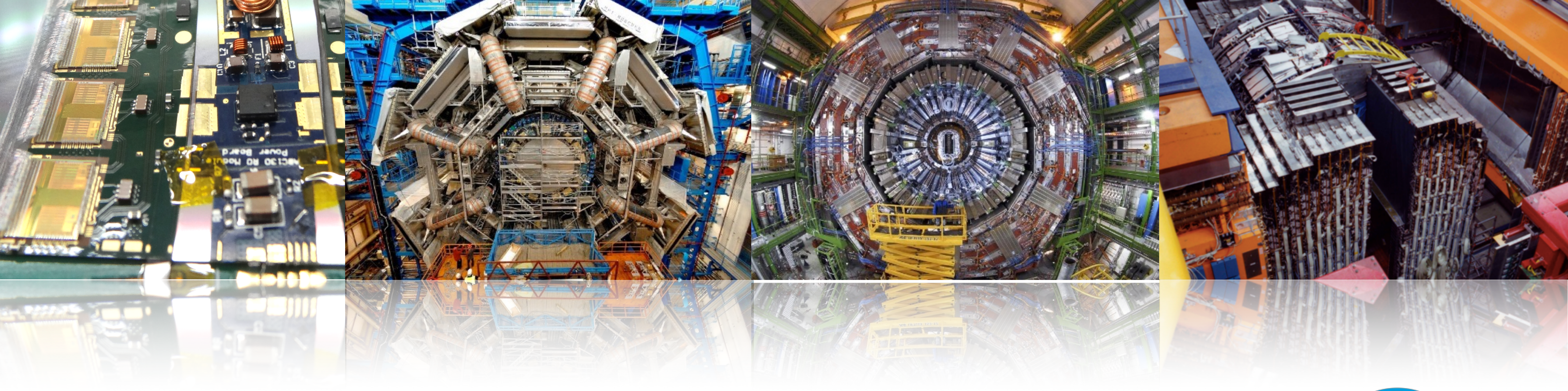


Detectors for High energy Physics

Ingrid Maria Gregor, Simon Spannagel

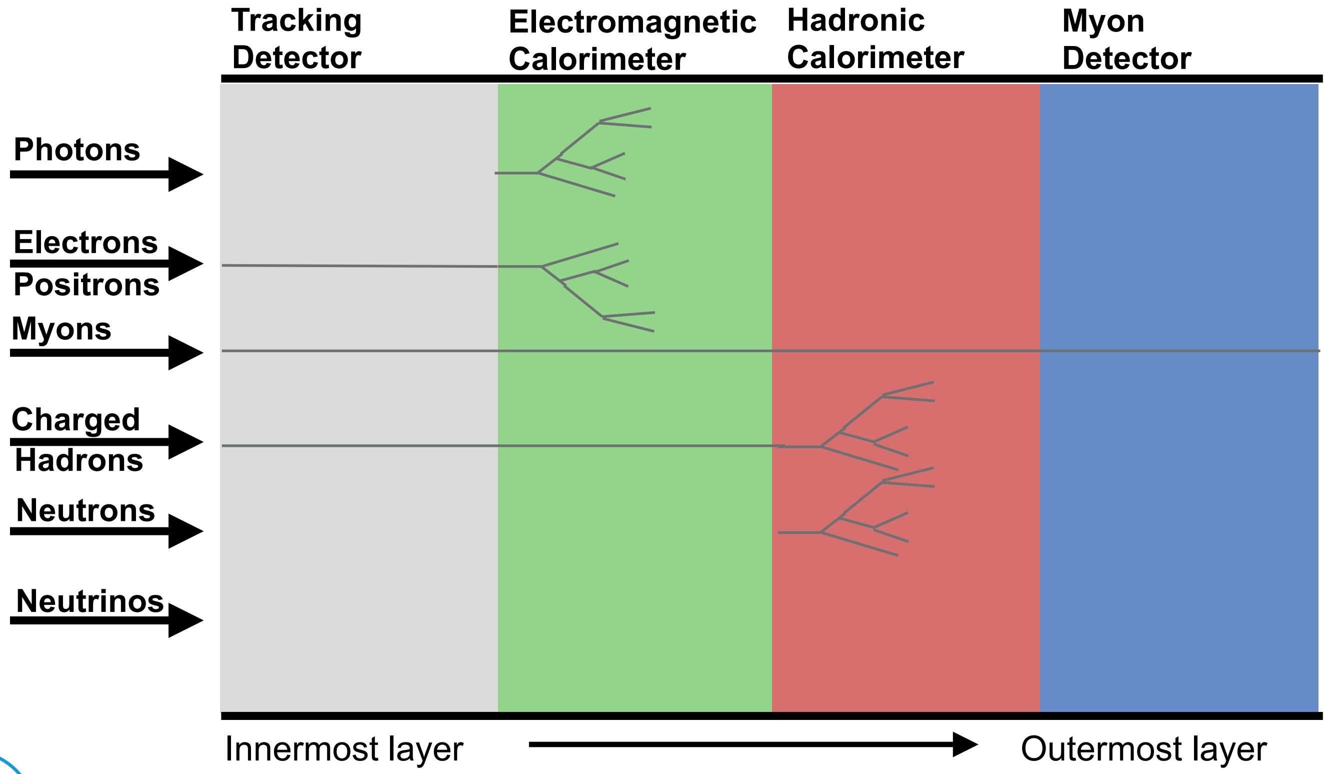
Part 5

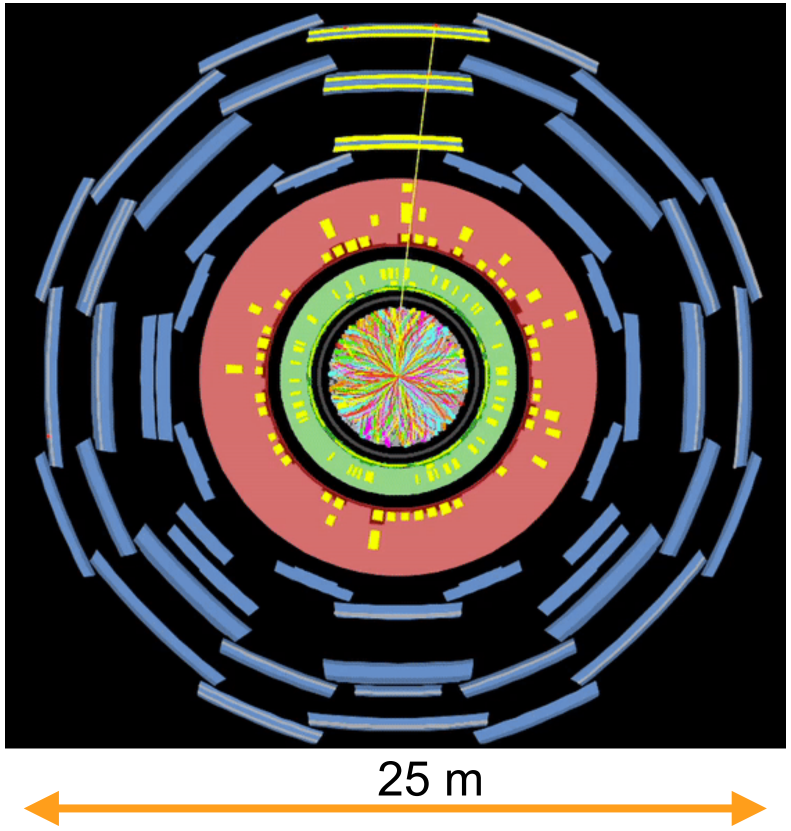
DESY Summer Student 2025

Detector Concepts

Particle Physics Detectors

- There is not one type of detector which provides all measurements we need -> “Onion” concept -> different systems taking care of certain measurement
- Detection of collision production within the detector volume
  - resulting in signals (mostly) due to electro-magnetic interactions





How to do a particle Physics Experiment

- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger
  - recording devices
- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data
  - many people to:
    - design, build, test, operate accelerate
    - design, build, test, calibrate, operate, understand the detector
    - analyse data

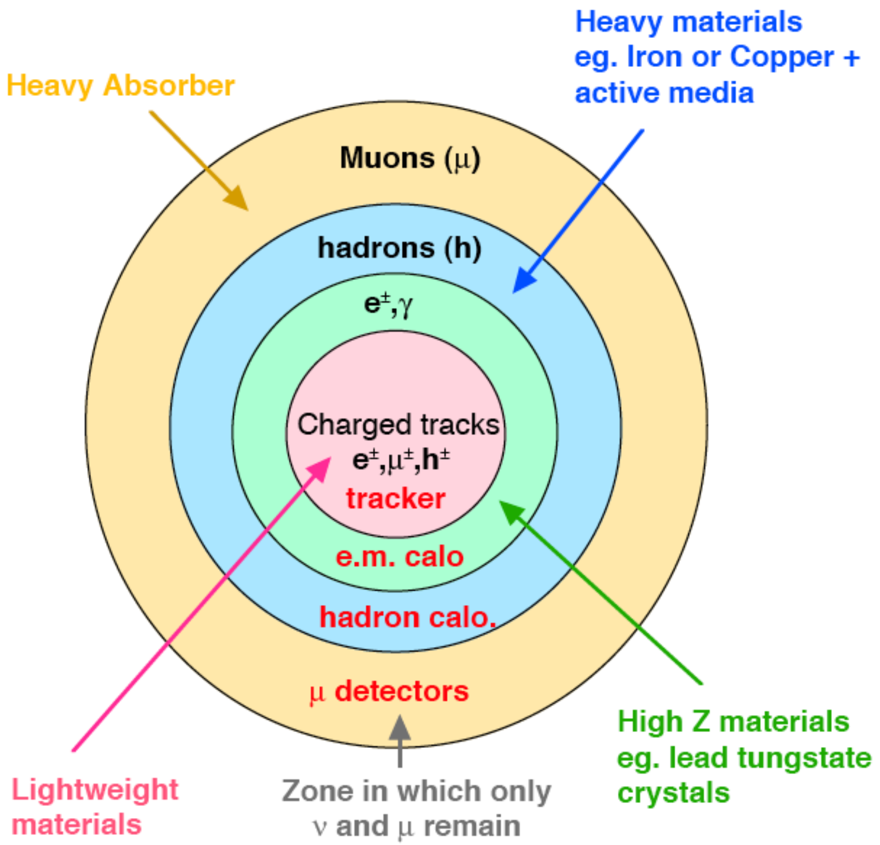
typical HERA collaboration: ~400 people
LHC collaborations: >2000 people

Pic: DESY

- lots of money to pay all this ….

Conceptual Design of HEP De

- Need detailed understanding of
  - processes you want to measure ("physics case")
  - signatures, particle energies and rates to be expected
  - background conditions
- Decide on magnetic field
  - only around tracker?
  - extending further ?
- Calorimeter choice
  - define geometry (length, X0)
  - type of calorimeter
  - choice of material depends also on funds



at a collider experiment

- Tracker
  - technology choice (gas and/or Si?)
  - number of layers, coverage, …
  - pitch, thickness, ….
  - also here money plays a role

Detailed Monte Carlo Simulations need to guide the design process all the time !!

A magnet for a LHC experiment

- **Wish list**
  - big: long lever arm for tracking
  - high magnetic field
  - low material budget or outside detector (radiation length, absorption)
  - serve as mechanical support
  - reliable operation
  - cheap
  - ….

$\Delta p_T/p_T \approx 1/BL^2$

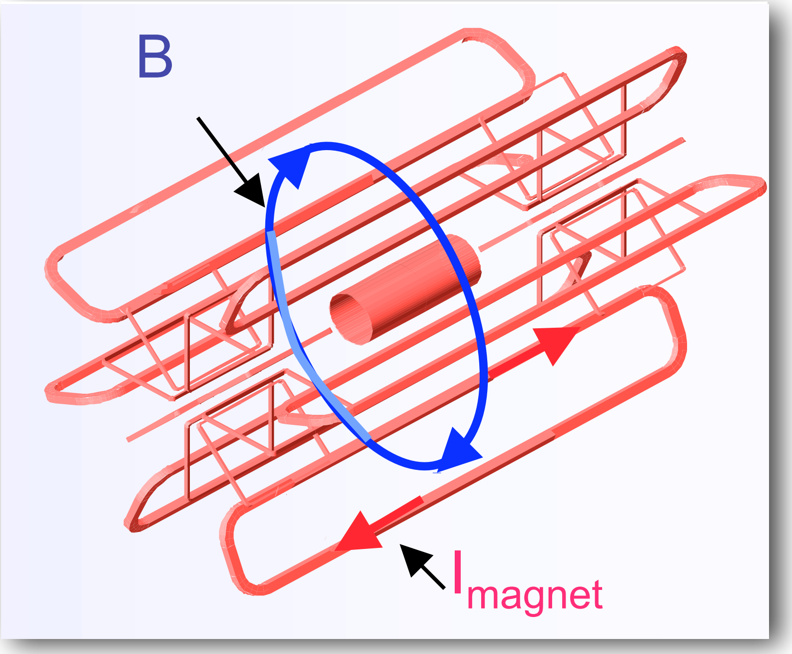
www.positoons.de

Eierlegende Wollmilchsau

- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

- **CMS decision**
  - single magnet with the highest possible field in inner tracker (momentum resolution)
  - muon detector outside of magnet

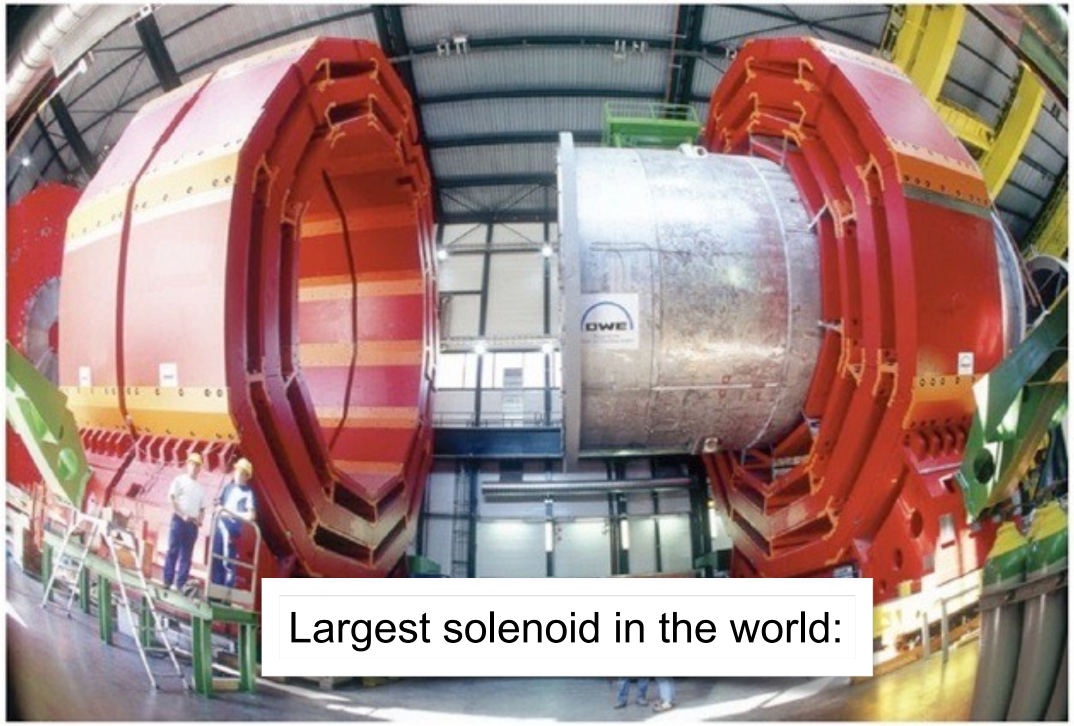
Magnet-Concepts: ATLAS -> Toroid

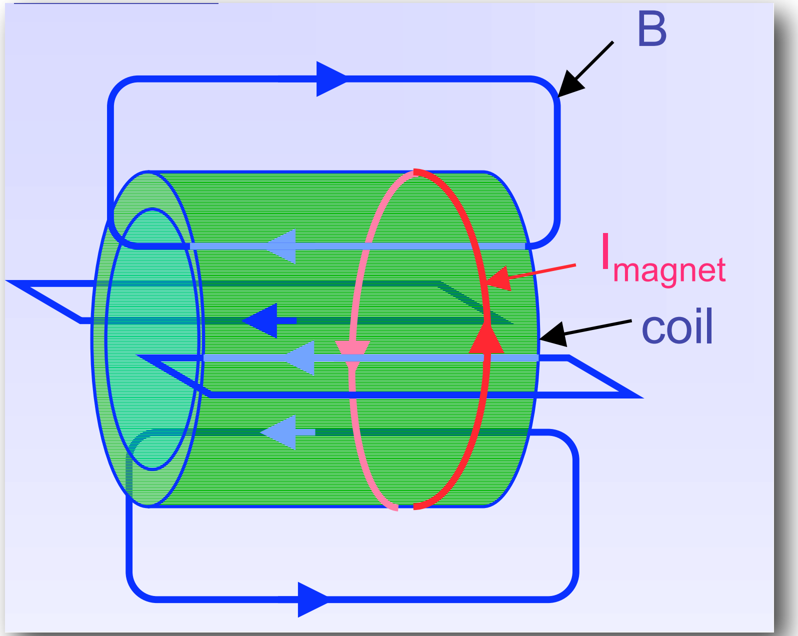


- Central toroid field outside the calorimeter within muon-system: <4 T
  - Closed field, no yoke
  - Complex field
- Thin-walled 2 T Solenoid-field for trackers integrated into the cryostat of the ECAL barrel

+ field always perpendicular to $\vec{p}$
+ relative large field over large volume
- non uniform field
- complex structure

Magnet-Concepts: CMS -> Solenoid

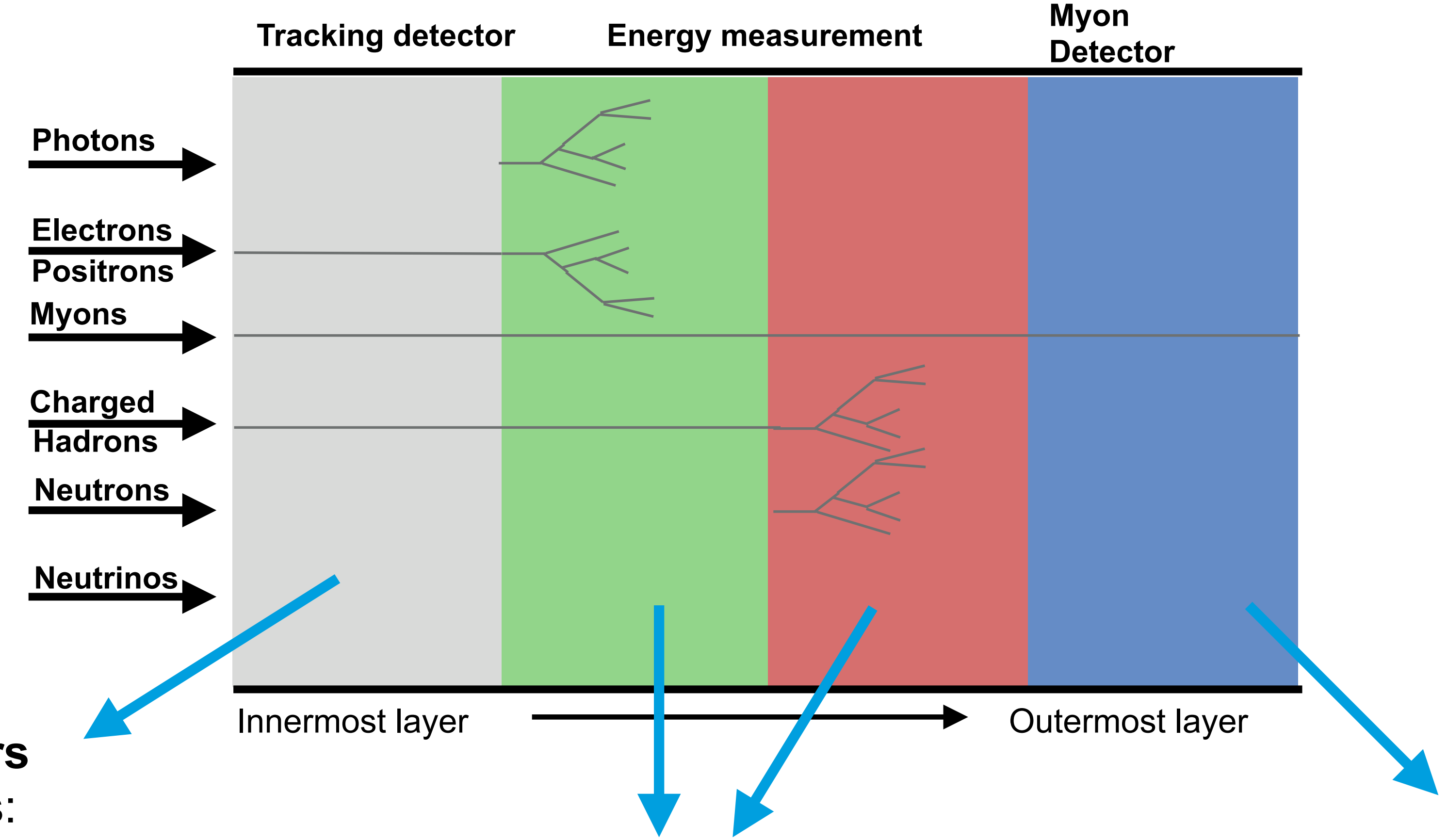




- Super conducting, 3.8 T field inside coil
- Weaker opposite field in return yoke (2T)
- Encloses trackers and calorimeter
- 13 m long, inner radius 5.9 m, I = 20 kA, weight of coil: 220 t

+ large homogeneous field inside coil
+ weak opposite field in return yoke
- size limited (cost)
- relative high material budget

Particle Physics Detectors



Tracking detectors

- Silicon detectors:
  - pixel
  - strip
- Gas detectors
  - wire chambers
  - time projection chambers
  - ….

Calorimeter

- Electromagnetic cal
- Hadronic cal

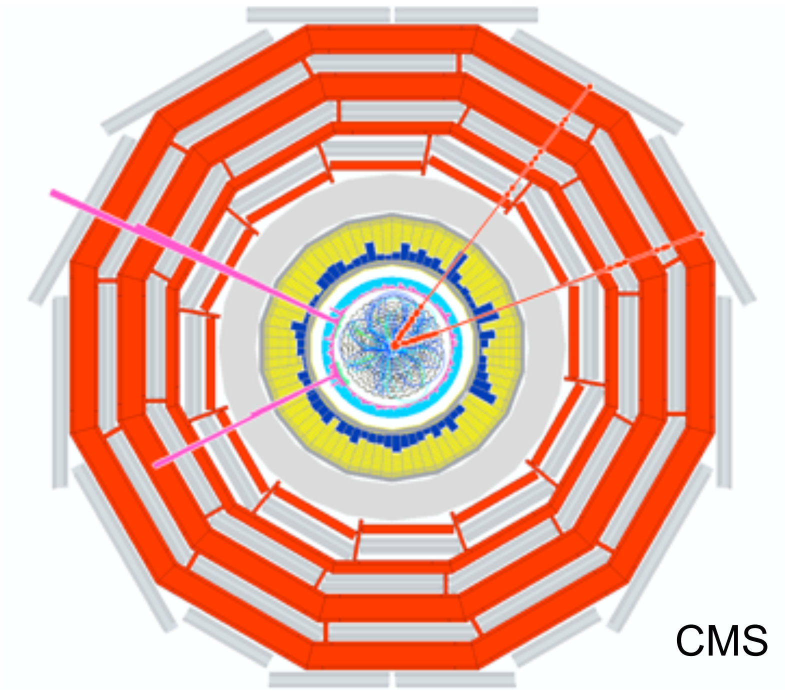
- Homogeneous
- Sampling

Muon detectors = outside tracker

- Gas detectors
  - Wire chambers
  - …

What is a Trigger ?

- Collisions every 25 ns with many simultaneous interactions
- A lot of information stored in the detectors - we need all information
- Electronics too slow to read out all information for **every** collision
- But: a lot of the interactions are very well known - we only want rare events
- “Trigger” is a system that uses simple criteria to rapidly decide which events to keep when only a small fraction of the total can be recorded.



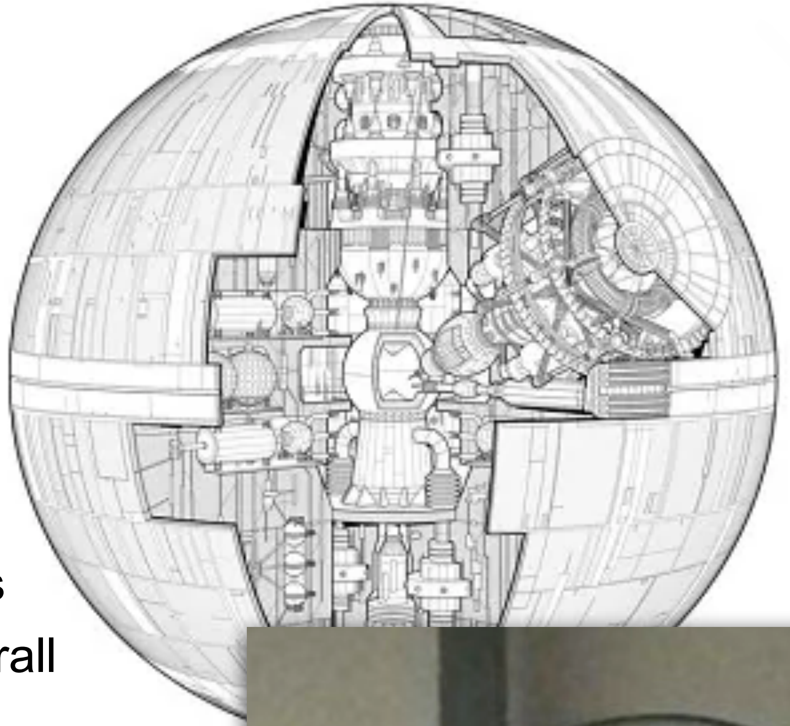
CMS

- Want to know the information of green cars
  - number of passengers
  - speed
  - weight
  - …..
- Trigger = system detecting the color and initiating the information transfer all information

Real Life Examples
And What Can Go Wrong ...

Disclaimer

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



A death star is nothing against a particle physics

- Idea of this part: some stuff you don't find in textbooks
- Collection of failures might give the impression of overall incompetence
  - Overwhelming majority of detectors run like a chime
  - Unbelievable effort to get large accelerators and experiments in a global effort to run so nicely
  - Even sociologists are interested in how we do this …

Some bias in the selection of detectors and examples based on my experience, my friends and other factors …

Problems in overall Concept

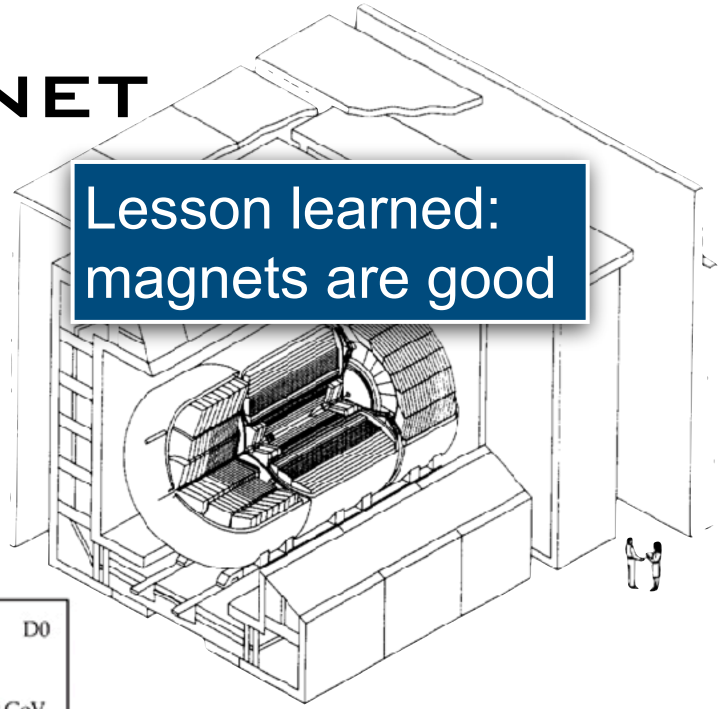
D0 without Inner Tracking Magnet

- D0 Experiment at Tevatron constructed to study proton-antiproton collisions
- **Top quark discovery** in 1995 together with CDF experiment

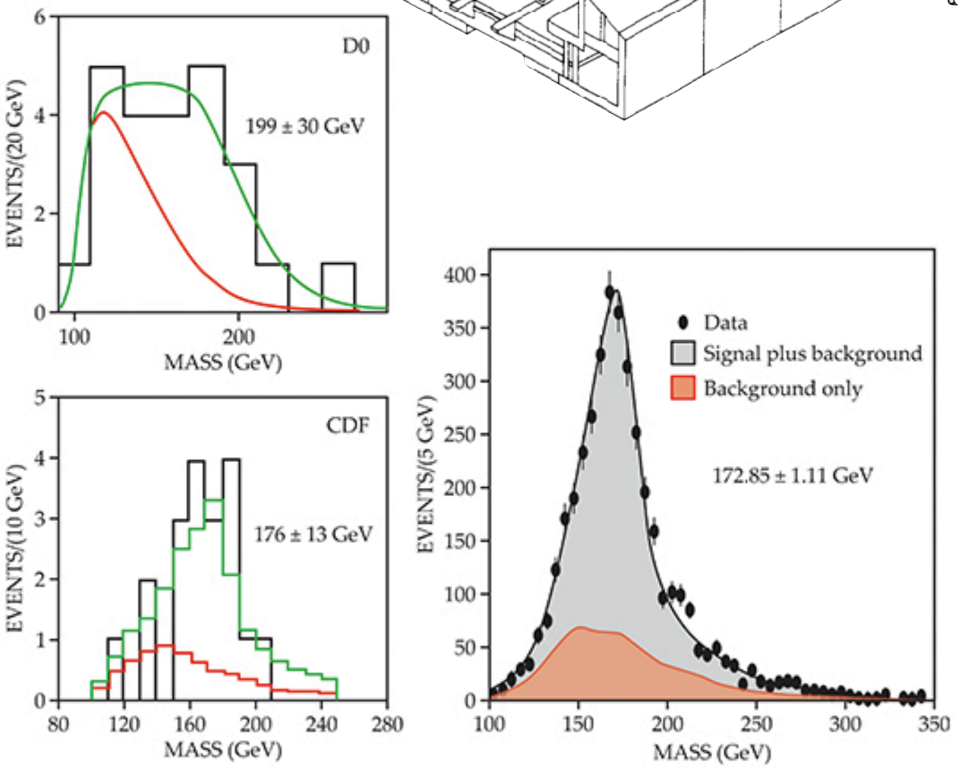
  - Original design for Run I: no magnet for tracking
    - “Focussing on parton jets for deciphering the underlying physics than emphasis on individual final particle after hadronisation”
    - Very compact tracking system
    - Uranium-liquid argon calorimeter for identification of electrons, photons, jets and muons

  - Effect of low momentum charged particles greatly underestimated resulting in analysis difficulties.

Run II system included a silicon microstrip tracker and a scintillating-fibre tracker located within a 2 T solenoidal magnet.



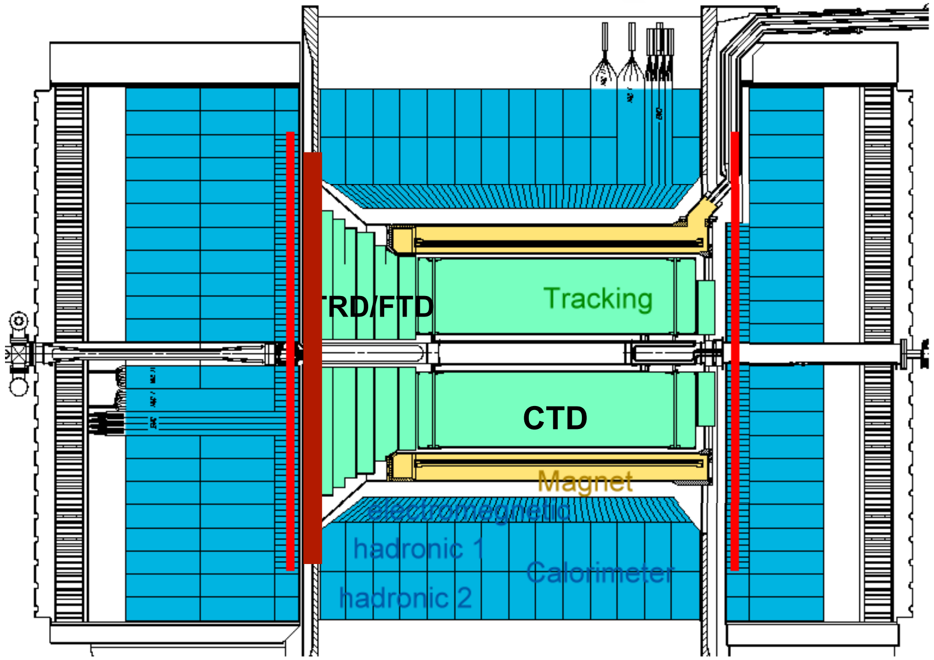
Lesson learned: magnets are good

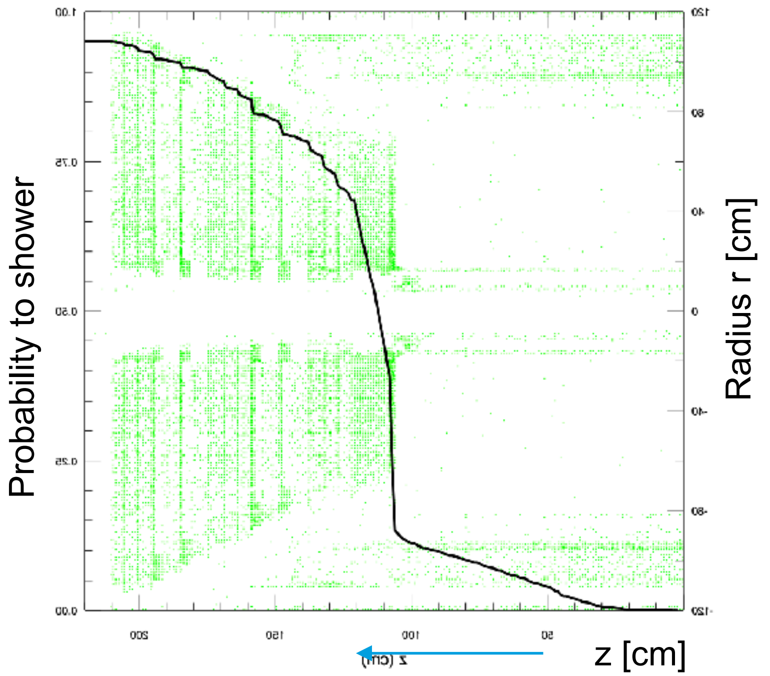


Top quark discovery

ZEUS TRD

- Zeus Transition Radiation detector for electron identification.
- Aim: h/e rejection ratio of about 10^{-2} for electron tracks embedded in jets (1 - 30 GeV/c).
  - However - central tracking detector (wire chamber) had 2cm end-plate for wire fixation
    - Electrons 100% probability to shower and thus were not present in showers anymore
  - Reason for mishap: no proper Monte Carlo simulation tools available at time of detector design
    - TRD used for Here Run I Replaced by Straw Tube Tracker for Run II



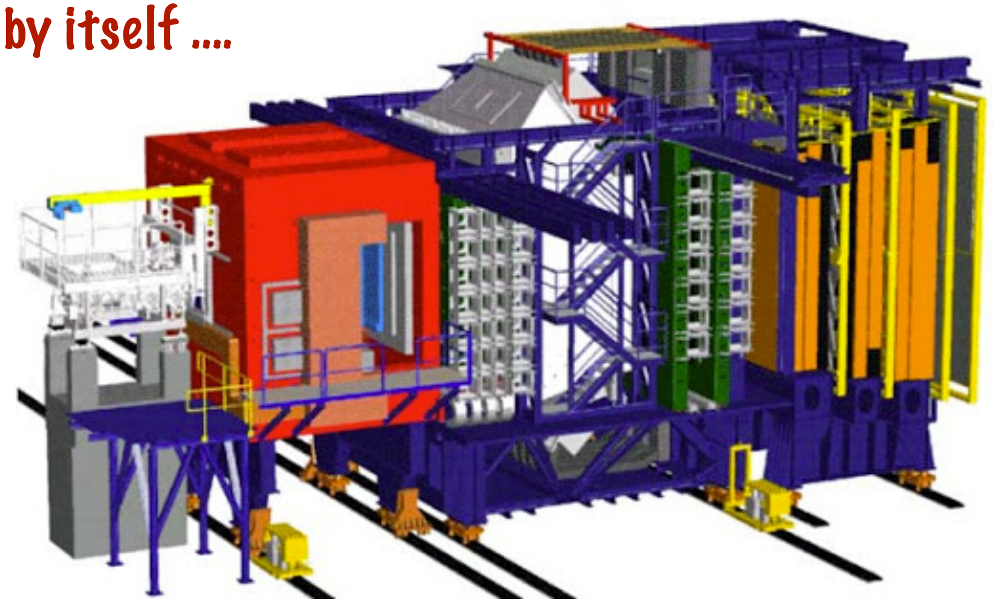


Lesson learned:
Monte Carlos simulations should include everything

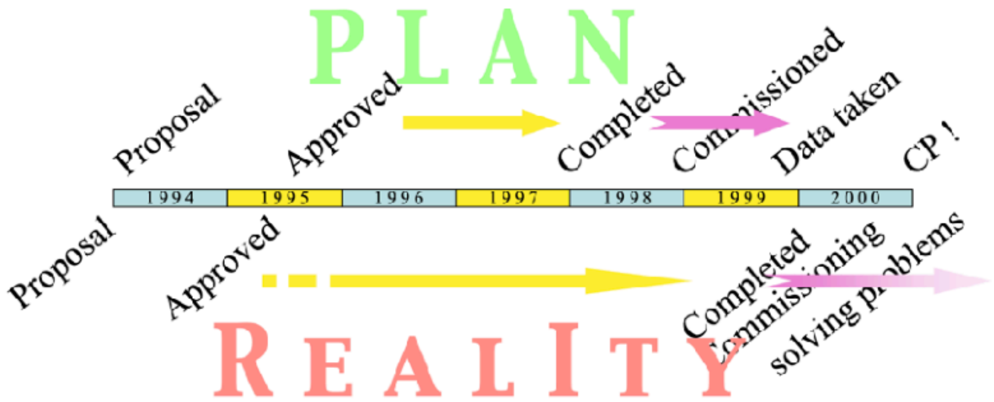
HERA-B

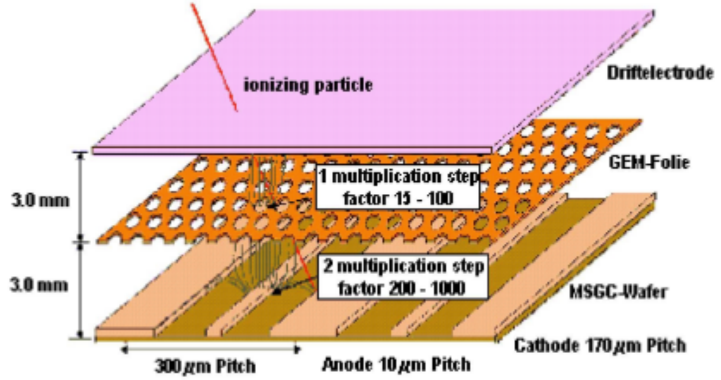
Would be a full lecture by itself ….

- HERA-B started as a search for CP violation in $B \rightarrow J/\psi K_s^0$.
  - Fixed target hadronic b-factory
- **Bad surprises:**
  - Inner and outer tracker demanded more R&D to get ready for the running at HERA-B
  - Additional R&D required for the tracking system: two year delay.



- In the mean time Belle and BaBar measured CP violation in B meson decays (ICHEP 2000)
- Decided to ramp Hera-B slowly down …..



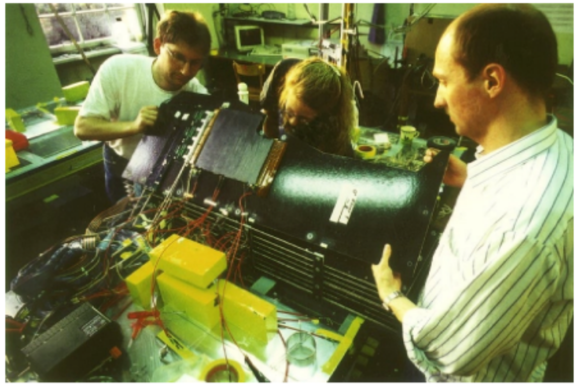


Frontier detector technology: microstrip gas chambers

- 300 μm strip pitch on glass substrate
- only 6 mm total height
- read out by custom made ASIC chips (HELIX)

http://www-hera-b.desy.de/general/info/CERN-Seminar.pdf

Challenges in Tracking System

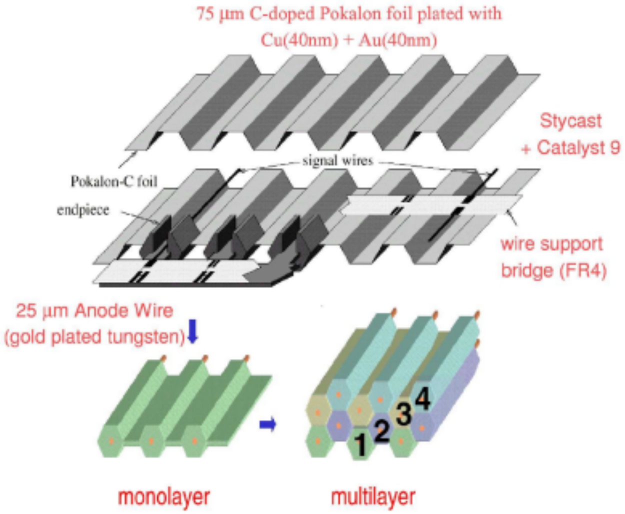


Inner tracker:

- Microstrip gas chamber based on new technology: micro-pattern gas detectors (GEMs)
  - particle flux too high for conventional wire chambers (pitch > mm) (too high occupancy)
  - area too large for Silicon Micro Strips (pitch 50 µm) (expensive, too many channels, large capacity…)
- Before production: Breakdowns occurred at the intolerable high rate of a few sparks per hour -> cured by changing field geometry
- During production: New massive ageing phenomena on production series chambers -> reduced HV stability due to radiation damage

Outer tracker:

- Honeycomb Drift Chamber with 5 mm and 10 mm drift cells
- Rapid ageing of chambers due to radiation environment
- Painful learning curve resulting in 1.5 years delay
- During running: started to lose channels due to faulty mounting of certain HV capacitors!



Reasons

03/03/03 06:10 7 **Comment** from **SG, UH**
Arriving at Hall West at 6:00, we don't see anybody around. The control room is dark and locked, and the HERA display announces "SHUTDOWN" (sounds a bit like Genesis 1,1, but that was a beginning...)

03/03/03 07:16 8 **Comment** from **Bernhard Schmidt**
... in fact, at 6:45 the darkness was quite complete.
And nobody around to say goodbye...Sleep well, old lady ;-)

- Very challenging particle physics experiment
  - Particle flux in detector
  - Radiation damage
  - Event rate
  - Data throughput
- Hera-B was a "flip/flop" experiment
  - Only one physics measurement:
    CP violation in B decays
  - No backup plan for reduced requirements

Not all bad ….

- More than 100 Phd theses
- Most technical challenges solved
- CMS changed tracking design

- Schedule from the start very tight in light of a challenging project
  - B-factories (e^+e^-) BarBar (SLAC) and BELLE (KEK) in construction
  - Competing with B-factories: HERA-B without a chance

2002 : CP-Violation measured with > 5σ

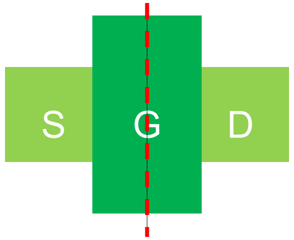
Hera-B: LHC detector prototype!

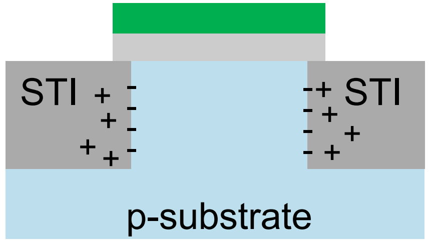
Unexpected Irradiation Failure

Radiation Damage in Silicon

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

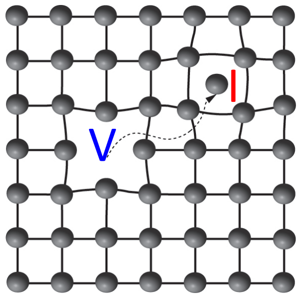
- **Surface effects:** Generation of charge traps due to ionising energy loss — Total ionising dose, TID **(problem for sensors and readout electronics).**
  - Cumulative long term trapping of positive charge
  - Increase of leakage current and oxide breakdown





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 **I**nterstitials

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 …

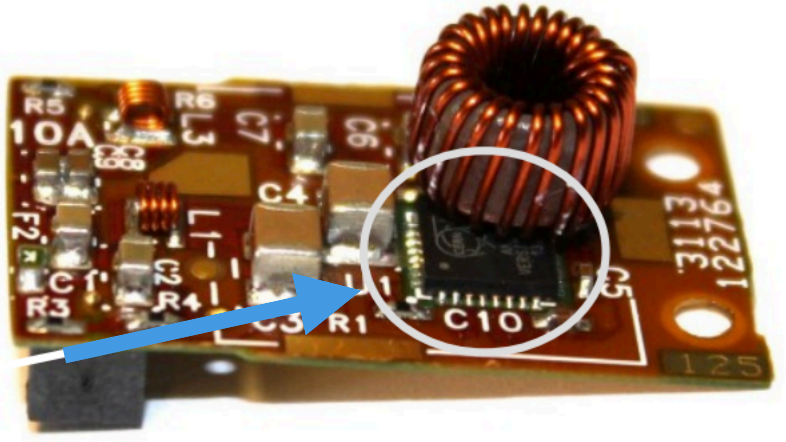
CMS DC-DC Converter

during running

- 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

- 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

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



Feast2

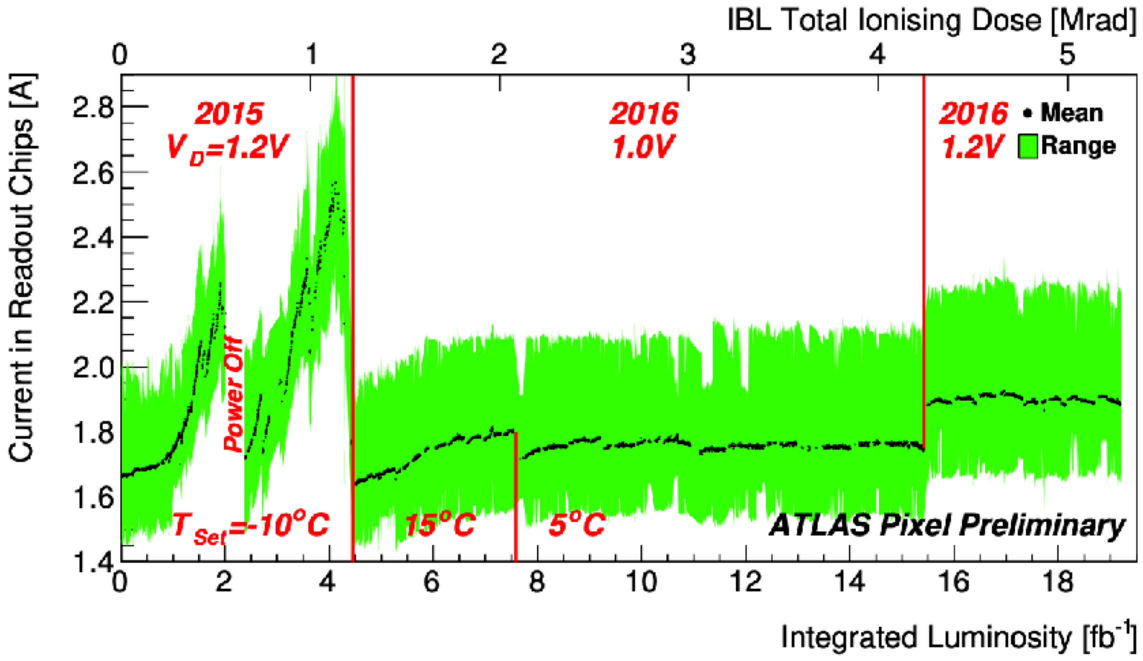
Consequences for operation
- lower input voltage helps
- stop disabling the output

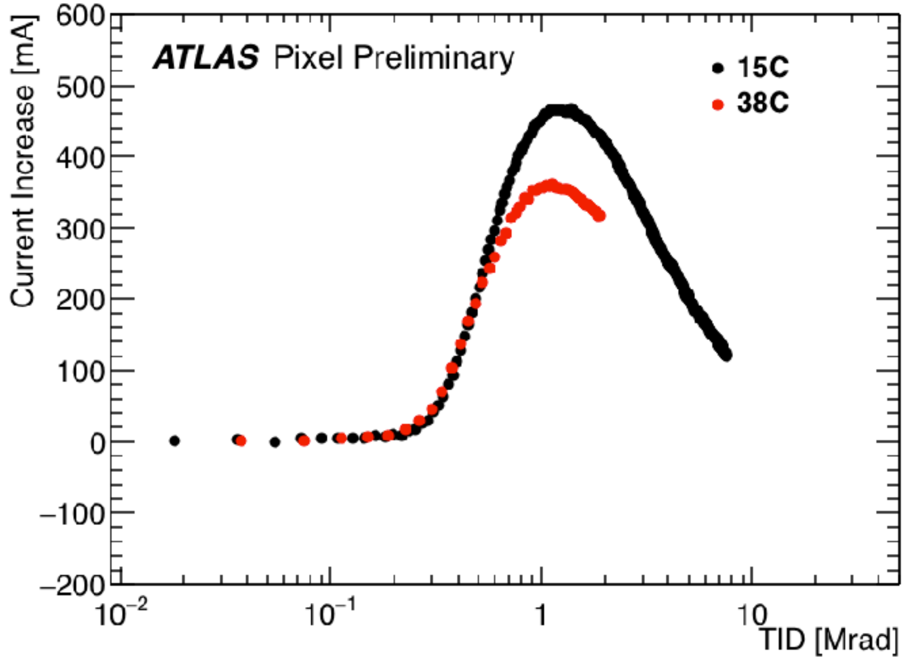
https://project-dcdc.web.cern.ch/project-dcdc/public/Documents/ExecutiveSummary2018.pdf
https://instrumentationseminar.desy.de/sites2009/site_instrumentationseminar/content/e70397/e282395/e287407/20190614_pixelphase1JIS.pdf

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



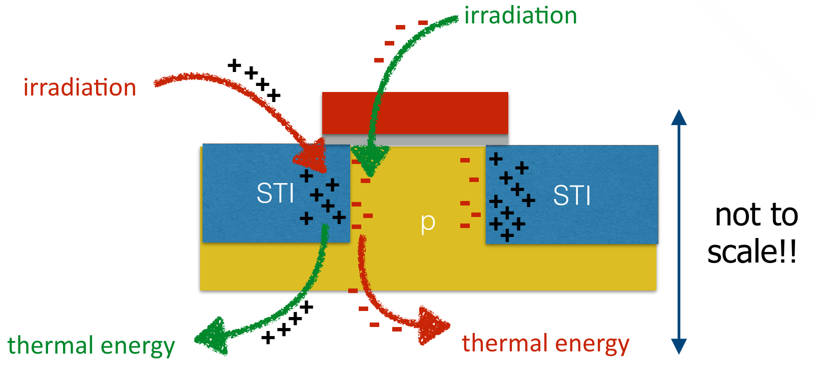


Mitigation plan:

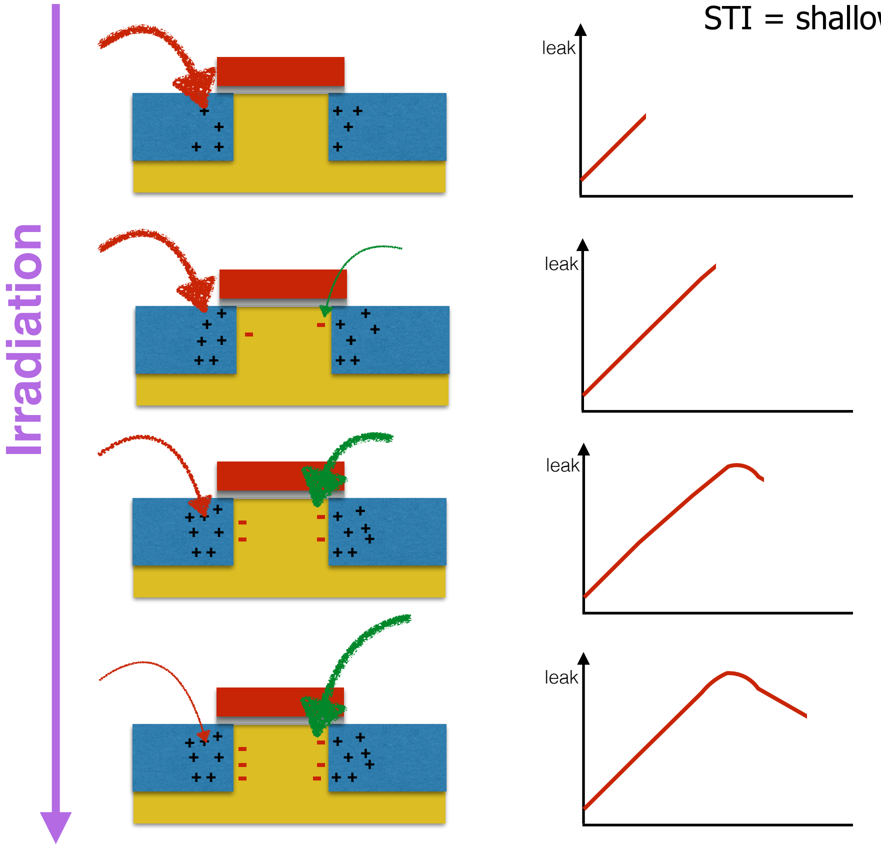
- Operating temperature was increased from −10 ◦C to and 10 ◦C then decreased to 5 ◦C.
- Digital supply-voltage was decreased to from 1.2 V 1.0 V until TID approached more than 4 MRad.

TID Bump

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



STI = shallow trench interface

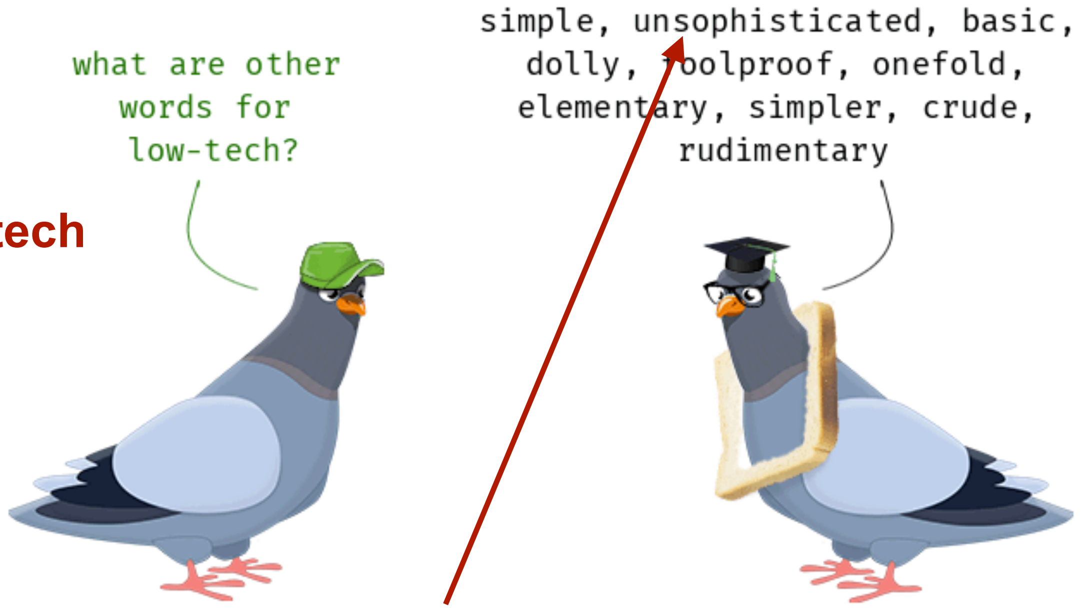


- The leakage current is the sum of different mechanisms involving:
  - the creation/trapping of charge (by radiation)
  - its passivation/de-trapping (by thermal excitation)
- These phenomena are dose rate and temperature dependent!
- Charge trapped in the STI oxide
  - +Q charge
  - Fast creation
  - Annealing already at T_{amb}
- Interface states at STI-Silicon interface
  - -Q for NMOS, +Q for PMOS
  - Slow creation
  - Annealing starts at 80-100C

“Low Tech” Failures

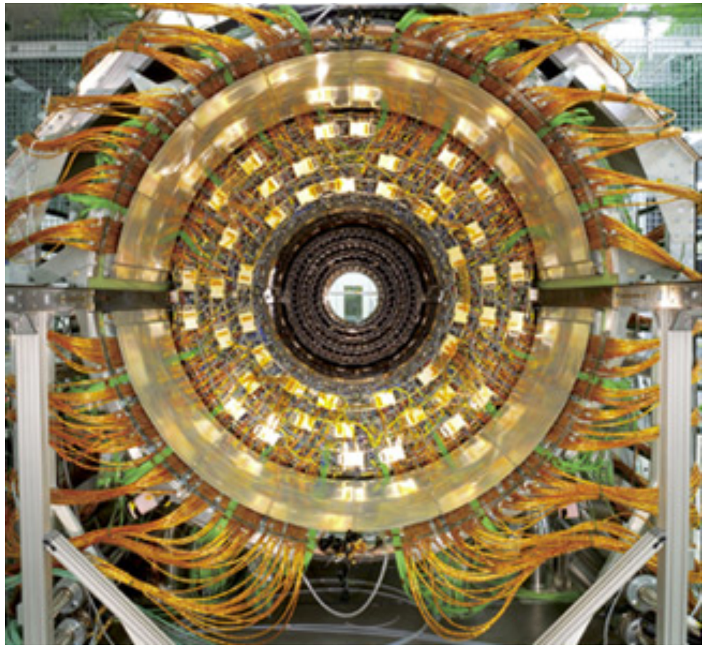
What is "Low" Tech ?

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



For particle physics experiments this is not true !

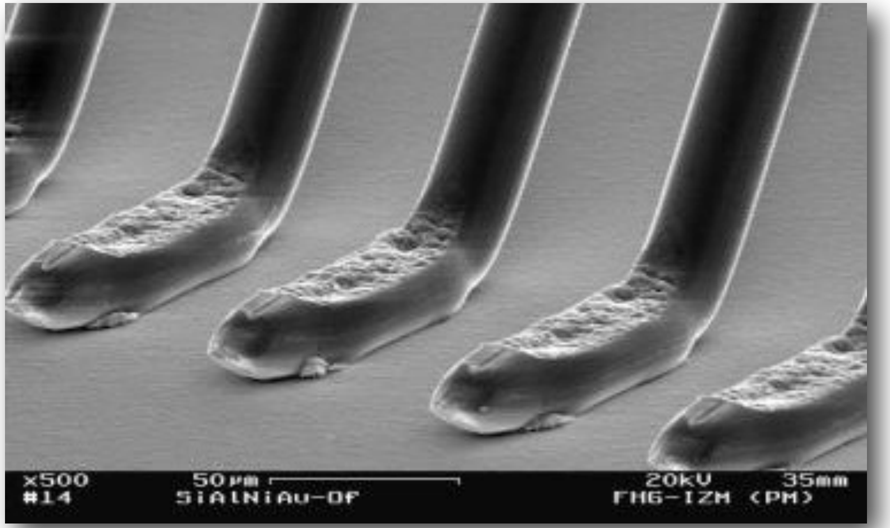
- However - some areas considered as "low tech" and people (and funding agencies) don't like to invest research money into those areas
  - Cables for powering
  - Power plants
  - Cooling
  - Data transfer (optical and electrical)
  - Non sensitive materials (mechanics)
  - Glues
  - …..

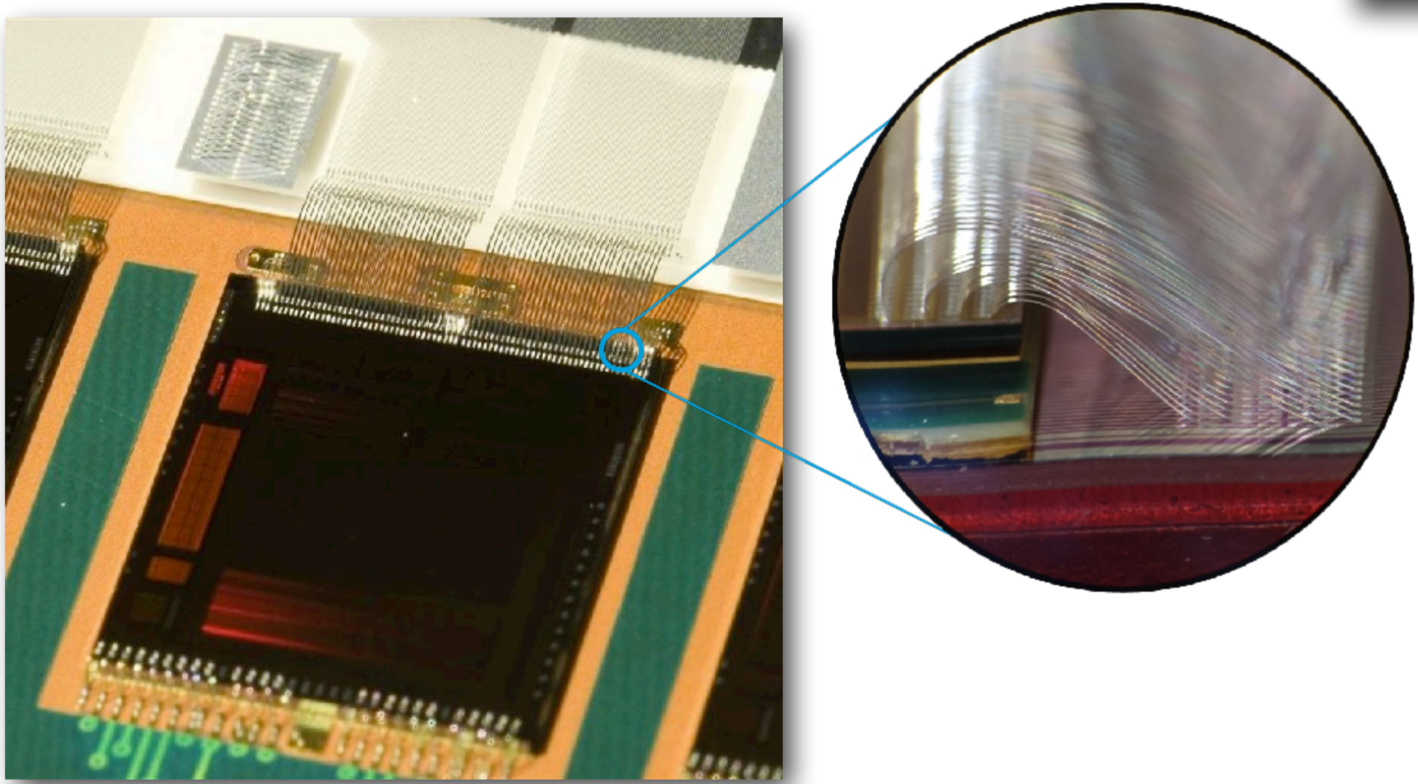


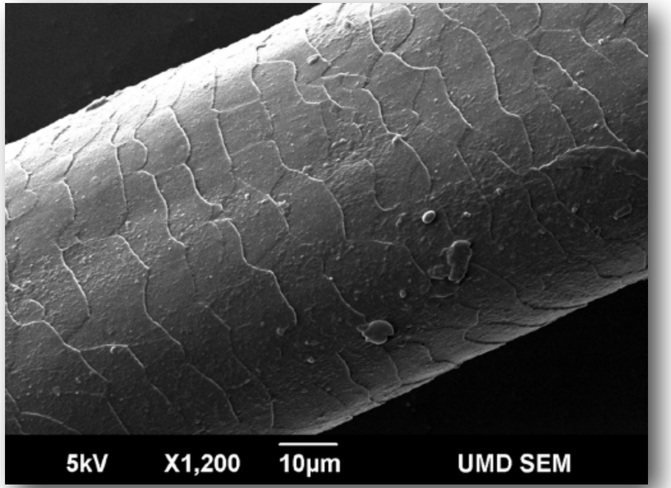
Wire-Bonds and Wire Breakage

Wire Bond Connection

- Very important connection technology: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- Ultrasonic welding technique
  - typically 25 micron bond wire of Al-Si-alloy
- Nowadays: Fully-automatised system with automatic pattern recognition



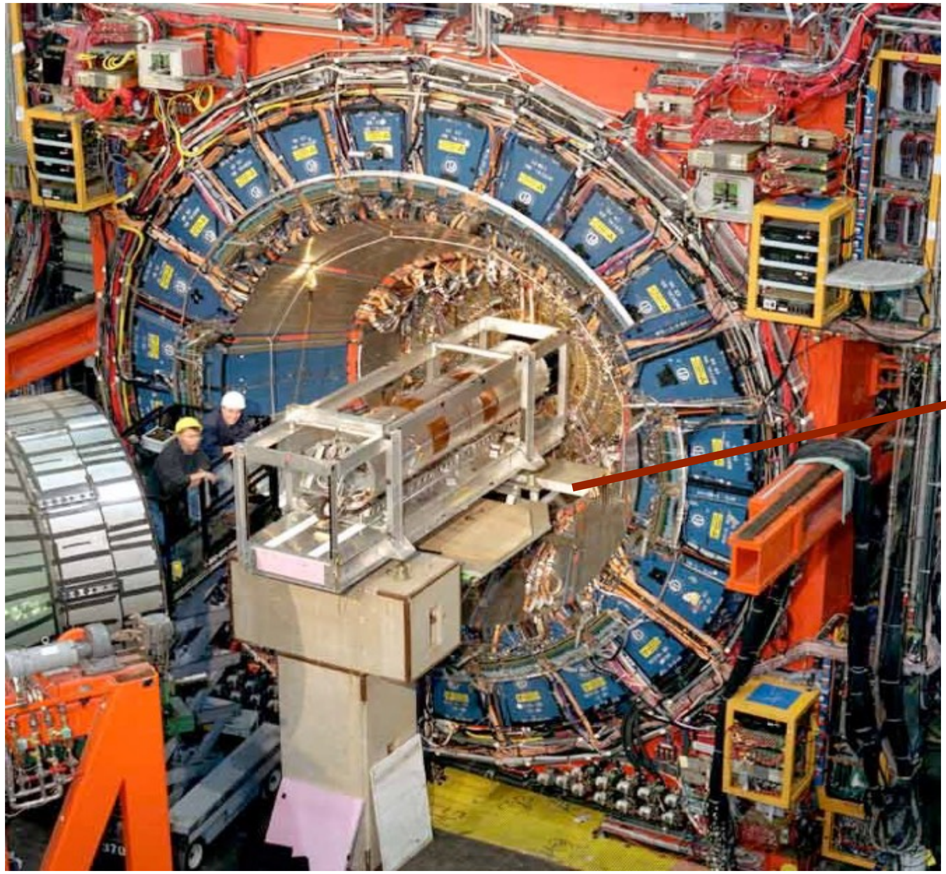


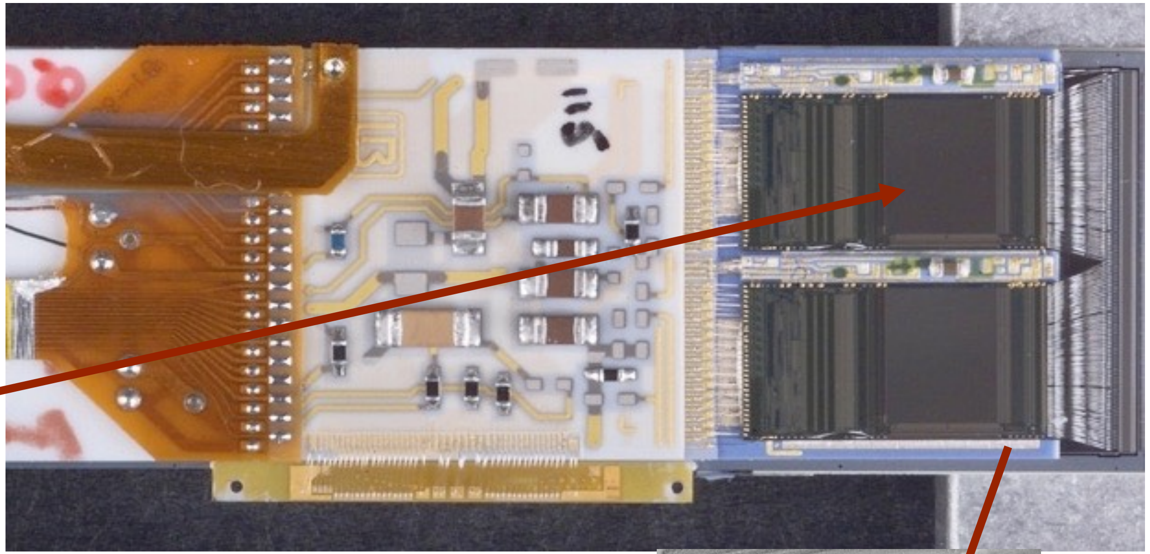


Comparison: human hair between 50 and 100 micron

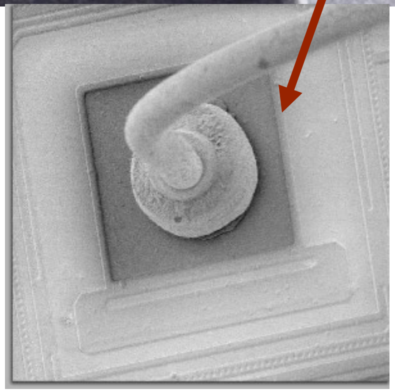
Problems with Wire Bonds (CDF, D0)

- During test pulse operation, Lorentz force on bonding wires (perpendicular to magnetic field) caused resonances …





…breaks wire bonds between detector and read out.

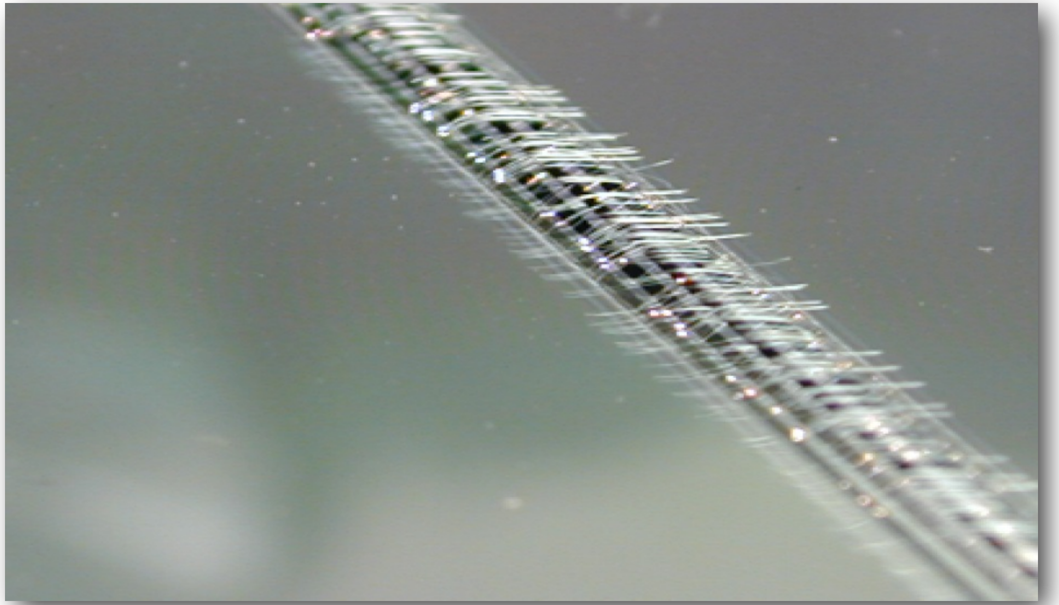


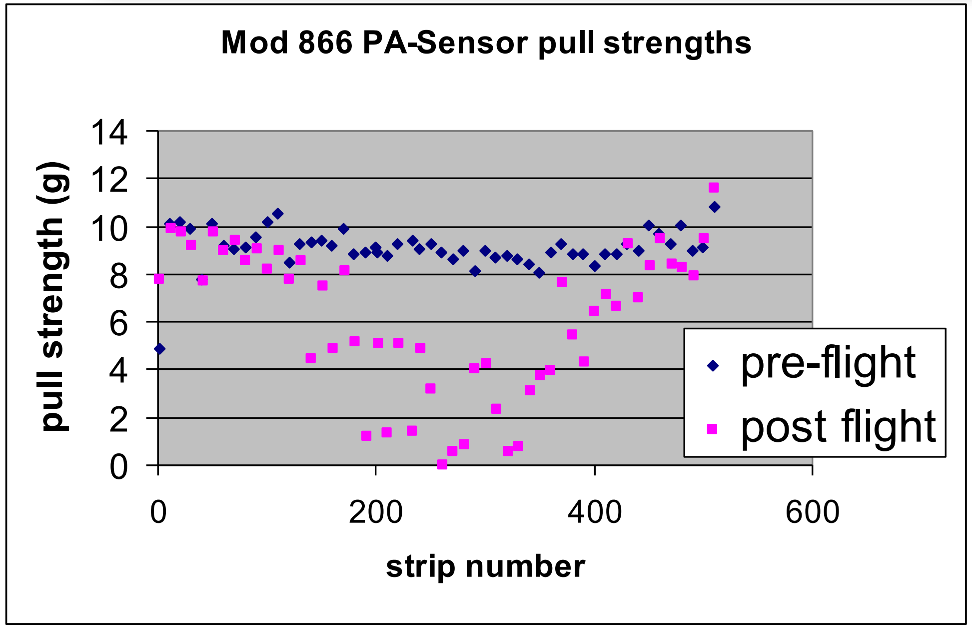
during running

More Wire Bond Wreckage

- Quality of wires tested by pull tests (measured in g)
- During CMS strip tracker production quality assurance applied before and after transport (via plane)
- Wire bonds were weaker after flight
- Random 3.4 g NASA vibration test causes similar damage

- Problem observed during production -> improved by adding a glue layer ("potting")
- No further problems during production

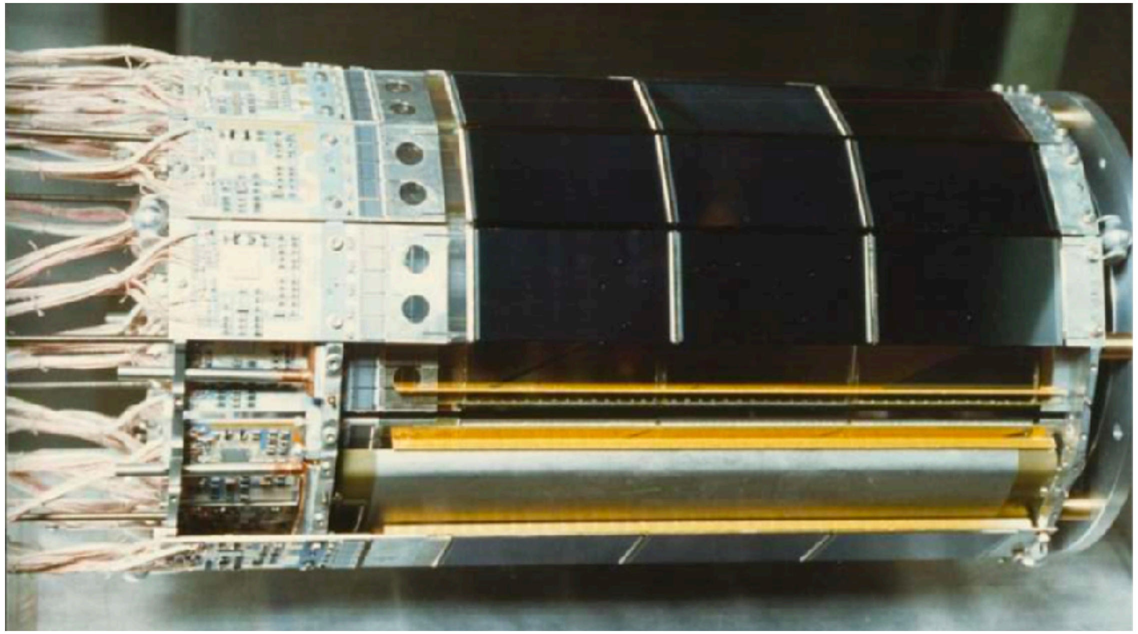




during production

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.



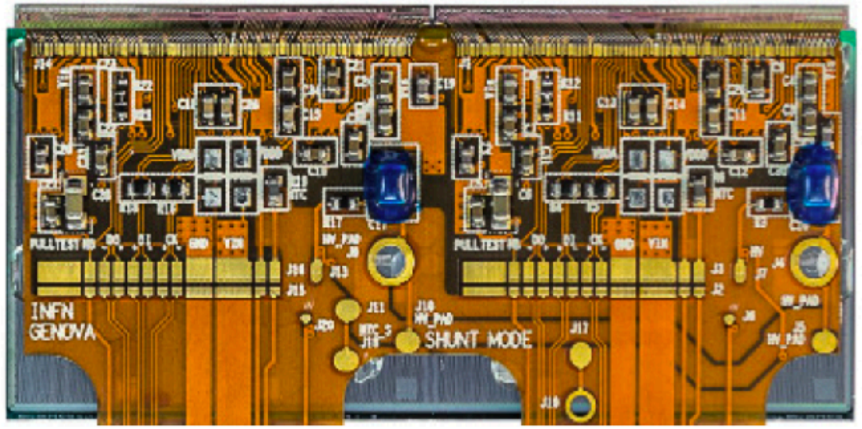
- Chain of problem causing damage:
  - MVD expert modified the control/monitoring software between consecutive data taking runs.
  - Inserted bug which stopped software in a state with cooling water off but with the low voltage power on.
  - Stopped software also prevented the monitoring of the temperature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

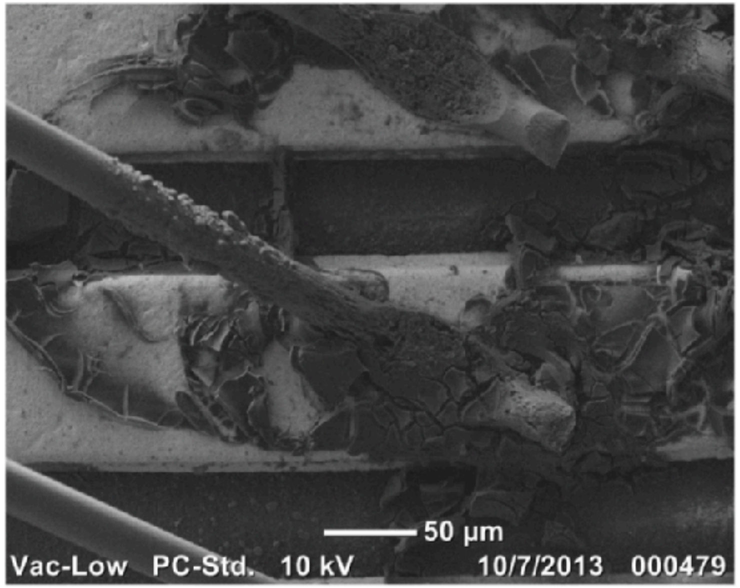
Lucky outcome:
- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

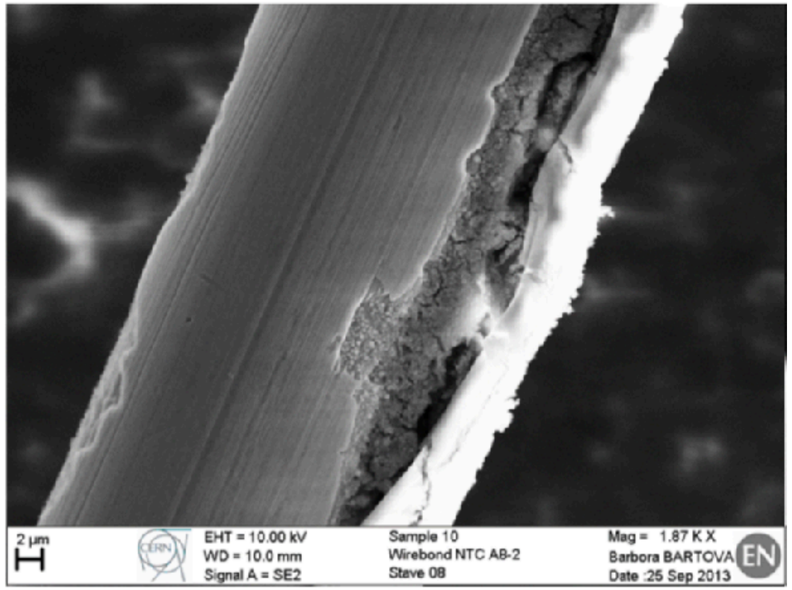
Mitigation plan:
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

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

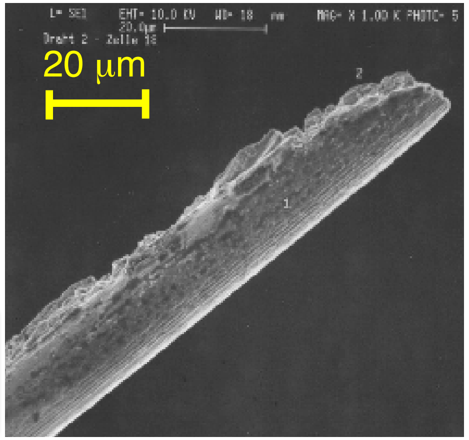
during production

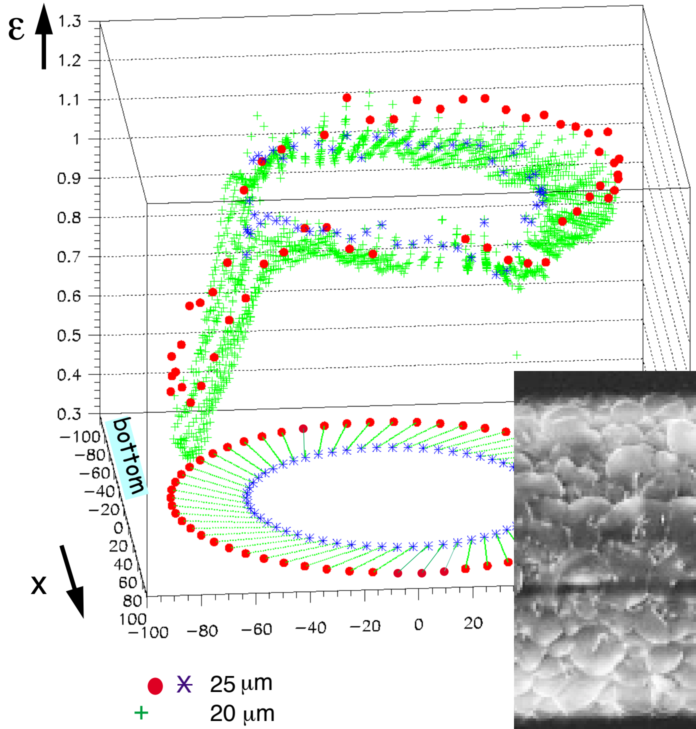
https://indico.cern.ch/event/435798/contributions/1074098/attachments/1134177/1622192/encapsulation_study_-_Oxford.pdf

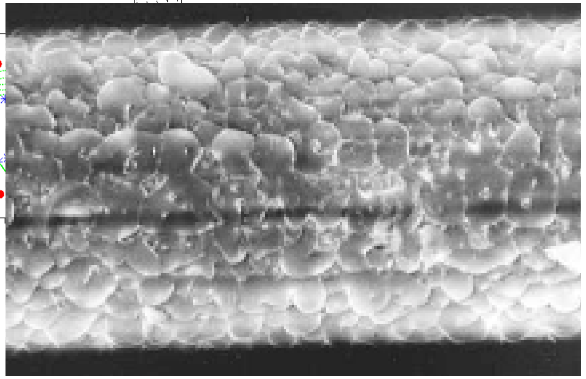
Wires H1 Central Jet Chamber

- Outer tracker of H1 -> broken wires in CJC1
- Observation / possible reason:
    - remnants from gold plating process lead to complex chemical reactions
- New design of crimp tube: jewels • better quality control

during production







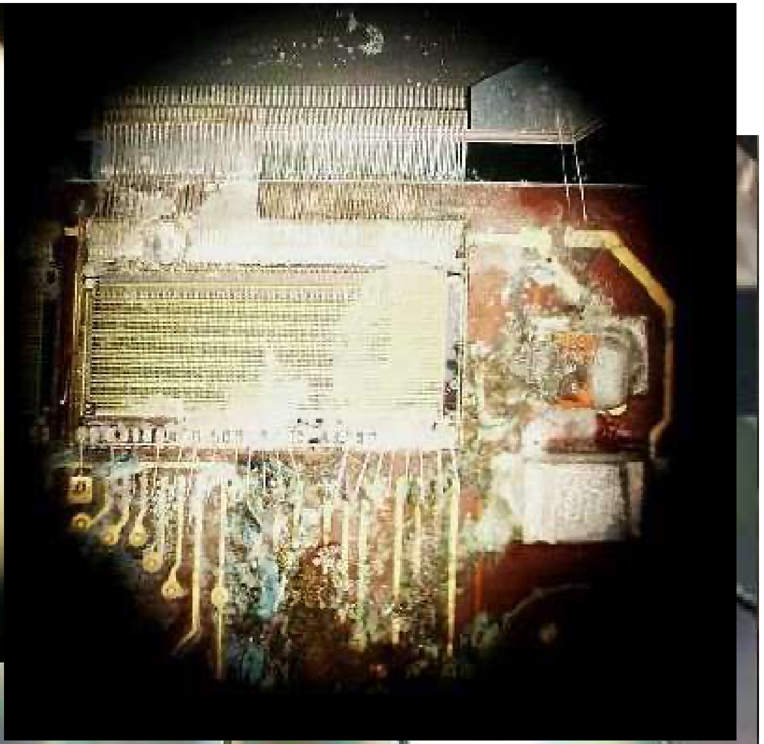
- Sense Wire Deposits in CJC2
- Observation / possible reason:
  y dependence implies most likely gas impurity
- Consequences:
    - sense wires replaced
    - changes in gas distribution
    - increased gas flow

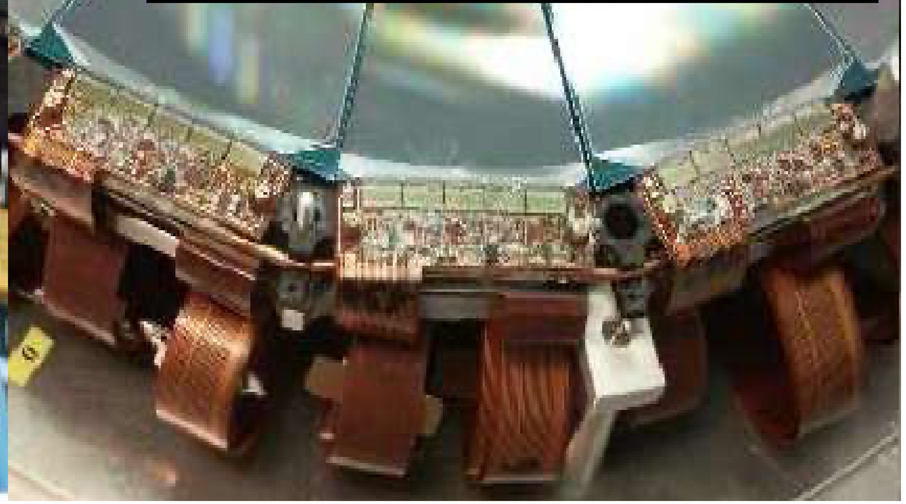
during running

Water Damage in Tracker ...

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

during running

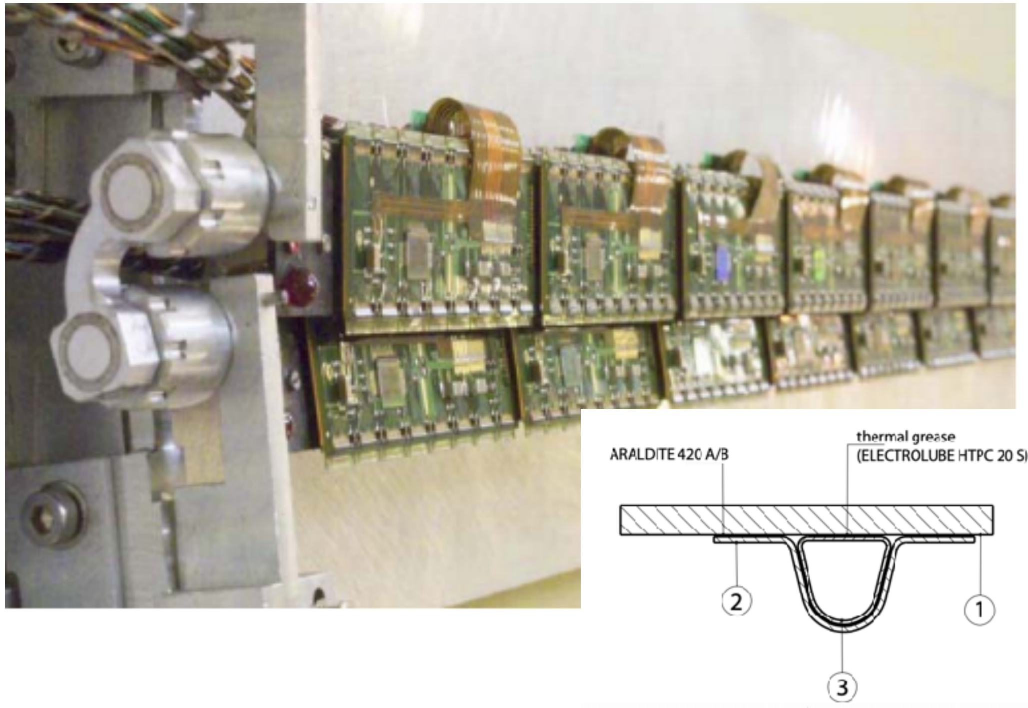


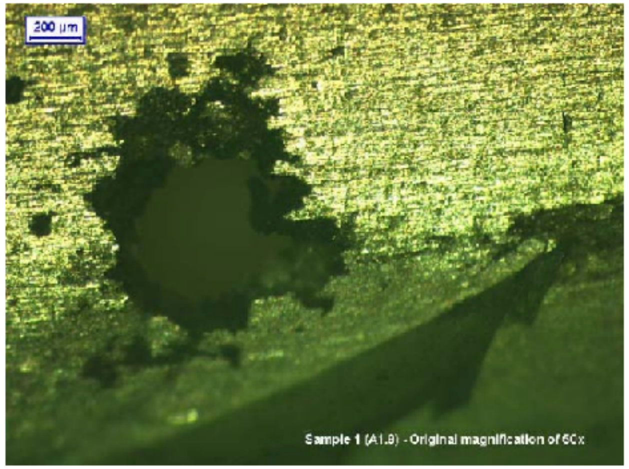


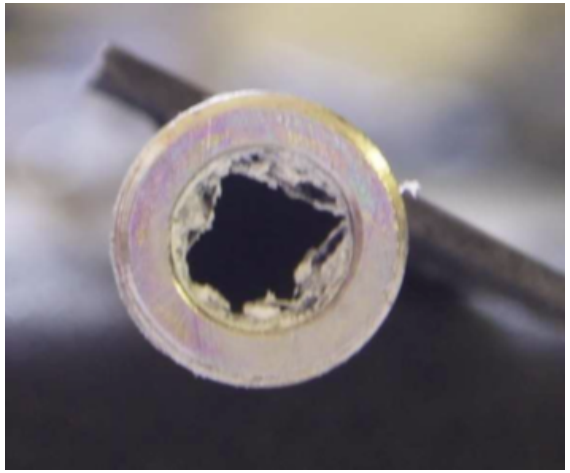
ATLAS Pixel Tube Corrosion

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.







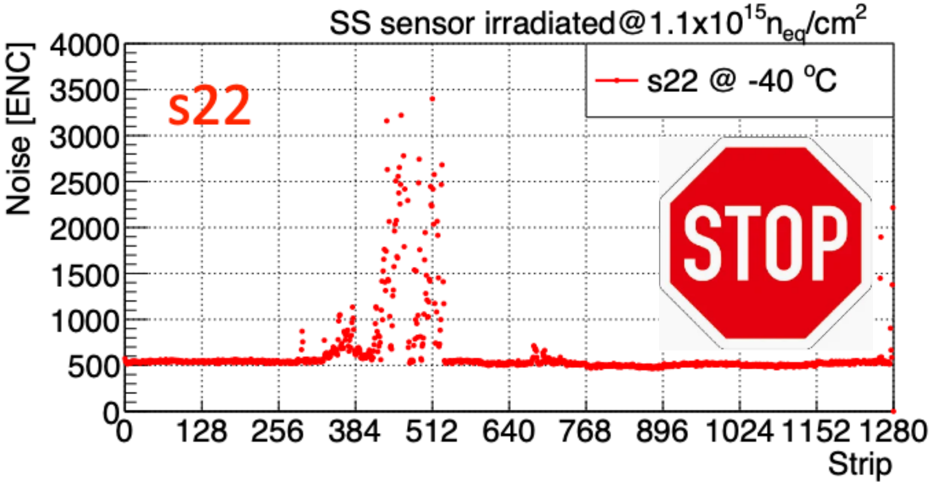
Six months delay in schedule
- Repair the 43 loaded staves with a pipe-inside-the-pipe
- Production of new staves with new Al compound and laser welding
- Repair of bare staves (~100)

Current unsolved ones

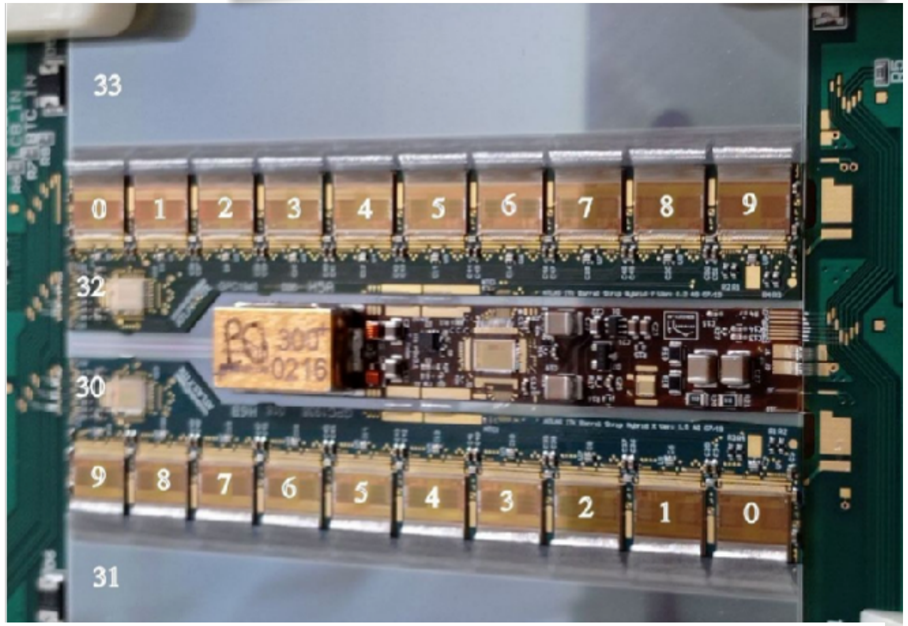
ATLAS ITk Strips: Cold Noise

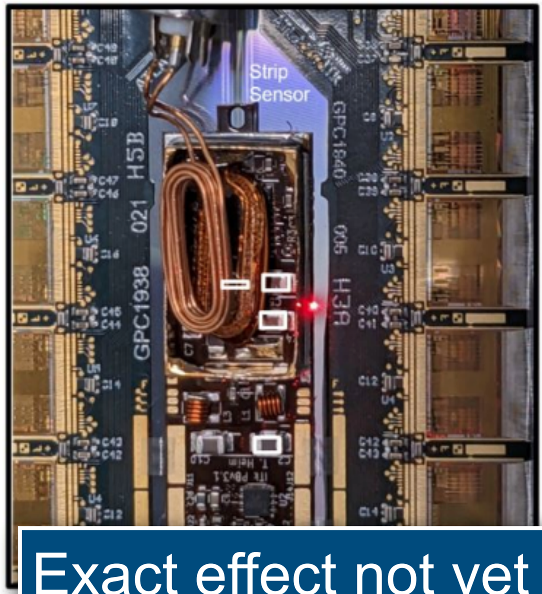
shortly before production

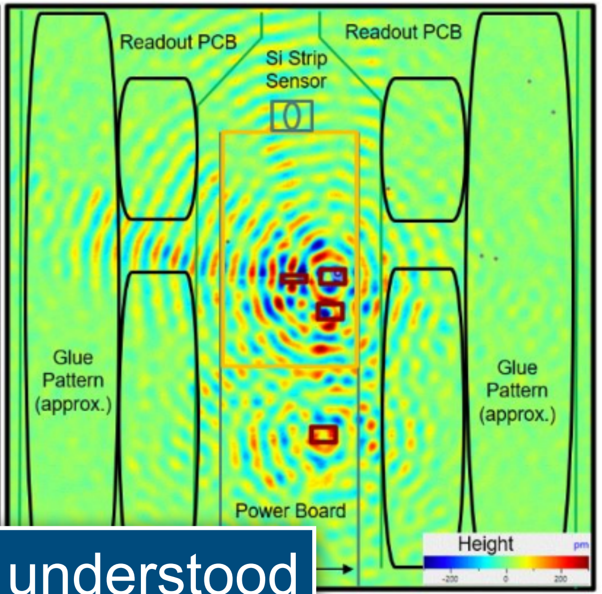
- Hybrids for readout and power board directly on silicon strip sensors
- Clusters of very noisy channels observed at operating temperatures of around -35 °C



- 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



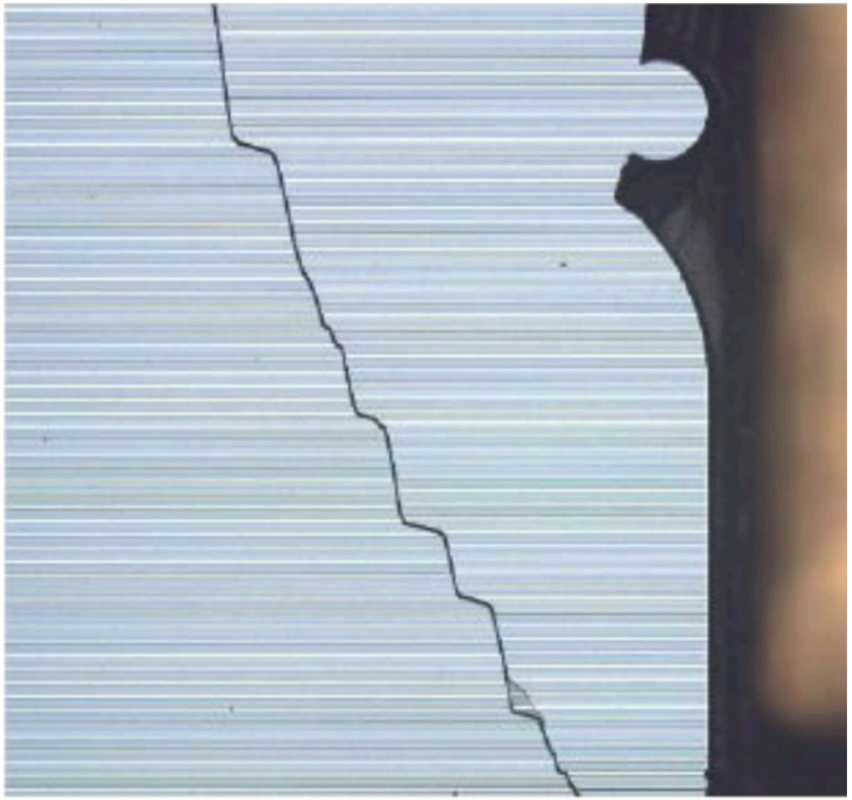




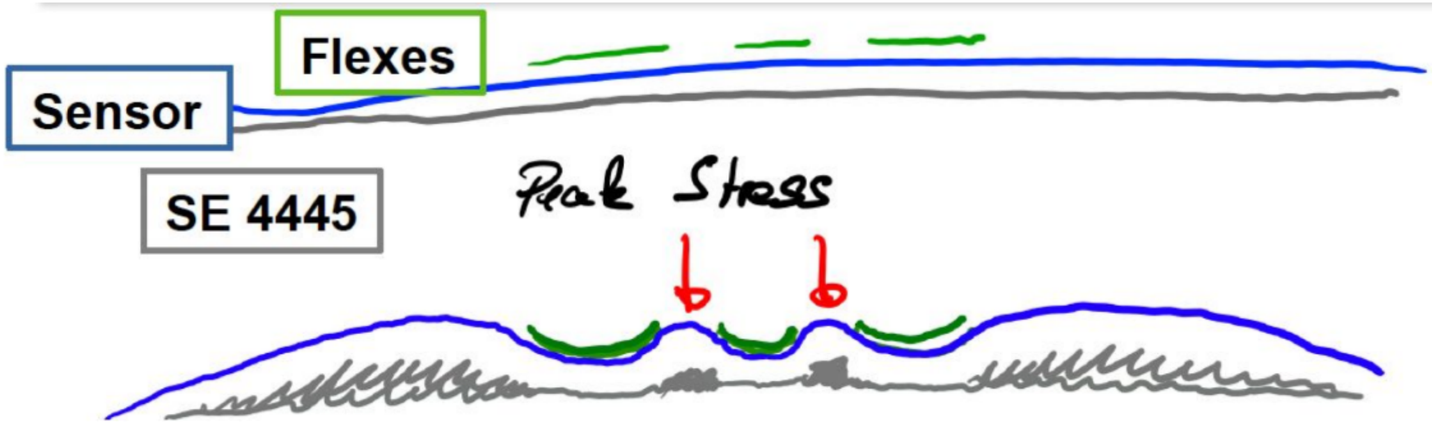
Exact effect not yet understood

Same Detector: Module Cracking

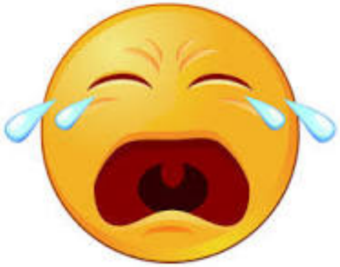
shortly before production



- Fraction of modules loaded on support structures show early breakdown (< 500 V), and 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



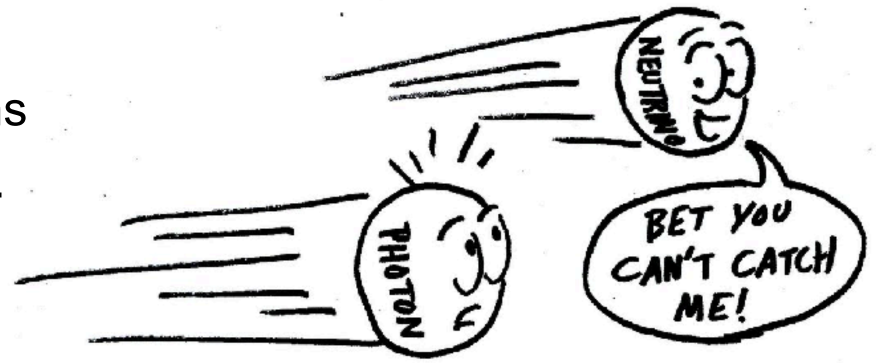
Qualitative understanding of origin of module cracking



Most Famous ones

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

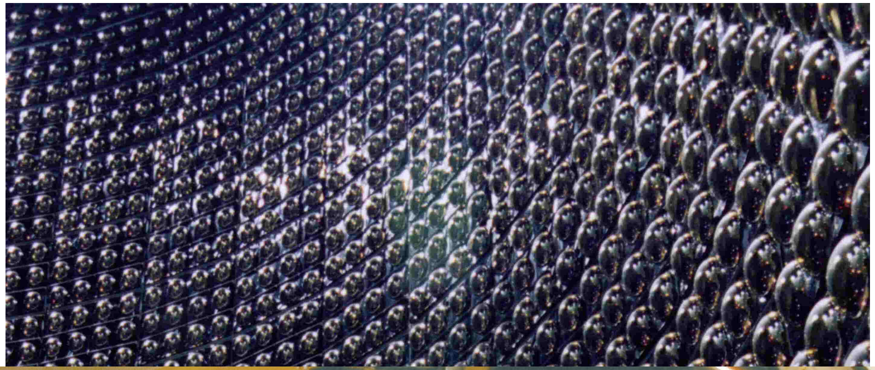
- Kink from a GPS receiver to OPERA master clock was loose
  - Increased the delay through the fibre resulting in decreasing the reported flight time of the neutrinos by 73 ns,
  - making them seem faster than light.

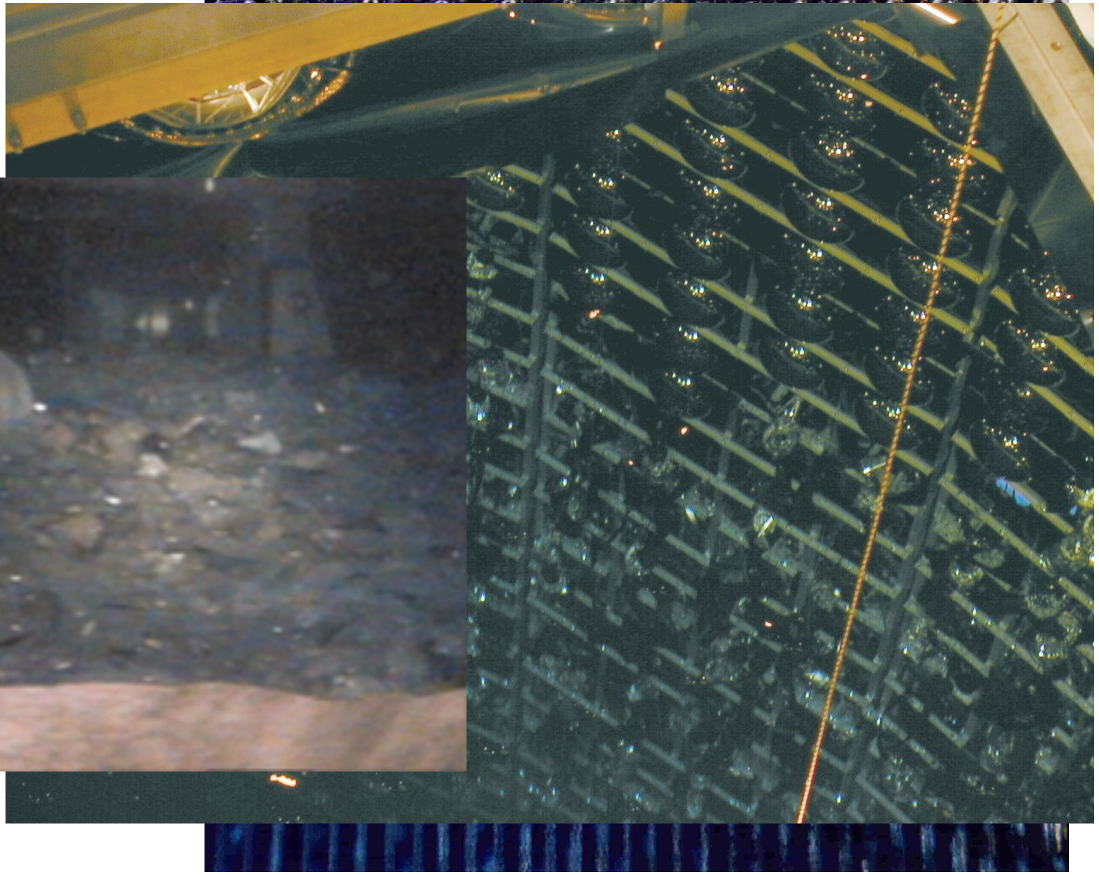
After finding the problem, the difference between the measured and expected arrival time of neutrinos was approximately 6.5 ± 15 ns.

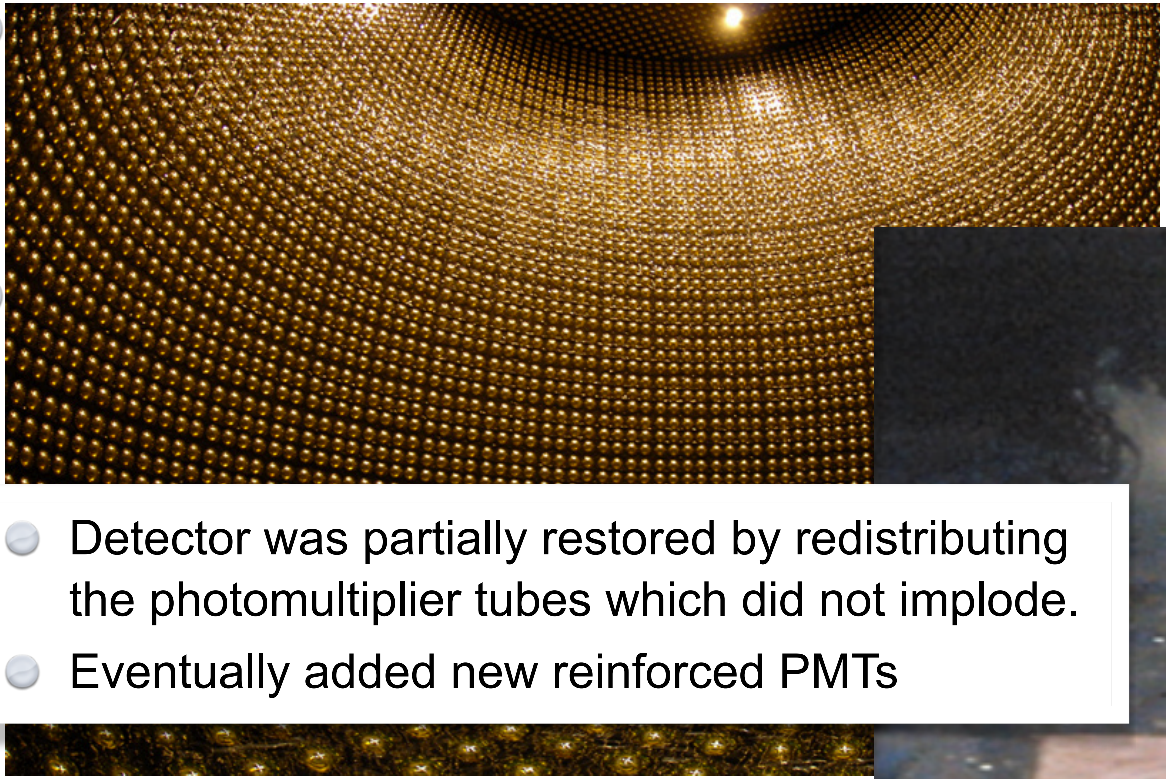
Maybe Most Famous Damage ....

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….

Summary

- We could only give a **glimpse** at the wealth of particle detectors. More detectors are around: medical application, synchrotron radiation experiments, astro particle physics, ...
- All detectors base on similar principles
  - Particle detection is indirectly by (electromagnetic) interactions with the detector material
- Large detectors are typically build up in layers (onion concept):
  - Inner tracking: momentum measurement using a B-field
  - Outside calorimeter: energy measurement by total absorption
- Many different technologies:
  - Gas- and semiconductors (light material) for tracking
  - Sampling and Homogeneous calorimeters for energy measurement
- Similar methods are used in astro particle physics
- **Always looking for new ideas and technologies!**

Literature

Text books:

- **N. Wermes, H. Kolanoski: Teilchendetektoren, Grundlagen und Anwendungen, Februar 2016, Springer**
- Frank Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer Verlag 2017
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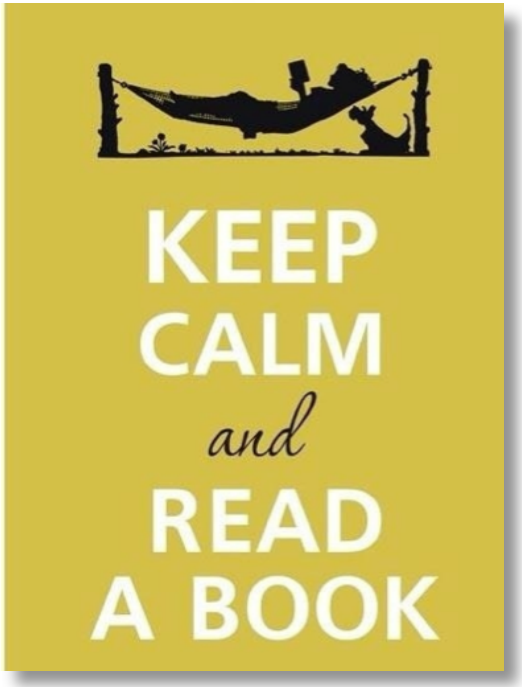
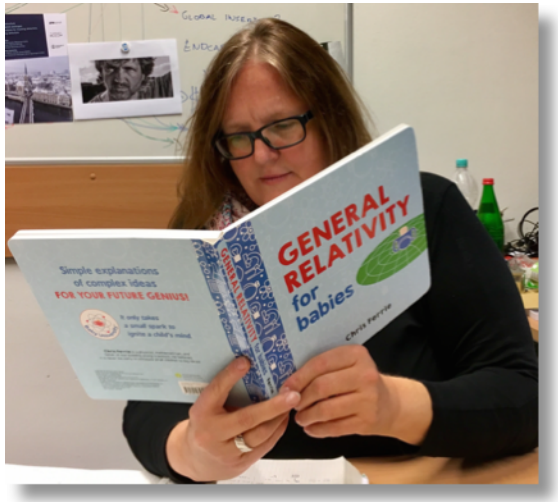


web:
Particle Data Group: *Review of Particle Properties: pdg.lbl.gov*
further reading:
The Large Hadron Collider - The Harvest of Run 1; Springer 2015



Symphony of Science

Symphony of Science Video