DE LA RECHERCHE À L'INDUSTRIE

cea

THE ISEULT WHOLE BODY 11.7 T MRI MAGNET

Lionel QUETTIER

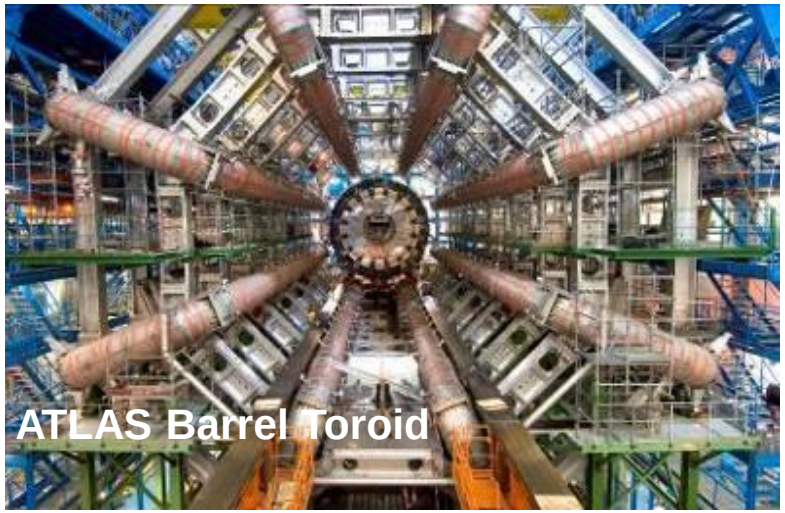
On behalf of the Iseult project team

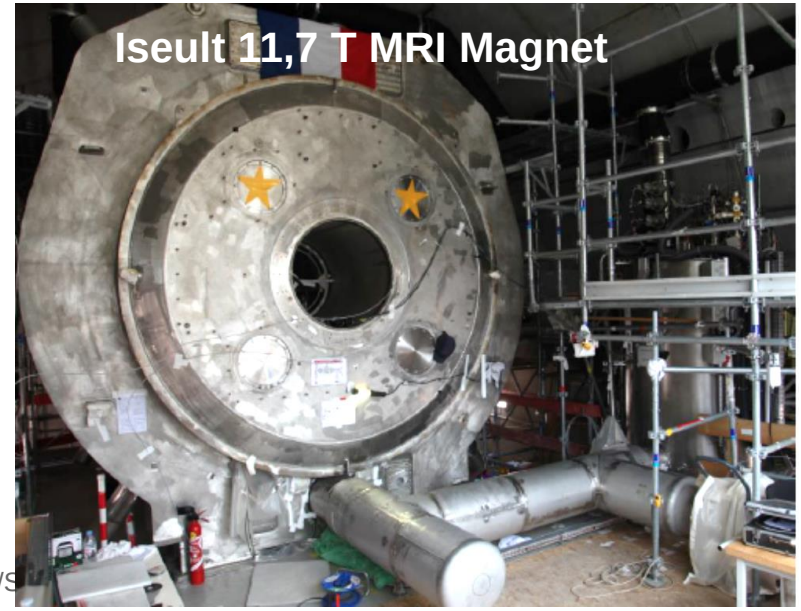
HIGH FIELD MAGNETS
FROM PARTICLE PHYSICS TO MEDICAL APPLICATIONS

30 years of history

1990s

LHC Experiments



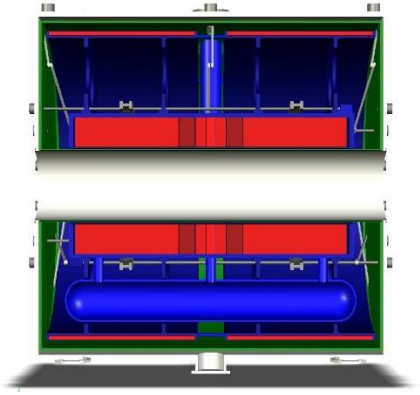


2010s

ISEULT 11.7 T MRI MAGNET
AN IDEA IN 2001…

The original idea

Pr. Denis Le Bihan CEA Neurospin

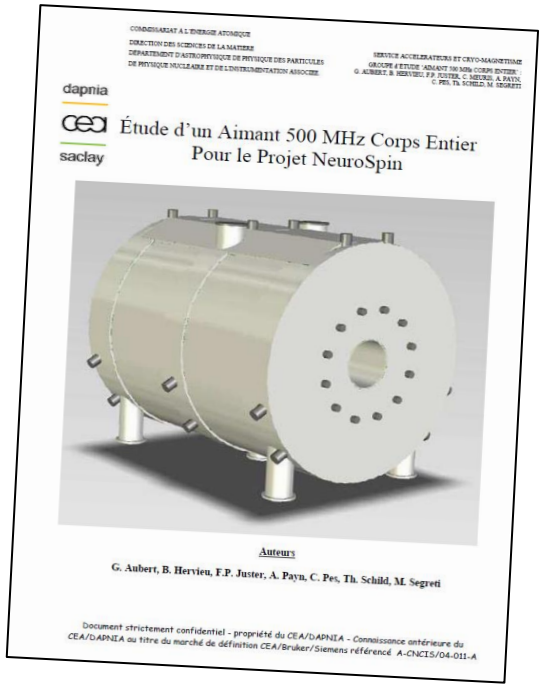


The initial specification

B_0	11.7436T (500 MHz)
Useful bore	900mm
Homogeneity Ø10cm	<0.1ppm
Stability	0.05ppm/h
10 gauss line inside magnet room	

A very preliminary magnet concept a few years later…July 2004

Size	Length 5m, Diameter 4m
Superconductor	64t (47t main coils, 17t compensation)
DP weigth	232kg (for main coils)
Cold structure	38t
Warm structure	48t
Whole system	153t



dapnia

cea saclay

Étude d'un Aimant 500 MHz Corps Entier
Pour le Projet NeuroSpin

Auteurs

G. Aubert, B. Hervieu, F.P. Juster, A. Payn, C. Pes, Th. Schild, M. Segreti

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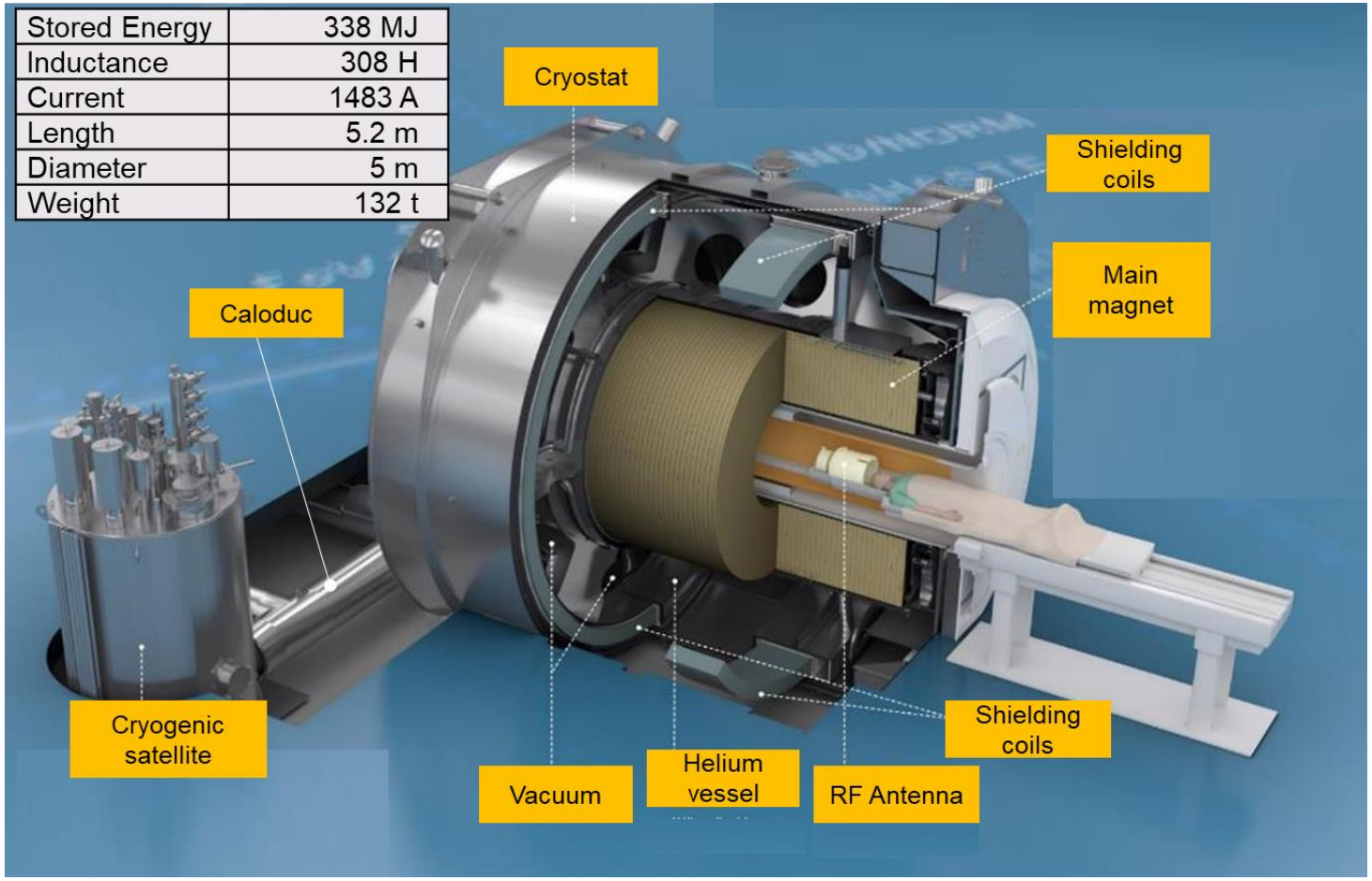
THE ISEULT MAGNET

A very challenging specification:

- **B0 / Aperture 11.72T / 900mm**
- **Field stability 0.05 ppm/h**
- **Homogeneity < 0.5 ppm on 22 cm DSV**
- **Stray field 5 G: 13.5 m axial, 10.5 m radial**

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Length	5.2 m
Diameter	5 m
Weight	132 t



Innovative solutions for a MRI magnet

- **170 NbTi double pancakes** for the main coil
- **2 NbTi shielding coils** to reduce the fringe field
- Cryostat for **superfluid helium at 1.8 K**, 1.25 bars
- **Dedicated cryorefrigerator (**80 l/h + 40 W @ 4.2 K)
- **Driven mode operation**, with two 1500 A power supplies for redundancy

ALL NEW CONCEPTS SUPPORTED BY MOCKUPS AND PROTOTYPES

Manufacturing techniques, mechanics, cryogenics,
quench analysis, electrical engineering…

CONDUCTOR DEVELOPMENT

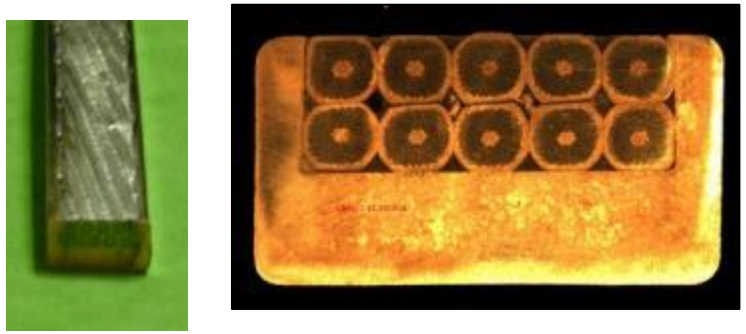
160 km of main coil conductor: 1500 A at 11.7 T and 2.8 K, 9.2 mm x 4.9 mm

60 km of shielding coil conductor: 2100 A at 5T, 1.8 K , 9.1 mm x 4.2 mm

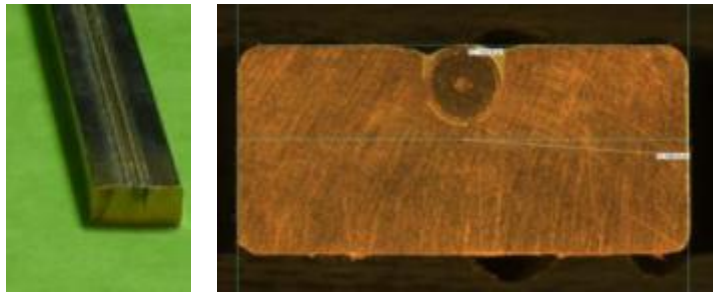
Manufactured by Luvata Waterbury, CT, USA,

LUVATA
A Group Company of MITSUBISHI MATERIALS

- *Critical current above the specification +10 %*
- *No cabling degradation*
- *Good dimensional reproducibility +/- 15 μm*
- *Yield strength > 250 MPa*



Main coil conductor : Rutherford cable with 10 Cu/NbTi strands in a copper channel using SnSb solder

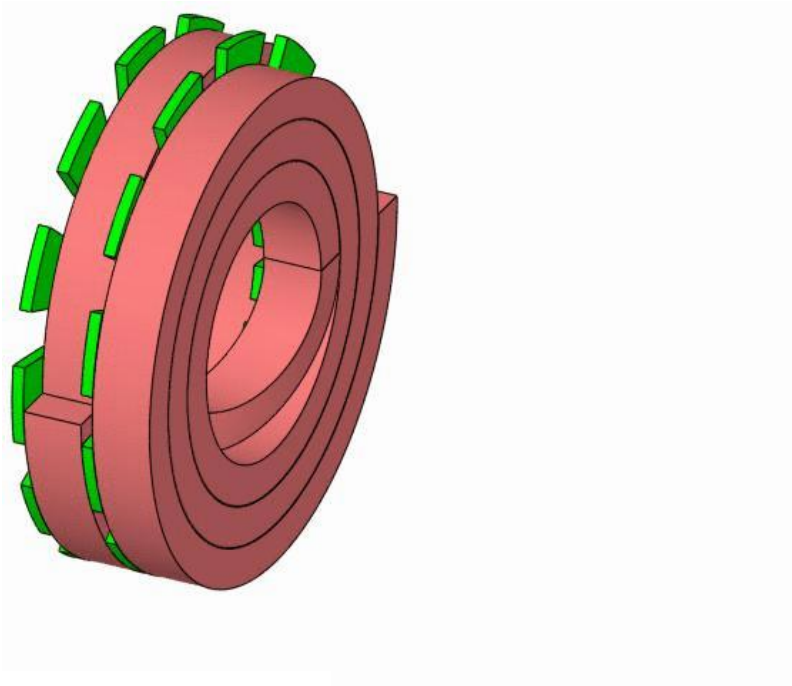


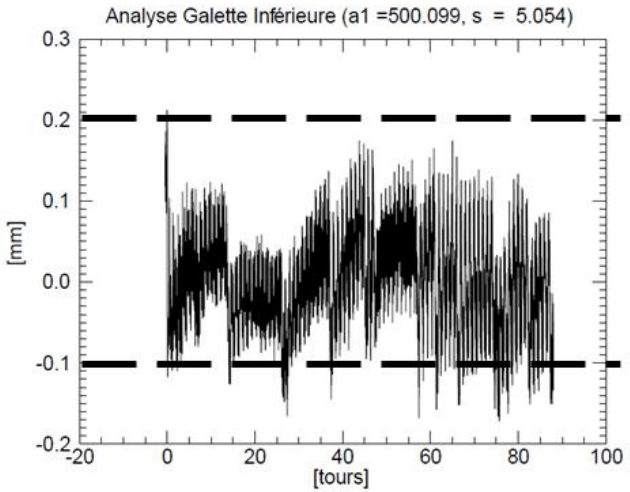
Shielding coil conductor: Cu/NbTi strand in a copper channel

MAGNET MANUFACTURING IN BELFORT (2010 – 2017)
DOUBLE PANCAKE WINDING TECHNIQUE

170 DG wound and controlled (external diameter of 2 m)

- 330kg each
- **Tolerance at inner bore +/-0,05mm**
- **Control of each +/-0,2mm**
- **Planarity 0,1mm**
- **Parallelism 0,2mm**





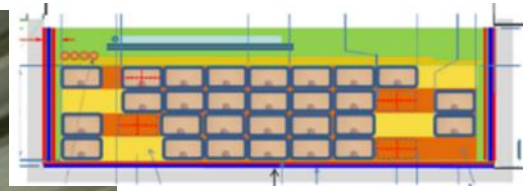
On-line control of the winding +/-0,2mm

MAGNET MANUFACTURING IN BELFORT (2010 – 2017)
DP STACKING AND CURING

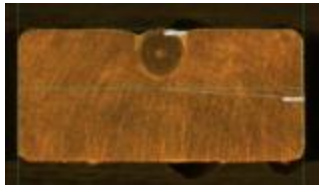
Position of each DP checked with laser tracker

Overall length of the main coil achieved within 1mm tolerance

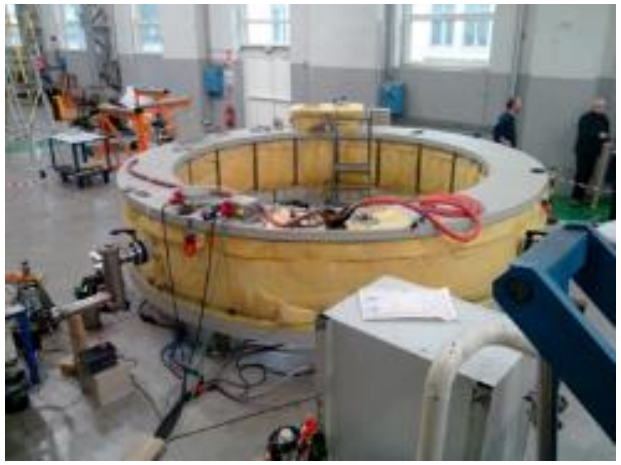
MAGNET MANUFACTURING IN BELFORT (2010 – 2017)
SHIELDING COILS MANUFACTURING



I/O radius	1.97 m/ 2.15 m
Layers	36
Turns per layer	53
Mass (1 coil)	12 tons
Peak field	3,86 T
Conductor	9,1 mm x 4,2 mm
Critical current	2100 A @ 5T @ 1.8 K



Shielding coil conductor NbTi WIC



Vacuum impregnation facility

Coil after resin impregnation

MAGNET MANUFACTURING IN BELFORT (2010 – 2017)
INTEGRATION MAIN COIL / SHIELDING COILS

MAGNET MANUFACTURING IN BELFORT (2010 – 2017)
CRYOSTATING

Helium vessel closure

Thermal shield assembly and MLI

Cryostat assembly

Final pulping and leak tests

2 WEEKS OF TRANSPORT FROM BELFORT TO SACLAY

Rotterdam
Eindhoven
Anvers
Bruxelles
Aix-la-Chapelle
Liège
Essen
Düsseldorf
Cologne
Bonn
Coblence
Francfort
Wiesbaden
Trèves
Sarrebruck
Amiens
Le Havre
Rouen
Caen
Paris
Saclay
Corbeil Essonnes
Orléans
Bourges
Nancy
Strasbourg
Belfort
Besançon
Parc naturel régional des Ballons des Vosges
Région de Lorraine

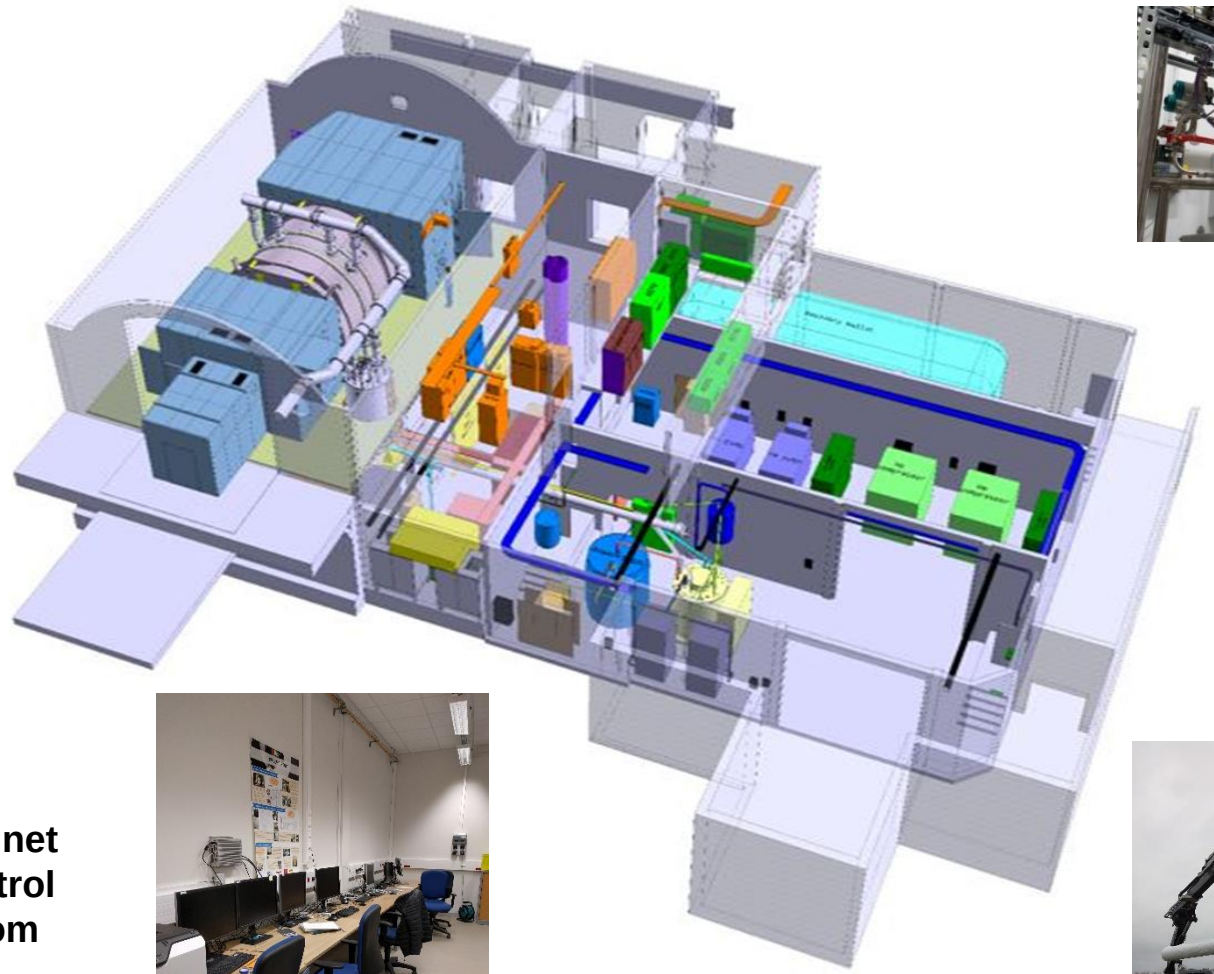
ARRIVAL AT SACLAY AND INSTALLATION IN THE ARCH

June 2017

A COMPLEX INSTALLATION TO OPERATE THE MAGNET

Power supplies

Cryogenic plant



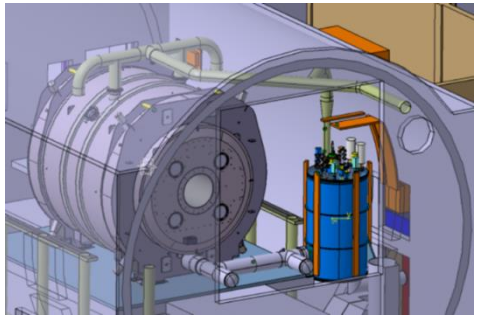
Vacuum Circuit

MSS/MCS racks

Dump Resistor

48 V batteries

Magnet control room

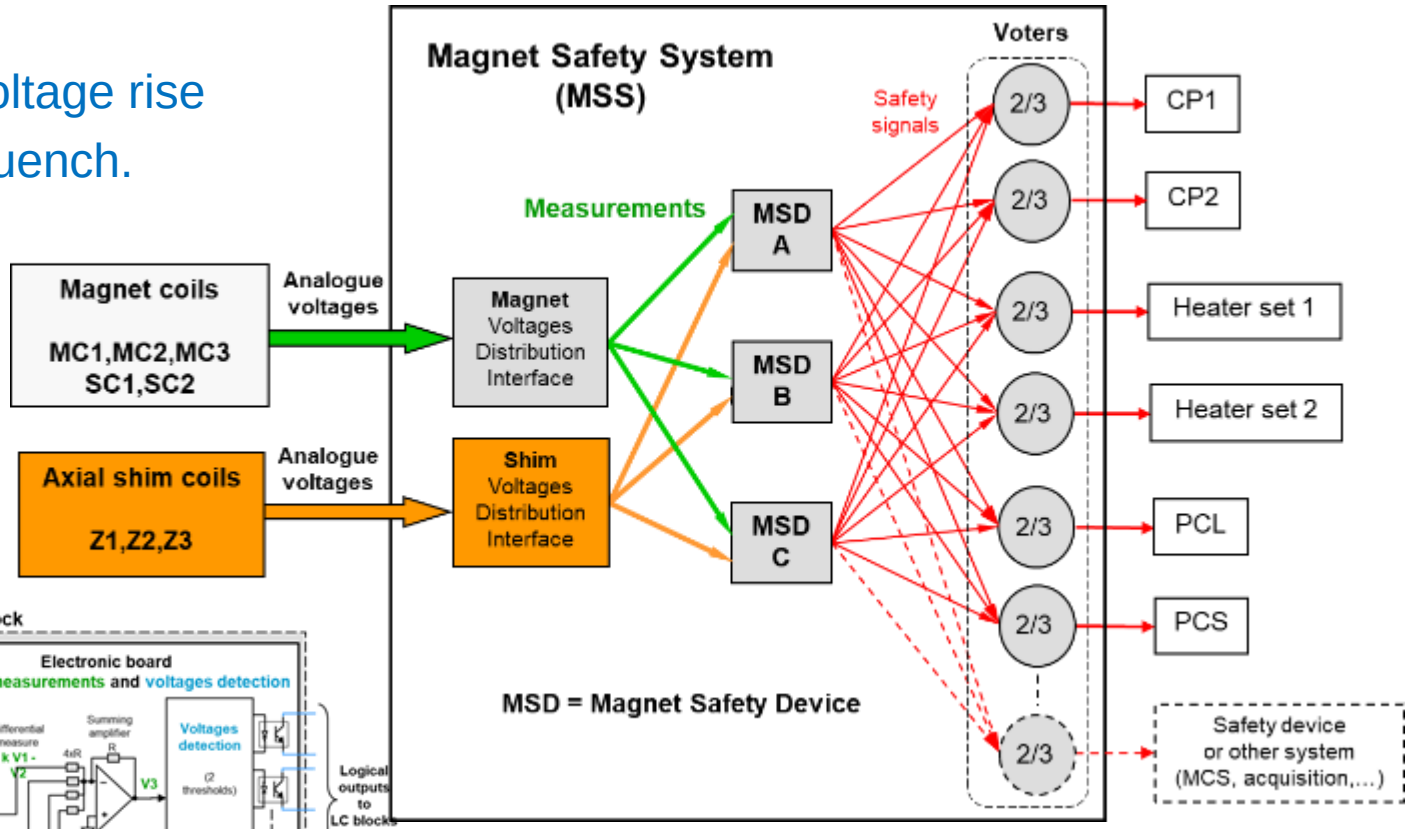


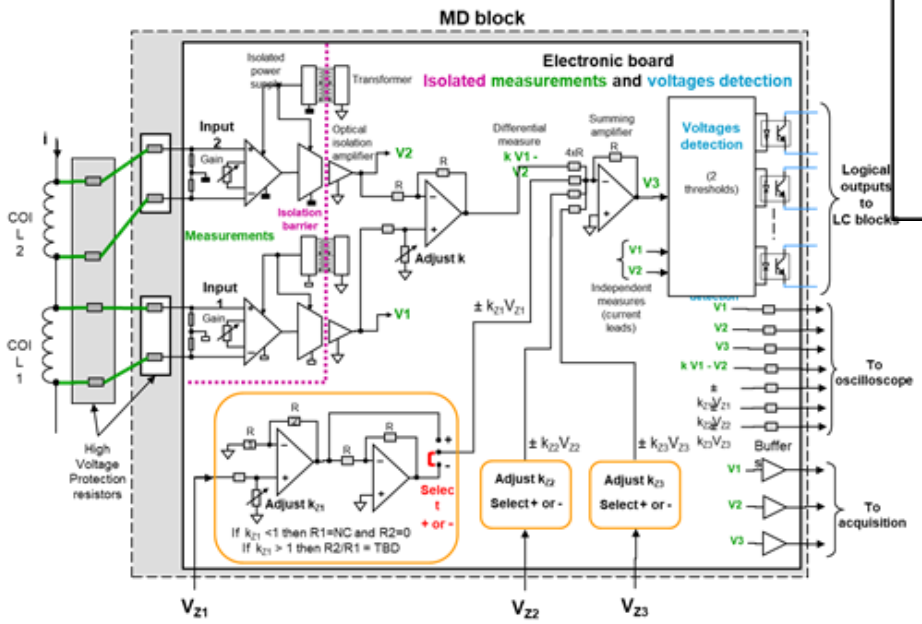
Cryogenic satellite

Commissioning started in 2010

MAGNET SAFETY SYSTEM – UNIQUE FOR A MRI SYSTEM

Detects the voltage rise due to a quench.

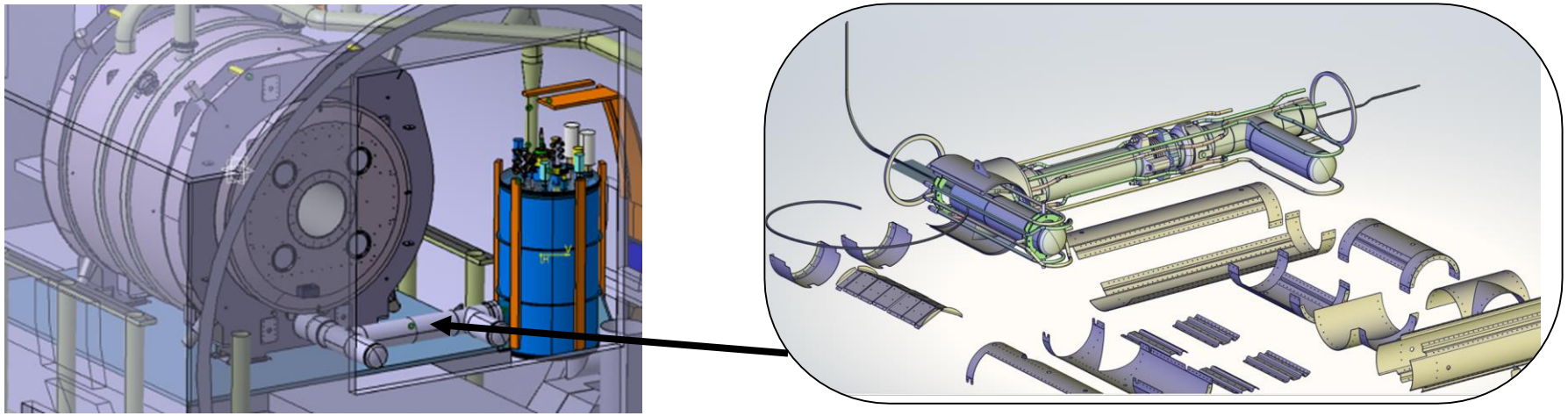




The reliability of MSS is always based on voting redundancy.

CALODUC ASSEMBLY – OCT 2017- OCT 2018

Caloduc : « umbilical cord » connecting the magnet with the cryogenic/electrical facilities



- **« Helium tight » connection of cryogenic circuits, electrical connection of superconductors and of the inner magnet instrumentation :** voltage taps (20), cryoshims (96), quench heaters (8), temperature sensors (96), strain gauges (24)

- **Complex mechanical structure** made of more than 200 parts (900kg mass)
  - Cold mass (1.8K)
  - Thermal Shield
  - Vacuum Vessel
  - Cooling circuits (TS and VV)

- **Mounting tolerances around 1 mm** ; to take into account the thermal shrinkage during cool down

CALODUC ASSEMBLY – OCT 2017- OCT 2018

Helium vessel assembly

Dye penetrant tests

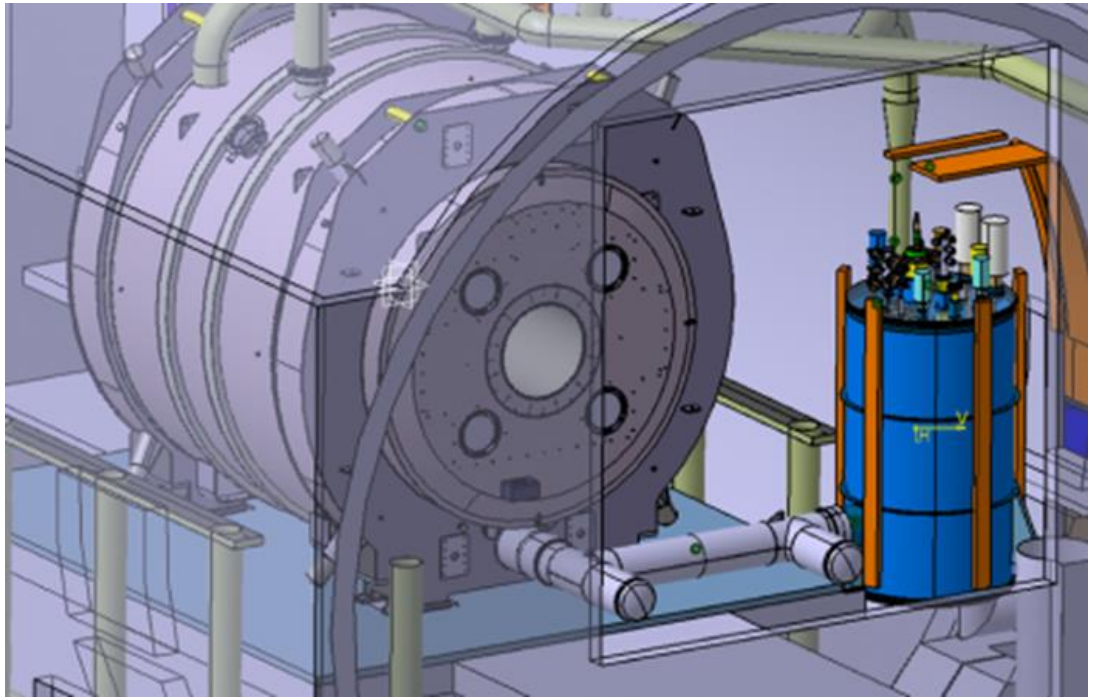
Cooling tubes local leak tests

MLI

Thermal shield

Vacuum vessel welding

CALODUC COMPLETION - OCTOBER 2018

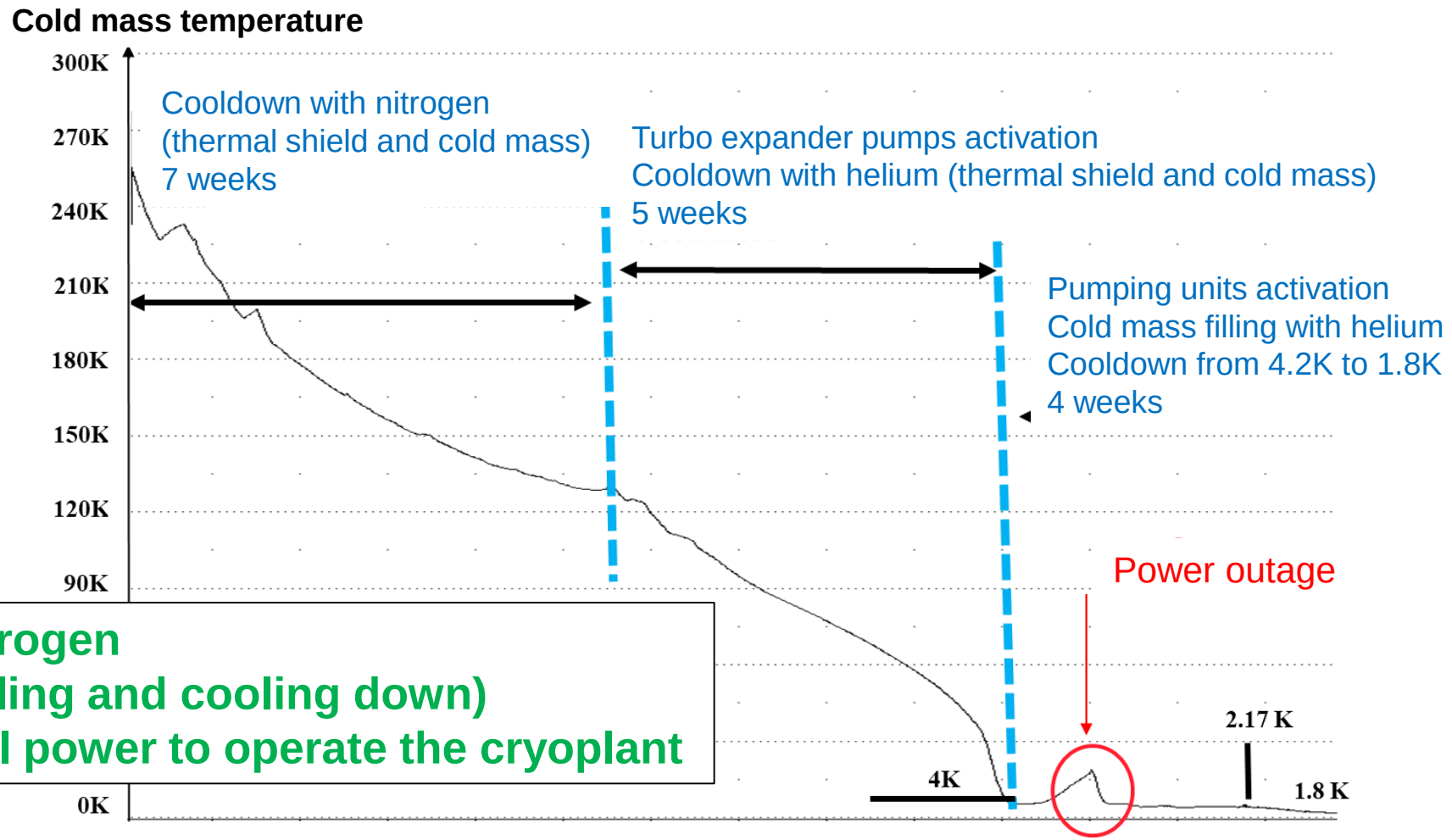


Final leak tests
(inner cooling circuits and vacuum vessel)

Leak rate of 5.10-9 mbar.l/s
on all the internal cooling circuits

COOLDOWN – 19 NOV 2018 – 7 MARCH 2019

- Huge mass to cool down: cold mass (105 tons @ 1.8K) + thermal shield (3.4 tons @ 55K)
- Coolding rate limited by the thermal gradients across the coils (50K max)



250 000 L liquid nitrogen
18 500 L helium (filling and cooling down)
150 kW of electrical power to operate the cryoplant

CRYO BUDGET

	Measured values
Liquefier parameters	**900W @ 55K (tranfer lignes + satellite)**
	40W @ 4.5K
	72 l/h @1.8K

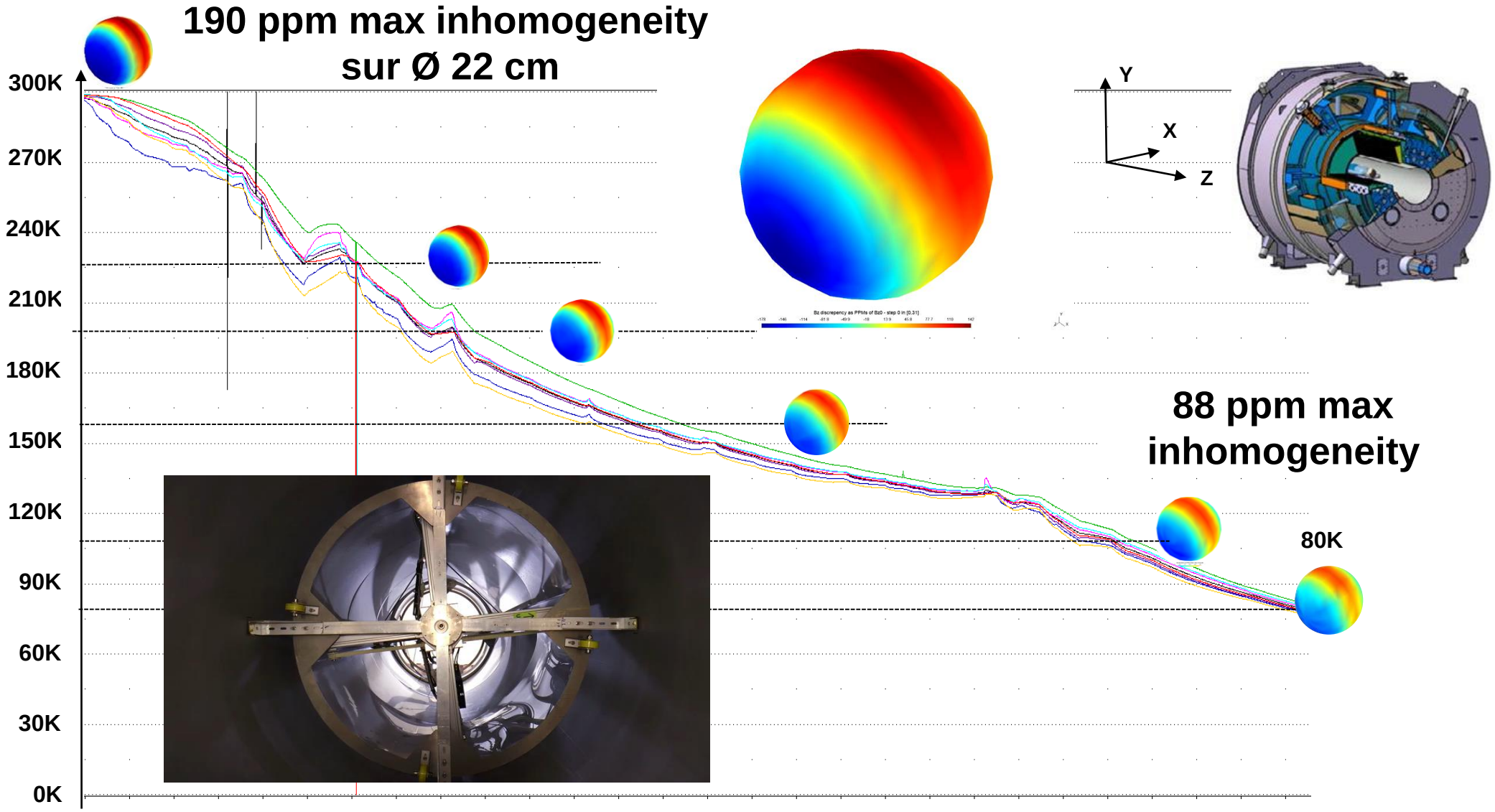
Item	Estimated	Measured
Magnet thermal shield @ 55K	570 W	**572 W**
Satellite + transfer lines @ 4.5K	27 W	**16 W (*)**
Cold mass (magnet + current leads) @ 1.8K	35 l/h	**17 l/h**

(*) without the transfer lines (too difficult to be measured accurately)

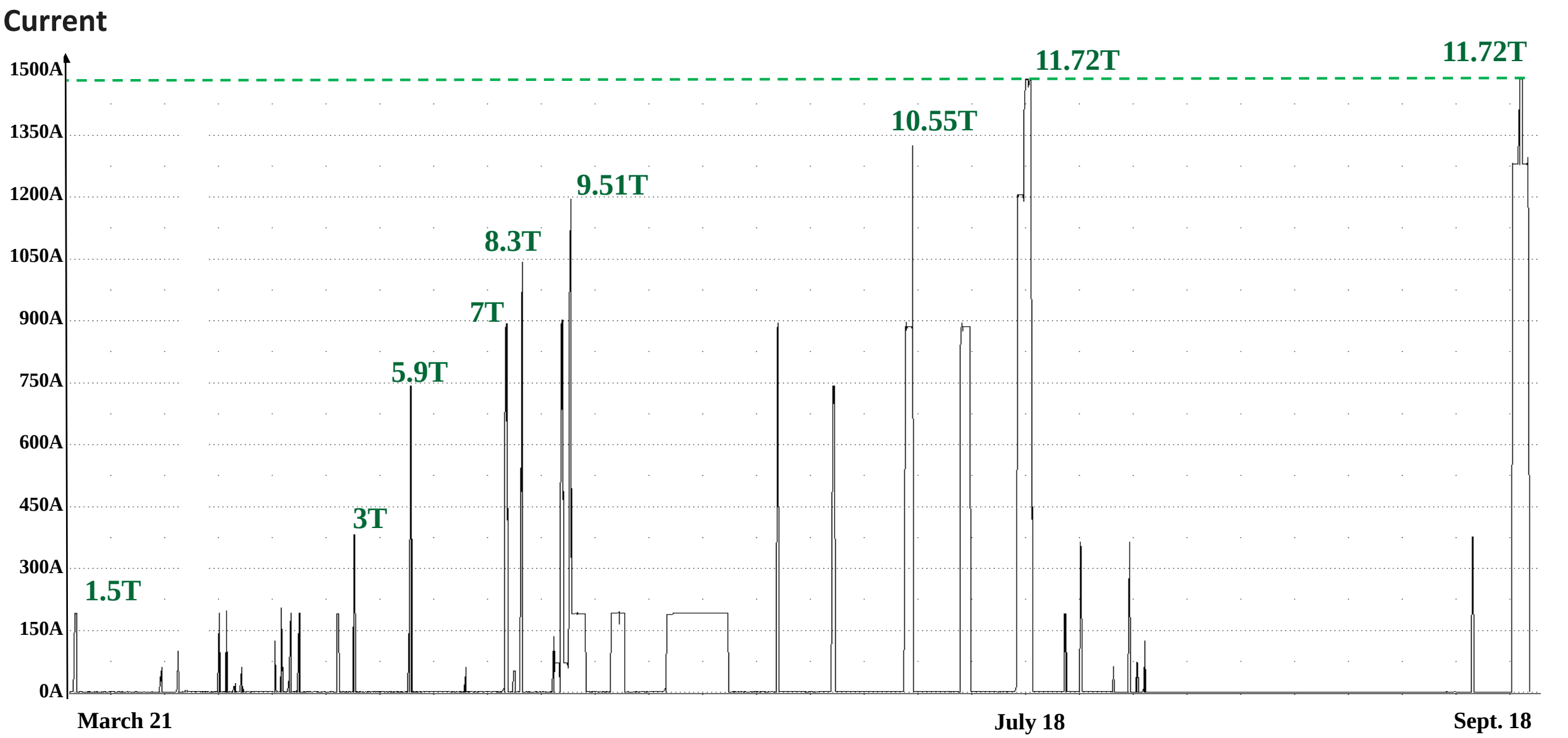
The cryoplant should be able to handle safely the additional thermal losses deposited when all the imaging system is in operation (especially during the gradient coil sequences in DC mode).

FIELD MEASUREMENTS DURING THE COOLING PHASE

COLD MASS TEMPERATURE



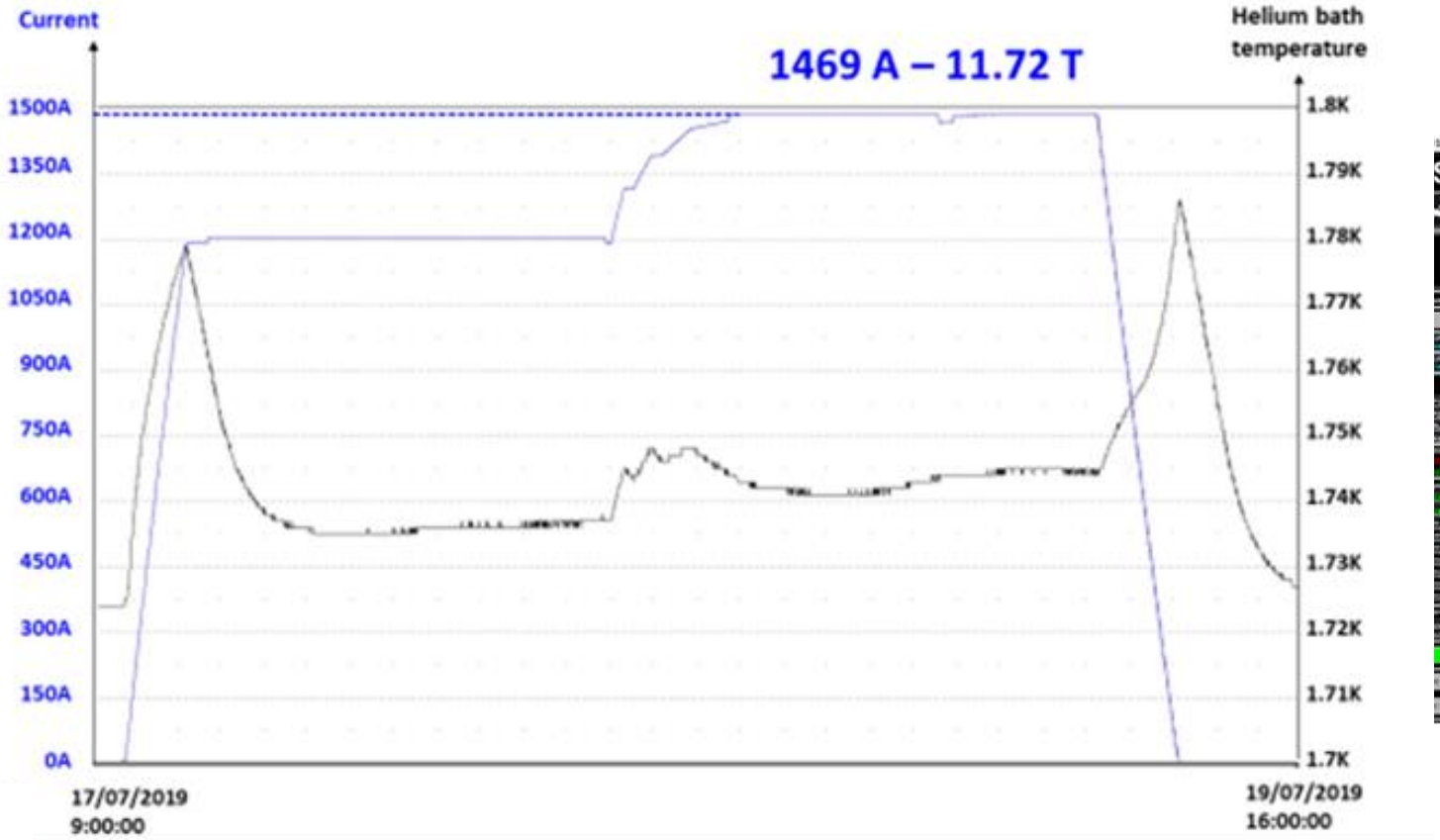
STEP BY STEP ENERGIZATION

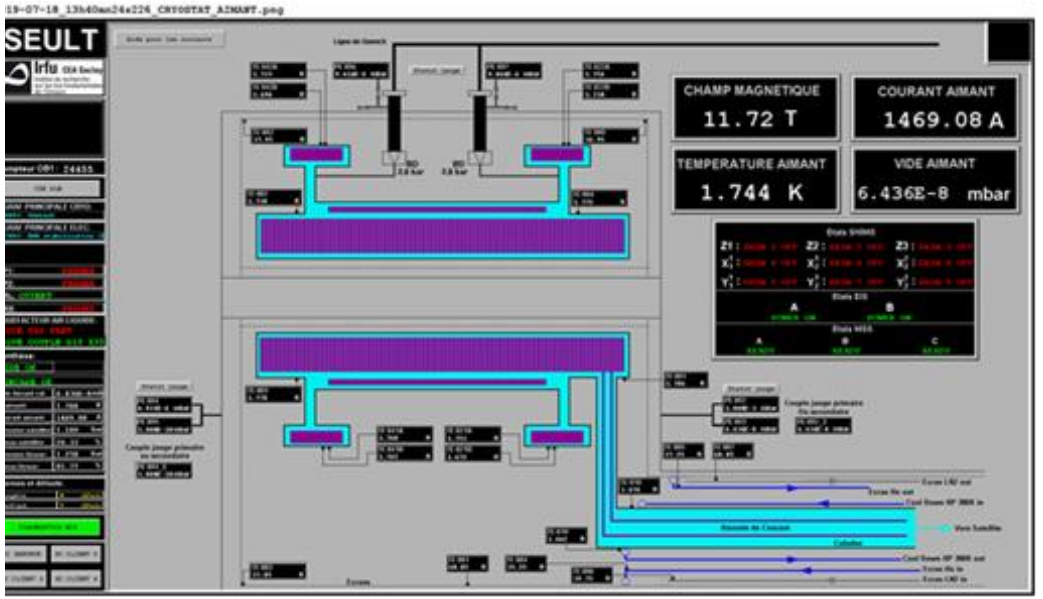


11.72T – JULY 18TH 2019

Test duration of 2 days

- Ramp-up in 30 hours
- Switching test between the two power supplies
- Plateau of 18 hours @ 11.72T
- Slow discharge in 3 hours to unload the magnet

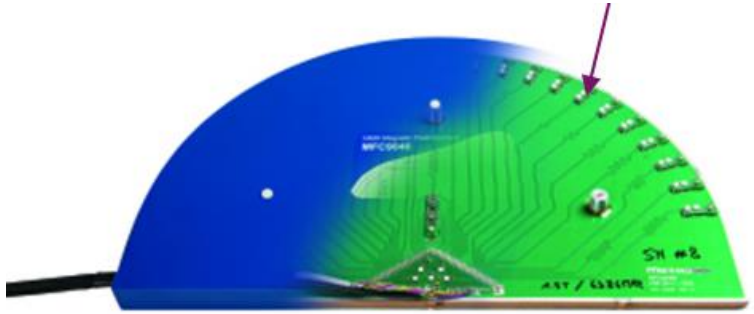




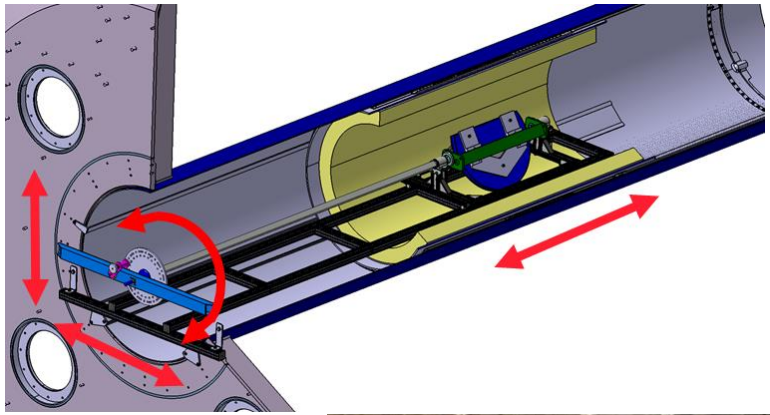
FIELD HOMOGENEITY MEASUREMENTS

- Magnetic measurements @ 1.5T, 3T, 7T and 11.72T

NMR probe



New Metrolab camera 499MHz
- 40 NMR probes
- 50 cm diameter



Mechanical system designed to allow translations/rotations of the probe array

FIELD HOMOGENEITY MEASUREMENTS

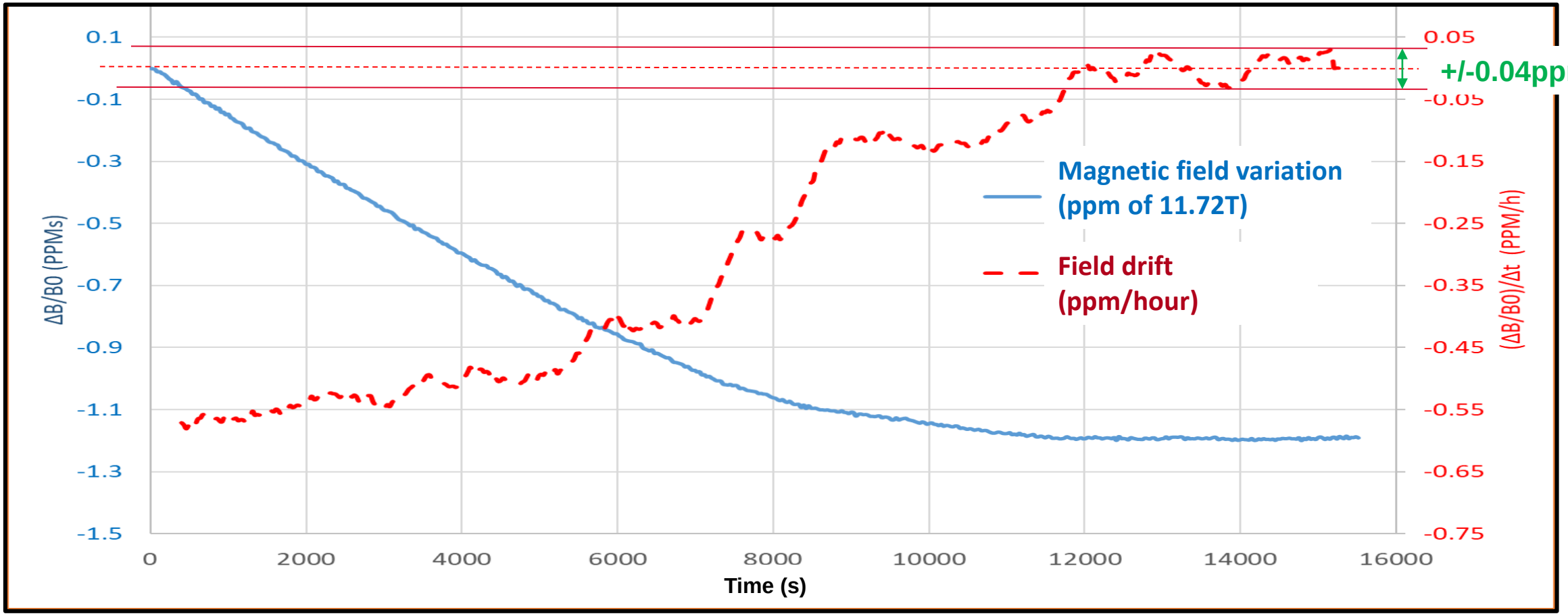
Magnetic field spherical harmonics expansion:

$$\frac{B_z(r,\vartheta,\varphi)}{B_0} = 1 + \sum_{n=1}^{\infty}\left(\frac{r}{r_0}\right)^n \left[Z_n P_n(\cos\vartheta) + \sum_{m=1}^{n}\left(X_n^m \cos m\varphi + Y_n^m \sin m\varphi\right) W_n^m P_n^m(\cos\vartheta) \right]$$

	300K	1.8K 1.5T	1.8K 3T	1.8K 7T	1.8K 11.7T	Cryoshim power
Z_1 [PPM]	-132	-16	-7	-5	9	+/- 300
Z_2 [PPM]	-105	-22	-16	-15	-17	+/- 70
Z_3 [PPM]	20	2	2	2	2	+/- 10
X_1^1 [PPM]	-1	22	21	22	24	+/- 32
Y_1^1 [PPM]	**59**	**63**	**59**	**60**	**62**	**+/- 32**
X_2^1 [PPM]	-	2	2	2	2	+/- 14
Y_2^1 [PPM]	-	-6	-6	-6	-7	+/- 14
X_2^2 [PPM]	-	-1	-1	0	-1	+/- 10
Y_2^2 [PPM]	-	0	-1	-1	-1	+/- 10

- **Very good agreement between the measurements (1.5T, 3T, 7T, 11.7T)**
- Field homogeneity spec achievable using the available cryoshimming power, except for Y11 (iron shims)

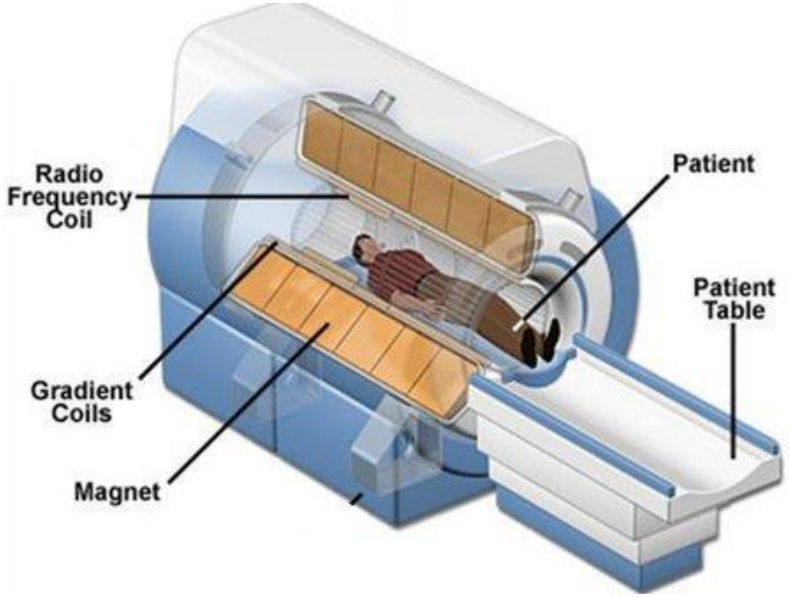
FIELD STABILITY

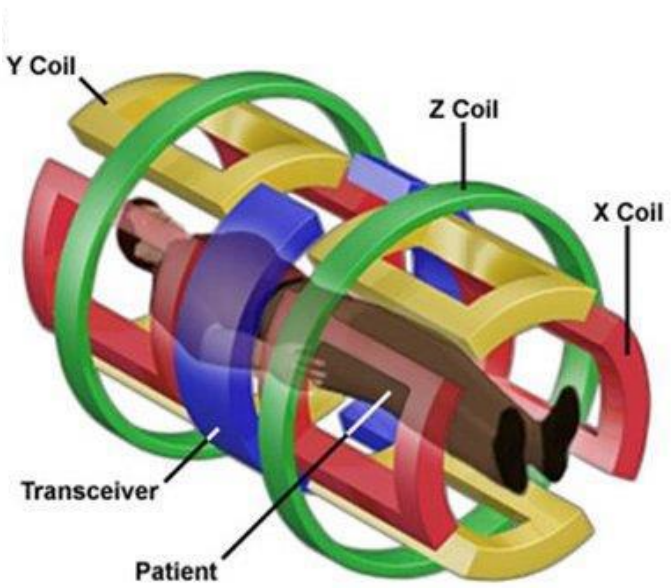


- Magnetic field drift adjusted using a fault current limiter
- **0.04 ppm/h obtained after only 4 hours of tests @ 11.72T (vs. spec 0.05ppm/hour)**
- Final setup will have to be done for at least one week

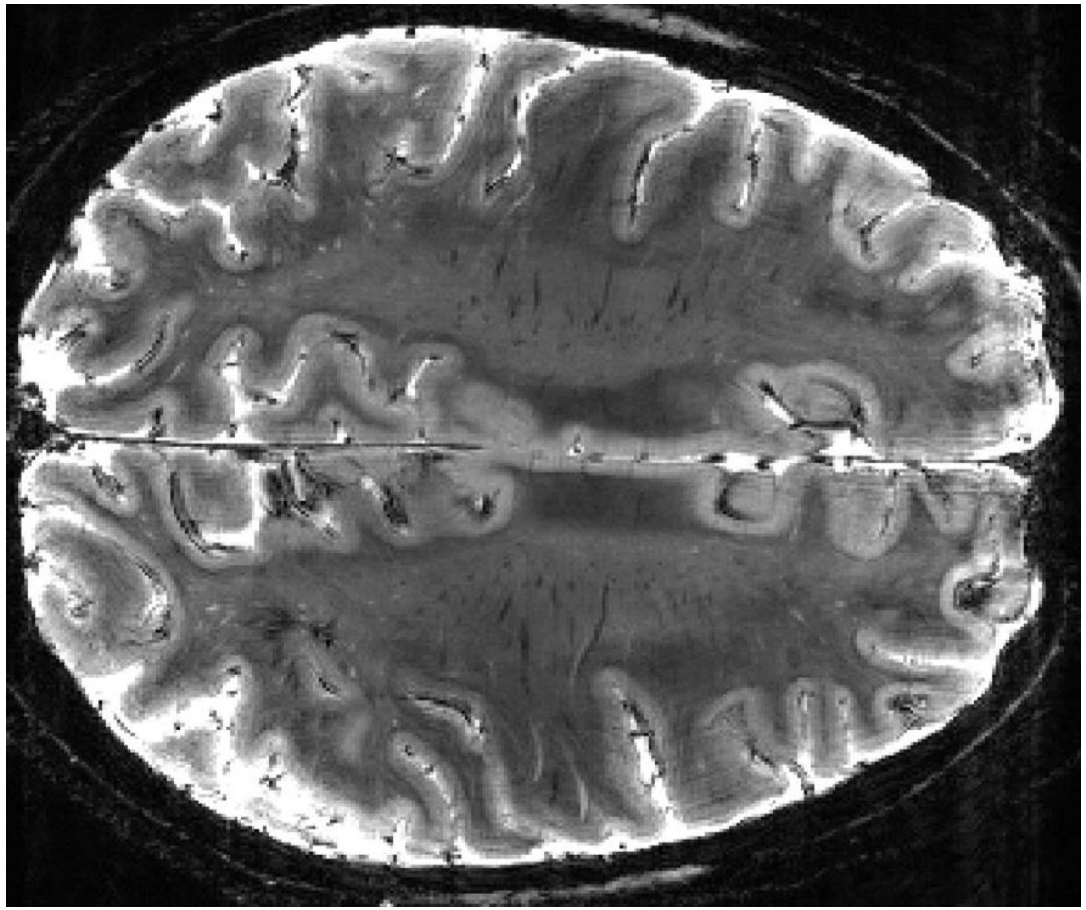
FINAL COMMISSIONING STEPS

- Installation of the MRI equipment (Gradient coils, RF antenna), of Faraday cages and of the patient bed
- New energization step by step
  - Adjustment of the field homogeneity (iron shims – cryoshim) / stability
  - Commissioning of the high-availability control and protection systems
  - Tests of the GC *vs*. magnet interaction
  - Final ramp-up to 11.75T and final shimming





First images of fruits, phantoms to setup the Iseult MRI system….



Brain image at 7T
(courtesy of Neurospin)

After 20 years, the brain first image @ 11.72T !!!

UHF MRI PARK EVOLUTION 2001-2019

2001
- 3T : ≈ 100 systems
- 2 systems 7T WB
- 1 system 8T WB

2019
- 7T : >70 systems installed (3 in France) – 6 to 10 new units per year

- **1 system 8T WB: Ohio State Univ (80cm)**

- **6 systems 9.4T WB: Minneapolis (65cm), Chicago (80cm), Tübingen (82cm), Jülich (90cm), Maastricht (82cm) Beijing (83cm)**

- **1 system 10,5T WB: Minneapolis – 88cm – passive shielding / images on human brain since 2018**

- **3 projets WB 11.7T:**
  - **Iseult – 90cm – active shielding / commissioning in progress**
  - **NIH (Bethesda): 68cm – passive shielding / ready for cooldown on site**
  - **NRI (Seoul): 70cm – passive shielding / delivered in may 2019**

Emerging projets 14T and more: Heidelberg, USA (Boston, Stanford), China (Beijing, Shenzhen)

Warm thanks to all the people involved in this crazy adventure !!!