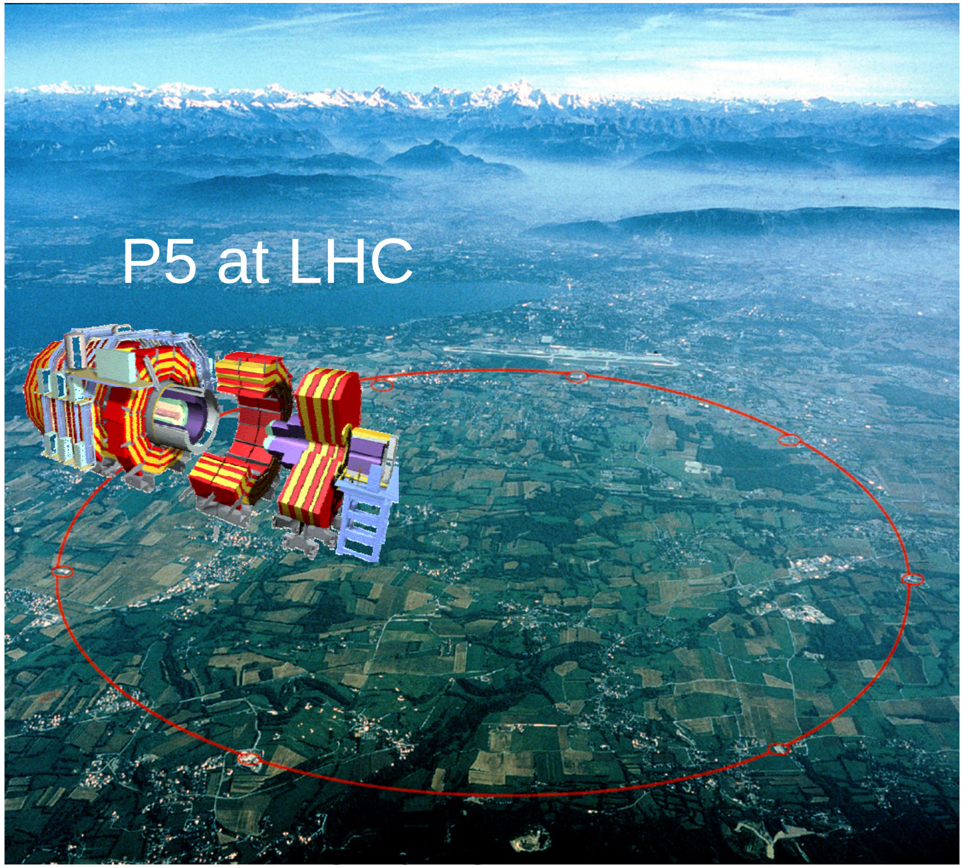
CMS Solenoid Construction and Test



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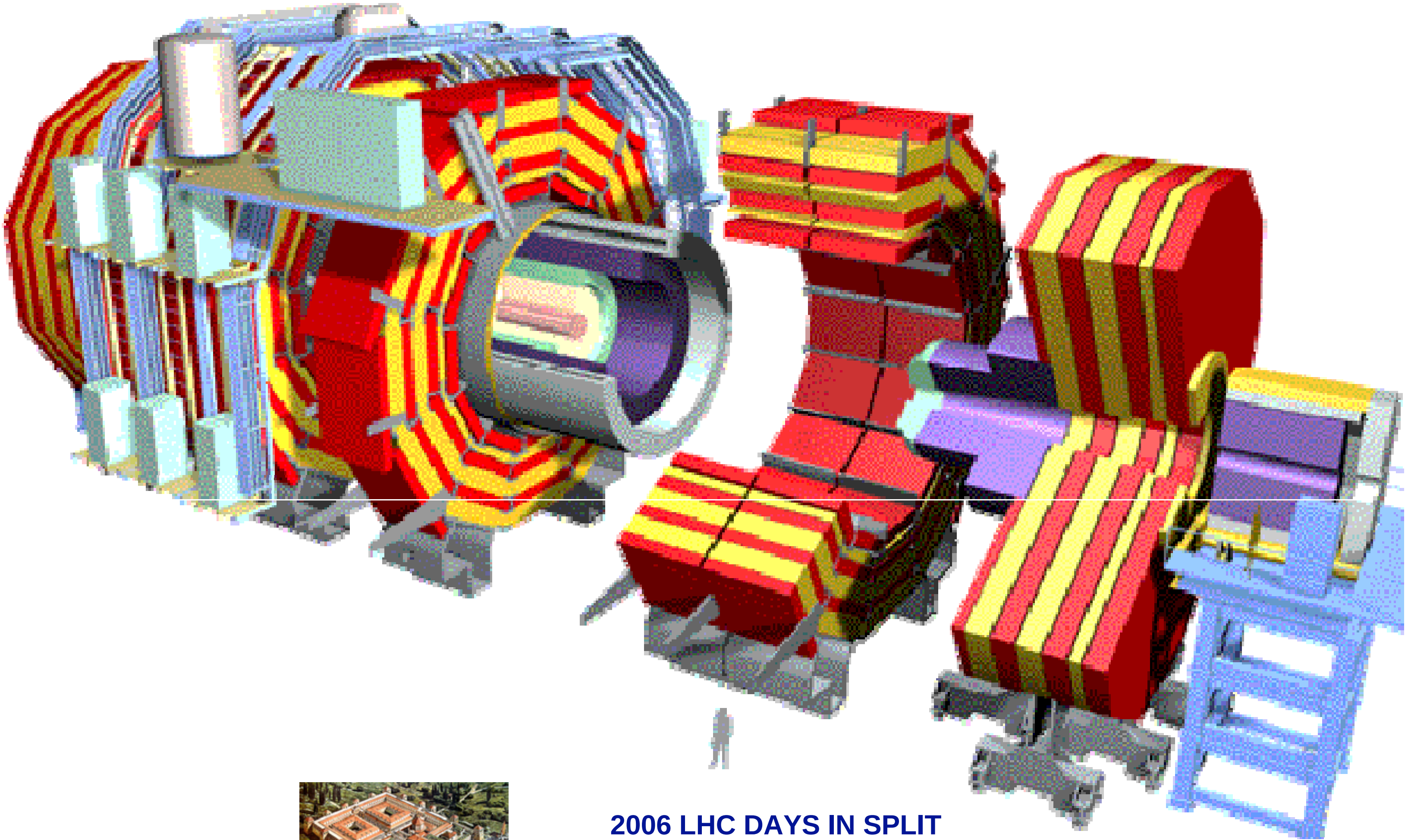
CMS is a general purpose LHC detector
based on a solenoidal magnetic field of 4T
in a 6m diameter free bore,
the detector layout is organized around the Magnet



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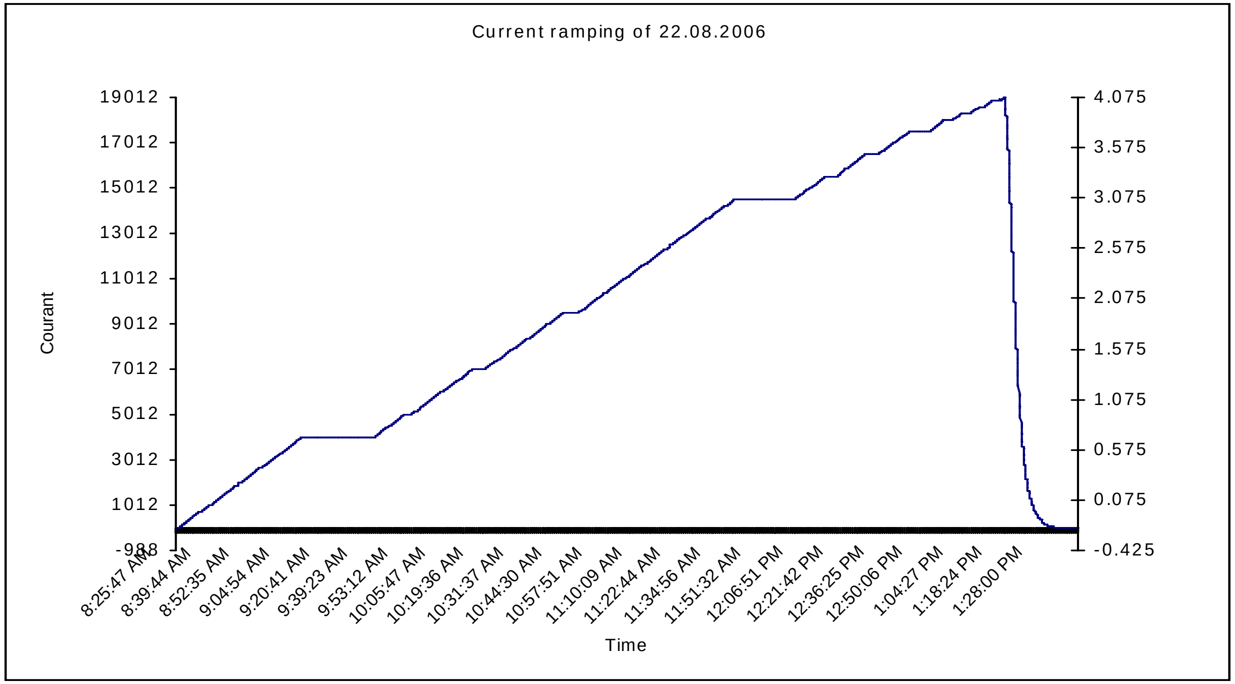
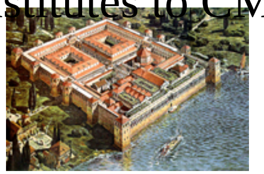
On the 22nd August 2006 the CMS Magnet has successfully reached its target field of 4 T



This result is the coronation of 15 years of efforts provided by all the Participating

Institutes to CMS and people of the CMS Magnet Project



Genesis of CMS Coil

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

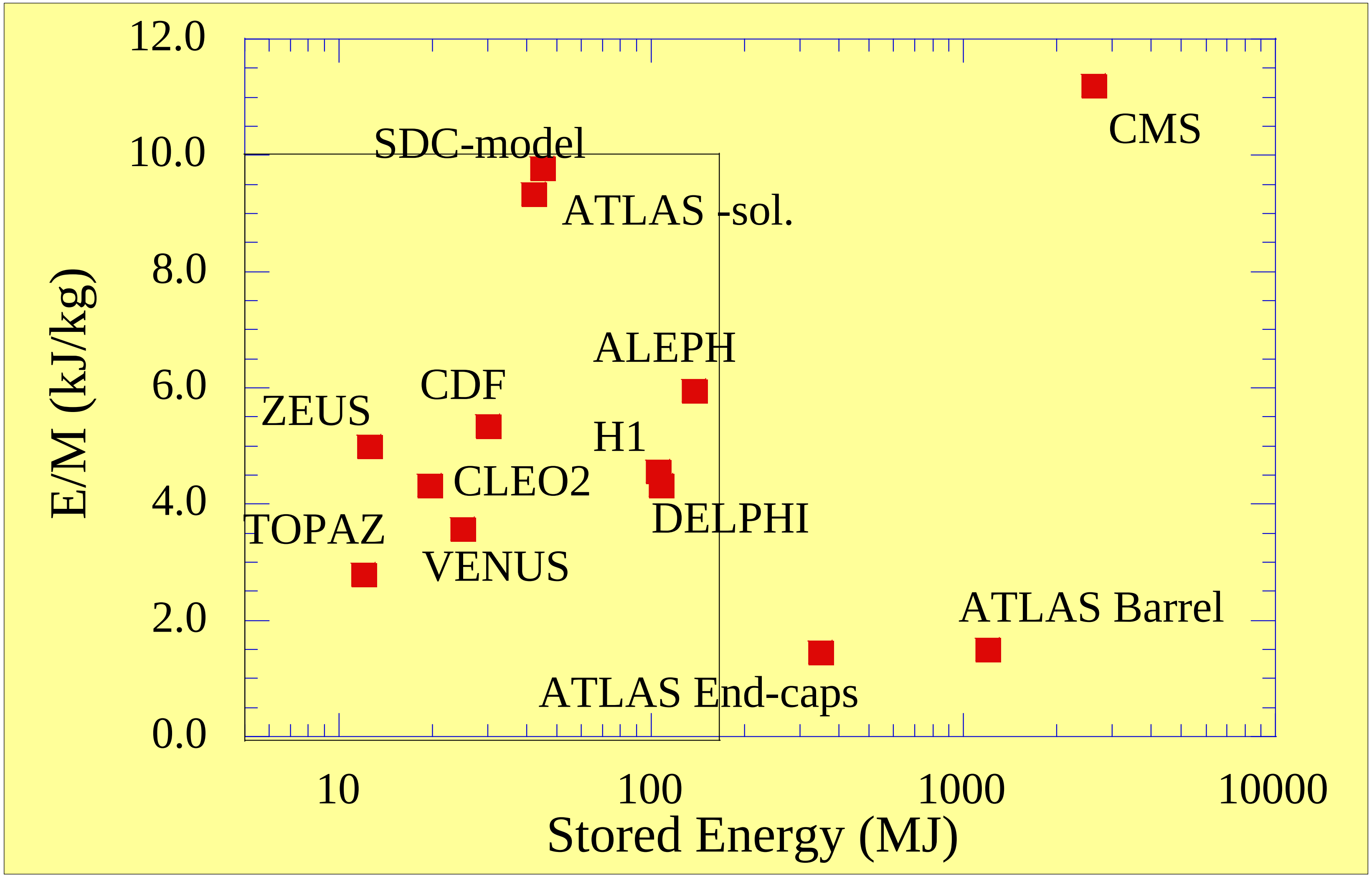
were approached for their great experience in the conception of big magnets for High Energy Physics experiments

CMS wrt ALEPH

Aleph, at LEP, has always been considered as a mock up for 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

Absolute and Specific stored Energy of Main large magnets for HEP Experiments



Key features of the CMS Coil

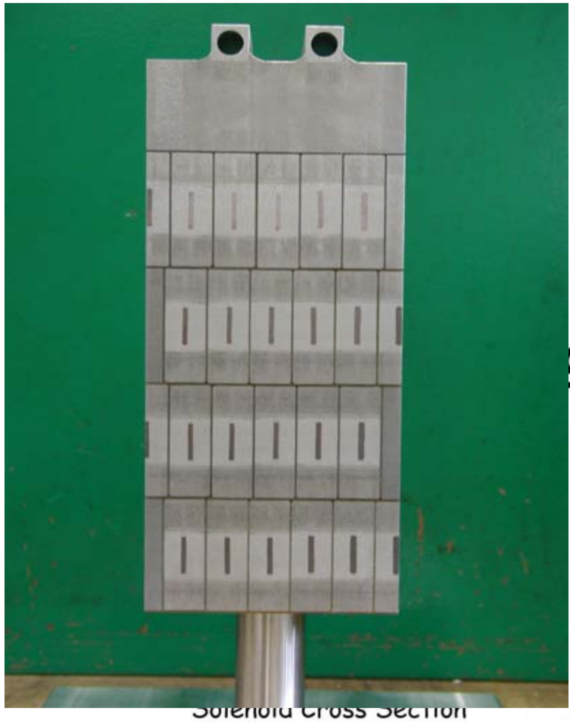
From Aleph

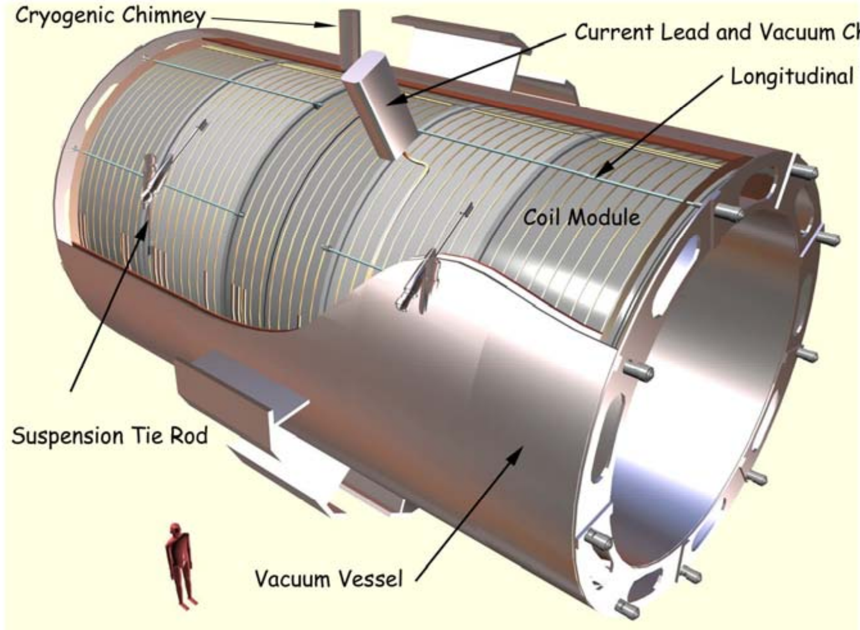
- Passive protection by Quench-Back effect
- Al stabilized NbTi conductor (insert of CMS)
- Indirectly cooled at 4.5 K by thermo siphon circuits
- Inner winding vacuum impregnated with epoxy resin

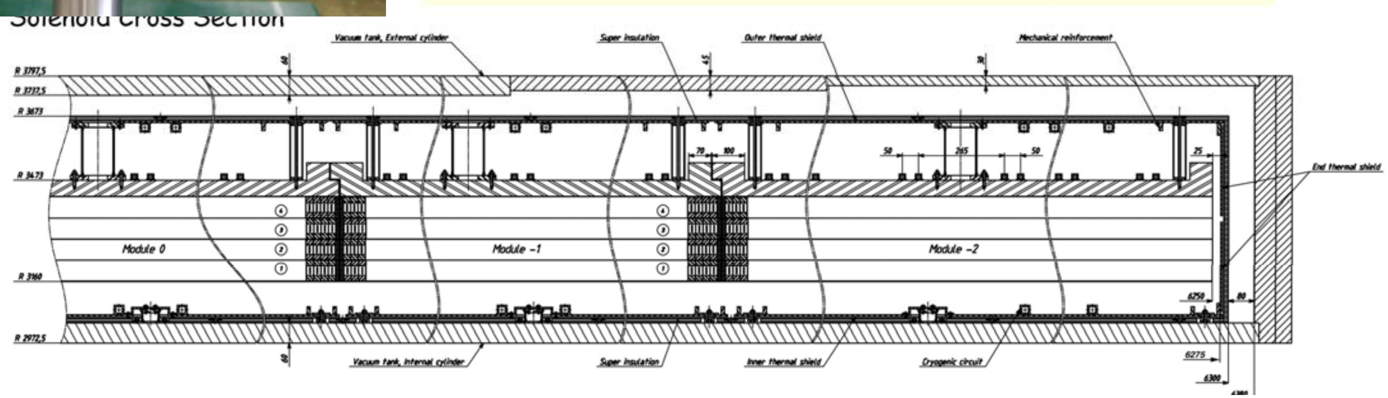
New for CMS

- Mechanically reinforced conductor (to contain magnetic forces)
- 4 Layers (because of needed Ampere-turns)
- 5 modules (to limit unit length of conductor)

The Preliminary design Design was achieved in 1996 by CEA



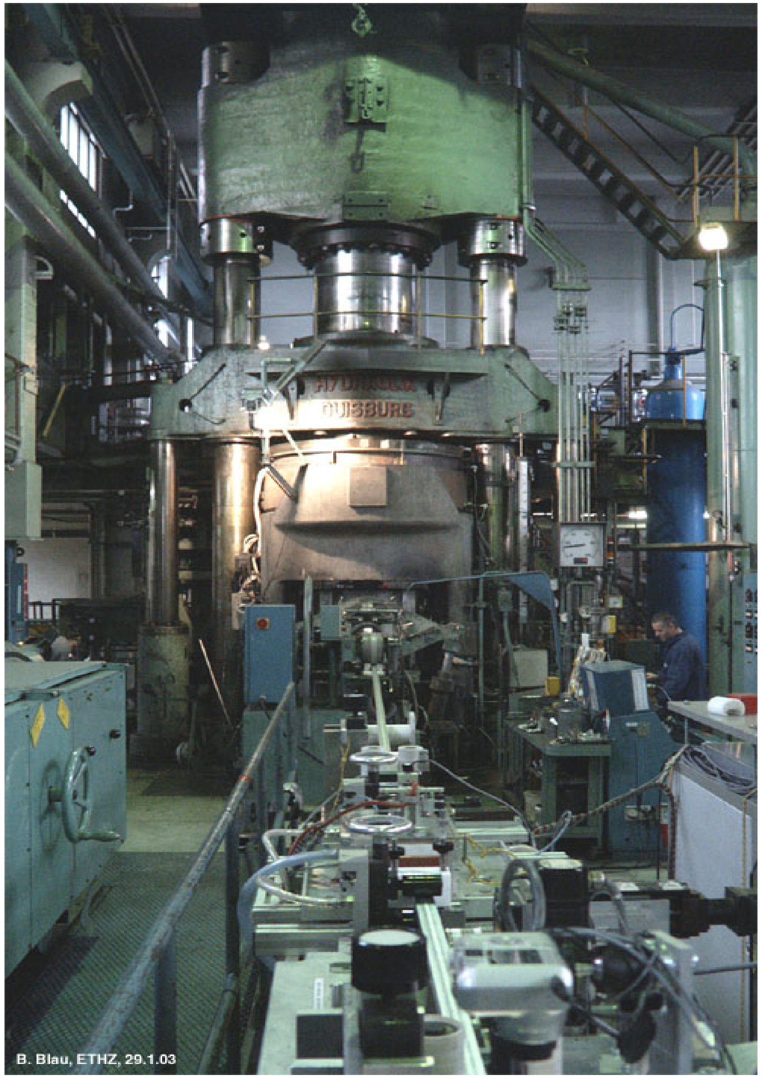




CMS Coil Parameters

Magnetic field at center	4 T
Nominal current	19120 A
Stored Energy	2650 MJ
Peak field at conductor	4.6T
Coil Length	12.5 m
Coil made of 5 modules with length	2.5 m
Inner Diameter	6320 mm
Outer Diameter	6950 mm
Each module is made of 4 layers	
Required conductor length	4 x 2400 m
Module Weigth = 4 x 8300 kg (Conductor)	
+ 8000 kg (Mandrel)	42 t
Total weigth of the coil	220 t

1993-1996 Early developments for 55km of CMS insert



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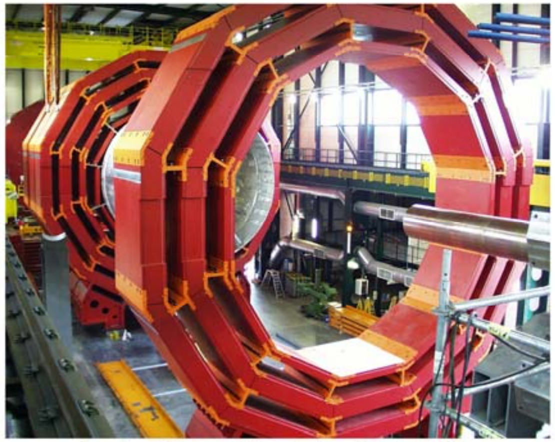
Construction of the Yoke 1998 - 2002

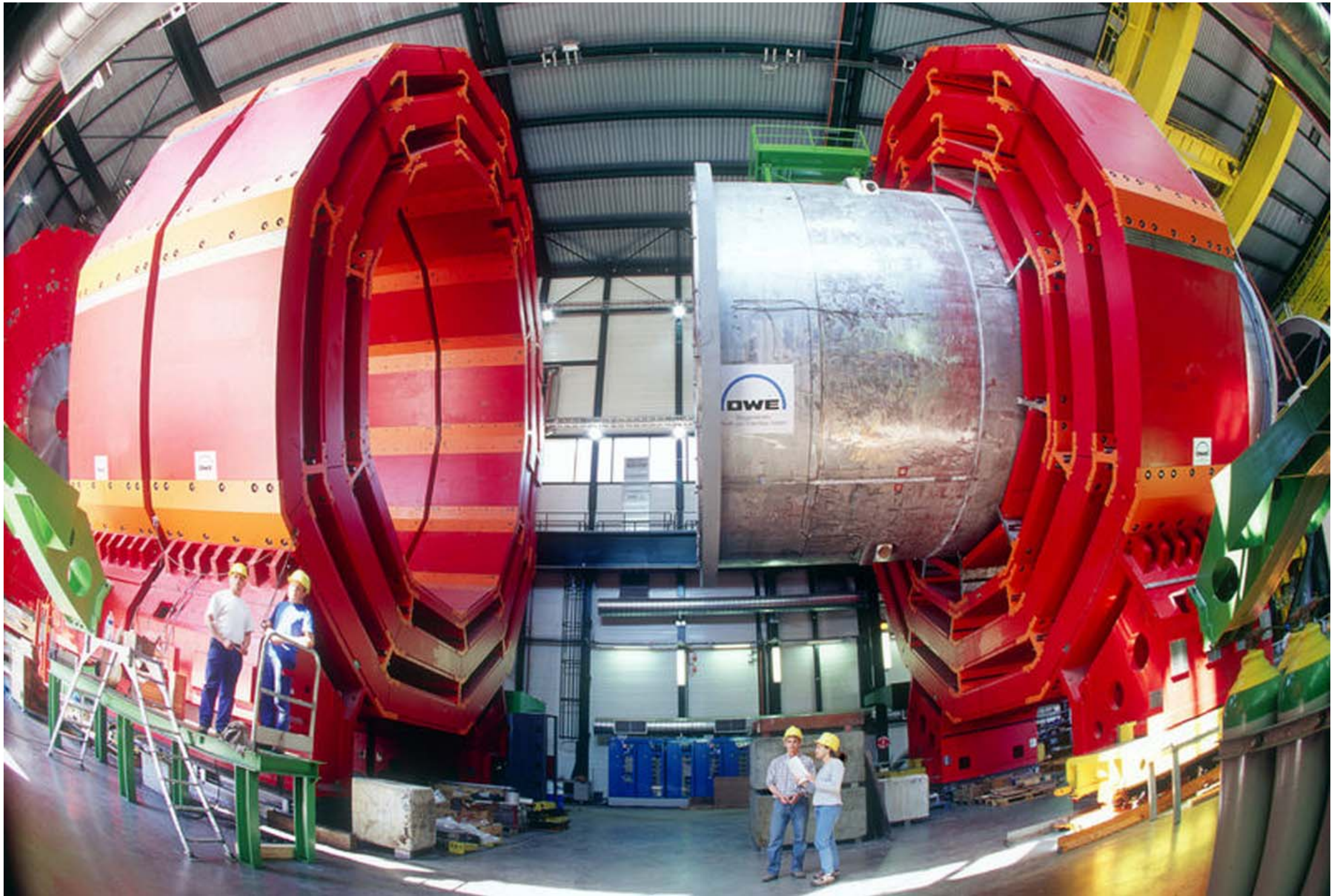
Pre-assembly at Deggendorf (1999)

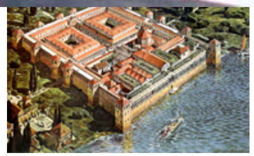


Extraction of YB+2 from the Ferris wheel assembly tooling (2001)

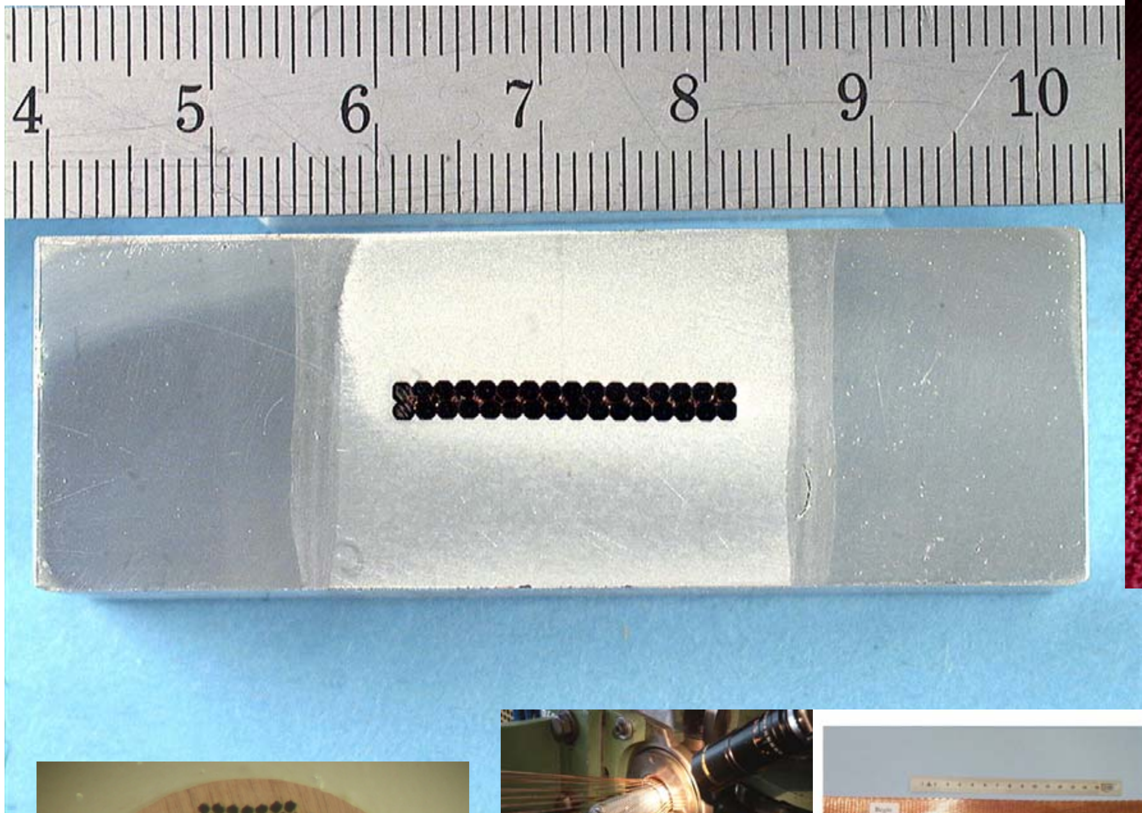
Final assembly at CERN

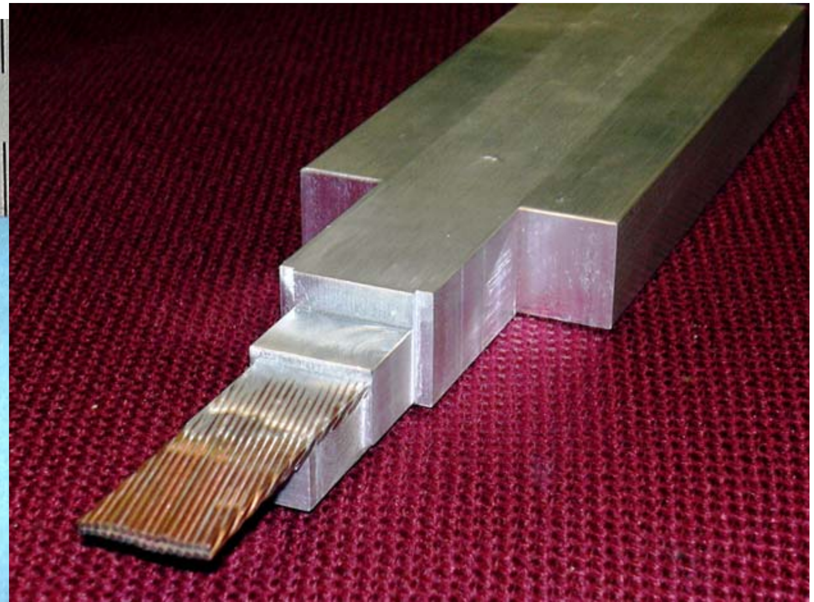
The Yoke has been completed in 2003 to be ready to accept the cold mass and the muon chambers

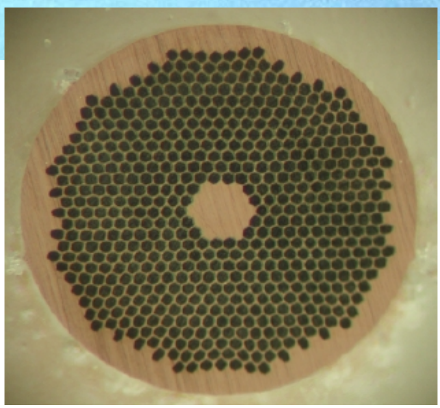




The CMS Conductor feasibility was proven in 1999 and 2 years were needed for the fabrication of its main components







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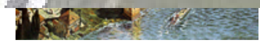
The Fabrication of the CMS conductor took place between 2001 and 2003



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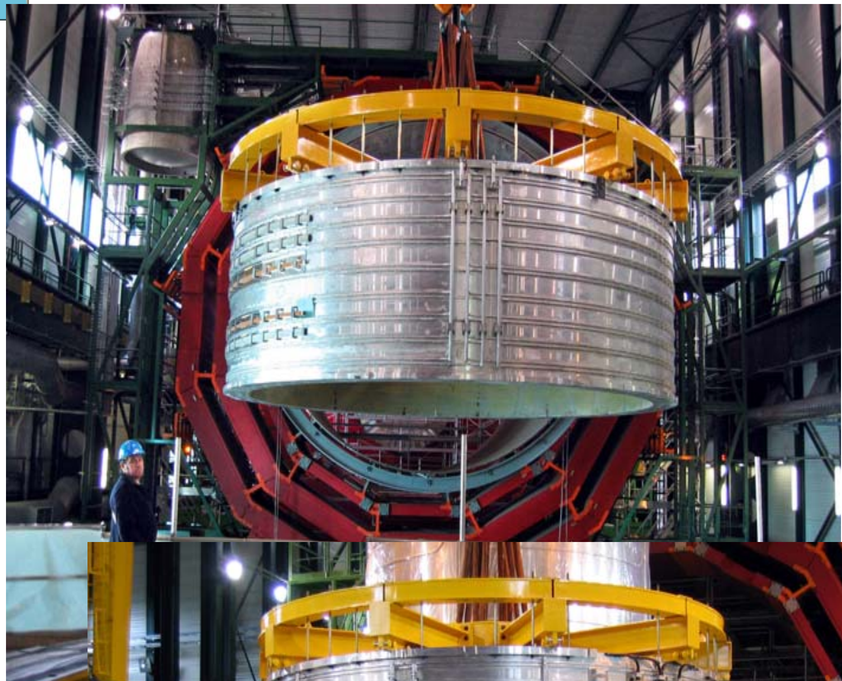
The winding has been done by ANSALDO Superconduttori under the supervision of INFN Genova from 2000 until 2005

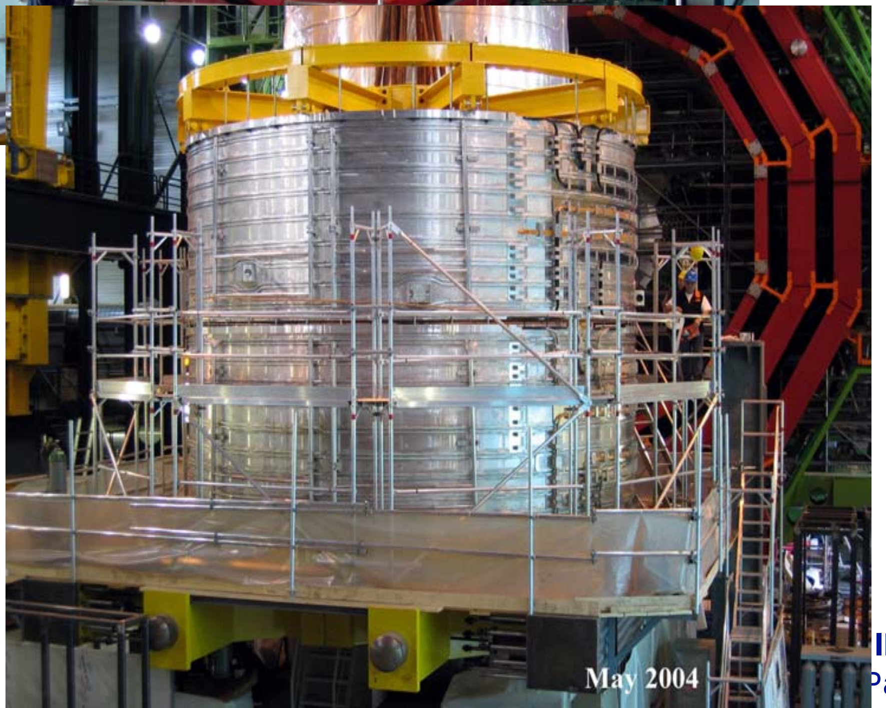
Impregnation of the first module
Feb 2003

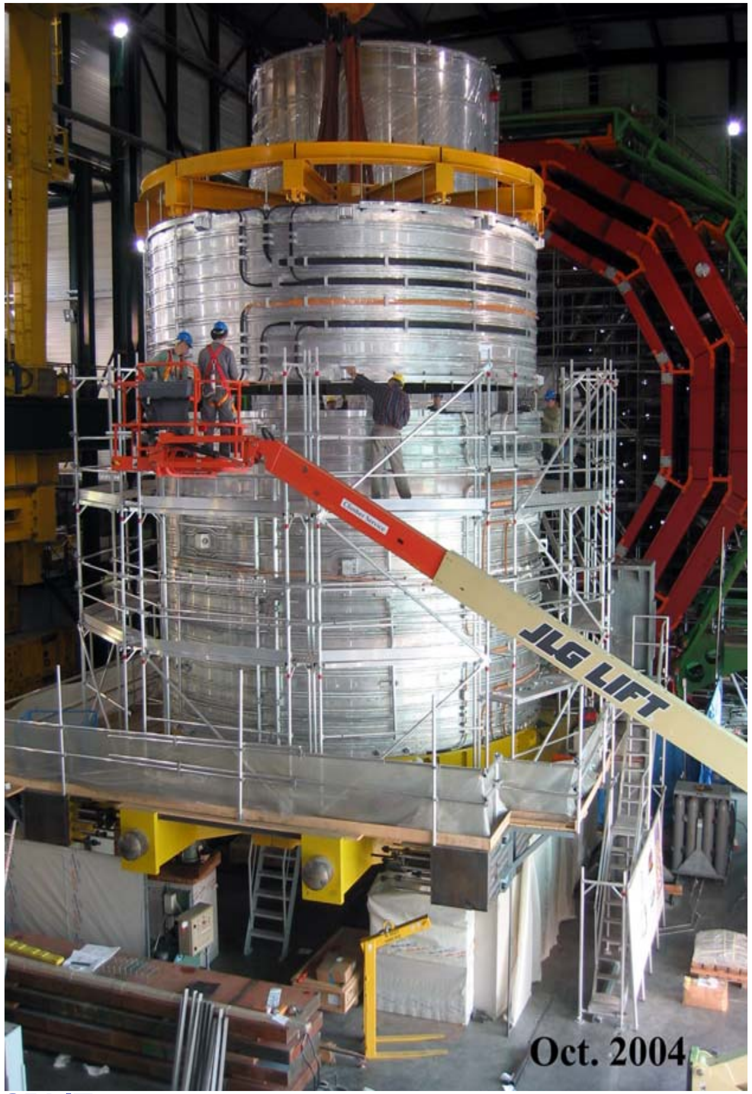
After impregnation each upper surface of modules was machined for good coupling

Coil Module Transportation
Jan2004 / Feb 2005

Pile-up of module at SX5







Electrical connection and instrumentation

Hydraulic connections

The 5 modules piled up (February 2005)

The cryogenic circuit closed to the chimney

Thermal shield installation
Feb-June 2005

Thermal shield assembly by Criotec (I)

Coil Swiveling August 2005

Coil insertion

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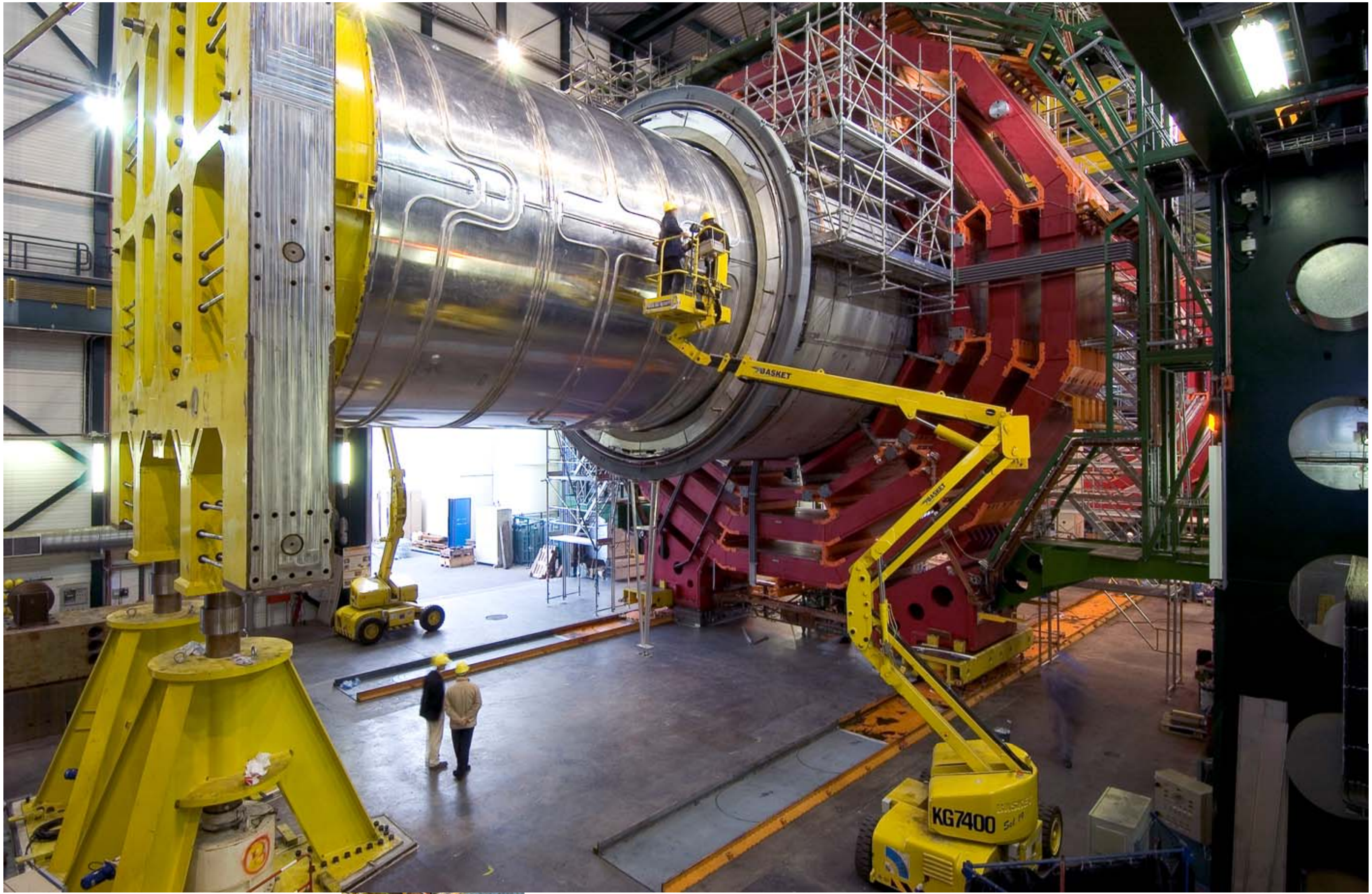
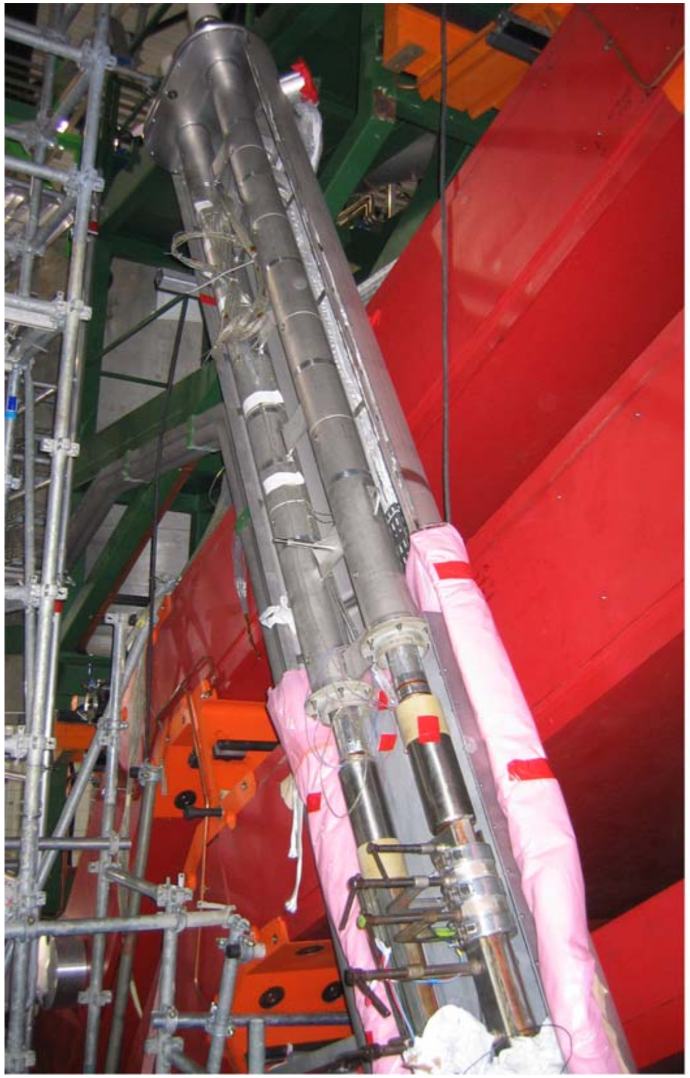
The Inner thermal shield being inserted in its vactank
Sept 2005

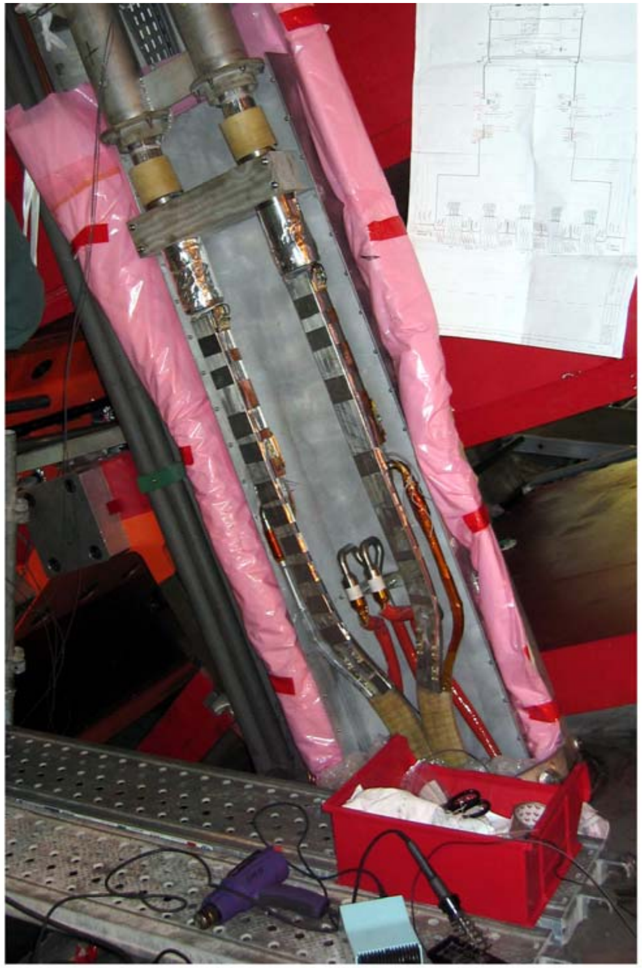


Connection to the cryogenic chimeny

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

Installation and connection of the current leads





The current lead chimney assembly

Cryogenics

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

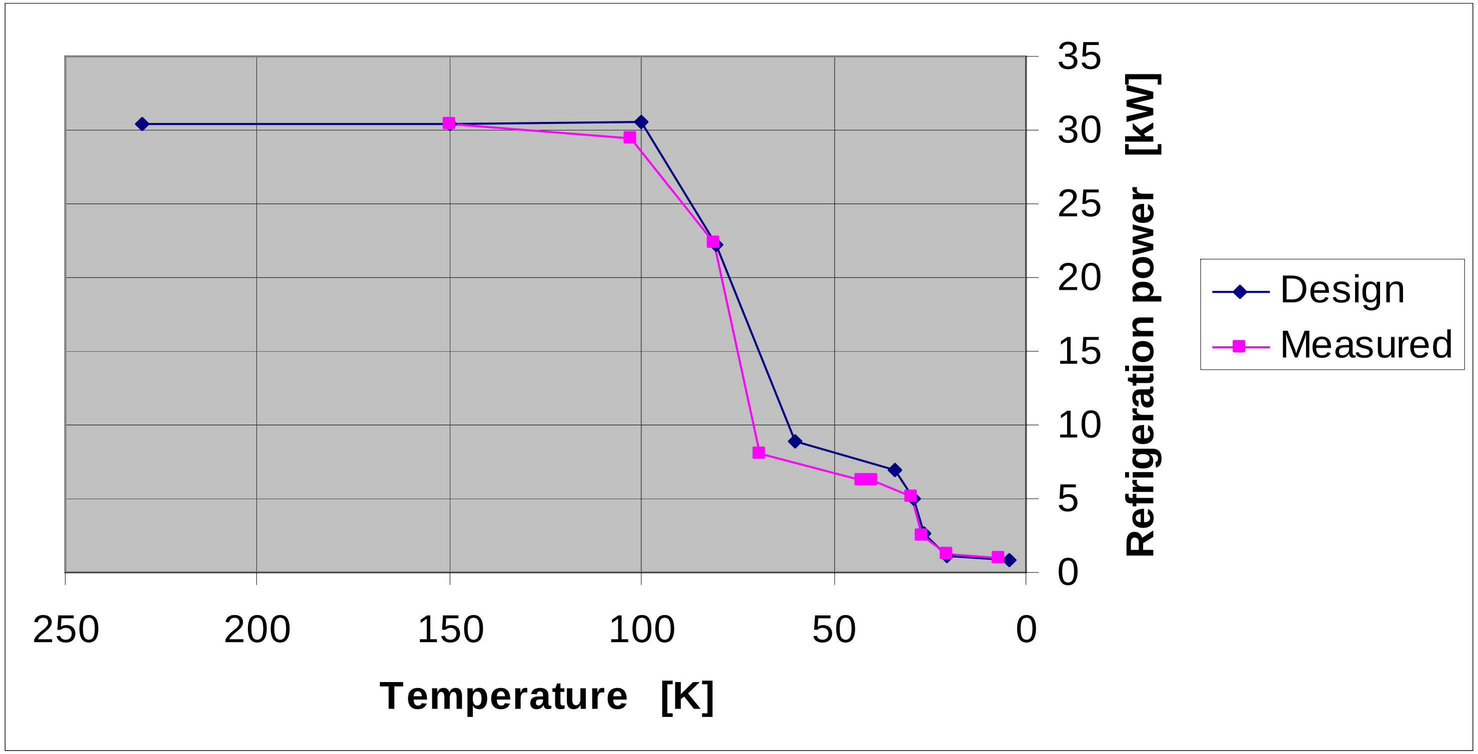
The compressor station, installed in 2001 has been commissioned mid 2002

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)

Nominal performance of the cryo plant were reached in March 2005 with the help of an addititional thermal load to simulate the coil

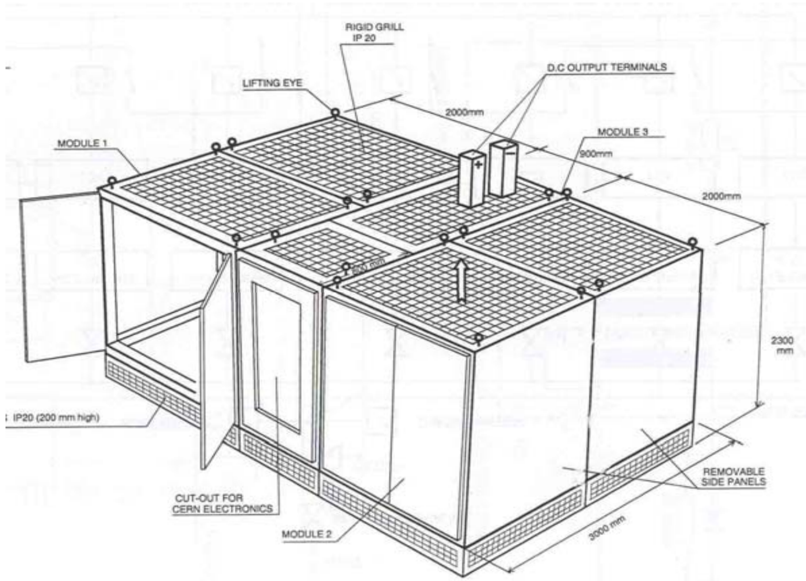
- Refrigeration power as a function of T

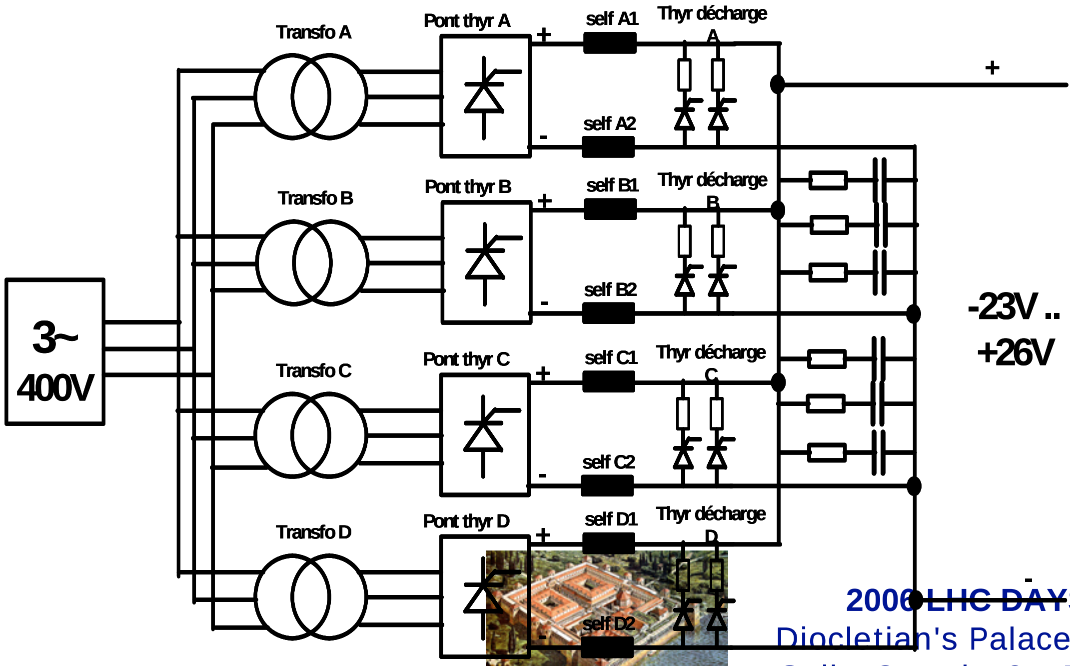


CMS Power Converter: 20 kA; +26/-23 V

Type: Tyristor bridge rectifier,
bipolar in voltage,

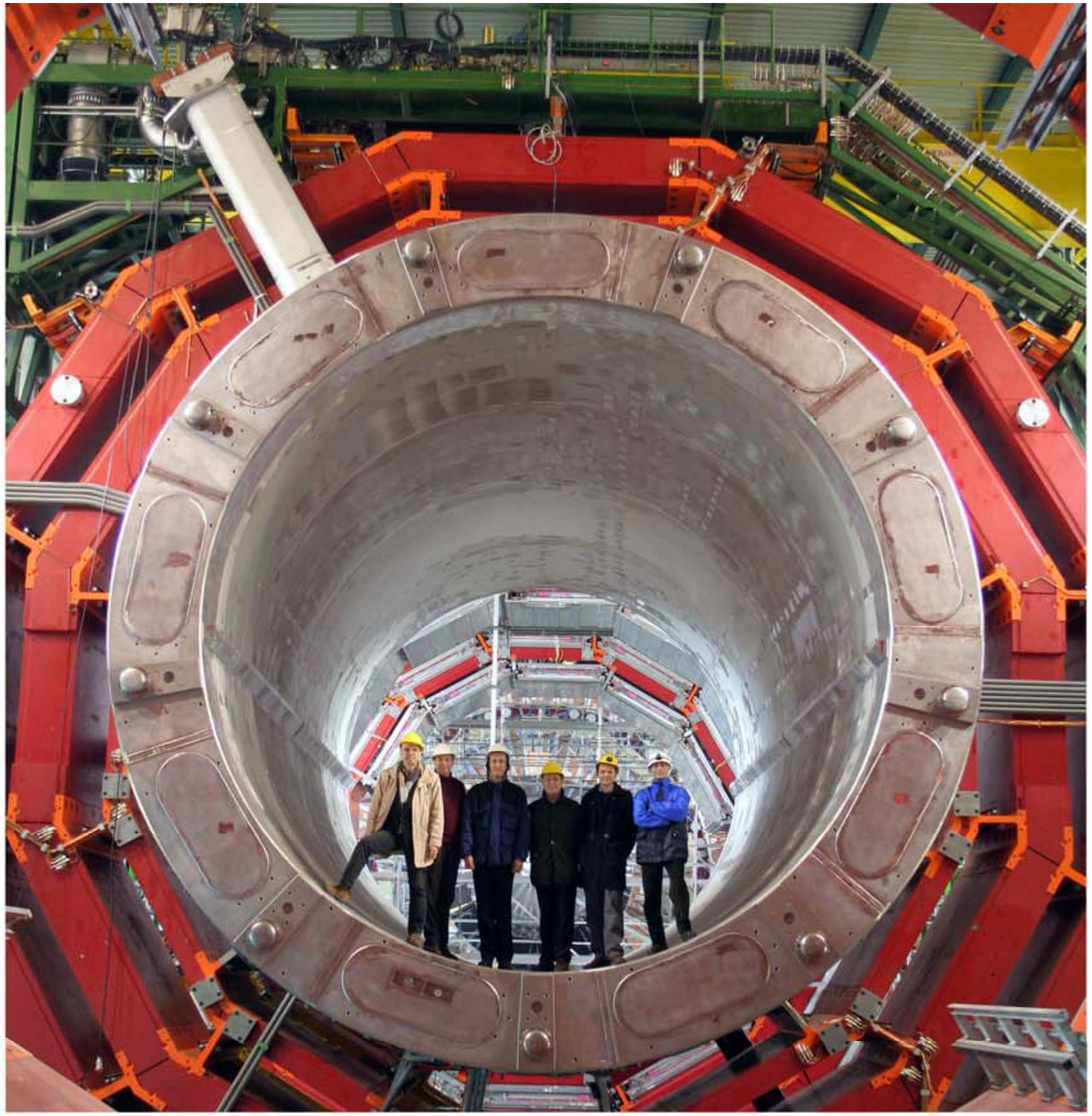
Output nominal voltage: -23V .. +26V
Output nominal current: 20000 A
Nominal power for ramping-up: 520 kW
Mains supply voltage: 400V, 50Hz, 3-phase
Mains supply current: 320 Arms
Voltage ripple: 1 %
Current precision: 5 ppm pk-pk





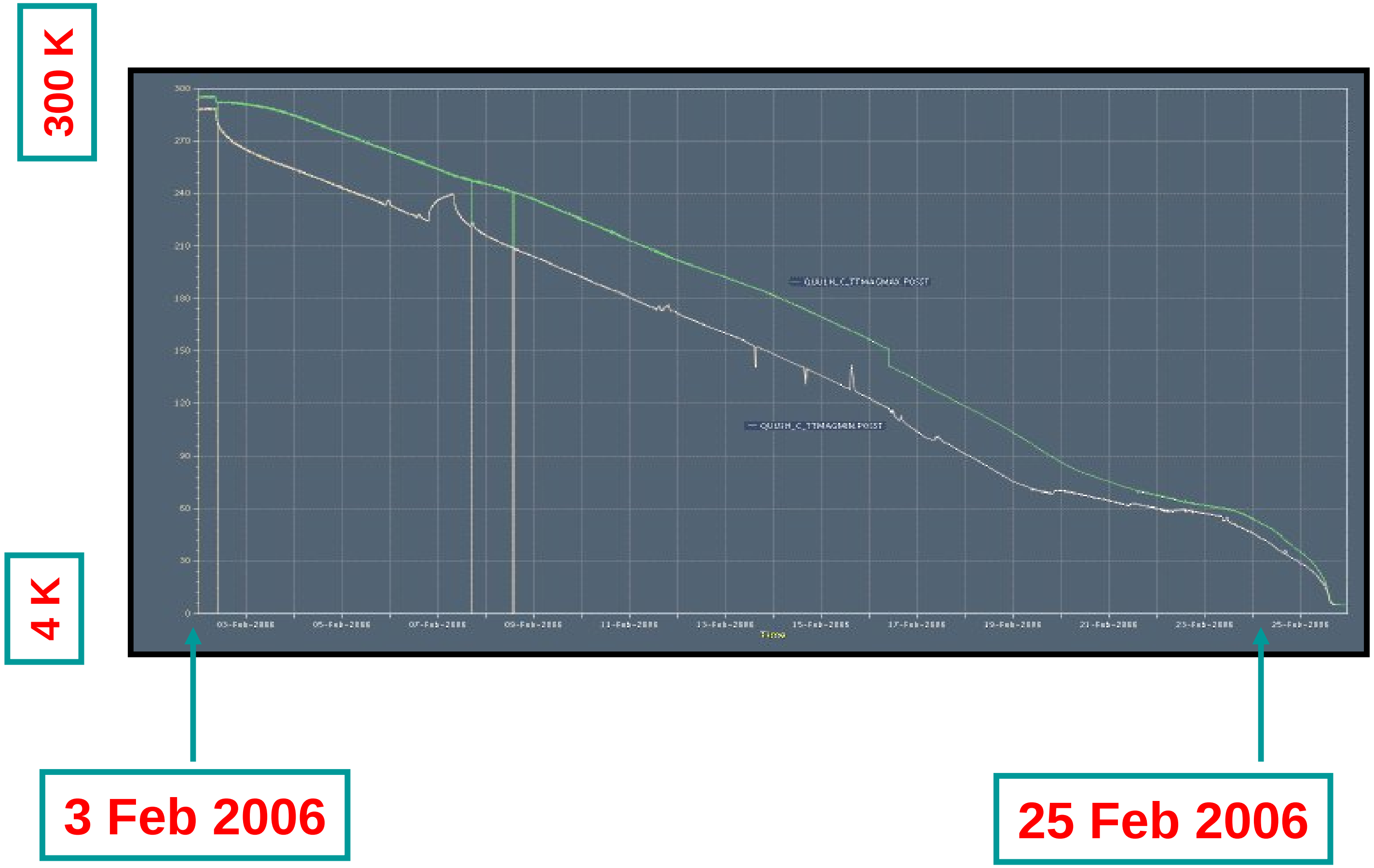
Dump resistor at SX5

Closing of the vacum tank flanges



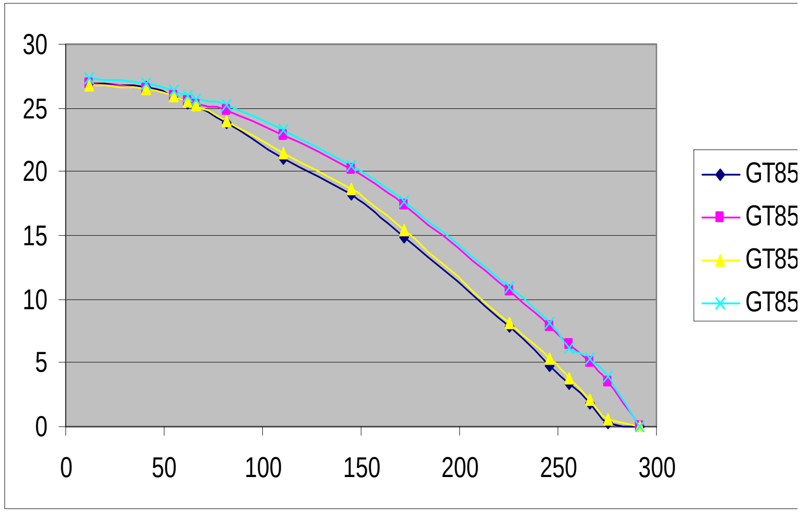
January 2006: End of the CMS Magnet Manufacturing

Cool down of the Coil went smoothly



Shrinkage and stress after cool down

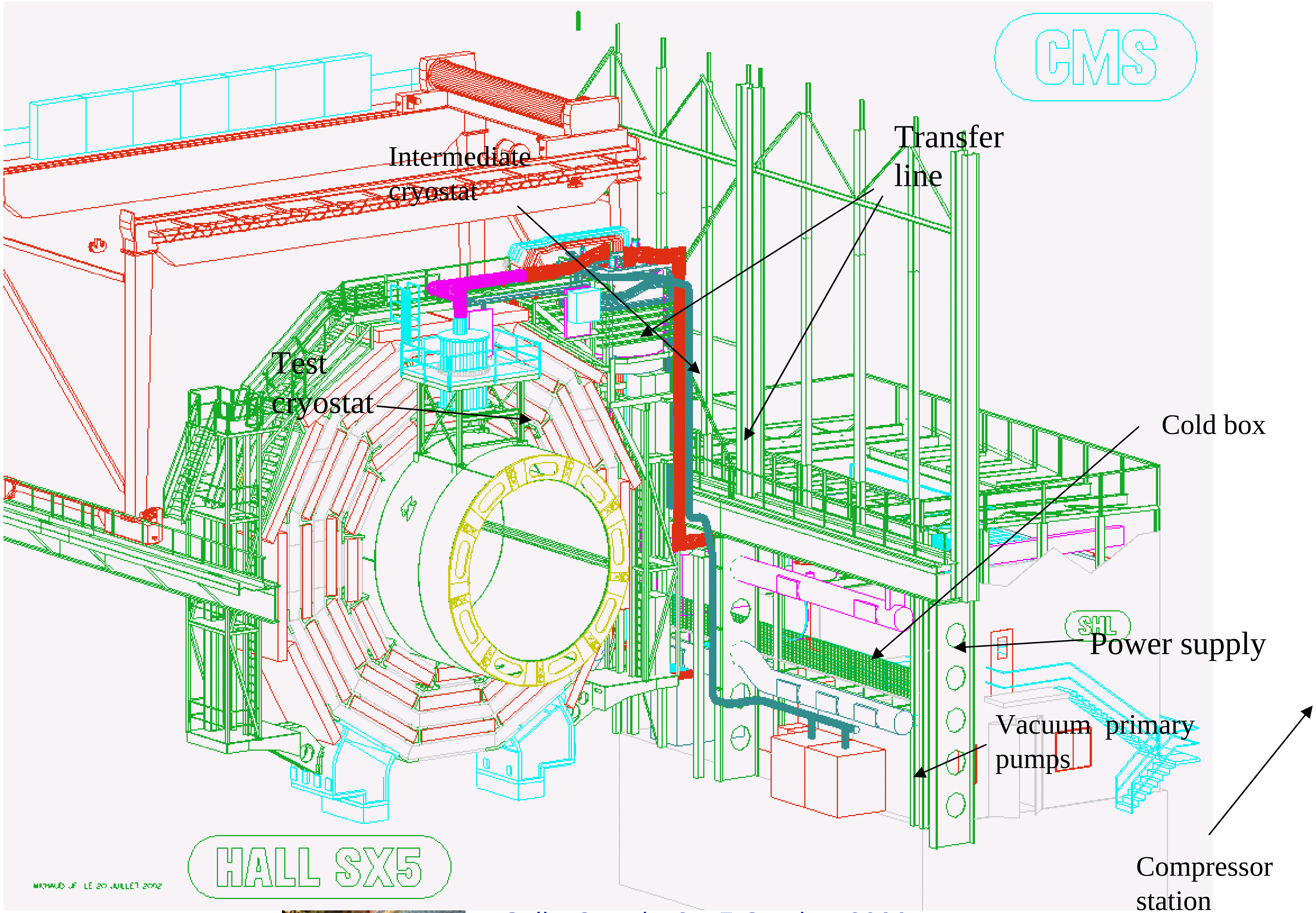
	Design value	Measured value
Cold Mass Shrinkage		
Longitudinal	26 mm	27 mm
Radial	14 mm	15 mm
Tie rod stress due to cool-down		
Vertical	50 MPa	47 MPa
Radial	150 MPa	156 MPa
Longitudinal	250 MPa	234 MPa

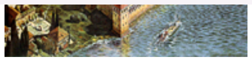


Displacemet mm

Temperature

Test Configuration in the SX5





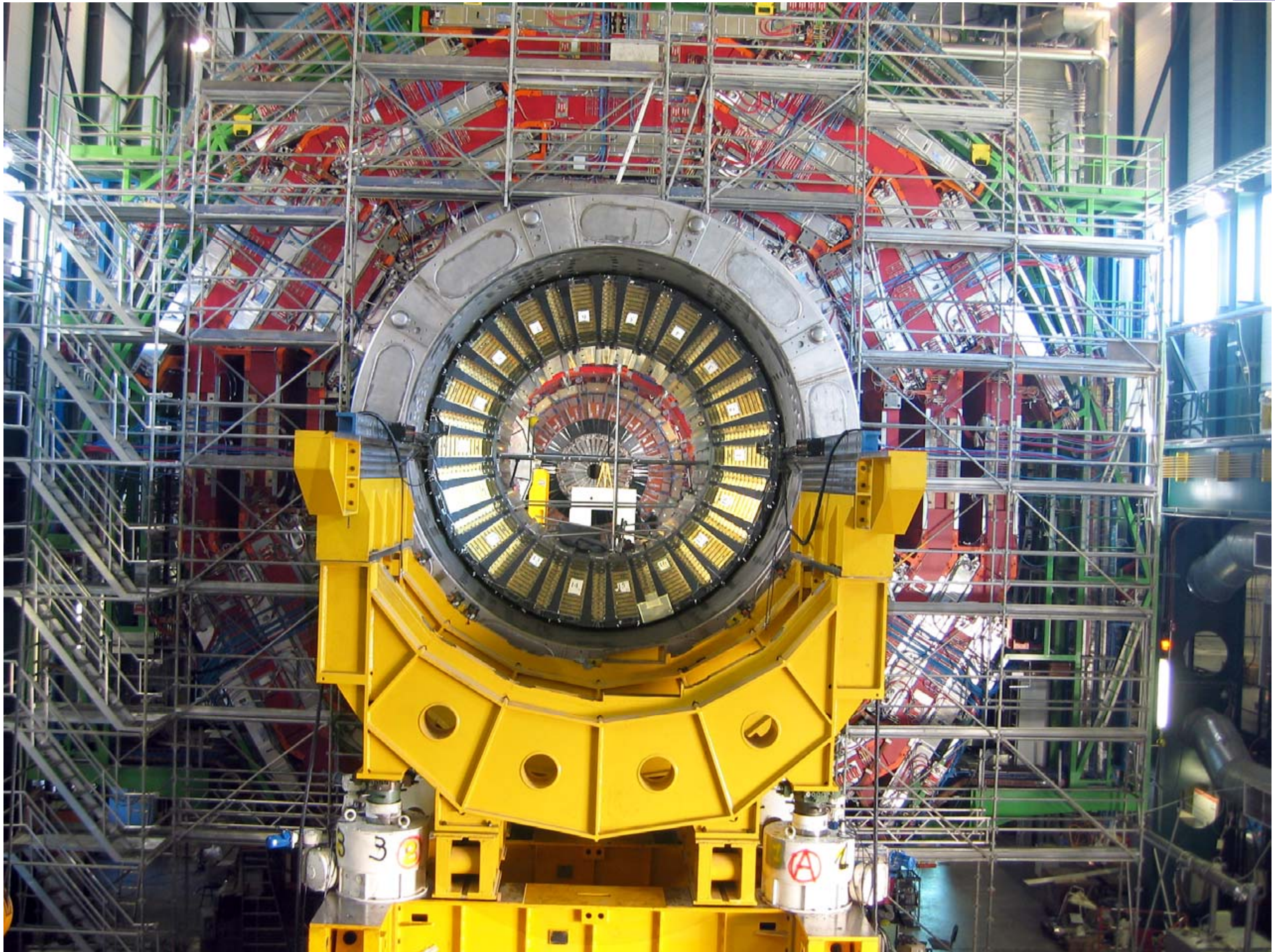
Preparation of the Magnet Test

- The Magnet Commissioning has been coupled with a so called Cosmic Challenge Test to show good working of the whole detector

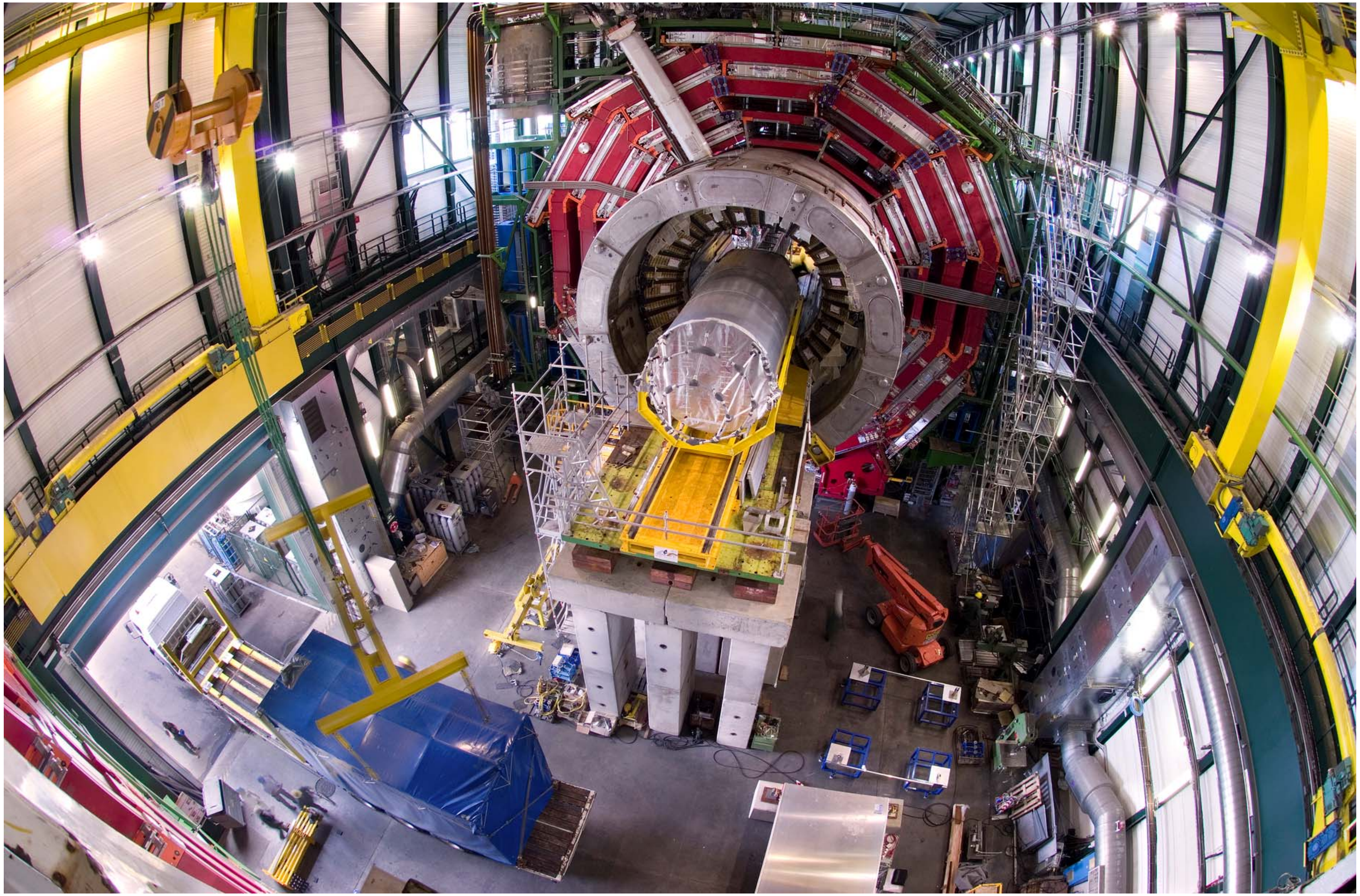
- This goal has implied the mounting of a significant part of Muon Chambers in the Yoke and Hcal + Ecal + Tracker parts

- The exercise has lasted until July 2006

HCAL Barrel inserted



Insertion of the Tracker



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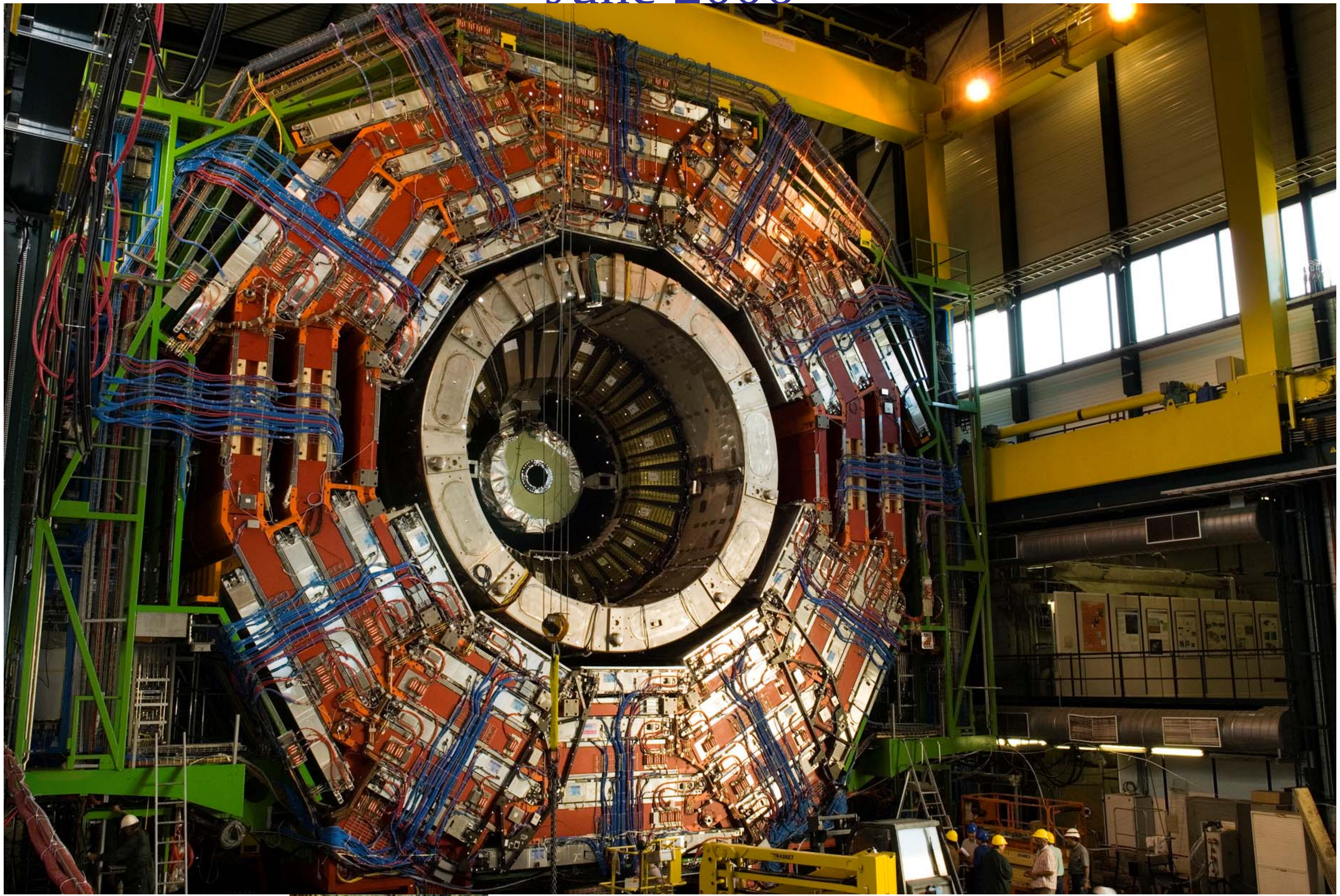
Barrel Yoke ready for closure with endcaps June 2006



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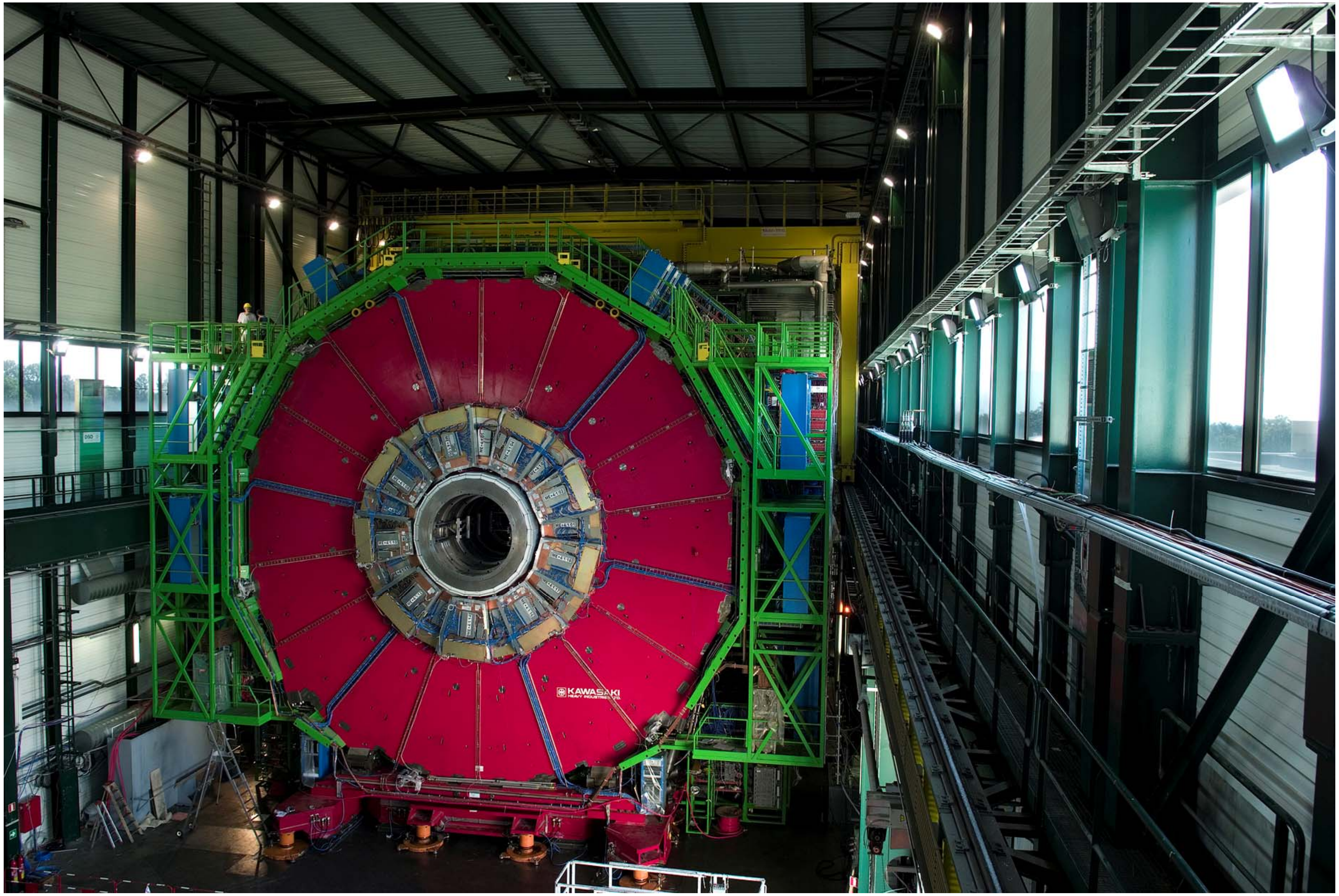
Survey has been constantly assured to reach an alignment of 1 mm wrt the ideal axis

Another basic achievement was the correct closing of all the Yoke elements

Air pads + grease pads are used to move each of the 11 elements of CMS

The preliminary marking of the position on the floor has been done to stay within a +/- 5 mm tolerance and get then an alignement with an accuracy of 1 mm with respect to the ideal magnetic axis of the yoke

Mid July 2006
CMS Closed: ready to inject high currents



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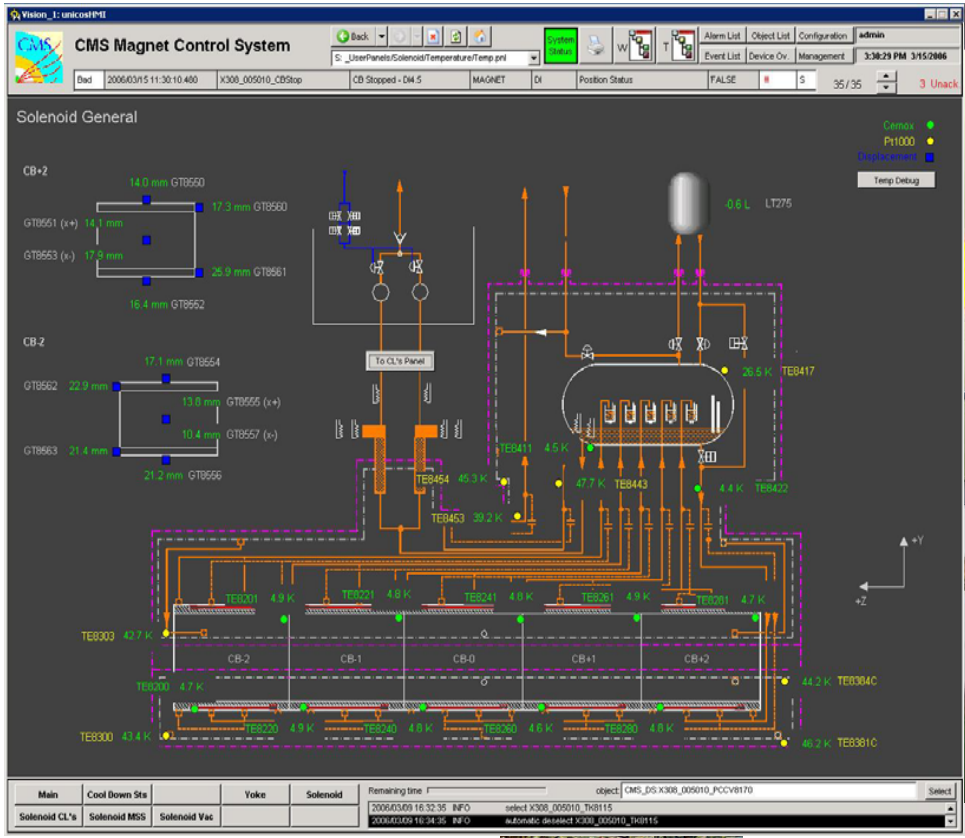
The Powering of the Magnet started on the 25 July

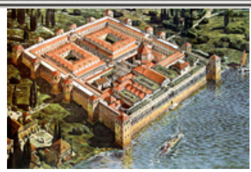
Goals :

- Ramp the Coil up to nominal current and check the 3 standard discharging modes comparing measures with design values
- In particular: overpressure during a fast discharge, final temperature of the coil after a FD, voltage on the current leads, real time constants of the circuits, temperature wrt to He flow in the current leads etc….

Magnet Control

MCS : Magnet Control System
MSS : Magnet Safety System
CDS : Constructor Detection System





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The Core to run the Magnet is the Cold Mass and its electrical behavior

L = 14 H

R = 30 mOhm at Room Temp

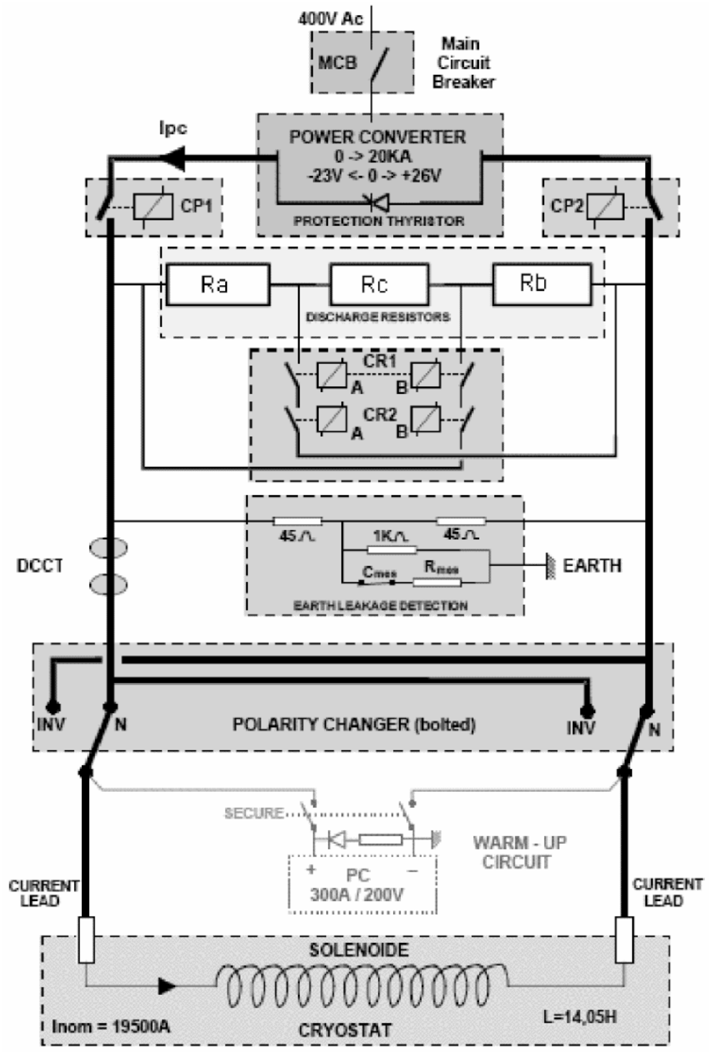
R fd = 30 mOhm

R sd = 2 mOhm

V of power supply is +26/-23V corresponding to a max theoretical di/dt of +1.8 A/s and -1.6 A/s

In practice (including line resistance and inductance) these values become +1.7 A/s to ramp up and -1.4 A/s to ramp down

In case of problems on the main the discharge can be done on a resistor bank in a "slow" mode to keep the magnet superconductive or a "fast" mode in case of quench



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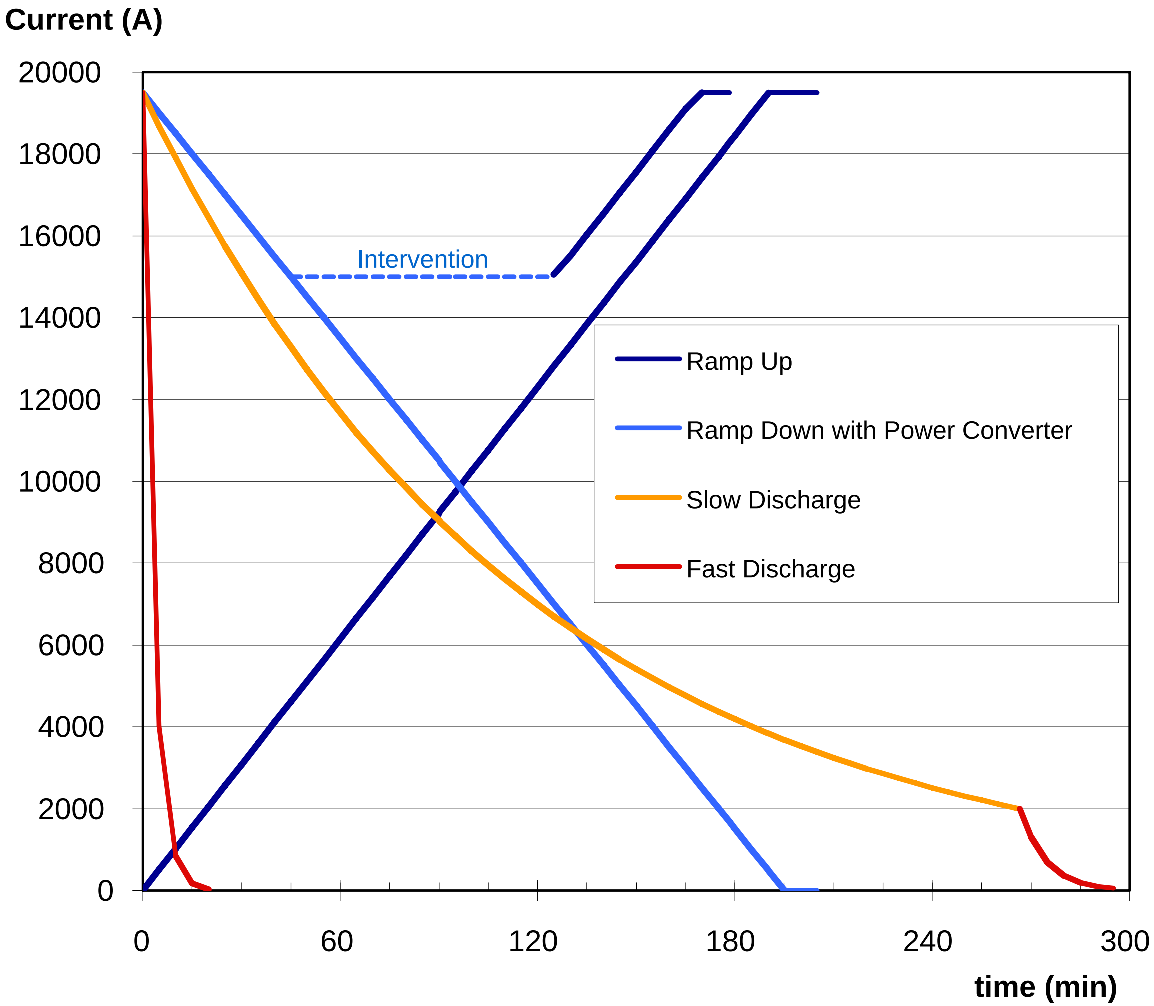
Powering and discharging modes

FD : 190 s (pseudo time constant) on a 30 mOhm Resistor

SD : 300 minutes on a 2 mOhm Resistor

Power supply : from +1.7 A/S to -1.4 A/s (+26/-24V)

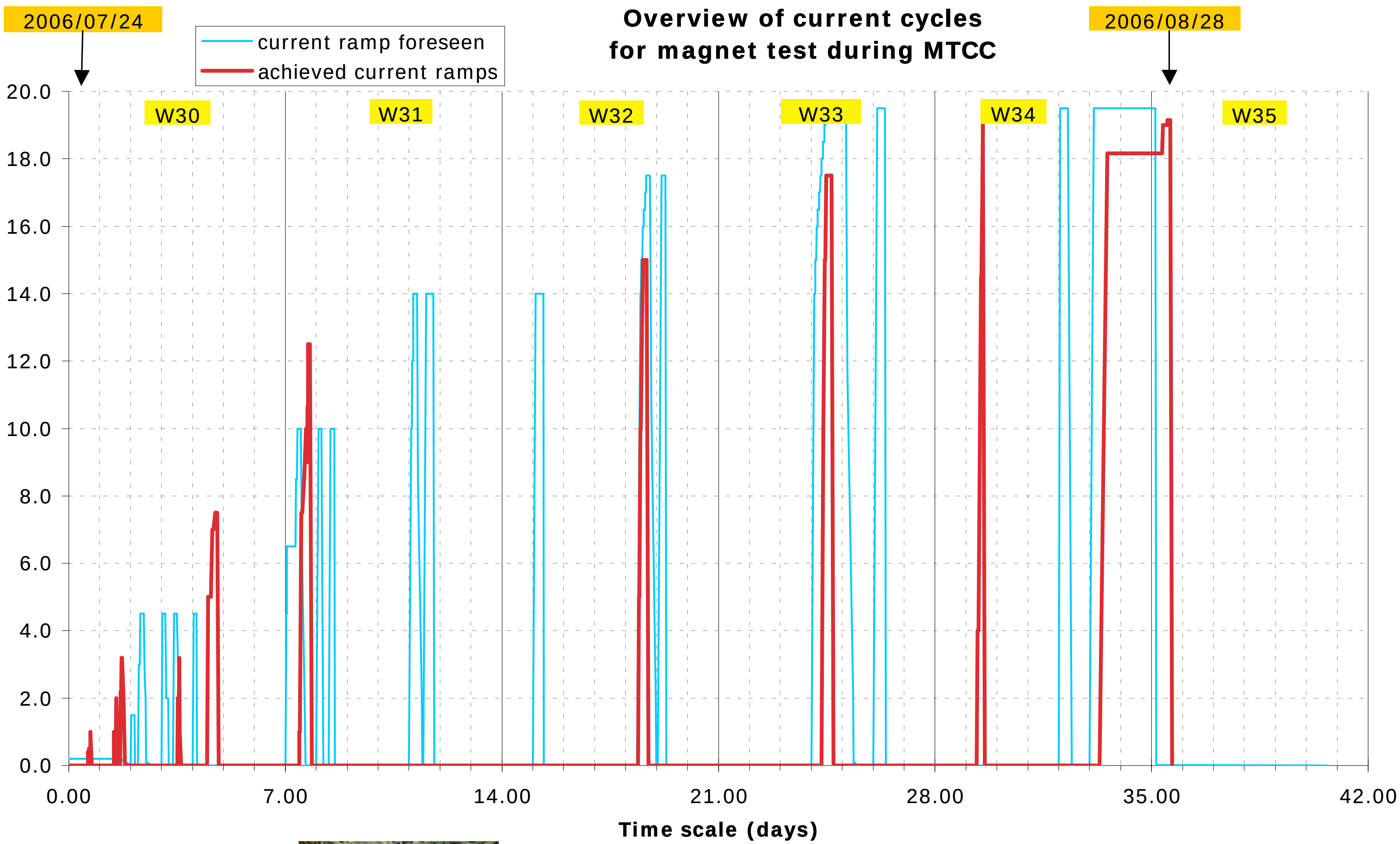
The ramping down with power supply is the standard mode because is driven by voltage (control of the speed) and allows flat tops and restarts



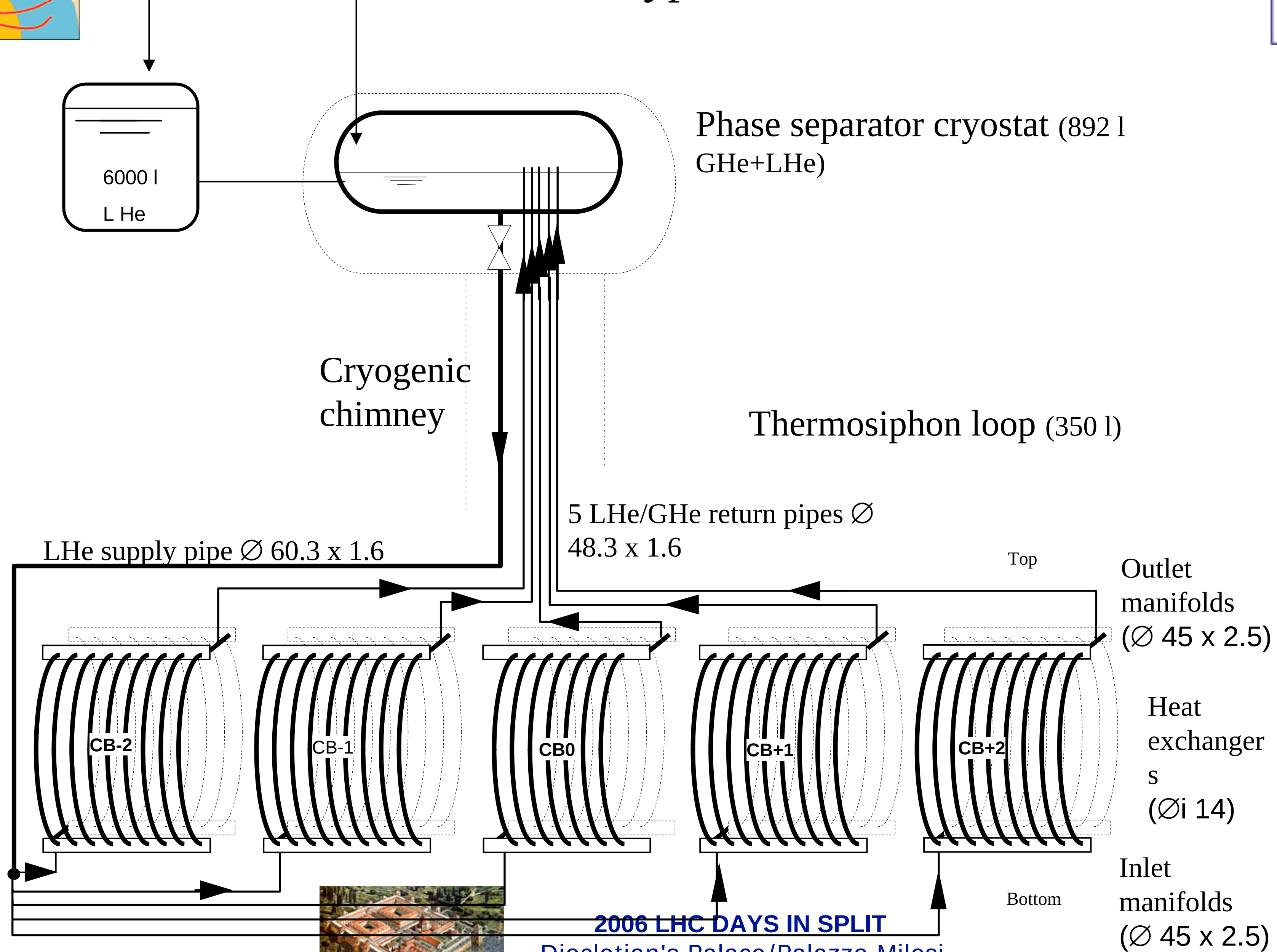
Powering steps as made during commisioning

- 25 July : 1 kA then 3.5 kA as preliminary test and discharge with power supply
- 26 July : 7.5kA followed by a fast dump which looked OK
- 31July : reached 12.5kA and generated a FD, but the magnetic relief valve did not work and we got the rupture of the safety disk.
- During the following week a mechanical relief valve was added in parallel
- 11 August : reached 15 kA (3T) followed by a good FD but magnetic safety valve not repetitive
- 17August: reached 17.5 kA followed by a very encouraging FD
- 22 August : reached 19kA and 4T, however a fast dump was accidentally triggered by the bad behavior of a DCCT in the stray field, nevertheless the FD behaved as expected. Shielding of the DCCT was improved.
- 26 and 27 August : the magnet has been operated constantly at 18kA (3.8T) for MTCC.
- 28 August : the magnet has been ramped up to 19.14 kA (4T + 3.05%) and staid at the nominal field for 2h completing the technical tests. It has been followed by a fast discharge still triggered by the DCCT.

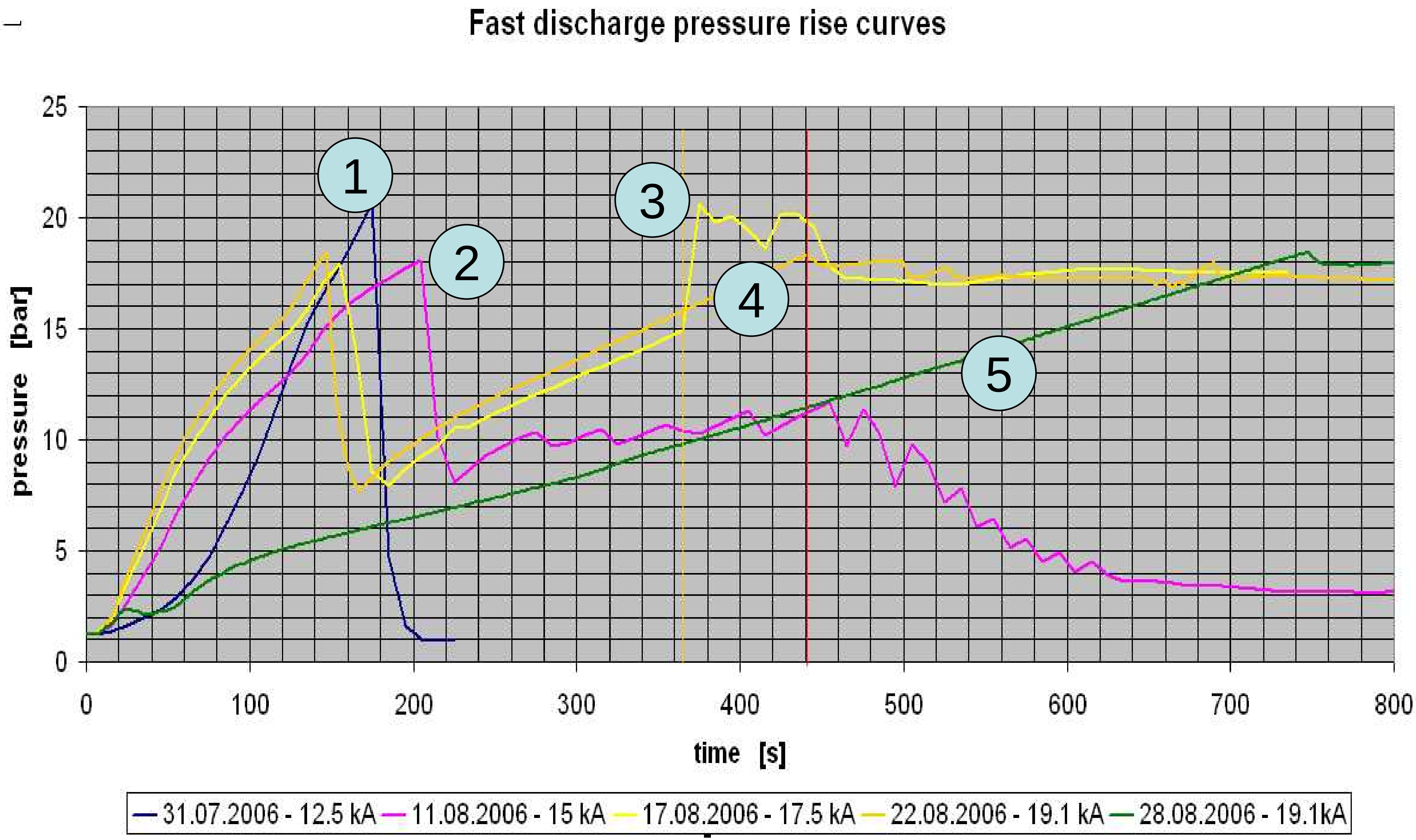
Magnet cycles in August 2006



Themoshypon circuits



He pressure in circuit during Fast Discharges



1 2 3 4 5

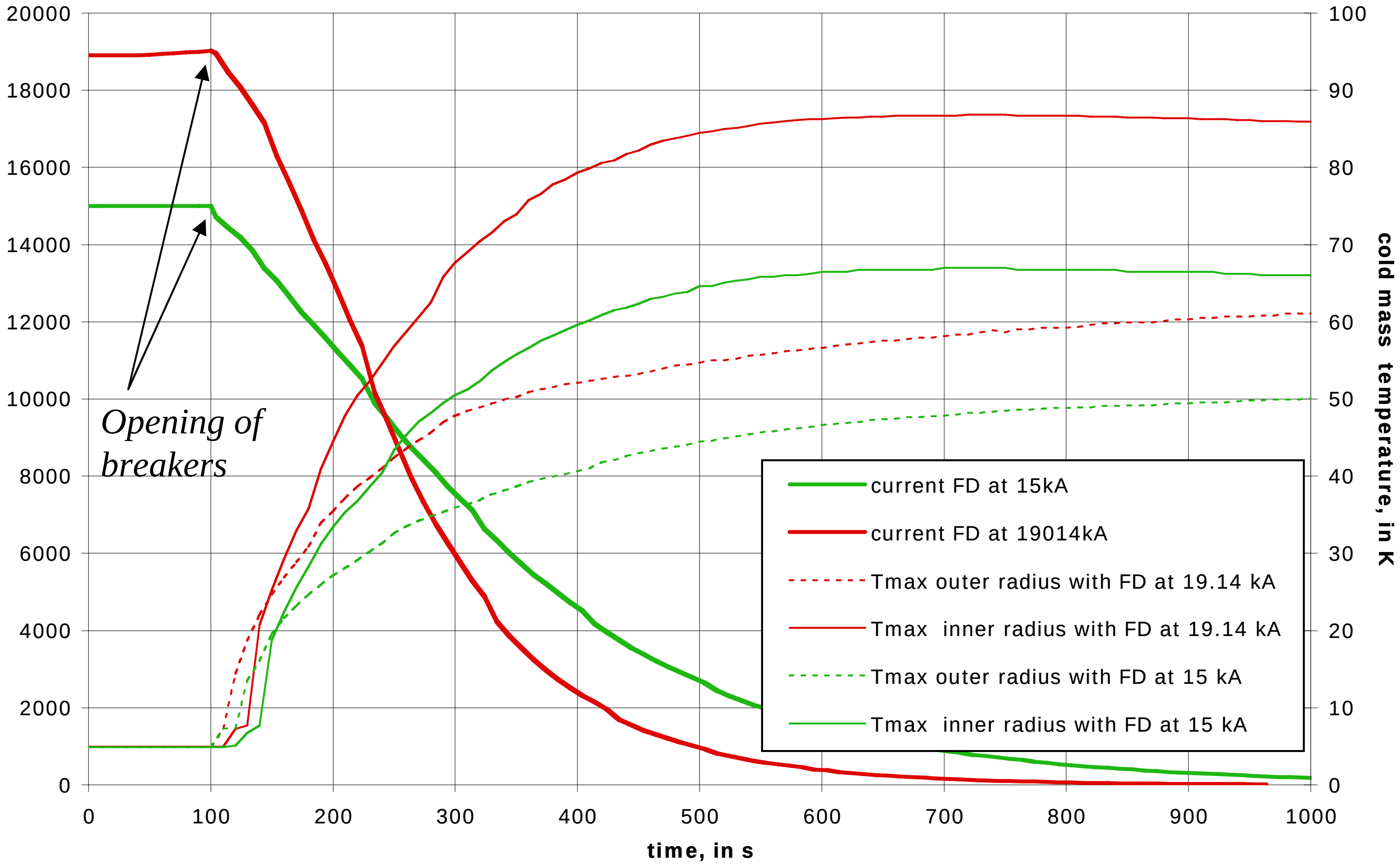
He release during a Fast Discharge

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

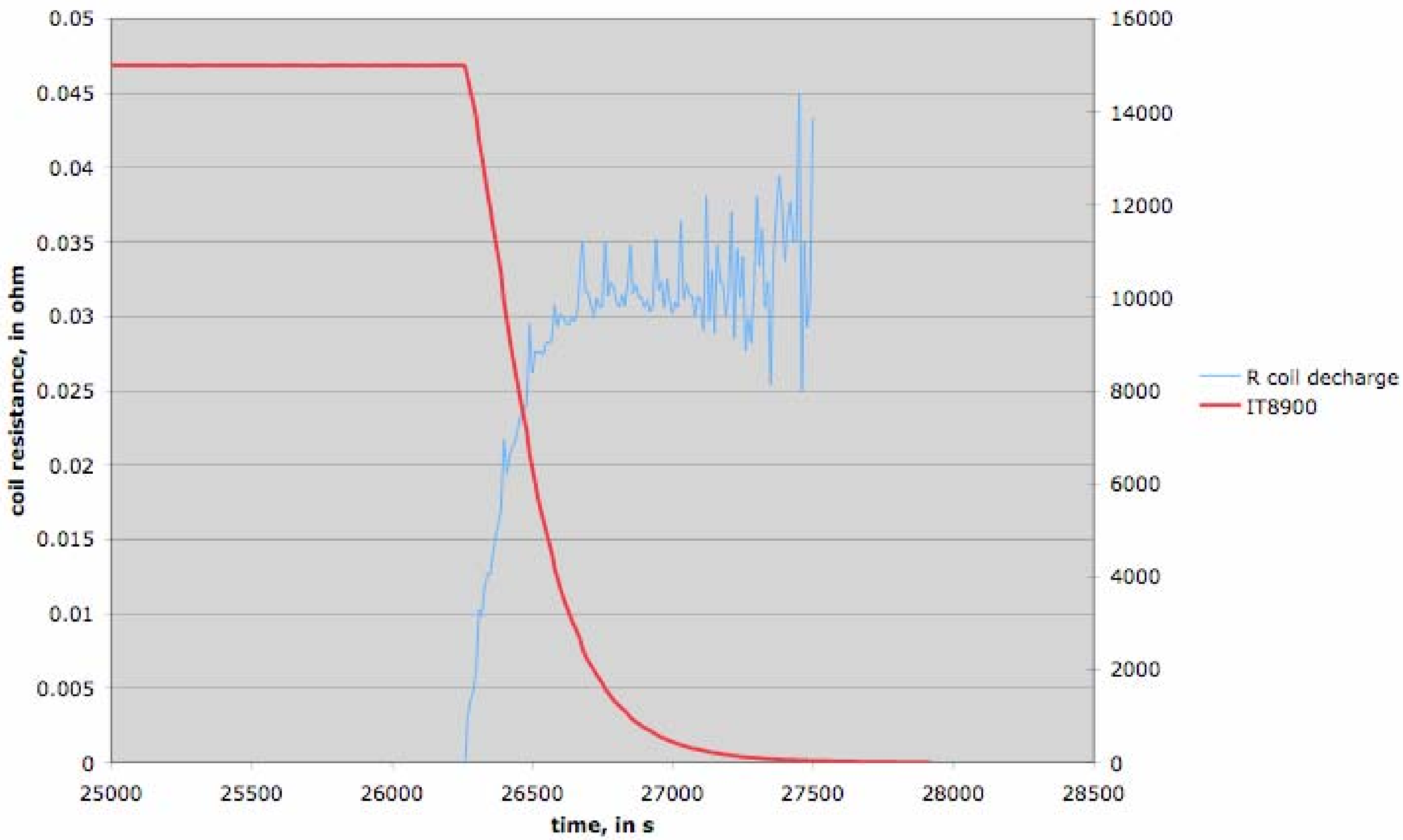
Main Results of the Magnet Test

Current and and coil maximum temperatures during FDs

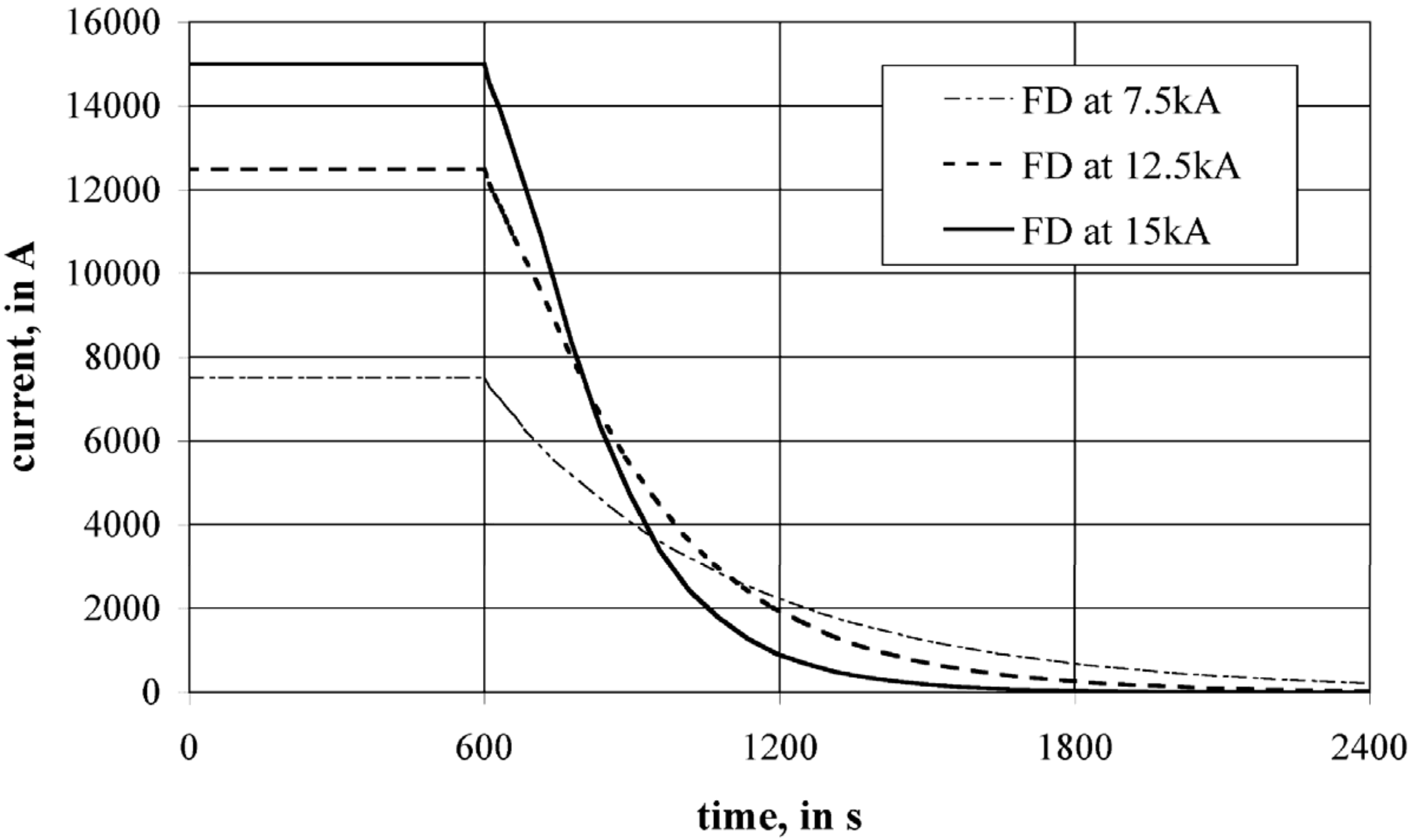
with a FD at 19.14 kA and 15 kA



Current and Coil Resistance during a FD



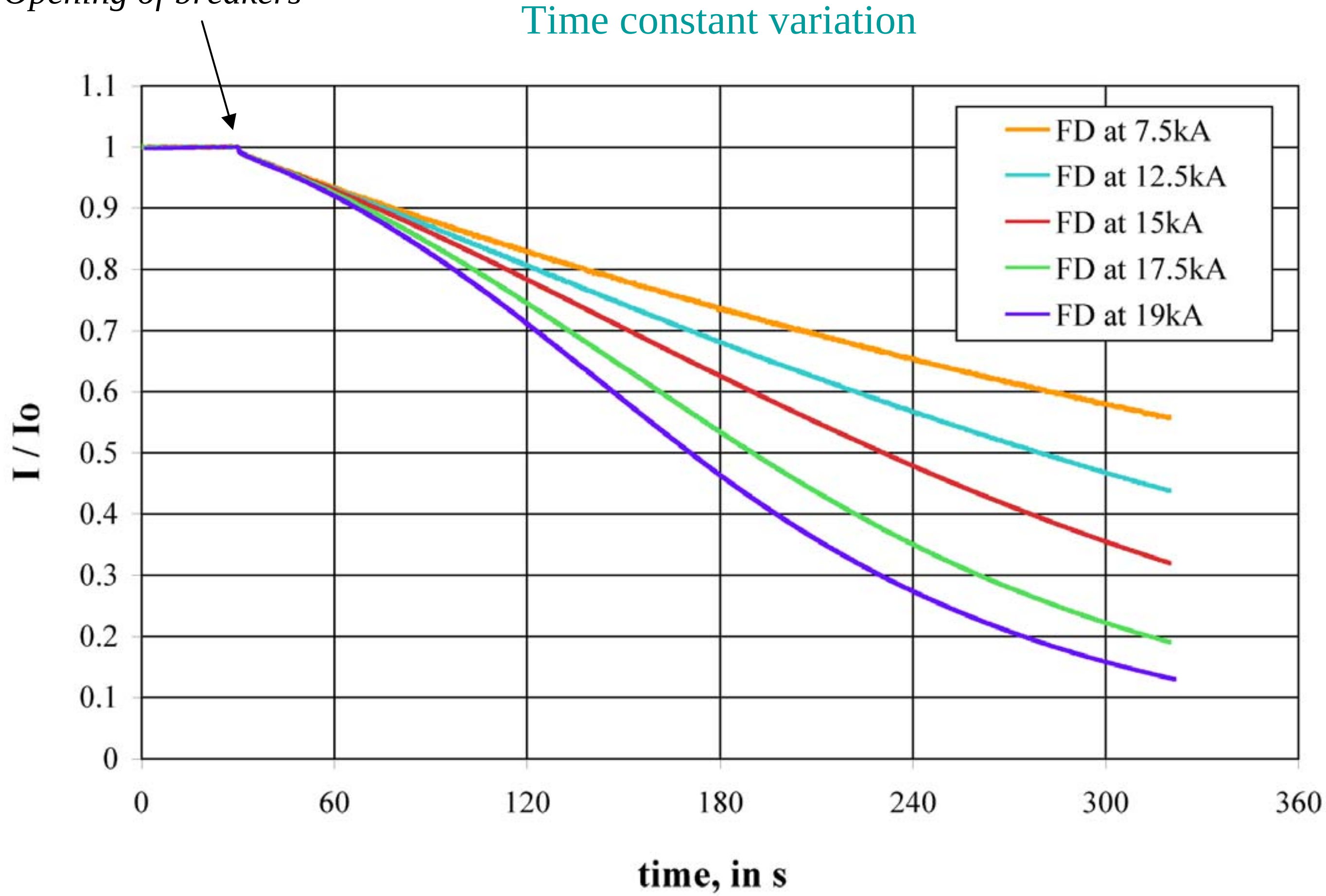
FD Current Decays



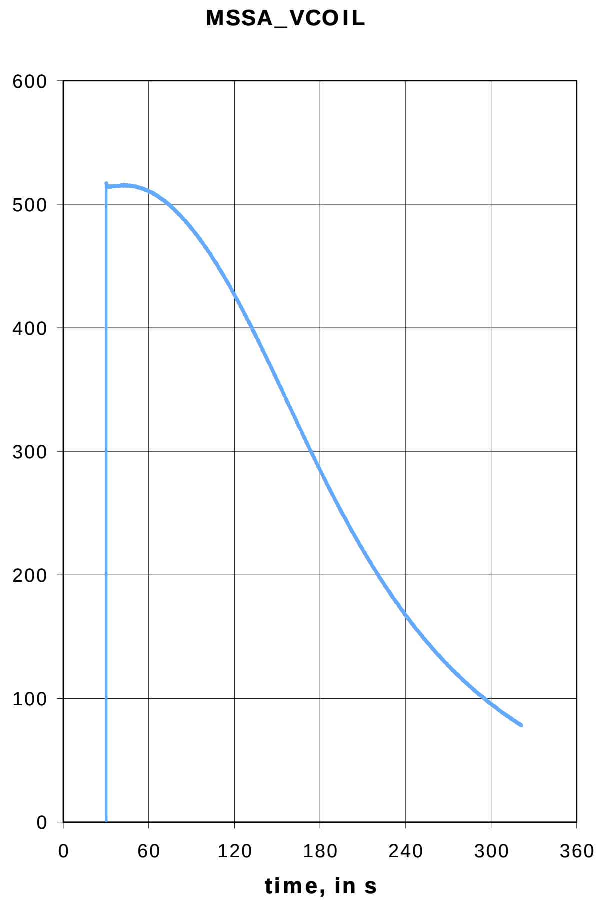
Decrease of time constant with current

Comparison of fast discharges

Opening of breakers



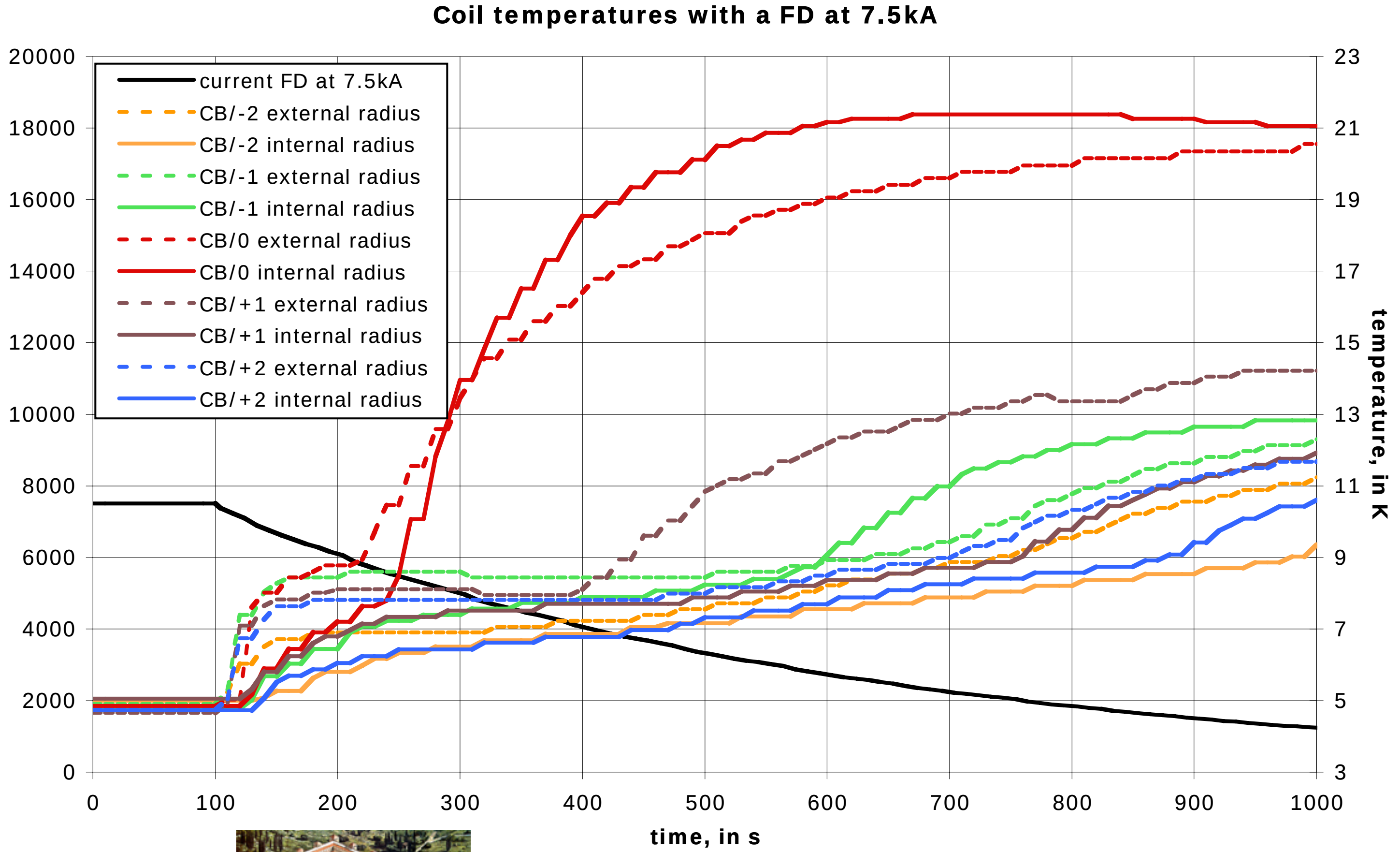
Coil Voltage during FD at 19 kA



Delays in full quenching of each module with FD at 7.5kA

Quench back of the coil during a FD at 7.5 kA

Module CB/0 fully quenched 350s before CB/-1



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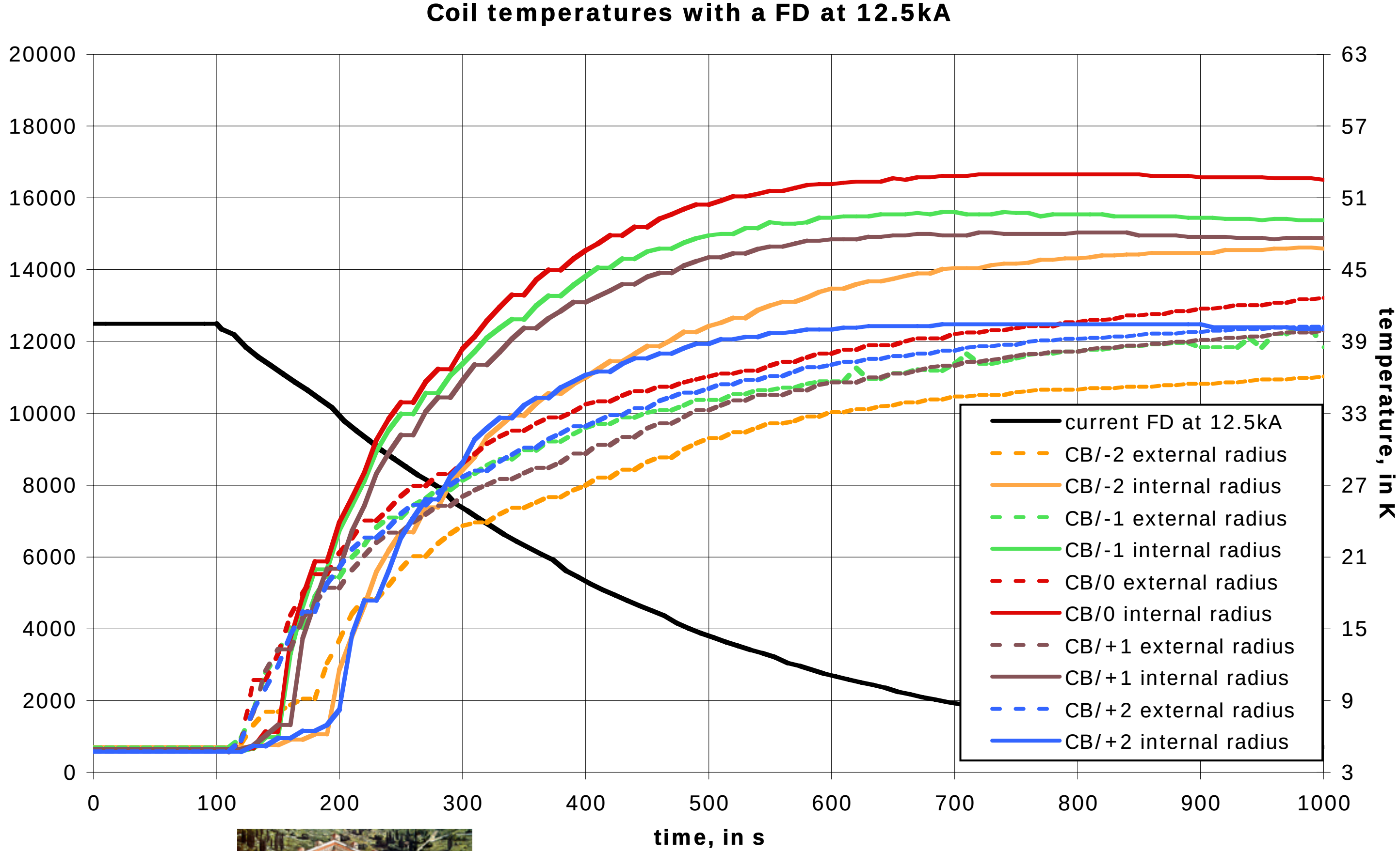
Delay in quenching of each module at 12.5 kA

Quench back of the coil during a FD at 12.5 kA

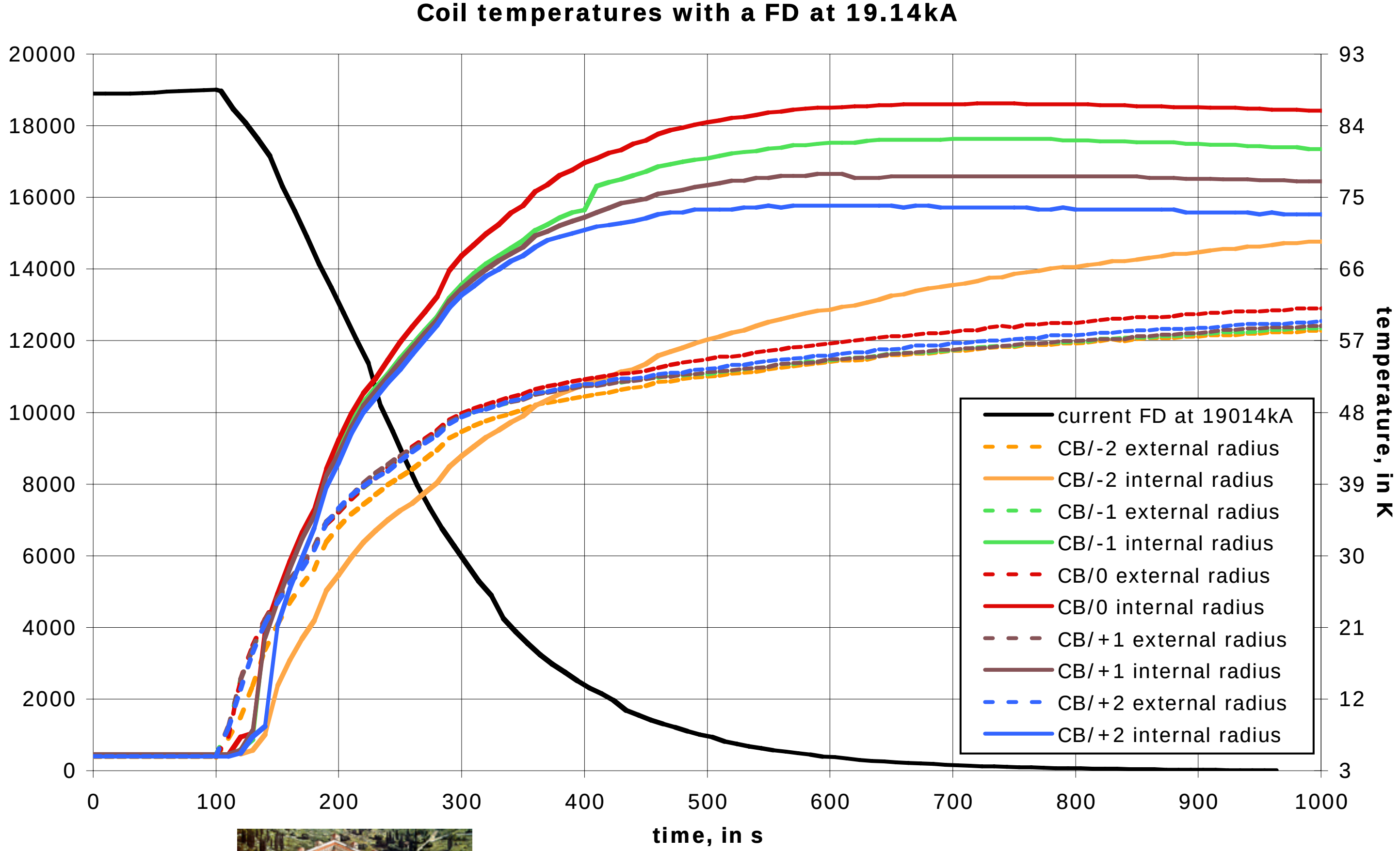
Module CB/0, CB/-1 and CB/+1 fully quenched 40s before CB/-2 and CB/+2



Dealy in quenching of each module at 19 kA

Quench back of the coil during a FD at 19.12 kA

All modules fully quenched 10s after CB/0



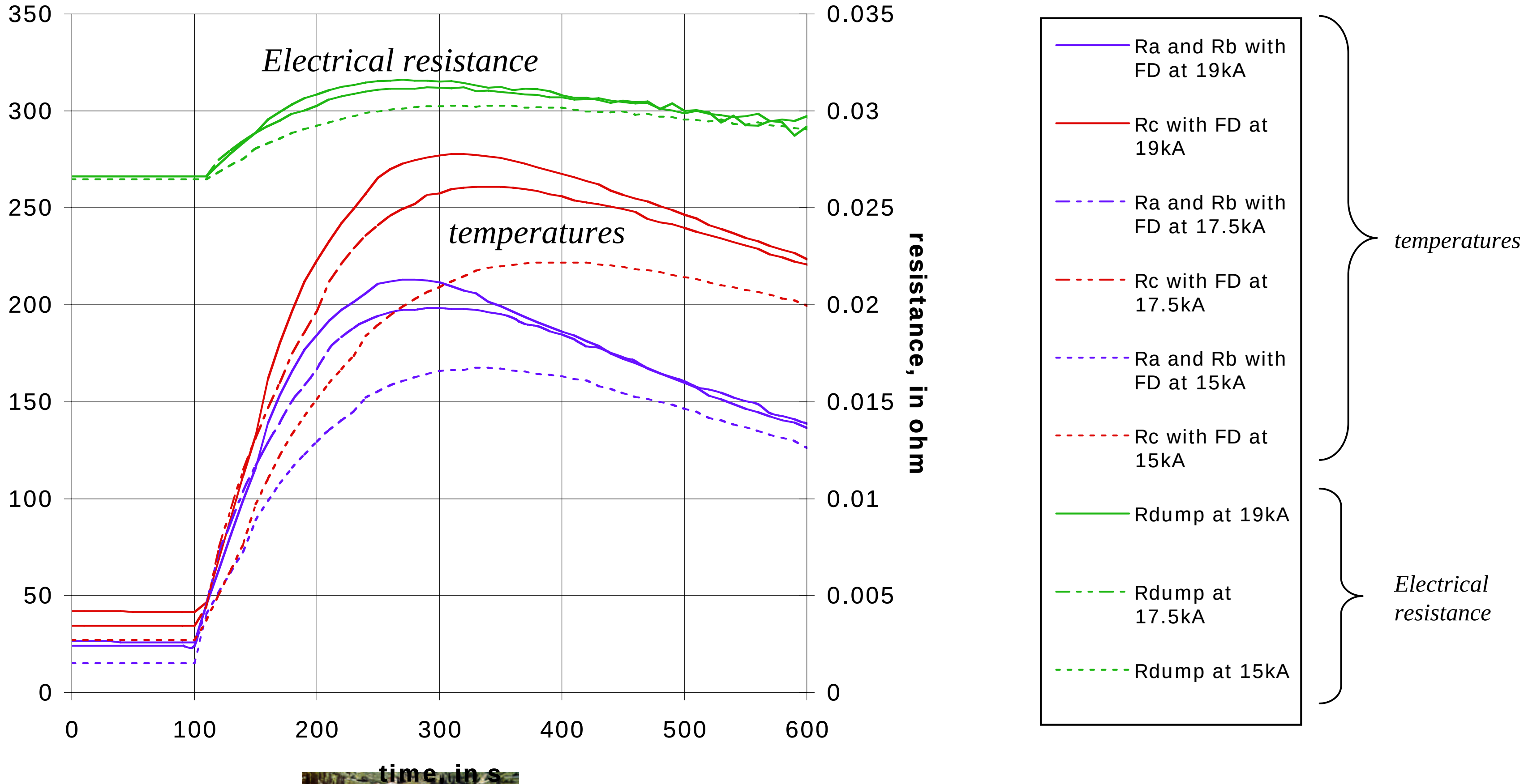
Summary table of FD parameters

FD current (kA)	Coil maximum temperature (*)	Coil average temperature	Coil maximum voltage	Coil energy	Time constant I_0/e
7.5	21.4 K	17.6 K	198.0 V	395 MJ	500 s
12.5	53.0 K	43.3 K	330.4 V	1.097 GJ	353 s
15	66.9 K	54.1 K	403.6 V	1.575 GJ	263 s
17.5	79.4 K	63.2 K	475.0 V	2.144 GJ	200 s
19.01	86.1 K	68.9 K	517.3 V	2.530 GJ	177 s
19.14	86.8 K	69.6 K	513.4 V	2.564 GJ	-

(*) always on CB/0, inner radius

Dump resistor

Temperatures and electrical resistance during the fast discharges



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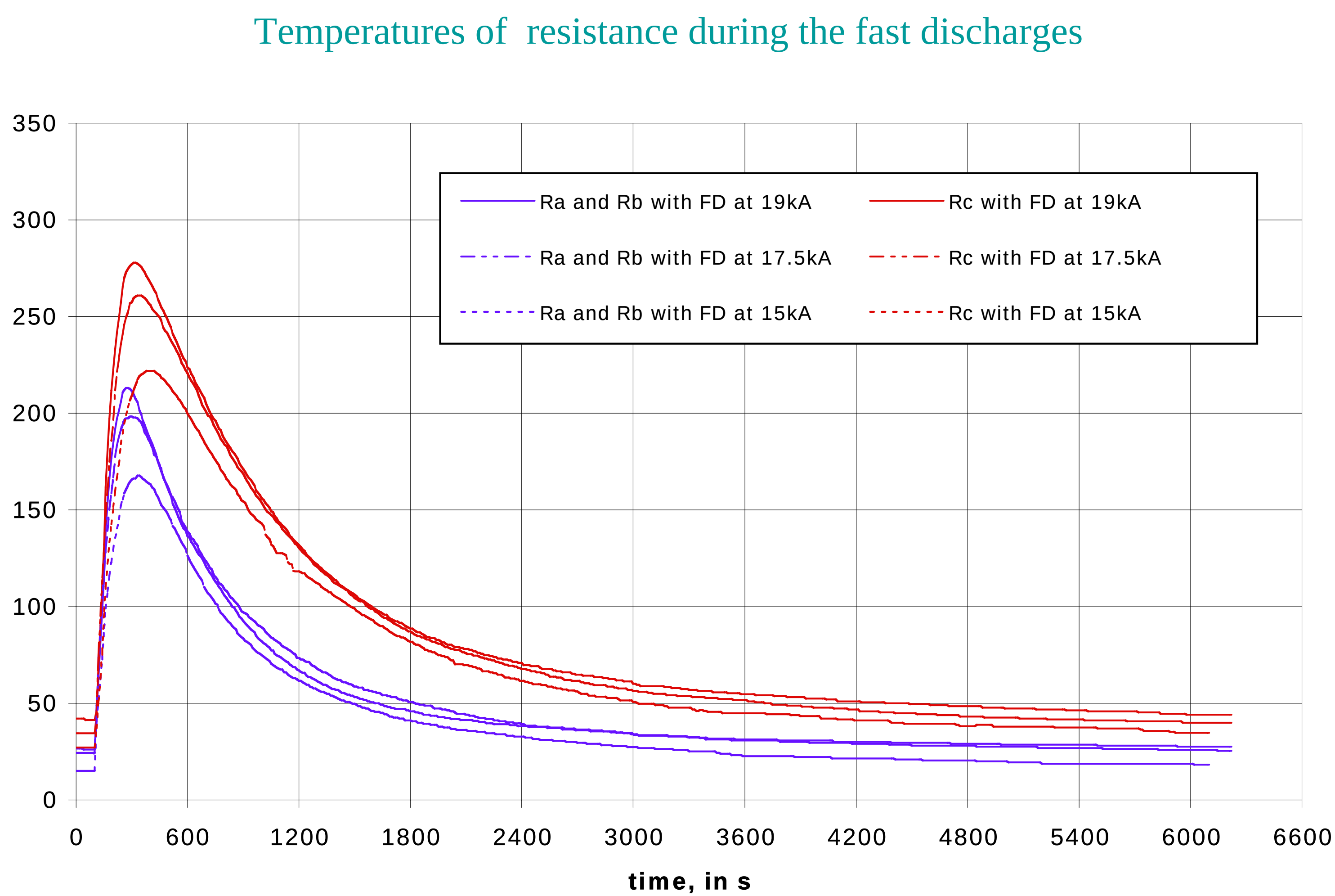
Dump resistance takes about 1 hour to recover RT



Busbars

Water cooled busbars

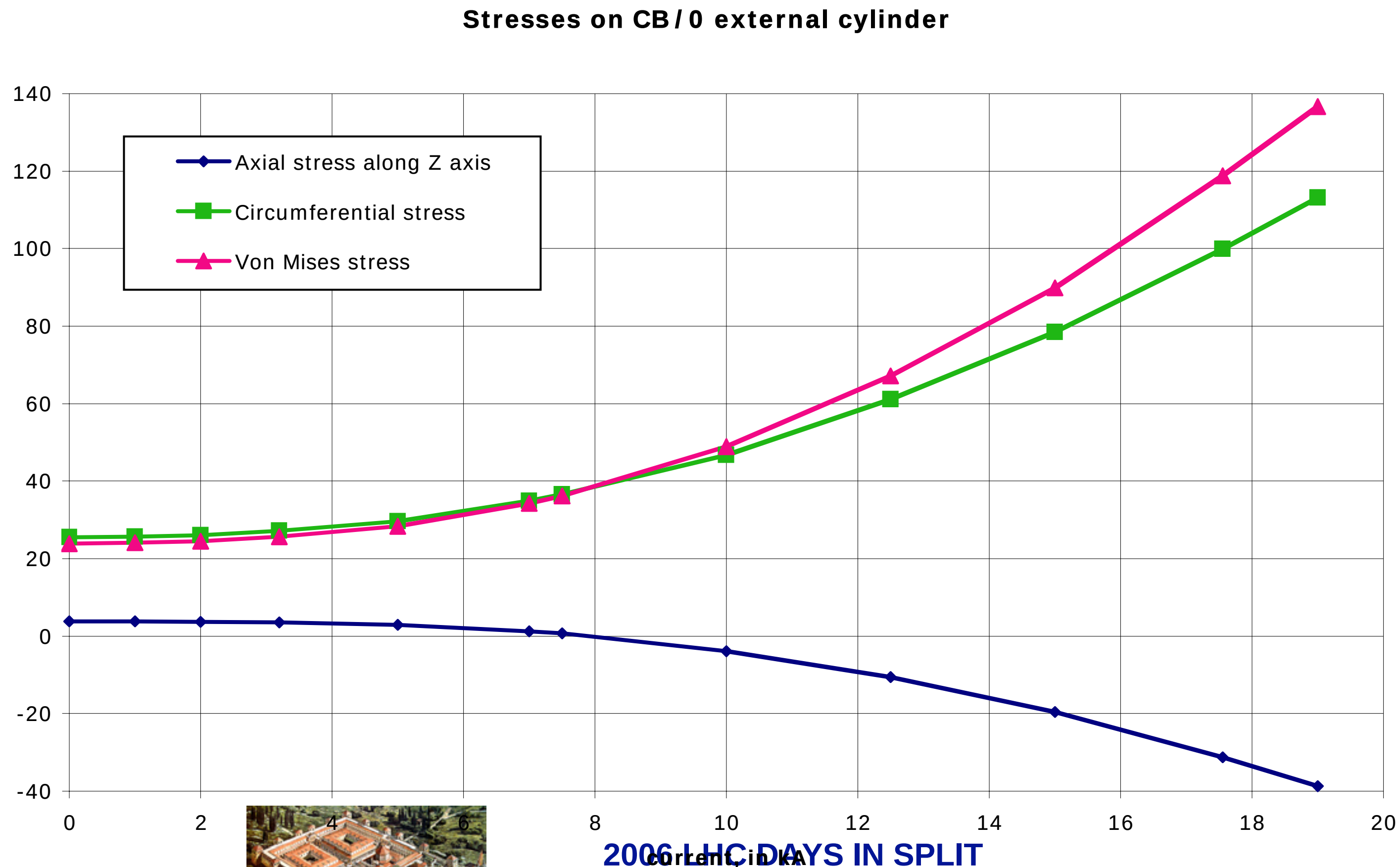
The water flow was set lower than specified at 4m3/hr, following a 1-hour test at 20kA on a short circuit:

	Ambient temperature	Bar temperature	Braids temperature
Ground level	24° C	27.2° C	27° C
On top of YB/0	29° C	27.7° C	31° C to 41° C

During the test, the temperature didn't exceed 27° C, average was 25° C, with an average ambient temperature of 21° C, at nominal current and during the 2-days run.

Stresses on CB0 mandrel

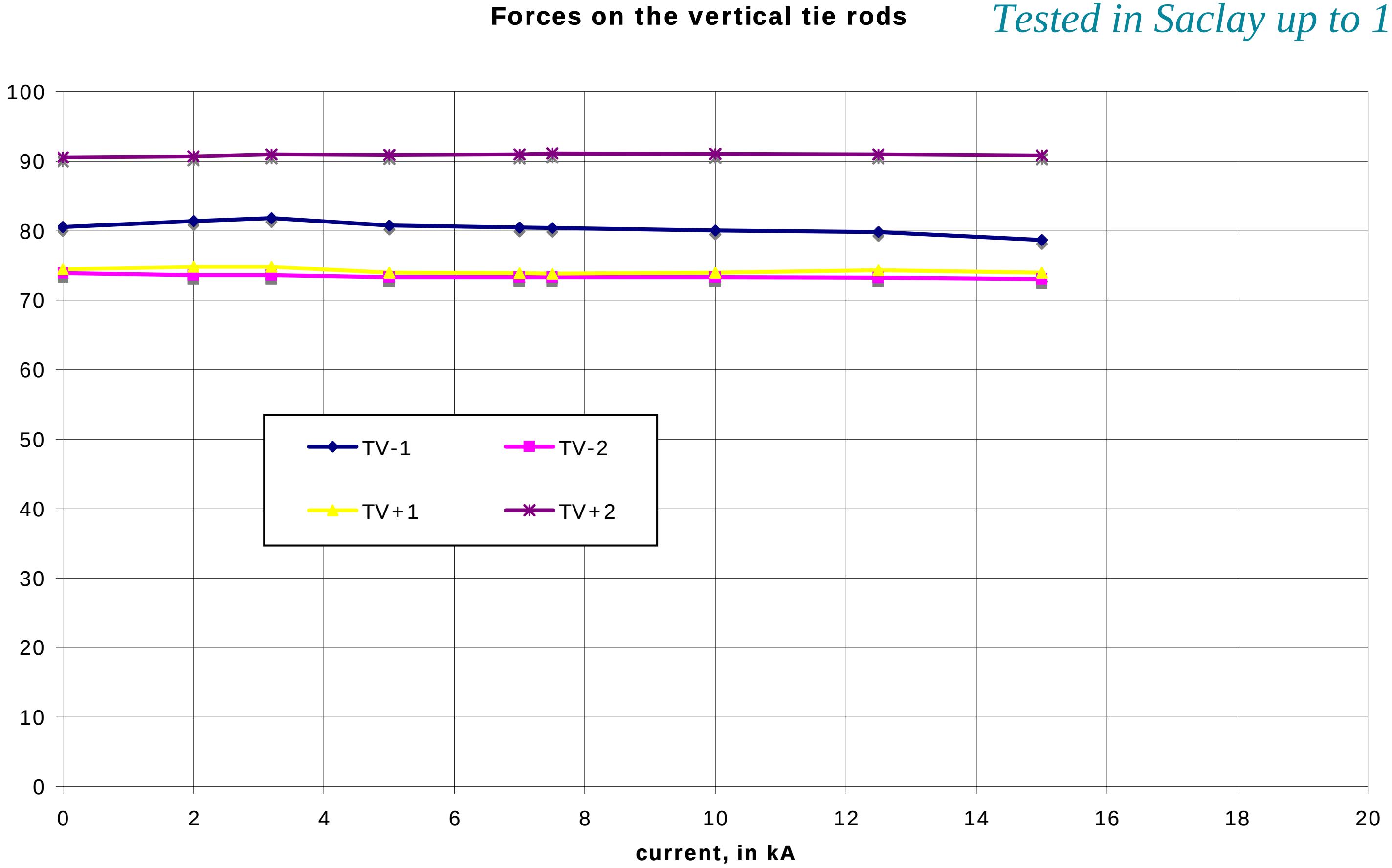
As shown on the fig. 2, the Von Mises stress measured is 34 MPa at zero field and 138 MPa at 4T. These values are in complete agreement with the computation performed by C. Pes in 1998 (32 MPa at zero field and 138 MPa at 4T) ! (see report 5C 2100 T –M 1000 031 98)



Vertical tie rods

The stress is between 75 and 92 tons each (weight + cooling+ magnetic forces) wrt 321 t max admissible

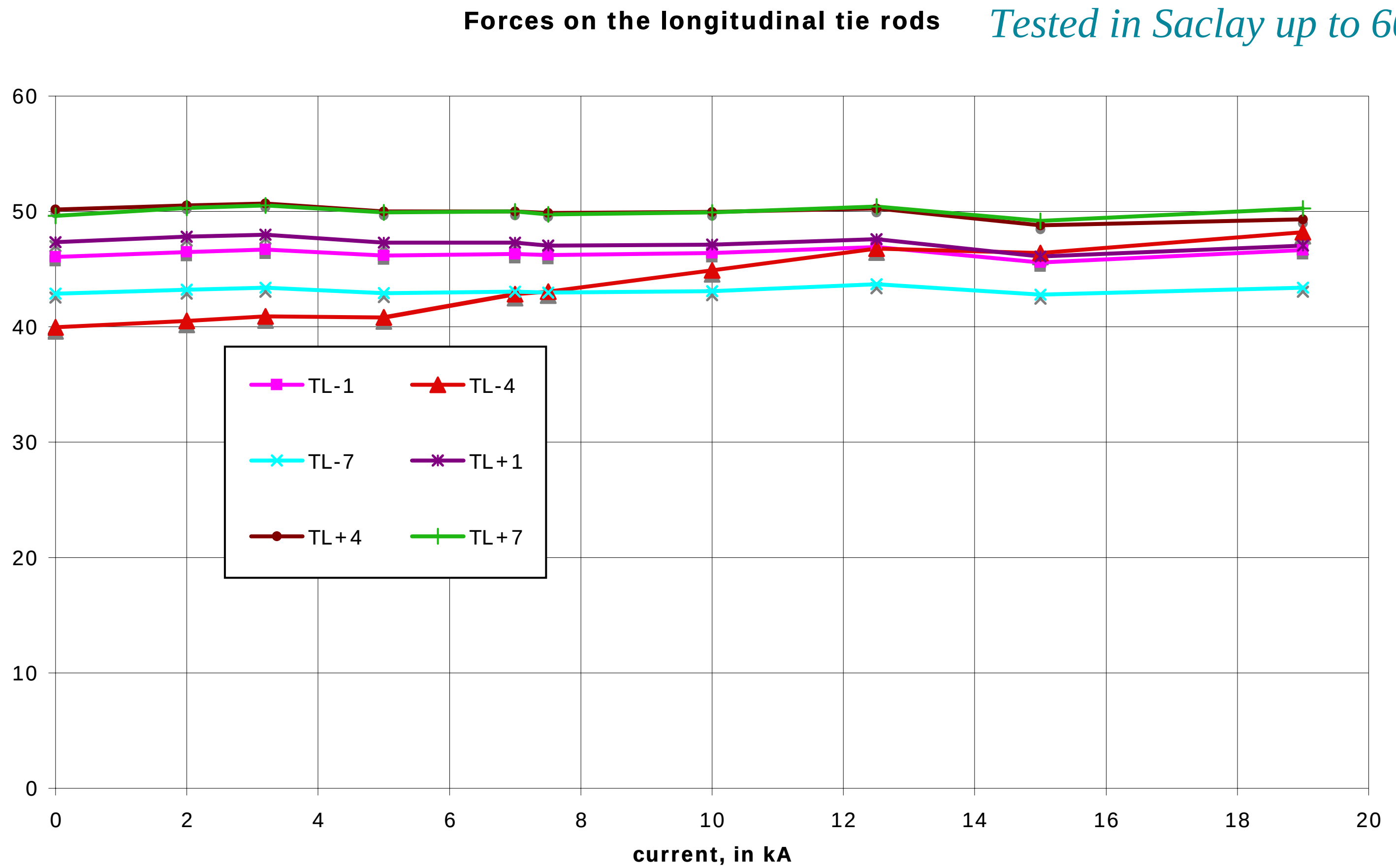
Tested in Saclay up to 100 tons



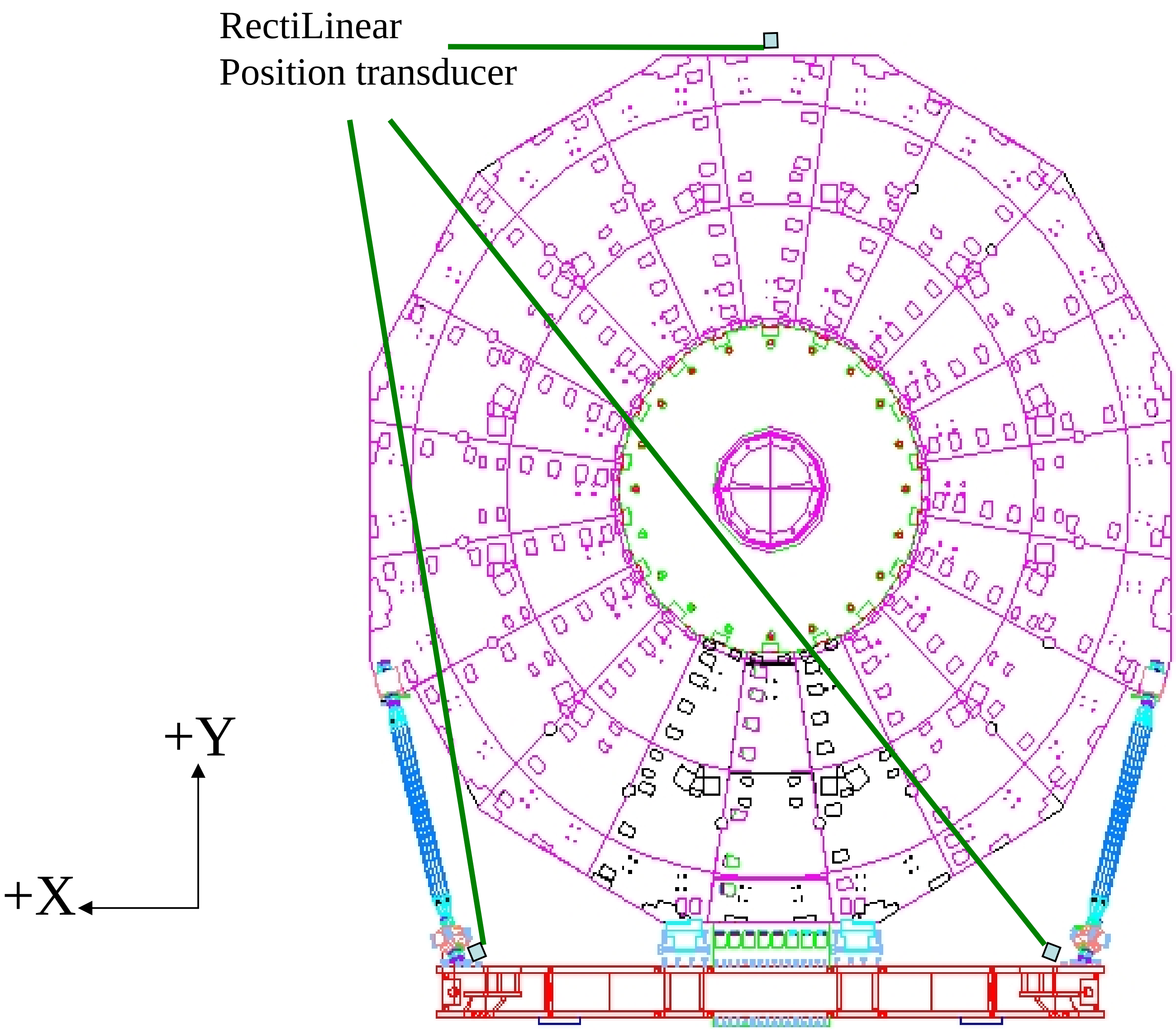
Longitudial tie rods

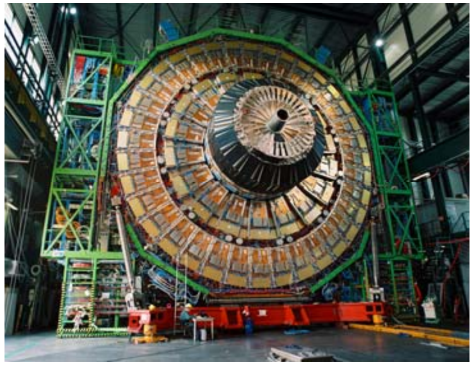
The stresses are between 40 and 50 tons each wrt 202 t max admissible, TL4 takes the charge later due to a higher pre-stress

Tested in Saclay up to 60 tons

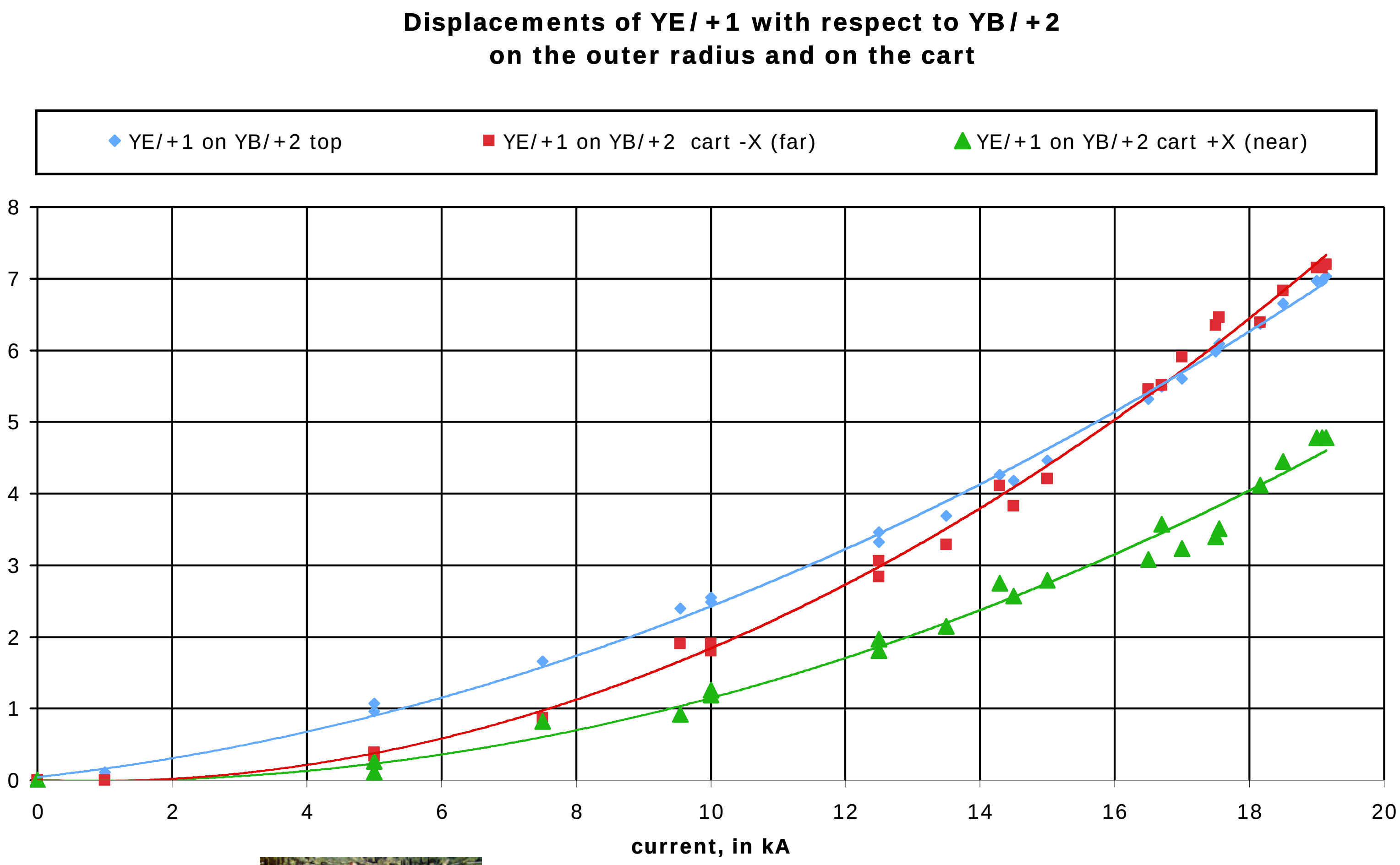


Displacement of Disk YE+1 compressed by 12.000 t

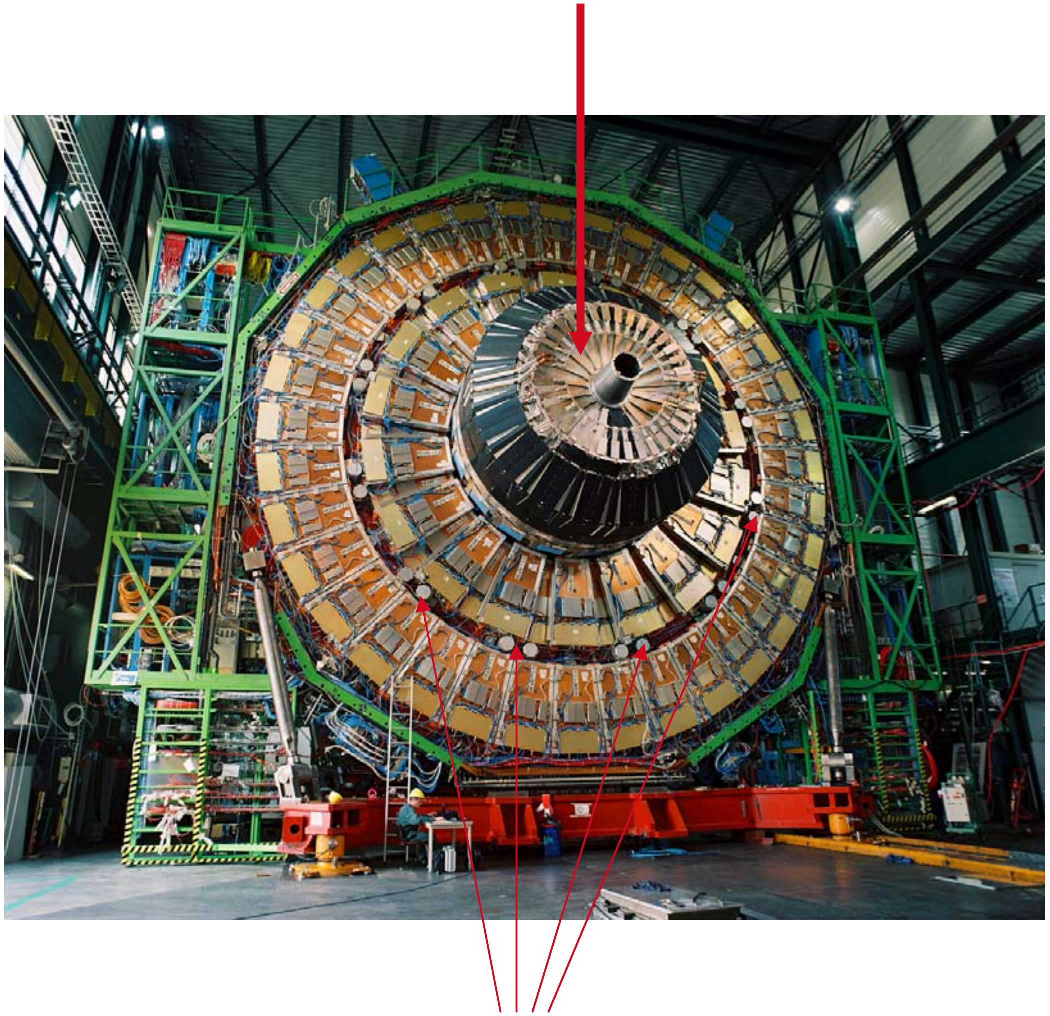


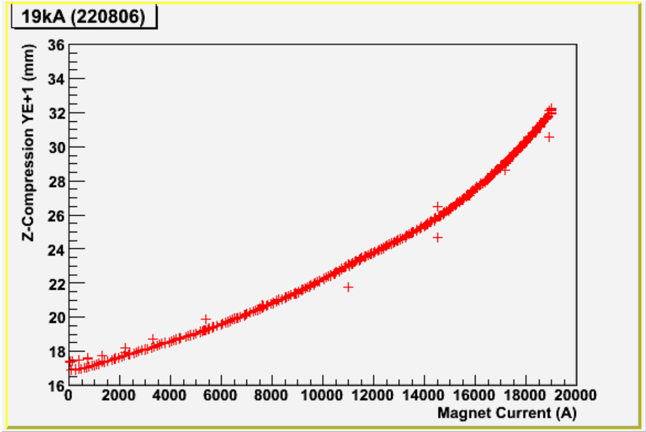


Displacements of YE disk with field



Due to the 10'000-tonne magnetic attraction force, the Nose moves toward IP by 16mm!





The 600 mm thick iron YE1 disk behaves like a Belleville washer and rotate around the circumferential line of Z-stops

Z-stops

Some consideration

- The Coil has a stable and reliable behavior in all conditions
- No spontaneous quench has occurred
- Two FD have been generated by the effetct of the fringe field on some ancillaries
- The regulation of the Helium flow on the current leads must be optimized to avoid under cooling of these elements

Next future actions

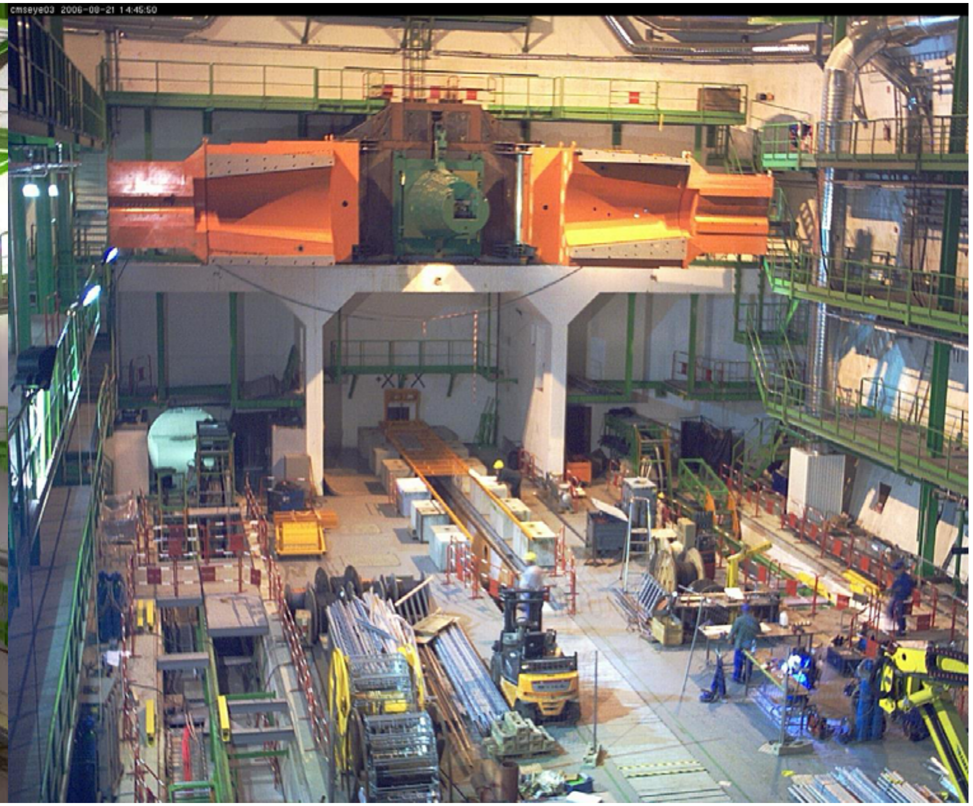
- Check the slow discharge behavior in parallel with the field mapping campaign (October 2006)

- Lower elements in the experimental cavern immediately after (starting November 2006)

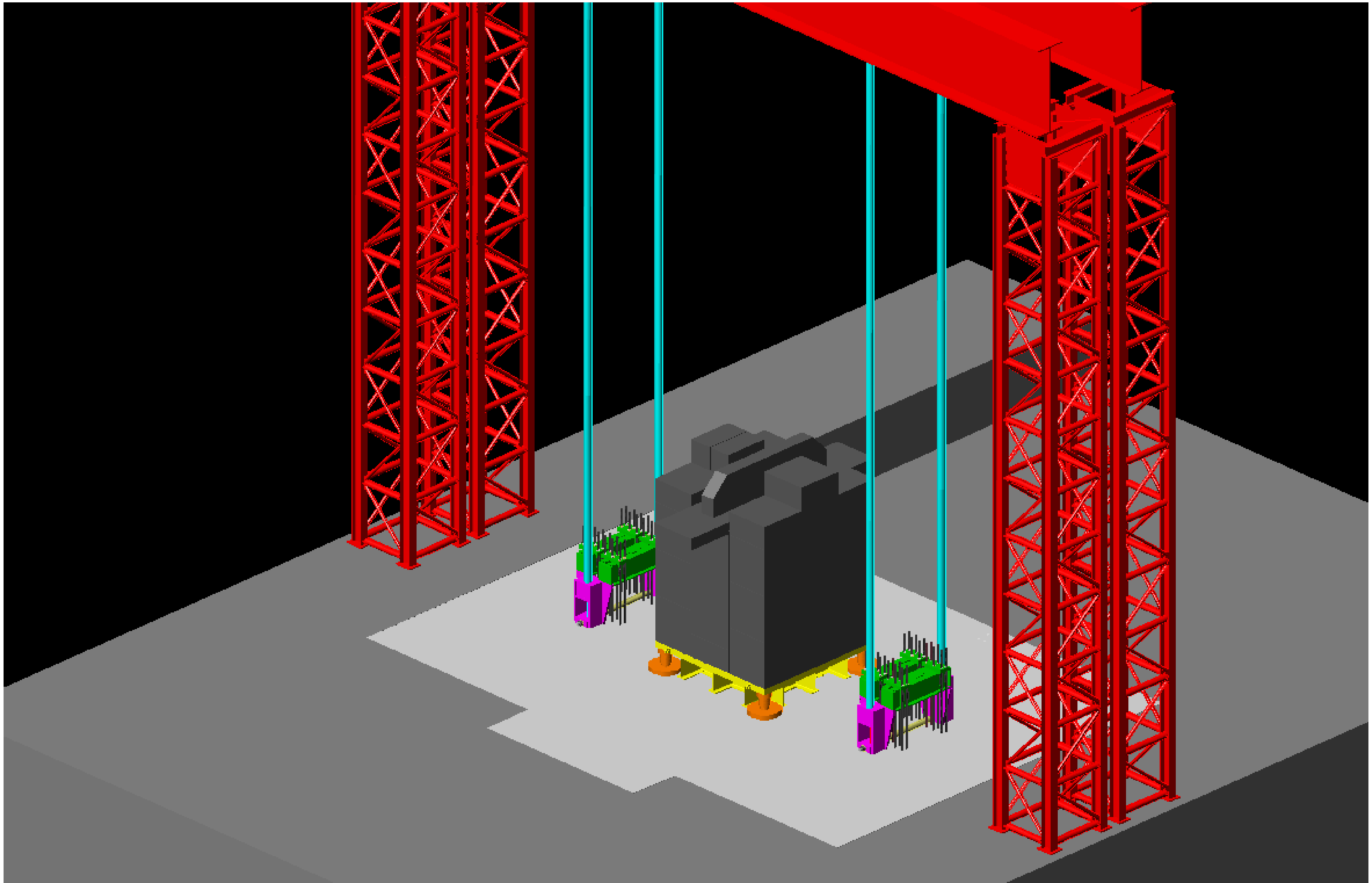
The experimental cavern is being equipped with ancillaries

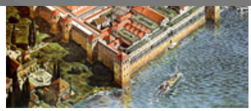
2005

Sept 2006

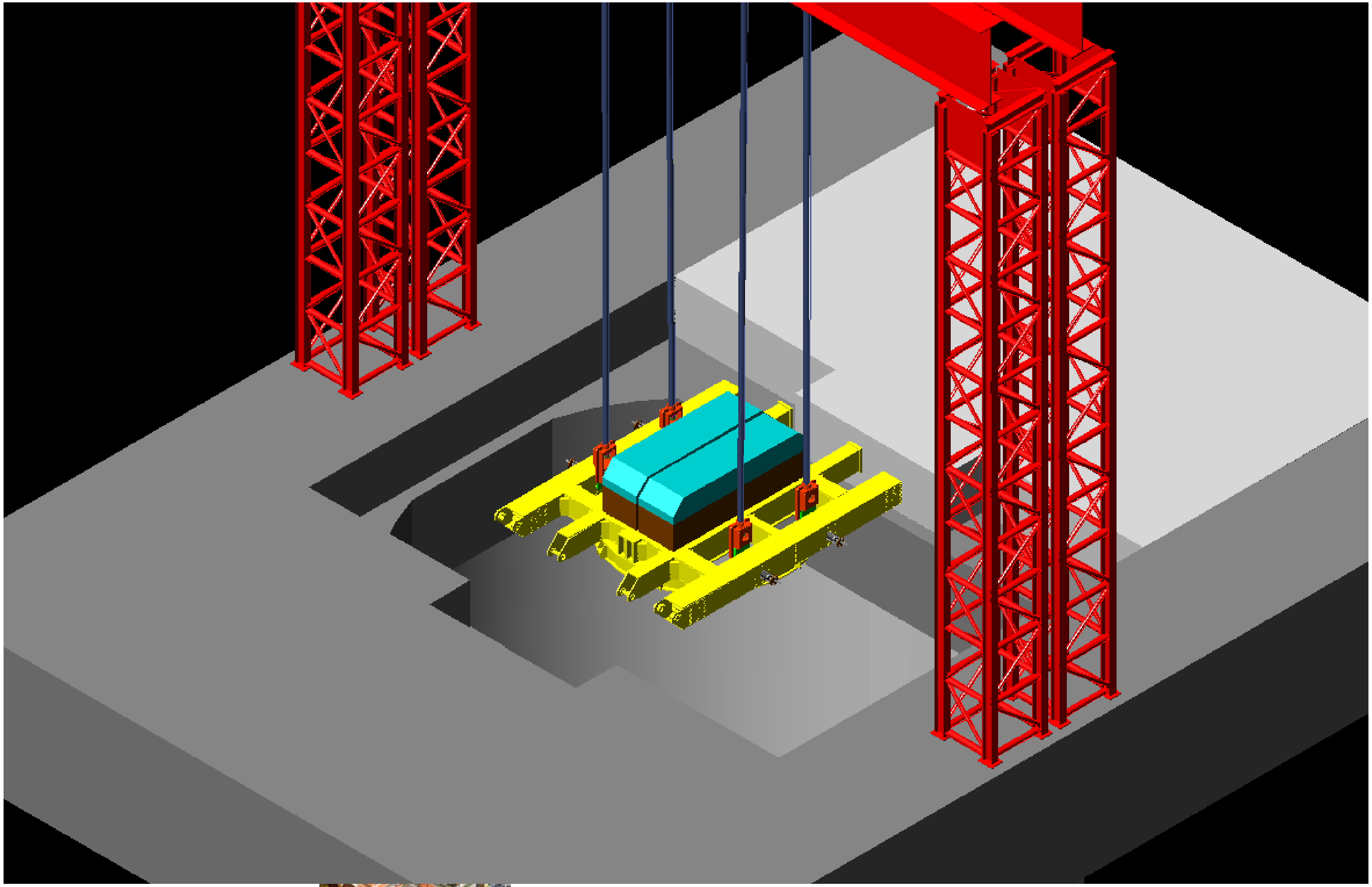


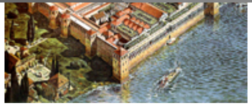
Main beam test at 2500 t pulling on the main plug (1700 t + 800 t additional)



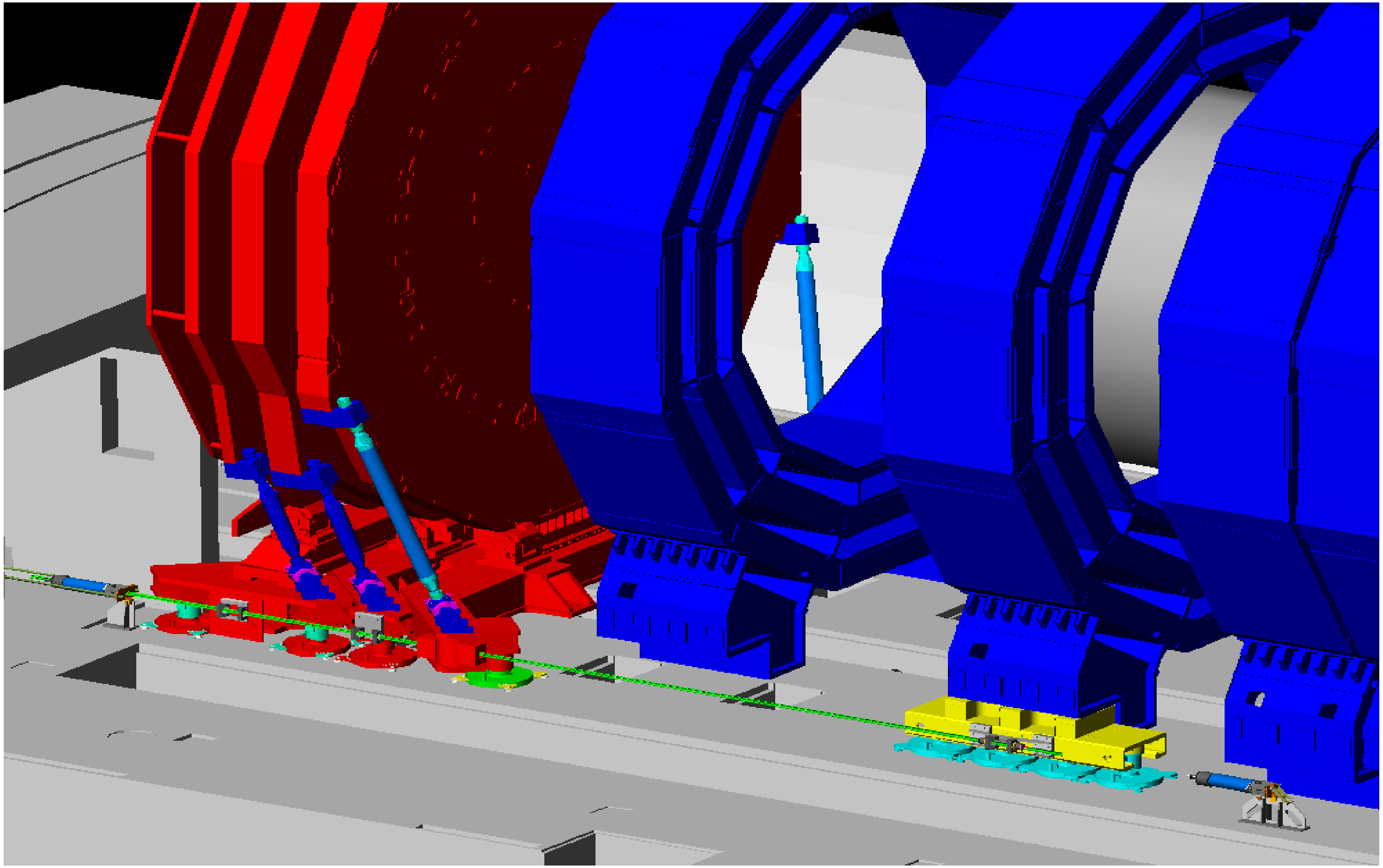


Lowering test with 250 t

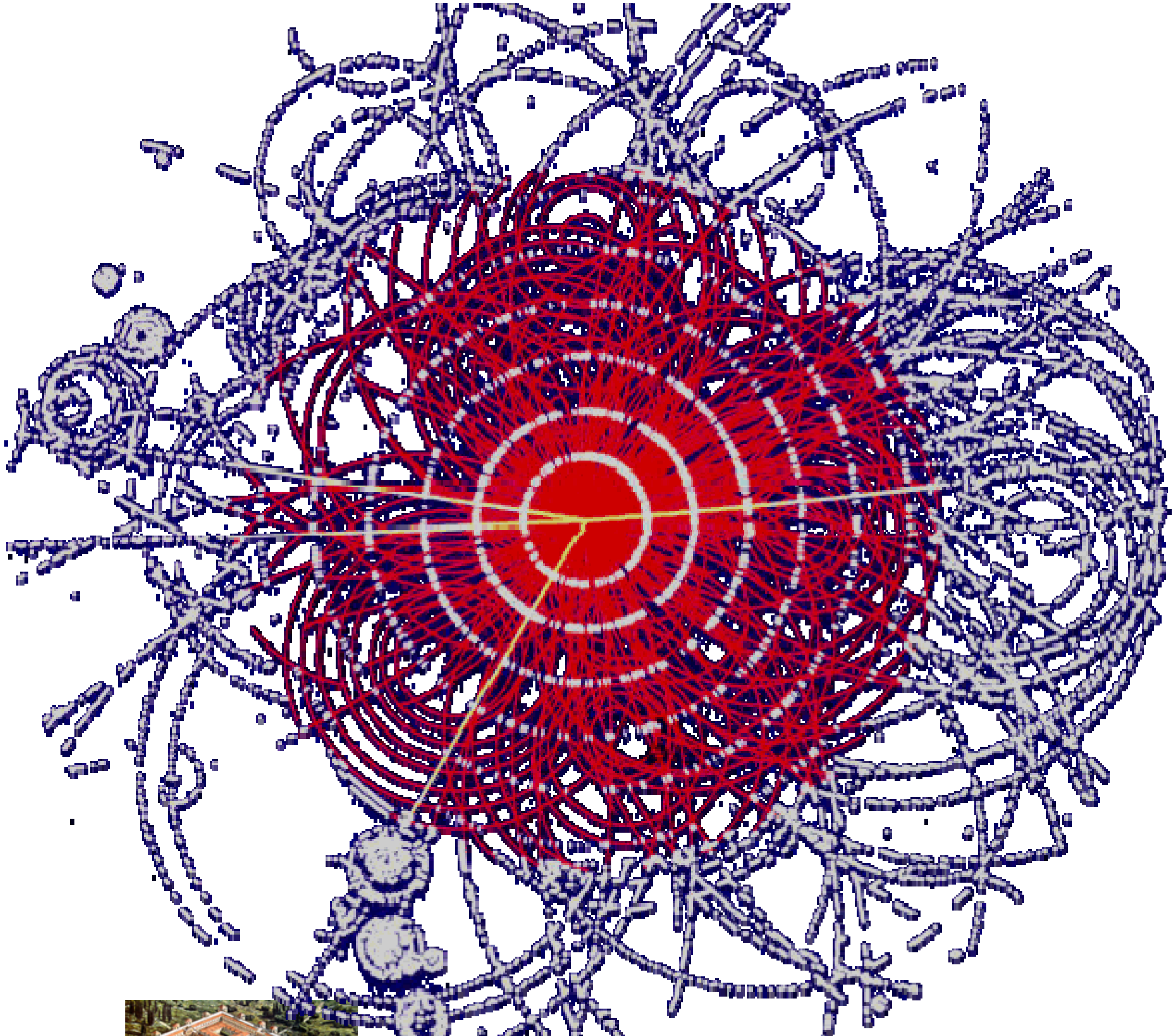




Jack system to open and close CMS in the UXC



...ready for physics in 2007



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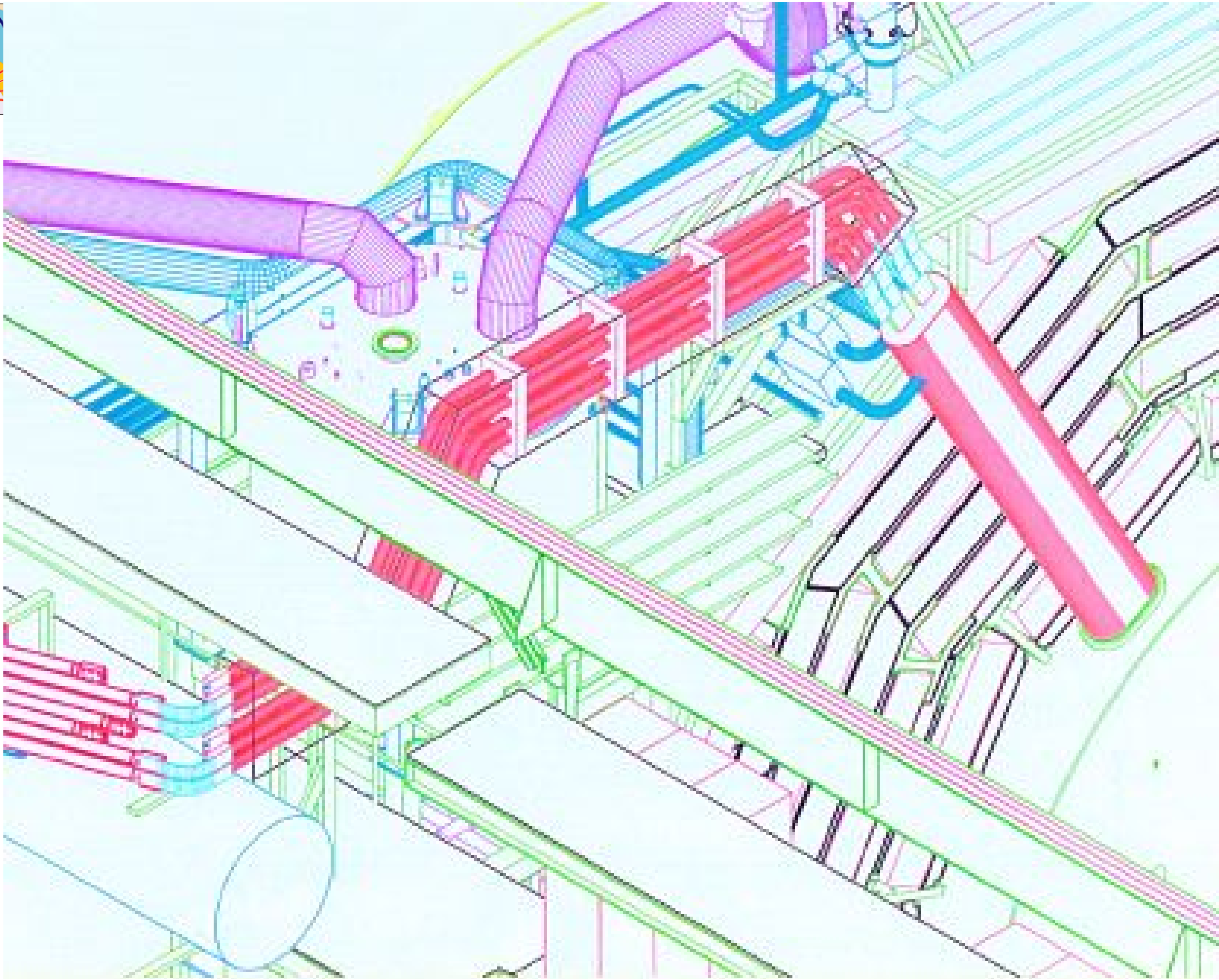
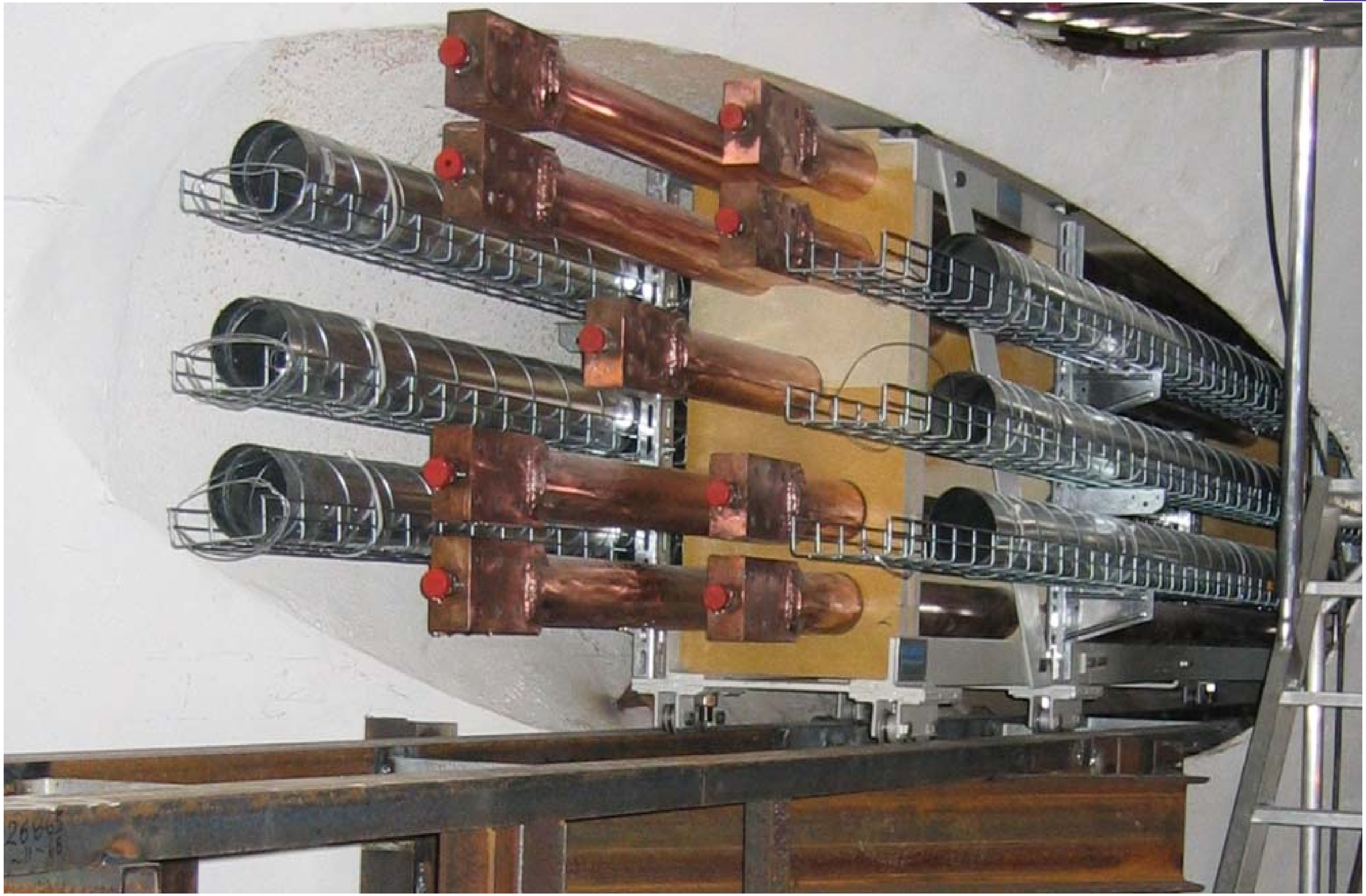
- The success of the Magnet Project, coupled with the Cosmic Challenge Test, is a major achievement for CMS

- All the Institutes are represented in the CMS Magnet and one of the efforts has been to give direct involvement to Instituites and Companies from every participating country



Copper Busbar in the pillar wall



Installation of Copper Busbar

Installation of Copper Busbar

Gold AWARD to Koncar

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Conclusions to LHCC(1)

- After 15 years from early design, R&D, pre-industrialization, 6 years of construction and about one year of installation, CMS coil has been tested successfully.
- From cryogenic, electrical and mechanical tests the coil fulfills all specifications and seems easy to operate.
- Installation of CMS detectors inside the experimental area can proceed.

Prospect for future (2)

- ATLAS central solenoid and CMS solenoid have used different techniques to achieve a high E/m ratio.
- There is a common proposal* to mix the two techniques to produce an even stronger conductor.
- This should allow the design of CMS-like solenoids with central field up to 5T.

* A. Yamamoto, D. Campi et al.

Conclusions (2)

- This good result open the way to the design of 5 T solenoids for future experiments.
- The way the CMS collaboration has been organized financially and technically to build the magnet seems a good model to follow.