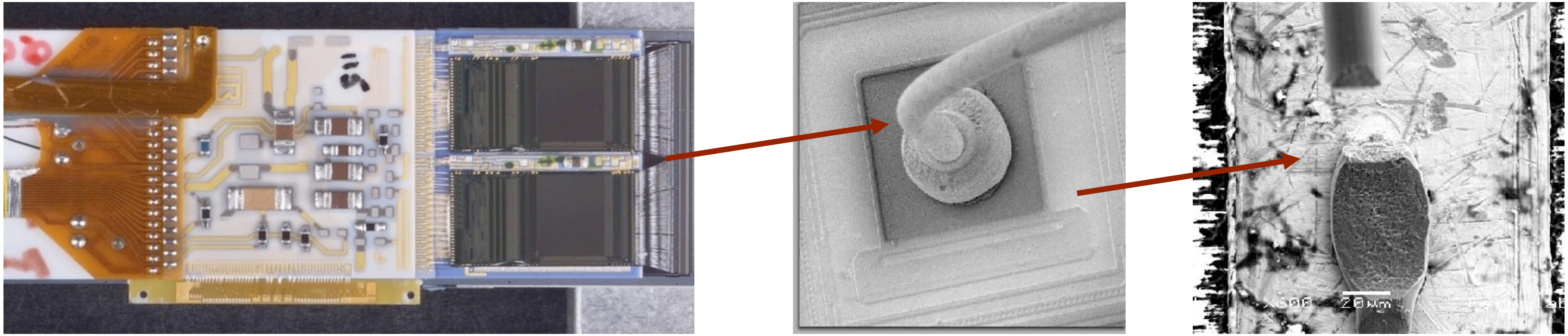
- Operating temperature was increased from −10 ◦C to and 10 ◦C then decreased to 5 ◦C.
- Digital supply-voltage was decreased to from 1.2 V 1.0 V until TID approached more than 4 MRad.

Wire-Bonds and Wire Breakage

Problems with Wire Bonds (CDF, D0)

during running

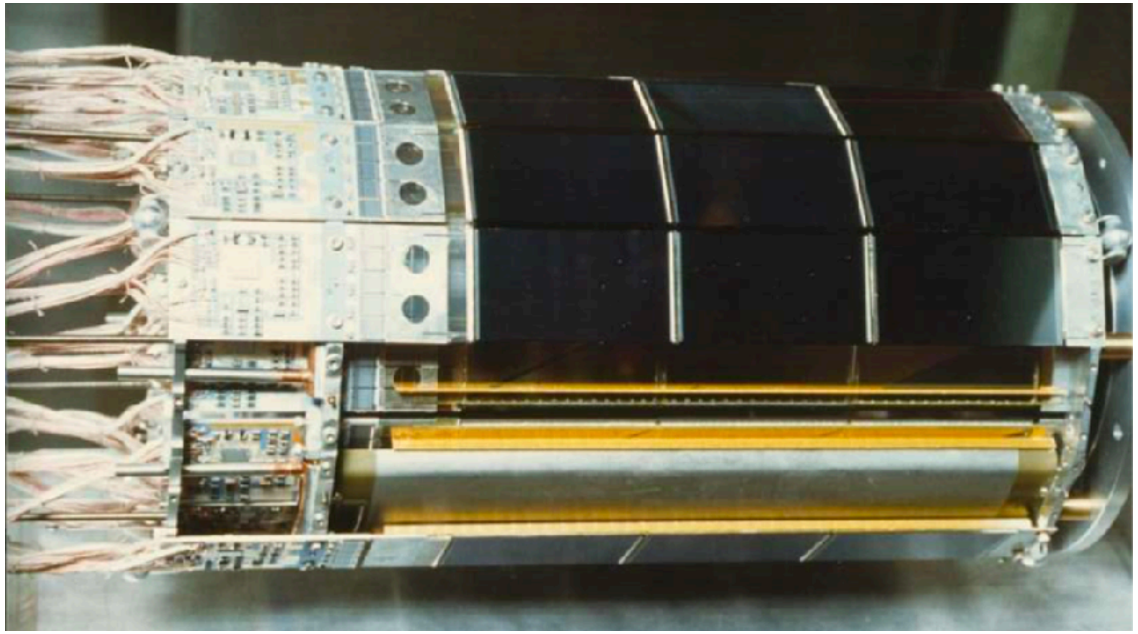
- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- Observation: During synchronous readout conditions, loss of modules (no data, Drop in current)



- 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:

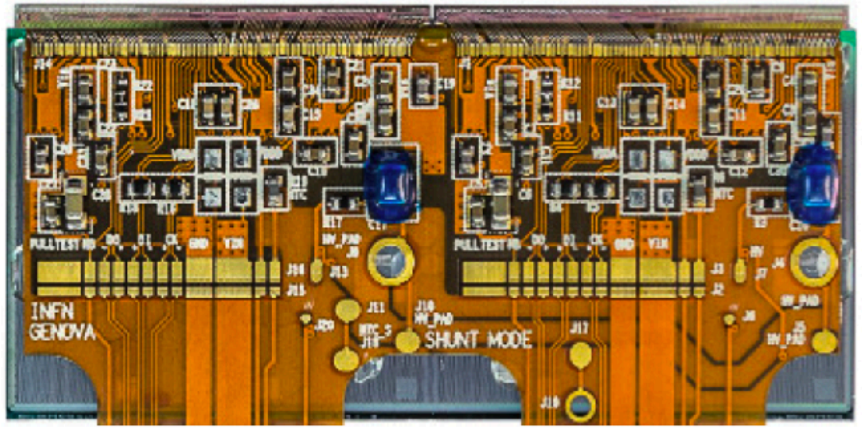
- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

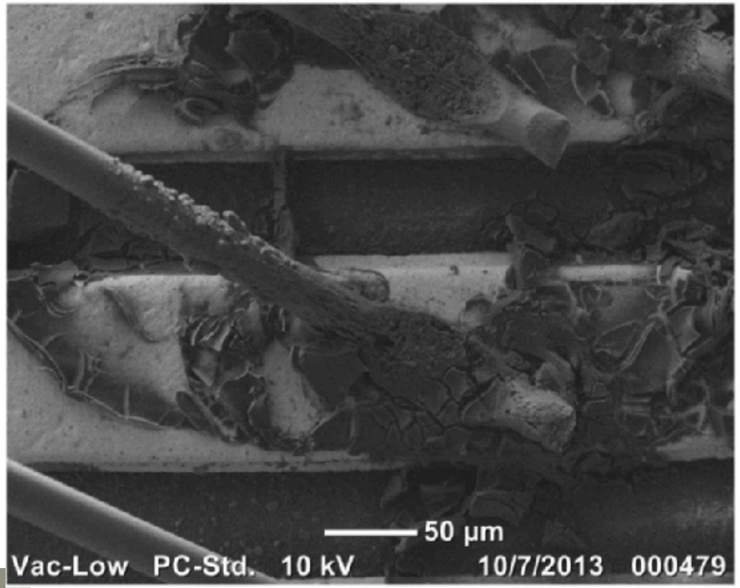
Mitigation plan:

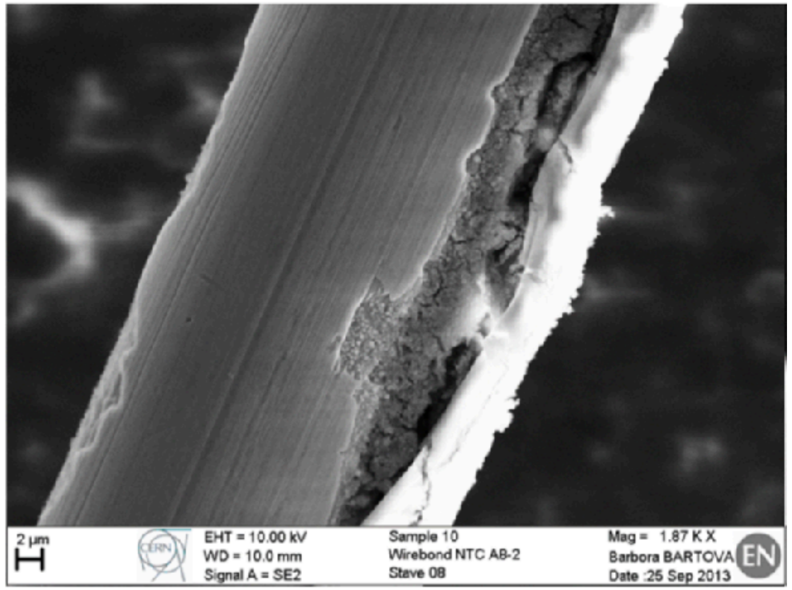
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

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

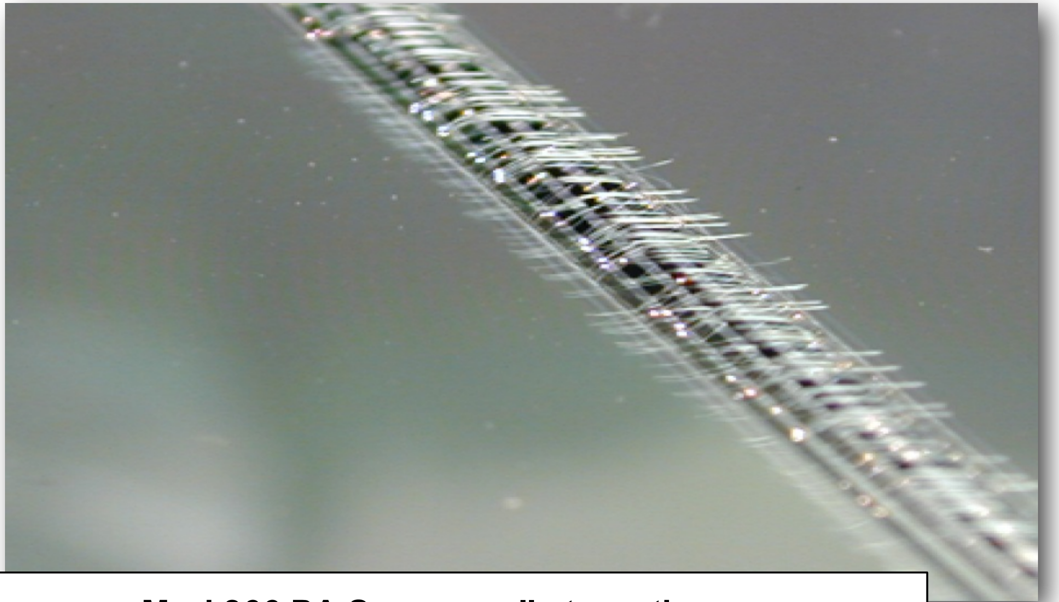
More Wire Bond Wreckage

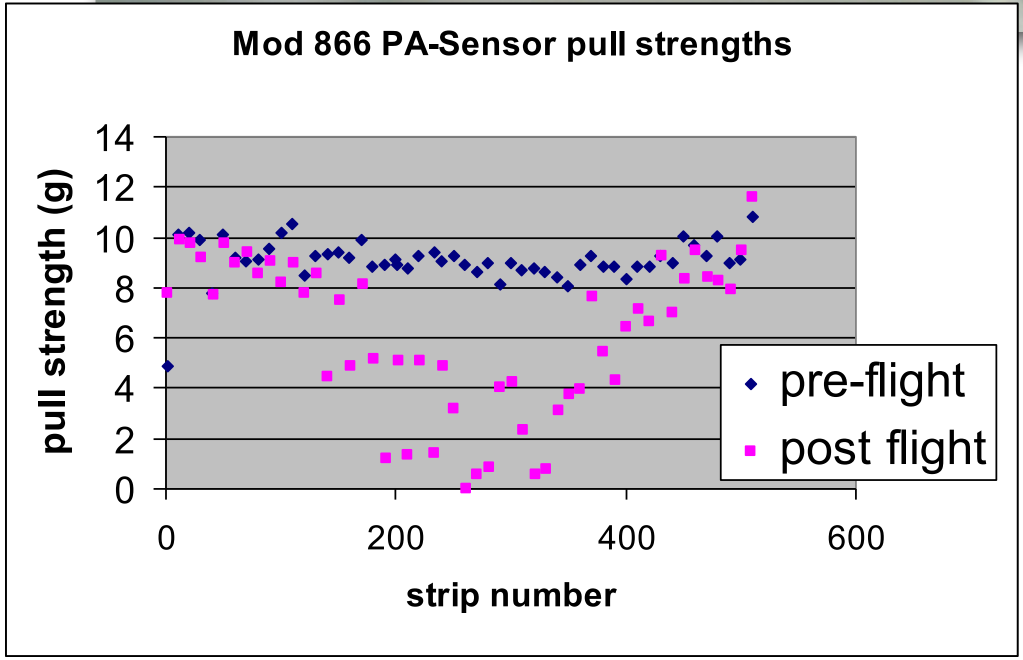
- During CMS strip tracker production quality assurance applied before and after transport
  - Quality of wires is tested by pull tests (measured in g)

- 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



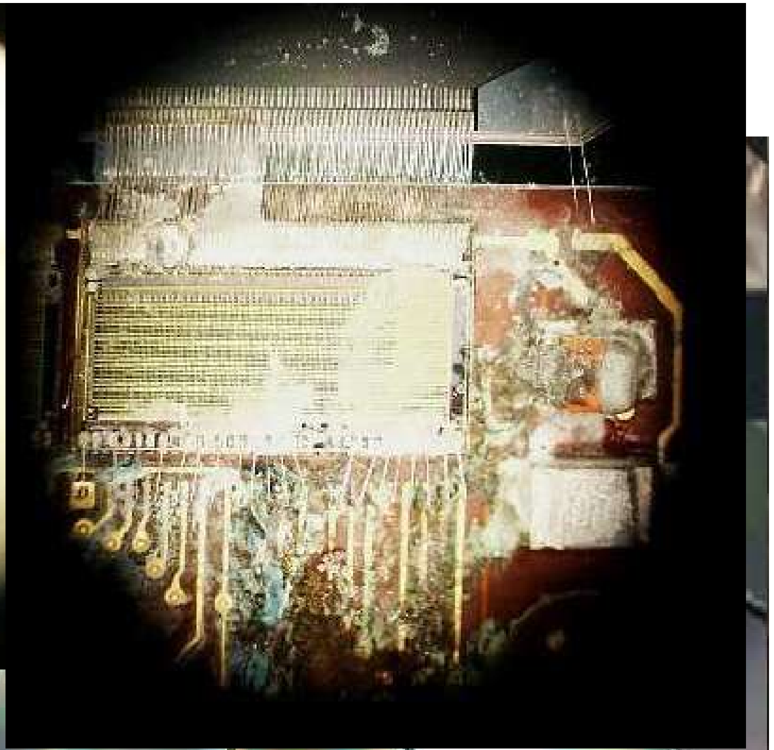


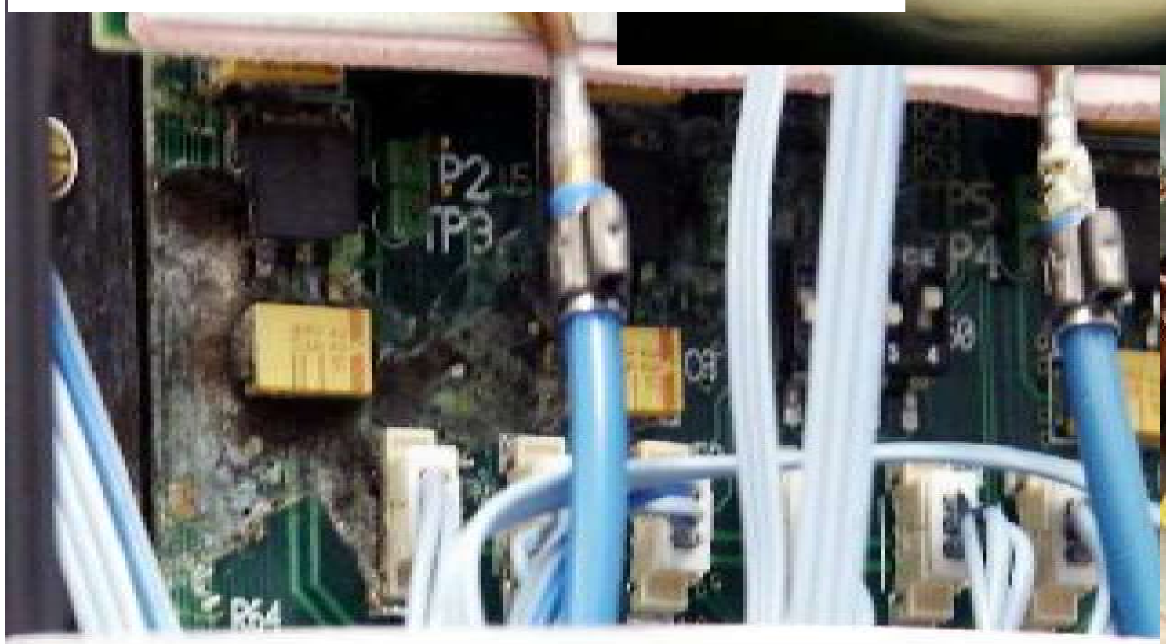
Cooling Damages

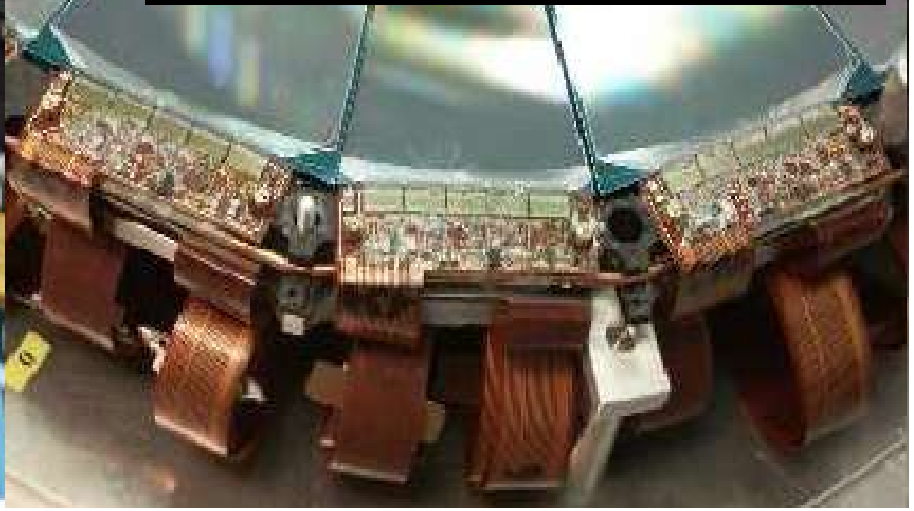
Water Damage in Tracker ...

- H1@HERA FST in 2004
- Imperfect crimp + hardening of plastic (age, irradiation) => water leak
- Water condensation => damage
- Tracker segment had to be rebuilt

during running



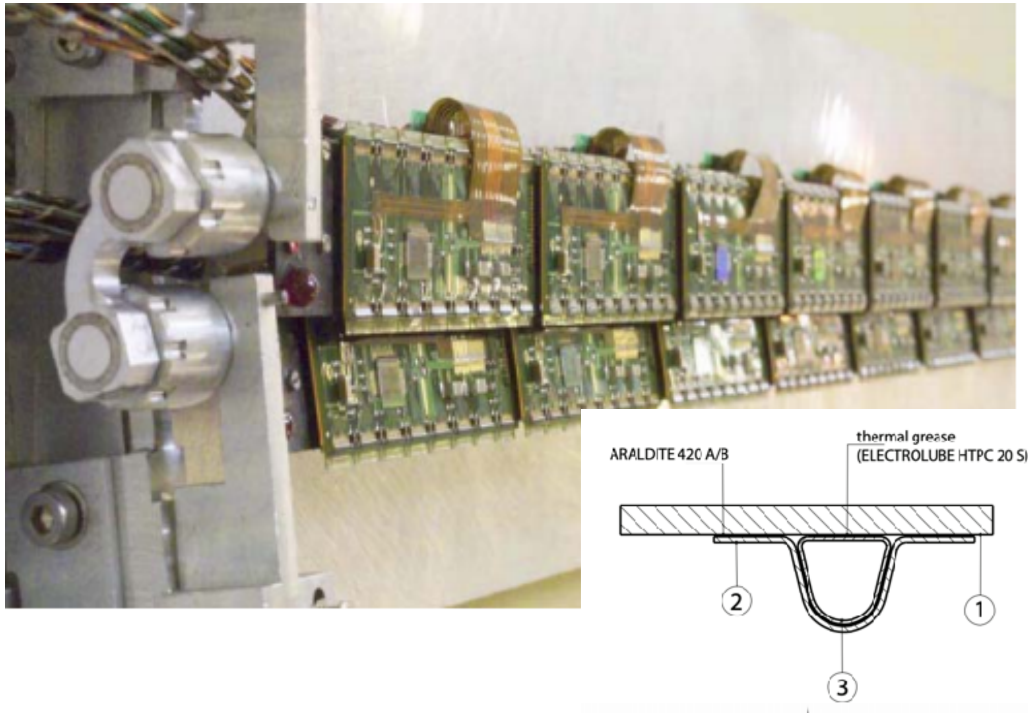


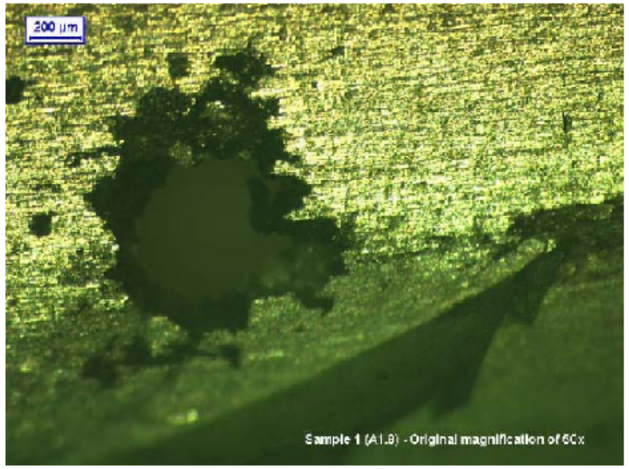


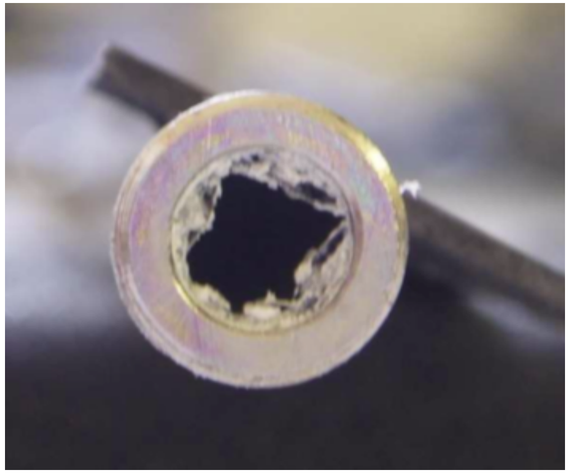
ATLAS Pixel Tube Corrosion

during production

- Cooling tube of current pixel layers were supposed to be very light in material
  - Bare pipe material (Al)
  - Ni plating used to allow for brazing of the pipe fittings
  - No proper drying procedure → water
- Water triggered corrosion process in the aluminium pipes.
  - Corrosion was due to galvanic process where water and traces of halogen (like Cl) acted as electrolyte.
  - Effect of the galvanic corrosion led in some cases to holes in the pipe.







Six months delay in schedule

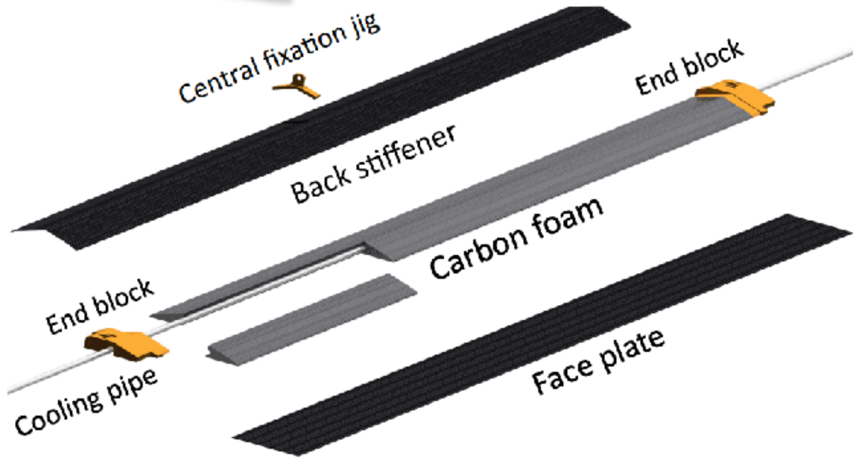
- Repair the 43 loaded staves with a pipe-inside-the-pipe
- Production of new staves with new Al compound and laser welding
- Repair of bare staves (~100)

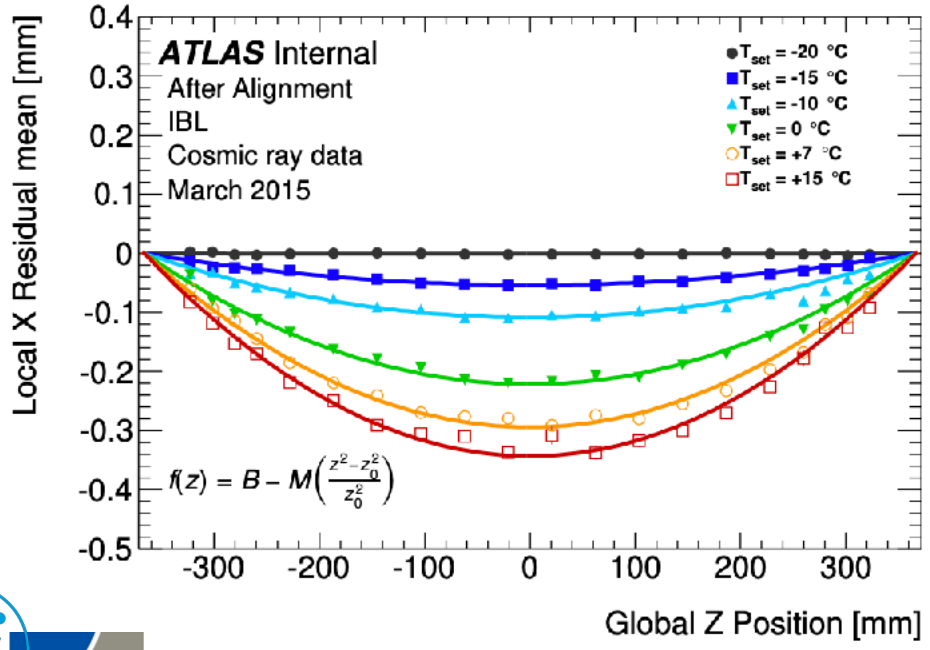
Problems with Mechanics

ATLAS IBL Stave Bow

during commissioning

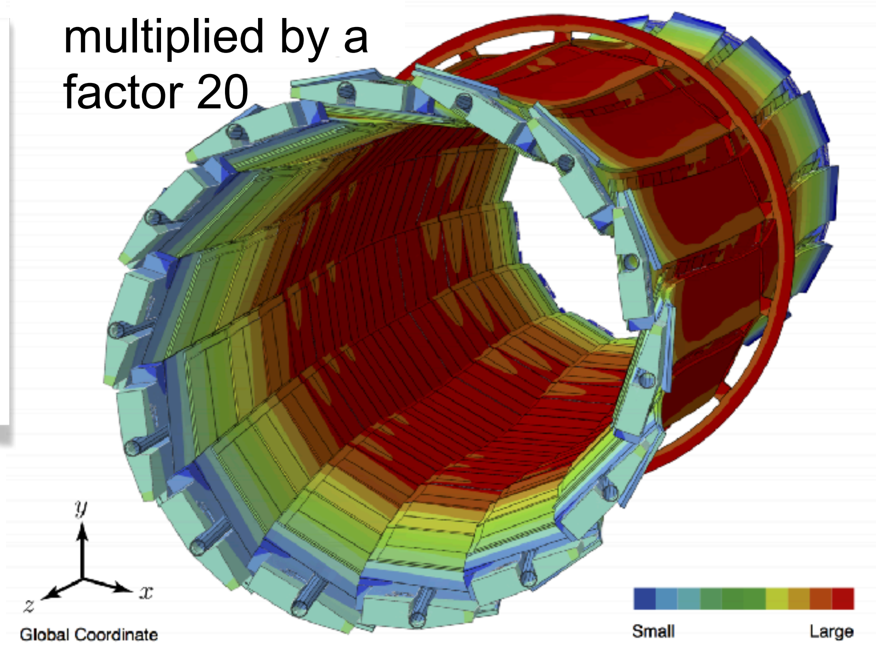
- Distortion depending on the operating temperature was observed.
- Caused by a mismatch between the coefficients of thermal expansion (CTE) of a bare stave made with the carbon foam and the flex attached on the bare stave.
- Maximum more than 300 µm at -20 ◦C with respect to the nominal position at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

Conclusions

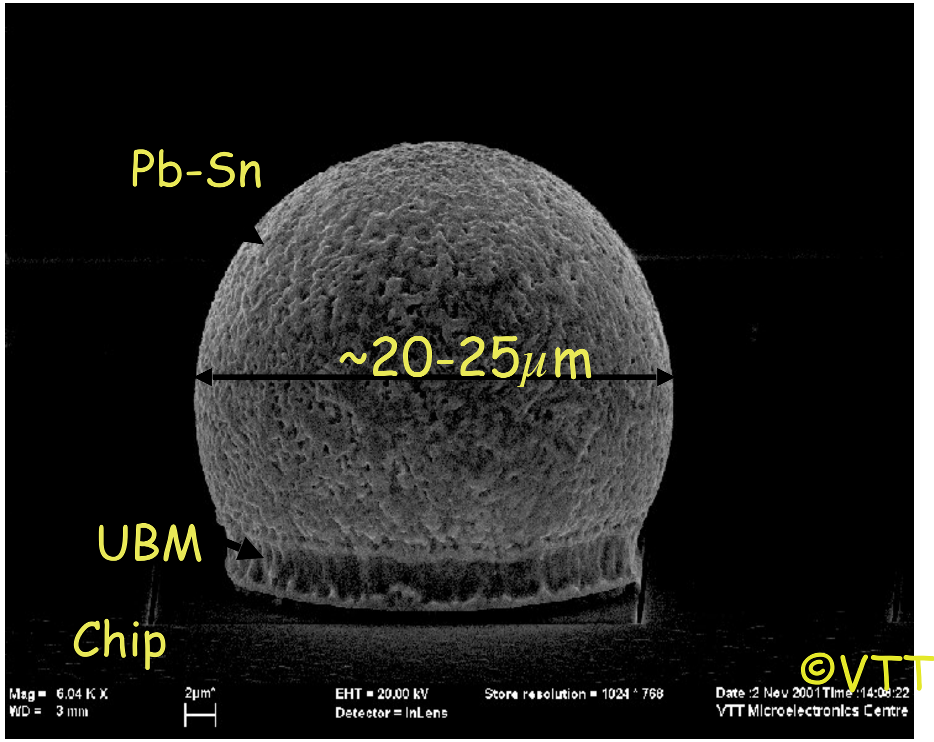
- Building a detector is super complicated - like building a death star
- Scaling from one module to thousands is not trivial

- 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
- …..

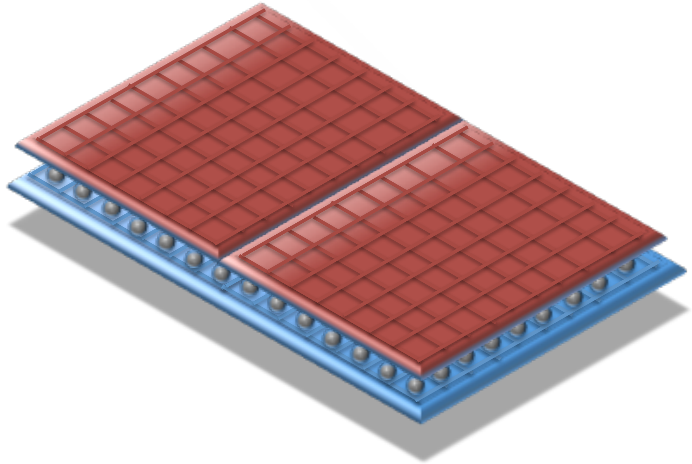
Solving and preventing theses kind of problems is also part of the fascination of detector physics!!

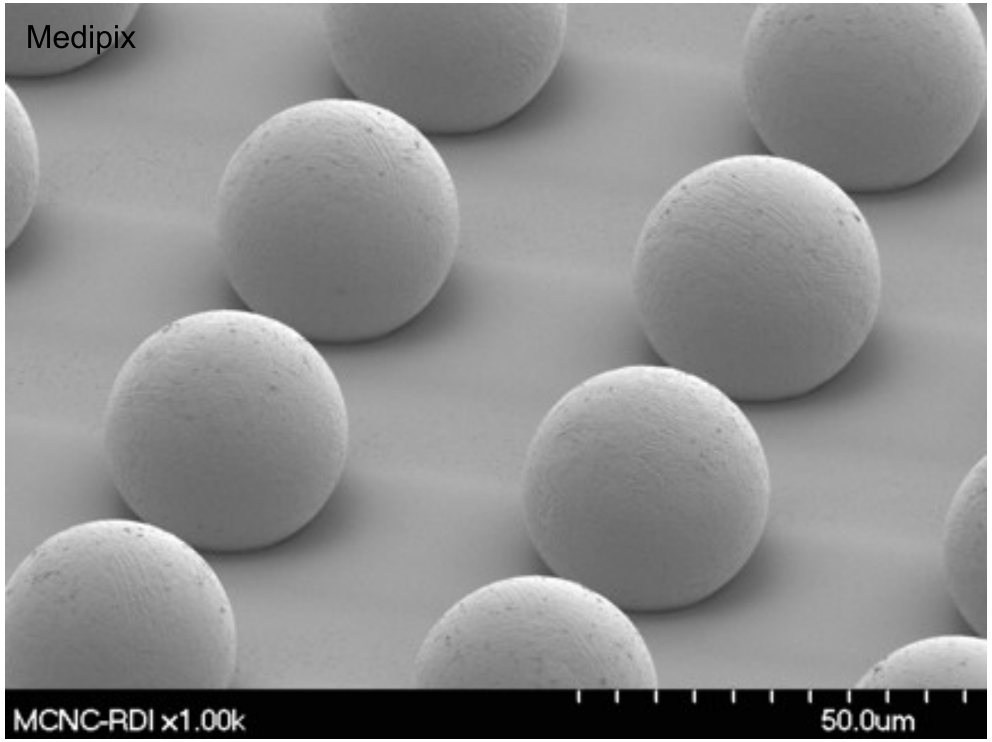
Backup

Bump Bonds



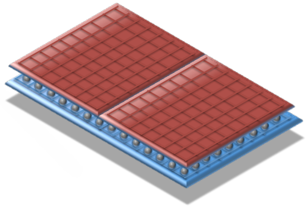
SEM picture of one Pb-Sn bump bond





Bump bonding process

For reference

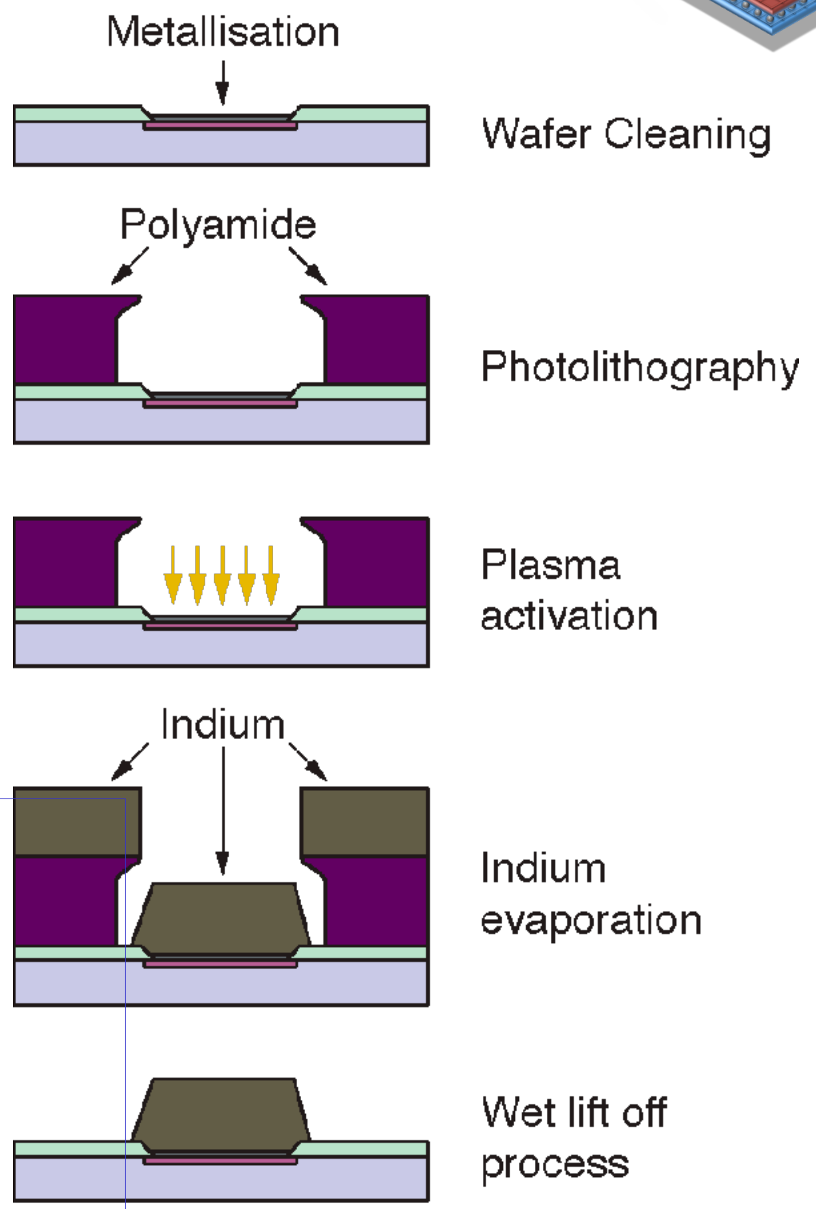


A typical bump bonding process (array bump bonding) is the following:

1. Deposition of an “underbump 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 spheres.

Process parameters:

- Resist Thickness: 15 μm
- Pre-bake: 30min @ 80 °C
- Deposition rate: 0.5 μm/min
- Dep. Pressure: 9 x 10 $^{-7}$ Torr
- Temp. during Dep. < 50 °C

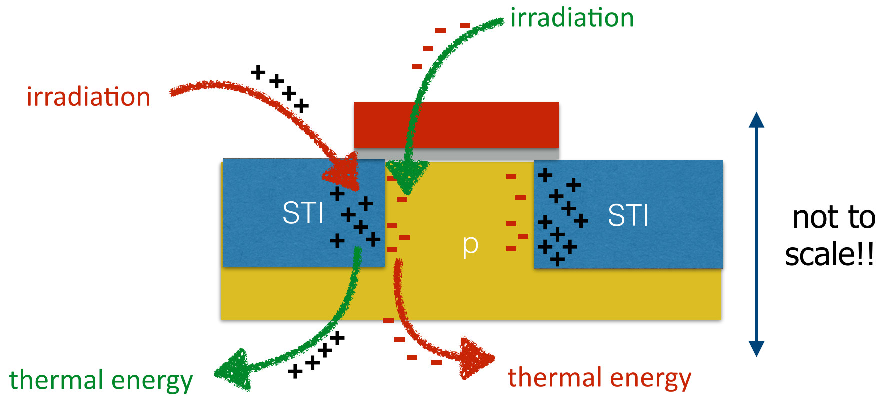


L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

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 dependen
- 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