Experience and key points

from

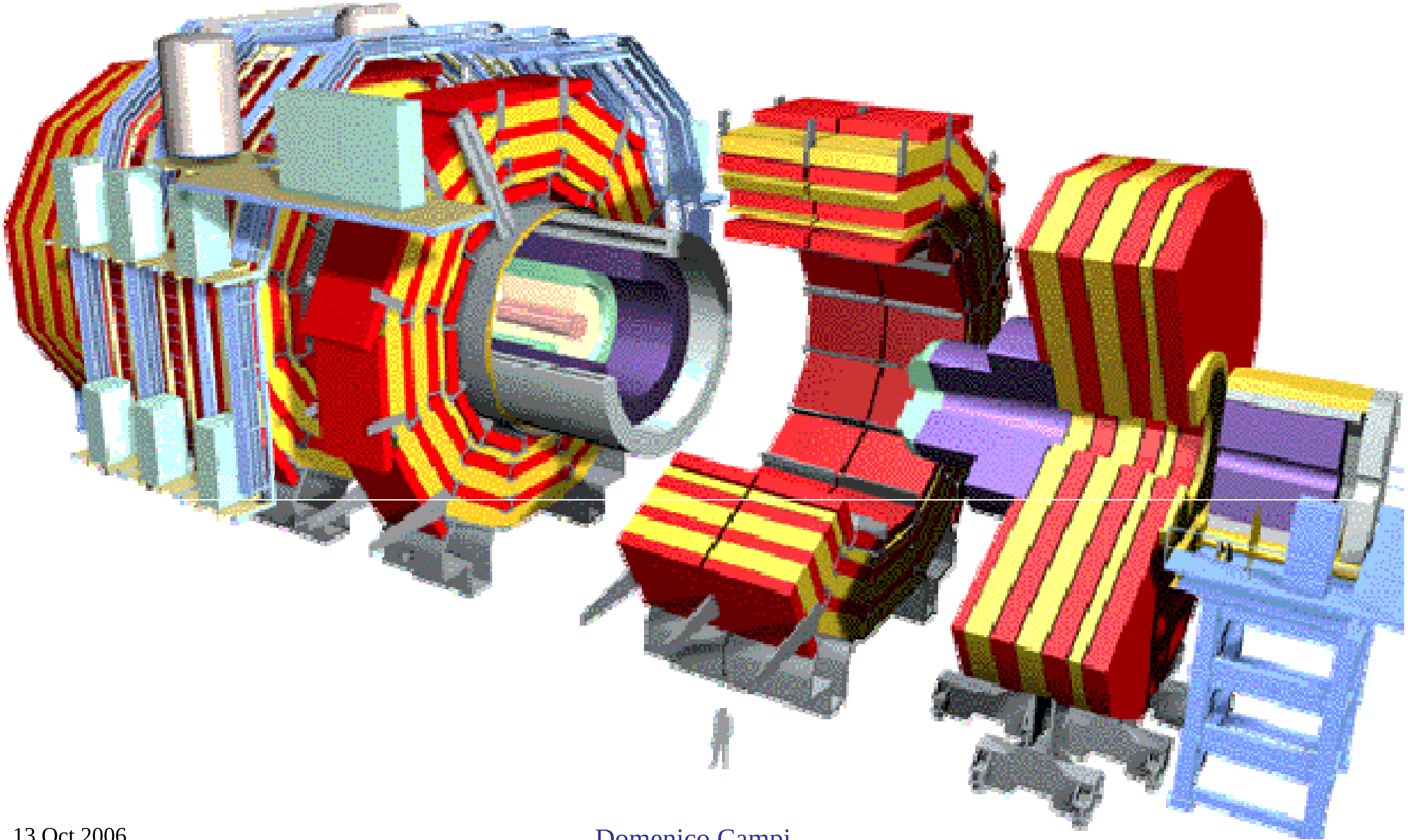
CMS Magnet Construction

(Coil in particular)

D.Campi - CERN/PH-CMI

CMS Magnet & Infrastructure Group Leader

The detector layout is organized around the Magnet concept, as well as civil engineering and related infrastruture



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CMS Magnet & Integration Group Leader

First requests

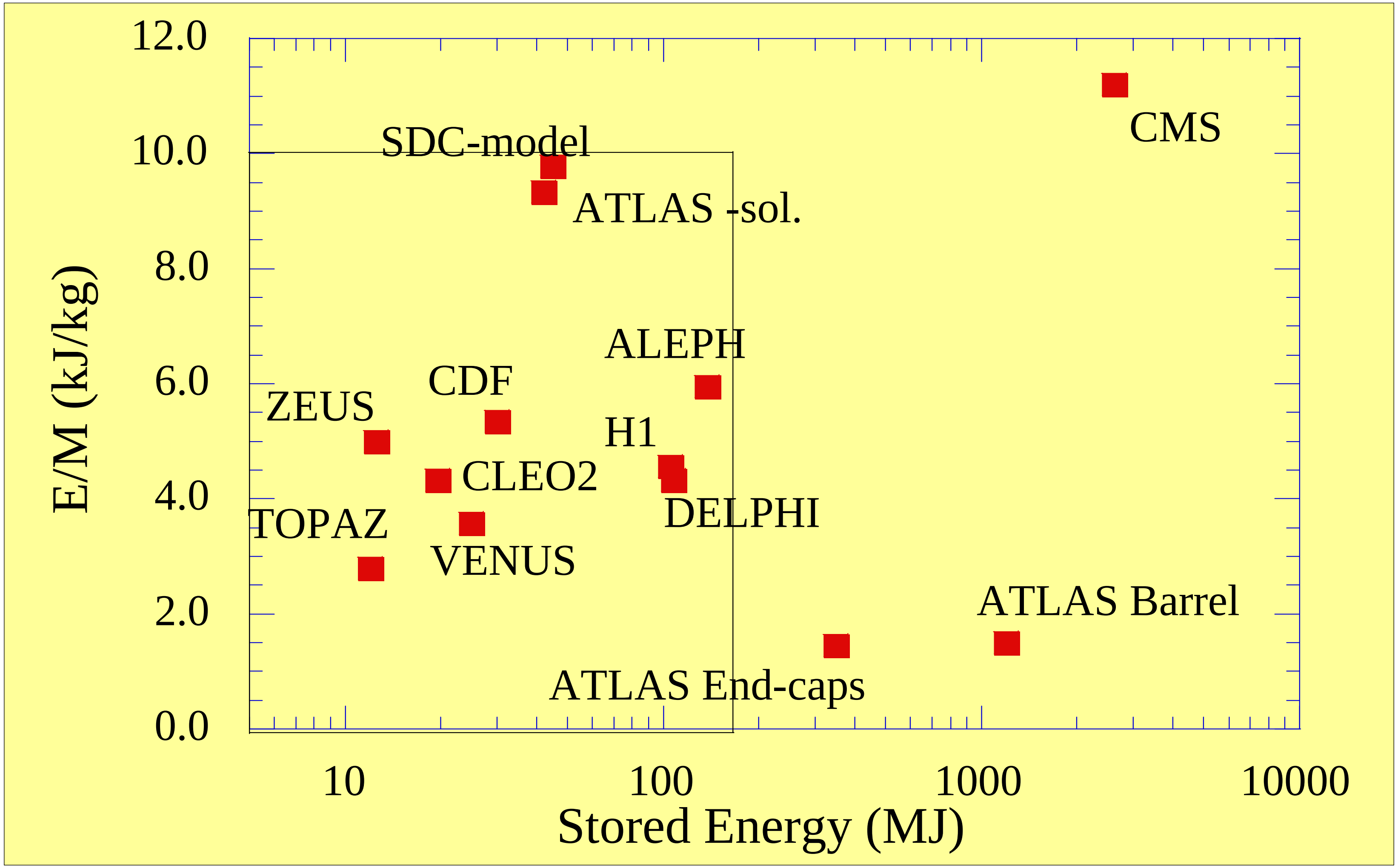
At the end of 1990 Michel, Jim, Karsten & Radi requested for their experiment CMS:

To have a solenoid around 6 m diameter and 13 m long with at least 3.5 T and if possible 4 T as ultimate field.

H. Desportes & R. Duthil / CEA Saclay and
A.Hervé/ CERN
were approached for their great experience, and in particular for the similarity of ALEPH wrt CMS

	CMS	ALEPH	factor
Inner Bore	6.3 m	4.96 m	1.25
Length	12.5 m	6.35 m	2
Central field	4 T	1.5 T	2.6
Nominal current	19 kA	5 kA	4
Stored Energy	2.65 GJ	137 MJ	20
Cold mass	220 t	25 t	9

CMS energy positioning



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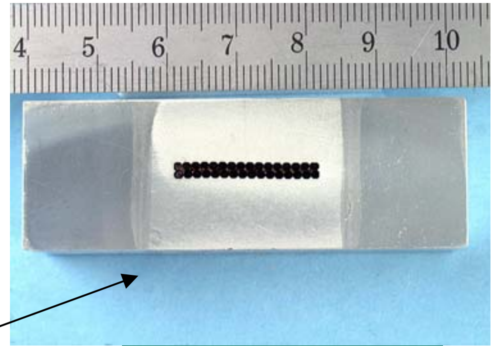
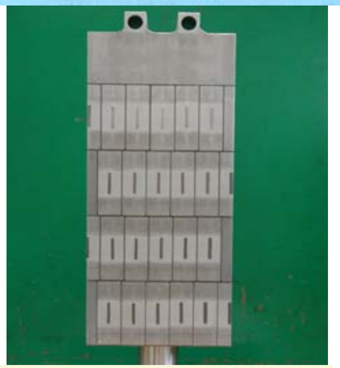
Conceptual improvements of CMS

NO RIGHT TO FAIL!

From Aleph

- <u>Passive protection by Quench-Back effect</u>
- Al stabilized NbTi conductor
- Indirectly cooled at 4.5 K by thermo siphon circuits
- Inner winding vacuum impregnated with epoxy resin





Innovations of CMS

- Mechanically reinforced conductor (to contrast locally magnetic forces)
- 4 Layers (because of the $42*10^{6}$ needed Ampere-turns)
- 5 modules (to limit unit lengths of conductor , facilitate construc
during impregnation)

13 Oct 2006

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CMS Magnet & Integration Group Leader

CMS Coil is a 15 years long history

- Industrial R&D, Pre-production and Prototypes from 1993 until 1999
- Approved in 1996
- 2 years for specifications and tendering
- Construction of components until 2005
- Final Assembly on site 2005 - 2006
- Powering and final tests 2006

It is clear that an overlap occurred among the different phases

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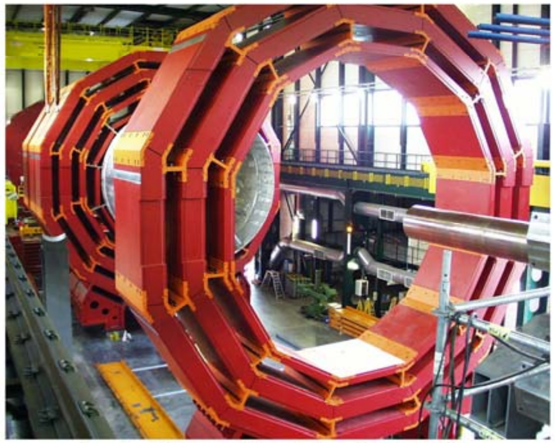
CMS Magnet & Integration Group Leader

Construction of the Yoke 1998 - 2002

Hubert Gerwig(PH- CMI):PJ Leader

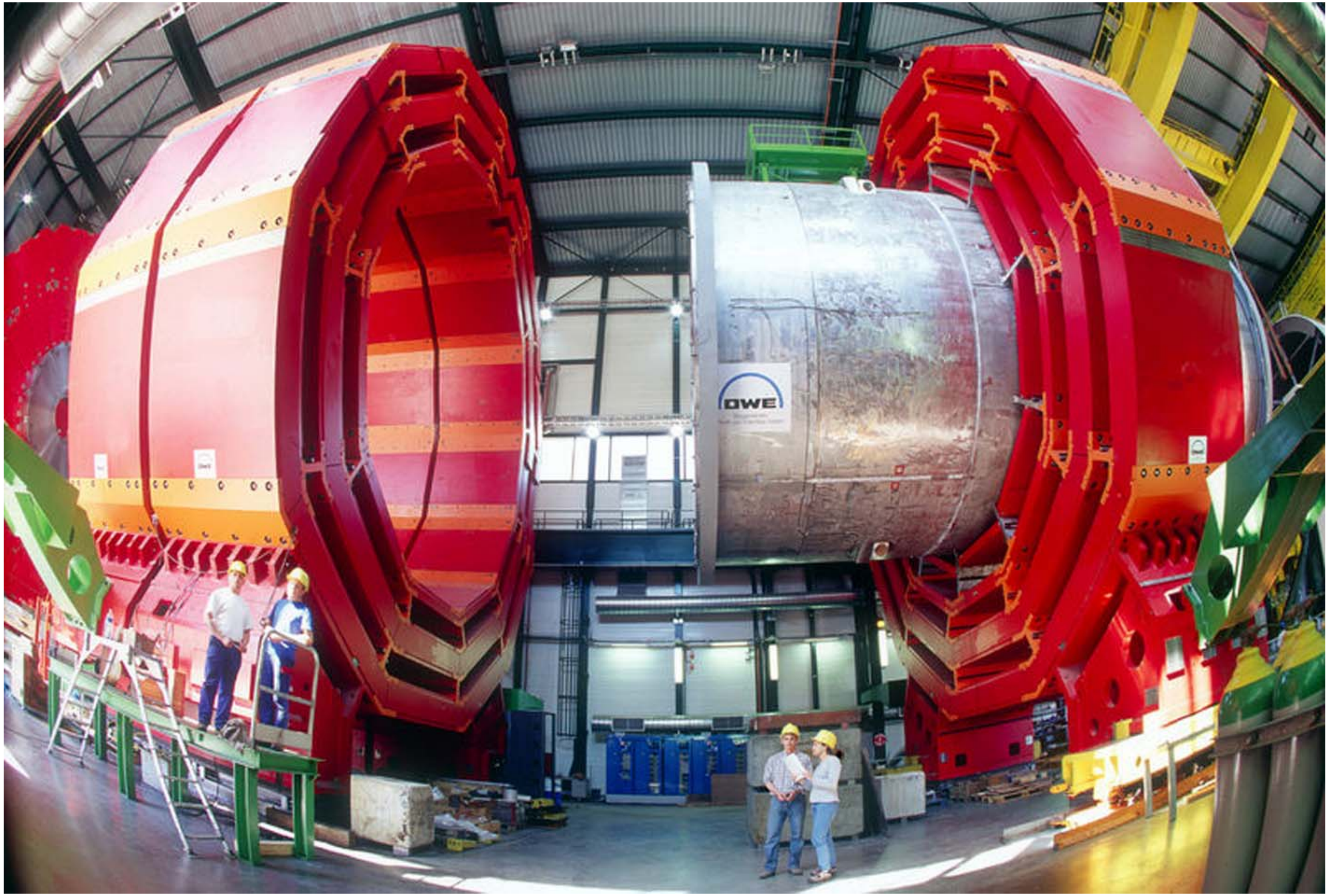
Pre-assembly at Deggendorf (1999)



Extraction of YB+2 from the Ferris wheel assembly tooling (2001)

Final assembly at CERN

The Yoke has been completed in 2003 to be ready to accept the cold mass and the muon chambers



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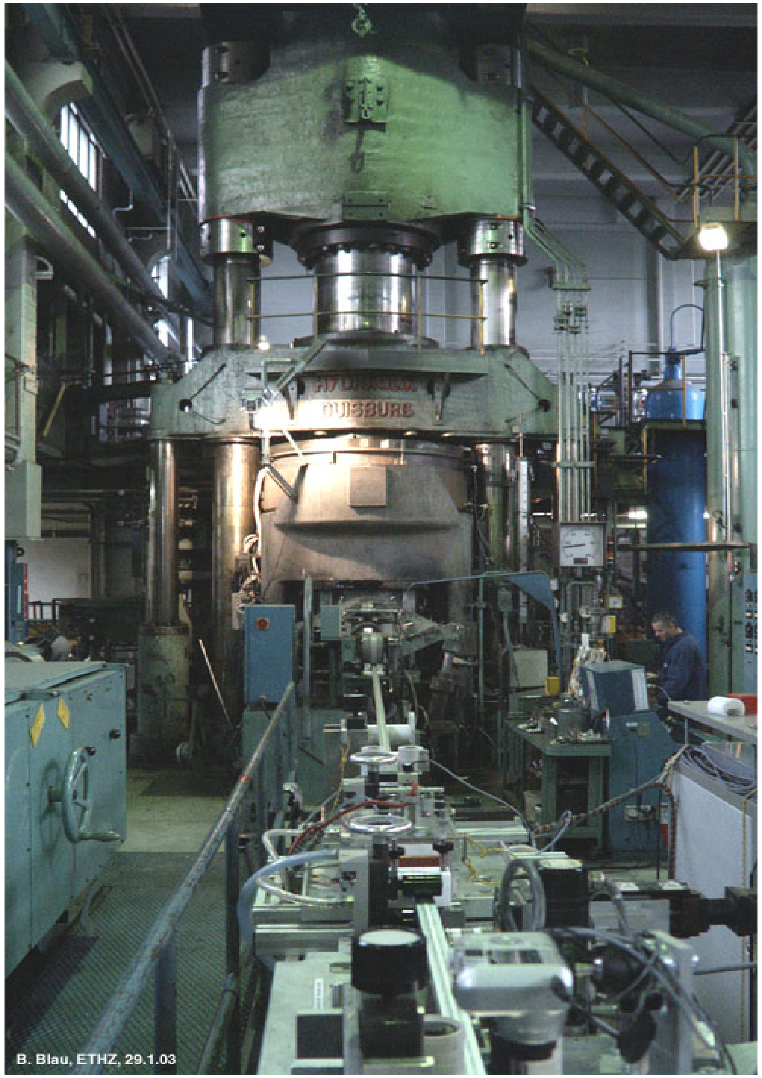
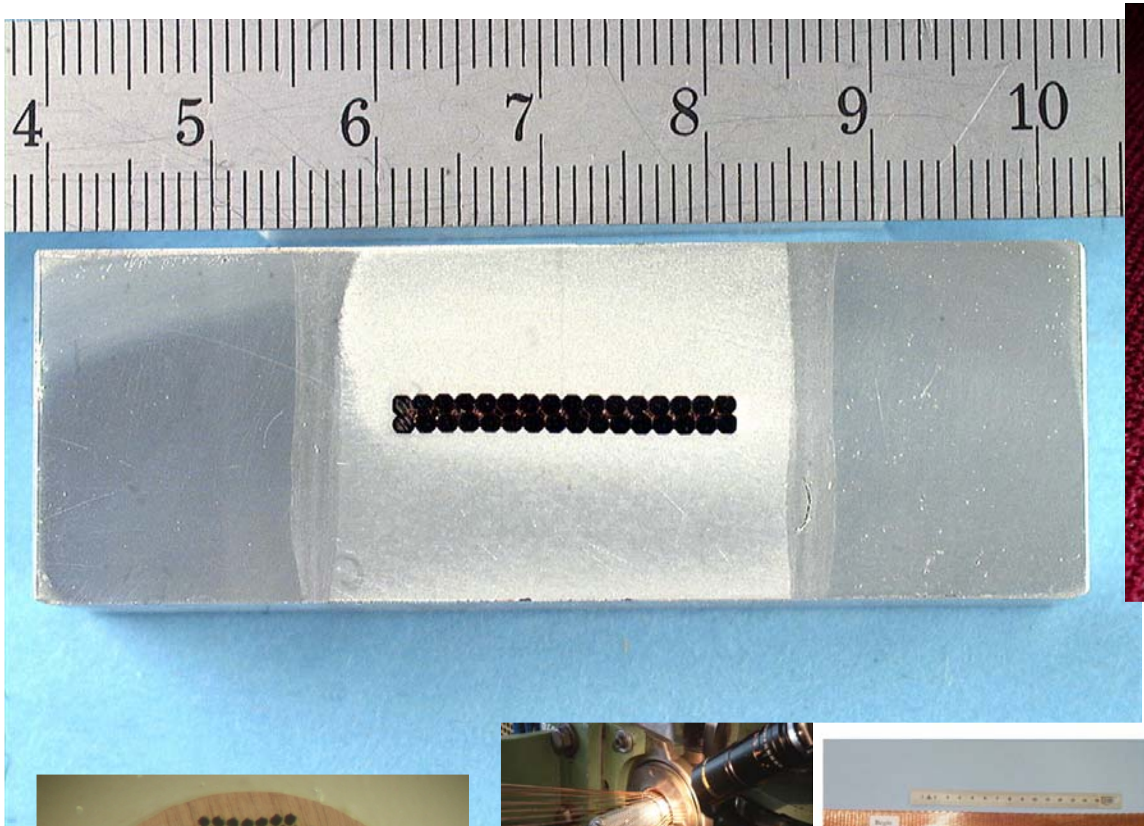
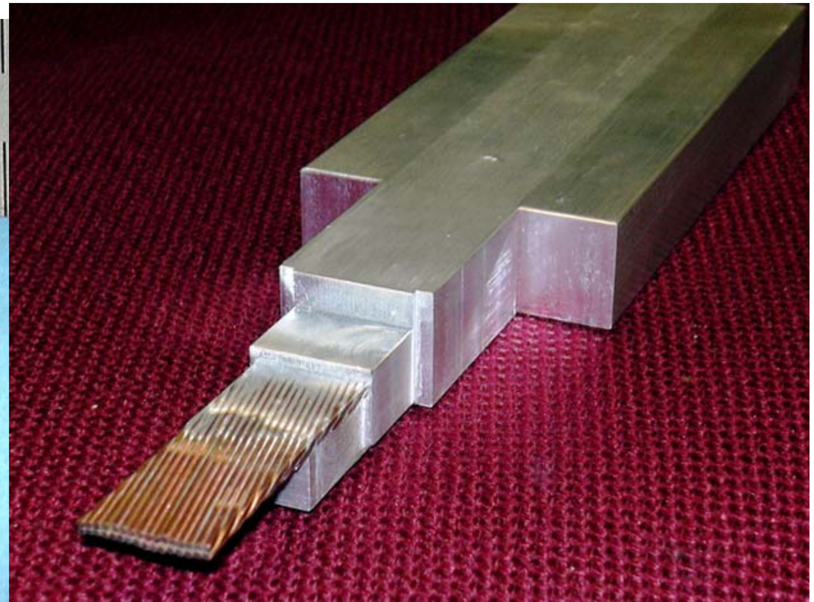
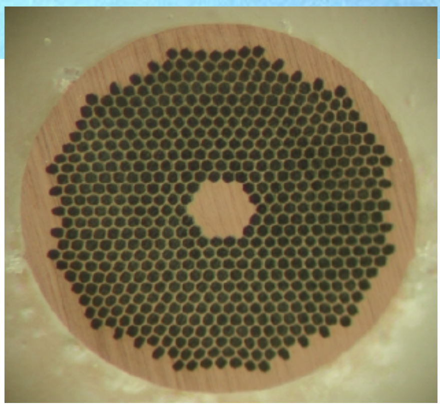
1993-1996 The first developments started for the conductor



To optimize the quality and keep the cost at the lowest level
Conductor <u>components</u> were procured and fabricated separately
from 1999 until 2002







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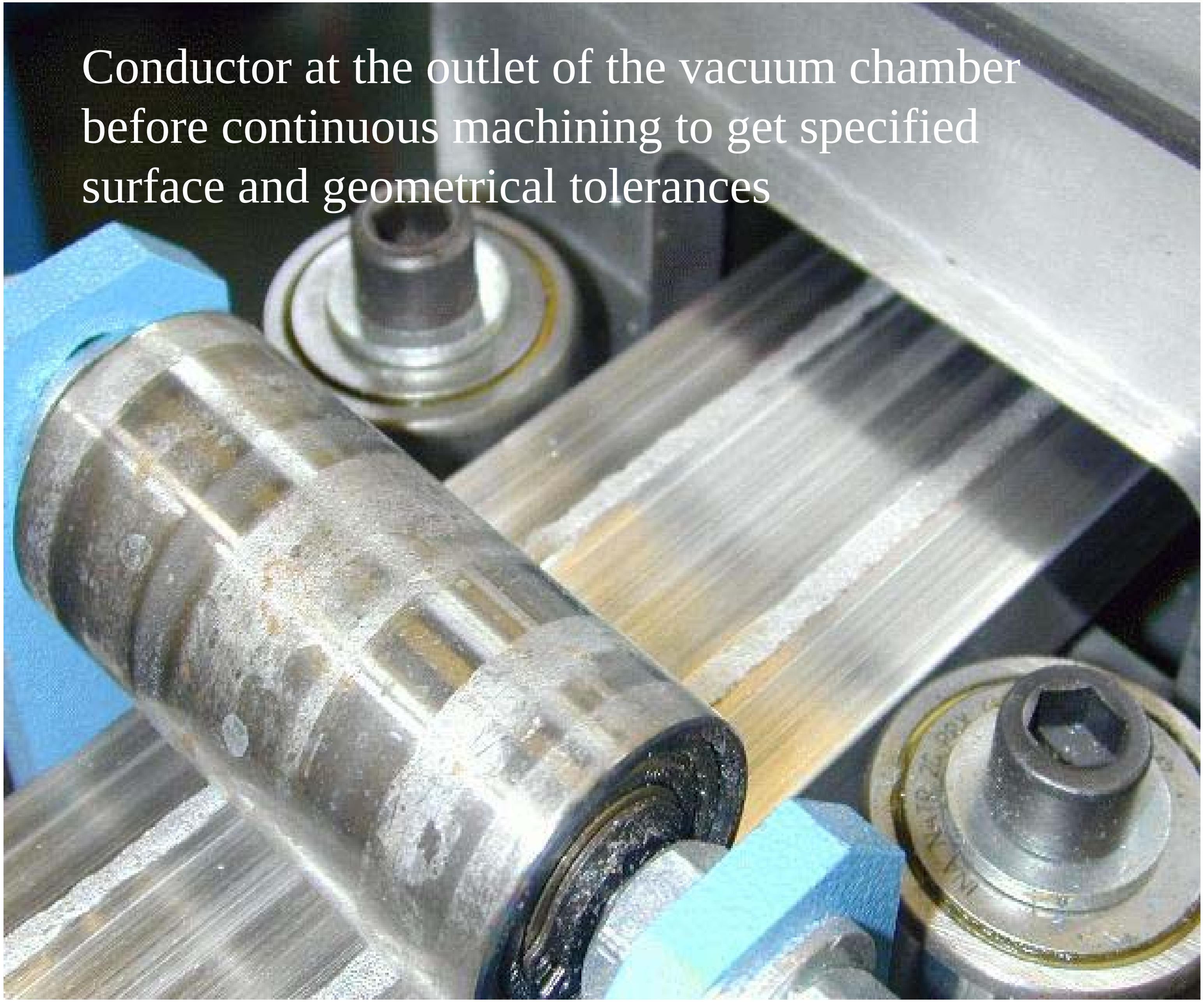
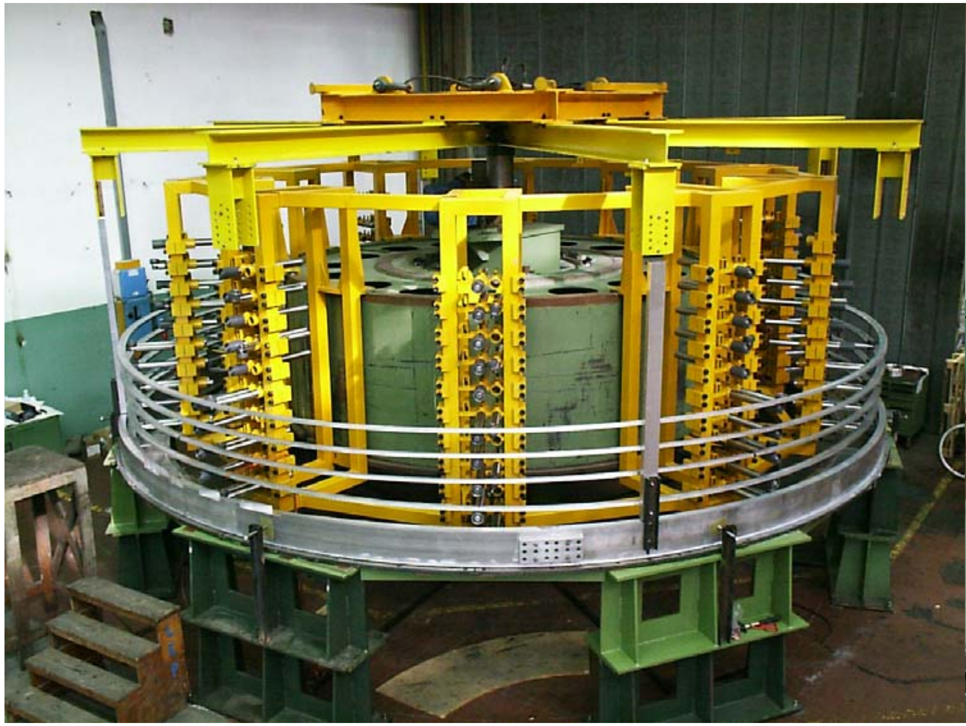
The Fabrication of the CMS conductor took place at TECHMETA between 2001 and 2003

Conductor at the outlet of the vacuum chamber before continuous machining to get specified surface and geometrical tolerances



R&D was also managed on winding technique to understand problems related with the 4 layer configuration

Winding



Impregnation

In particular understand how to bend and how to stack such a stiff conductor facing the unavoidable keystoning and avoiding damages to the insulation

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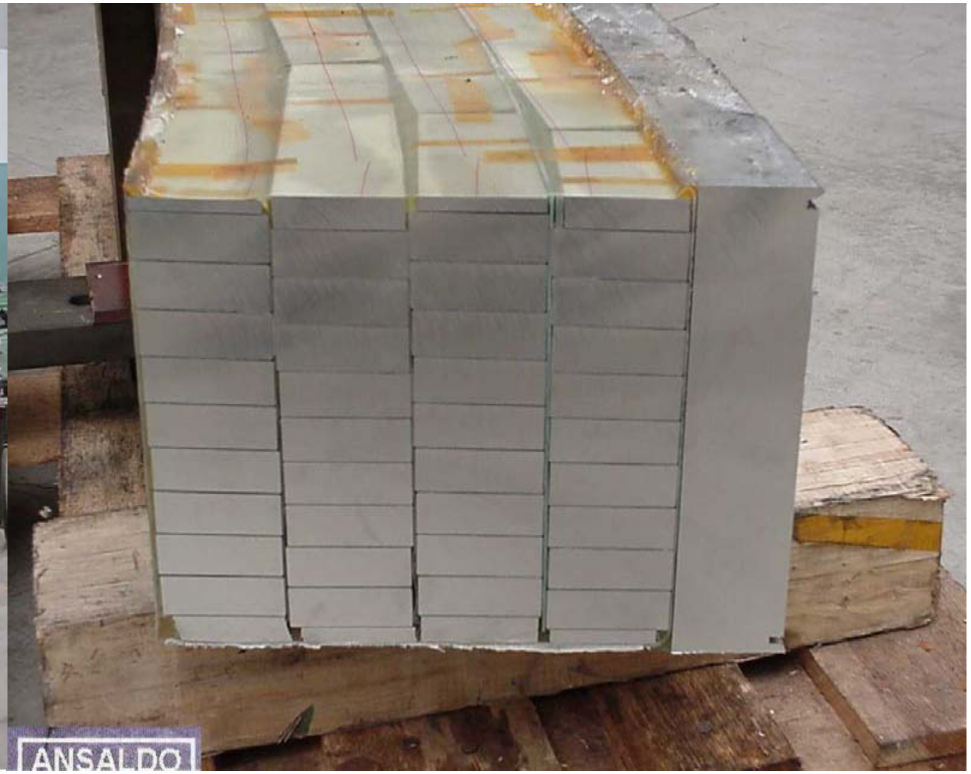
Winding prototype finished

The quality had still to be improved despite the good preliminary indications

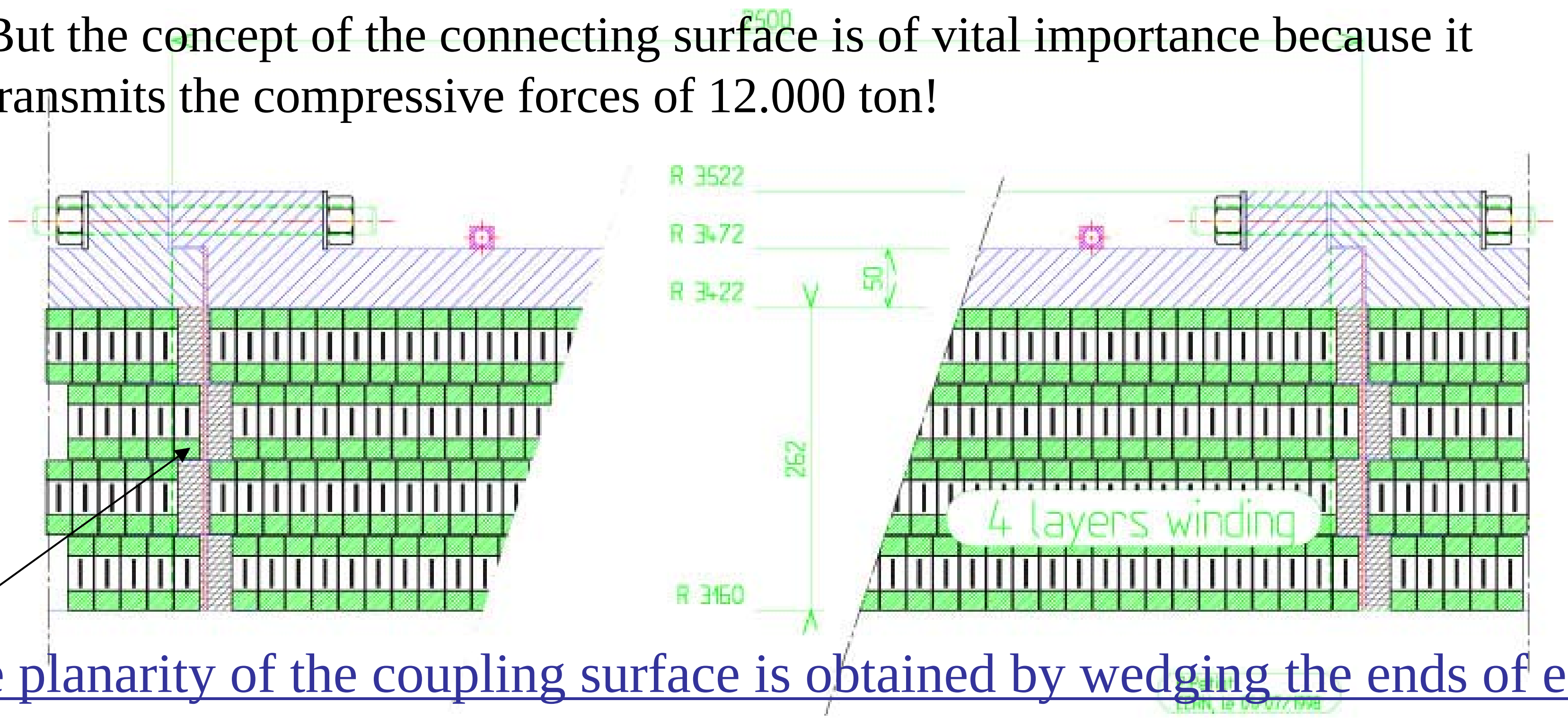


The design was frozen in 1998 after demonstration of industrial feasibility of the modules coupling

At the beginning the coil was conceived as a monolith to facilitate construction

To reduce the risks in the fabrication of the conductor lengths (2.5 km instead of 12.5 km each) and the risk of a single enormous impregnation, the coil was sectioned into 5 modules

But the concept of the connecting surface is of vital importance because it transmits the compressive forces of 12.000 ton!



The planarity of the coupling surface is obtained by wedging the ends of each turn

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The construction of the 5 modules has been done by ANSALDO Superconduttori under the supervision of INFN Genova from 2000 until 2005

Impregnation of the first module occurred in Feb 2003

After impregnation each upper coupling surface of the modules was machined

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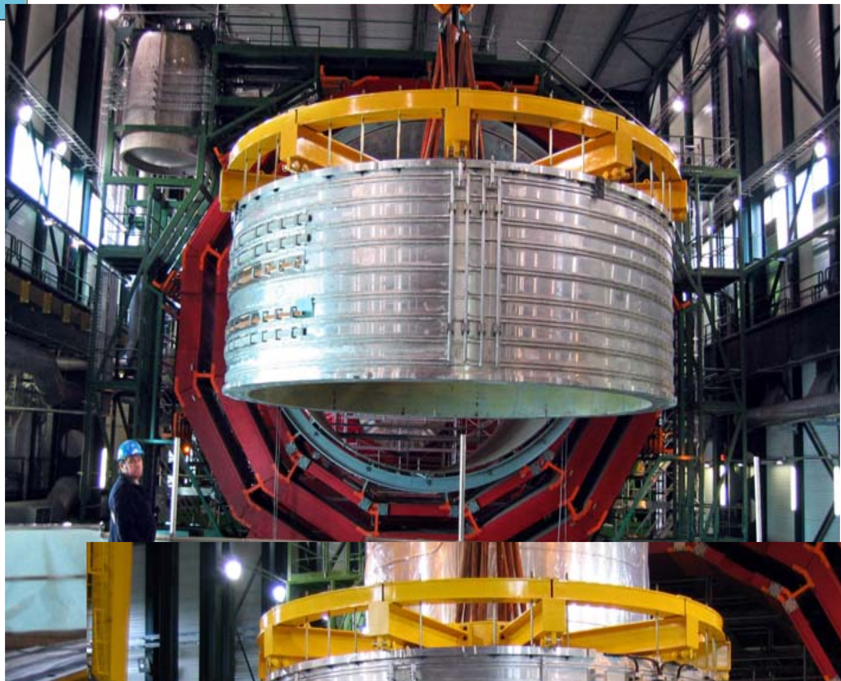
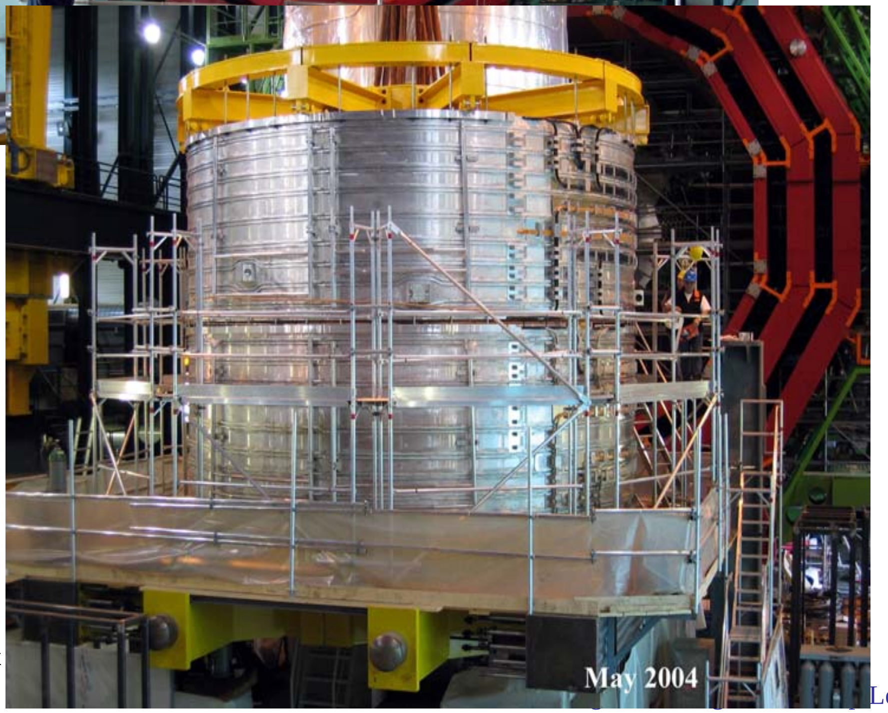
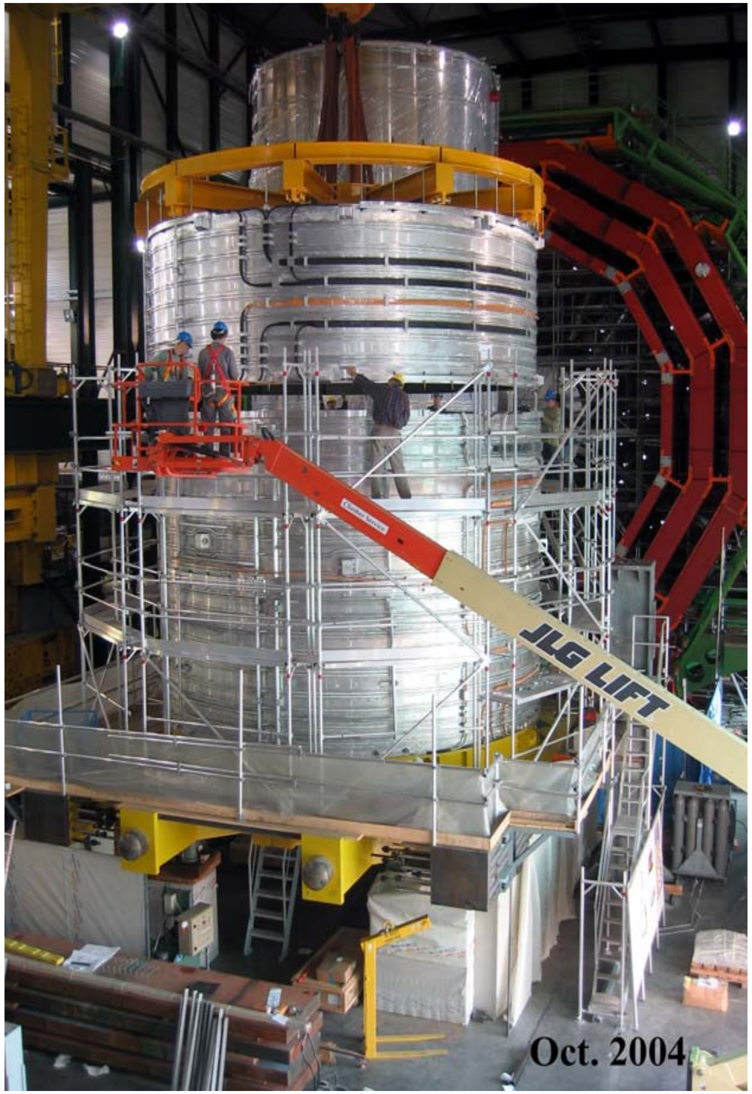
Coil Module Transportation
Jan2004 / Feb 2005

Pile-up of module at SX5







Electrical Connection with R<1.5 10-9 Ohm/m

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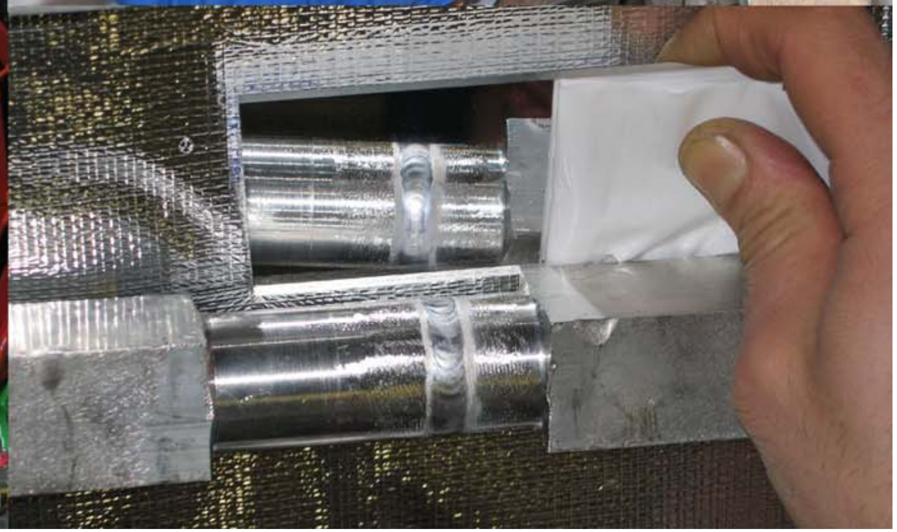
Hydraulic connections

The 5 modules piled up (February 2005)

The cryogenic circuit closed to the chimney

Thermal shield installation
Feb-June 2005



Coil Swiveling August 2005

The Coil is cantilevered on the so called swivelling platform

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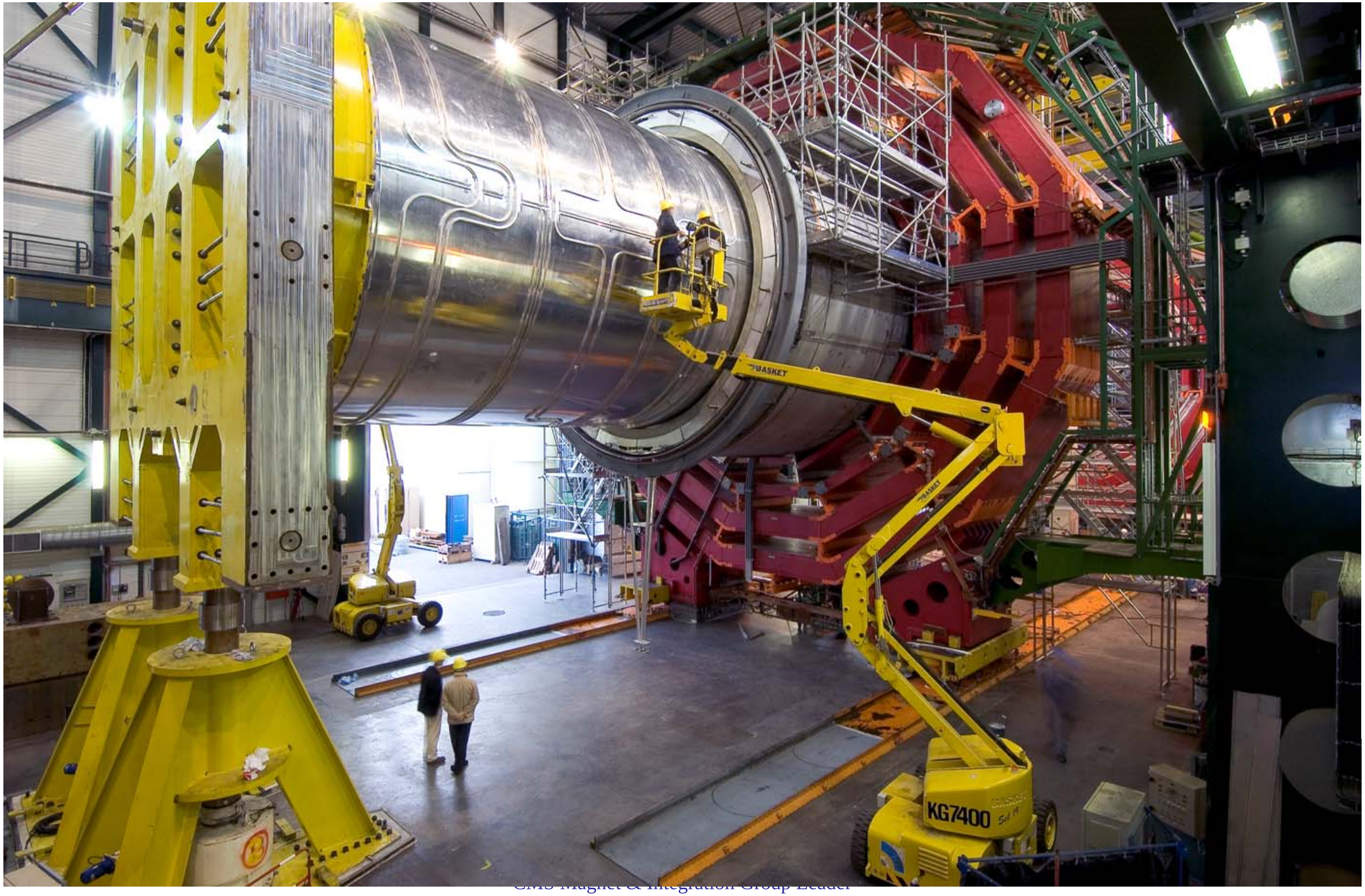
Coil insertion with a clearence of 50 mm

The Inner thermal shield being inserted in its vactank
Sept 2005

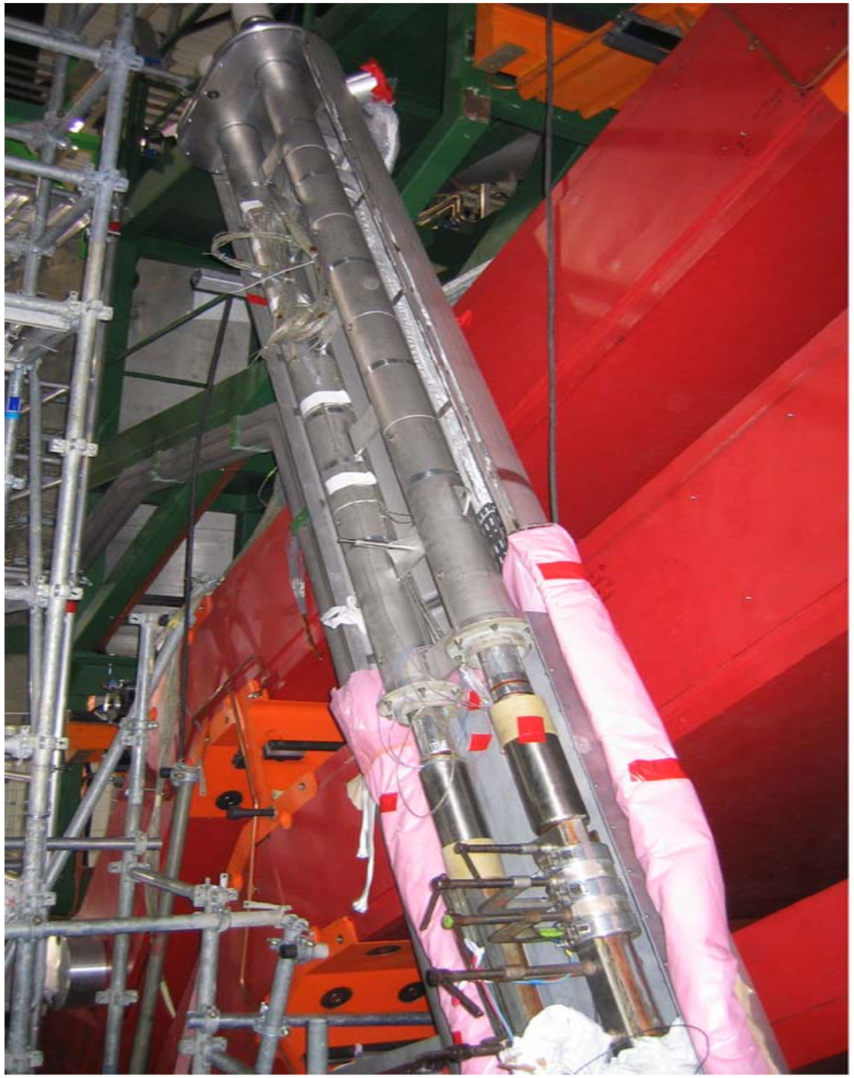


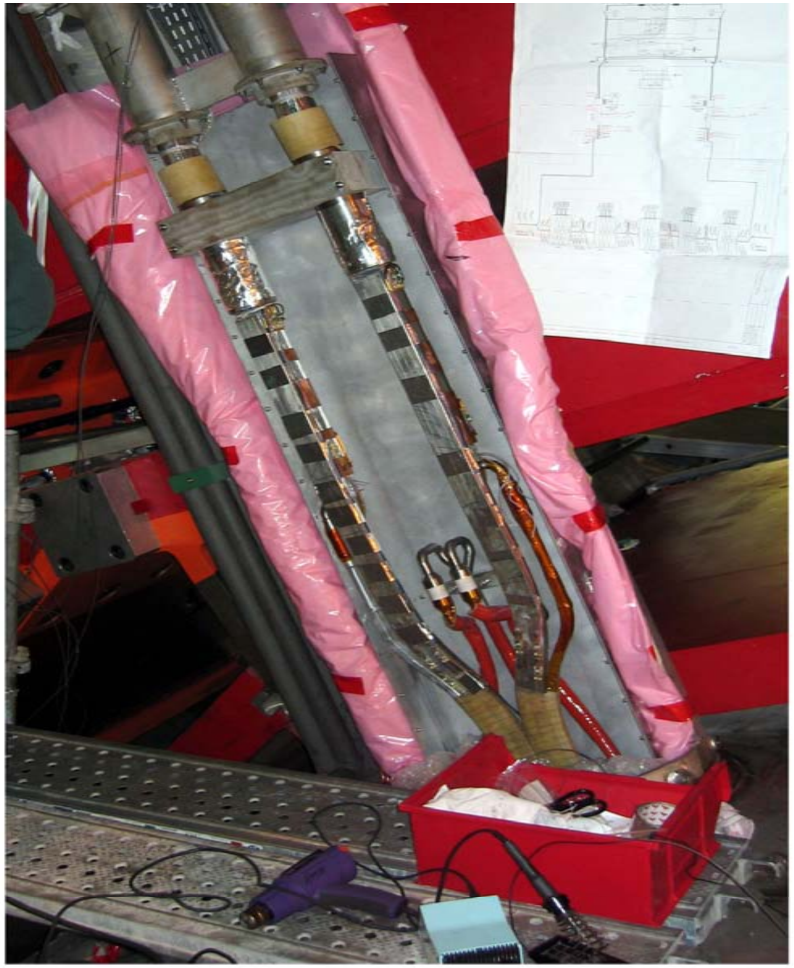
Connection to the cryogenic chimney

The doubling of the thermosyphon circuit has complicated the construction

The cryogenic chimney links the cold mass
to the phase separator cryostat
by SDMS (F)

The current leads have been designed, built and tested (He flow wrt to current) at Saclay before being installed on site





The current lead chimney assembly

Cryogenics was installed more than 1 year before powering the magnet to allow good debugging of the system

The plant has been specified for the following performance:

- During cool down : up to 30 kW
- In steady state : 800 W at 4.45 K + 4500 W at 60-80 K + 4 g/s liquefaction
- In failure mode : up to 40 g/s liquefaction

PJ Leader: G. Perinic

The compressor station, installed in 2001 has been commissioned mid 2002

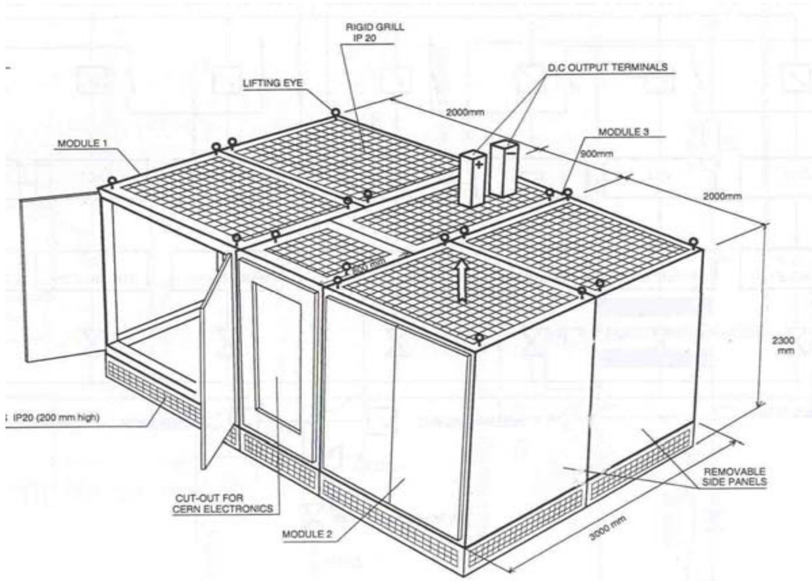
The cold box has been installed from May to Nov 2002 and commssioned from July 2003 until March 2005

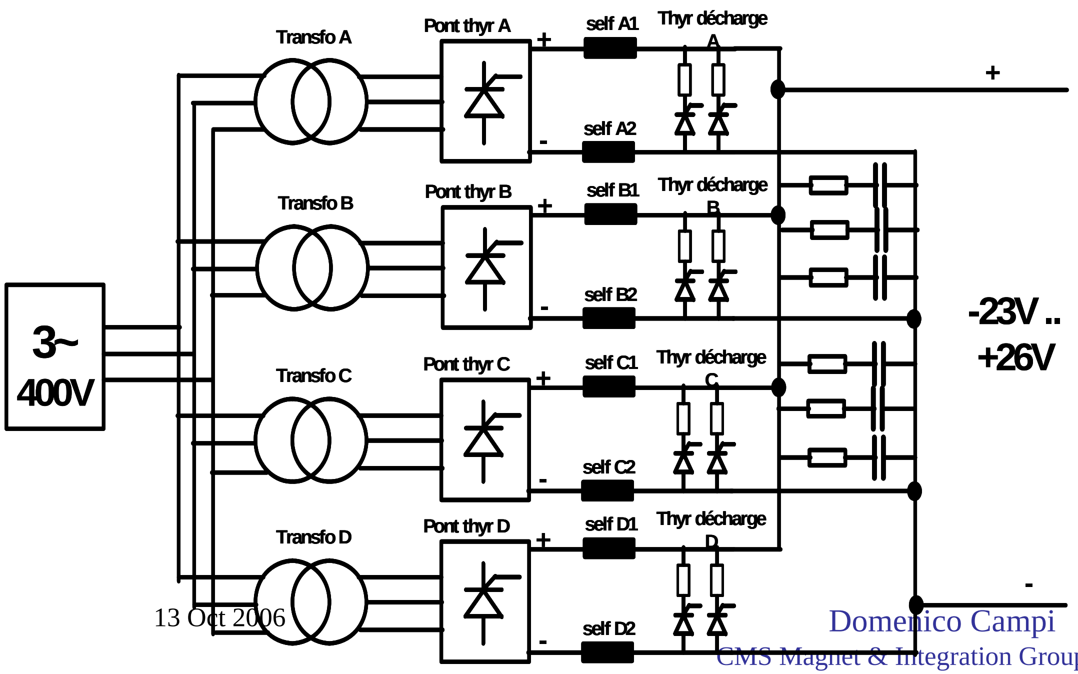
Some problems encountered due to oil coalescer performance (which generated pollution of the circuits) and start up of the 3rd stage turbine in the cold box (which had repetitive failure)

CMS Power Converter is bipolar : 20 kA; +26/-23 V

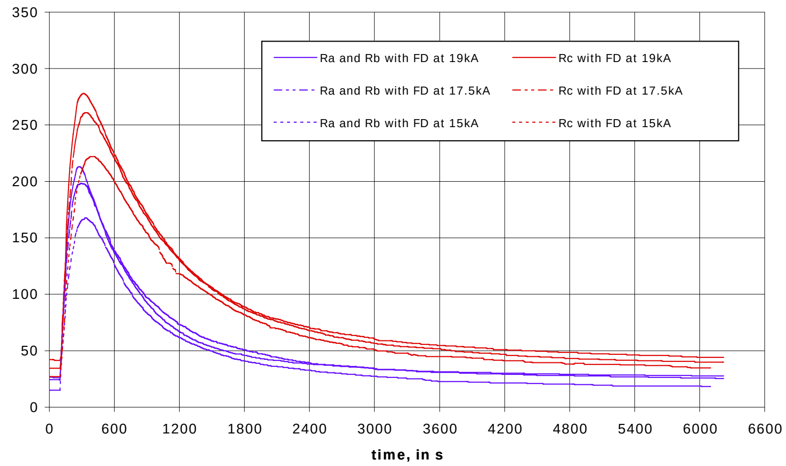
Type: Tyristor bridge rectifier,
bipolar in voltage,

Output nominal voltage: -23V .. +26V
Output nominal current: 20000 A
Nominal power for ramping-up: 520 kW
Mains supply voltage: 400V, 50Hz, 3-phase
Mains supply current: 320 Arms
Voltage ripple: 1 %
Current precision: 5 ppm pk-pk

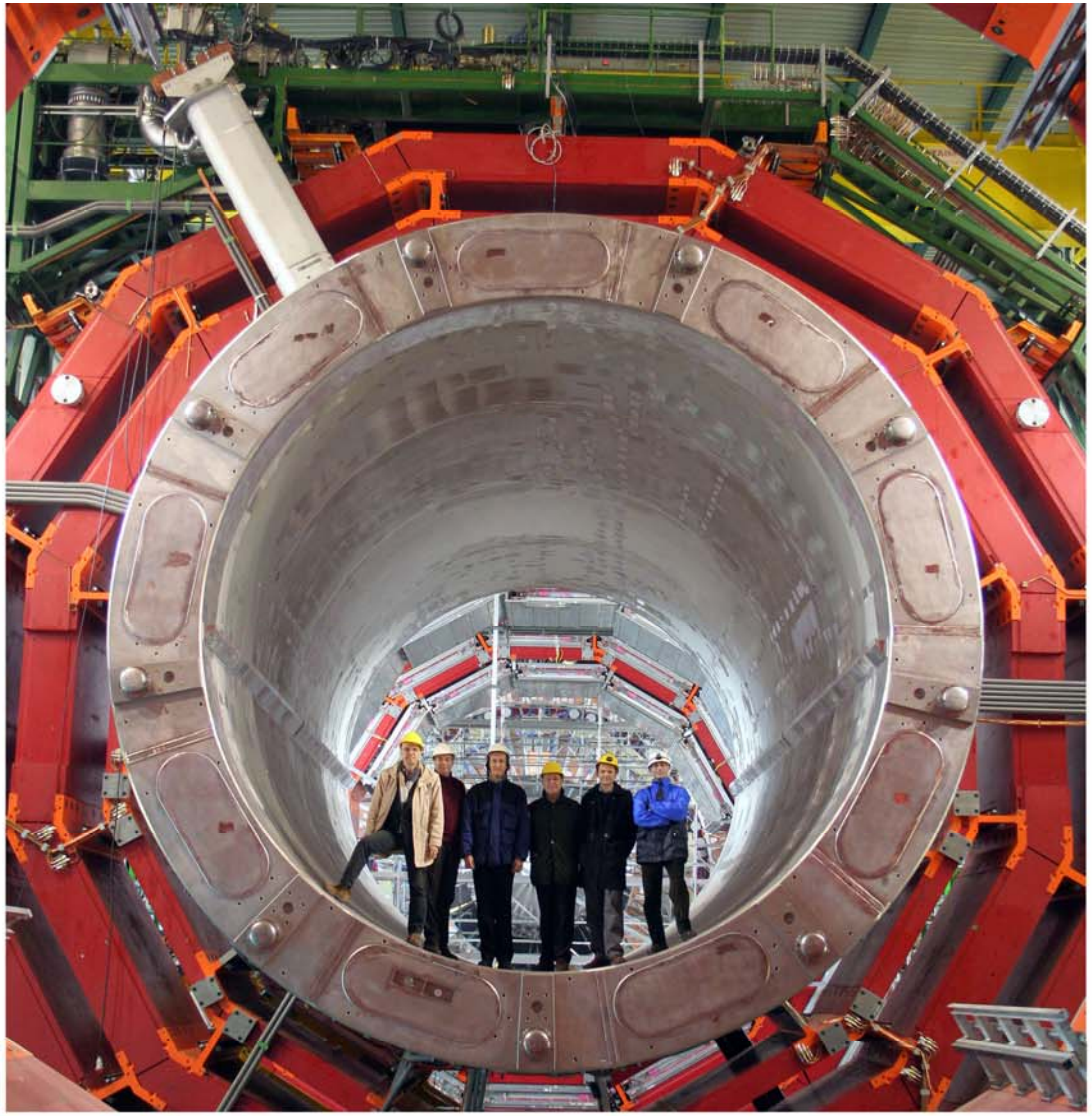




Dump resistor at SX5 are cooled by natural convection to avoid active elements

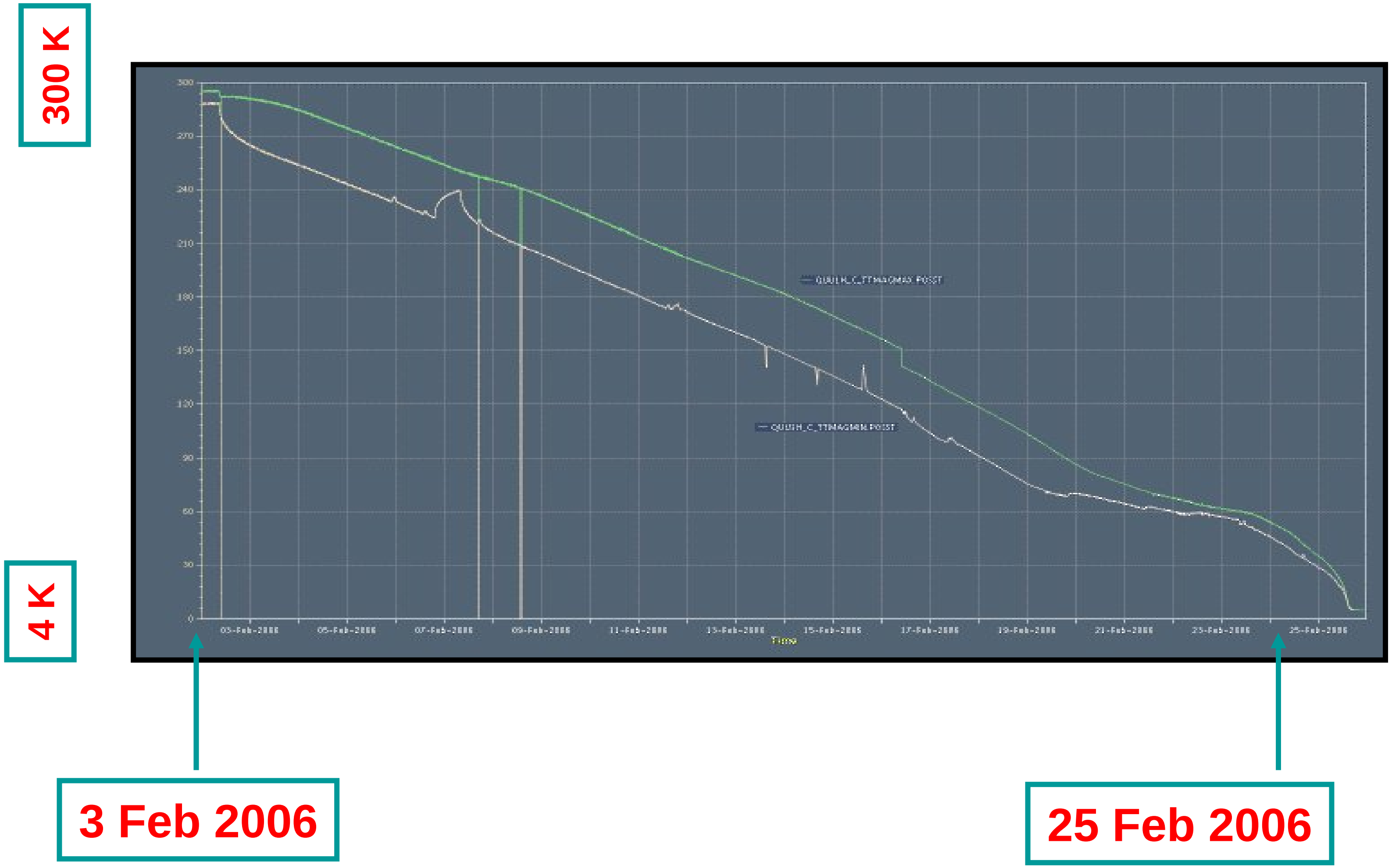


Vacuum was made already in Dec 2005



January 2006: End of the CMS Magnet Manufacturing

Cool down was achieved very smoothly in Feb 2006



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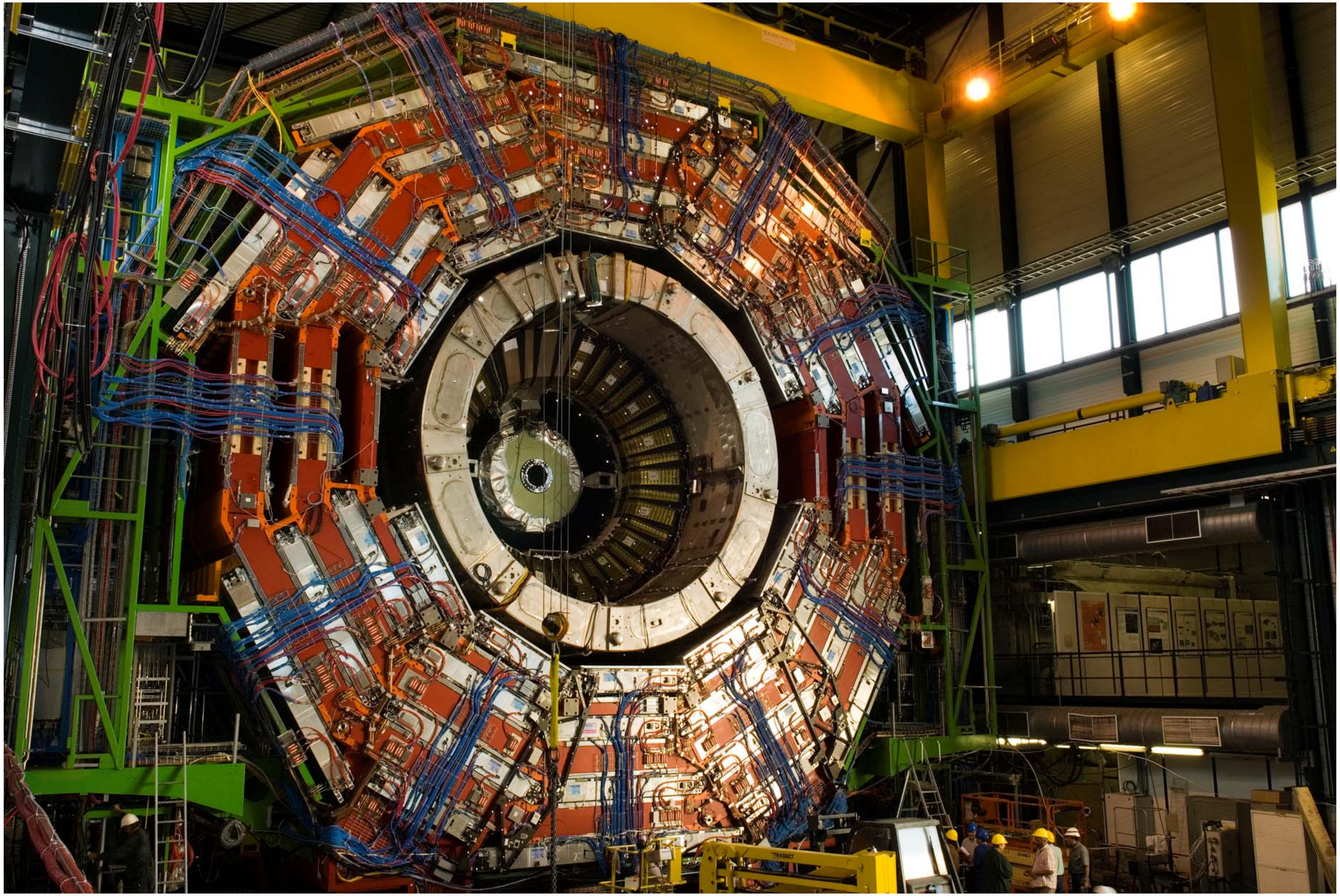
CMS Magnet & Integration Group Leader

June 2006 : the barrel yoke wheel where moved on air and grease pads



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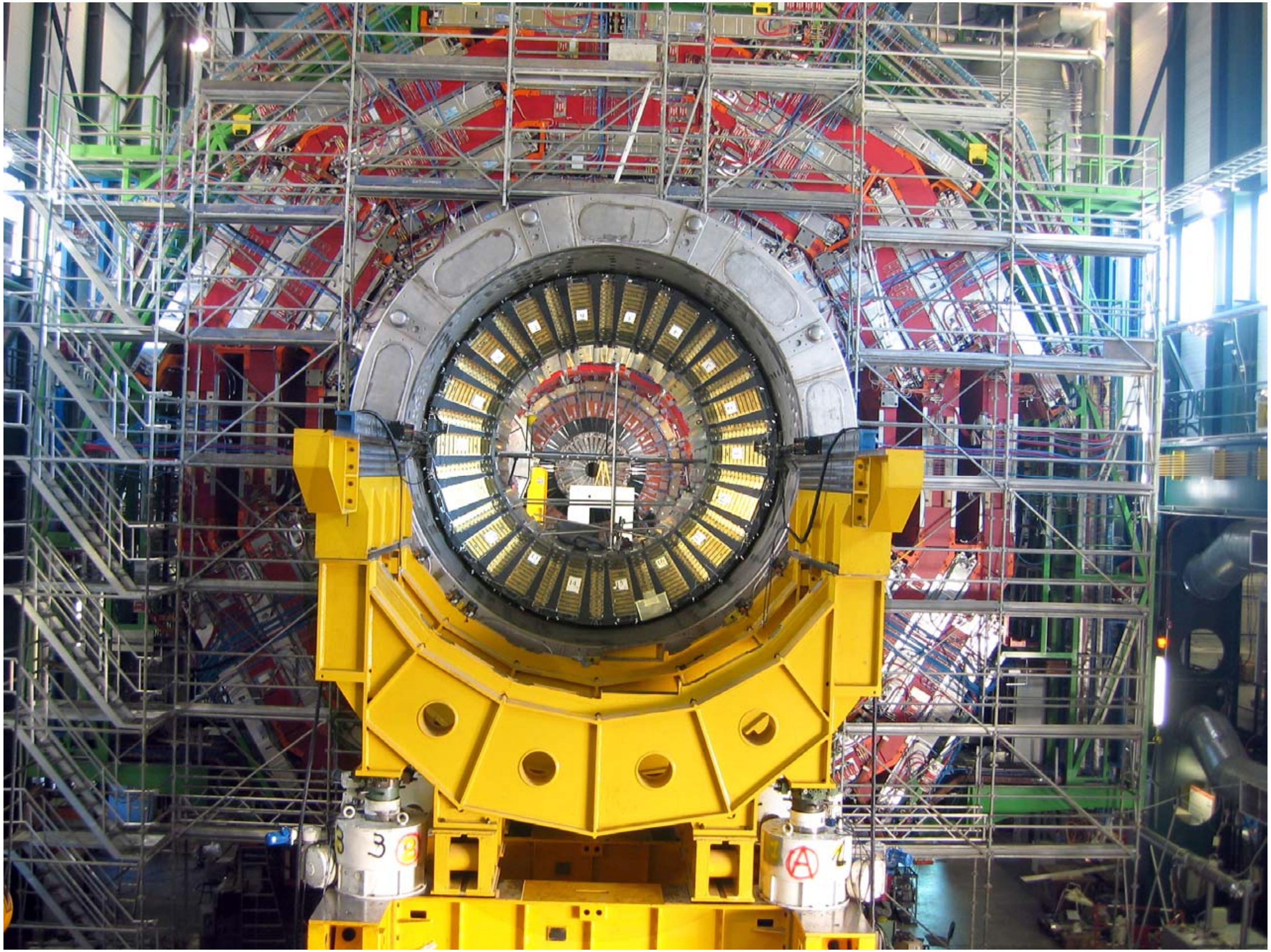
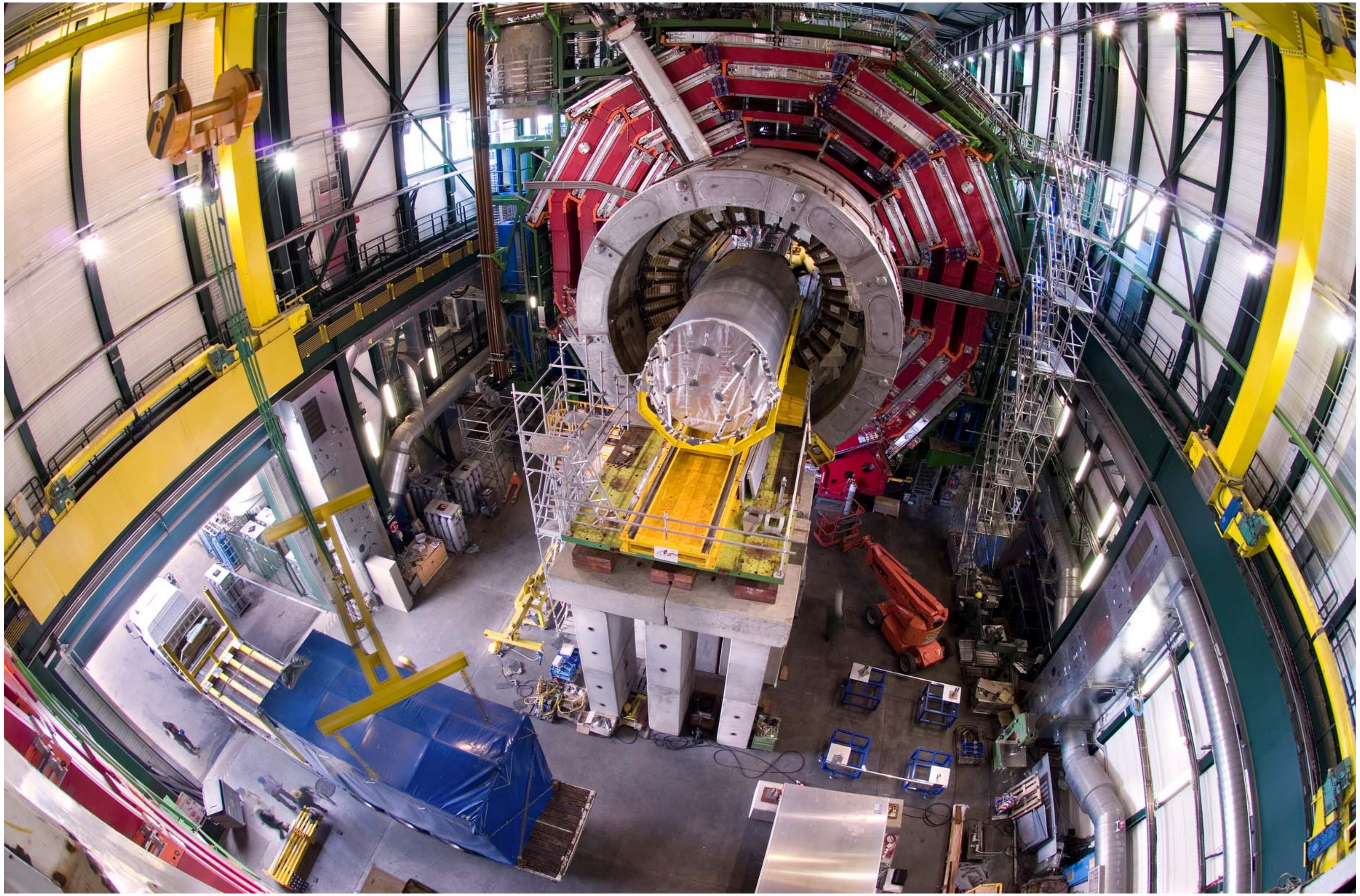
HCAL Barrel inserted



Insertion of the Tracker



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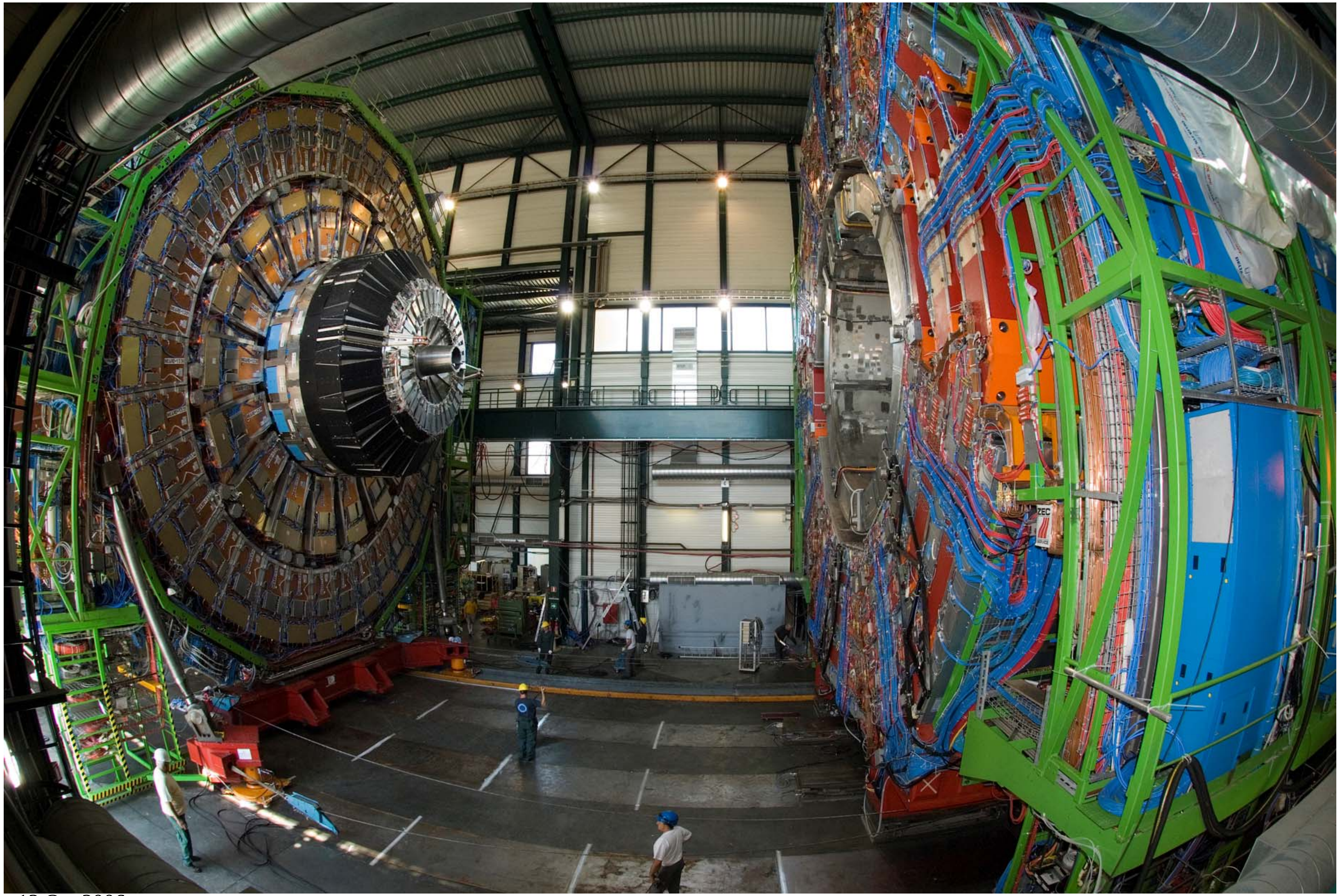
Survey has been constantly assured to reach an alignment of 1 mm wrt the ideal axis



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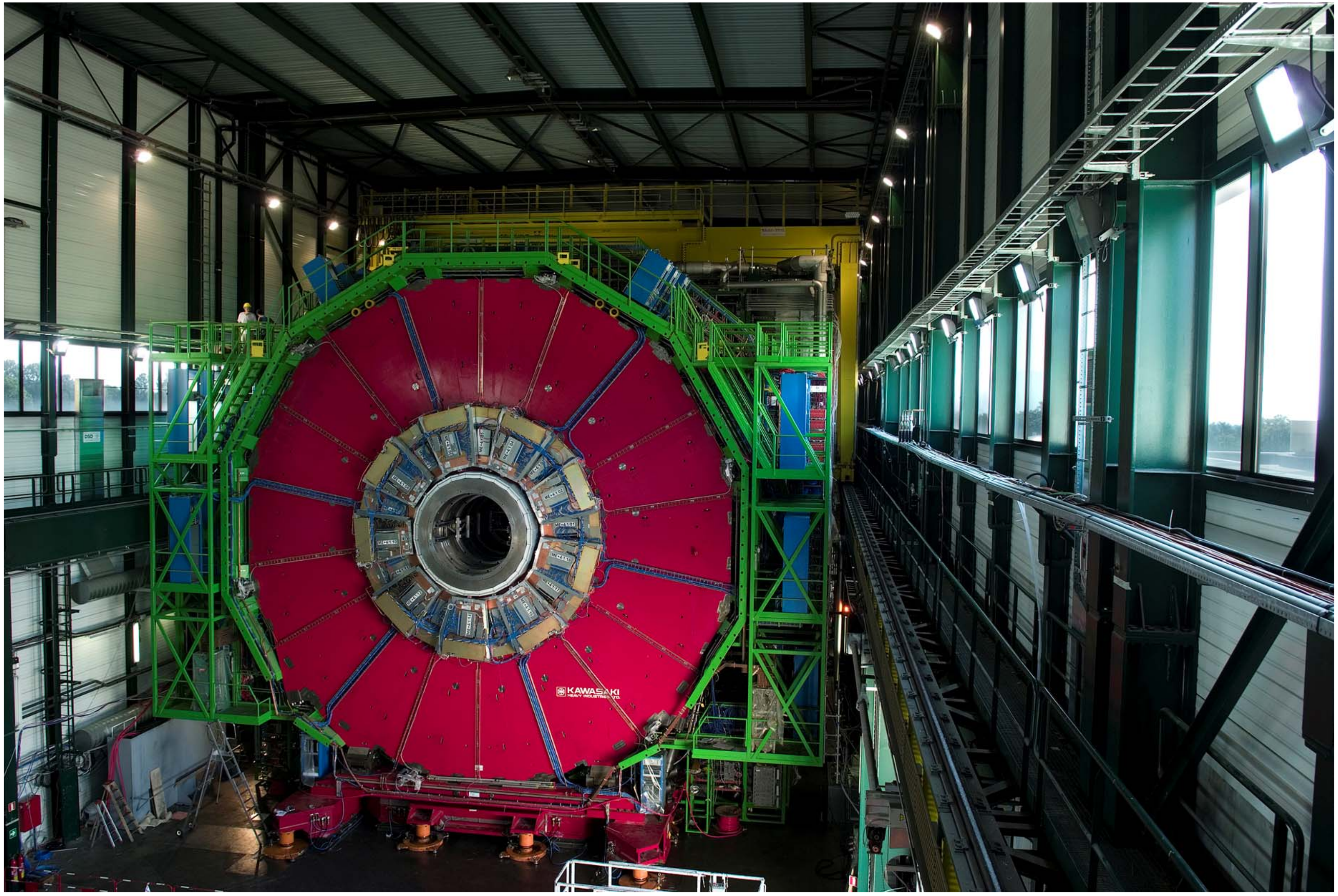
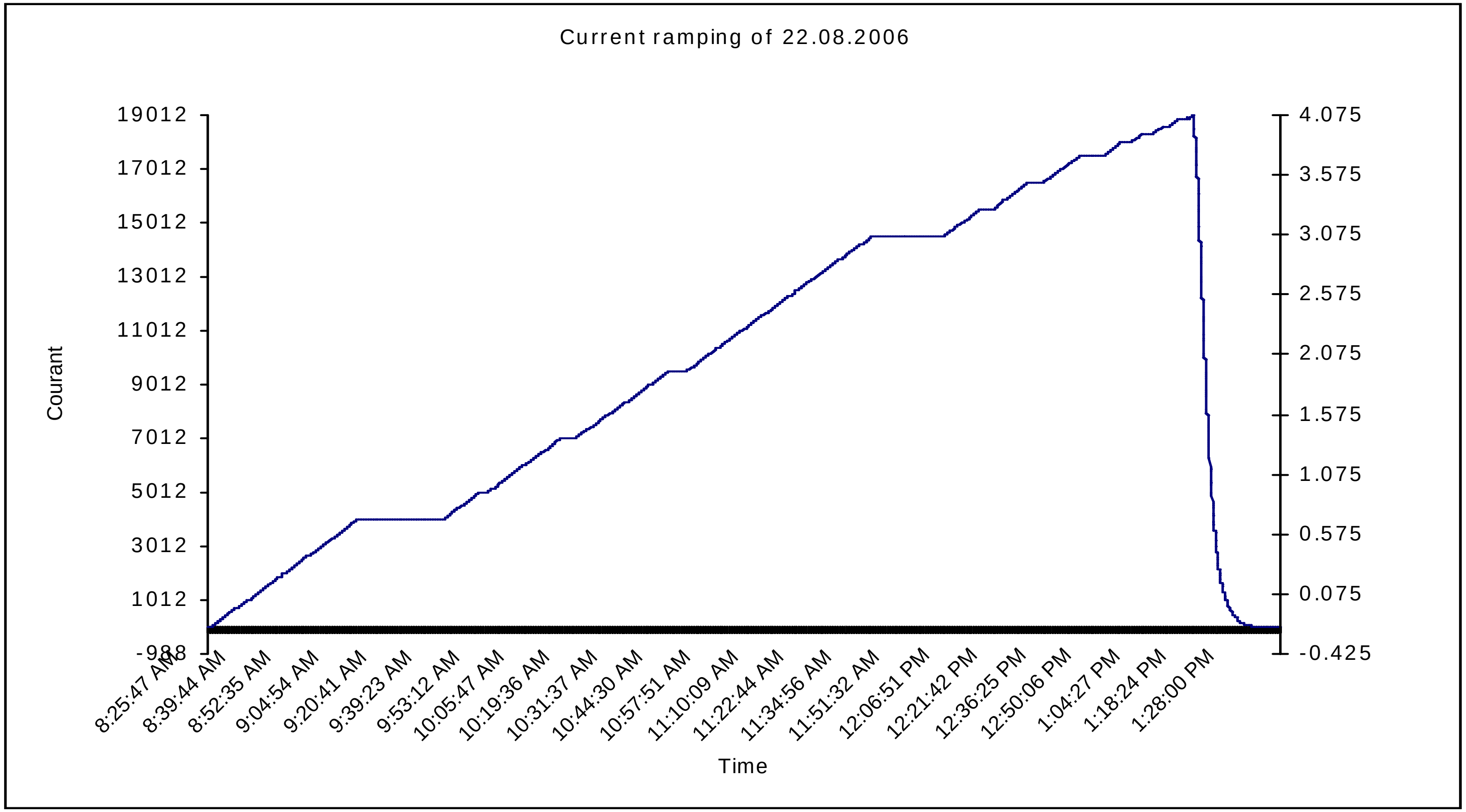
Mid July 2006
CMS Closed: ready to inject high currents



On the 22nd August 2006 the CMS Magnet has successfully reached its target field of 4 T



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CMS Magnet & Integration Group Leader

Some consideartions

After the powering of the CMS Coil we are in a position to evaluate with a certain criticism the years related with its construction and retain or modify the main choices at the profit of future projects

I will try to evidence *in a qualitative way*, the points that, in my view, have been of key importance to the positive completion of the project

Domenico Campi
CMS Magnet & Integration Group Leader

Previous experiences have been of basic importance

CMS is conceived on the base of the ALEPH experience

Improvements should stay within an acceptable margin of risk for such expensive projects

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CMS Magnet & Integration Group Leader

Technical solutions have been validated jointly with industry

R&D made jointly with industry to be sure of the industrial feasibility on large scale (but industry cannot be left alone either for motivation either for costs!). For CMS Magnet:

- *Co-extrusion of the insert*
- *Continuous electron beam welding of the conductor reinforcement*
- *Reinforcement section extrusion*
- *NbTi filament production*
- *Surface preparation of the mandrel for good adhesion*
- *Winding technique,*
- *etc..*

No surprises during tendering!

Wherever possible we have validated solutions with prototypes or mock

- i.e: Thermosyphon piping layout, outlet of the cryo-chimeny, He circulation through natural convection, keystoning of the conductor during bending, adhesion of the epoxy resin to mandrel, full scale mechanical test of the supporting tie rods, pre-production lengths of strands, conductor insert, short lenghts of finished conductor, electrical junctions, bending of the insert prior ti insertion in the vactank etc…

- Short, but complete, module of 30 cm length with dummy conductor

Not all could be prototyped!

- It has been impossible to power at 4.2 K any single module (too high cost of a dedicated cryostat, and in addition the test would have not have produced the same forces due to the absence of the full 4T field).
- It has been impossible also to test on large scale the continuous EBW. We relied on static tests and on existing continuous plant experience .

Redundancy

- The doubling of the He thermosyphon has increased the complication of the construction
- Advantages must be weighted wrt to the additional risks coming from these difficulties
- No save on additional checks : i.e. daily qualification of the welders on crucial circuits and double leak tests (local and integral)
- Redundant monitoring of electrical insulation
- We have minimized active elements in the protection chains (i.e.: quench back and naturally cooled dump resistor, etc…)

Transportation

- From the very beginning CMS Coil (and Magnet in General) has chosen geometries and dimensions to make also largest element to be transportable.
- In some cases, like the winding, the construction on site has also be taken into account (for example for the “monolithic” winding, which in principle facilitates the construction, but the logistic was heavy and thus risky).
- The sectioning of the Coil has reduced the unit lengths of the conductor, with the related reduction of technical risks of degradation during welding and transportation of spool

Pre-assembly

- To avoid bad surprises on site, wherever possible we have pre-assembled large components at the constructor premises

Each wheel of the barrel yoke, endcap yoke disks, swiveling platform, each coil modules with the next one.

When this has not been possible we have experienced additional time loss like in the assembly of the thermal screen

Cost estimate

CMS Magnet cost had been scaled mainly from L3 for large mechanics and from Aleph for Coil (applying specific and adequate scale factors for each item)

At the end the project has finished with a cost of 124 Mchf wrt an initial estimate of 118 Mchf, made ten years before

52 MCHF for the Yoke and 72MCHF for the Coil

(details can be given with a certain confidentiality)

The Magnet is a Common Project of CMS

Financial Participation of Institutes to the project by:

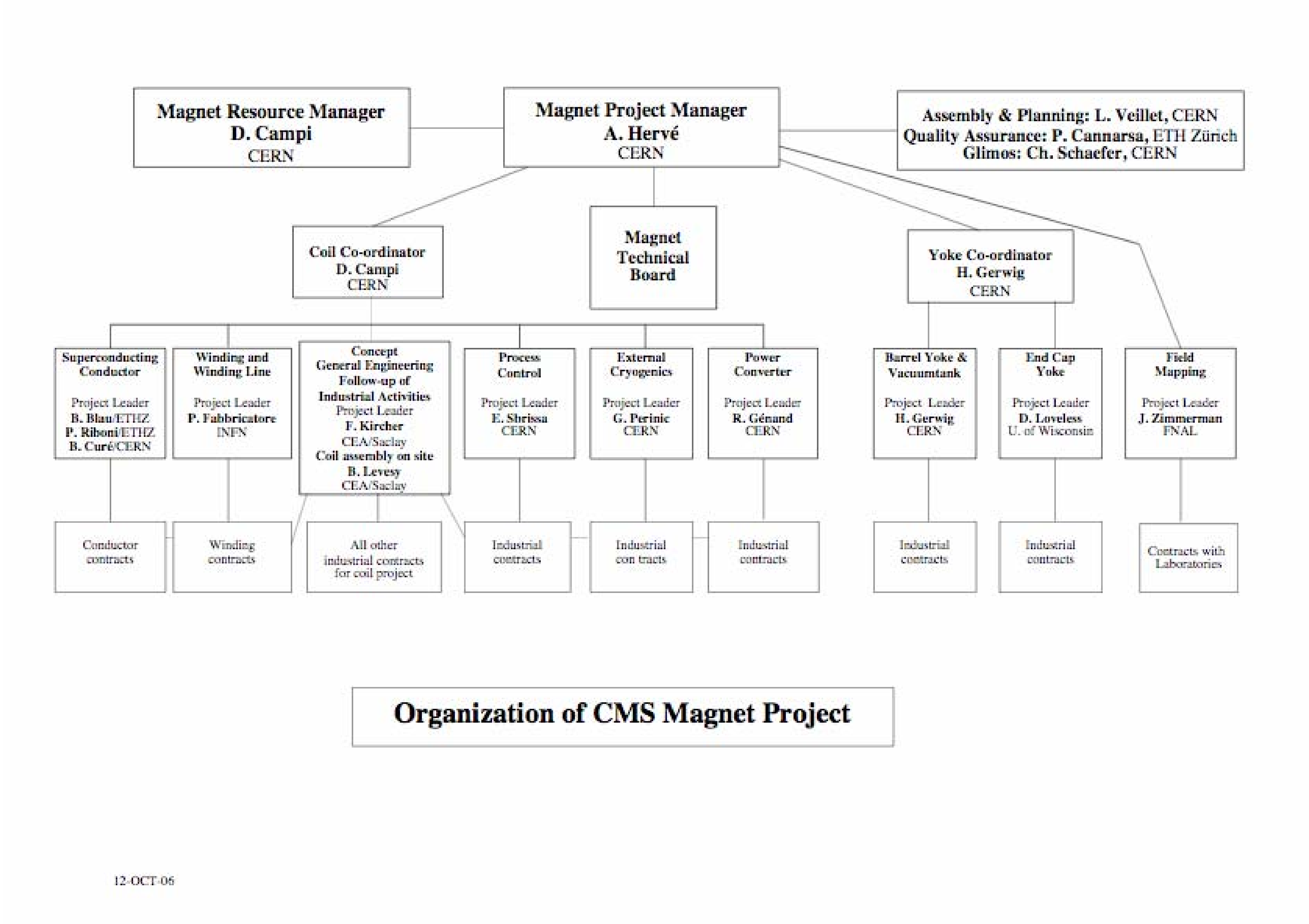
- *Injection of money in the common fund*
- *Direct payment of contract (with or without technical responsibility)*
- *In kind contribution (provide one part at an agreed accounted cost)*
- *A mix of the previous alternatives*

Organisation

- The project has been organized with a central CMS coordinating team to harmonize technical solutions, coordinate planning, and insure the “interfaces”, (which are at the end the bottleneck of the critical path)
- Technical responsibilities have then be shared according to specific skills and (when possible) proportionally to financial participation
- Services and ancillaries have been managed by the host laboratory to harmonize choices related with operation and thus reduce spare part cost, also in view of having a common running team (shared with other experiments)
- The Magnet Technical Board (MTB) informed periodically all the partners of the advancements of the project and was the seat of common technical debate.

Domenico Campi
CMS Magnet & Integration Group Leader

Organisation



CMS Magnet : Technical Participants

- CEA / Saclay : Concept, and General Engineering

- ETH / Zürich : Barrel Yoke and Compound Conductor

- INFN / Genova : Winding and Coil Assembly

- Fermilab : Strand procurement and Field Mapping

- ITEP : Barrel Yoke and Coil Suspension

- University of Wisconsin : End Cap Yoke

- CERN* : Barrel Yoke, External Cryogenics, Power Converter, Controls, Conductor and Project Coordination

*PH/CMI, AT/ECR, AB/PO, PH/DT1, TS/MME, TS/SU

Specific Tooling

A lot of specific and dedicated tooling has been designed for the CMS Magnet

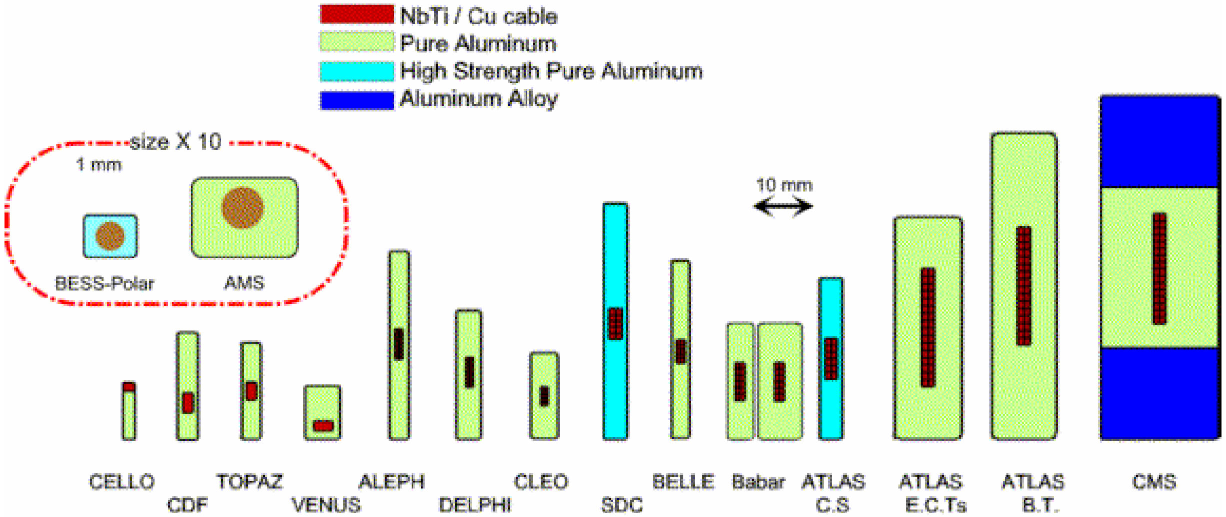
- The “Ferris Wheel” to mount the barrel yoke
- The swiveling platform
- The winding machine
- The EBW plant
- The continuous US monitoring unit for continuous co-extrusion and continuous EBW checks
- The brushing machine to clean the Rutherford cable before co-extrusion
- Etc…..

Domenico Campi
CMS Magnet & Integration Group Leader

PART OF THIS TOOLING IS STILL AVAILABLE

Developments

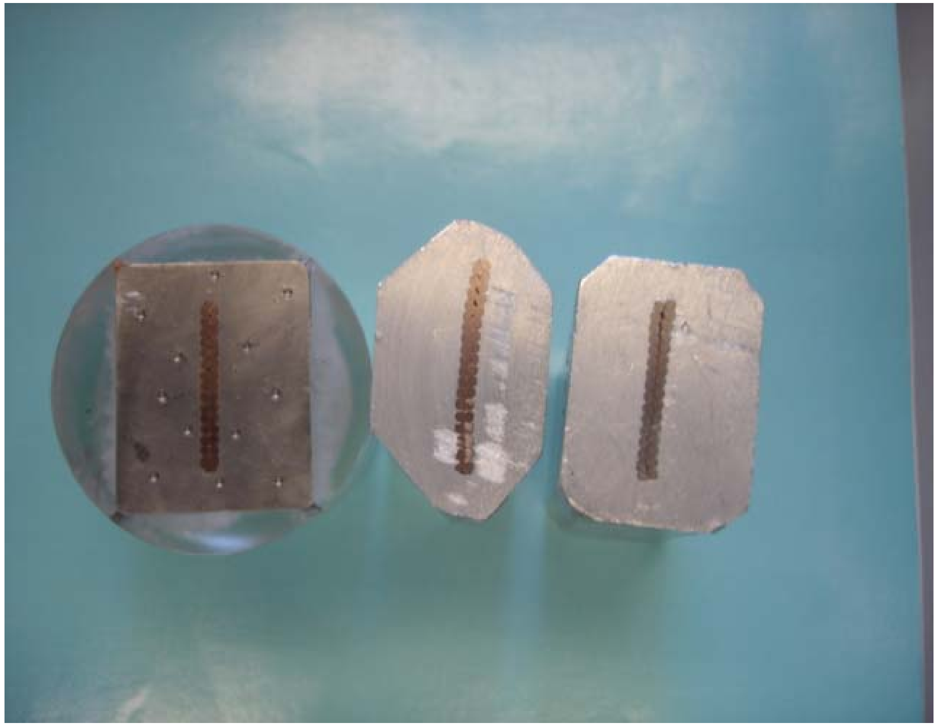
- Also with the aim of keeping alive part of the existing tooling we have started investigation on a new and more performing conductor
- We have joined the developments made for the ATLAS Central Solenoid (A.Yamamoto / KEK) and the CMS concept to propose a mechanically improved conductor



Improvements wrt to CMS conductor

- The CMS Configuration has been used replacing the stabiliser 5N8 Pure Al with 0.1 % Ni al doped Alloy used by Yamamoto in Atlas
- In addition the Al 6082 Al Alloy of CMS has been replaced by Al EN AW-7020 (Al-Zn4.5Mg1 alloy), extrudable and weldable
- The full mechanical characteristic of the Al-0.1%Ni doped alloy are got only after a coldworking, with an equivalent section reduction in the order of 20% (the improvement in this alloy is kept also after the curing cycle for polymerization at 145 C).
- <u>One of the main problem to solve is how to coldwork the insert section, keeping the good bonding and avoiding to destroy filaments</u>

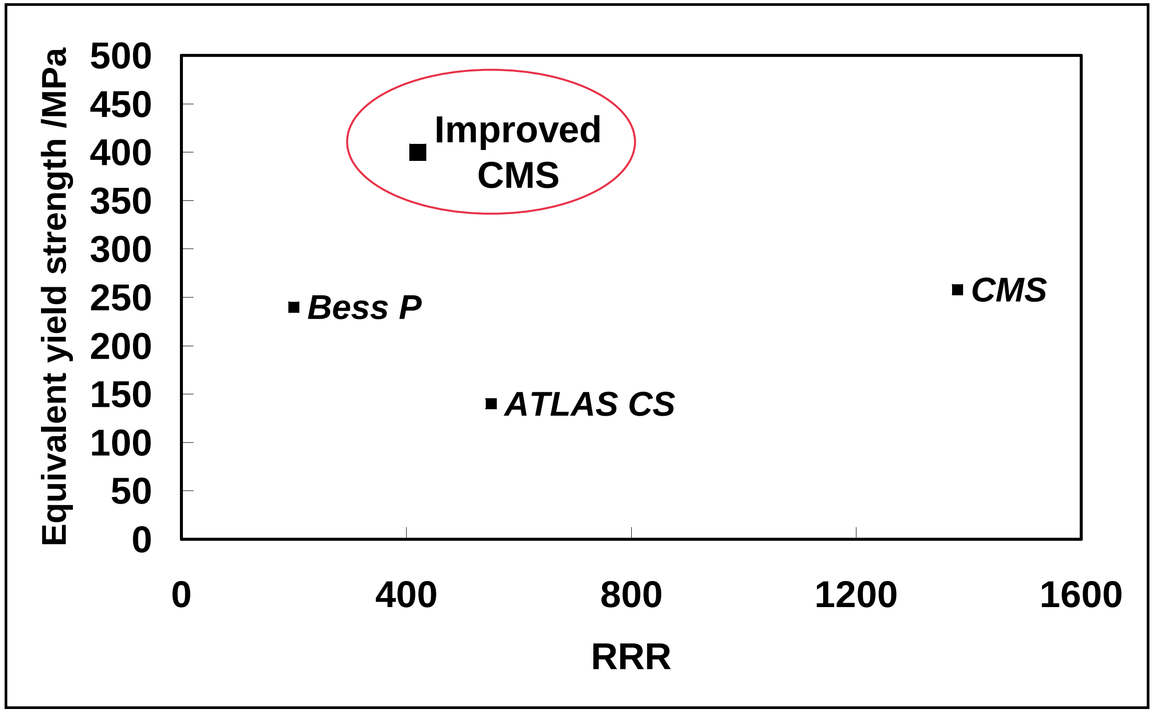
Coldworking of the CMS insert



A method to cold work the insert with a reduction of the section of 21%, has been tested with Outokumpu at Fornaci di Barga, which allows, through different passes, a local deformation of the section without flow of the stabilizer wrt filaments (this method is differnt from turk head principle or skin passes)

Comparison of properties,

basis for a comparison of 4.2 K properties



$$\sigma_c S_c = \sum_i \sigma_i S_i = \sigma_{AlNiinsert} S_{AlNiinsert} + \sigma_{7020} S_{7020}$$

sAlNiinsert = stress in the insert

s7020 = stress in the reinforcement

SAlNiinsert = cross sectional area of the insert

S7020 = cross sectional area of the reinforcement

The contribution of the Rutherford cable is neglected

Conclusions

- The 4T CMS Magnet has been successful from the technical, financial and organizational point of view.
- It has validated the concepts of the reinforced conductor and the 4 layer winding
- Starting from these achievements the way is open to higher fields. The mechanically improved CMS conductor, should allow achievements in the order of 5 to 6 Tesla. The optimization of the magnet design is made according to physics requirements