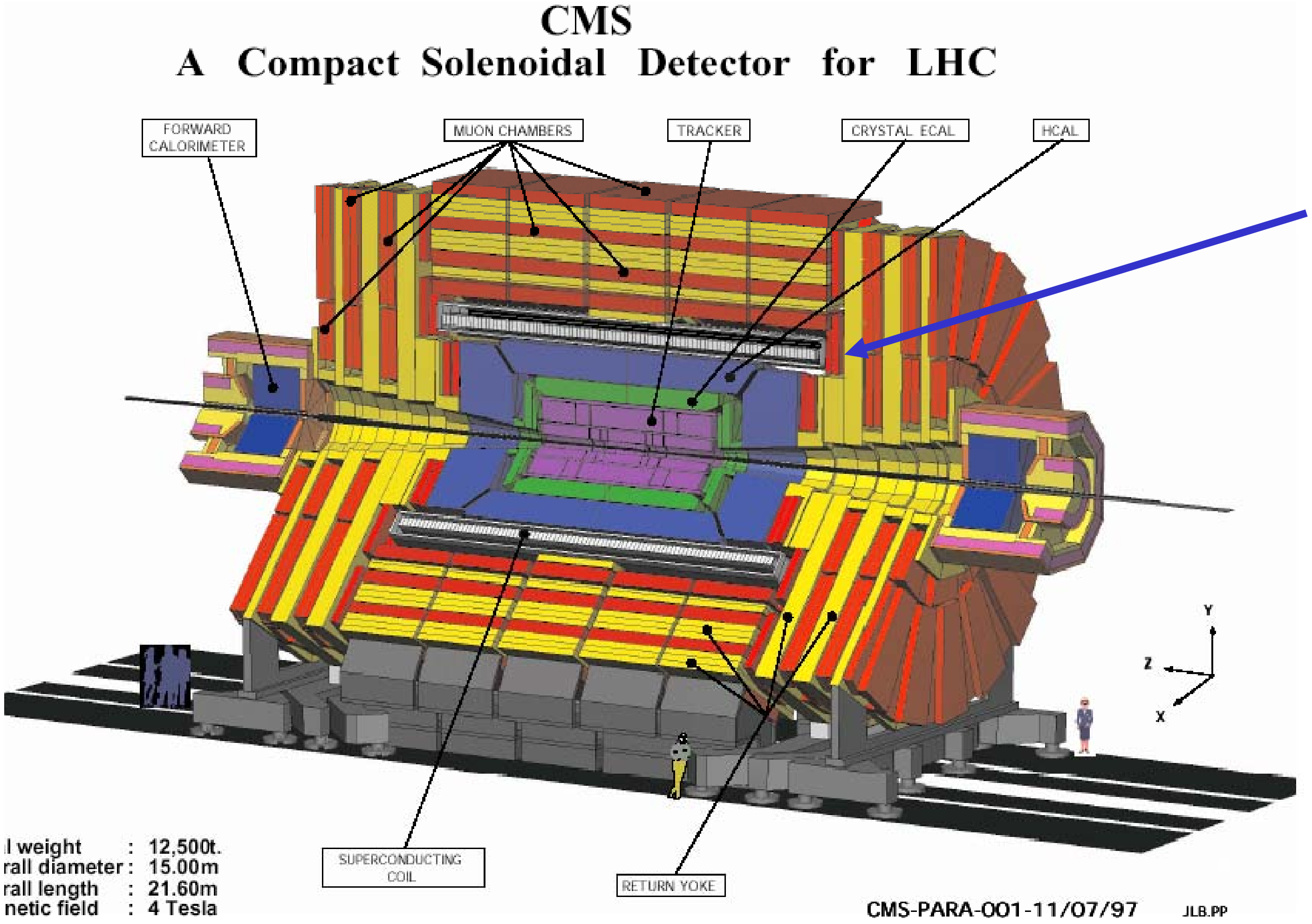
Prospect to Reach 5T
from experience gained from the large 4-T CMS coil

A. Hervé / ETHZ

CLIC08-Workshop,16 October 2008

Compact Muon Solenoid (CMS)



Based on Large SC Solenoid

6 m diameter

13 m long

Strong Field 4T

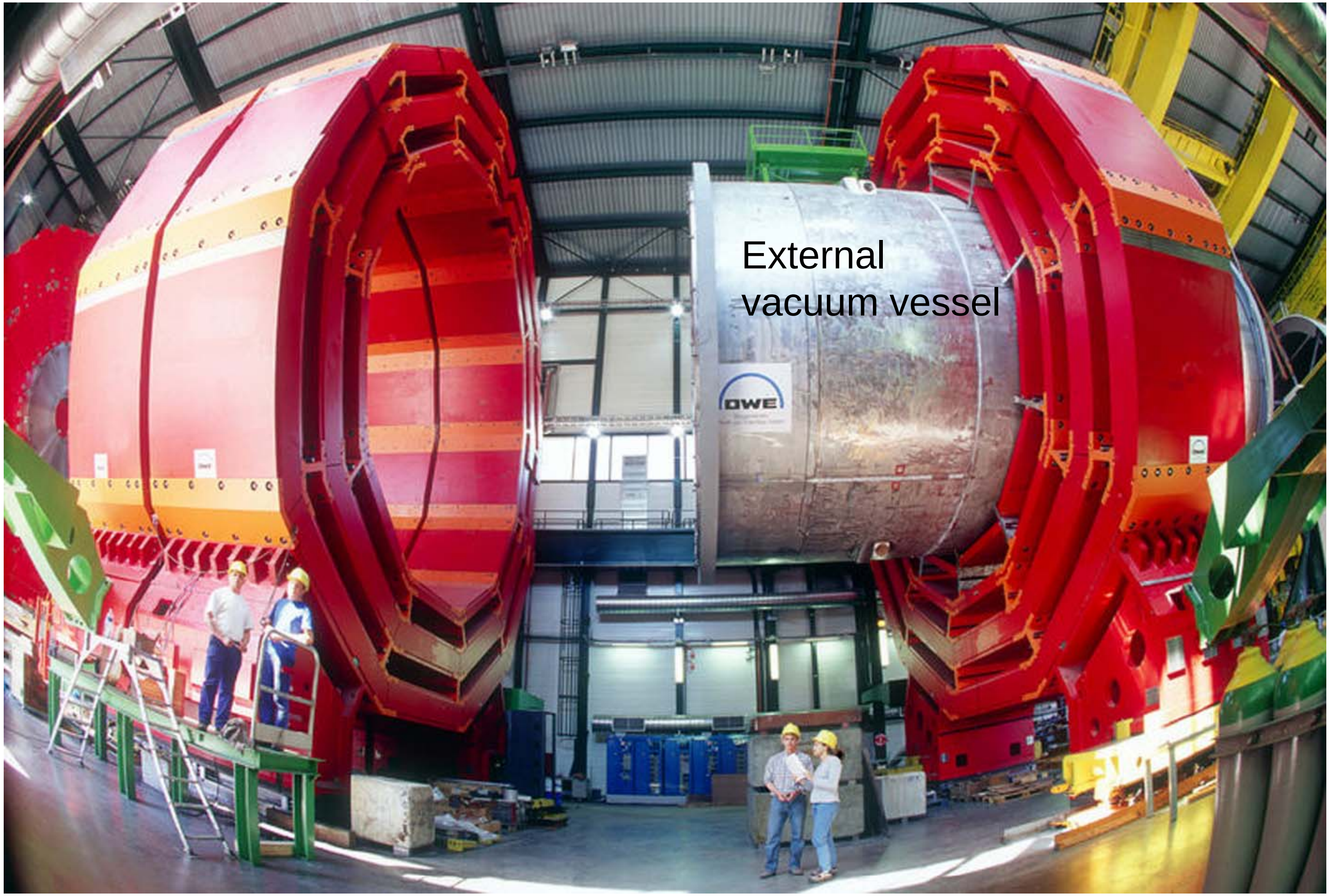
With a 9’000 ton Return Yoke

Institutes participating to the Magnet

The Magnet is a 125MCHF Common Project of the Collaboration the main participating Institutes to the Magnet Project have been

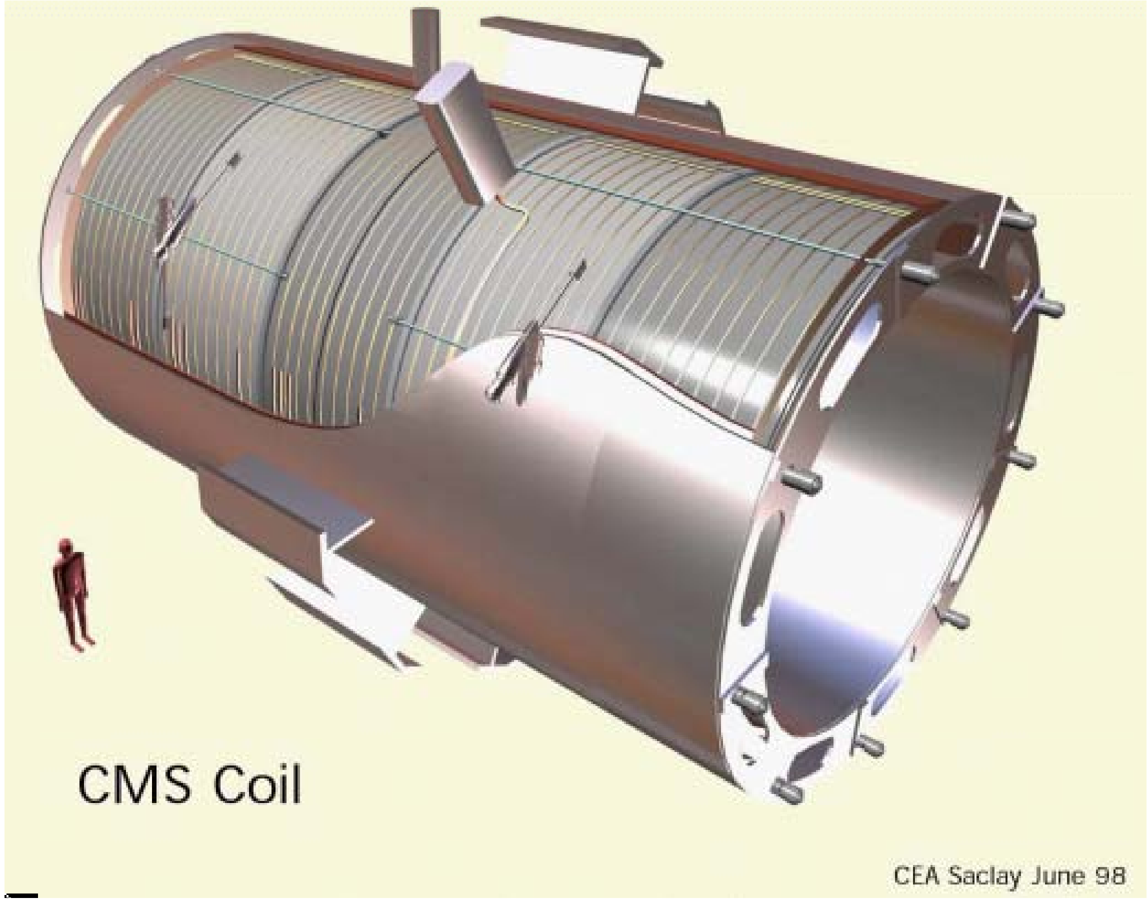
- CEA / Saclay : Engineering and integration
- ETHZ / Zürich : Conductor
- INFN / Genova : Winding
- Fermilab : Strand procurement and Field Mapping
- University of Wisconsin : End Cap Yoke construction
- CERN : Barrel Yoke, External Cryogenics, Conductor, Control, Project Management and Coordination

Yoke has been completed in 2003 ready to accept the cold mass



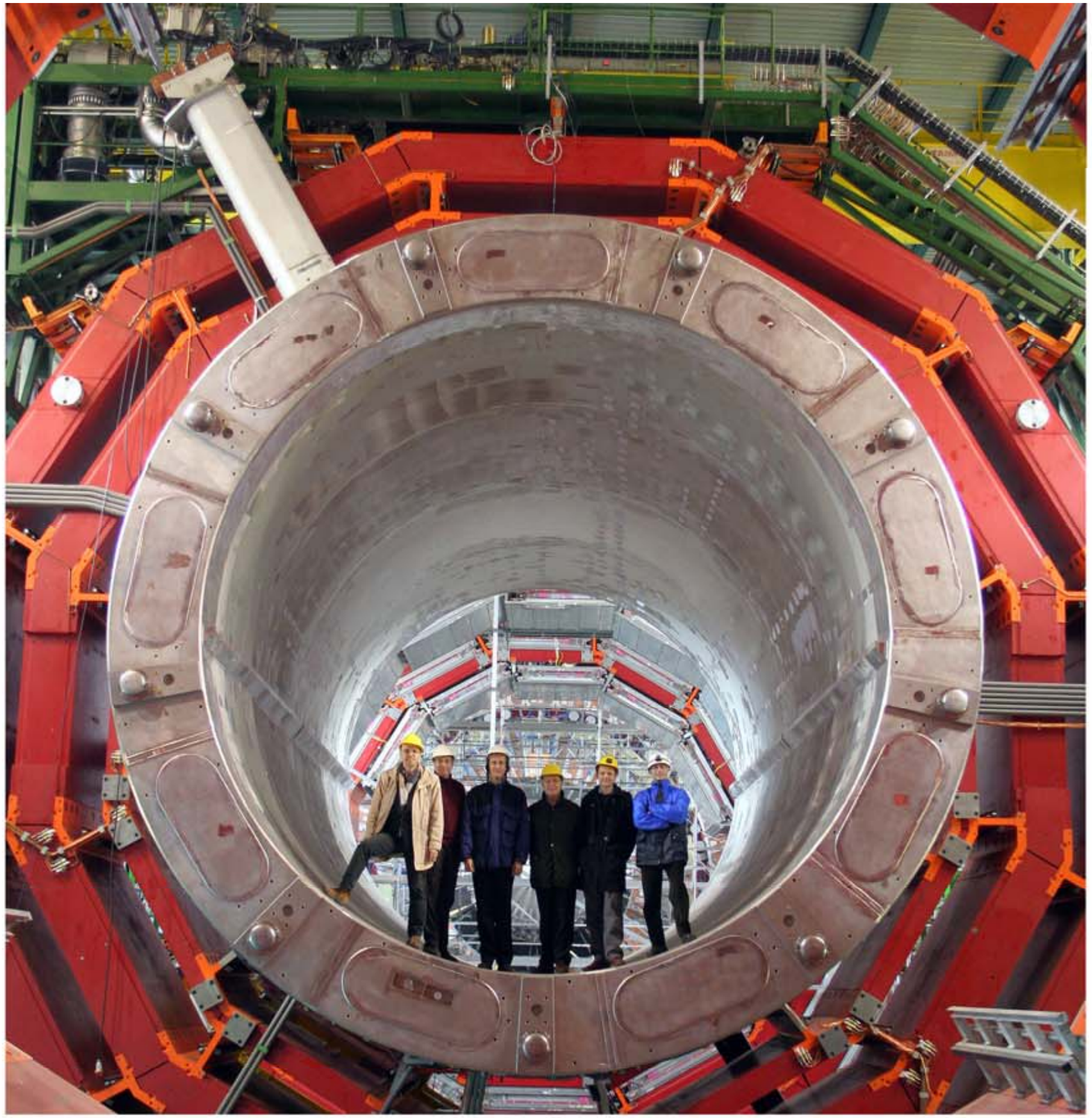
External vacuum vessel

The superconducting coil



Magnetic length	**12.5 m**
Free bore diameter	**6.0 m**
Central magnetic induction	**4.0 T**
Max induction on conductor	4.6 T
Nominal current	19.2 kA
Mean inductance	14.2 H
Stored energy	**2.6 GJ**
Stored energy / unit of cold mass	**11.6 kJ/kg**
Operating temperature	4.5 K

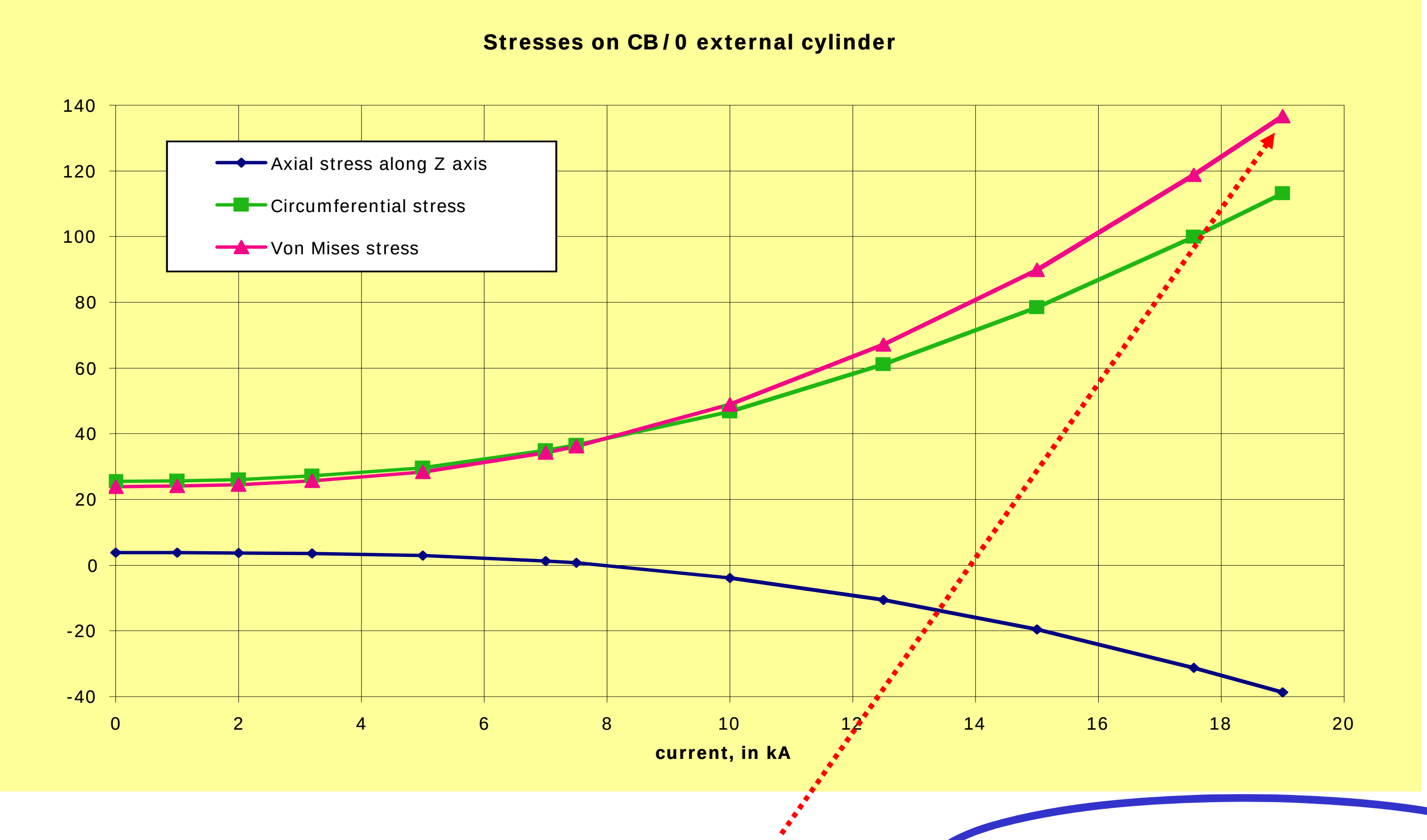
February 06: the coil was ready to be cooled



January 2006: End of the CMS Magnet Manufacturing

Magnet tested on Surface in August 2006

(Here we show stresses in Cold Mass)

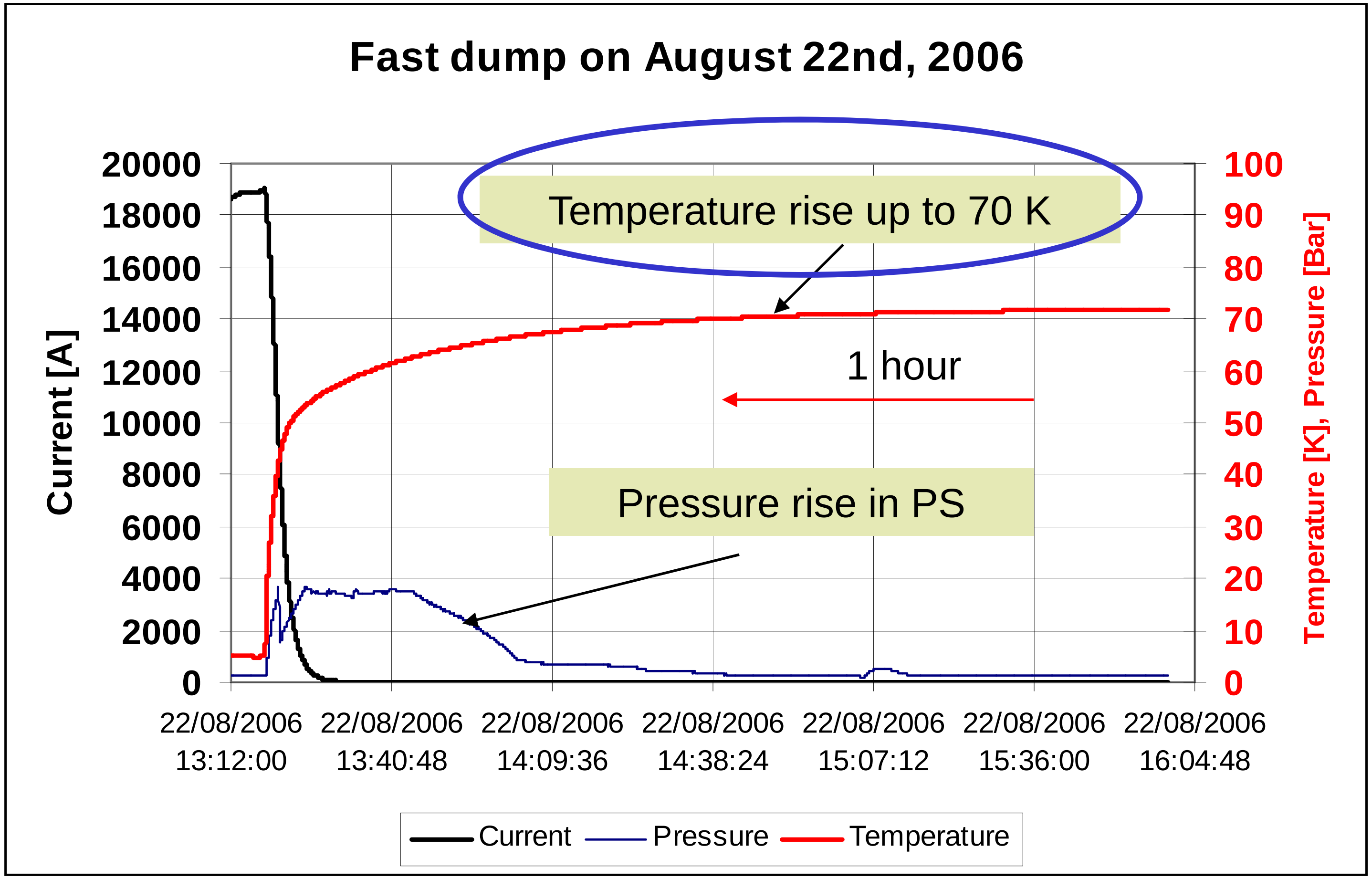


- Von Mises stress measured at 4T : **138 MPa**
- Complete agreement with computation of 1998.

$$\Rightarrow \epsilon = \frac{138}{75000} = 0.185\%$$

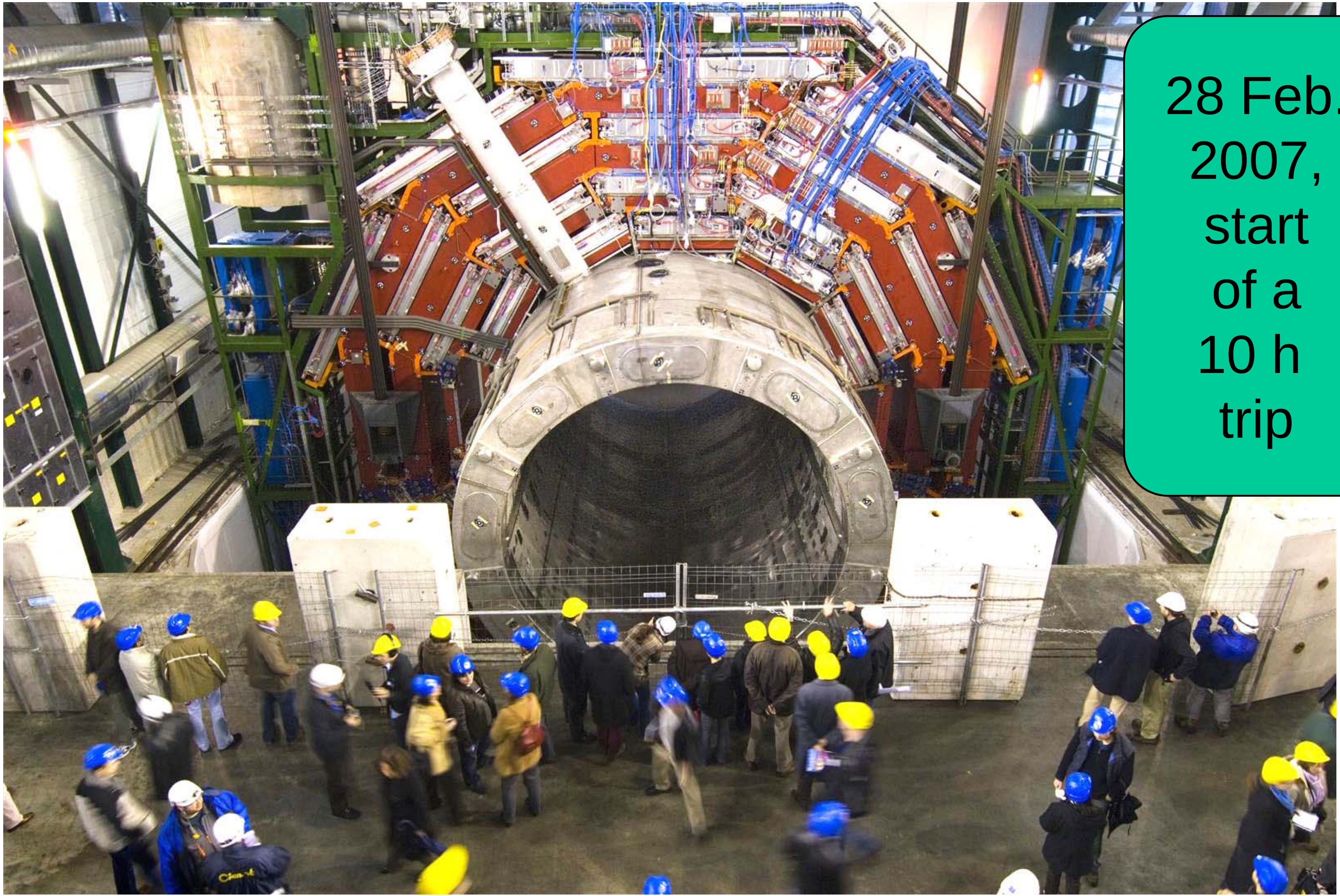
0.2% is conventional elastic limit of aluminum!

Temperature rise after fast-dump on dump resistors is < 70 K



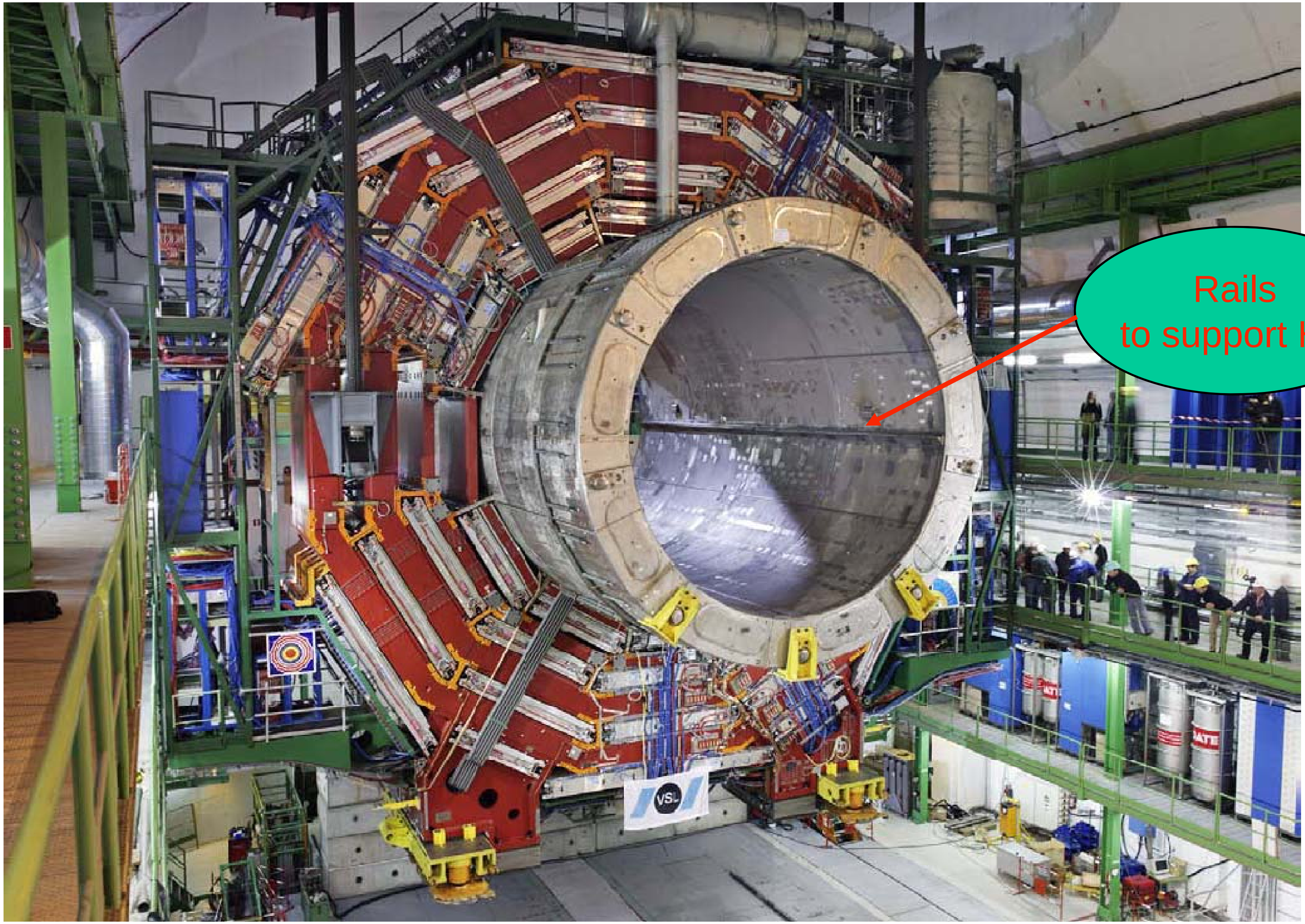
This is not to induce dangerous thermal stresses in the coil!

Lowering the coil element after surface test



28 Feb.
2007,
start
of a
10 h
trip

Soft landing of a 2000-ton load!



Rails
to support HB

Review of the Design Options

Parameters retained for the coil in the early 1990s

1990: 1.5-T ALEPH* taken as demonstrator

- NbTi Rutherford cable, pure aluminum stabilization, *enthalpy stability margin > 1.5 K*

- External mandrel for *indirect cooling by thermo-siphon*, *inner winding*, *potted under vacuum with fiber-glass/epoxy resin*

- Use external mandrel for a *passive protection scheme* based on the *quench-back* effect

- In case of fast dump, extract 50% of the energy in a dump resistor and keep the *final temperature of the cold mass < 70 K*

- Allow, as ultimate case, 100% of the energy in the cold mass *accepting to reach 130 K a few times* during the lifetime of the coil

* J.M. Baze, H. Desportes et al., Design Construction and Test of the Large Superconducting Solenoid ALEPH, IEEE. Trans Magn. Vol 24, 1988

Additional parameters due to *increased* B_0

- Large 20 kA conductor, *four-layer winding, and five modules*

- Magnetic pressure of 64 bars, thus:
high-strength aluminum alloy is required

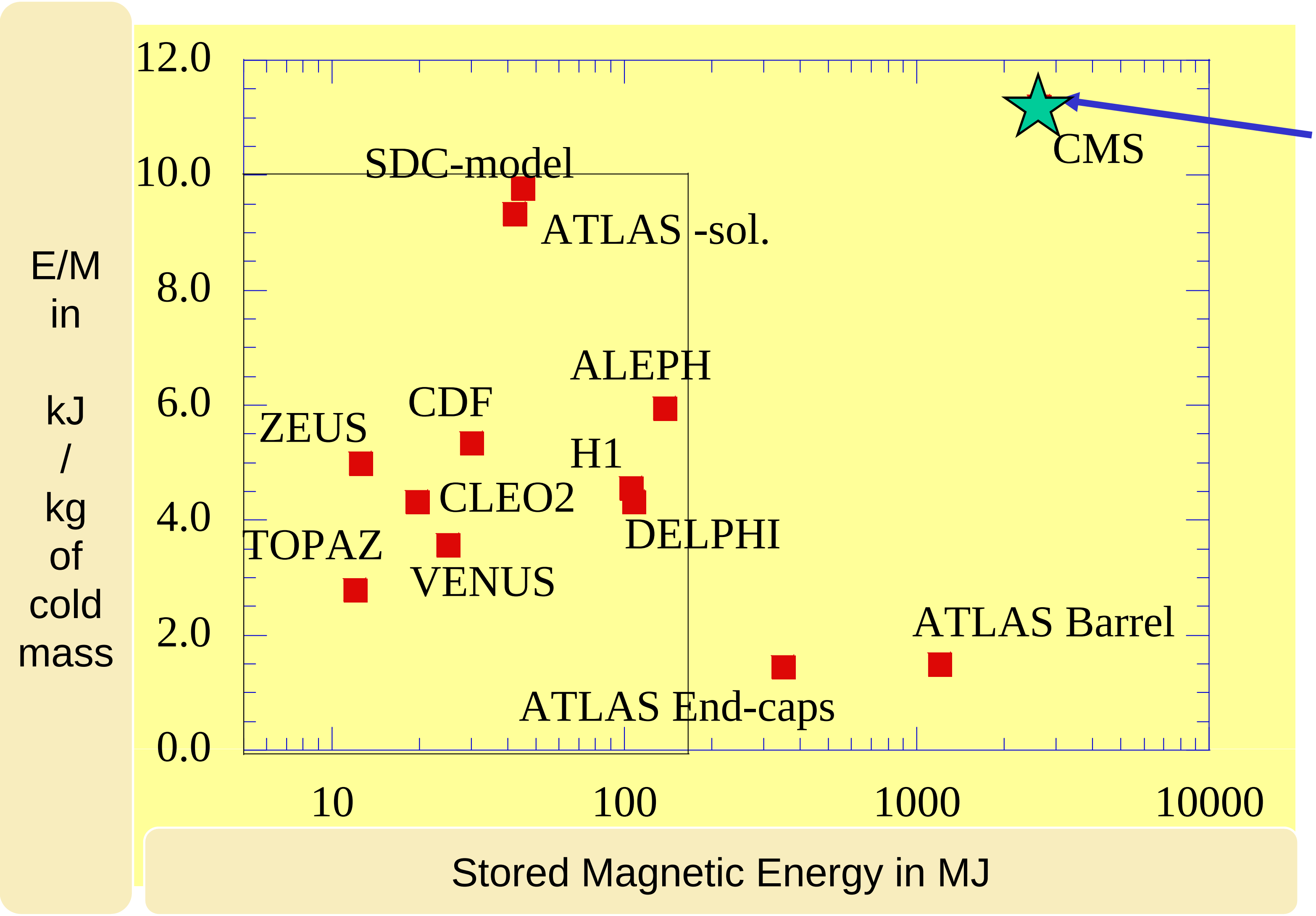
Founding assumption of CMS (J.C. Lottin) was to position
this alloy directly on the conductor

- *Hoop strain reaches 0.15%, must stay < 0.2% using von Mises str*

A large 12’000-ton axial magnetic compressive force
has to be transmitted from module to module

- Stored magnetic energy 2.6 GJ, the specific ratio
E/M reaches 11.6 kJ/kg of cold mass

E/M ratio vs E for several solenoids



This *'anomalous'* positioning meant that *innovative solutions were needed* to face this challenge

Critical Review of Main Design Choices

- It is interesting to *critically* review the design choices made by the International Team to meet this challenge

- Then examine the possibilities of *increasing* the central field *to 5T* using the same technology

(For example recent proposals for ILC and CLIC use 4T and 5T coils building on CMS principles)

Review of the Design Options

Main challenges that the design team had to face in the early 1990s

Main design and construction challenges

1. Extrude a large section NbTi Al stabilized conductor — Sc
2. Obtain a compound reinforced conductor with the necessary mechanical strength — M
3. Build precise mandrels although they cannot be stress relieved — M
4. Wind precise layers using a very stiff conductor — M
5. Limit shear stress on insulation inside the coil in particular in between two modules — M
6. Insert a 220-t coil inside a vacuum vessel having an horizontal axis — M

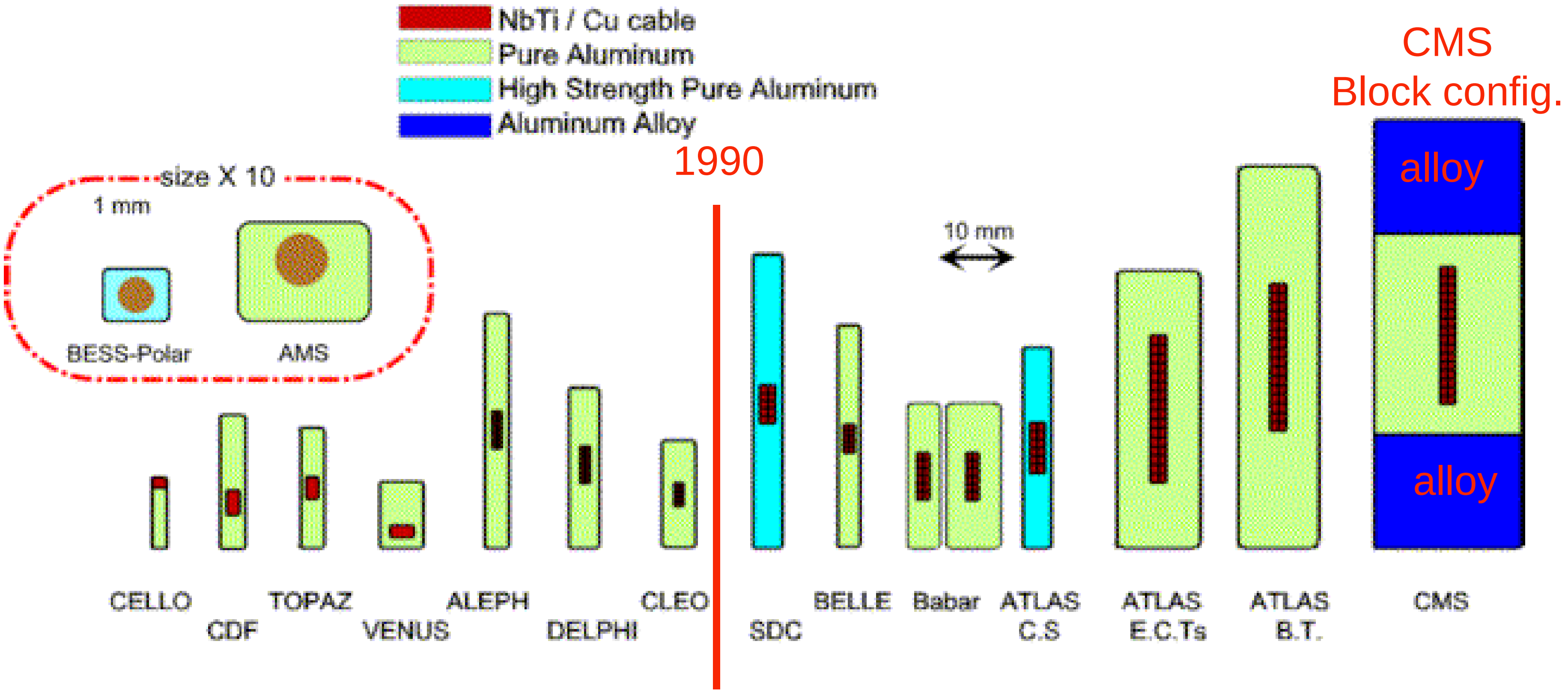
5 challenges out of 6 were mechanical challenges!

Challenge N°1

Extrude a large section stabilized conductor

Evolution of conductors with time

Extrusion of large pure aluminum sections was readily solved by Steve Horvath (ETHZ) et al. in the early 90s (see MT14 for example)

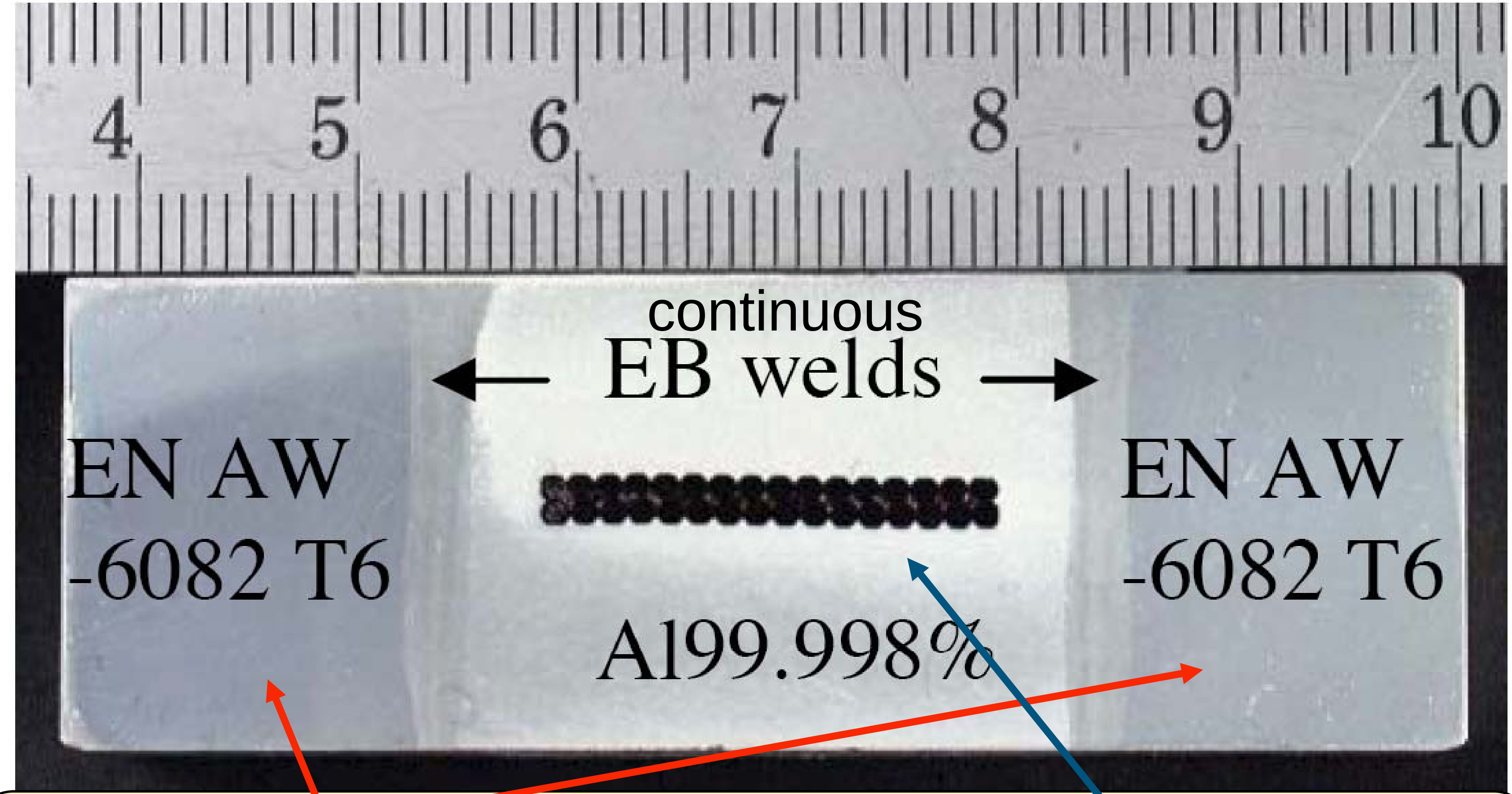


From A. Yamamoto, “Advances in Superconducting Magnets for Particle Physics”, *IEEE Trans. Appl. Superconduc.*, vol. 14, no. 2, pp. 477-484, June 2004.

Challenge N°2

Obtain a compound reinforced conductor with the necessary mechanical strength

CMS Reinforced Conductor

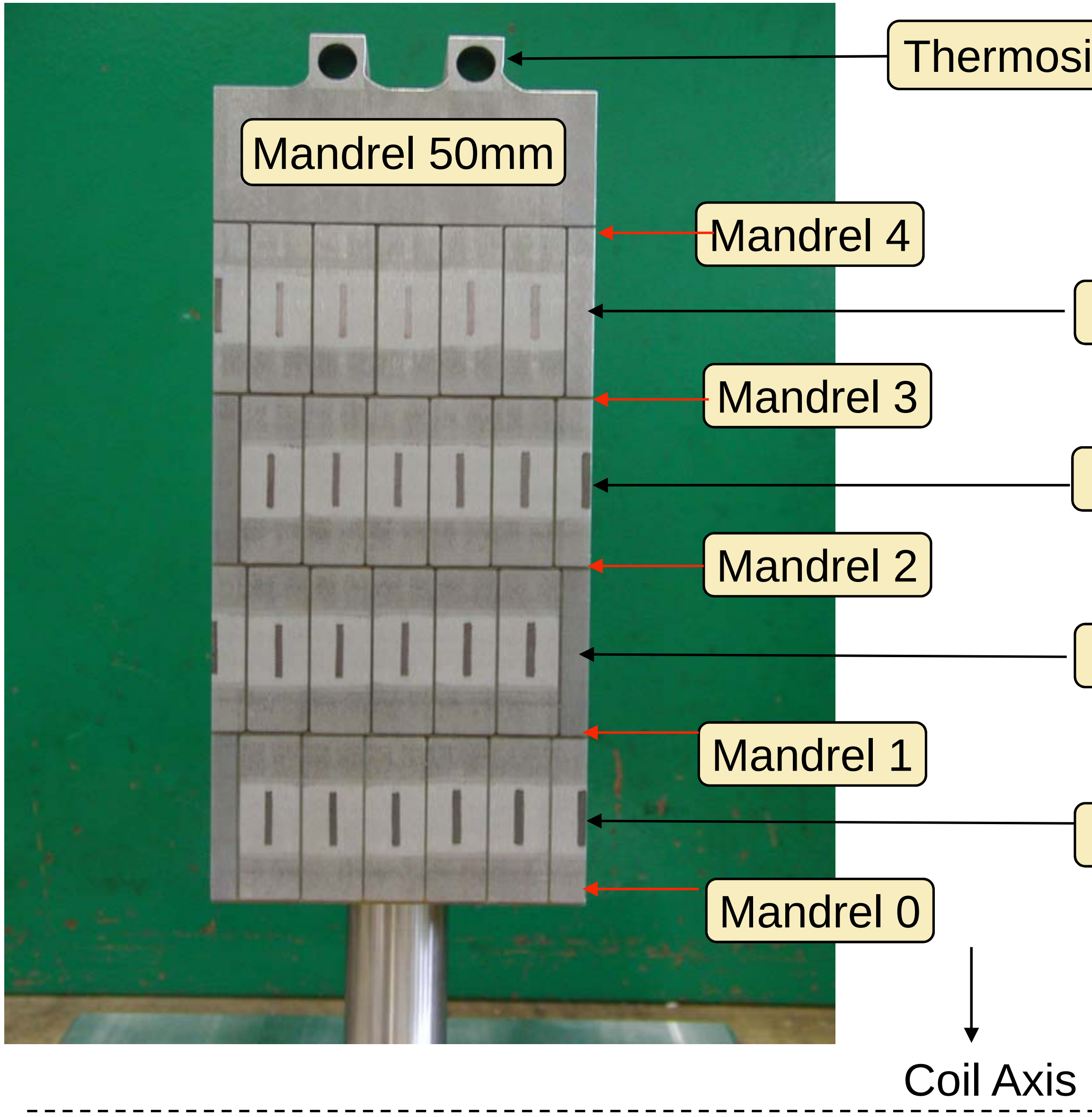


aluminum alloy sections added to

"standard" conductor

32 strands => Temperature Margin 1.8K

Each *layer* is supported by its *'own' mandrel*



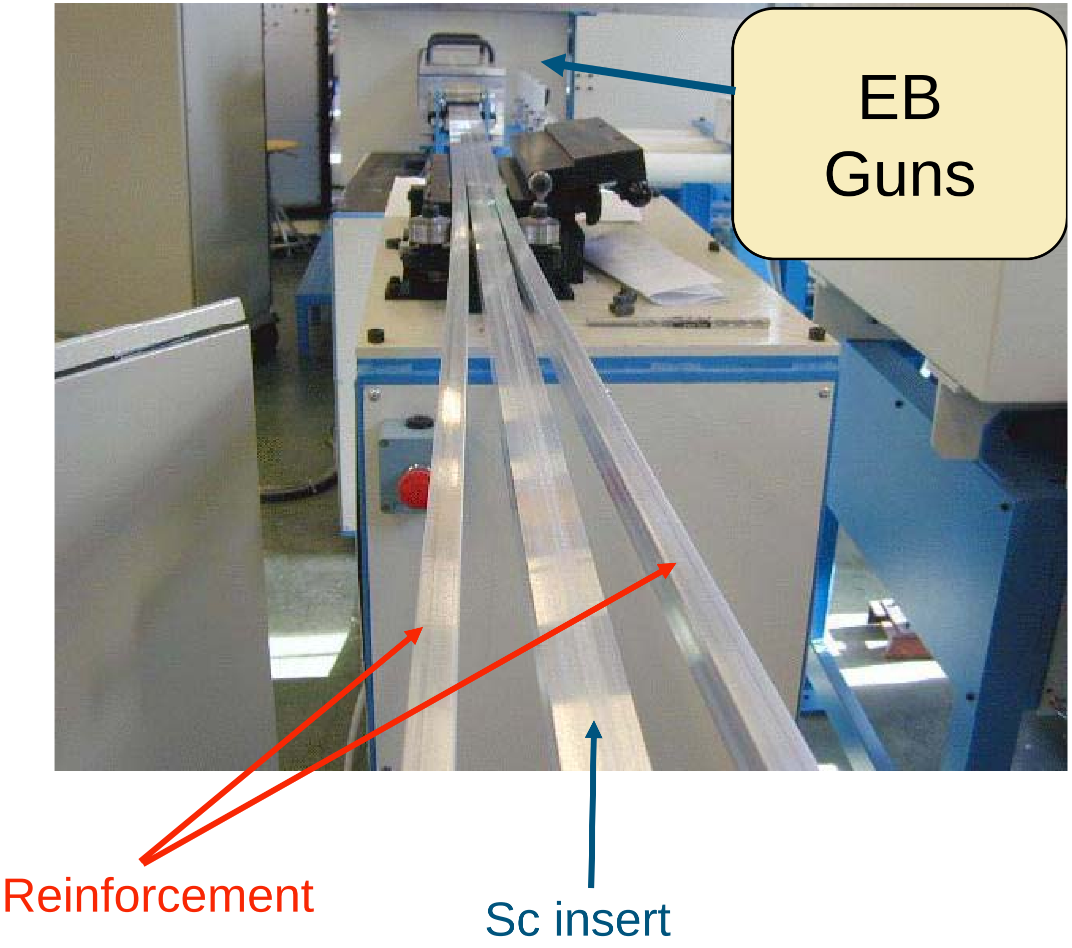
After curing reinforcements create criss-crossed matrices *mimicking perfectly fitting individual mandrels*

Reinforcement of conductor by EB welding

Electron Beam welding has been retained because

- It satisfied the needs
- We had in-house expertise

Clearly, in the future, other technologies may be easier and cheaper!



56 km of conductor have been successfully produced

Choice of Reinforcing Alloy

AA 6082 T6 has been chosen,
(hard temper T6 *obtained after curing cycle* of the coil)

This allows winding with a not too stiff conductor!

Challenge N°3

Build precise mandrels although they cannot be stress relieved

Construction of Mandrels

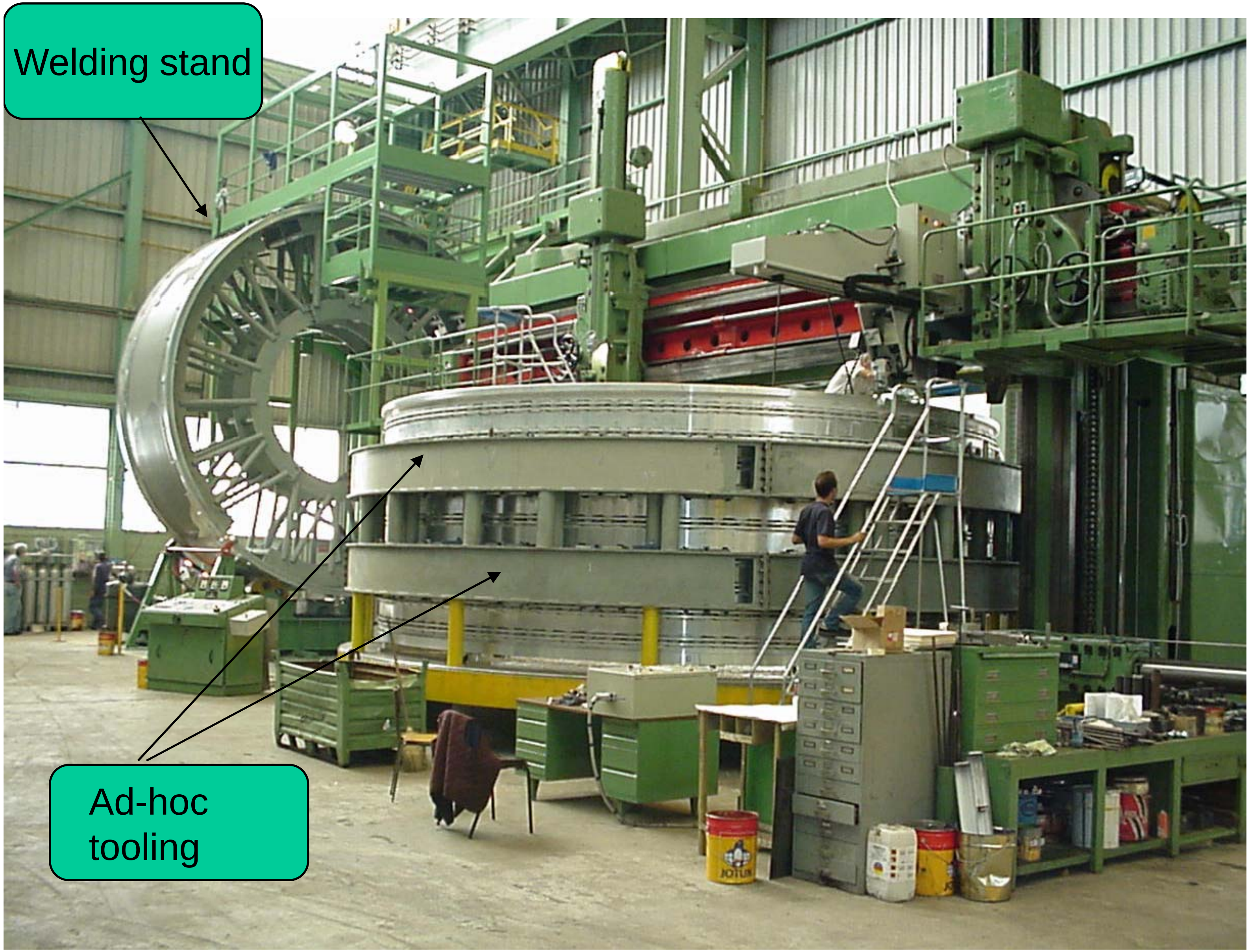
- AA 5083 H321 has been retained

- Weldments *just* meet the specification connected with the 0.15% hoop strain

- It is *very* difficult [*impossible*] to procure thick aluminum alloy plates (> 80 mm) with the necessary properties

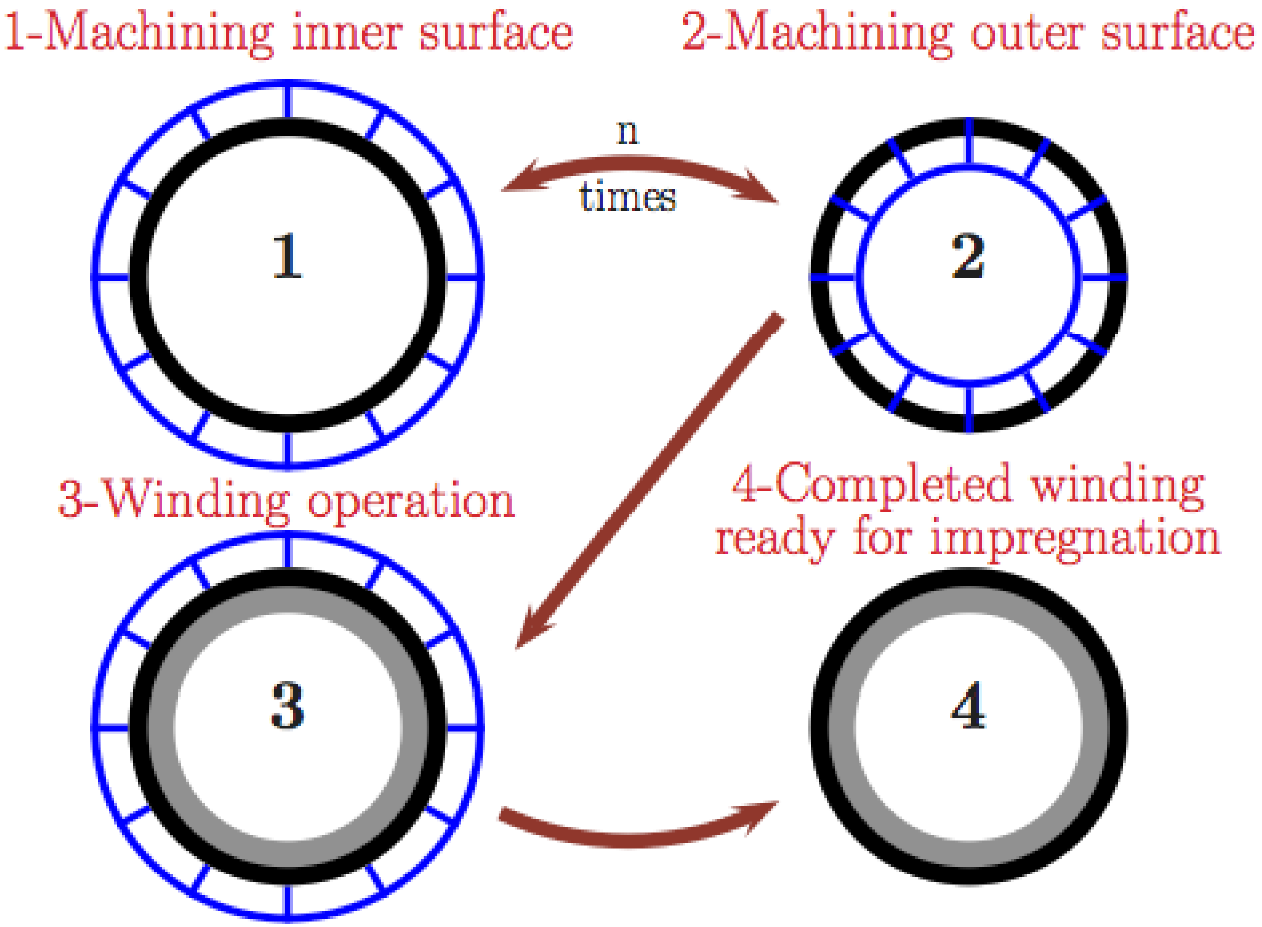
This was an *a posteriori justification* of the reinforced conductor

Construction of mandrels



Mandrels are very thin structures that *cannot be stress relieved* before or during machining, *otherwise mechanical properties are lost*

Maintaining cylindricity of mandrel



As mandrel cannot be stress-relieved, shape is first maintained by ad-hoc tooling, then conserved by *stiffness of winding pack*.

Challenge N°4

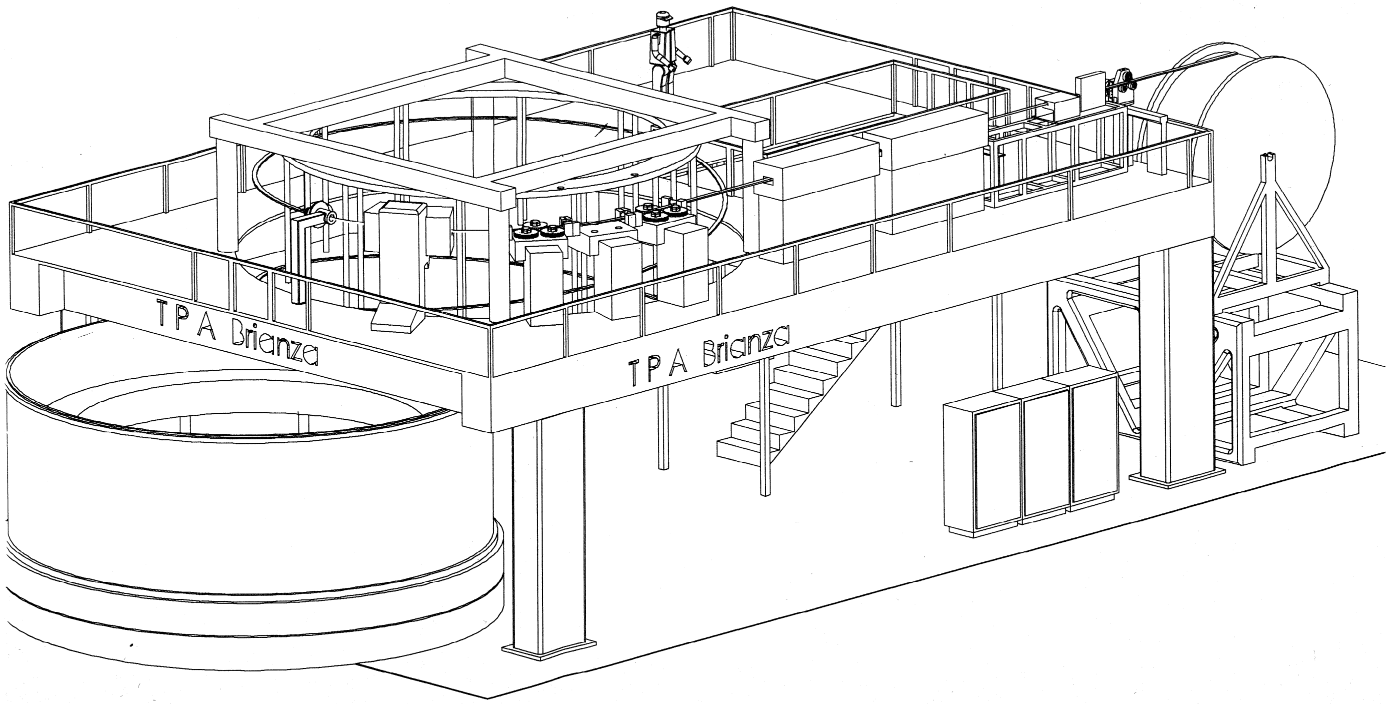
Wind precise layers using a very stiff conductor

Winding has been done with an ad-hoc tool

The stiff conductor is wound in a *4 layer* configuration

By *inner winding* technique

Followed by *epoxy resin impregnation* under vacuum

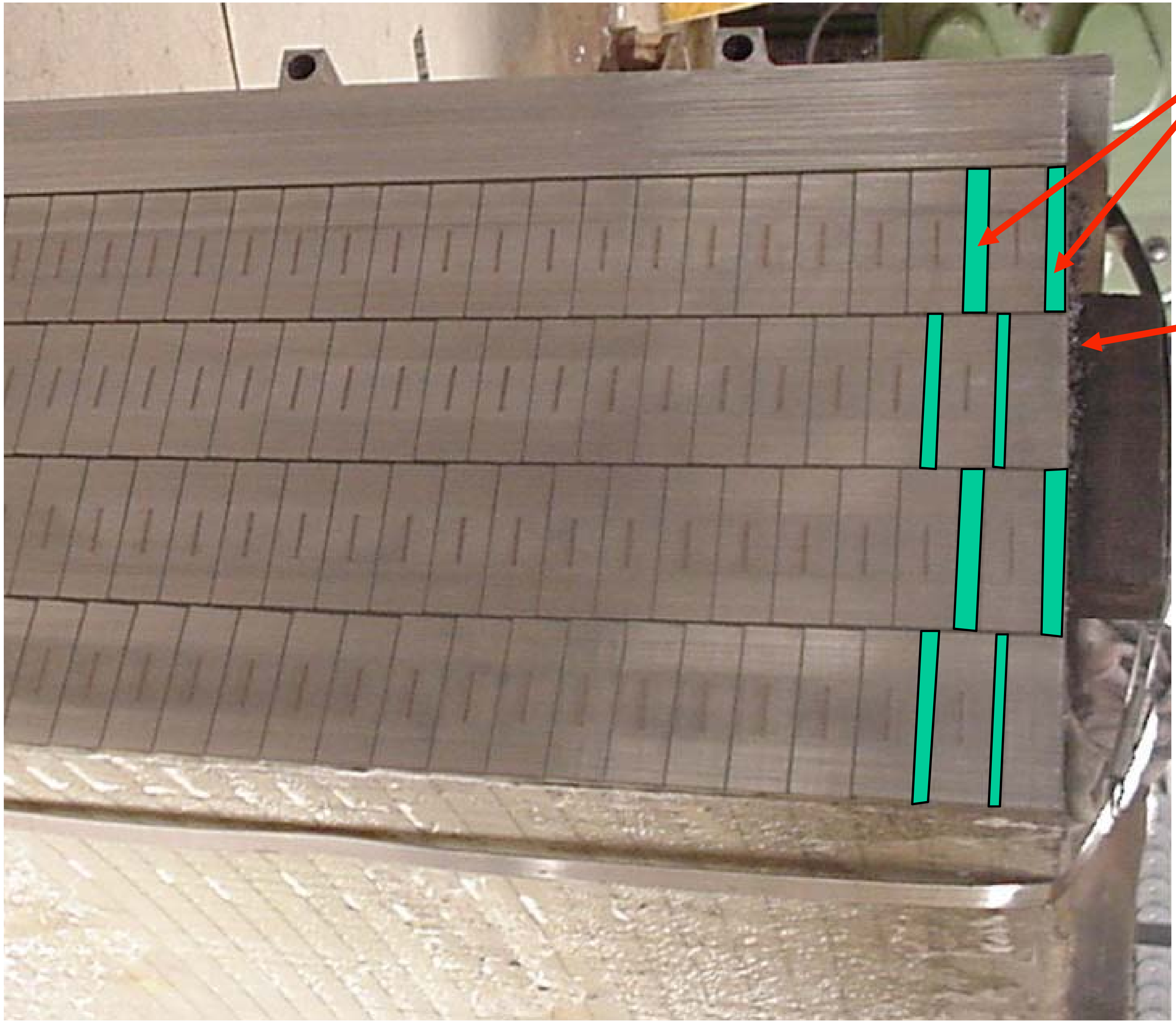


After a dedicated pre-industrialization, by Ansaldo-Superconductori, winding such a stiff conductor proved easy to do!

Challenge N°5

Limit shear stress in between two modules when transmitting the
12’000 ton axial compressive force

Cut through the Coil prototype

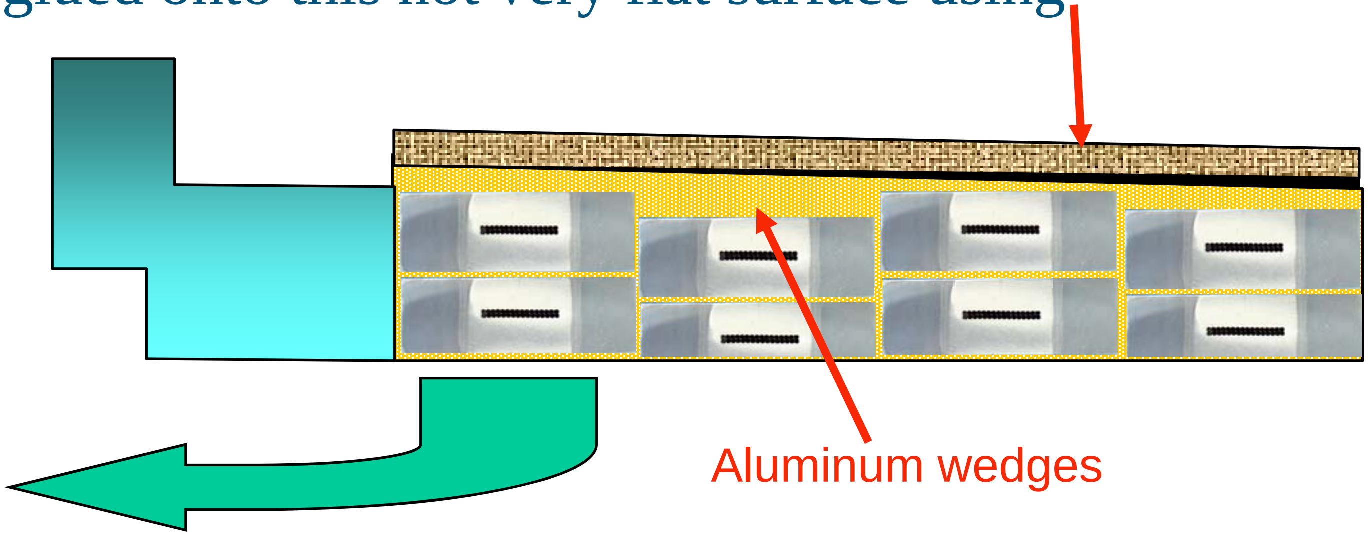


Al wedges have been used to terminate the modules with a fairly flat surface.

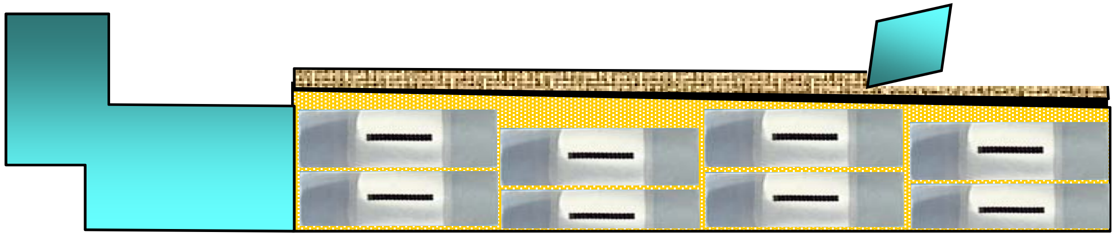
This is *not sufficiently flat* to transmit the large compression force module to module without *inducing dangerous shear stress* in the insulation.

Preparing module to module coupling

5 mm G11 plates are glued onto this not very flat surface using STYCAST resin

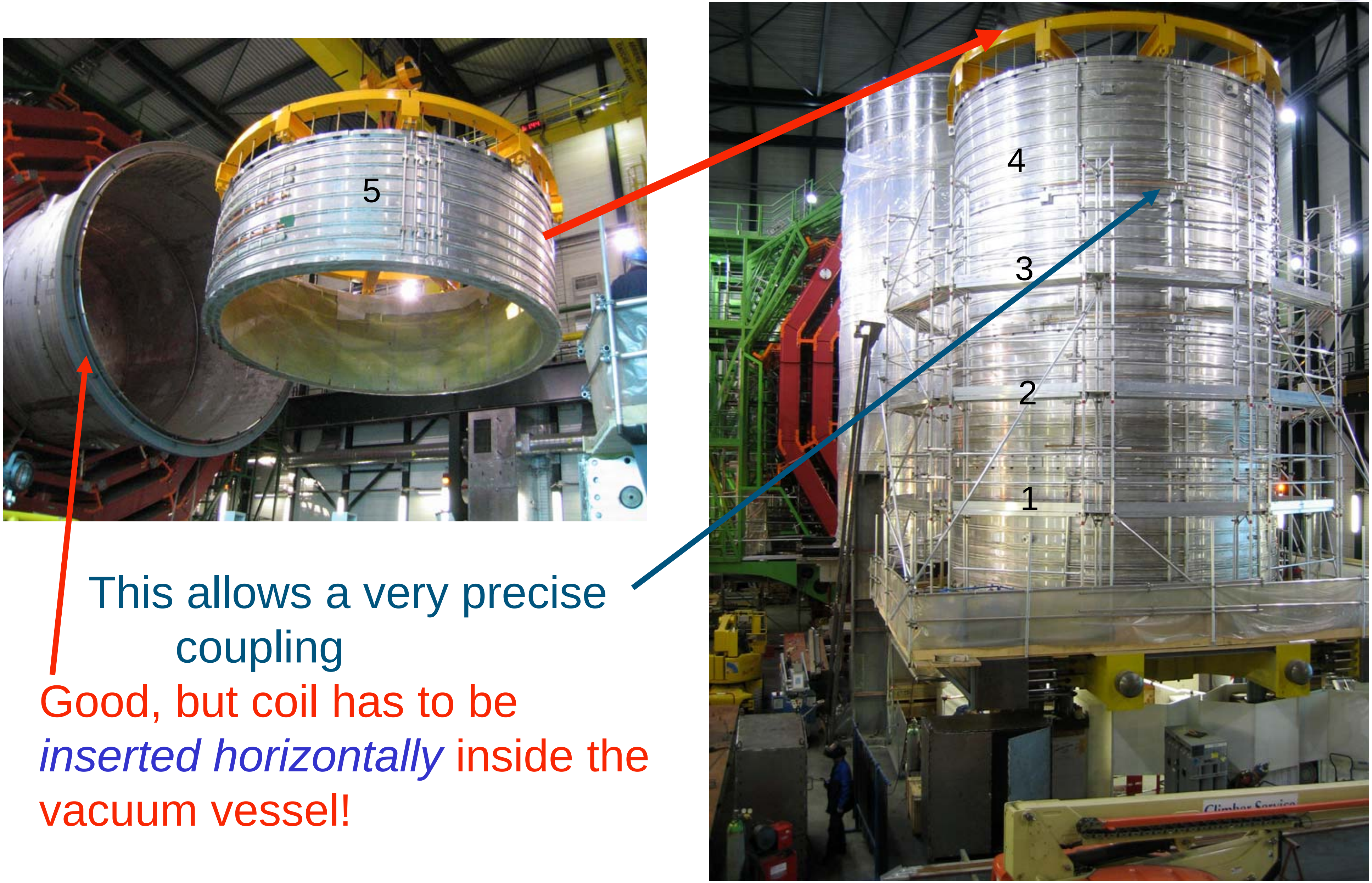


Then each 50 t module is then positioned *on a large vertical lathe* for machining the top surface



Top surface of module machined on lathe

The coil has been assembled with vertical axis



This allows a very precise coupling

Good, but coil has to be *inserted horizontally* inside the vacuum vessel!

Challenge N°6

Insert a 220-ton coil
inside a vacuum vessel
with horizontal axis

Large tooling is needed to bring it horizontal

220 ton object rotated in 15 mn

August 2005: Coil swivelling

Move outer vac tank over solenoid

Can the Basic Element of the CMS Coil Concept: the Reinforced Conductor, be Improved to Reach 5T?

The NbTi Superconducting Cable

B_{nom}=4T, I_{nom}(4T)=19.3kA, T_{oper}=4.5K, B_{max}=4.6T

- CMS cable has 32 NbTi strands, of present day ultimate performance, designed for:
  $Ic(4.5K, 4.6T) = 3 * Inom(4T)$
  For NbTi this is equivalent to:
  $Ic(4.5+1.8K, 4.6T) = Inom(4T)$.
- This is the definition of a *Temperature Margin of 1.8K*
- However, during CMS magnet test, we have allowed the temperature of the coil to *increase by 0.8K at 4T, without quenching,* thus a *Temperature Margin of 1K seems sufficient*.

The NbTi CMS Cable for a 5T Coil

Bnom=4T, *Inom*(4T)=19.3kA, *Toper*=4.5K, *Bmax*=4.6T

- In fact, the present CMS cable can (*electrically*) *power the coil to 5T*, with a *Temperature Margin of 1K, because it satisfies:*

Bmax of 5T coil

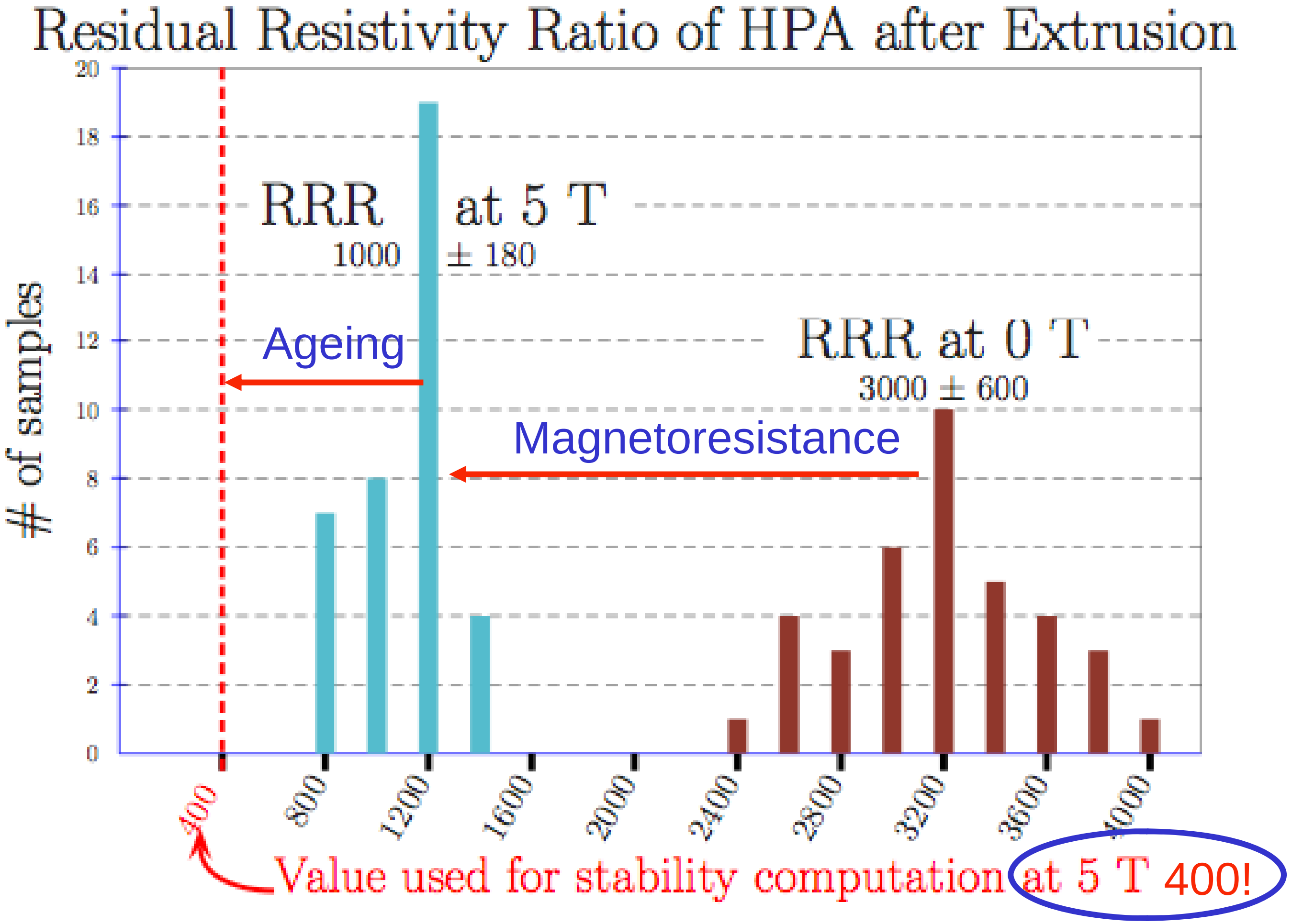
$$Inom(5T) = Inom(4T)*1.25 = \quad Ic(4.5+1K,\ 4.6T*1.25)$$

equivalent for NbTi to:

$$Ic(4.5K,\ 4.6T*1.25) = 2*Inom(4T)*1.25 = 2*Inom(5T)$$

Thus to run at 5T the CMS cable needs only a marginal improvement to keep a comfortable Temperature Margin > 1K, maybe adopting a 40-strand cable

Properties of pure aluminum in CMS coil and effect of ageing



Value used for stability computation at 5 T 400!

In addition pure aluminum *does not participate* to the mechanical strength

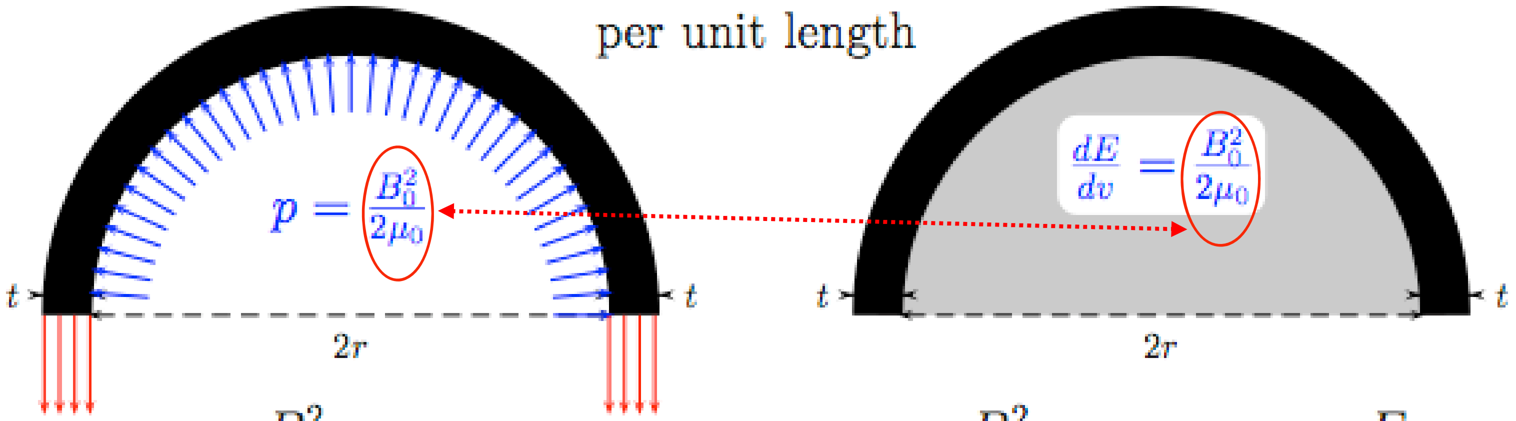
Can we use a more adapted stabilizer, with RRR around 400 with better mechanical properties?

Stored Energy/per unit length of cold mass

Force consideration

Energy consideration

per unit length



$$2r\,\frac{B_0^2}{2\mu_0} = 2\;\alpha\;t\;\sigma$$

$$\frac{B_0^2}{2\mu_0}\,\pi r^2 = 2\pi r t\;\rho\;\frac{E}{M}$$

α : ratio of structural material

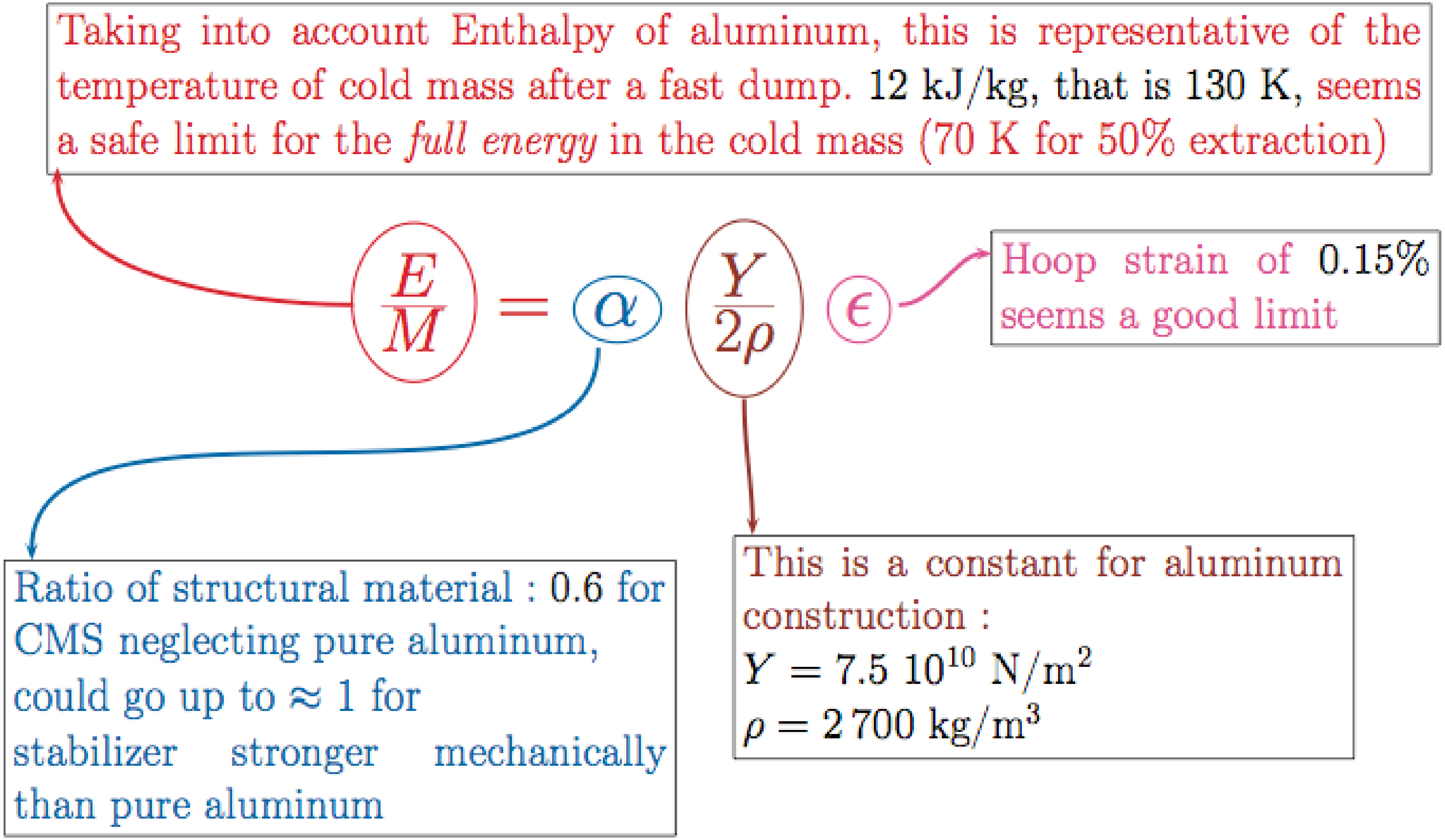
ρ : density of aluminum

with hoop strain $\epsilon = \frac{\sigma}{Y}$ then :

$$\boxed{\frac{E}{M} = \alpha\,\frac{Y}{2\rho}\,\epsilon}$$

Y : Young's modulus of aluminum

CMS parameters and what can be varied?



Taking into account Enthalpy of aluminum, this is representative of the temperature of cold mass after a fast dump. 12 kJ/kg, that is 130 K, seems a safe limit for the *full energy* in the cold mass (70 K for 50% extraction)

$$\frac{E}{M} = \alpha \frac{Y}{2\rho} \epsilon$$

Hoop strain of 0.15% seems a good limit

Ratio of structural material : 0.6 for CMS neglecting pure aluminum, could go up to ≈ 1 for stabilizer stronger mechanically than pure aluminum

This is a constant for aluminum construction :

$Y = 7.5\ 10^{10}\ \mathrm{N/m^2}$

$\rho = 2\,700\ \mathrm{kg/m^3}$

E/M and ϵ are strictly correlated

$$\frac{E}{M} = \alpha \; \frac{Y}{2\rho} \; \epsilon$$

Neither B_0 nor r appear in the formula!

$\Rightarrow$ When increasing B_0 or r more material has to be added to create more ampere-turns and resist the magnetic pressure to limit the strain at 0.15 %

$\Rightarrow$ This material is available to maintain E/M at the same value of 12 kJ/kg.

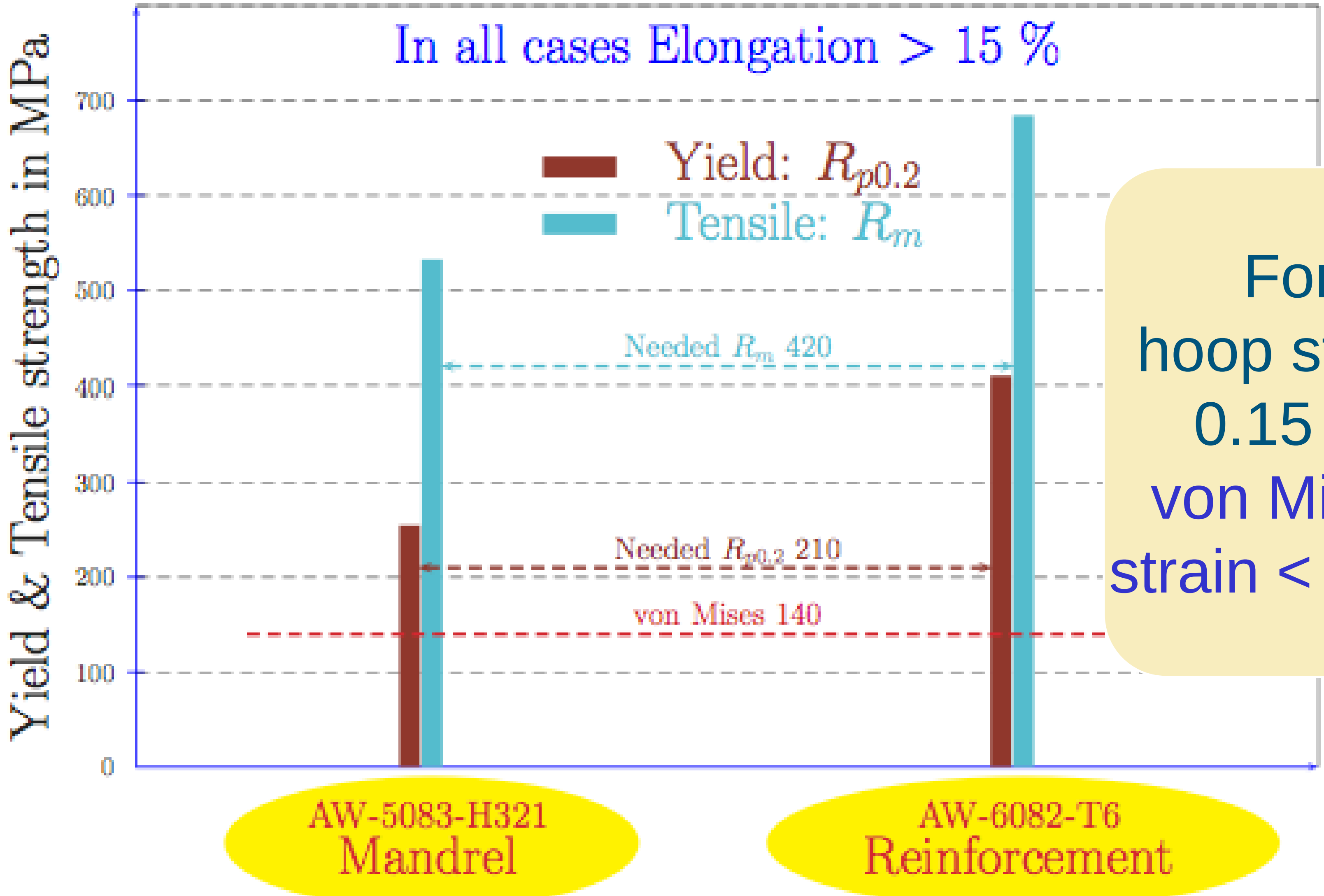
B_0 and r do not appear in the formula

Thus there is nothing magic with B_0 or r!

However, B_0 and r are not without influence on difficulties and cost!

Not forgetting the cost of the return yoke
if one wants to limit the stray field!

Thus Properties of CMS Alloys at 4.2 K are sufficient!



For
hoop strain
0.15 %
von Mises
strain < 0.2%

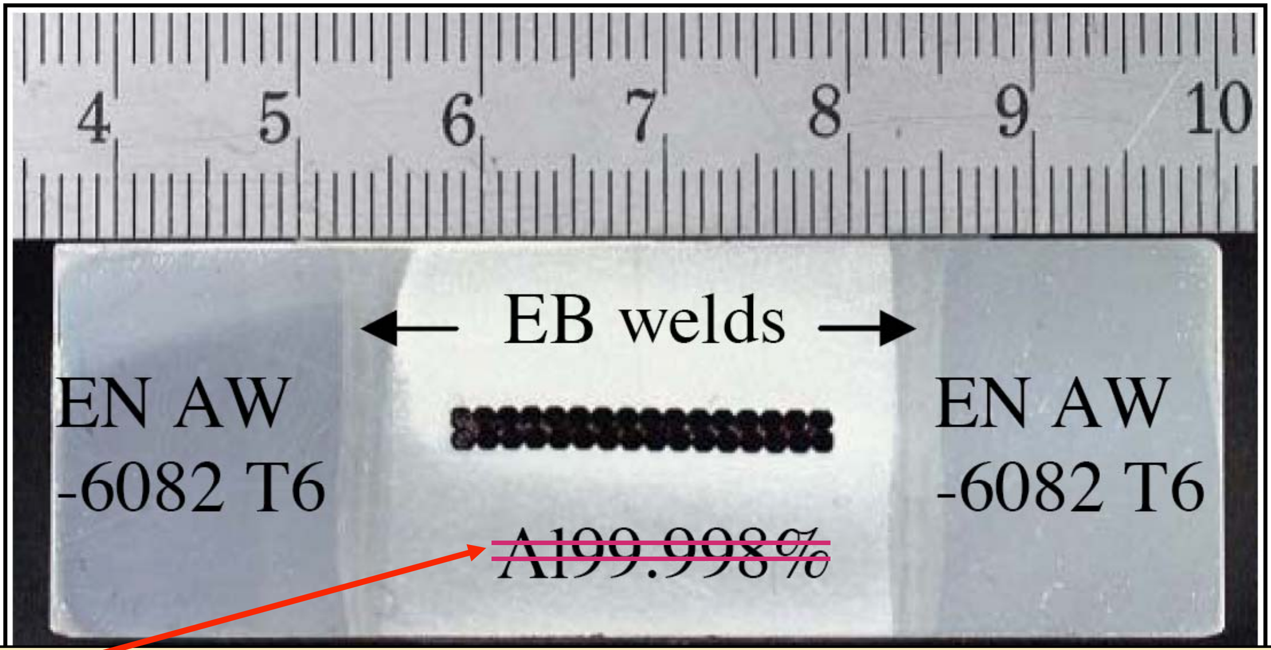
Also just OK for weldments !

E/M and ϵ are strictly correlated

$$\frac{E}{M} = \alpha \quad \frac{Y}{2\rho} \quad \epsilon$$

- The only parameter that could be safely increased is α, the ratio of structural material in the coil, from 0.6 in CMS to maximum 1.
- Thus, if the stabilizer can be considered as structural material, we can relax ϵ still using the same value of $\frac{E}{M} = 12\,\frac{\mathrm{kJ}}{\mathrm{kg}}$, $(= 70\,\mathrm{K}$ in the coil after a fast dump).

There is an R&D proposal to produce 200 m of “Improved CMS Conductor”



Replace pure aluminum stabilizer by:

- cold drawn Al-0.1wt%Ni alloy
- developed for the ATLAS thin solenoid superconductor

(A. Yamamoto et al., Development towards Ultra-thin Superconducting Solenoid Magnet for High Energy Particle Detectors, Nuclear Physics B (Proc. Suppl.) 78 (1999), pp.565-570)

Advantages of an Improved Conductor

- Would allow relaxing the hoop strain ϵ, or E/M, or both
- The full conductor would stay in nearly fully elastic state at maximum hoop-stress of 110 MPa
- No aging (degradation of RRR) would have to be considered.

Findings
&
Conclusion

Findings of the design team-I

- NbTi cable extruded in a stabilizer *is applicable up to 5 Tesla*, *maintaining a stability margin of 1.2 K* (32 strands -> 40)
- There is a *risk in increasing the temperature of cold mass after a fast dump over 70 K* (130 K in emergency situation)
- It seems *difficult to design for a hoop strain exceeding 0.15 %,* (0.2% wrt. von Mises stress) respecting construction codes
- It seems *impossible to construct thick mandrels* with the needed mechanical properties

Thus the use of reinforced conductor still seems a good solution

Findings of the design team-II

- Increasing the field means increasing the amount of material to create the ampere-turns and limit the hoop-strain, for example
6 layers for *5T* compared to *4 layers* for *4T*

- This added material will keep the ratio *E/M at 12 kJ/kg* of cold mass, thus *respecting the 70K* limit after a fast dump

- Aluminum Alloys 5083-H351 for the mandrels and 6082-T6 for the reinforcement are directly usable

- The replacement of the pure *aluminum stabilizer* by *cold drawn Al-0.1wt%Ni alloy** would allow increasing the mechanical performance of the conductor, and stay in a nearly *fully elastic state*

* A. Yamamoto et al.

Conclusion of the design team-III

The CMS design would suit *any new 3.5* or *4-Tesla coil*.

A 5-Tesla large thin coil, respecting all parameters considered safe today, would be a *natural extrapolation of the CMS design*, *with the possible use of an improved conductor* using cold drawn Al-0.1wt%Ni alloy as stabilizer.

Conclusion of the design team-II

Reaching 5T requires to launch an R&D program (*being already discussed between Saclay, Genova and CERN*) to:

- Check possibility of using “Yamamoto’s alloy” in a reinforced conductor à la CMS.
- Find an easier and less expensive technique to replace EB welding to attach the reinforcement.
- Secure a safe industrial solution for the co-extrusion of the sc cable.

Thank You!

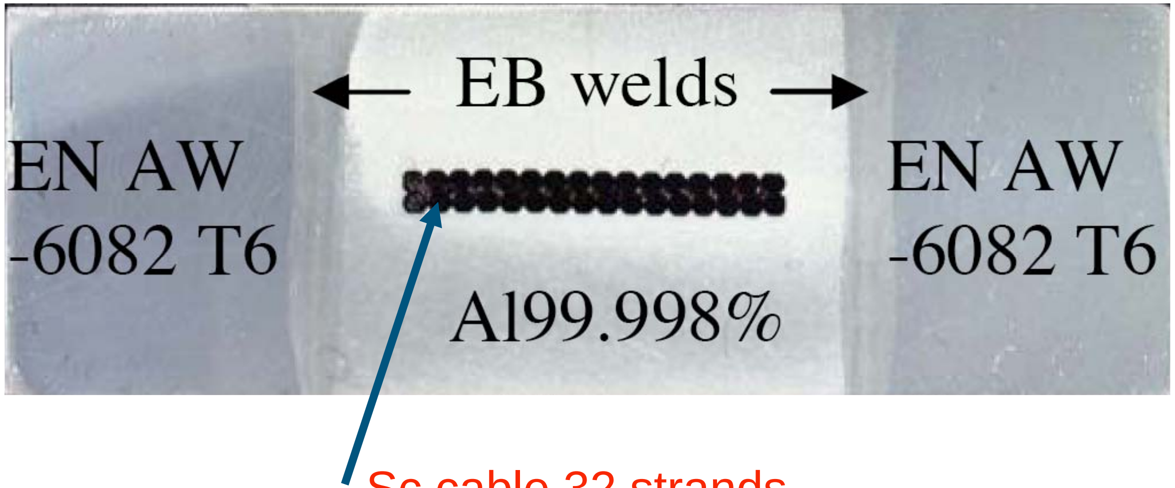
Back-up slides

Reminder - CMS Coil features

- The 4-Tesla CMS coil, 6 m free bore, has been successfully tested on the surface in 2006 and operated underground in Oct. 2008

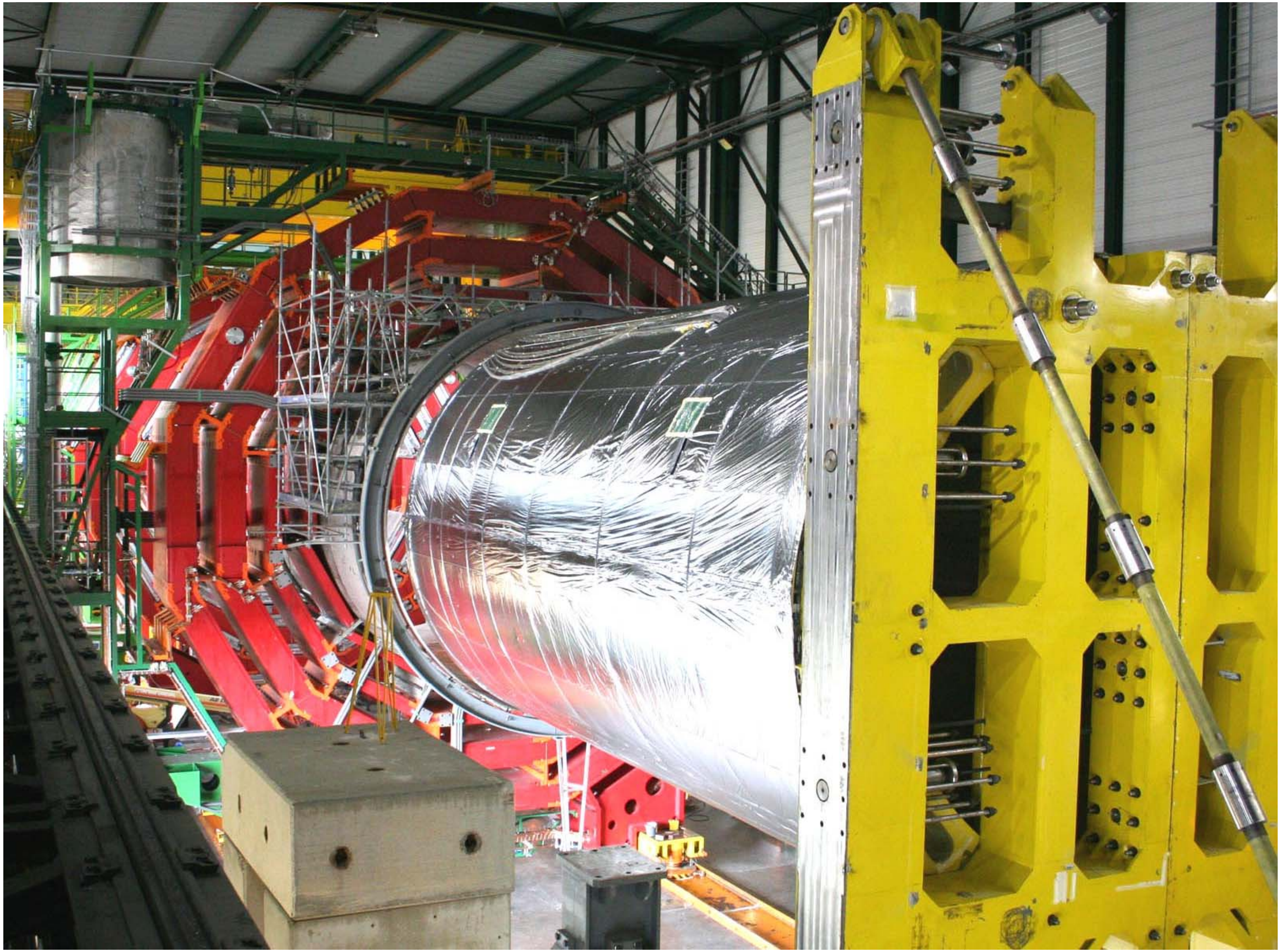
- The coil is designed for a 0.15% hoop strain, and a final cold m
t

Its distinctive feature is the use of a reinforced conductor

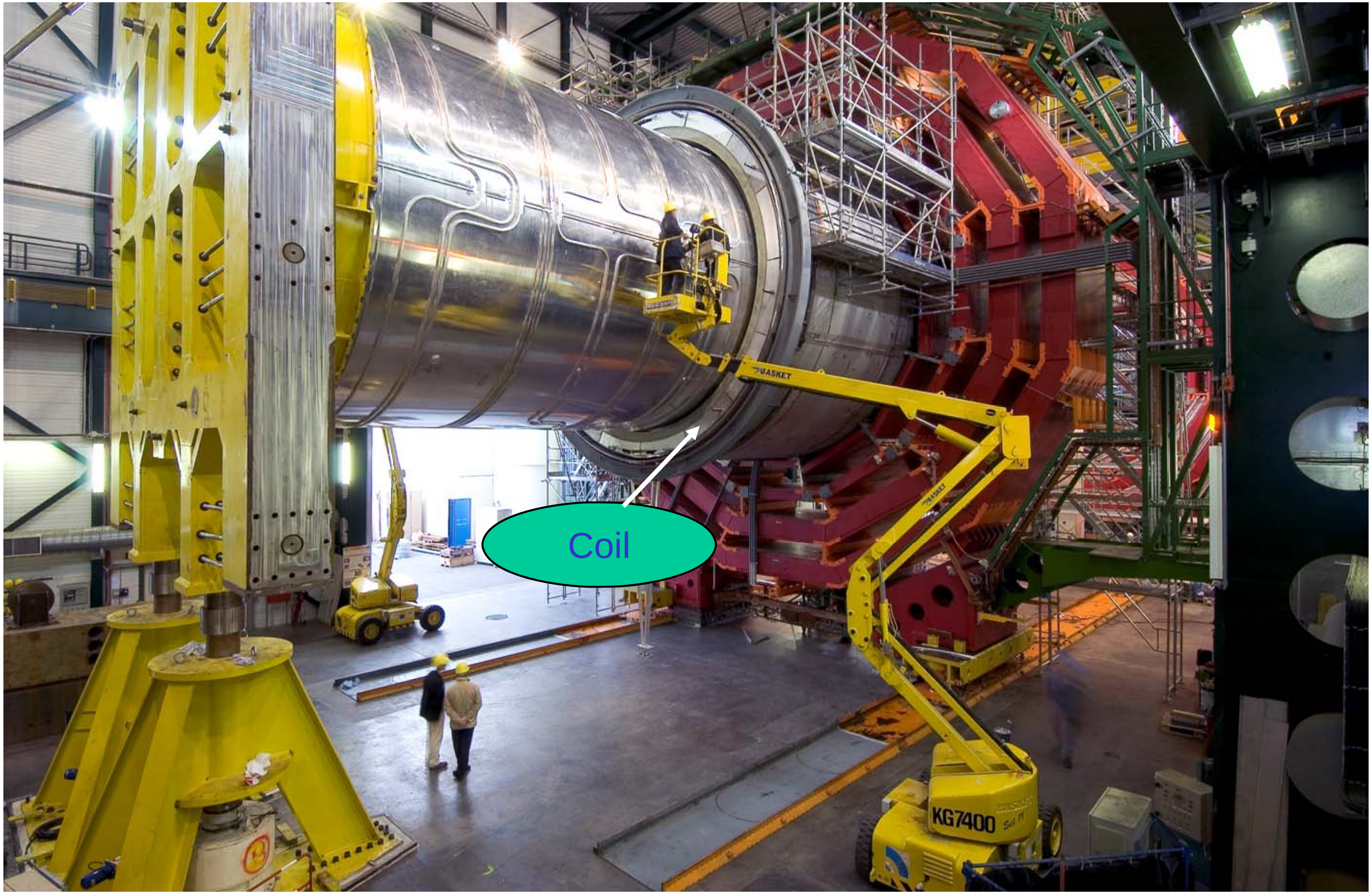


Sc cable 32 strands

Aug 2005: ready to insert!



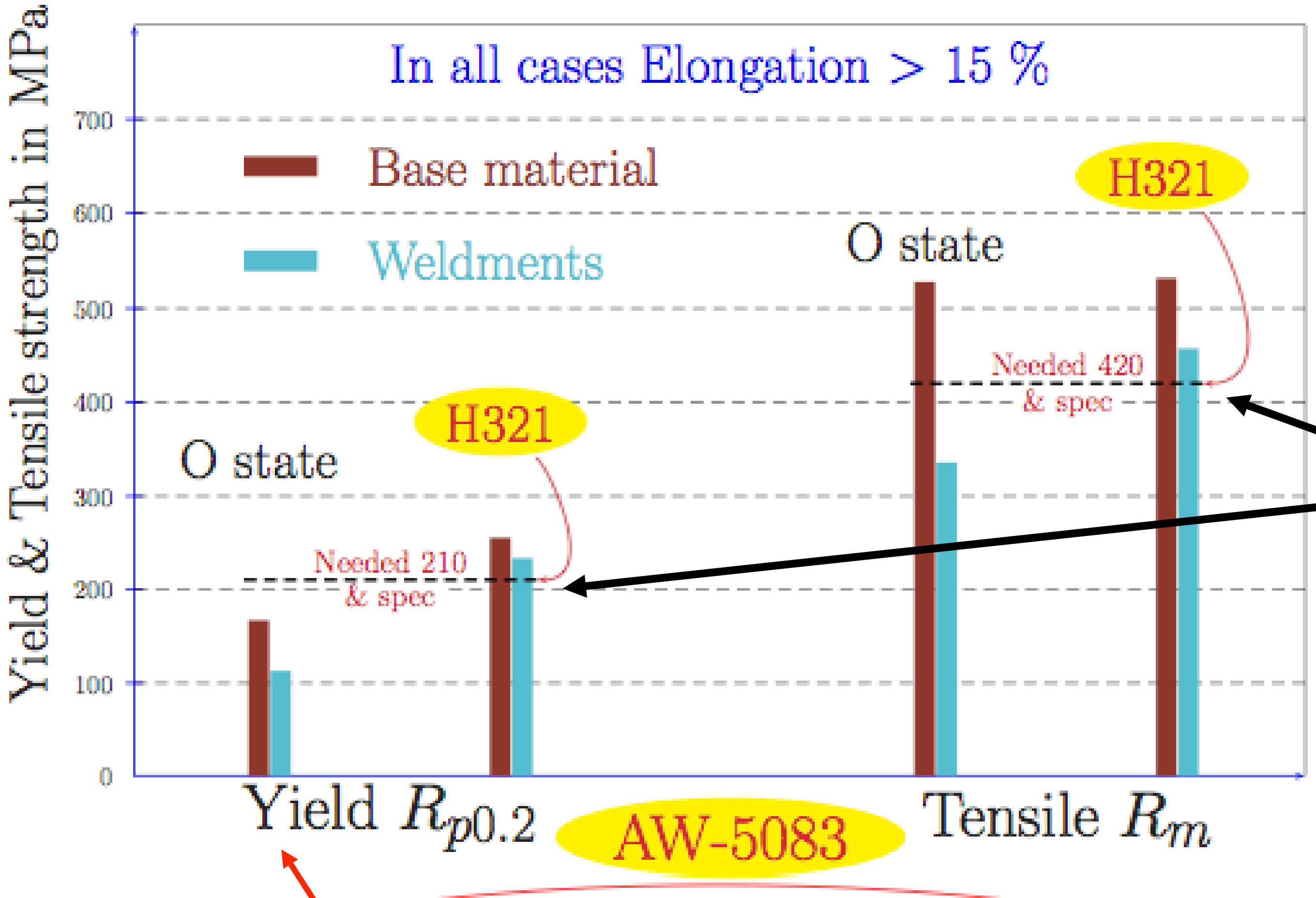
Same tooling is used to insert inner vac tank



Seamless ring for flange region

Flange regions need thicknesses > 80 mm,
there seamless rings were used with good properties

Mandrels in AA 5083-H321

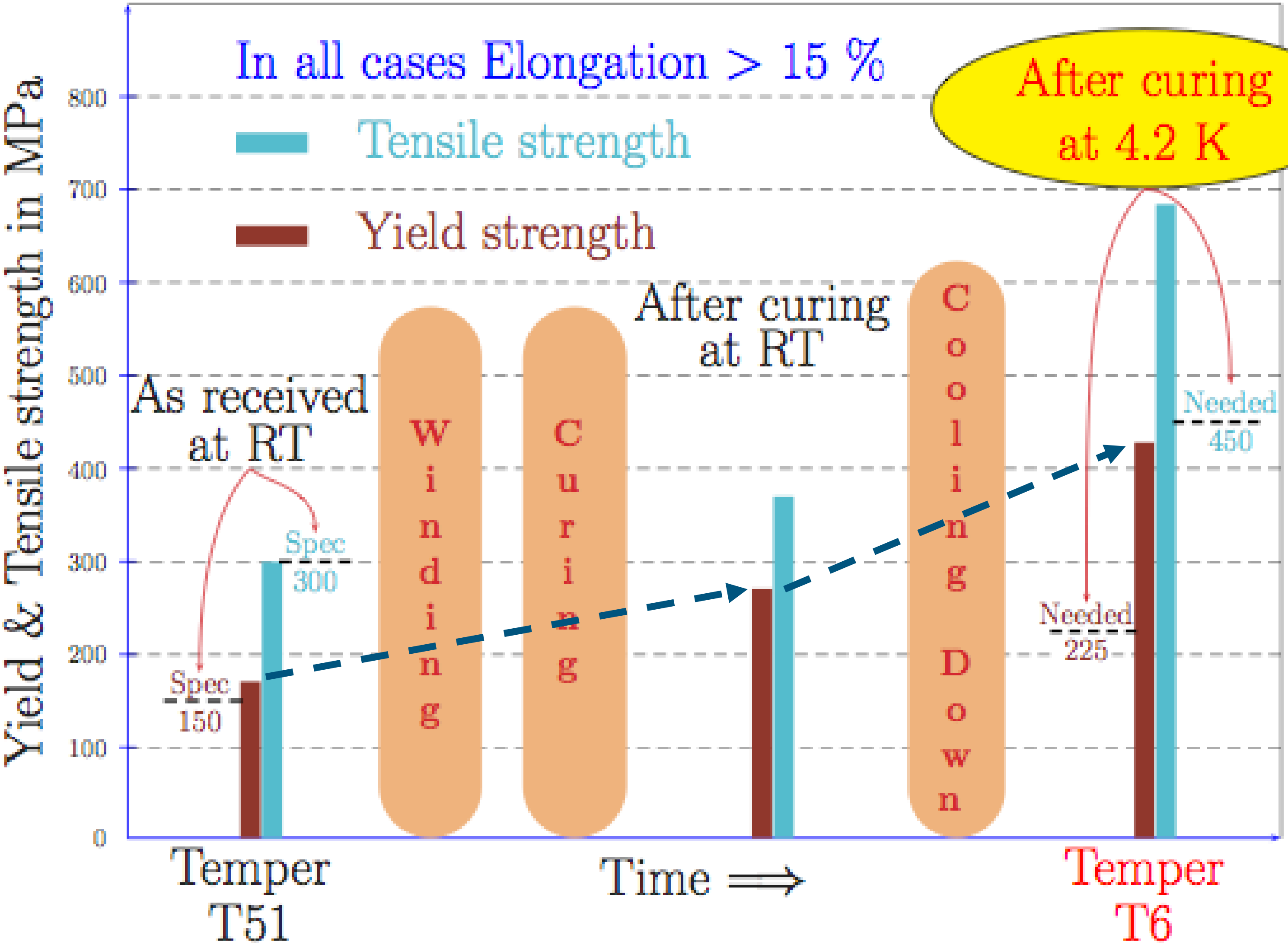


The O state (stress-relieved) *does not* satisfy the requirements!

For thickness < 80 mm

Temper H321 *Just Sufficient In Welds!*

Evolution of AA 6082 during process



Spools of reinforcement are received as under-aged stabilized temper T51