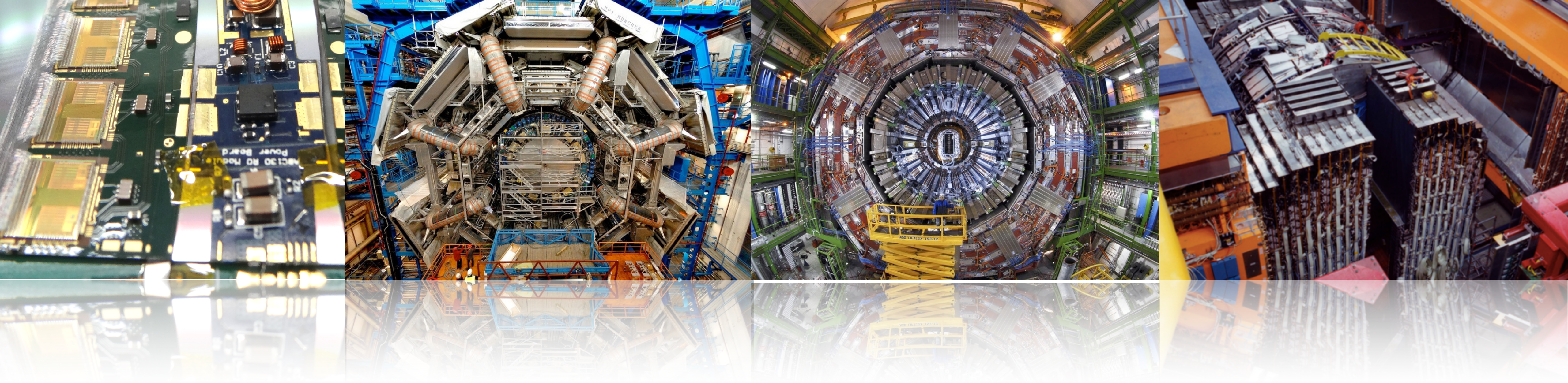


What can go wrong …

Some Examples

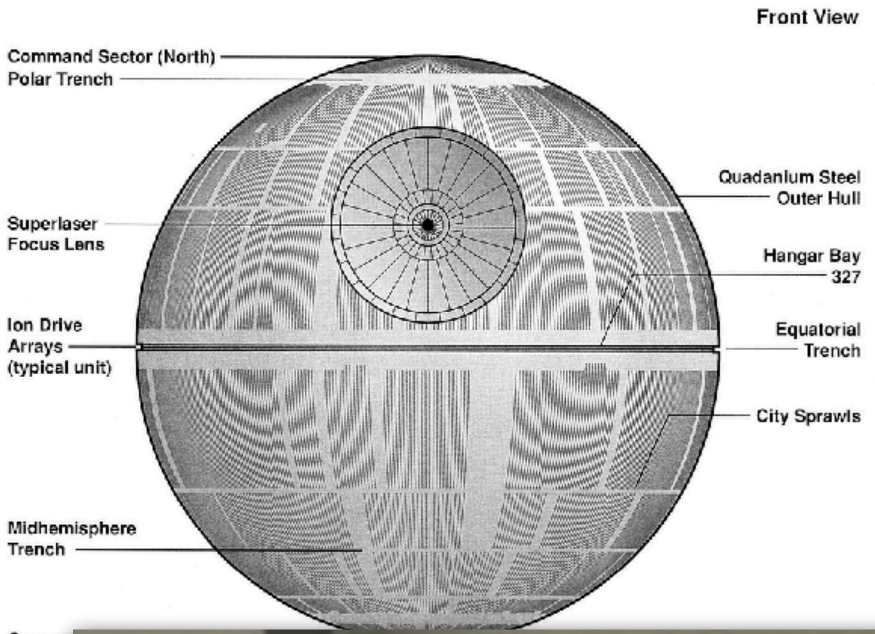
Prof. Dr. Ingrid-Maria Gregor
DESY/Universität Bonn
SoSe 22

Disclaimer

- Designing a large (silicon) detector for particle tracking or identification is a very complex business
- Many very nice examples exist
- Also some examples of failures

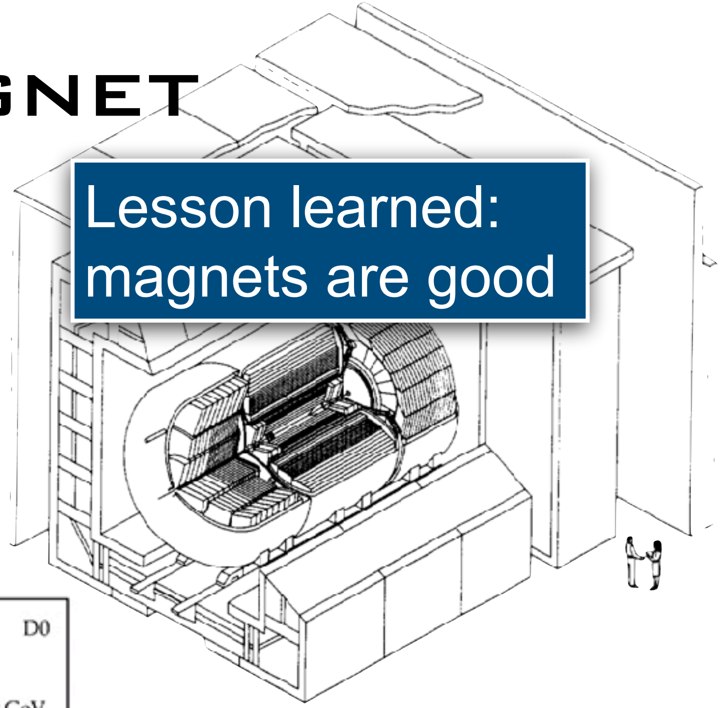
- Idea of this talk: some stuff you don't find in textbooks
- Collection of failures might give the impression of overall incompetence
  - Overwhelming majority of detectors run like a chime
  - Unbelievable effort to get large accelerators and experiments in a global effort to run so nicely
  - Even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

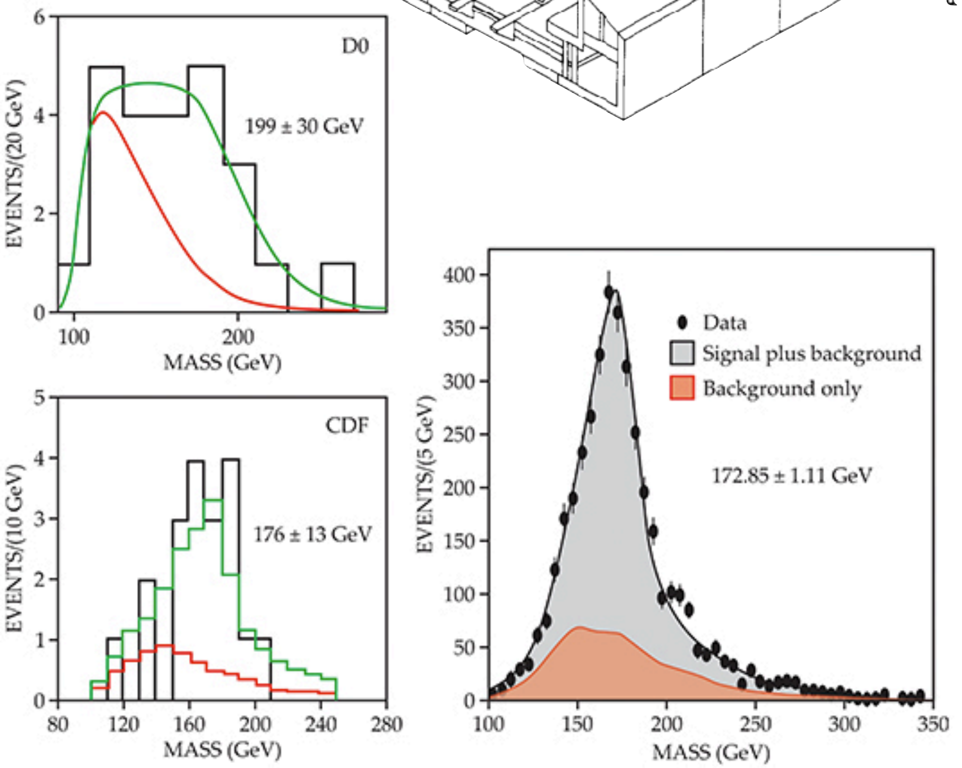
D0 without Inner Tracking Magnet



Lesson learned: magnets are good

- 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.



Top quark discovery

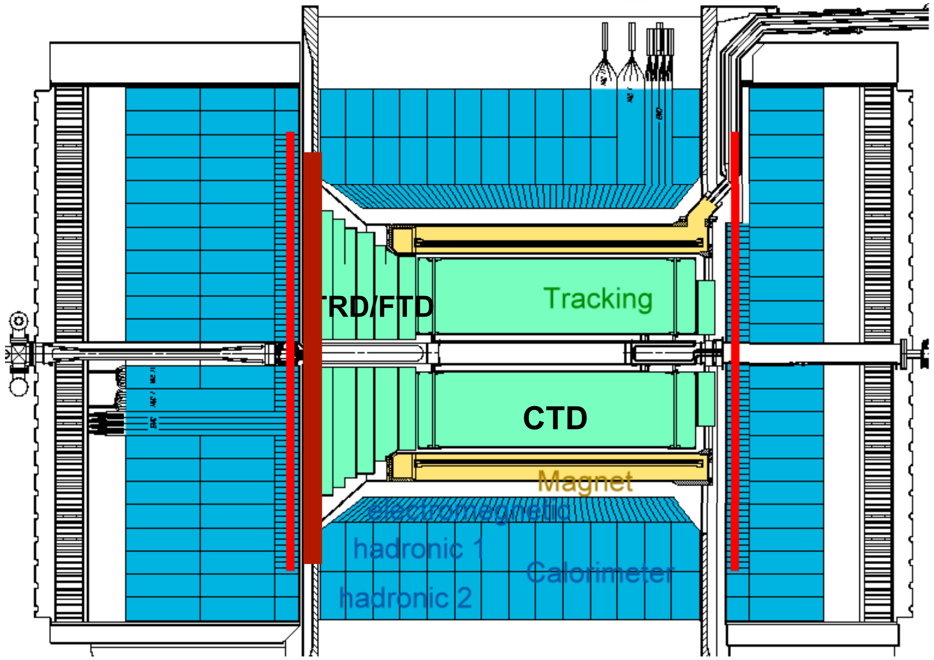
ZEUS TRD

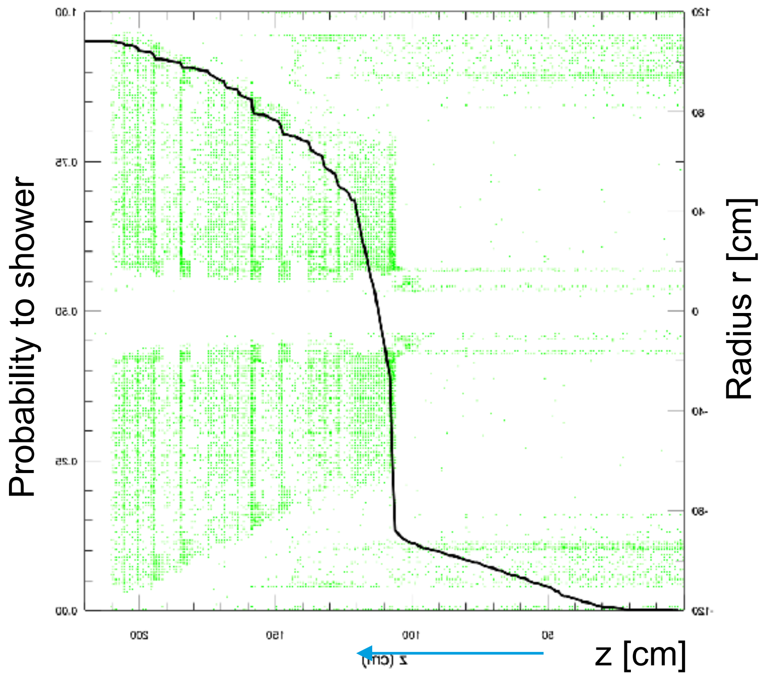
- Zeus Transition Radiation detector for electron identification.
- Aim: h/e rejection ratio of about 10^{-2} for electron tracks embedded in jets (1 - 30 GeV/c).

- 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





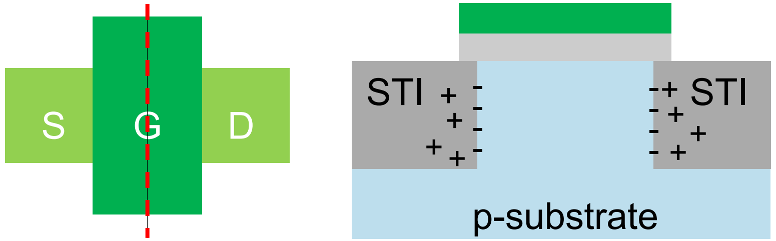
Lesson learned:
Monte Carlos simulations should include everything

Unexpected Irradiation Failure

Radiation Damage in Silicon

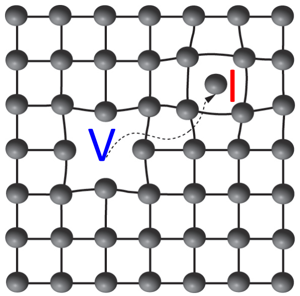
- Radiation damages the silicon on atomic level significantly leading to macroscopic effects.

- **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 …

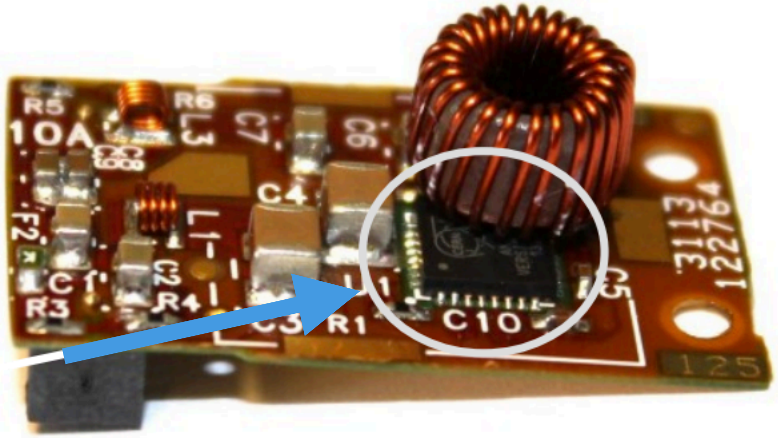
CMS DC-DC Converter

during running

- 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

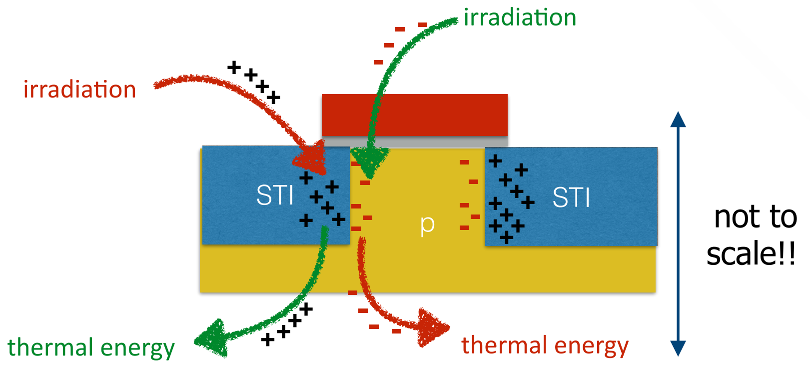
https://project-dcdc.web.cern.ch/project-dcdc/public/Documents/ExecutiveSummary2018.pdf
https://instrumentationseminar.desy.de/sites2009/site_instrumentationseminar/content/e70397/e282395/e287407/20190614_pixelphase1JIS.pdf

TID Bump

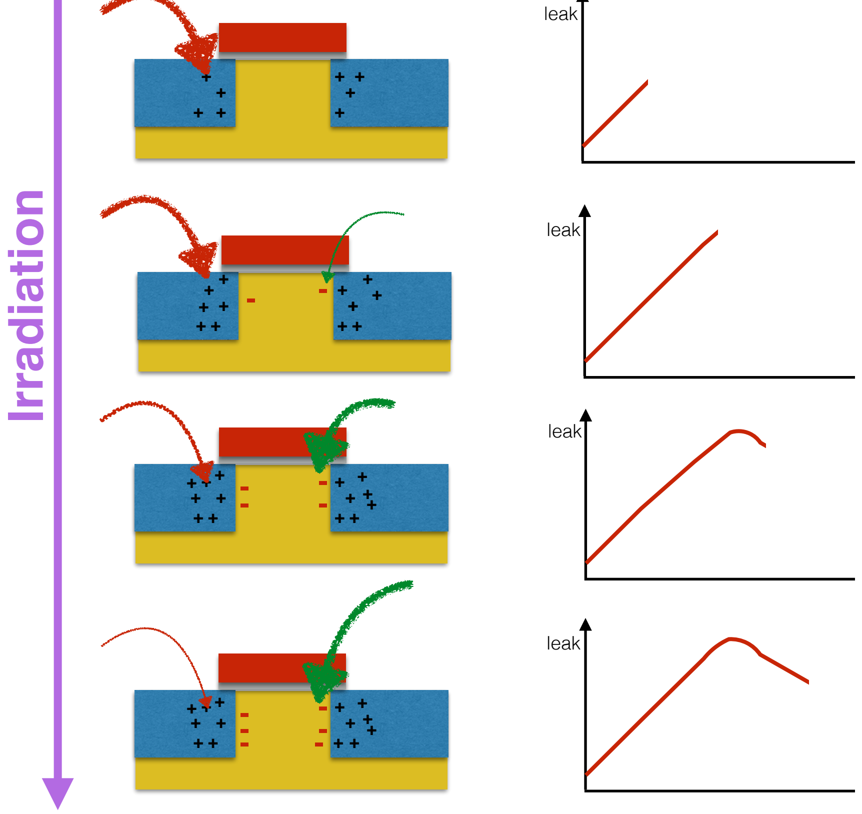
Surface effects: Generation of charge traps due to ionizing energy loss (Total ionising dose, TID) **(main problem for electronics).**

- 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



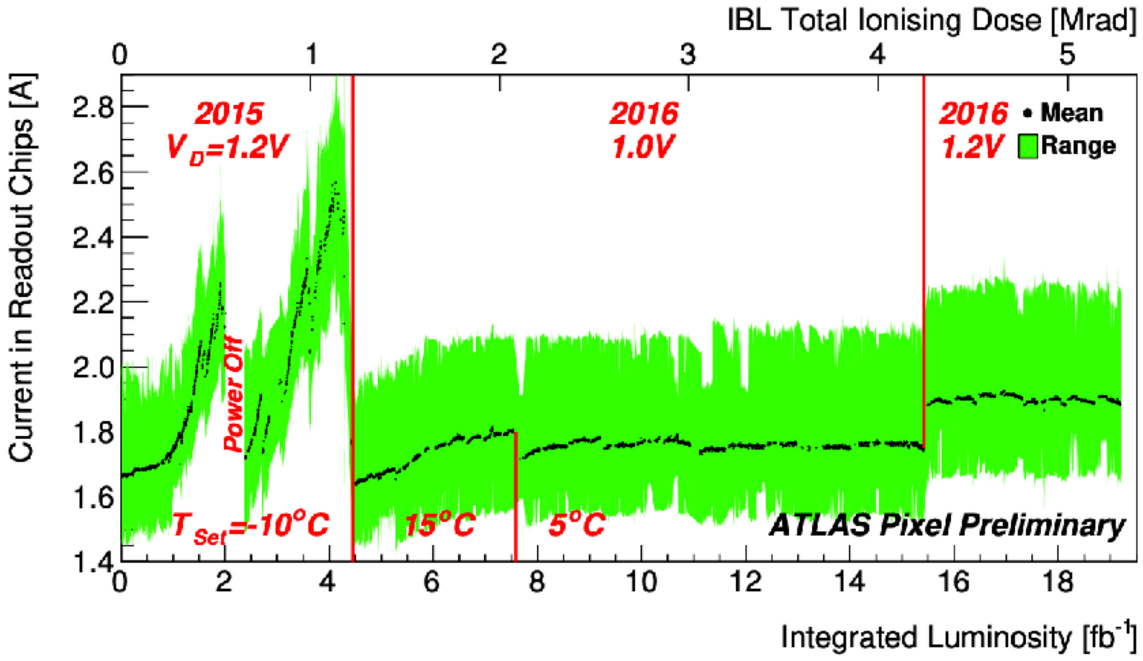
STI = shallow trench interface

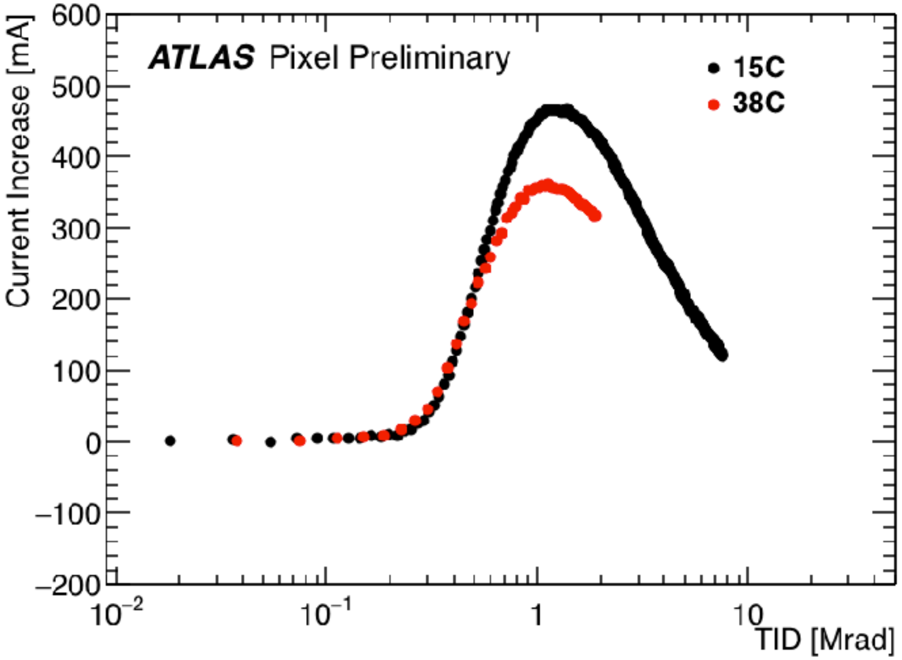


ATLAS IBL TID Bump

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



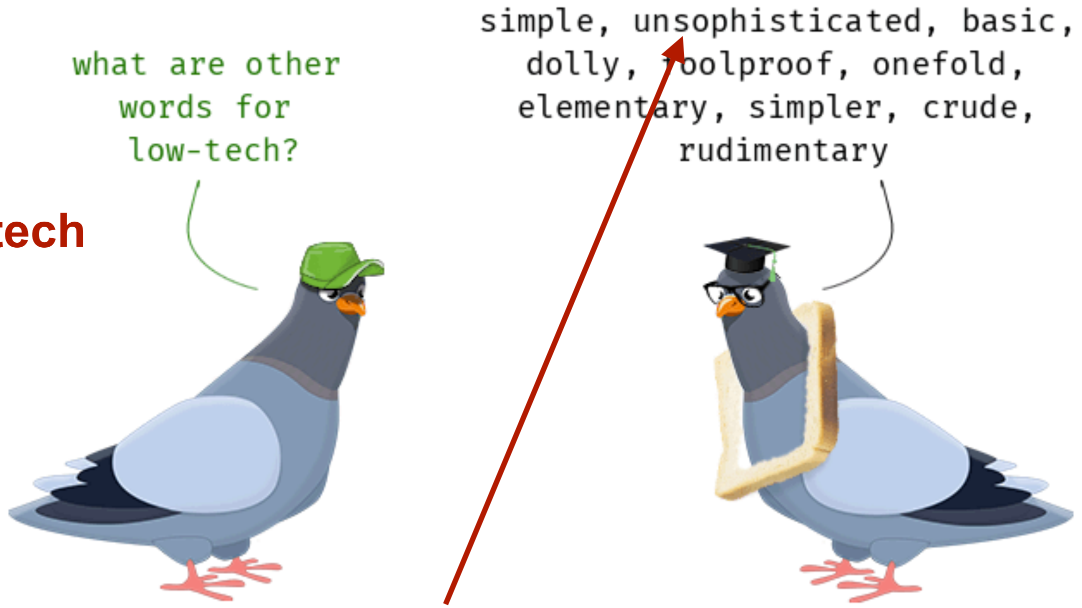


Mitigation plan:

- 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.

"Low Tech" Failures

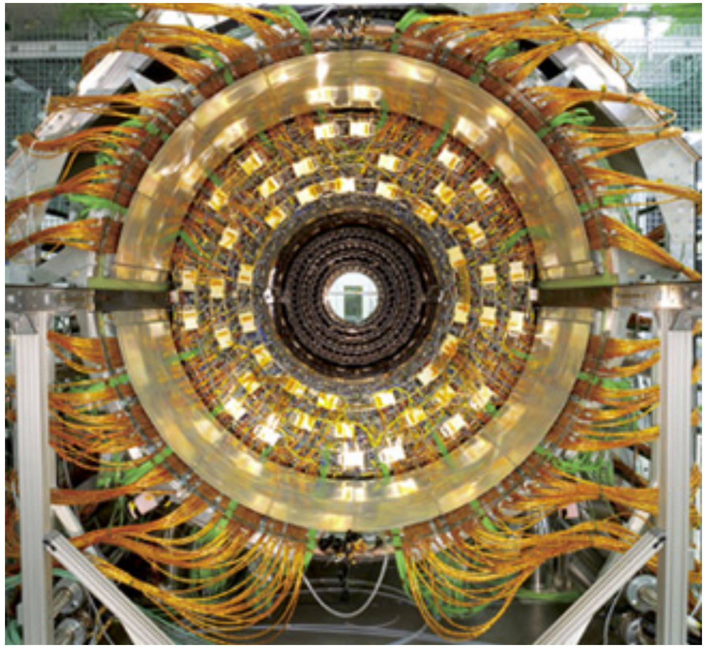
What is “Low” Tech ?



- 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
  - …..

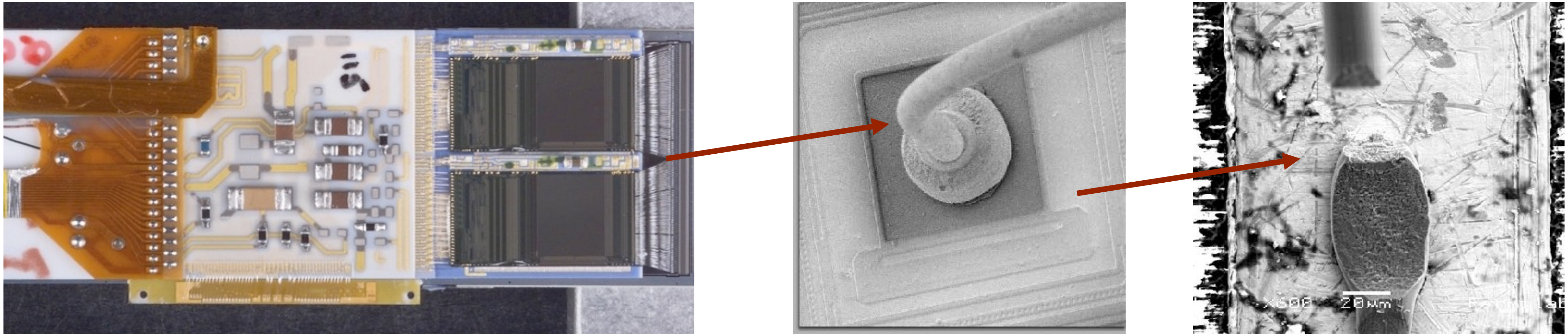


Wire-Bonds and Wire Breakage

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)

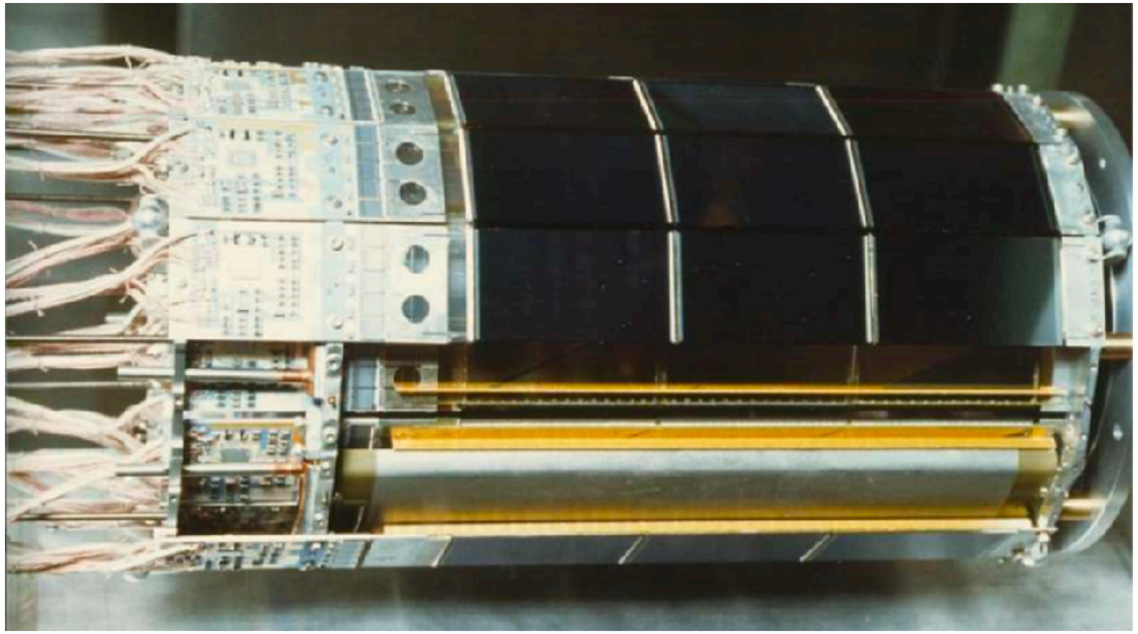


- Tests revealed:
  - Bonds start moving due to Lorentz Force in magnetic field
  - Wire resonance in the 20 kHz range
  - Current is highest during data readout
  - Already a few kicks are enough to get the bond excited

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:

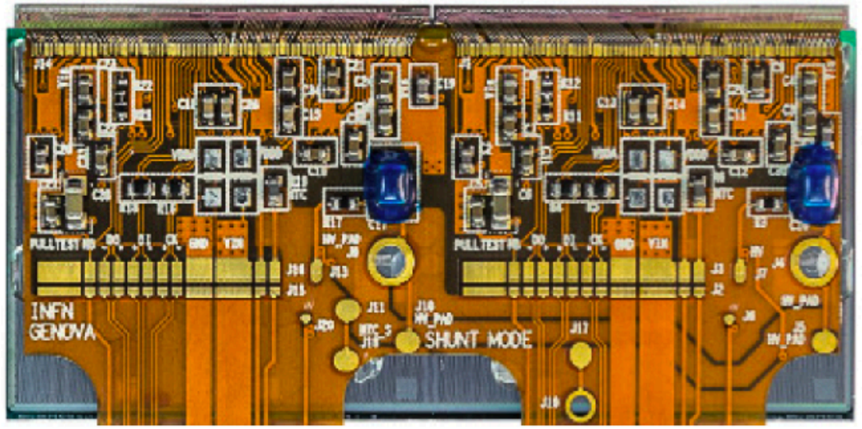
- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

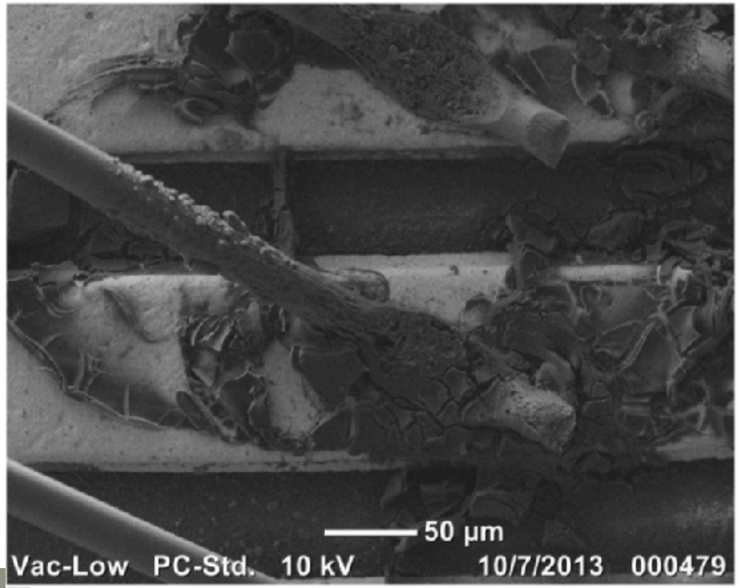
Mitigation plan:

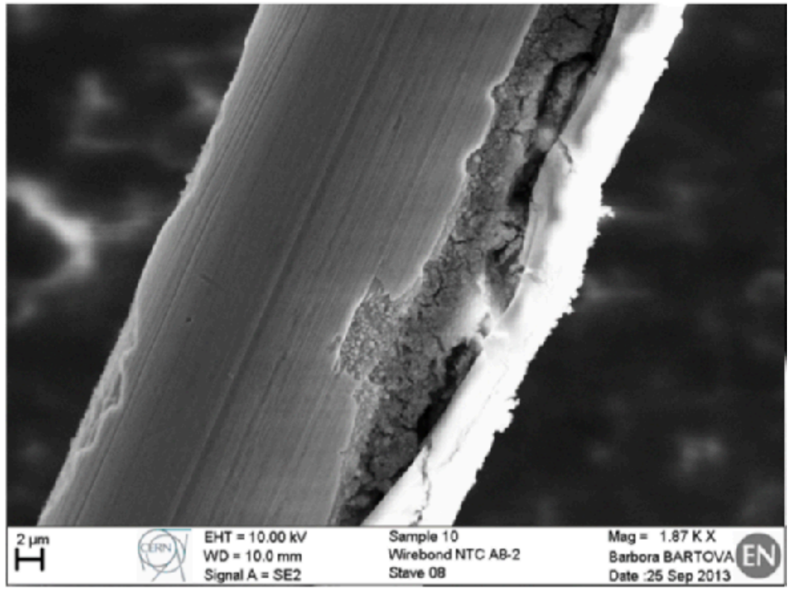
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

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

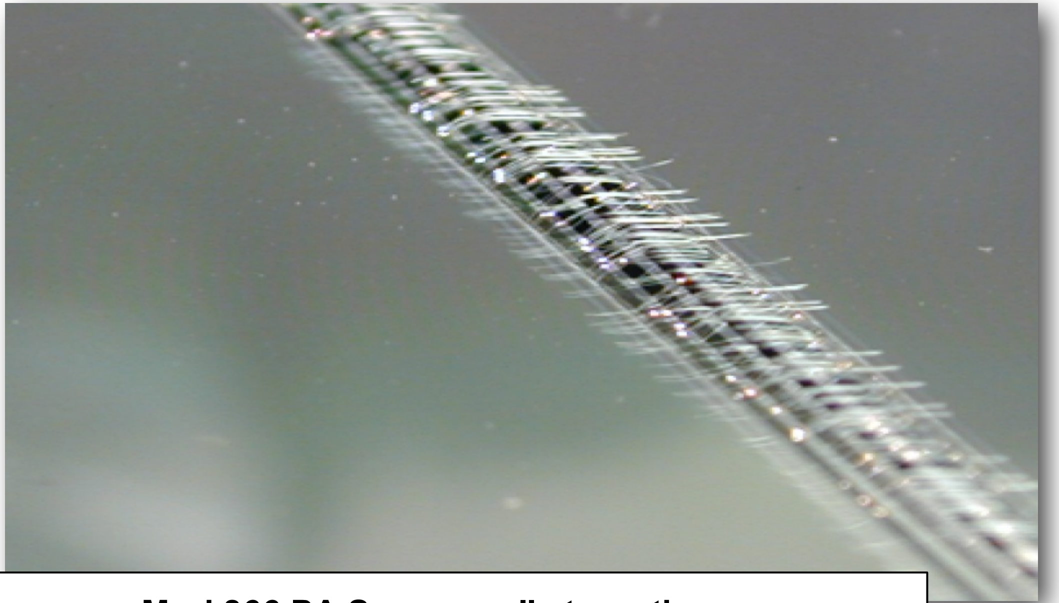
during production

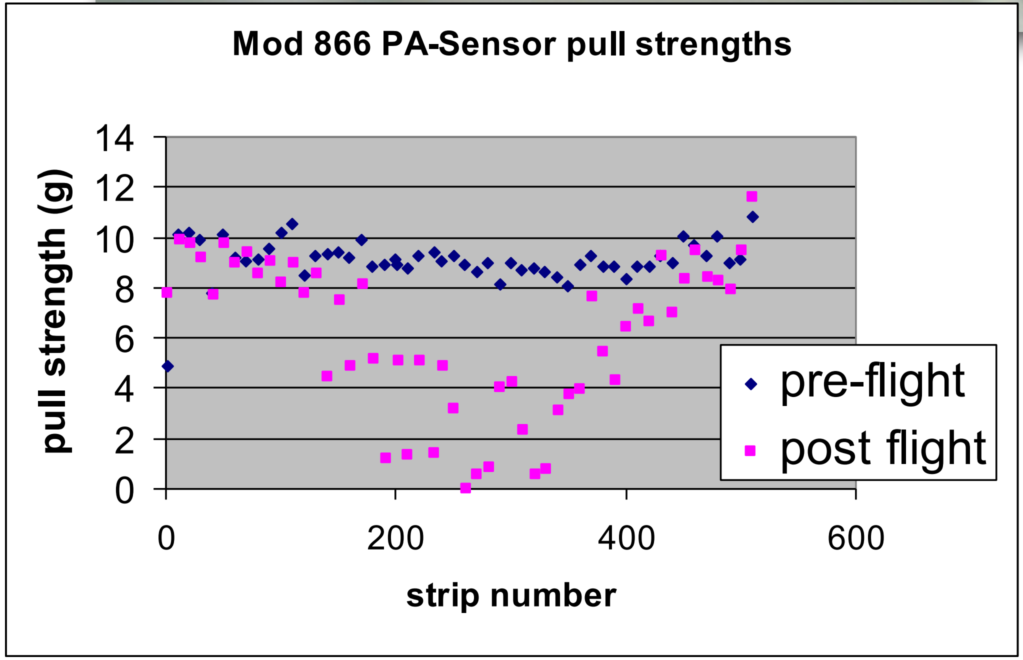
https://indico.cern.ch/event/435798/contributions/1074098/attachments/1134177/1622192/encapsulation_study_-_Oxford.pdf

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



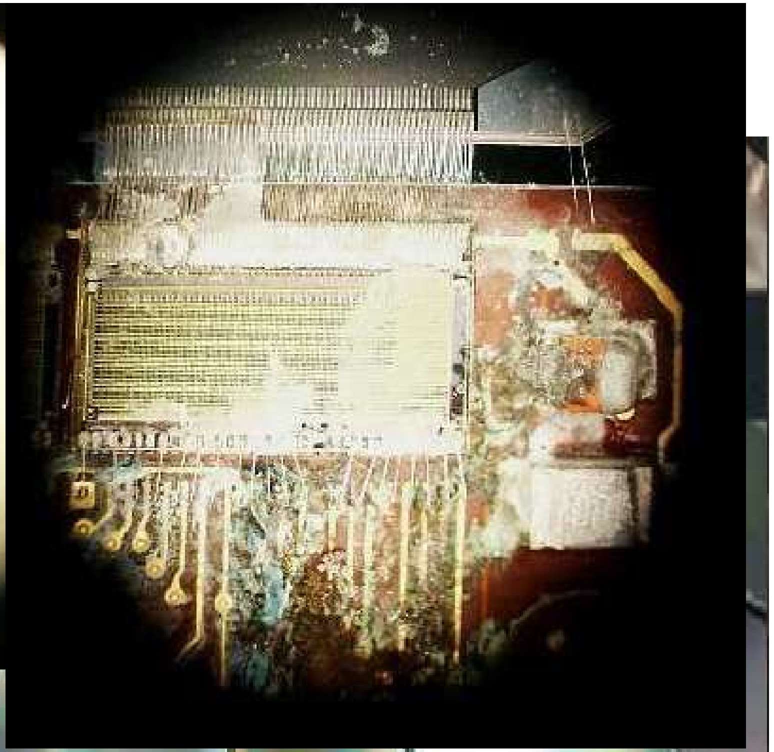


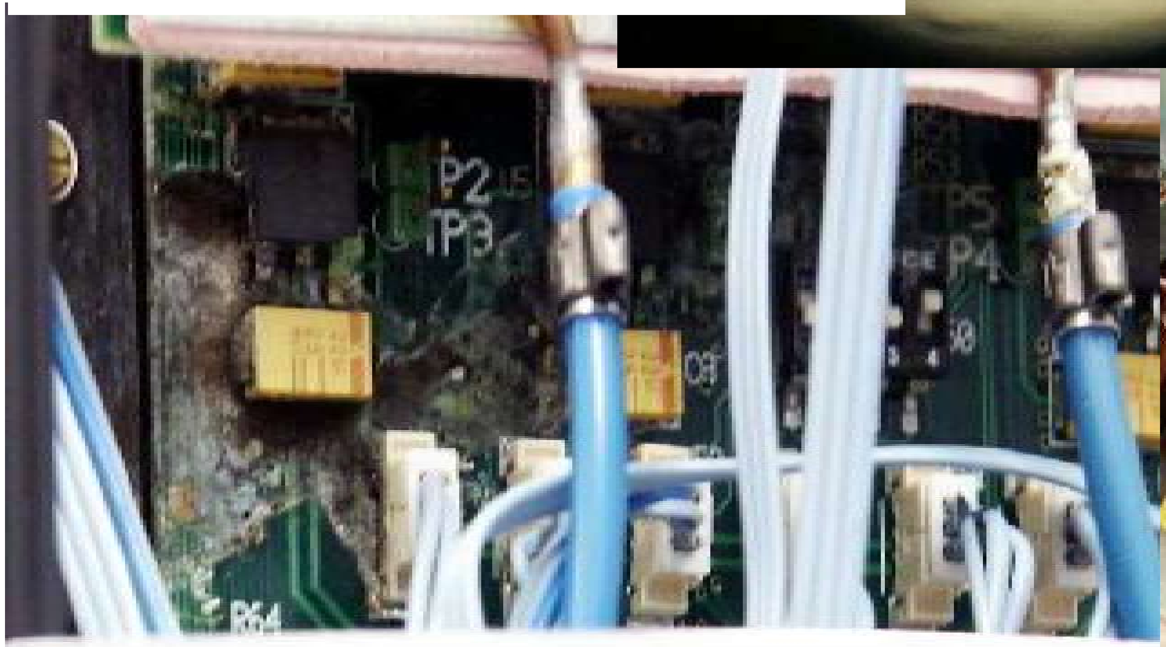
Cooling Damages

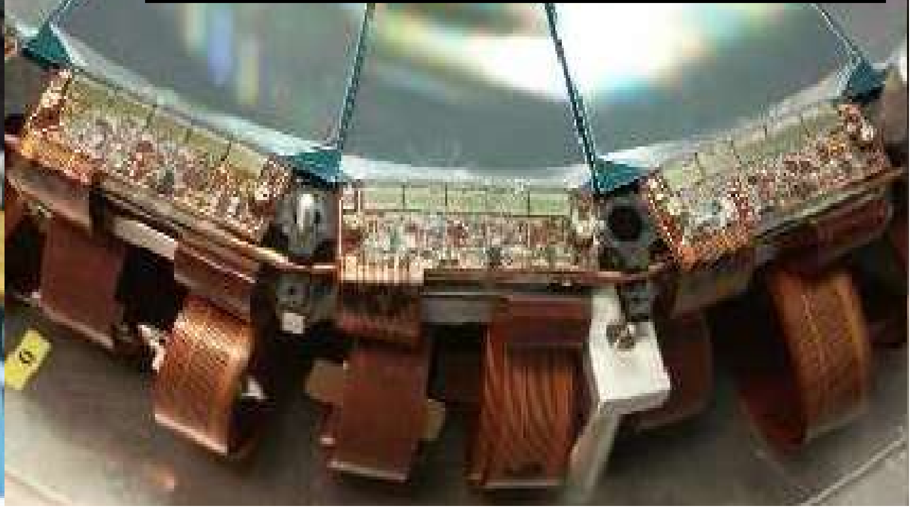
Water Damage in Tracker …

- 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



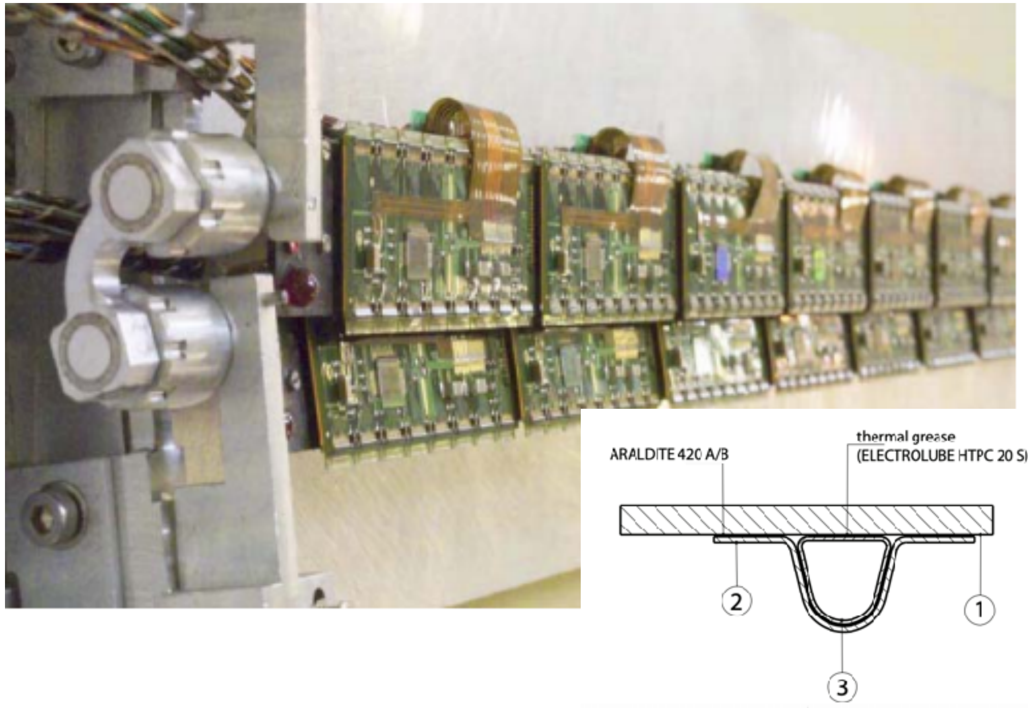


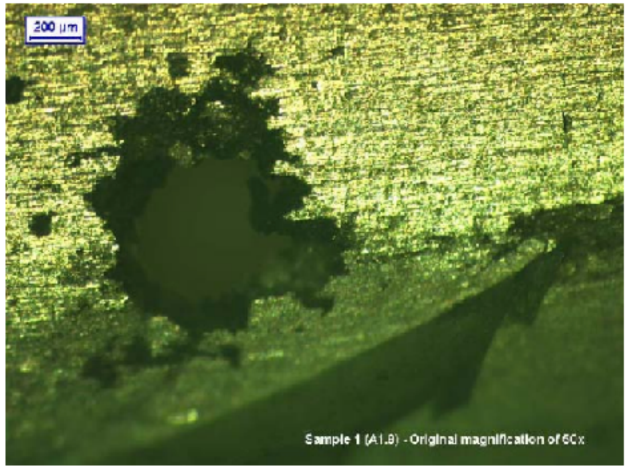


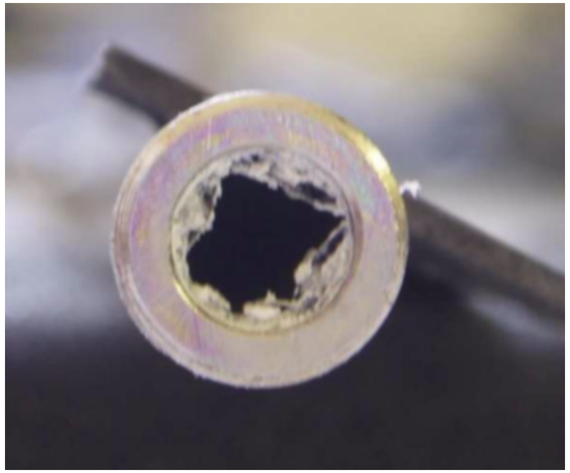
ATLAS Pixel Tube Corrosion

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

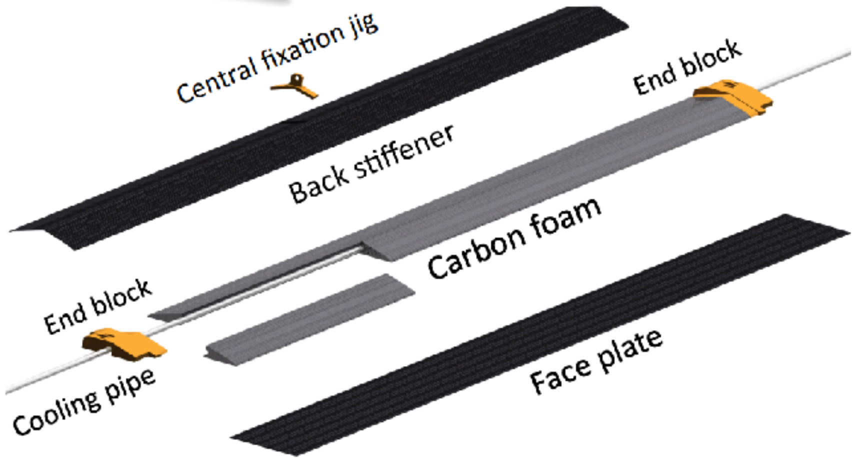
- Repair the 43 loaded staves with a pipe-inside-the-pipe
- Production of new staves with new Al compound and laser welding
- Repair of bare staves (~100)

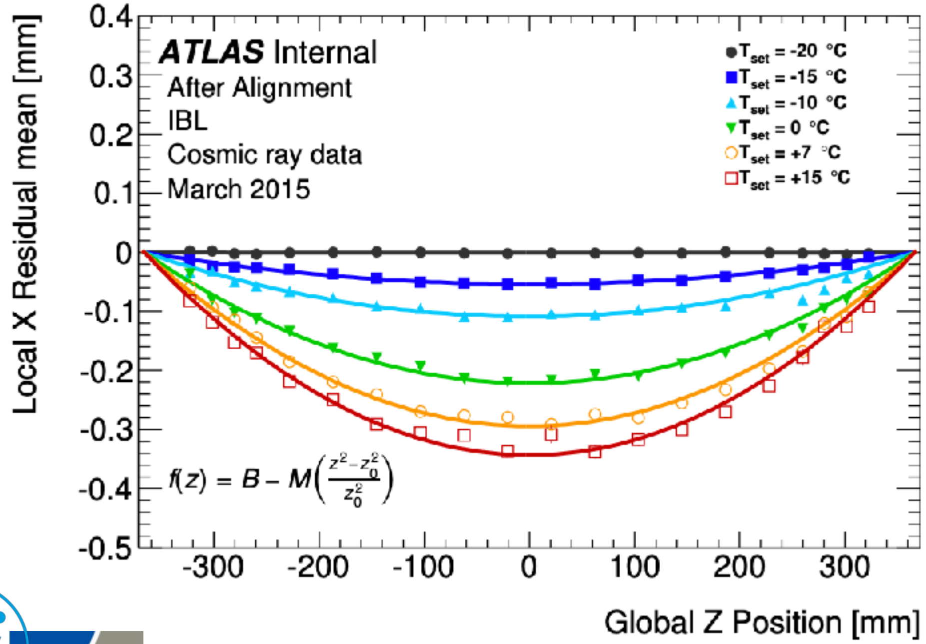
Other Problems and Famous Problems

ATLAS IBL Stave Bow

during commissioning

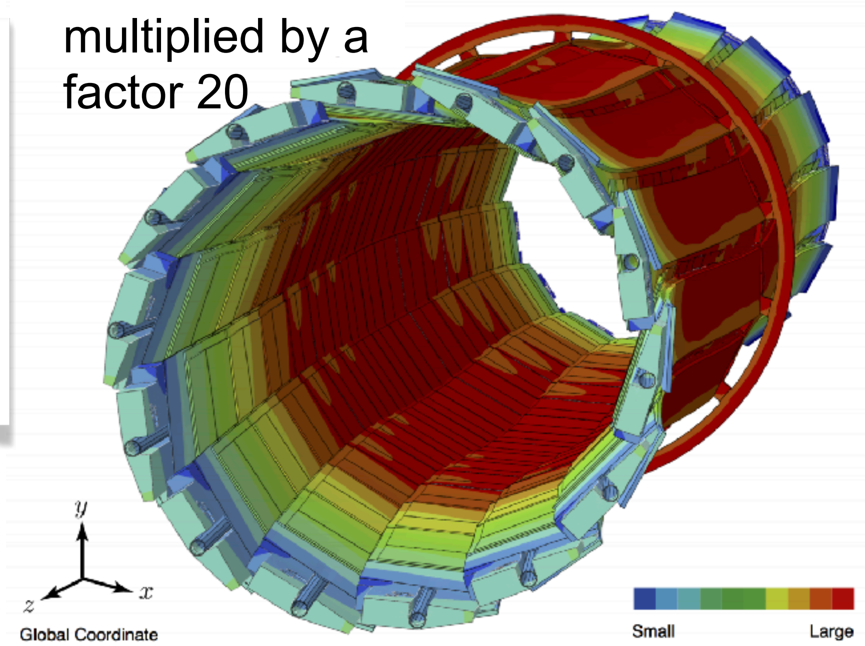
- Distortion depending on the operating temperature was observed.
- Caused by a mismatch between the coefficients of thermal expansion (CTE) of a bare stave made with the carbon foam and the flex attached on the bare stave.
- Maximum more than 300 μm at -20 ◦C with respect to the nominal position at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





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

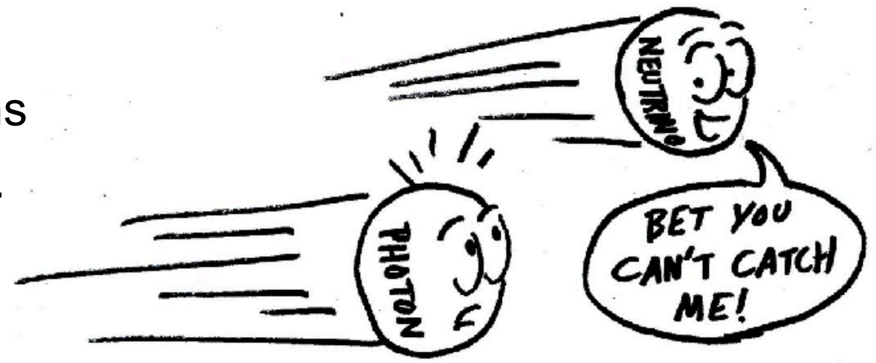
multiplied by a factor 20



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

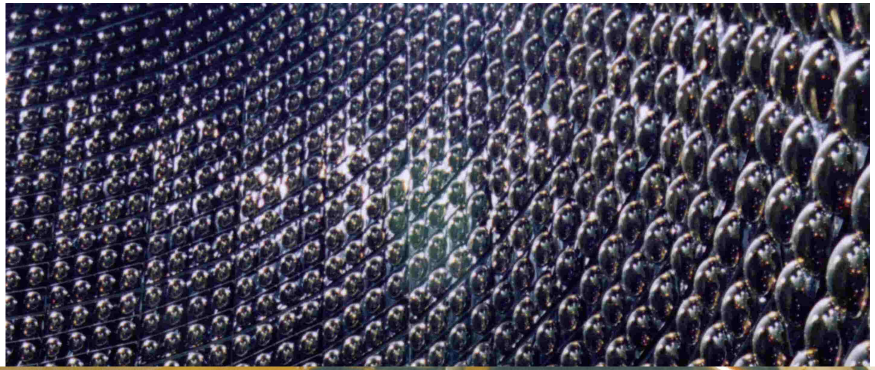
- Kink from a GPS receiver to OPERA master clock was loose
  - Increased the delay through the fibre resulting in decreasing the reported flight time of the neutrinos by 73 ns,
  - making them seem faster than light.

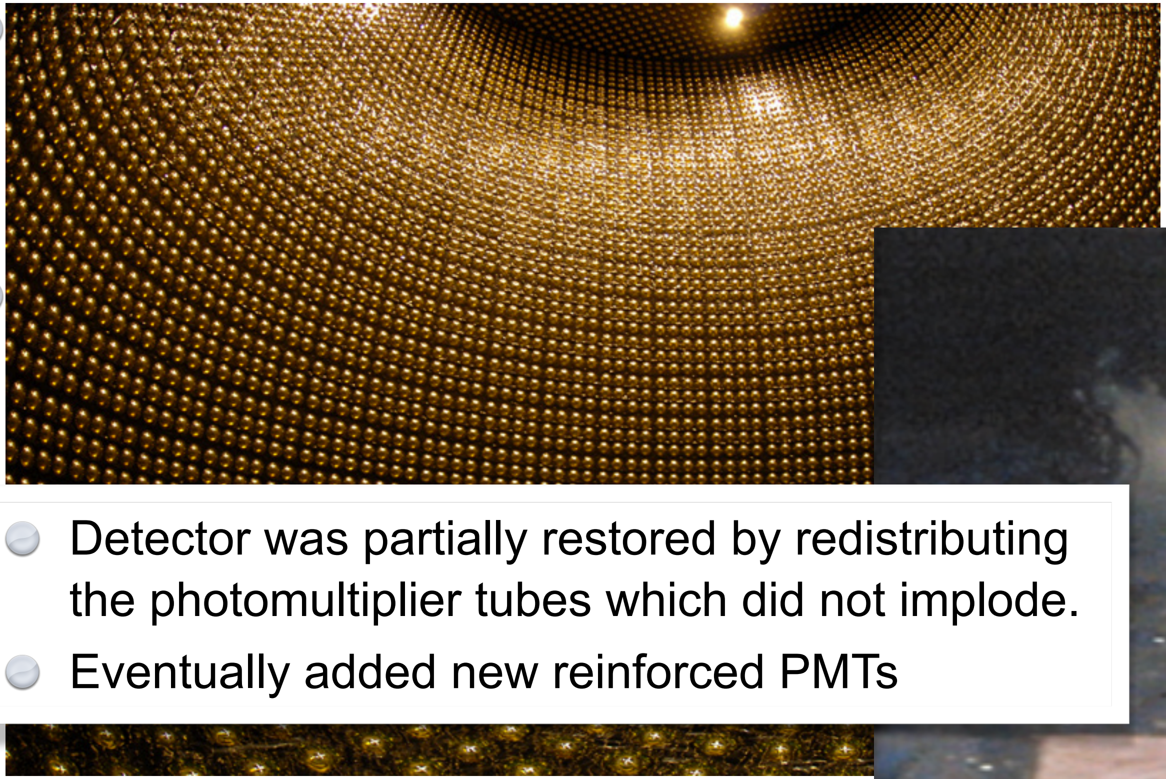
After finding the problem, the difference between the measured and expected arrival time of neutrinos was approximately 6.5 ± 15 ns.

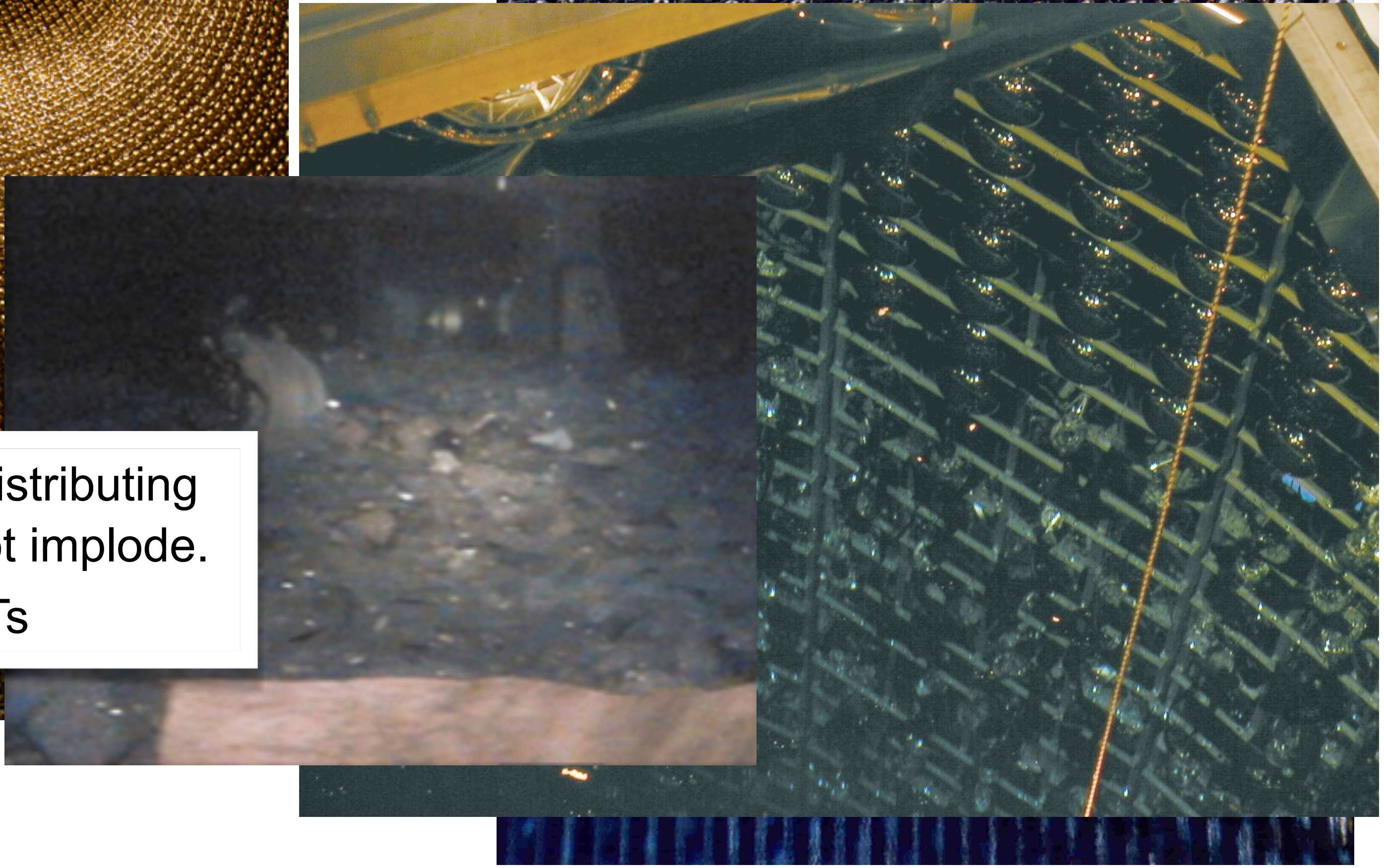
Maybe Most Famous Damage ....

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



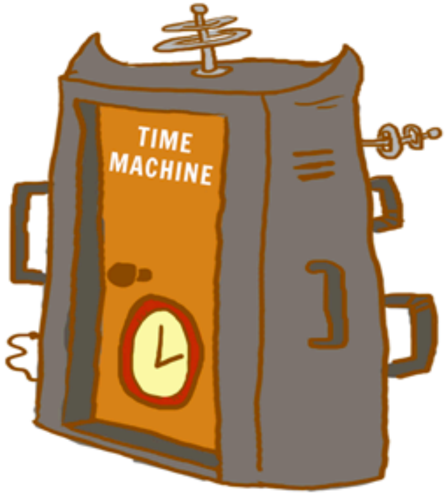




- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.
- Eventually added new reinforced PMTs

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
- …..

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