Lessons from the CMS TOB Mechanics

Forum on Tracking Detector Mechanics

3-4 July 2012, CERN

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CERN – PH/DT

http://indico.cern.ch/event/Forum_on_Tracking_Detector_Mechanics

Acknowledgements

To the many people having contributed in the design, construction or testing of the TOB. The following list surely still misses some names.

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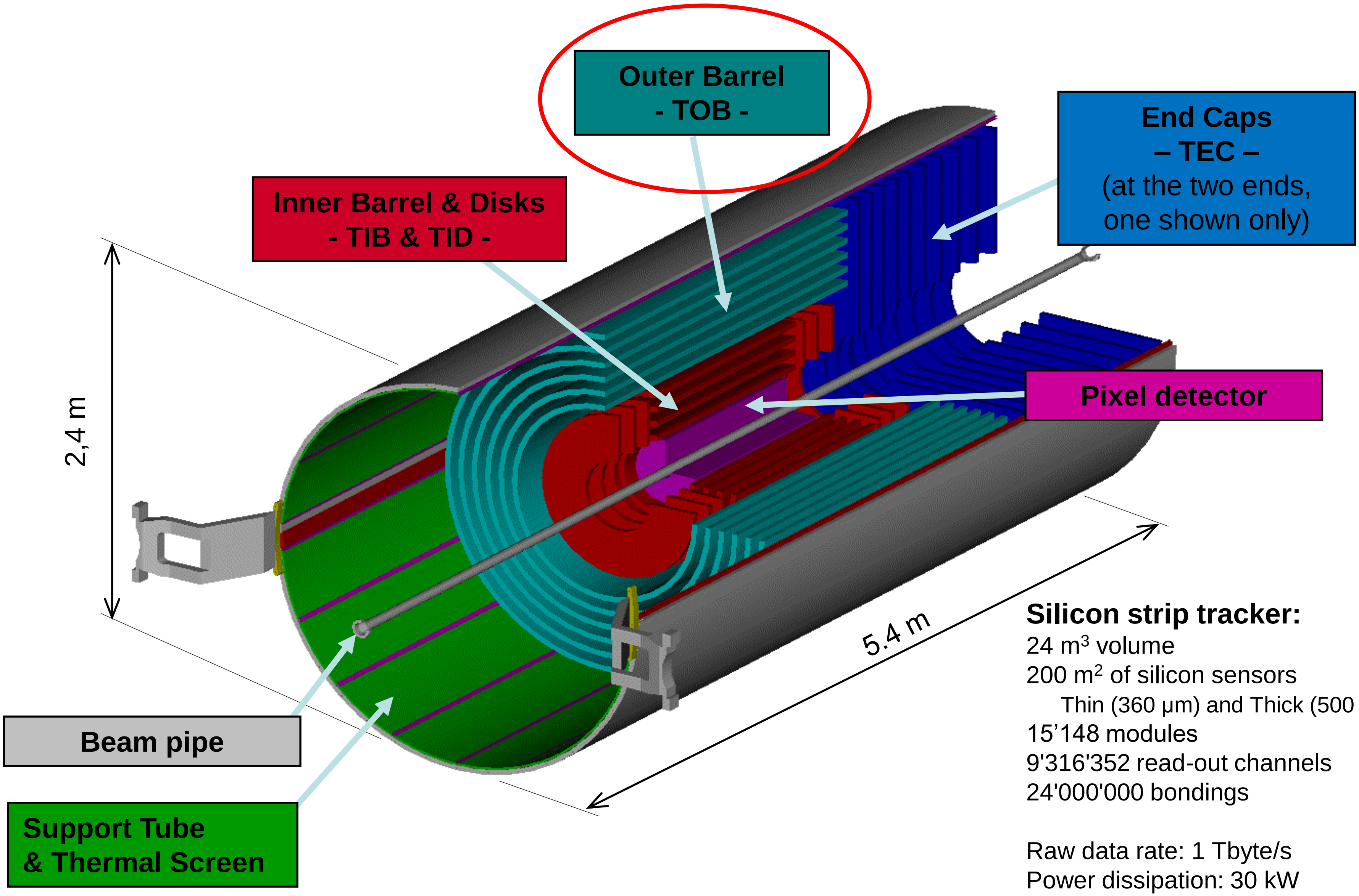
CMS Tracker

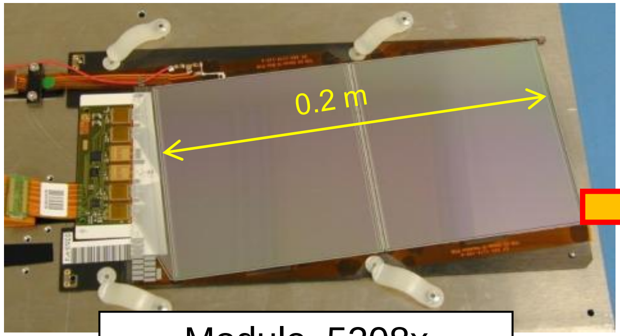


Silicon strip tracker:

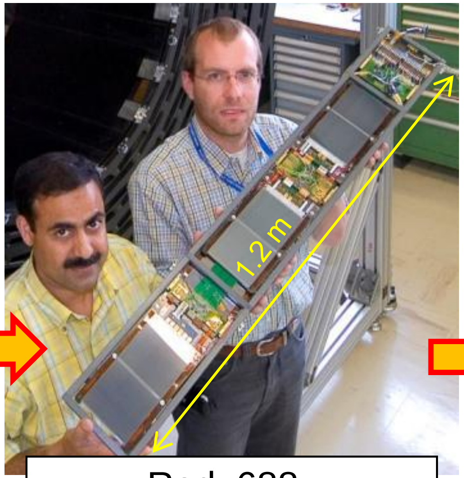
24 m^3 volume
200 m^2 of silicon sensors
Thin (360 μm) and Thick (500 μm)
15’148 modules
9'316'352 read-out channels
24'000'000 bondings

Raw data rate: 1 Tbyte/s
Power dissipation: 30 kW
Operating temperature: -10°C

CMS TOB, Tracker Outer Barrel



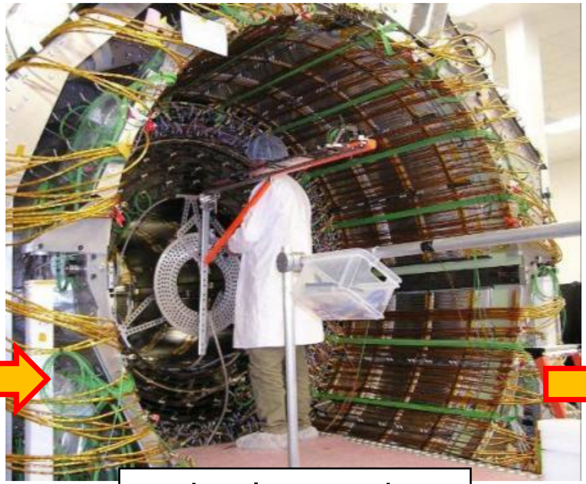
Module, 5208x
(34% of CMS Silicon Tracker)
Assembled in the U.S.



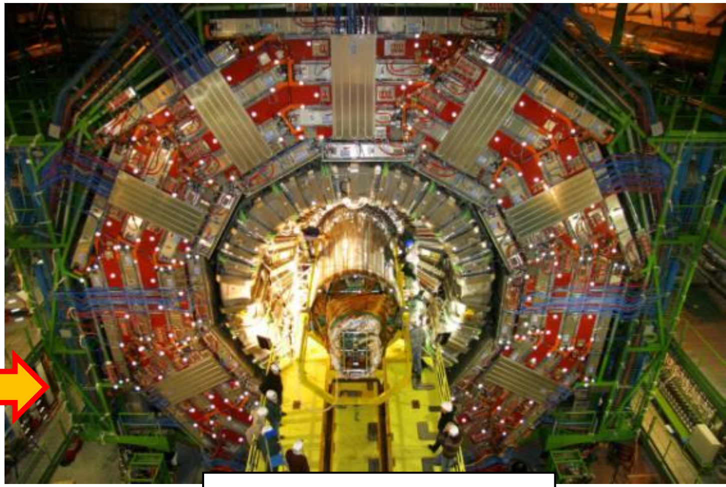
Rod, 688x
Finland, U.S., CERN

Wheel, 1x
CERN

Rod to Wheel



Wheel to Tracker



Tracker to CMS

Lessons from the CMS TOB Mechanics:

- Transports
  - Module bond-wire damage
  - Production transports
- Support structure (“Rod”) manufacture:
  - Cooling pipes
  - Precision assembly

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Transport needs

Most delicate: 700 completed rods with modules, transported in batches during ~2 years from U.S. to CERN.

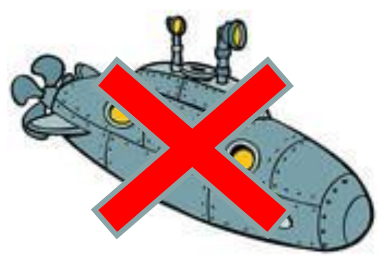
Helsinki:
Rod frames

CERN:
Rod cabling
Final TOB integration

Fermilab:
Modules
Rod assembly

UCSB:
Modules
Rod assembly

But how?

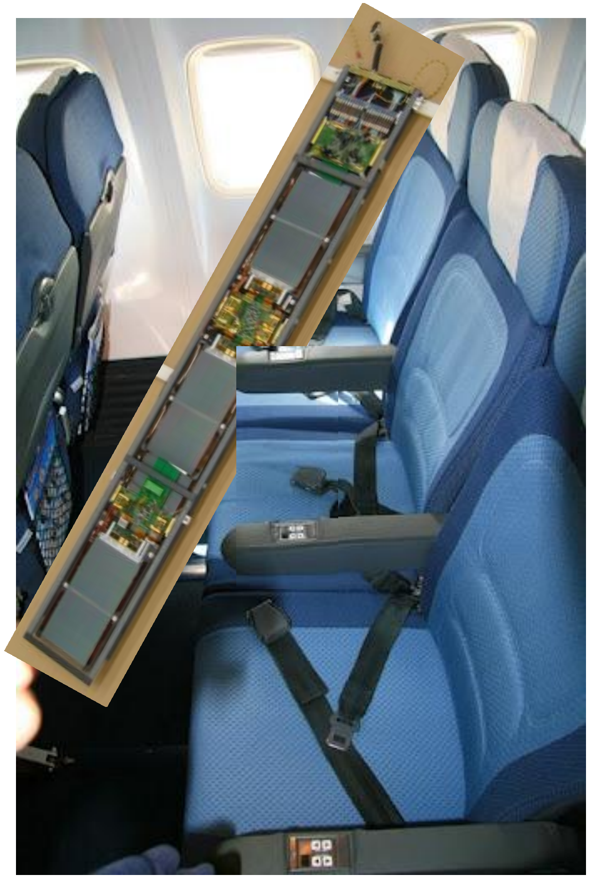


At lot of handling, slow...

Yes, but can one trust the transport pros?

Transport methods

- One option was to profit from the dense personnel traffic between Fermilab, Santa Barbara and CERN.
  - Hand-luggage (very limited in space + mass)
  - Luggage (not the safest option...)
  - Buy a 2nd passenger seat (sounds safe, but...)

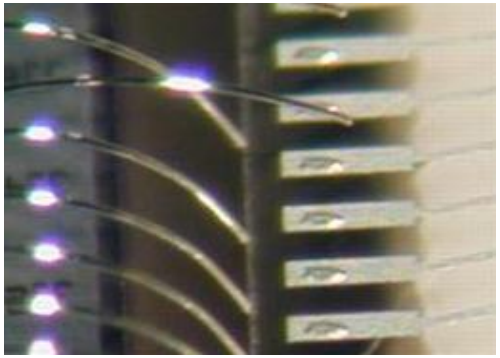


First ideas were proposed in the good old times.
Then we got September 11th 2001, and never tested all these...

Transport methods

- So, we decided to plan for rod transport by air, in good shipment casings with a lot of foam, warning stickers, ShockLogs and praying...
  - This was a project as such.
- For the modules we still opted to use physicists with hand-luggage.
  - This seemed with no risks, providing that the airport security lets pass, as they did.

Lessons from the CMS TOB Mechanics:



- Transports
  - Module bond-wire damage
  - Production transports
- Support structure (“Rod”) manufacture:
  - Cooling pipes
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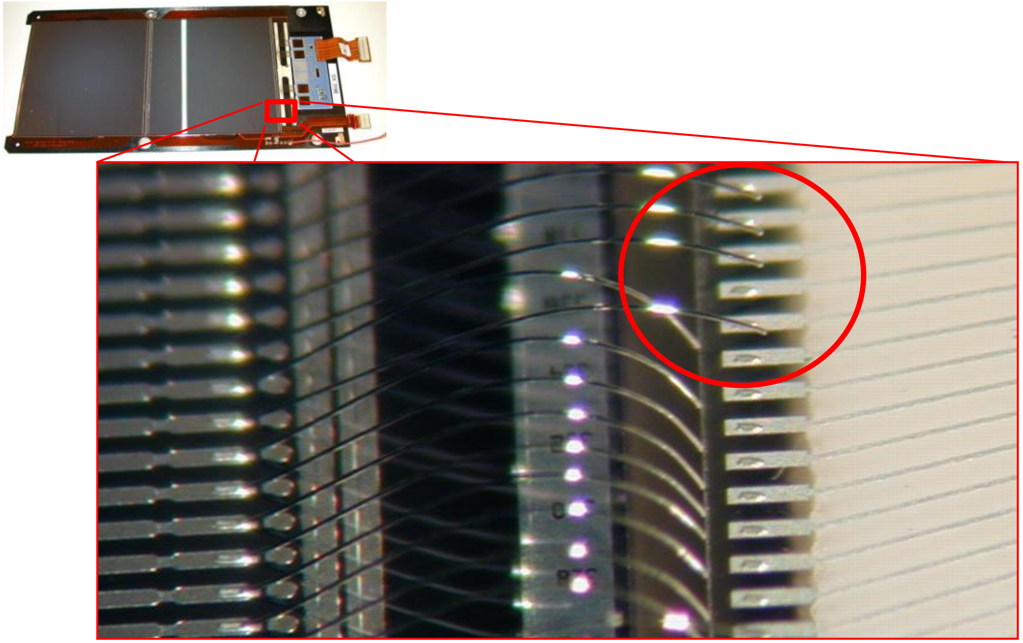
First transports – First shocks!

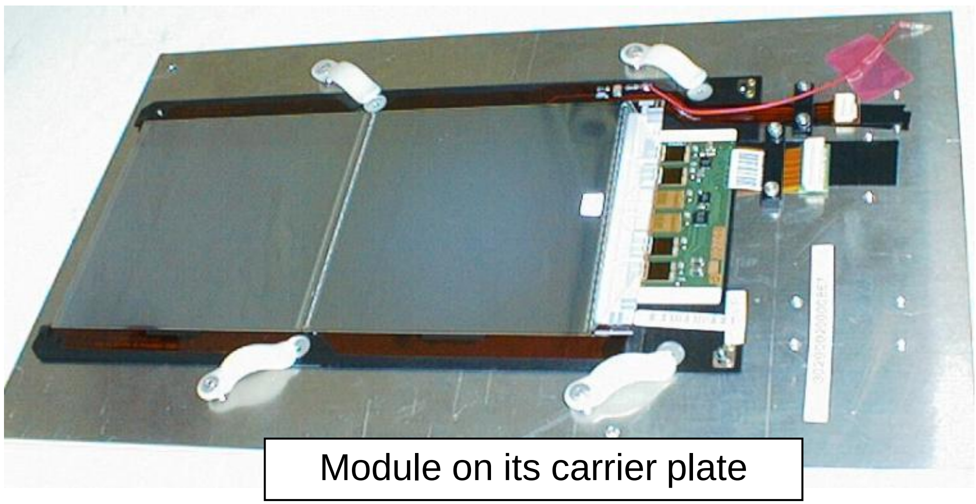
- First pre-series TOB modules were transported as hand-luggage (considered safest method!) and some via freight. The result was *a major shock*: Hundreds of bond-wires were broken in the modules in both transports!



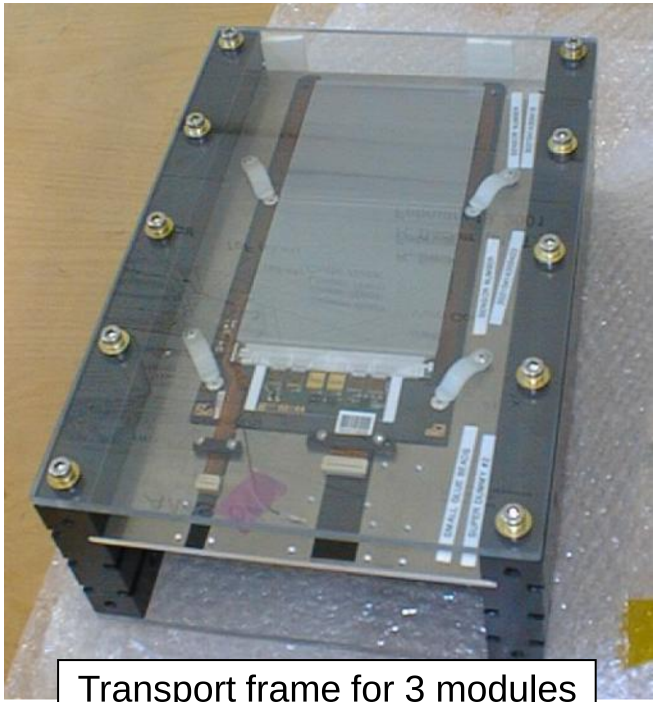
- 'Everything' was suspected, including shocks by bad handling. The module production responsible did not believe this to be the reason in the hand-luggage case (he did the transport himself...).

Broken bond-wires

- Suspects for the bond breakage:
  - Bad bond welds
  - Shocks
  - Vibration
  - Thermal effects (did not seem likely)
  - Other ?

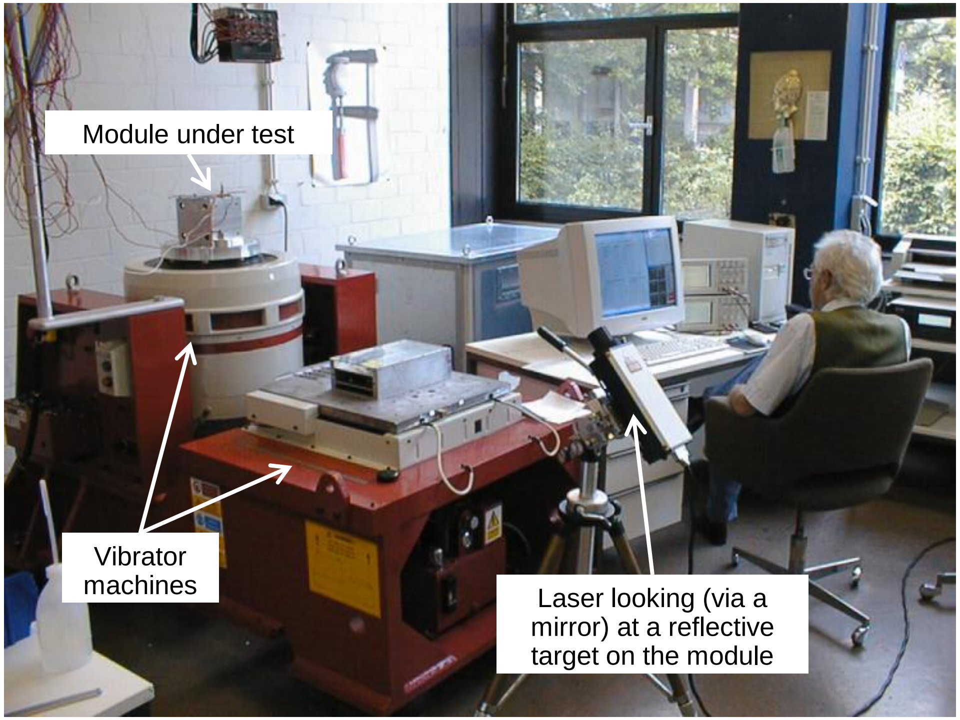


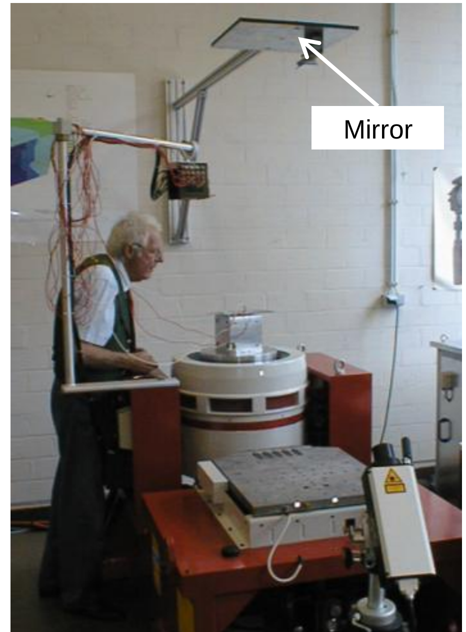
Module on its carrier plate

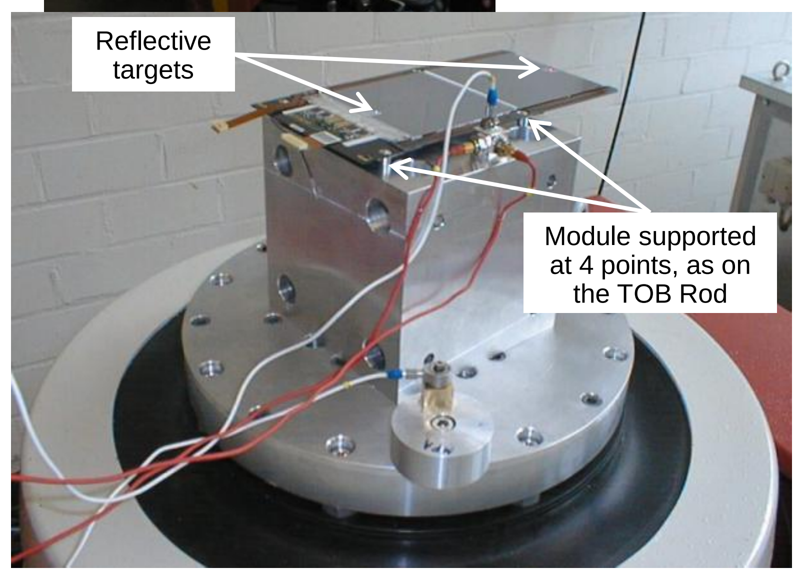


Transport frame for 3 modules

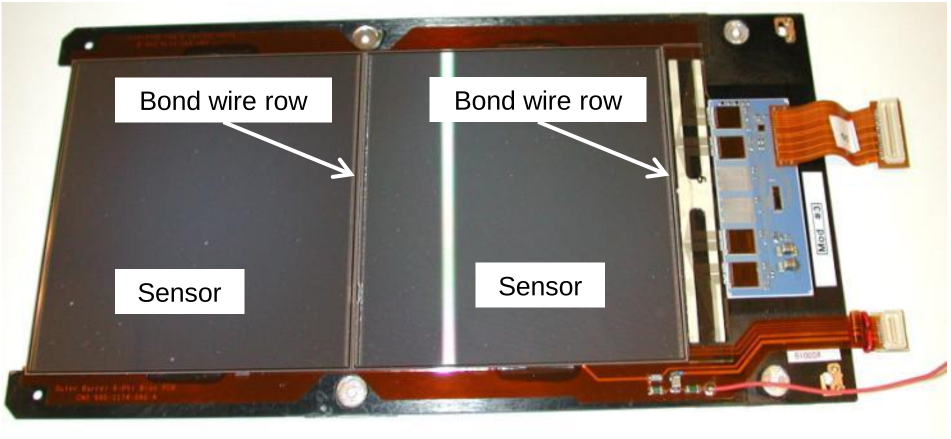
Module vibration tests in Aachen

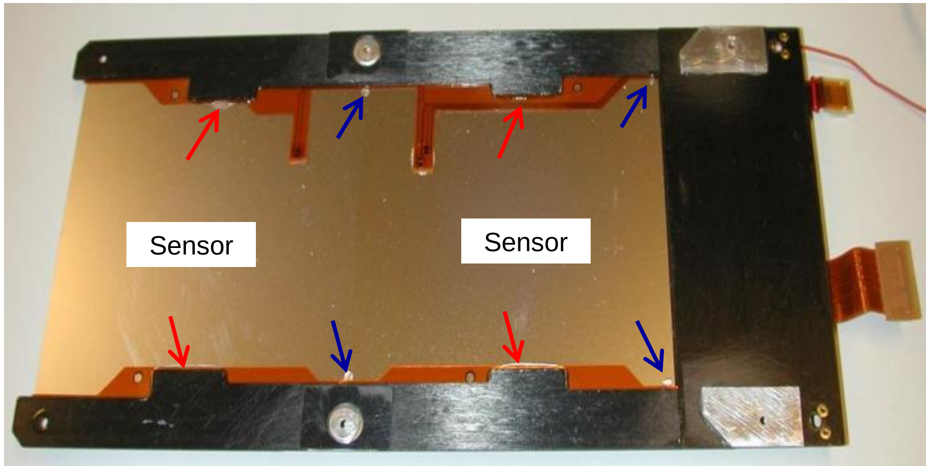






Module reinforcement versions



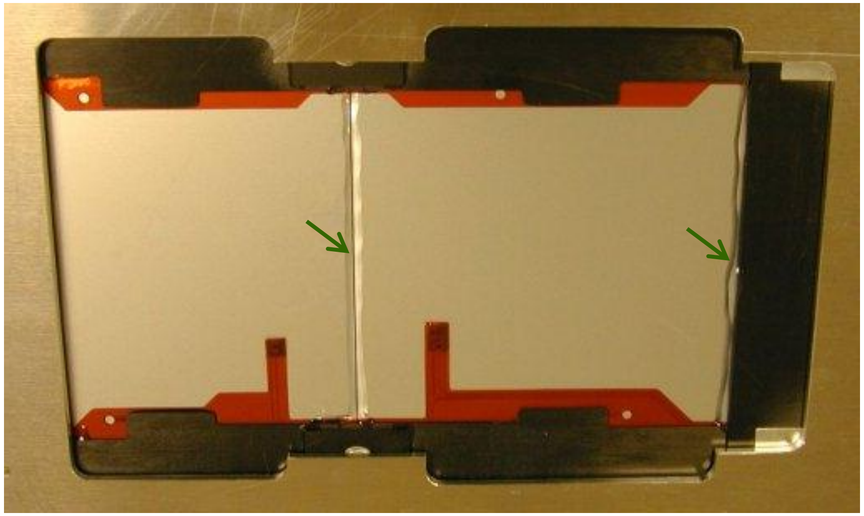


3 module versions were tested:

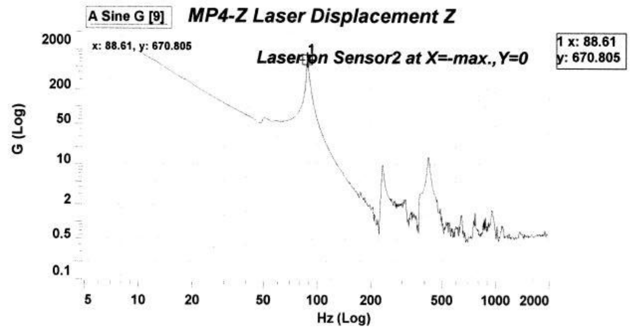
(A) Sensors supported from the middle tabs only. Original TOB module design.

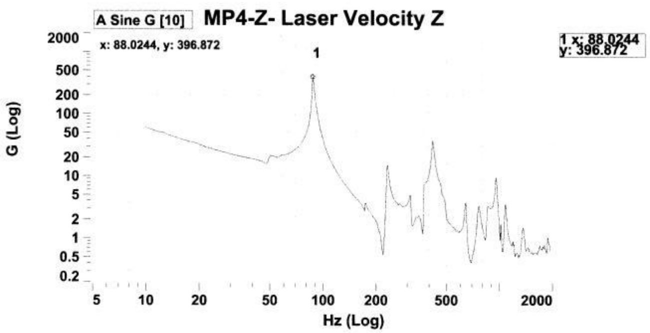
(B) Adhesive reinforcements in sensor corners.

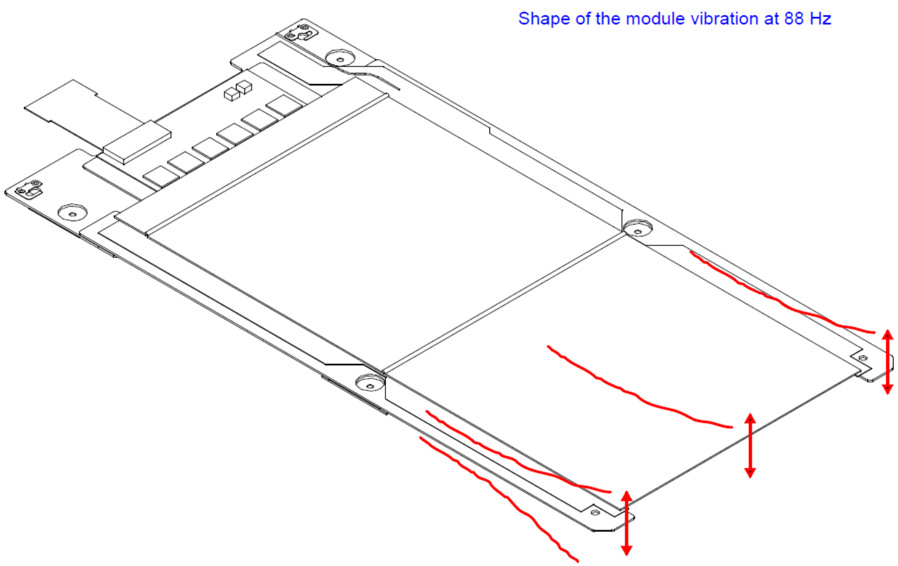
(C) Adhesive reinforcements along sensor edges.



Test 1: Search for resonance frequencies





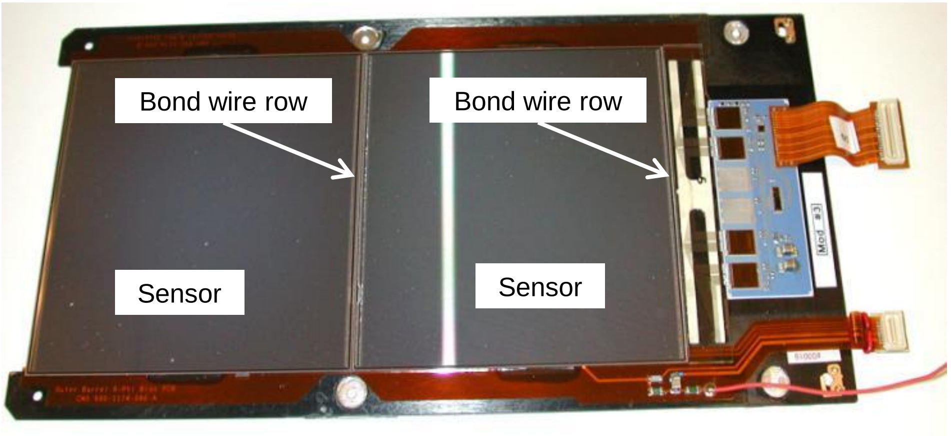


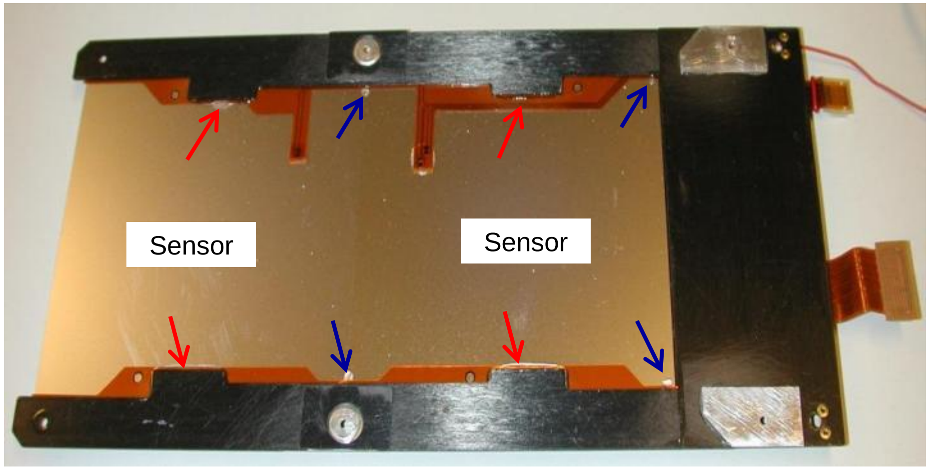
- Low acceleration sine sweeps, 0.1 and 0.5 g :
  - First resonance frequency 88 Hz, cantilever mode of sensor 2.
  - Second resonance frequency 220-240 Hz, most likely a transversal flexing of the sensors (and electronics?)
- Same results for all modules, reinforced and non-reinforced
- No bonds broken, even at resonance.

Test 2: Simulated 'transport' accelerations

- Used a NASA random vibration spectrum, simulating loads during transports.
  - 3.4 g acceleration, which can easily happen during transports.
    - ~ normal vibration levels in an airplane.
  - 6.8 g continuous acceleration which we considered as reasonable upper limit for these tests.

Results of the simulated ‘transport loads’





(A) Sensors supported from the middle tabs only.
Original TOB module design.

Substantially damaged in the 3.4 g test.

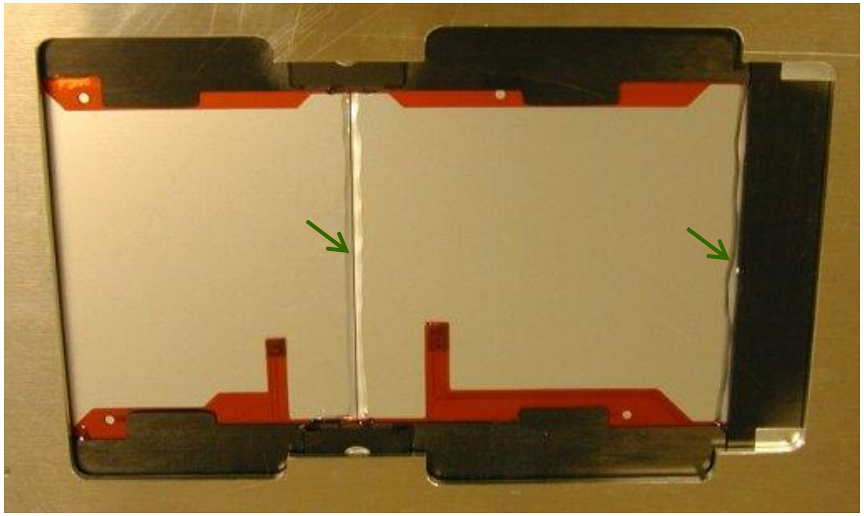
(B) Glue reinforcements in sensor corners.

Survived 3.4 g but was substantially damaged at 6.8 g.

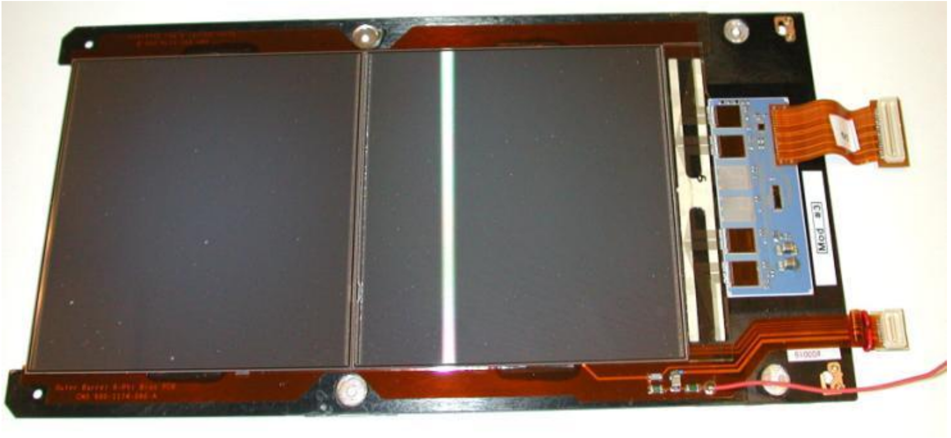
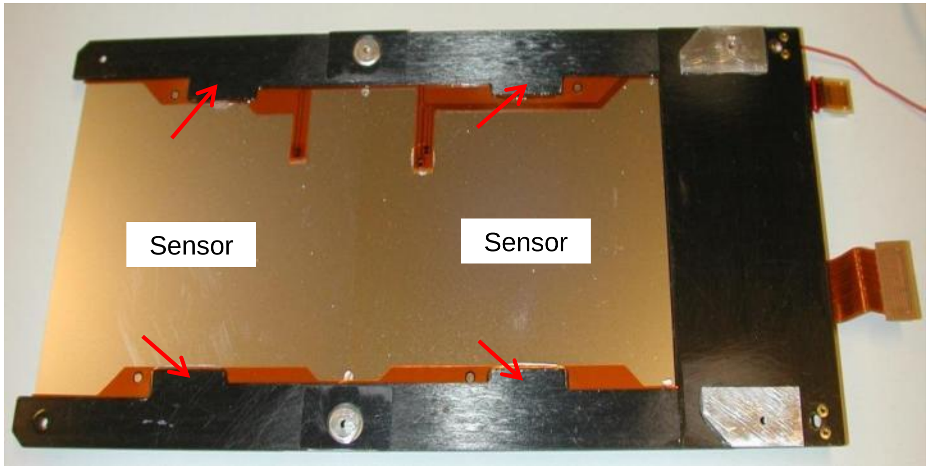
(C) Glue reinforcements along sensor edges.

Survived the 6.8 g without damage.

→ Conclusion: Needed to add the full reinforcing glue to the modules.



Why did we have this problem?

- The idea of the original TOB module design was to limit bowing and stresses in the module by reducing bi-metallic effects between the carbon fibre frame (CTE: ~ 0 ppm/K) and the silicon sensors (CTE: 2.6 ppm/K)
  - The sensors were glued to the frame only at the tabs (red arrows)

- The design was ok during bonding (sensors supported temporarily on a back-plate) and in lab + in beam-tests (very careful handling).
- But did not survive at all vibrations in a normal air-plane. It did survive transport in car...

- **Adding adhesive** (SYLGARD® 186 Silicone Elastomer) **along the sensor edges solved this problem.**
  - That same adhesive was finally used also for potting the sensor-to-sensor wire-bonds.

Lessons from the CMS TOB Mechanics:

- Transports
  - Module bond-wire damage
  - Production transports
- Support structure ("Rod") manufacture:
  - Cooling pipes
  - Precision assembly

Equipment for the Transports

- We were convinced that we need to use commercial transports, to ensure a continuous flow of Rods through Finland → CERN → US. → CERN
  - 'Hand-luggage' or 2nd passanger seat not ok
  - Few, big transports not ok, as we needed to have Rods simultaneously at all stages of assembly work.

→ Needed excellent transport / storage boxes.

  - A big project was launched to prepare the equipment.
  - Credits of the work and success to Paul Tipton et al. / University of Rochester and Fermilab.

Rod transport boxes

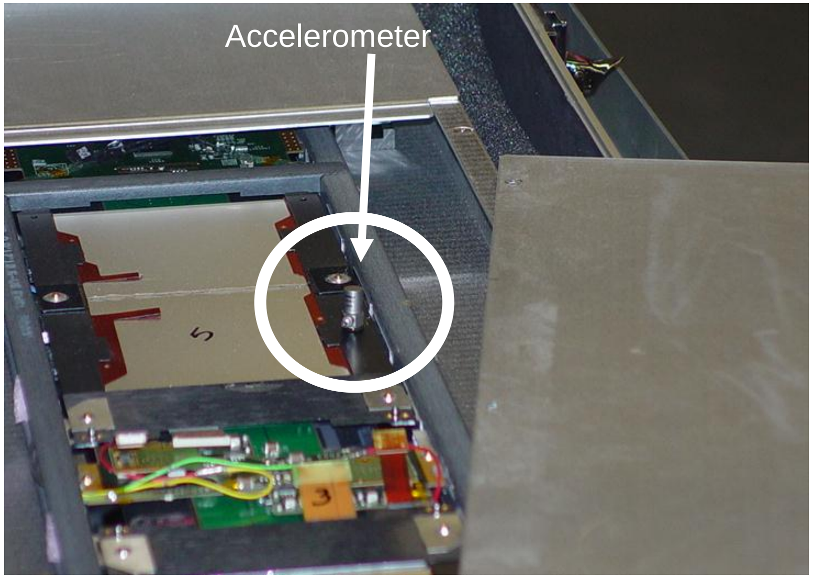
- Sheet aluminum, very rigid with lid
- Rod clamped at 6 locations, butted at the end
- Two-piece lid allows for operation while still in box
- 215 fabricated

Rod transportation crates

- Hardigg AL5545-2305AC transport crates
- 6 inches of made-to-fit closed-cell antistatic polyurethane foam on inside top and bottom of crate, 2.5 on the sides
- Exterior toroidal cushions as feet of crate

- We needed 6 crates.
- But even more were needed by the US military to get to Irak.
- They got their crates first...

Testing



- With 100 g shocks on the crate the Rod had max acceleration <30 g and vibrated with ~30 μm amplitude.
- The drop and vibration tests showed that the Rods and Modules were robust and well protected by the transport boxes and crate.

Transports during Production phase

- Several major shocks on the Transport crate were recorded
  - One event was beyond the 100 g limit of the accelerometer.
  - Several events between 10 g (our alarm limit) and 80 g.
- In the 80 – 100+ g events the crate has probably fallen from ~ 1 m height.
  - The loaded crates were labelled ‘DO NOT STACK’, but...

- Still, most importantly, we never lost production Rods or Modules due transport!

Summary on:

- Transports
  - Module bond-wire damage
  - Production transports

- Any transport is a risk.
- The biggest loads the HEP equipment encounter during their 20+ years life can well be during the few transports.
- Transports can be successfully done, but need preparations
  - Components and assemblies need to be designed to resist the transport loads.
  - Suitable equipment is a must (can mean a lot of money and manpower)
  - Transport qualification tests are a must !
- No transport insurance can recover unique equipment lost in transports, especially when the schedule is tight and spare part stocks are limited.
  - Boxes, even the most clearly labelled ones, can (and will) fall or even get lost during transports.
  - In the TOB, a loss of a 40-rod crate would have meant a 'hole' in the final Tracker.
    - We were lucky, no such event happened...
  - Try to split the transports into 'affordable' sets.
    This probably increases costs and requires more work, but would be safer.

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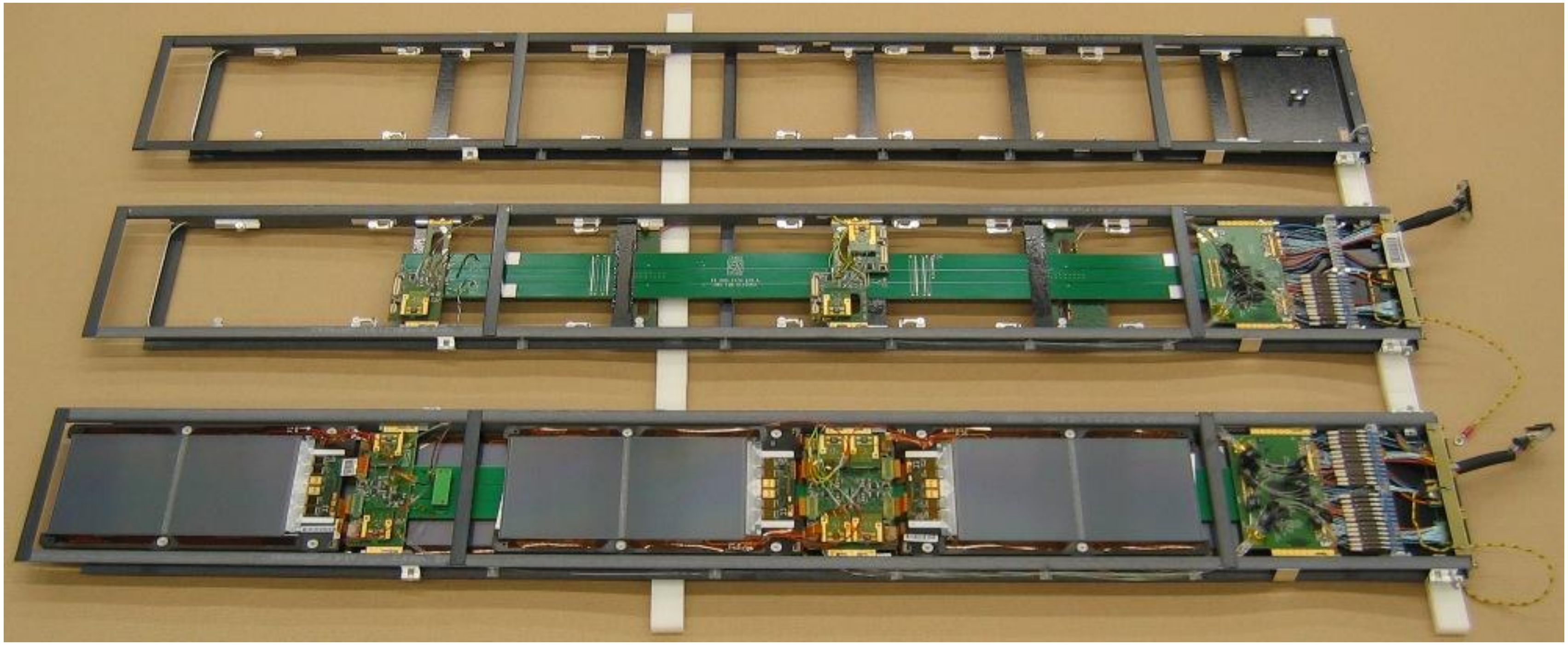
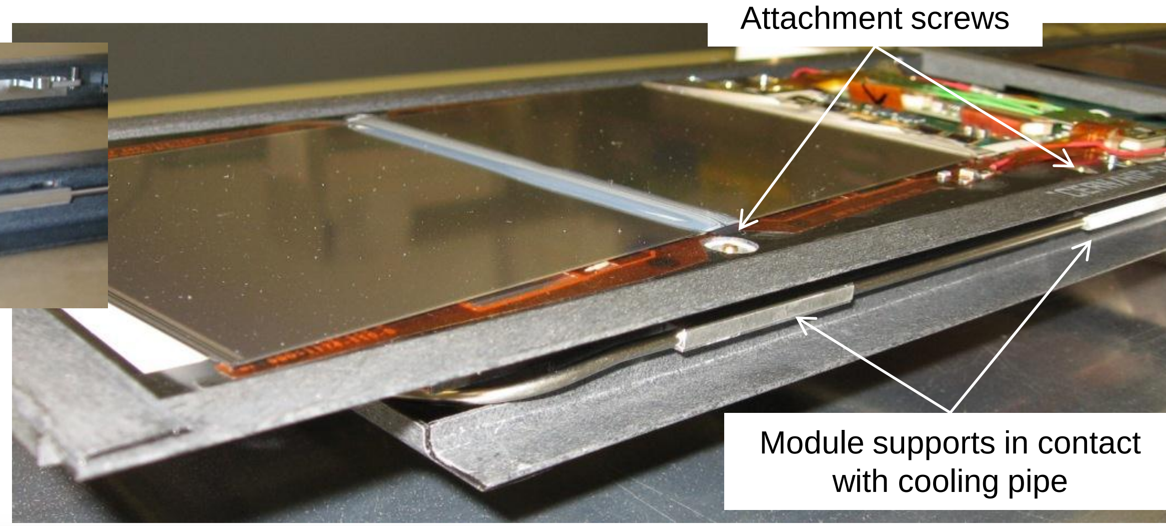
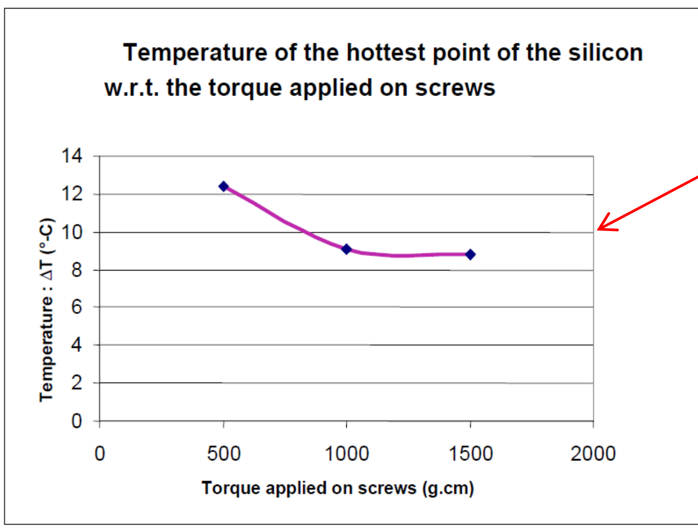
Rod frame supports the modules and the services



Module support / cooling contacts





ΔT of max 10˚C between silicon and coolant allowed

- Double-sided module with caps

- Screws fixing module on the blocks

- 1000 g.cm seems to be adequate (quite tightened)

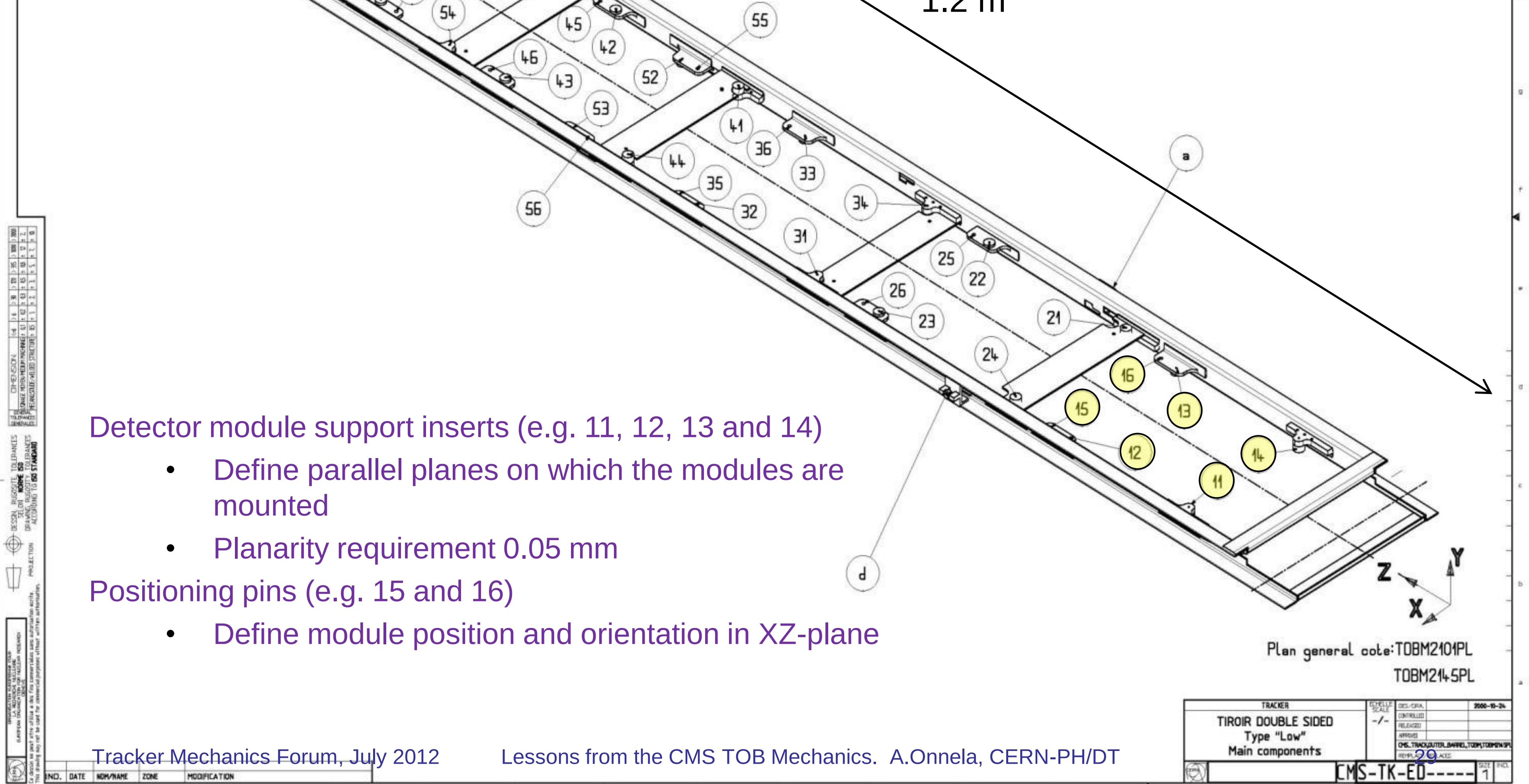
Tracker General Meeting
July 13th 2001

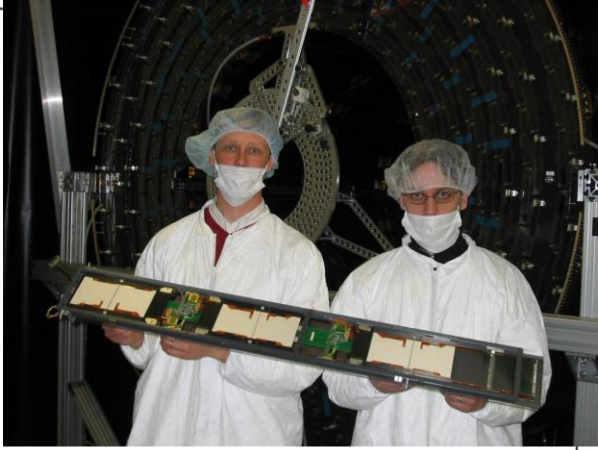
TOB Module Cooling Tests
M.Mermoud EP/CMT

21/22

The module support / cooling contact pieces must be precisely located:

1. For module positioning
2. For tight thermal contact (no gaps)
3. Avoid breaking module when tightened





Detector module support inserts (e.g. 11, 12, 13 and 14)

- Define parallel planes on which the modules are mounted
- Planarity requirement 0.05 mm

Positioning pins (e.g. 15 and 16)

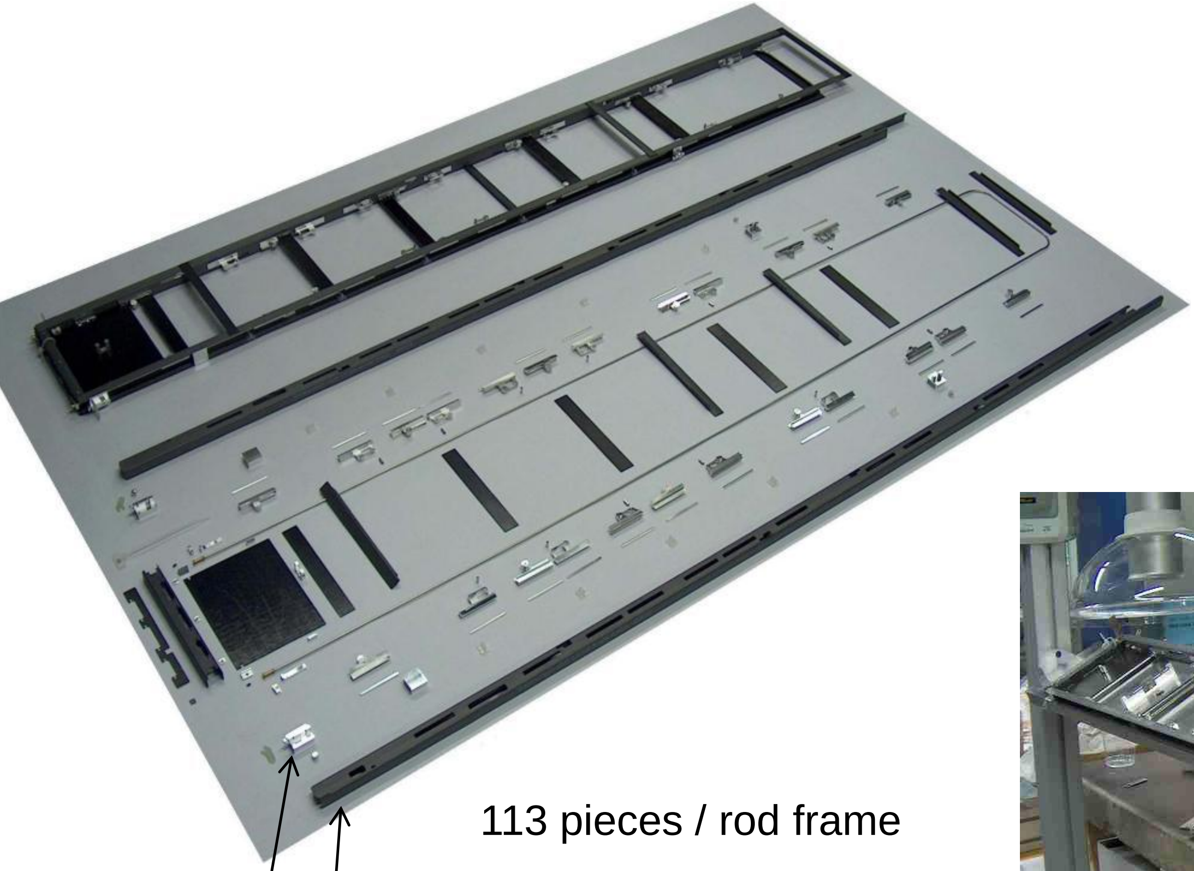
- Define module position and orientation in XZ-plane

Manufacture

Different methods were prototyped,

e.g. machining of module support surfaces to final precision (very difficult with light-weight structures).

Chosen method: From modest accuracy components to assemblies of high accuracy.



Metallic inserts

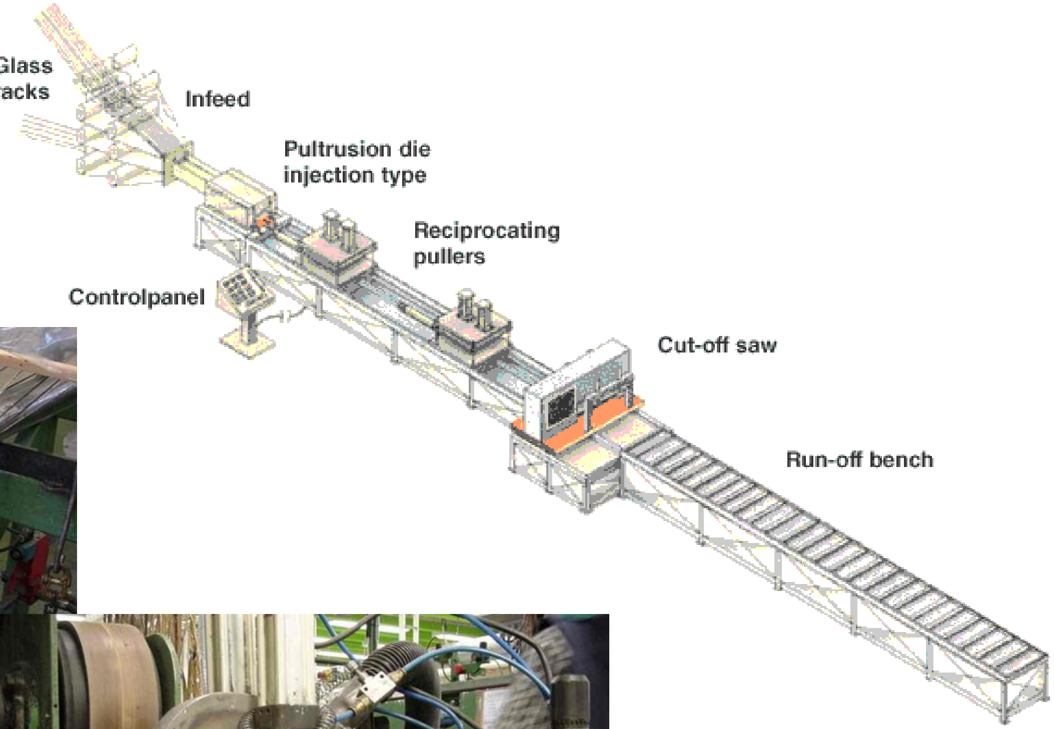
Carbon fibre pieces in ~1 mm precision

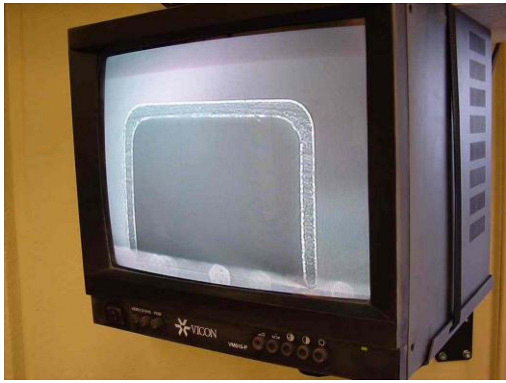
113 pieces / rod frame

760 rod frames in total (688 needed + 72 spares) = 85880 pieces in total !

1. Components placed stress-free on an accurate gluing jig
2. Capillary glue (Araldite 2020) added + room-temperature cure

Industrial production of components



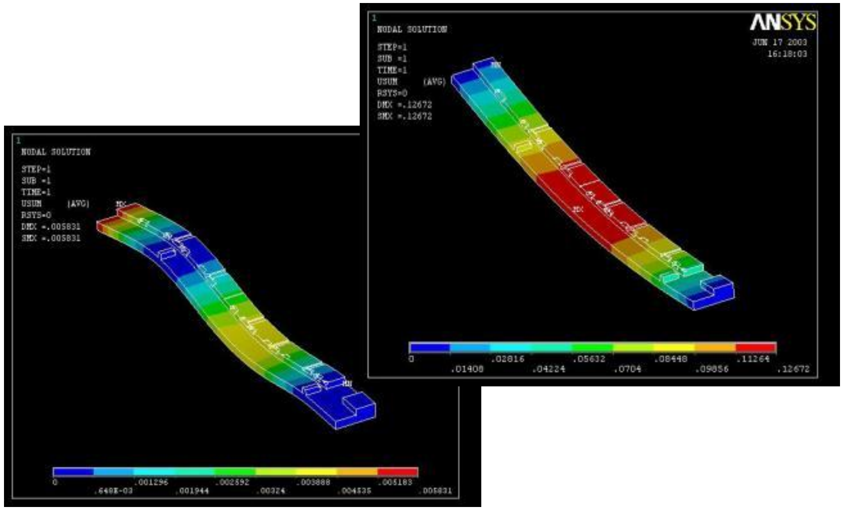


Pultrusion

Industrial production of components

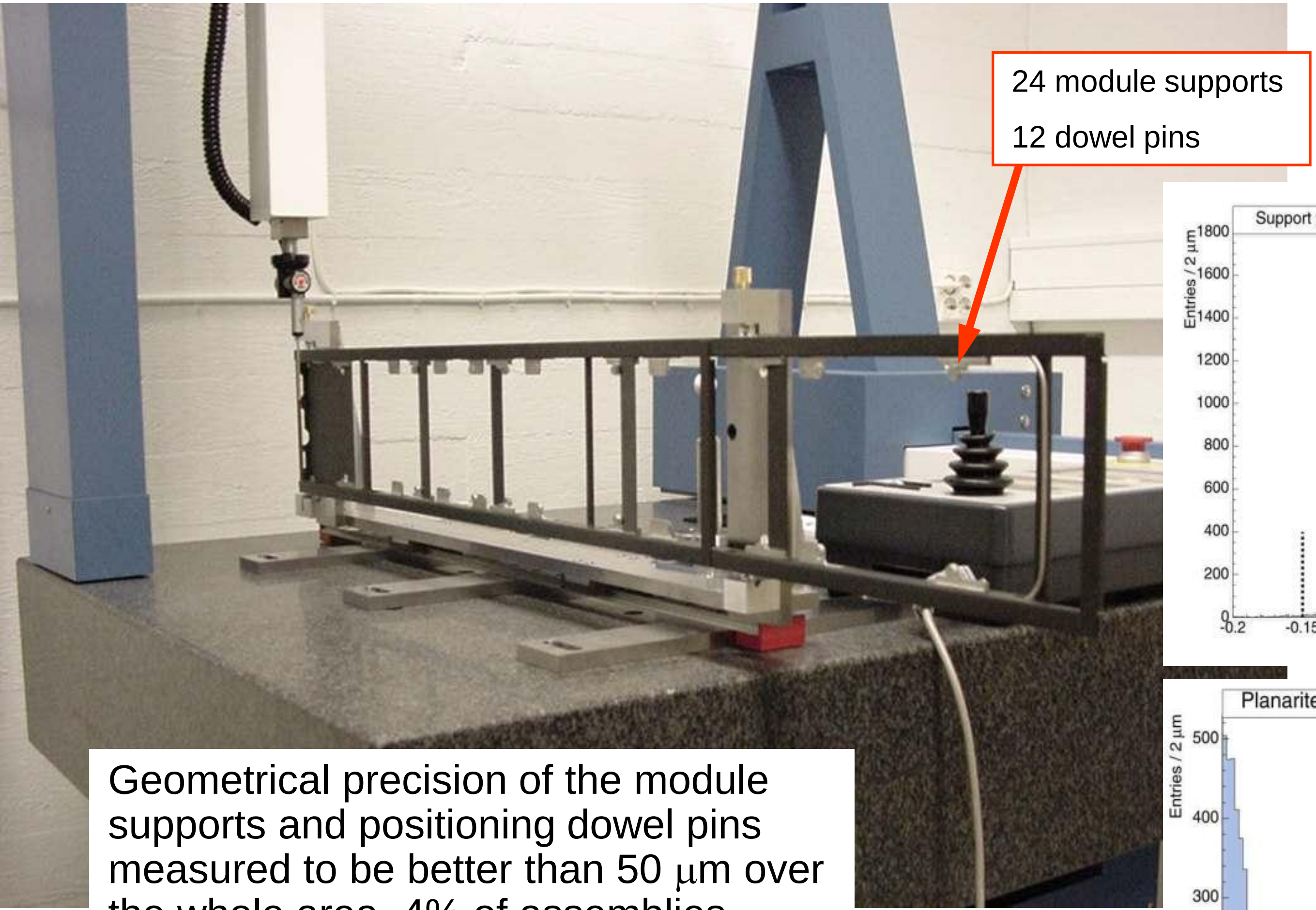
Water-jet cutting worked excellently,
even for thin C-shape profiles

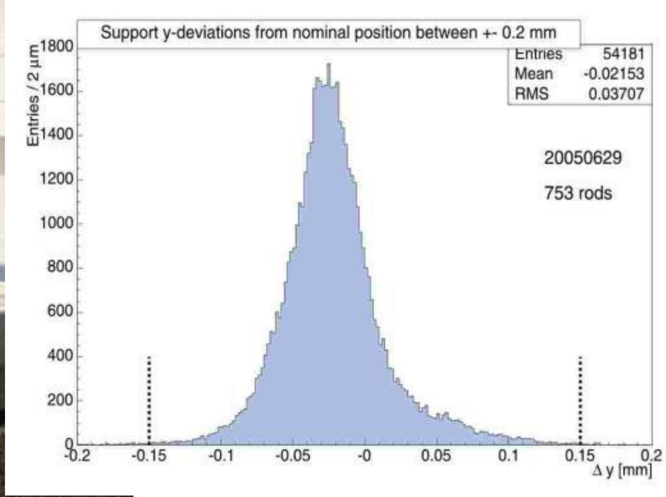
Assembly

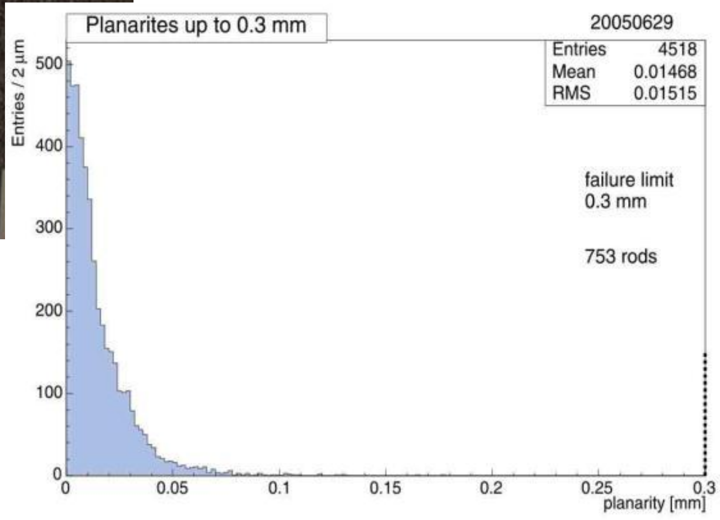


High-quality workmanship <u>very</u> essential.

Measurements

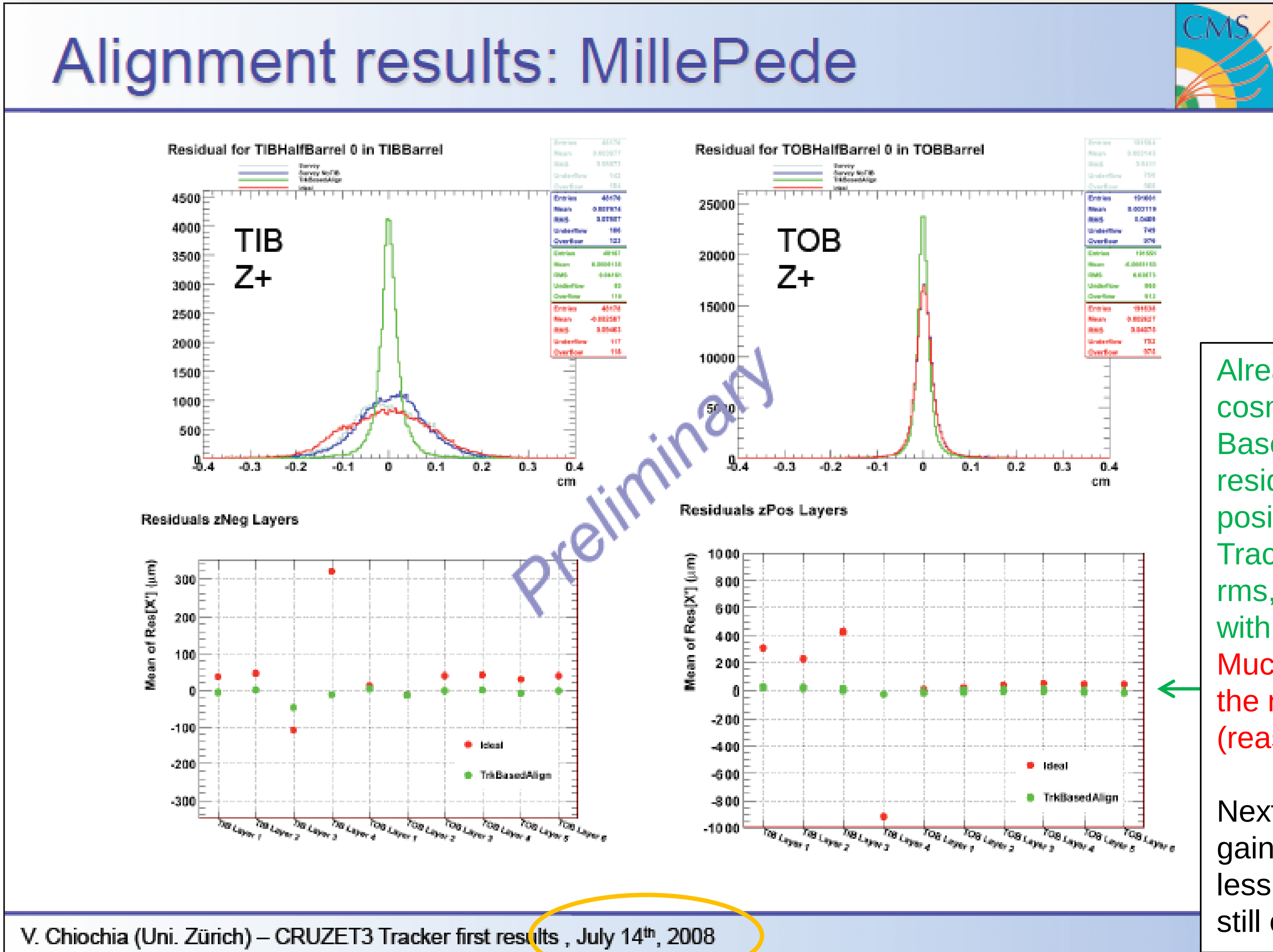






Geometrical precision of the module supports and positioning dowel pins measured to be better than 50 μm over the whole area. 4% of assemblies found out of tolerances, and corrected.

Mechanical precision vs. Alignment with Tracks



Already after first cosmic runs with Track Based Alignment the residuals for module positions <u>within the full</u> Tracker are at ~50um rms, and improve within 2008 to ~30um.
Much better than what the mechanics can (reasonably) do!

Next Tracker: Aim to gain in mass, maybe less precise structures still ok.

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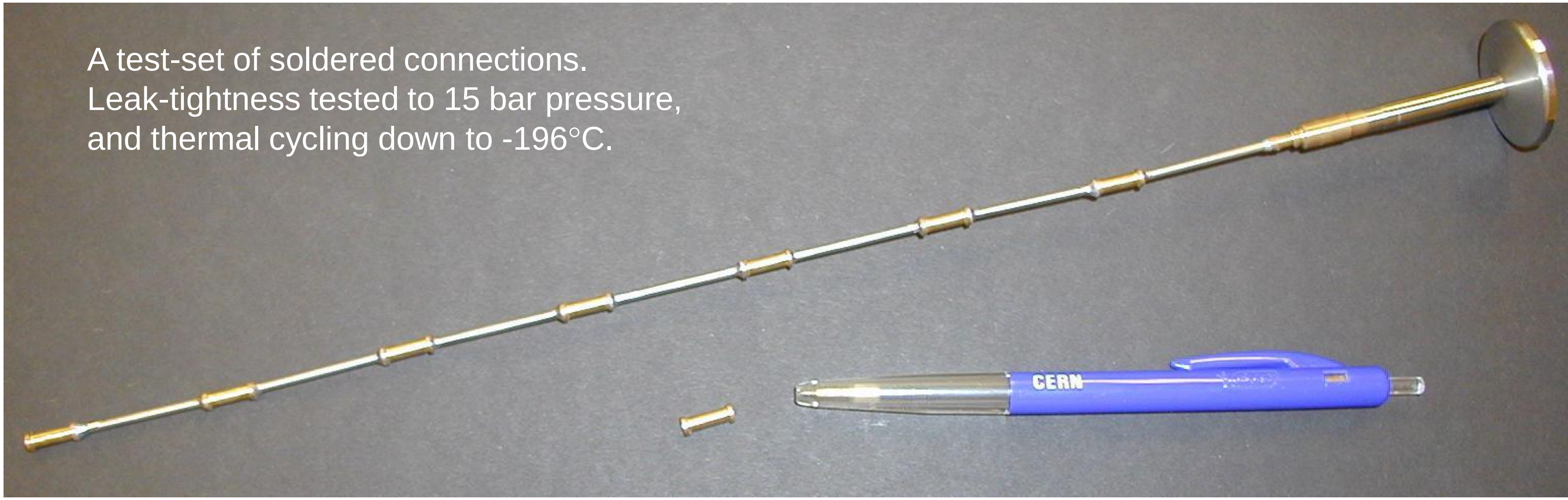
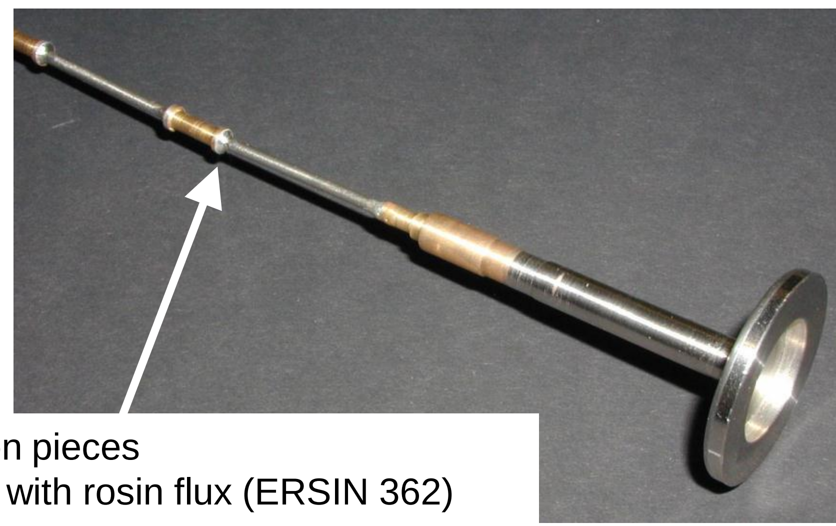
  - Cooling pipes

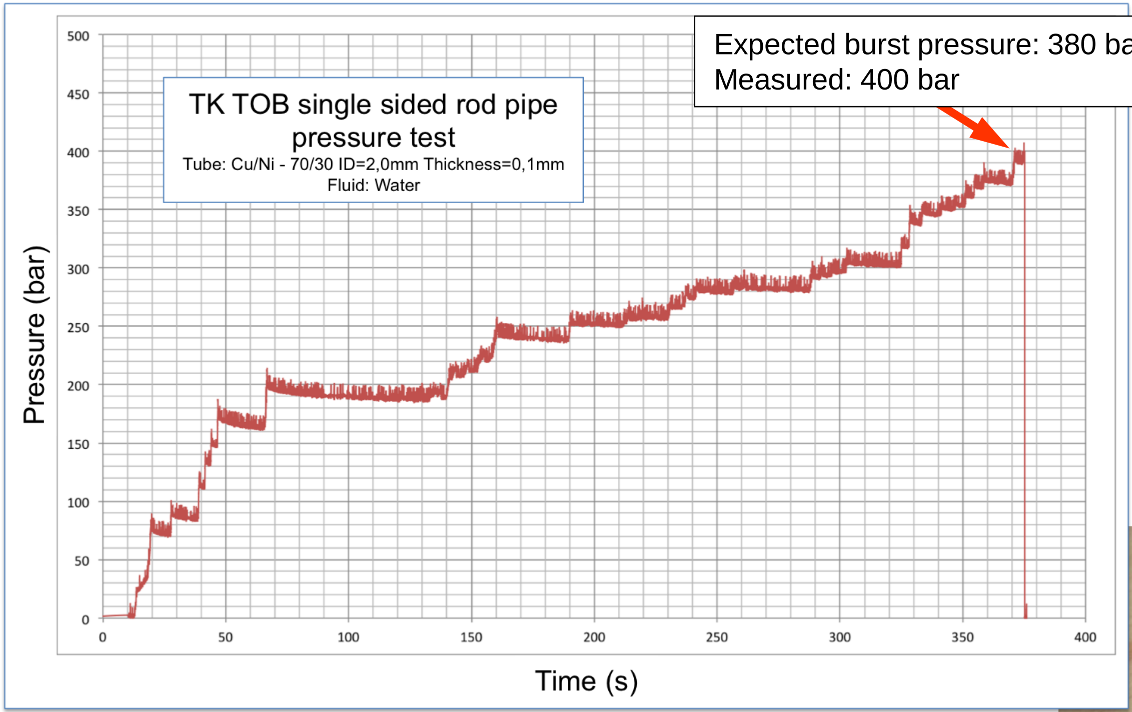
Cooling pipes in CuNi with soft soldered joints

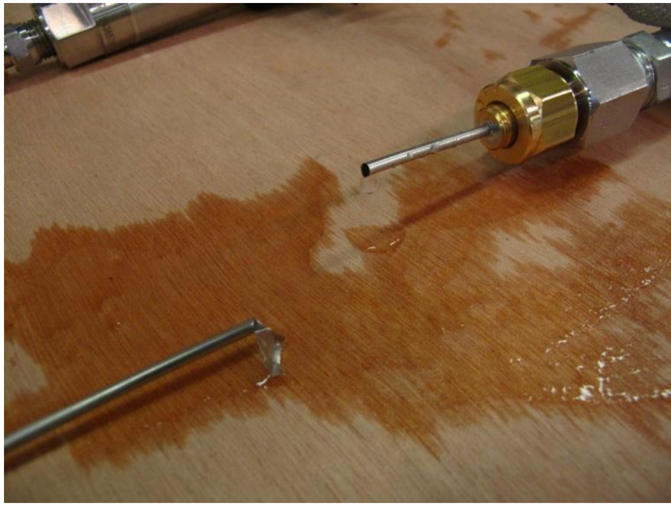


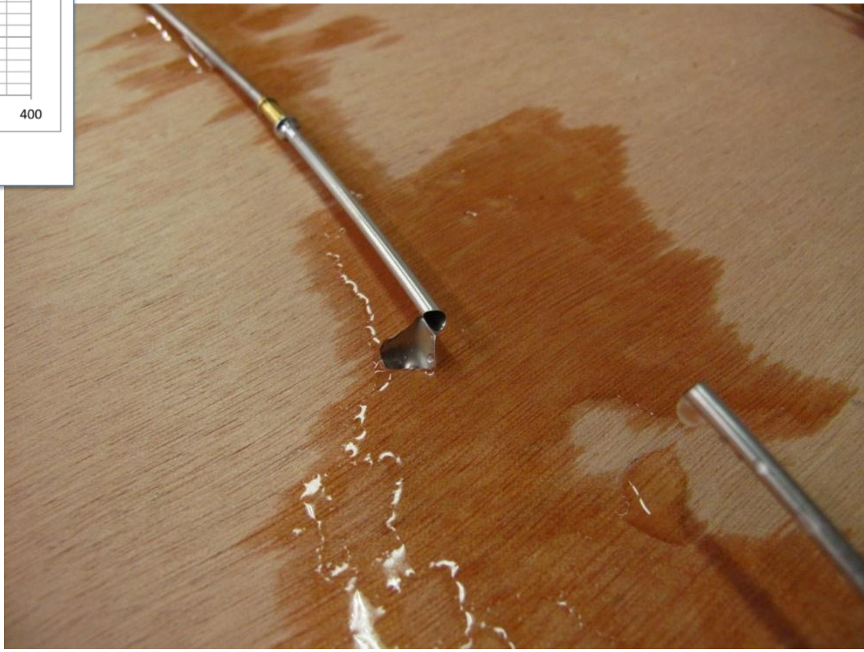


Copper-nickel 70/30 pipes and brass connection pieces
Soldered with eutectic Sn62% - Pb36% -Ag2% with rosin flux (ERSIN 362)

High pressure tests on Rod pipes





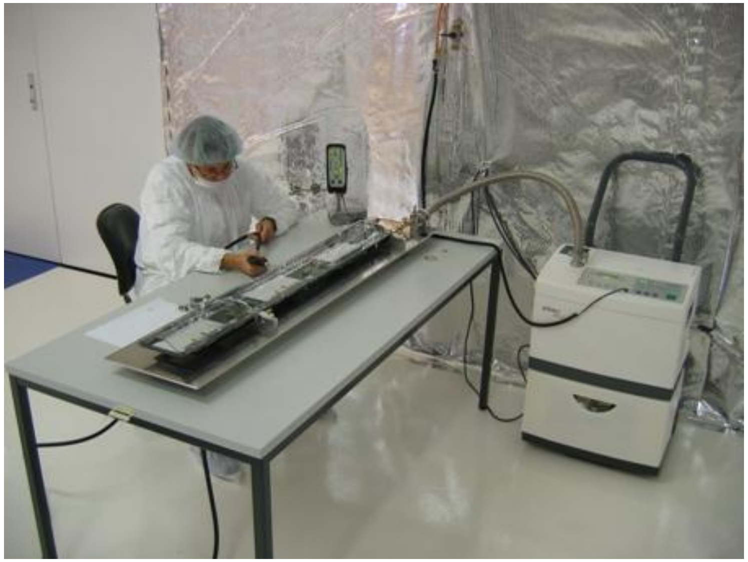


Jérôme DAGUIN, CERN

However, in the production some years ago...

“Bubble test” of bent and soldered rod pipes
with water and 20 bar (not 200 bar) air
→ **850 pipes tested, 10% of them leaked !**
All leaks in the pipe wall (well known problem also in Atlas…)

Leak testing of completed Rods



Helium leak-detection, test in vacuum mode.

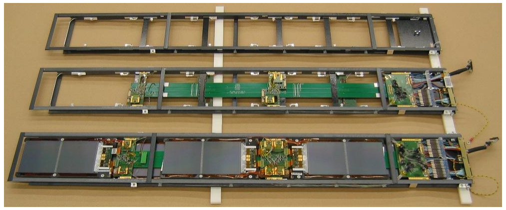
Alarm limit 10^{-8} mbarl/s (bubble-test at best ~10^{-5} mbarl/s).

Fortunately, only ~ 1% of pipes found now leaking, even if tighter test and rods gone through all production chain, thermal cycling, transports, etc. These leaks were repaired by soldering, to be fully He leak-tight.

But still, not very comfortable situation…

Summary on:

- Support structure ("Rod") manufacture:
  - Precision assembly
  - Cooling pipes

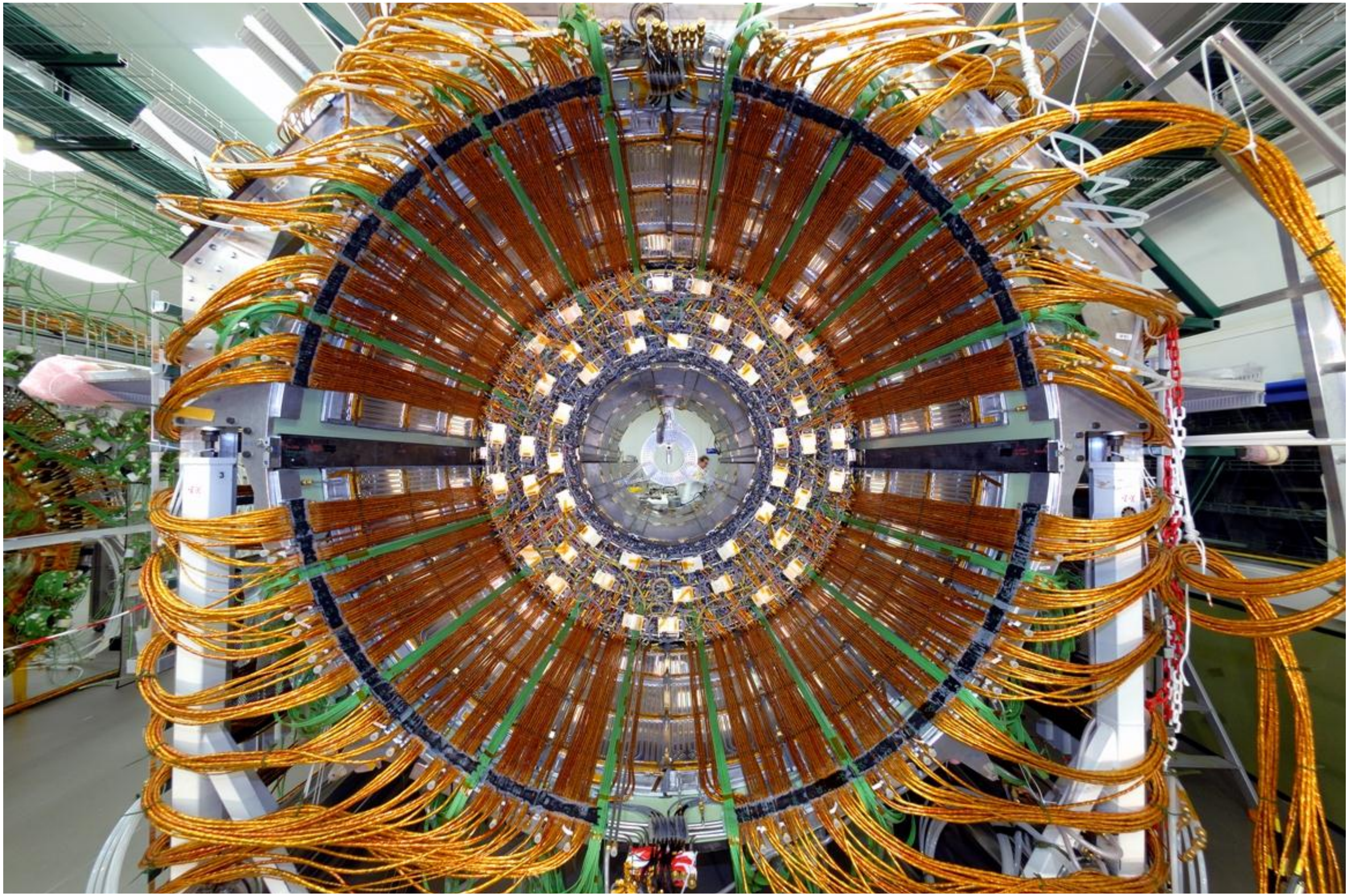


- High-precision structures were successfully made from modest precision components, using precision jigs and room-temperature gluing.
  - But is labour-intensive and requires good jigs that need to be thought early on.
  - Pultrusion + Water-jet cutting worked excellently for preparing rather complex composite material parts.
- For next Tracker, if mass can be gained, less initial mechanical precision could maybe be tolerated.
  - Structural stability remains still a must
  - There is room for optimisation and taking lessons from the present Trackers and their operation.

- Thin-walled cooling pipes can be tricky.
  - Qualify and test the materials early, including connections.
  - Design and prepare for leak-testing at various stages.
  - If leak-repairs can be done, that is useful...

The last lesson from the CMS TOB: Choose carefully the colour of the cables.

That is all what remains visible in the end.

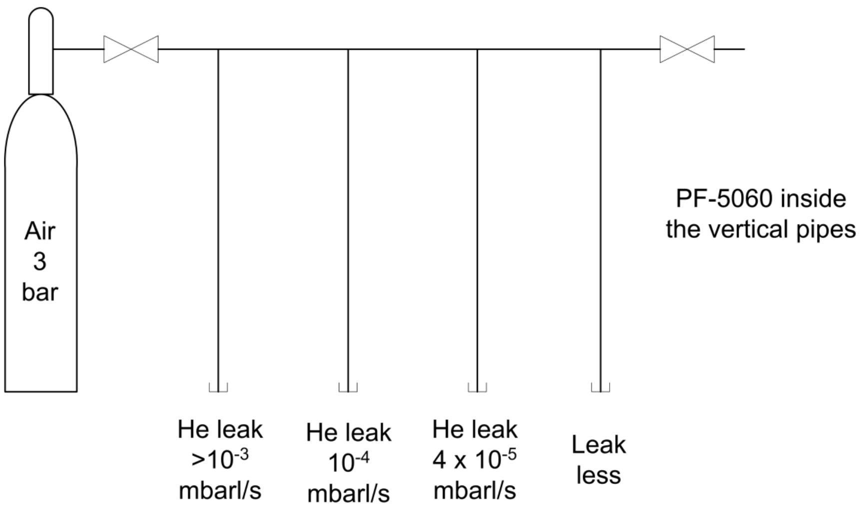


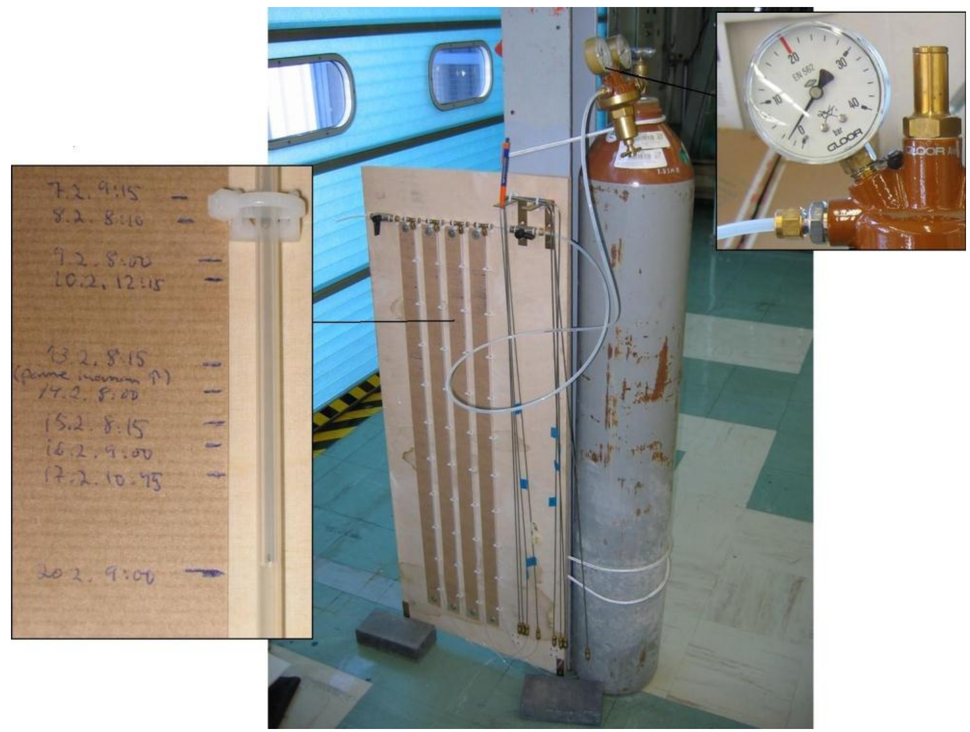
Thank you for your attention!

Spares

Relevance of the leaks?

- Losses of final cooling fluid C_6F_{14} (PF-5060) are relevant both financially (~100 CHF/kg) and environmentally (global warming potential of about 7400 times higher than CO_2).
- Correspondence between Helium leak and the leaks of the final cooling fluid studied using final type rod pipes with varying levels of measured leaks.





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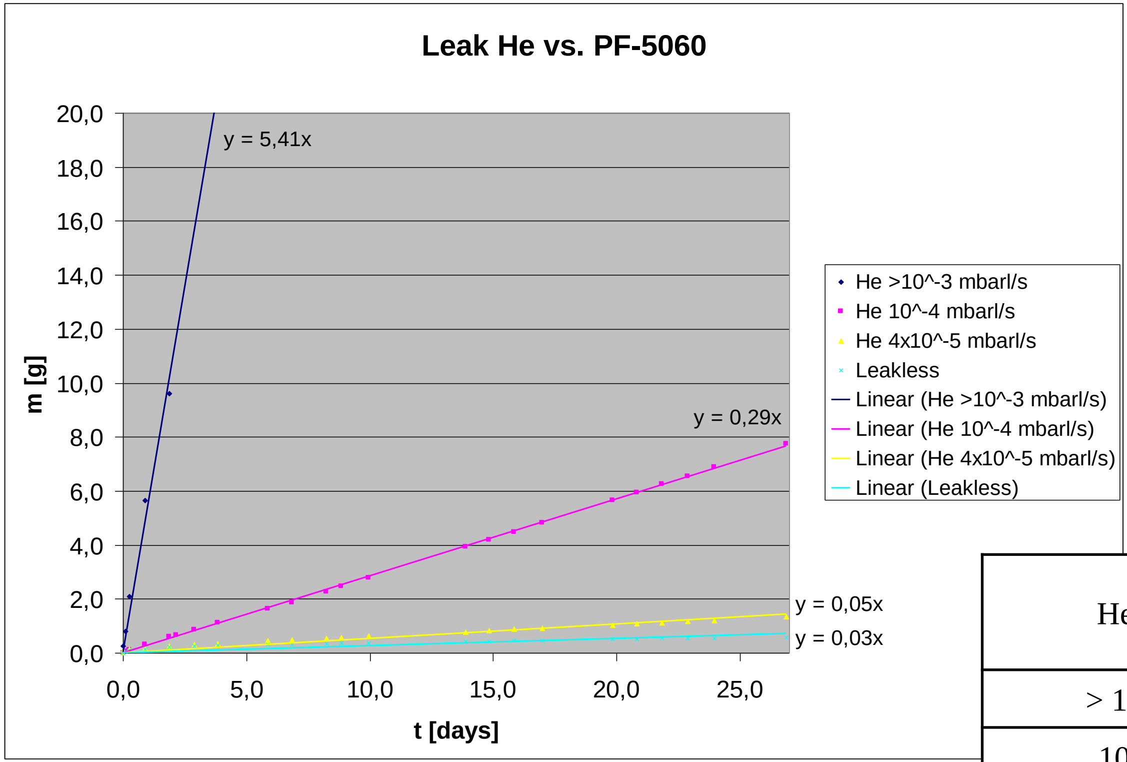

He leak size	Loss of PF-5060	
	[g/a]	[ml/a]
> 10^{-3} mbarl/s	1870	1113
10^{-4} mbarl/s	105	63
4 x 10^{-5} mbarl/s	18	11
< 10^{-10} mbarl/s	8	5

Bubble-test can spot leaks down to 10^{-5} mbarl/s of He, i.e. to ~10 g/a of the final fluid PF-5060.

With He testing (1000-100'000x more sensitive) drop to insignificant leak levels for fluid loss.

But, even tiny leaks are signs of weak-spots, which can become problems in long-term operation.