IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P3 given at the virtual ASC 2020, October 28, 2020.

The Quest for Ultra-High Fields in Brain MRI:

The Iseult 11.7 T Whole Body Magnet

and its expected impact on MRI research

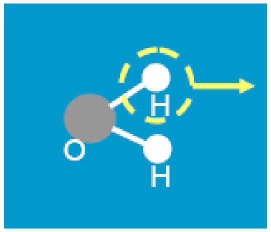
Pierre Vedrine
CEA Paris Saclay

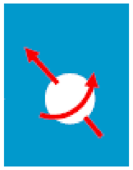
ASC 2020 VIRTUAL CONFERENCE Oct 24 – Nov 7 2020

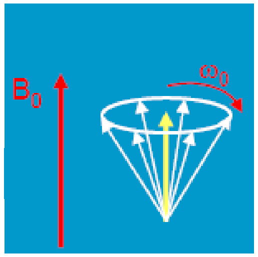
MAGNETIC RESONANCE IMAGING (MRI) POWERFUL TOOL TO EXPLORE THE BRAIN

1937 Rabi (Nobel Prize 1944) - resonance method for recording magnetic properties of atomic nuclei
1940 Zavoyski – discovery of electron paramagnetic resonance
1946 Block, Purcell (Nobel Prize 1952) – developments of new methods for nuclear magnetic precision measurements, and related discoveries
1973 Lauterbur (Nobel Prize 2003) – First MR images on samples
1977 Mansfield (Nobel Prize 2003) – First clinical MR images

- NMR measures magnetization of atomic nuclei in the presence of external B_0 magnetic field
- Particles with mass (proton) spin on their axis at Larmor frequency
- Signals are obtained from the NMR observation of proton in body water







Larmor frequency ($\omega > \gamma$ Bo)

ω is the precession frequency (Hz)

γ is the gyromagnetic ratio

Spin precession around Bo direction

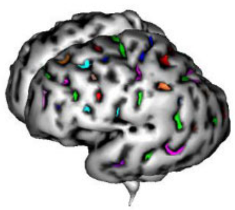
"Why NMR and MRI Need Ultra-high Field Superconducting Magnets: A Biomedical Research Perspective"

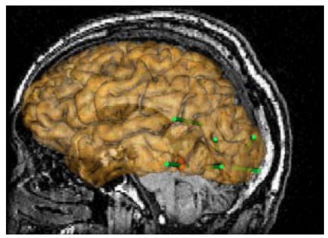
Joanna Long, University of Florida, National High Magnetic Field Laboratory

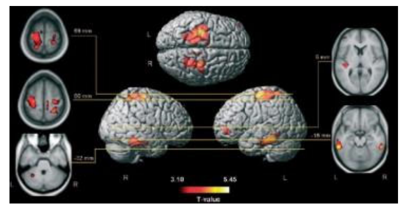
Plenary Session Tuesday, November 3rd 3:45 pm-4:45 pm

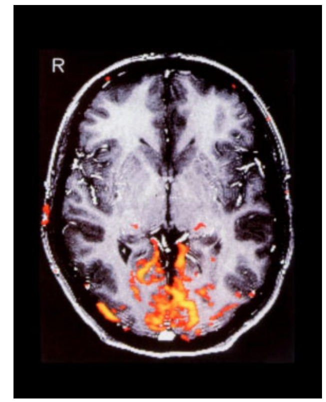
MEDICAL IMAGING AND NEURO-IMAGING

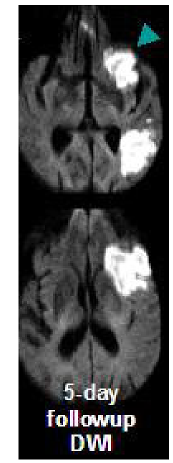
One of the best tool to study the human brain











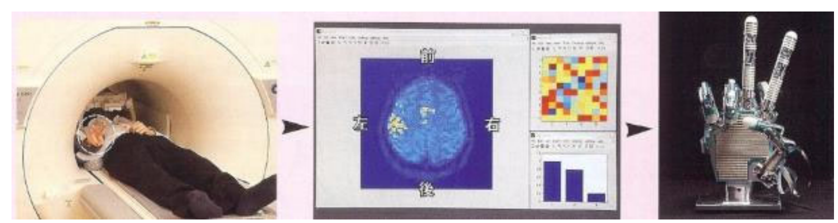
Health

- Neurology / Neurosurgery
- Development, aging, rehabilitation surgery
- Psychiatry, mental disorders

Neurosciences ...
structures & functions of the brain

Interaction, society

- Social behavior and culture, art, ..
- Human-Computer Interaction
- Learning, education, ...



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In Recent Decades Neuroscience Made Extraordinary progress

Human brain singularity

Pathological brain singularity

Cognitive Neurosciences

Clinical Neurosciences

Neuroimaging

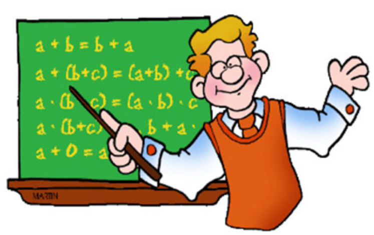
Physics, Electronics

Medicine & Biology

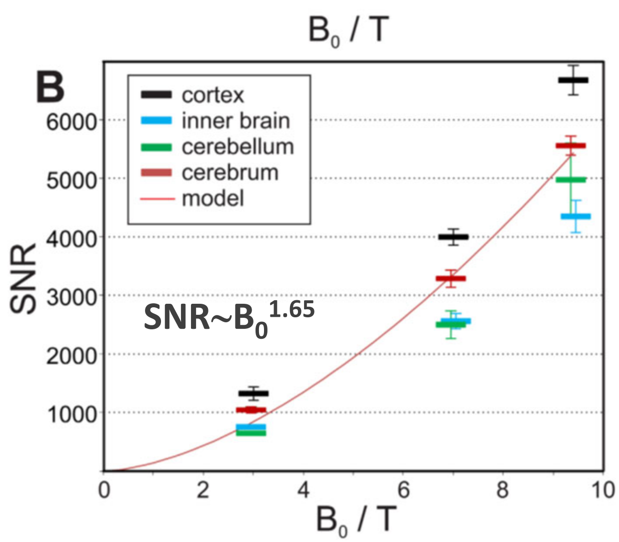
Mathematics & Statistics

Image Processing

Psychology & Sociology



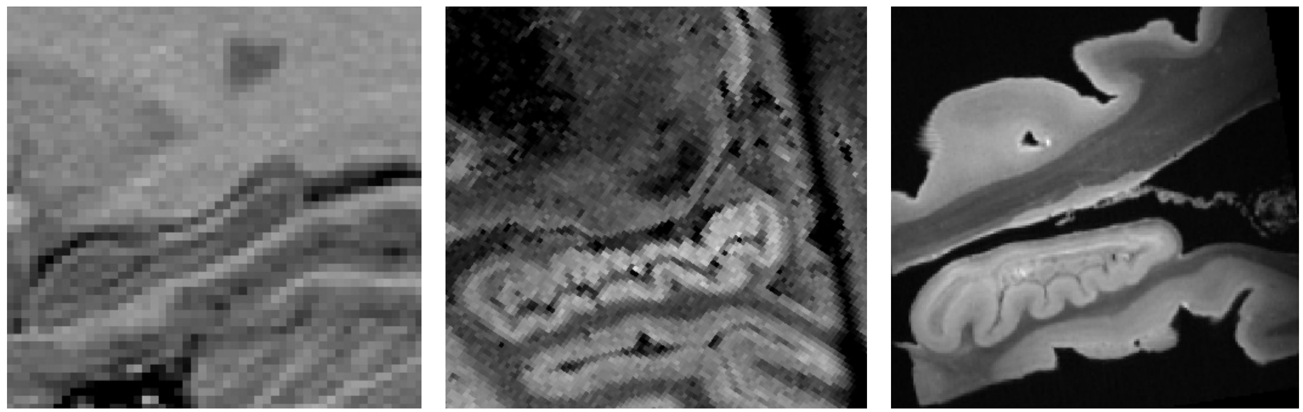
SNR GAIN ∝ B0 : CLINICAL RESEARCH APPLICATIONS



Pohmann et al.
Magn Reson Med 2016;75:801–809

Example of a human hippocampus image - Courtesy Neurospin/CEA

3T **7T** **11.7T (post-mortem)**



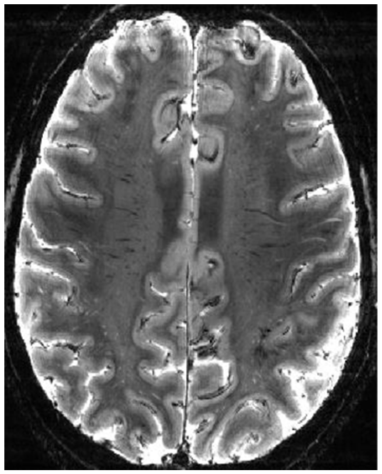
1 to 2 mm resolution | 0.5 to 0.3 mm resolution | 0.1 to 0.2 mm resolution

At the ultra-high spatial resolution provided by 7T and soon 11.7T MRI :

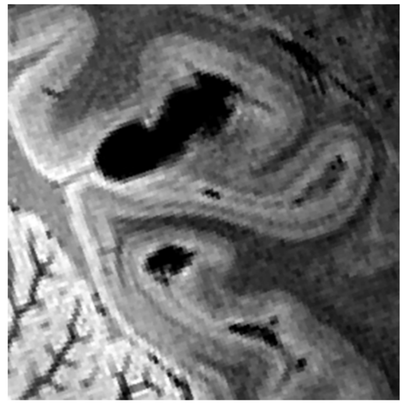
⇒ **High accuracy segmentation of the hippocampus becomes possible!**

⇒ Highy interesting information for clinical research : Alzheimer's Disease, epilepsy, schizophrenia …

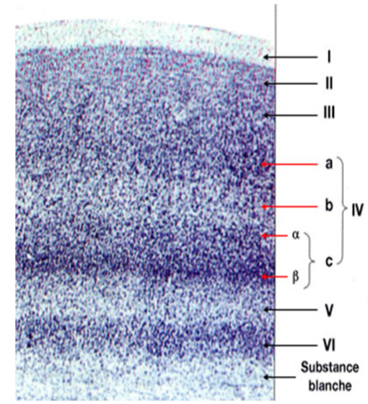
SNR GAIN AND FUNCTIONNAL SENSITIVITY ∝ B0 : NEUROSCIENCE APPLICATIONS



Anatomical 7T MRI (T2*)

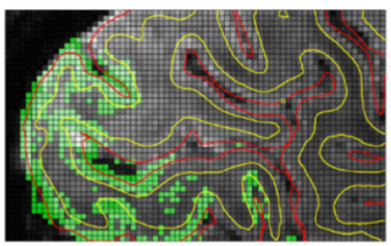


Zoom on the cortical layers



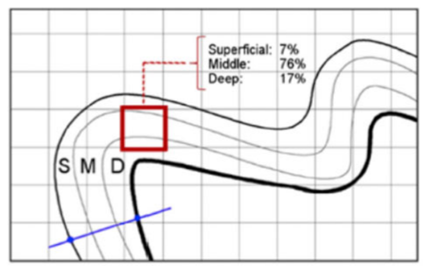
Cortical layers observed in histology

A.



7T functional MRI: 800 μm isotropic

B.



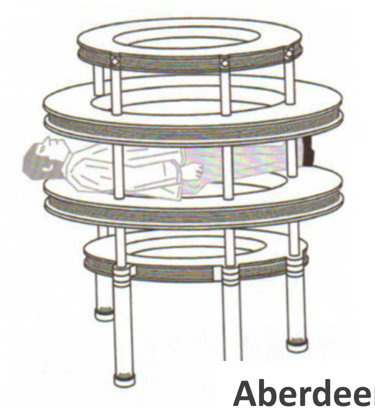
Voxel distribution over the three gray matter layers.

Selective Activation of the Deep Layers of the Human Primary Visual Cortex by Top-Down Feedbacks. Kok et al. Current Biology 2016

At 7T: first cortical layer-specific cognitive studies, at 11.7T : towards 500 μm isotropic fMRI …

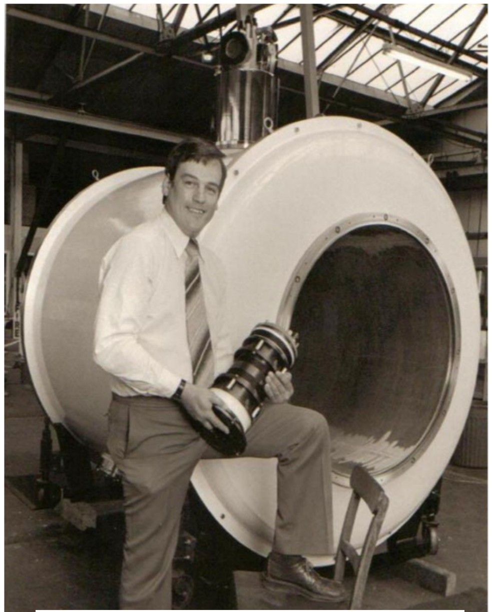
EARLY NMR IMAGING MAGNETS 1977 - 1981

1978 Philips 0.15T MR scanner
1979 Siemens 0.2T MR scanner
1981 Superconducting MRI scanners (0.5 T, Oxford)
1983 GE generates images with 1.5T scanner

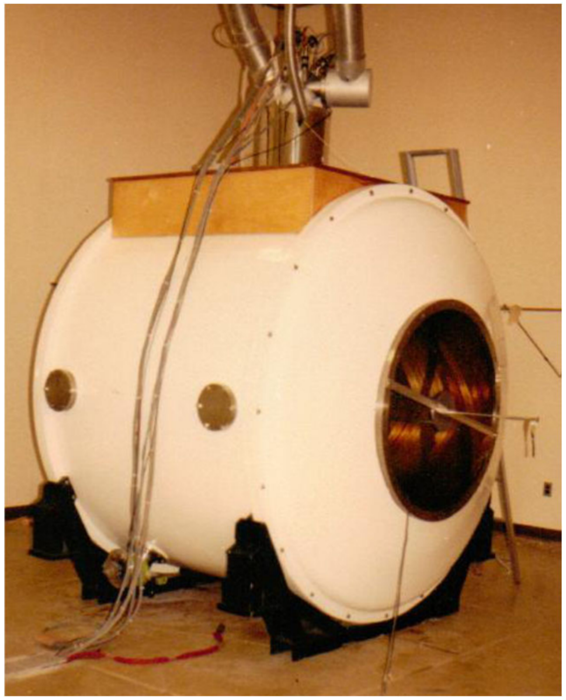


Aberdeen 0.03T resistive magnet - 1977

0.15T Resistive magnet - 1980



John Woodgate and the first 0.3T NMR Imaging Magnet for EMI



First 1.5T magnet (STAR)

Courtesy G. Gilgrass

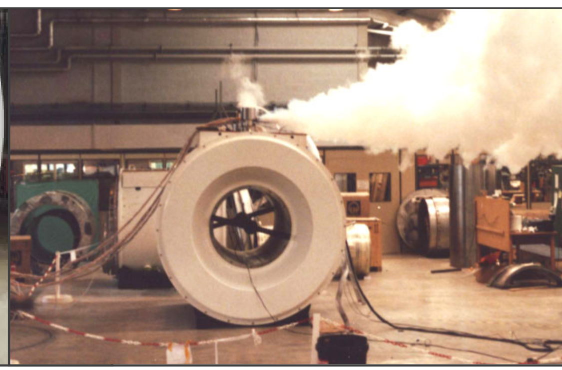
FAST EVOLUTION OF MAGNET DESIGN 1982 - 2005

1986 Actively-shielded superconducting scanners
1991 fMRI invented – (15 yrs after first clinical images)
1993 Philips: Compact, actively shielded, no LN shield scanners
1994 Diffusion Tensor Imaging invented
1997 GE introduces ZBO scanners: no LHe refill over lifetime
2000 Commercial 3 T MRI from GE, Siemens and Philips
2001 GE, Philips: High-field Open MRI systems
2005 Siemens: wide-bore cylindrical scanners (70-cm patient bore)

2015 100 million MRI scans per year

2015: 7 Tesla Active Shield
First clinical (FDA approved) system – first installations:
- *University of Erlangen, Germany*
- *Cambridge University, UK.*

1985 - First 1.5T Active Shield
Test Bed



Courtesy G. Gilgrass

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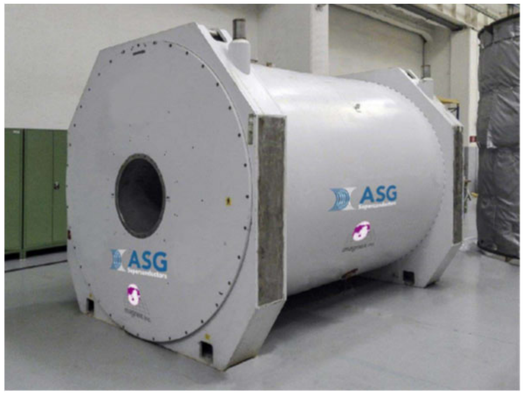
EXAMPLES OF EXISTING ULTRA HIGH FIELD MRI MAGNETS

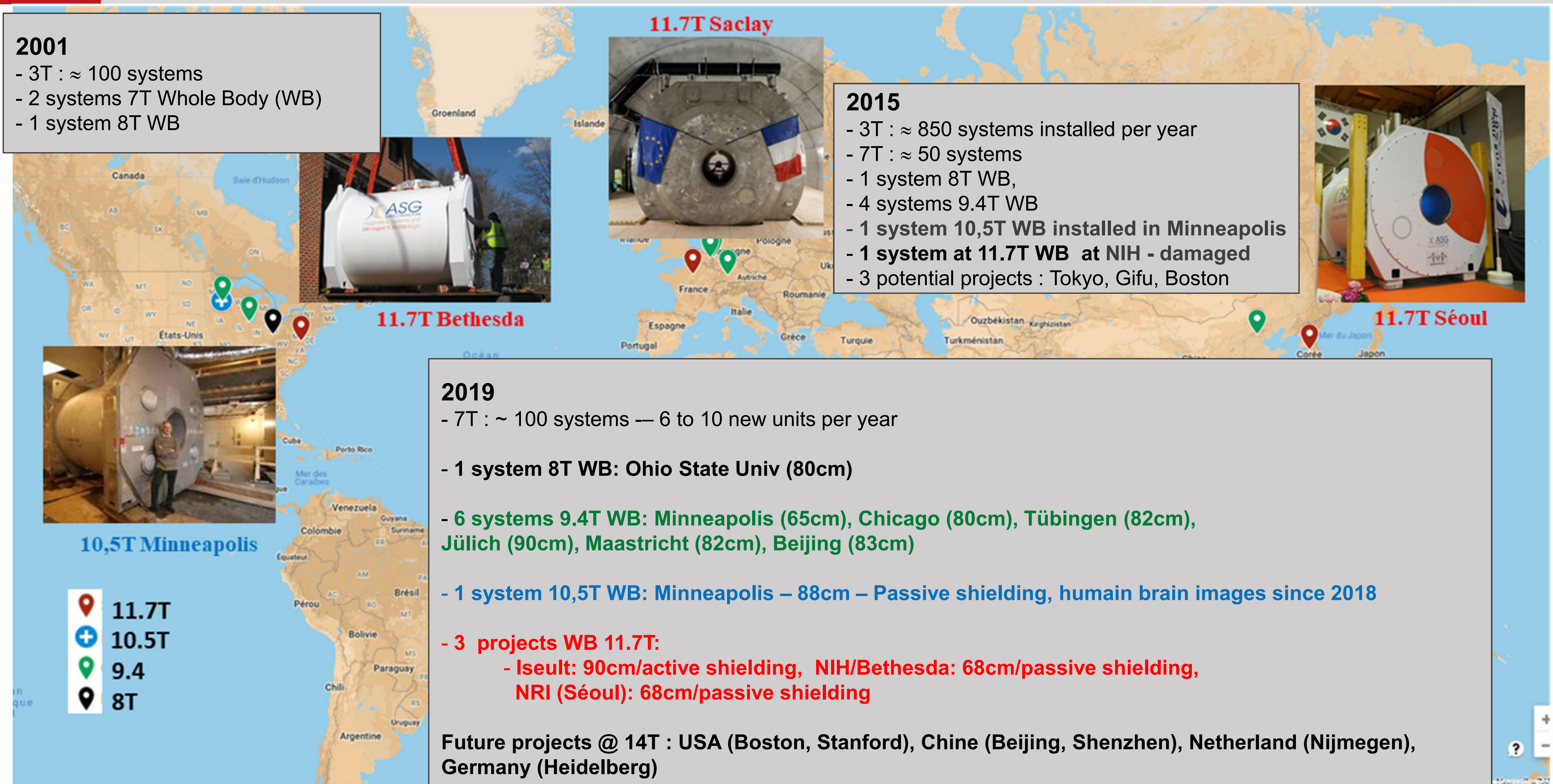
9.4 T 90 cm 54 tons MRI PET Scanner
in operation at Julich, Germany

10.5 T 88 cm Passively Shielded
in operation, CMRR, Minneapolis, USA



11.7 T 68 cm MRI Passively Shielded Head Scanner to be commissioned,
NIH Clinical Center, Bethesda, USA – Gachon Medical University, Seoul, Korea

MRI WORLD-WIDE PARK EVOLUTION



2001
- 3T : ≈ 100 systems
- 2 systems 7T Whole Body (WB)
- 1 system 8T WB

2015
- 3T : ≈ 850 systems installed per year
- 7T : ≈ 50 systems
- 1 system 8T WB,
- 4 systems 9.4T WB
- **1 system 10,5T WB installed in Minneapolis**
- **1 system at 11.7T WB at NIH - damaged**
- 3 potential projects : Tokyo, Gifu, Boston

2019
- 7T : ~ 100 systems –- 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, humain brain images since 2018

- 3 projects WB 11.7T:
- Iseult: 90cm/active shielding, NIH/Bethesda: 68cm/passive shielding, NRI (Séoul): 68cm/passive shielding

Future projects @ 14T : USA (Boston, Stanford), Chine (Beijing, Shenzhen), Netherland (Nijmegen), Germany (Heidelberg)

ISEULT 11.7 T MRI WHOLE BODY MAGNET
AN IDEA IN 2001…

The original idea

Pr. Denis Le Bihan CEA Neurospin

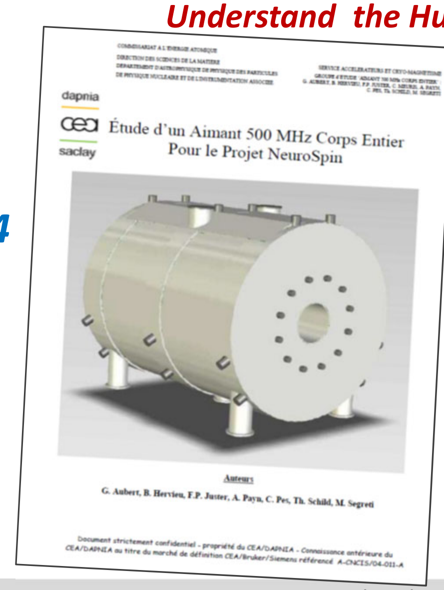
ISEULT
Understand the Human Emotions

The initial specification

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

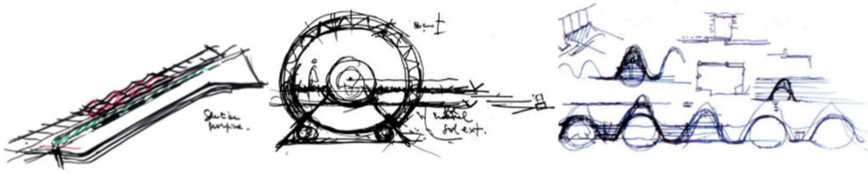
A very preliminary magnet concept a few years later… July 2004

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

NEUROSPIN : A UNIQUE FACILITY FOR NEUROSCIENCE RESEARCH

When art meets science: the arches of Neurospin

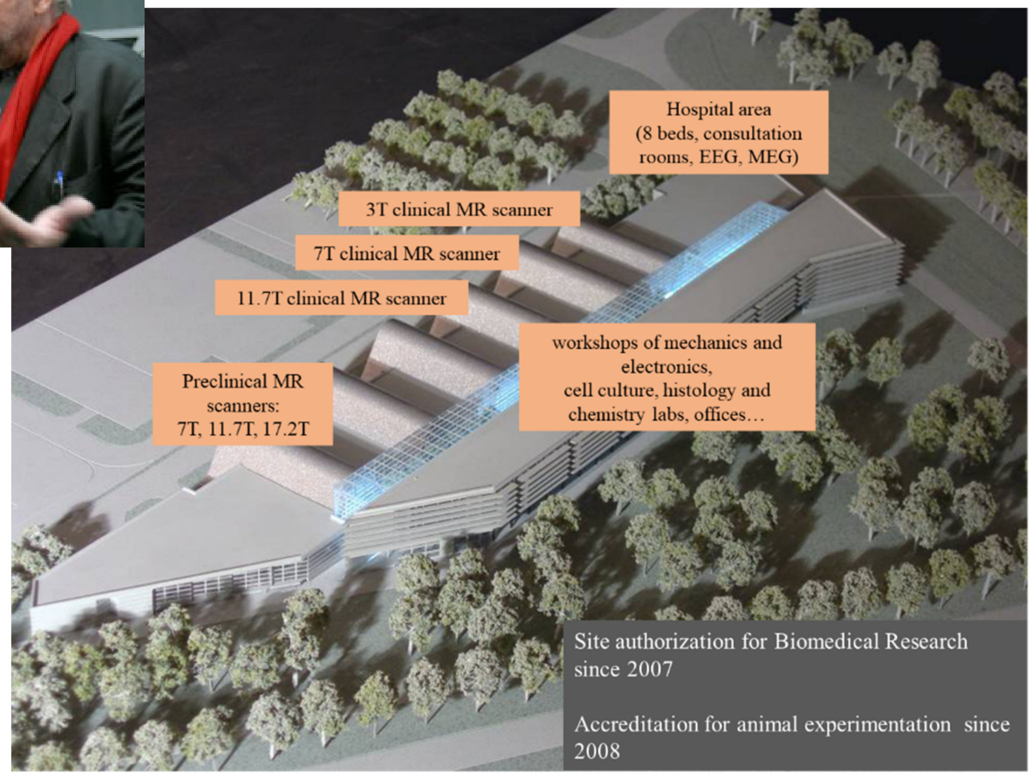


3 teslas
Siemens

7 teslas
Siemens

11,7 teslas

Claude Vasconi, French Architect 1940-2009



Neurospin was opened at CEA Saclay in 2007

Facility equipped with several commercial MRI systems

ISEULT PROJECT- A FRENCH GERMAN INITIATIVE

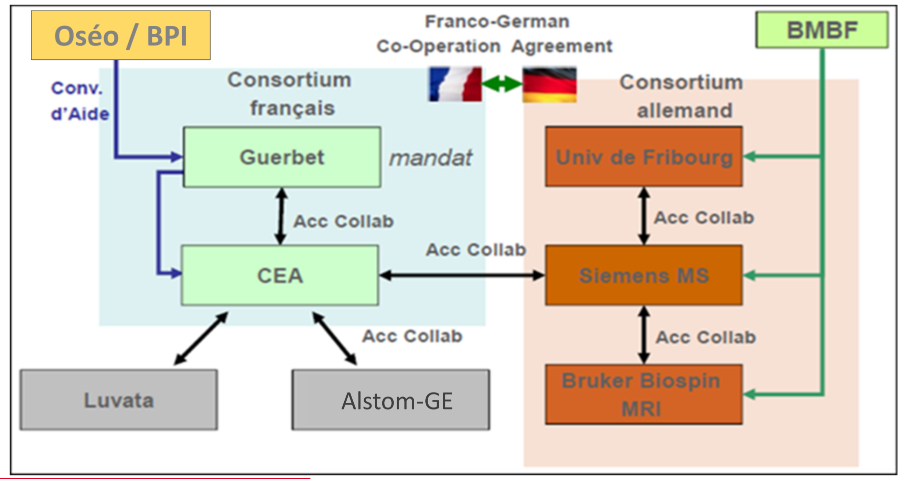
French-German industrial collaboration developing :
"Molecular Imaging at Ultra High Magnetic Fields"

Agreement signed between Président Jacques Chirac and Chancellor Gerhard Schröder in 2004.

Funding agreement for the French Consortium validated by the French Industrial Innovation Agency in 2006.

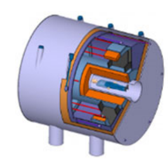
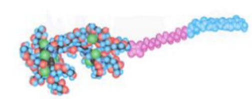
Leader of French Consortium : Pharmaceutical Company Guerbet

Contrast for Life

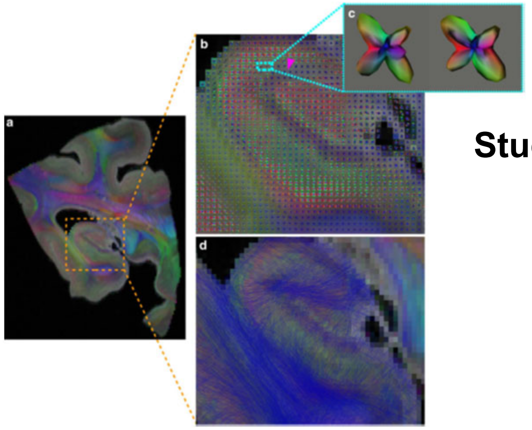


3 Workpackages

- **Development of an ultra high field MRI system (11.7T)**
- Develop a new generation of gradient system
- Develop a new generation of contrast media

WP1	WP2	WP3
		
Ultra-hight field MRI system operating at 11.7T	Translational research to clinical magnets (7T)	New contrast media for Alzheimer's Disease, stroke and Brain tumors)
CEA, *Siemens*	**Siemens,** *Freiburg, Bruker*	**Guerbet,** *CEA*

ISEULT PROJECT - SCIENTIFIC GOALS



Post-mortem inference of the human hippocampal connectivity at 11.7T.
J. Beaujoin, C. Poupon et al.
Brain Structure and Function, 2018.

Study the brain anatomy and connectivity at unprecedented spatial resolution

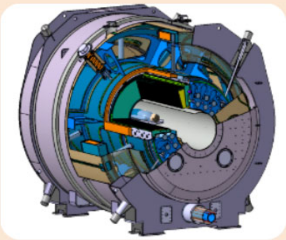
Explore brain function and metabolism using new contrast mechanisms

Identify new biomarkers for the diagnosis or monitoring of neurological and psychiatric disorders

Effects of anesthetic agents on brain blood oxygenation level at 17.2T.
L. Ciobanu, D. Le Bihan et al.
PLoSOne, 2012.

Exploration of the brain at the mesoscopic scale :

- ***Non-invasive imaging***
- ***Whole human brain***
- ***In vivo***



Ultra High Field MRI :

- *Signal increase*
- *New contrasts*

⇒ *New discoveries*

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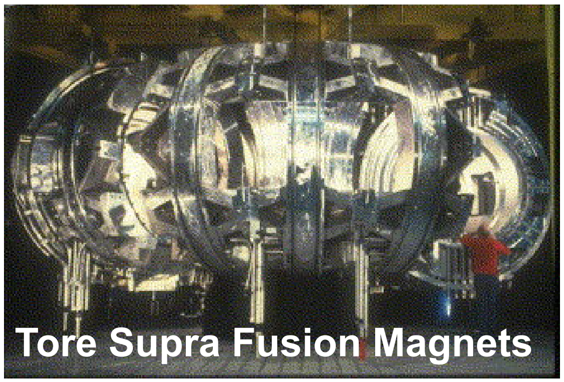
40 Years of History of Large SC Magnets

1980s


Tore Supra Fusion Magnets


LNCMI 8 T Solenoid

1990s LHC Experiments


ATLAS Barrel Toroid


CMS Solenoid

2000-2010s MRI


Iseult 11,7 T MRI Magnet

The Iseult Magnet

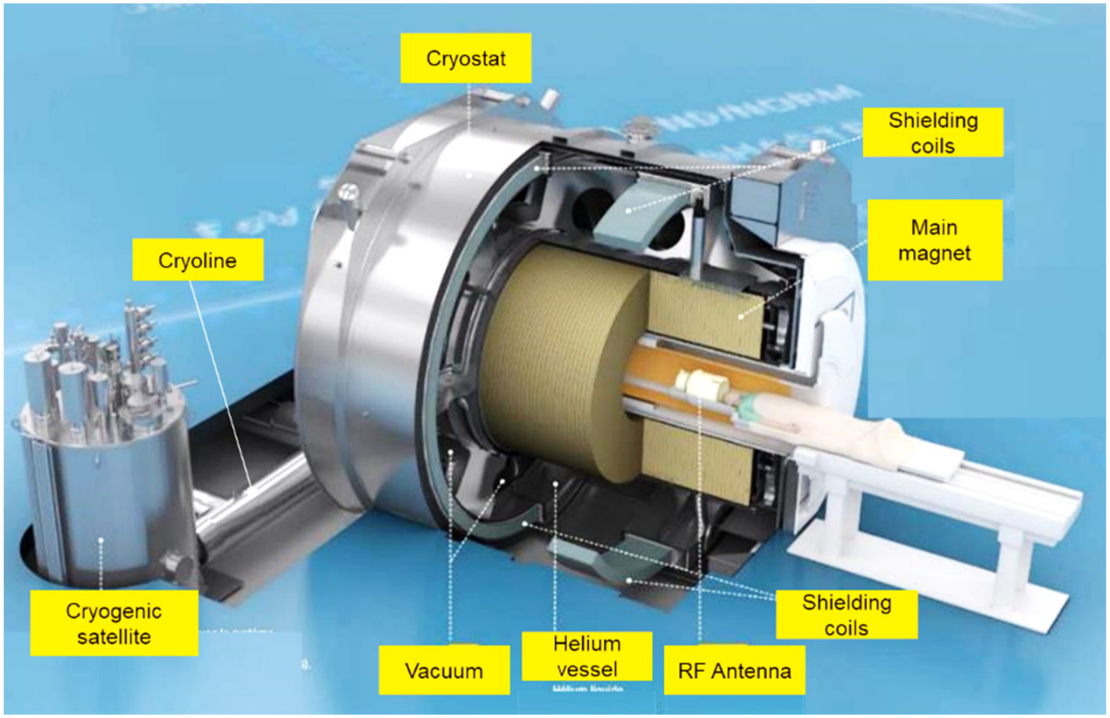
A challenging specification:

- *B0 / Aperture* *11.75T / 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*

Innovative solutions for a MRI magnet

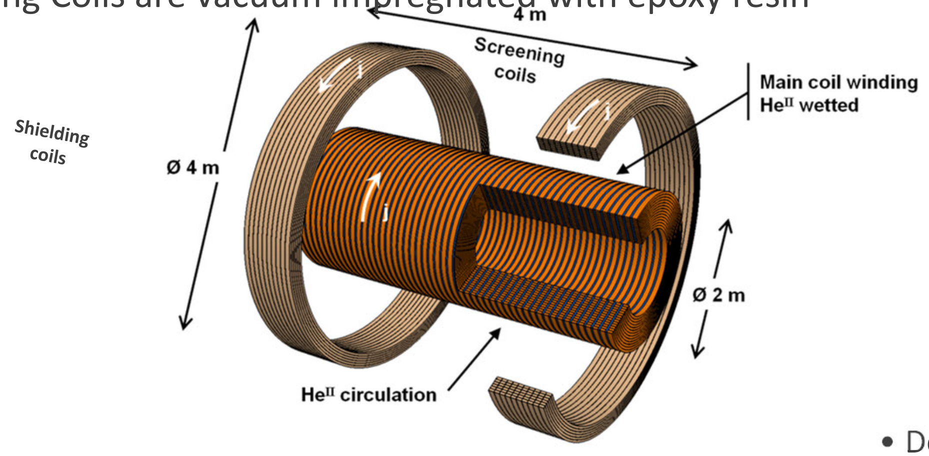
- ***170 NbTi double pancakes*** *for the main coil*
- ***2 NbTi shielding coils*** *to reduce the fringe field*
- *Cryostat for* ***superfluid helium at 1.8 K****, 1.25 bars*
- ***Dedicated cryorefrigerator*** *(70 l/h + 40 W @ 4.2 K)*
- ***Driven mode operation*** *with two 1500 A power supplies*

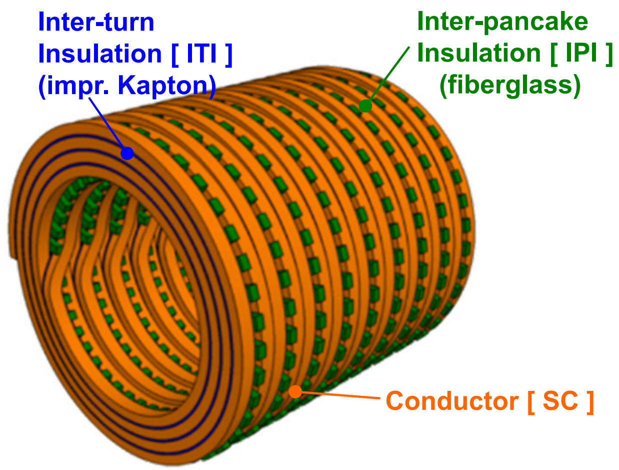
Stored Energy	*338 MJ*
Inductance	*308 H*
Current	*1483 A*
Length	*5.2 m*
Diameter	*5 m*
Weight	*132 t*

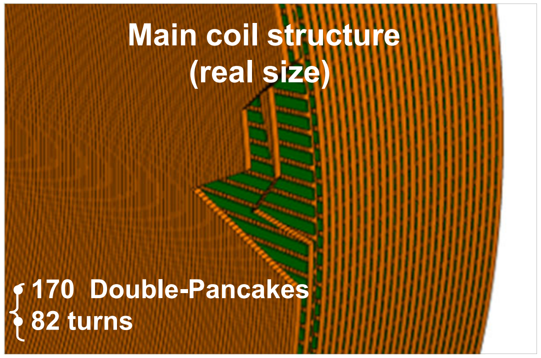


WINDINGS & CRYOSTABILITY

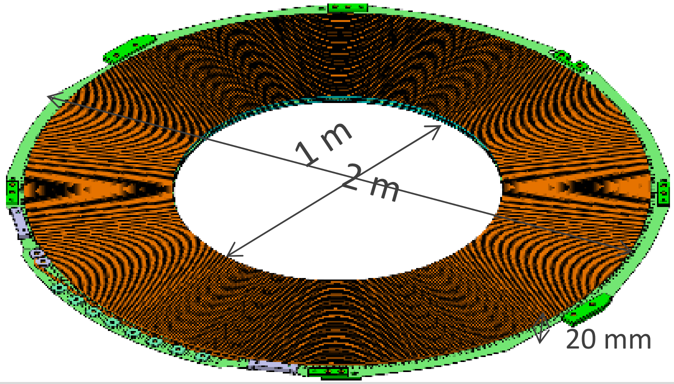
- Specific design for the Main Coil made of **«Wetted» Double-Pancakes** using **Non-Insulated Conductor** to ensure the **Cryostability**
- Shielding Coils are vacuum impregnated with epoxy resin







- Double pancake stacking

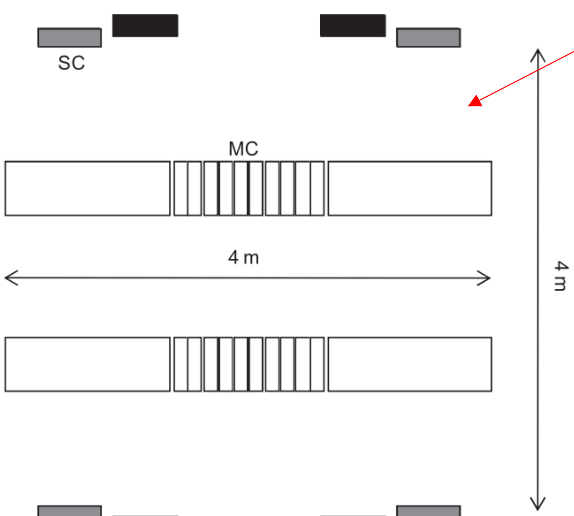


WINDINGS AND HOMOGENEITY

▶ The objective is to design a magnet theoretically **intrinsically** homogeneous

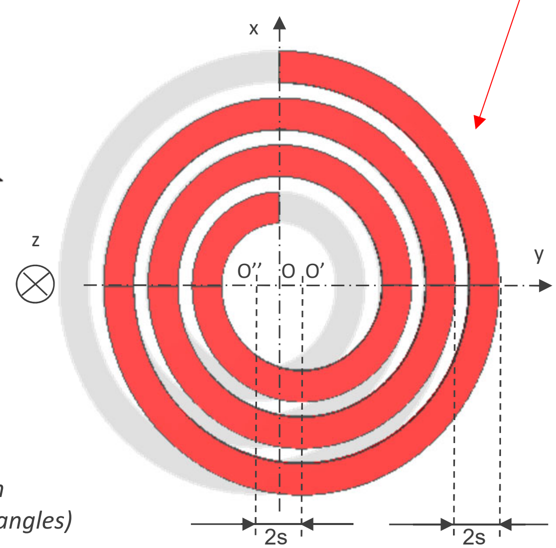
$$B_z(r,\theta,\varphi) = B_0 + \sum_{n=1}^{\infty} r^n \left[\cancel{Z_n} P_n(\cos\theta) + \sum_{m=1}^{n} \begin{pmatrix} \cancel{X_n^m} \cos m\varphi \\ + \\ \cancel{Y_n^m} \sin m\varphi \end{pmatrix} W_n^m P_n^m(\cos\theta) \right]$$

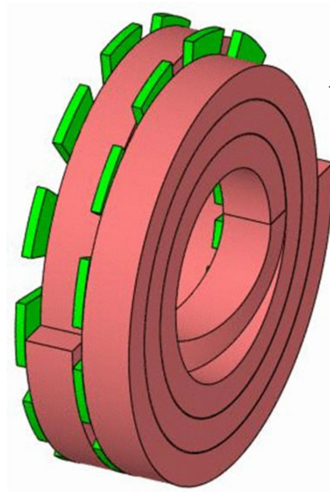
- Block design



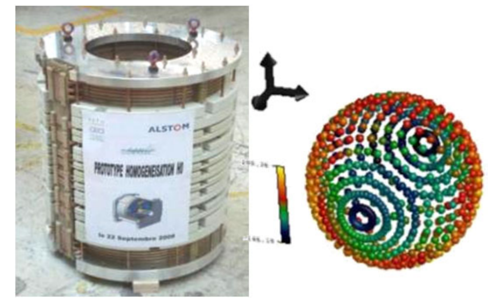
Winding pack design with SCs position optimization from the conductor mass only minimization criteria (gray rectangles) to a nearly force free position (black rectangles).

- SPECIAL PANCAKE LAYOUT





CEA Patent WO/2007/077383

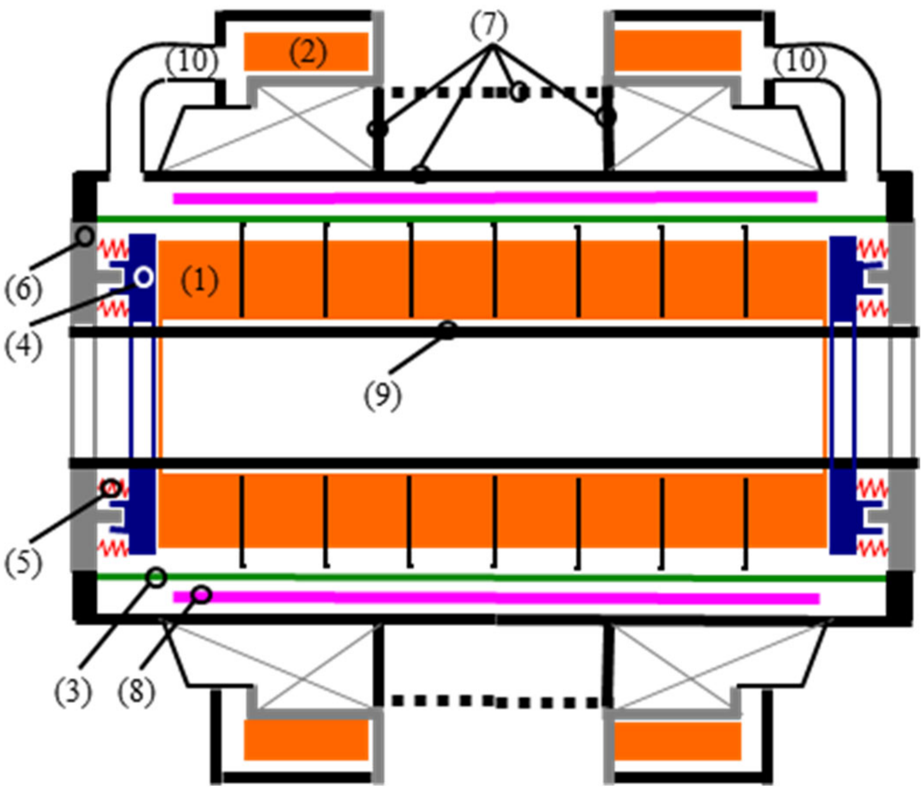


H0 Prototype

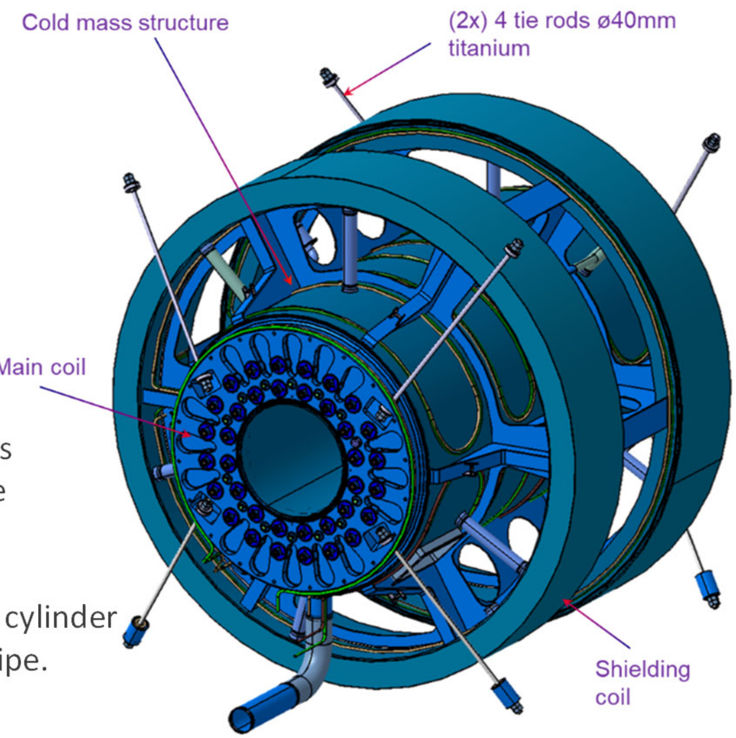
Assembly of 24 double pancakes producing a homogeneous field of 1.5 T and field map measured in 648 points on a 30 cm diameter sphere (300 ppm peak to peak)

ISEULT HELIUM VESSEL ASSEMBLY PRINCIPLE

One key concept is that the main coil is **only mechanical linked to the helium vessel by its extremities** with spring washers and without any inner mandrel or outer support cylinder.



(1) Main Coil
(2) Shielding Coil
(3) MC outer cylinder
(4) MC base plate
(5) Spring washer stacks
(6) Cold mass end-plate
(7) Cold mass structure
(8) Cryoshim
(9) Helium vessel inner cylinder
(10) Coils connection pipe.



Electrical System for Driven Mode Operations

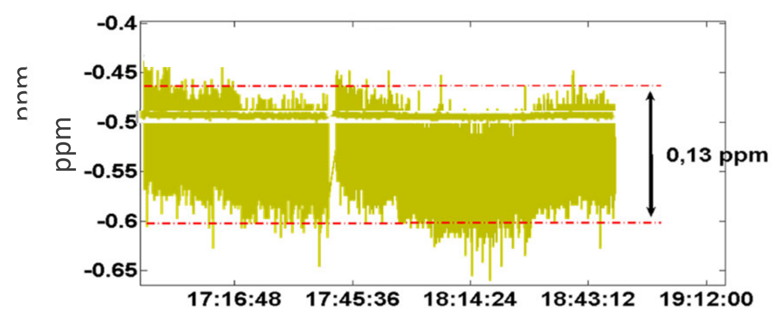
The quench protection scheme and the risk of developing superconducting joint using multi-strand cable required the need of a driven mode scheme for the power supply.

But the ***specification of +/- 0,05 ppm/h*** cannot be reach with a stabilized power supply (max. 1 ppm/h).

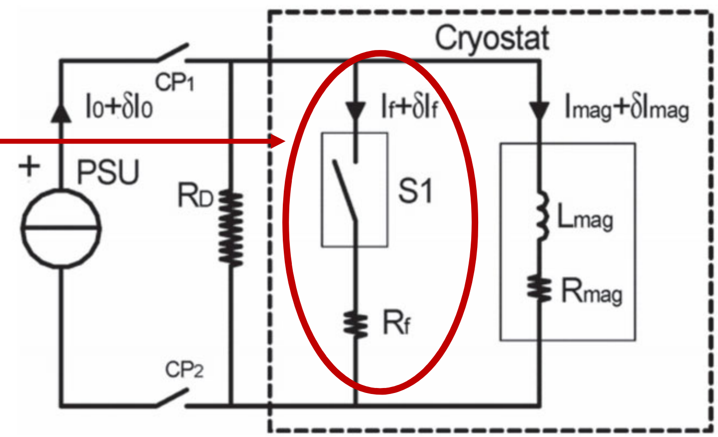
=> ***New concept to stabilize the magnetic field for Iseult***

Fault current limiter (FCL) and filtering resistance
in parallel with the magnet and the power supply

Validated on prototype magnet



Current stability on prototype magnet H0 (1.5 T, 900 A, 1H):



Iseult electrical diagram

Fault current limiter (FCL) in series with a filtering resistance Rf, in parallel with the magnet

CEA Patent WO/2009/063150

cea

A Reliable System for 24 Hours Safe Operations

Active Quench Protection
through voltage detection and external dump resistor

Maximum terminal voltage:	*3600V*
Hot Spot temperature (MC):	*120K*
Hot Spot temperature (SC):	*150K*

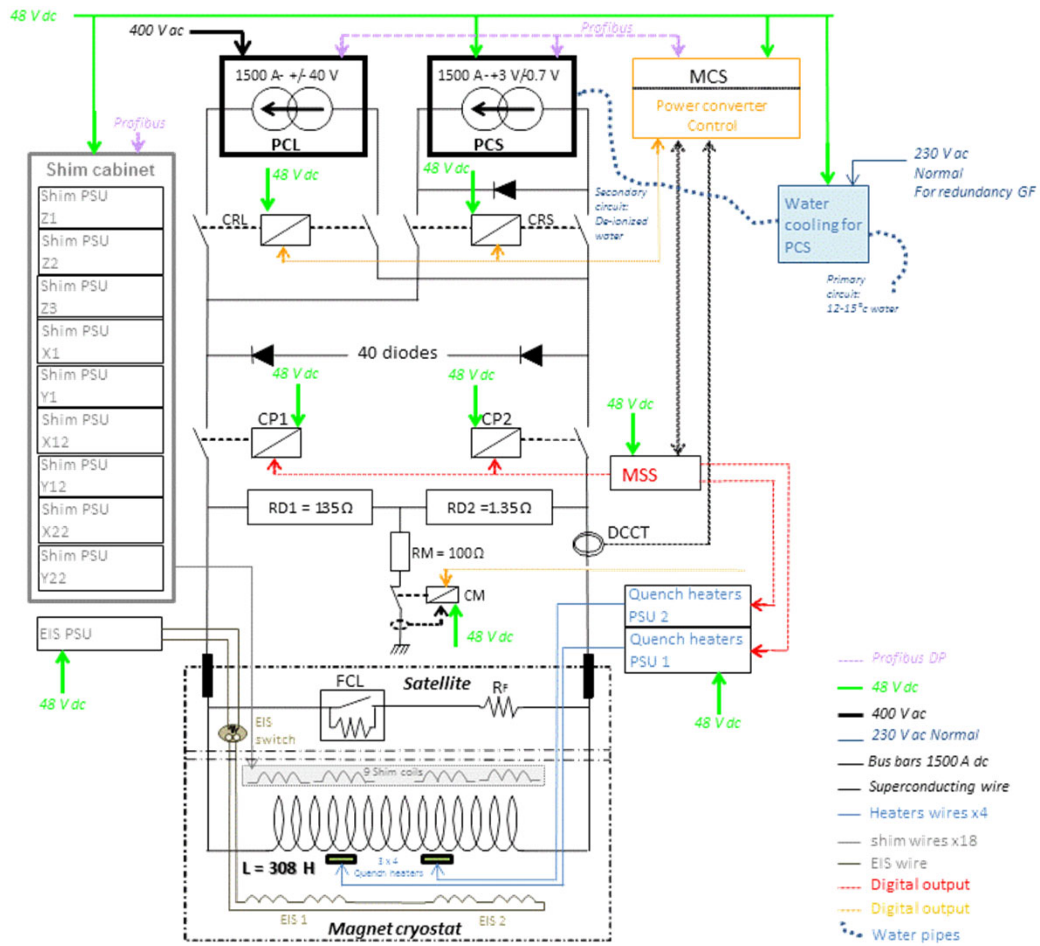
High availability

Redundancy of all key equipment

Two power supplies

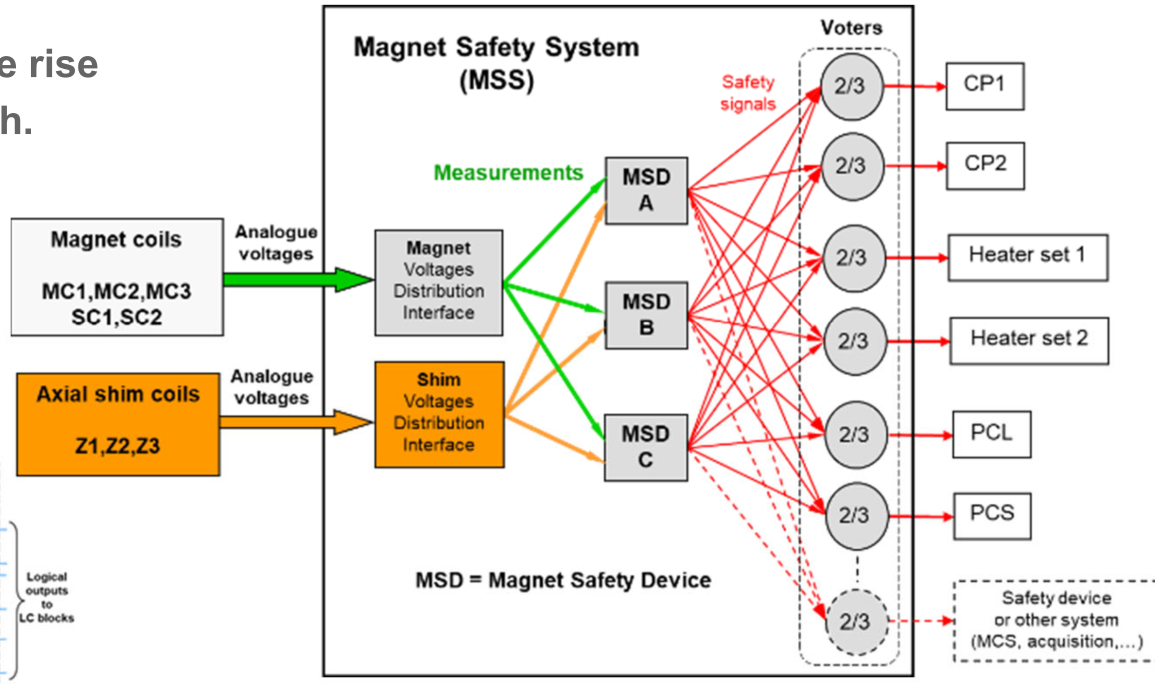
48V batteries in case of power failure

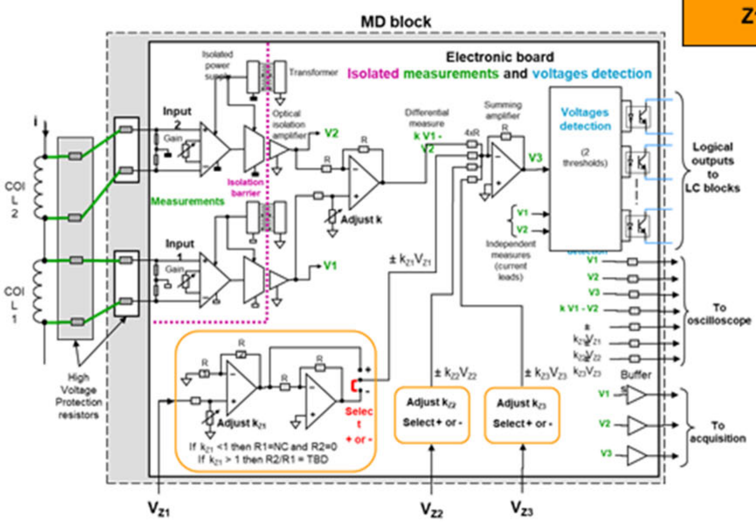
Building equipped with a diesel generator



ACTIVE MAGNET SAFETY SYSTEM – UNIQUE FOR A MRI SYSTEM

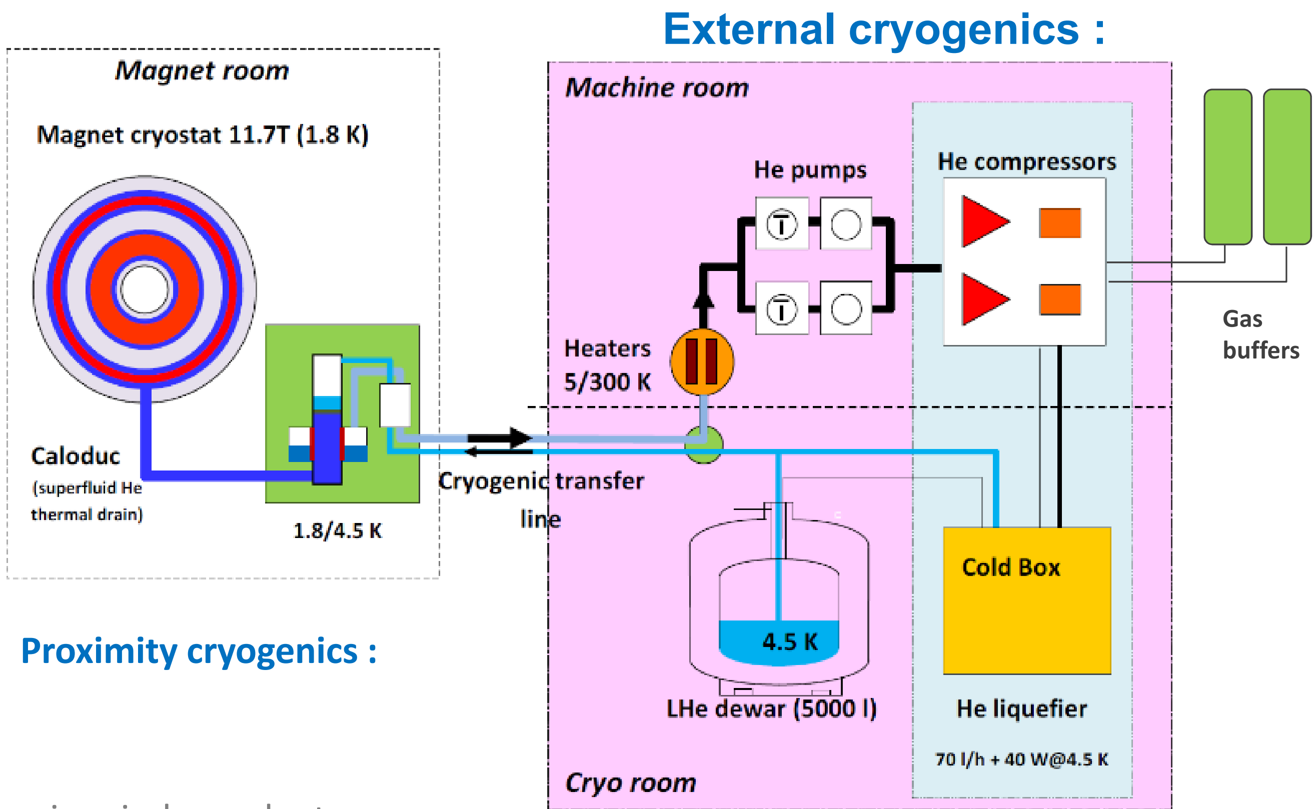
Detects the voltage rise due to a quench.





The reliability of MSS is always based on voting redundancy.

GENERAL SCHEME OF THE CRYOGENIC EQUIPMENT



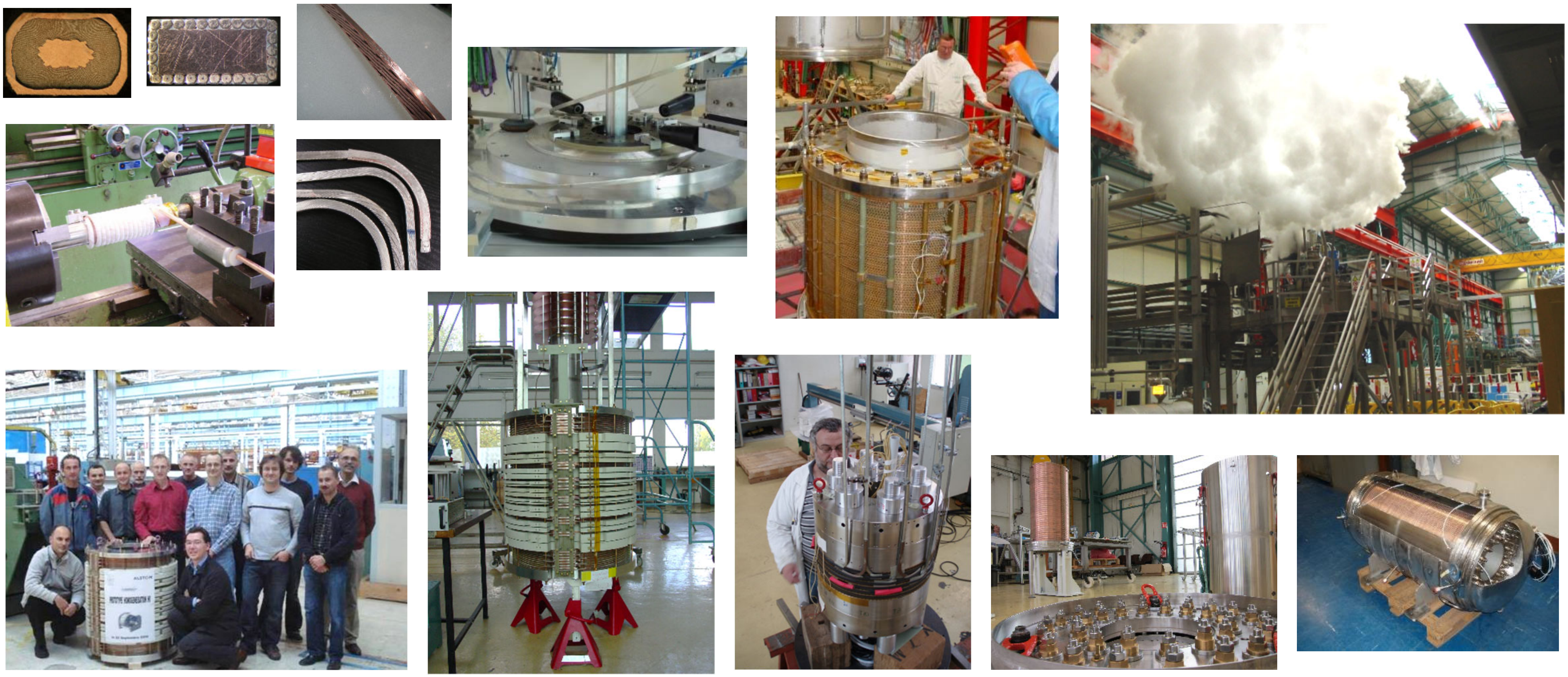
Make the magnet and cryogenics «independents»

Use reliable technologies and redundancy of equipment

Continuous operation in case of failure of cryoequipment

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P3 given at the virtual ASC 2020, October 28, 2020.

STRONG R&D AND PROTOTYPING ACTIVITIES 2006-2009



Conductors, winding techniques, mechanics, cryogenics, thermo-hydraulic studies…

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CONDUCTORS

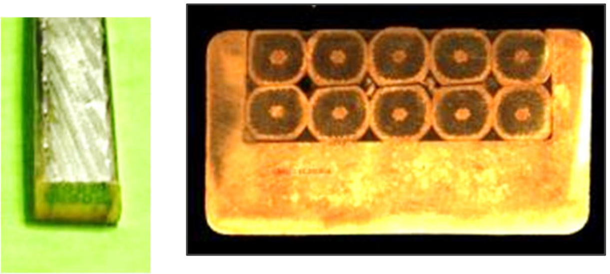
160 km of **main coil conductor**: **1500 A at 11.7 T and 2.8 K**, **9.2 mm x 4.9 mm**

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

R&D Alstom/CEA

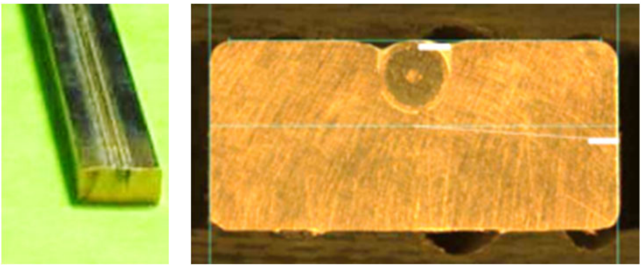
Manufactured by Luvata Waterbury, CT, USA,

A Group Company of MITSUBISHI MATERIALS



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

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

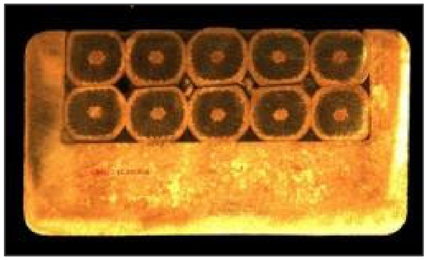


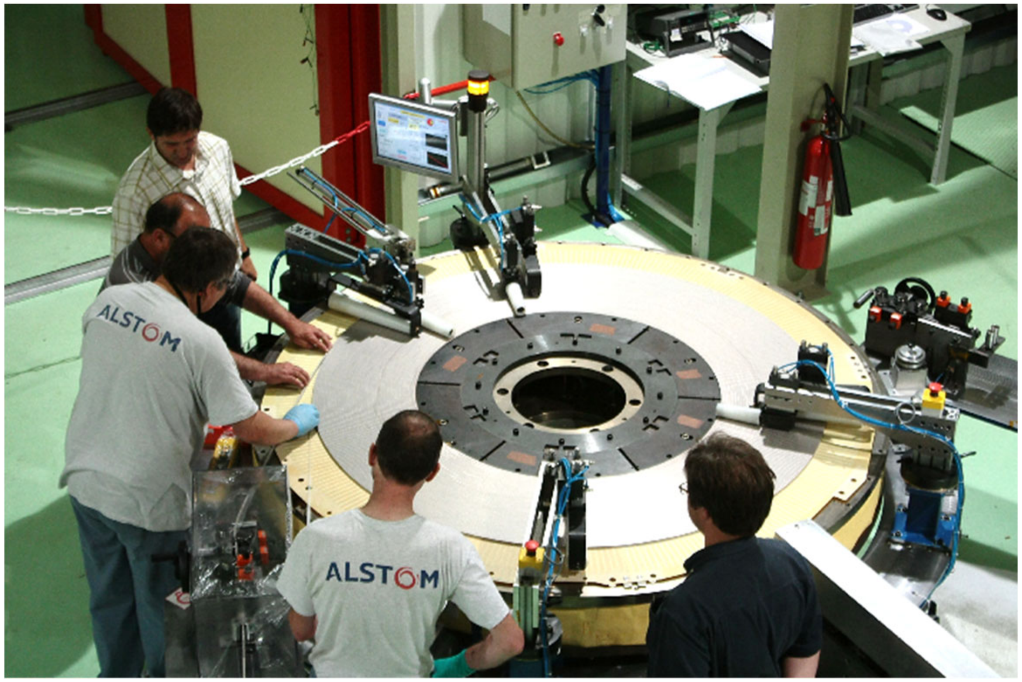
Shielding coil conductor: Cu/NbTi strand in a copper channel

MAGNET MAMUFACTURING (2010 – 2017)
DOUBLE PANCAKE WINDING TECHNIQUE

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

- *330 kg each*
- *Tolerance at inner bore +/-0.05mm*
- *Control of each turn +/-0.2mm*
- *Planarity 0.1mm*
- *Parallelism 0.2mm*





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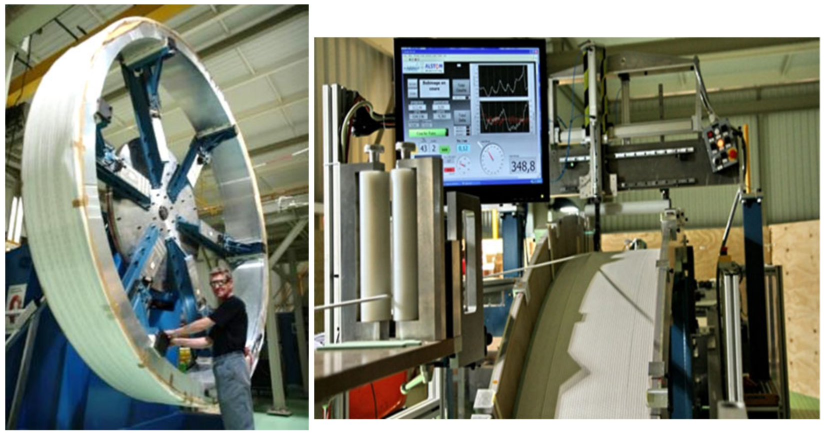
MAGNET MANUFACTURING (2010 – 2017)

ALSTOM

Main coil - DP stacking



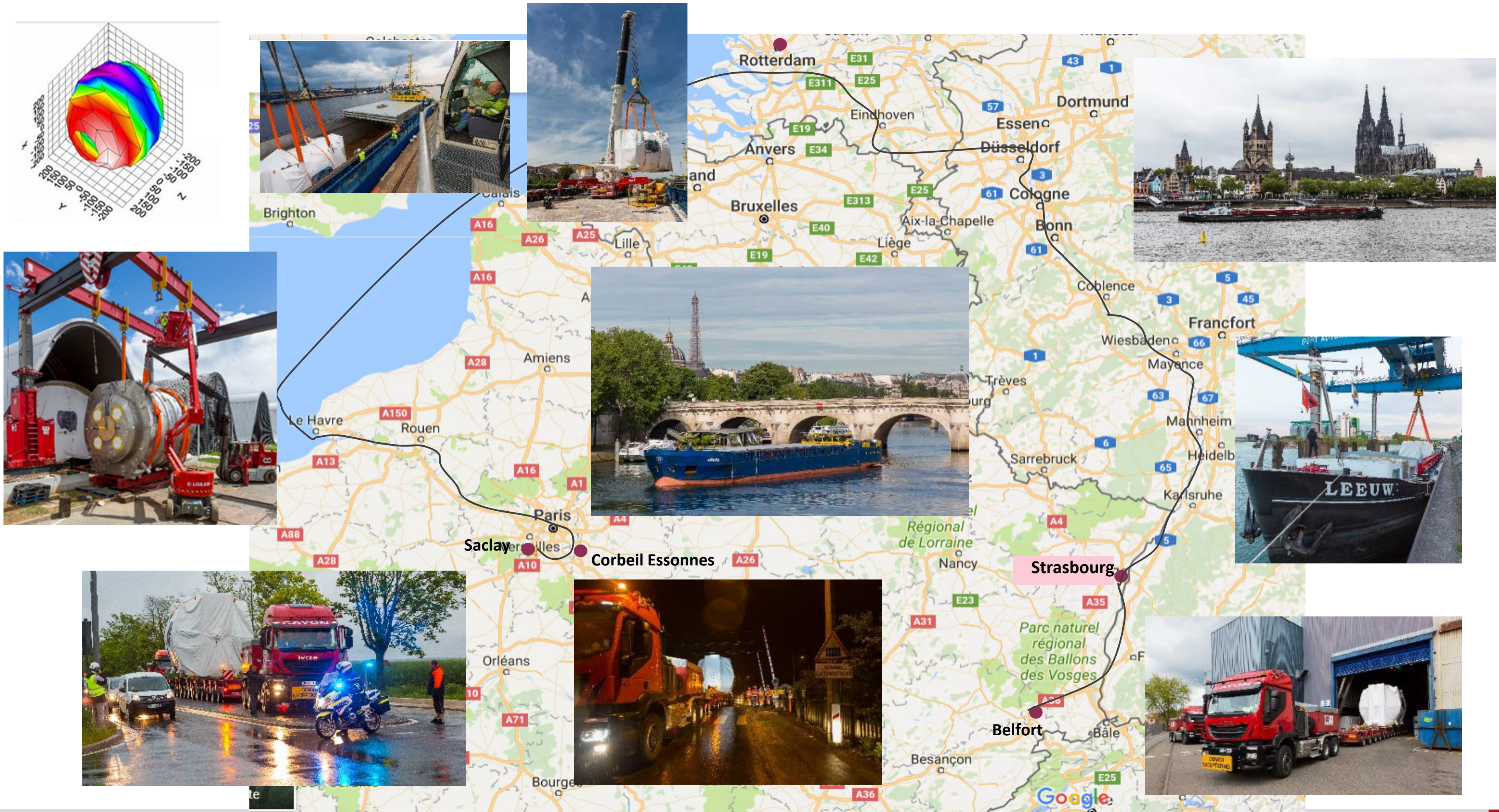
Shielding coil fabrication

Main coil / Shielding coils integration

MLI wrapping

Vacuum vessel welding

2 Weeks of Transport From Belfort to Saclay – May 2017



MAGNET CONNECTION TO CRYOPLANT- OCT. 2017 – OCT. 2018

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)

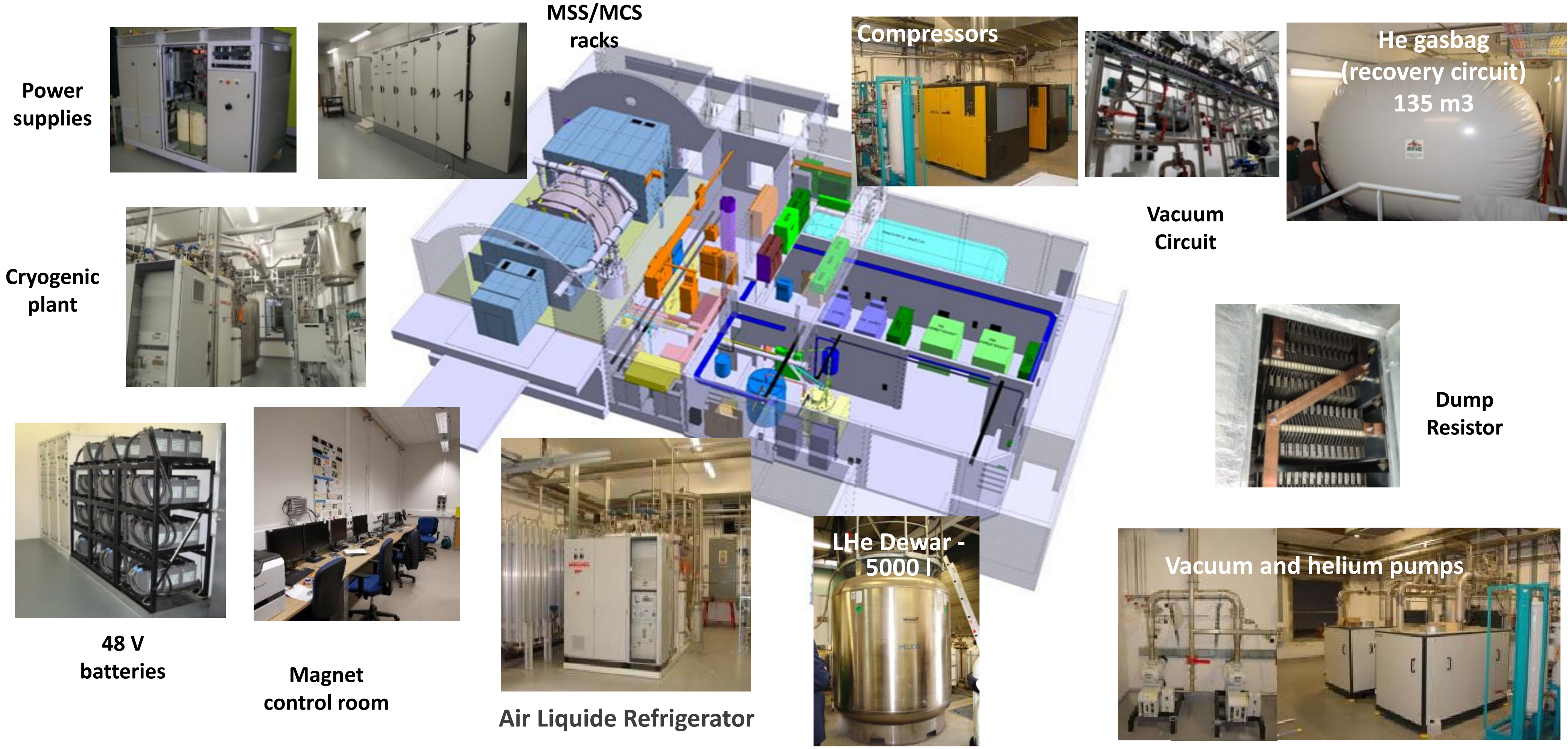
Circuits assembly

MLI

Vacuum vessel welding

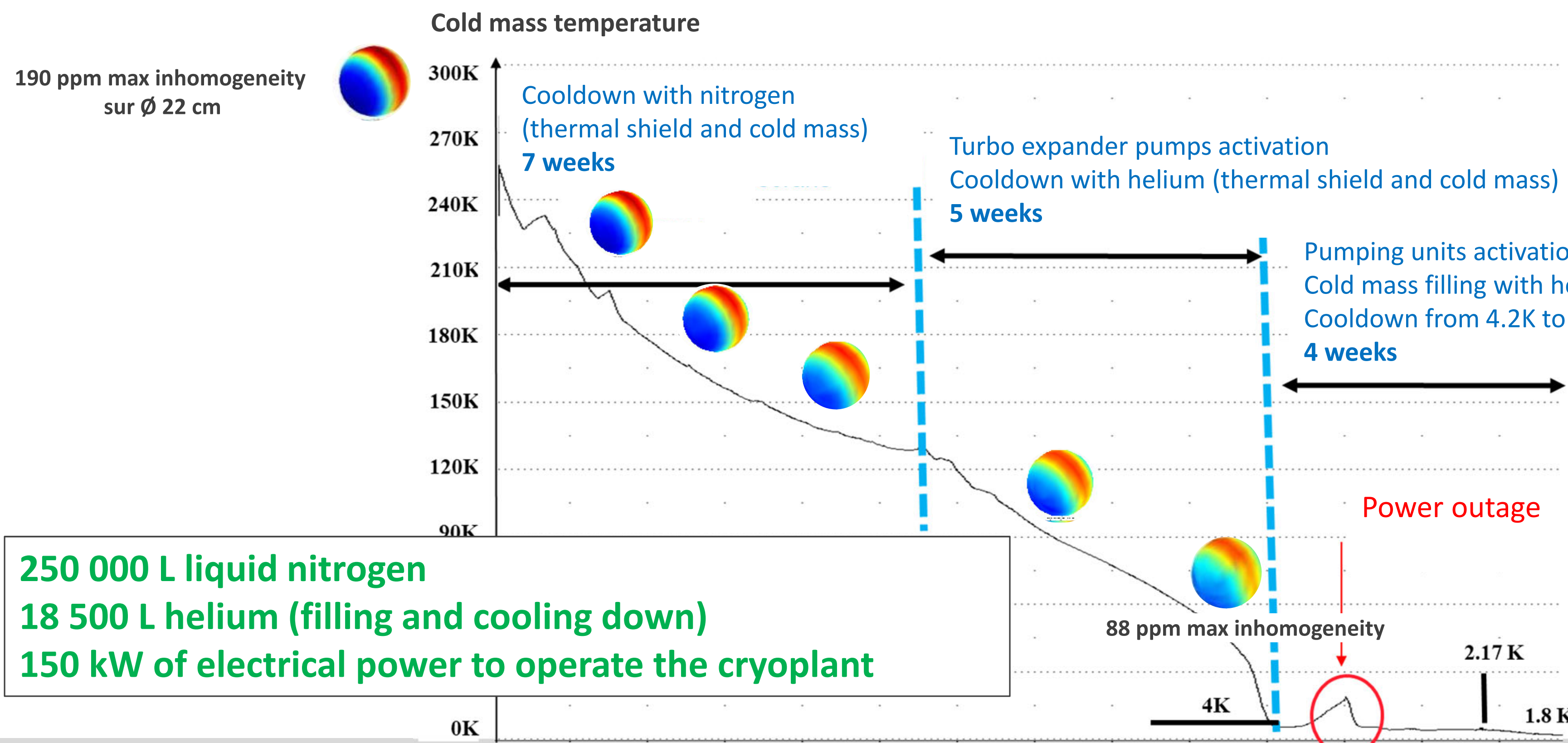
Final leak tests
(inner cooling circuits and vacuum vessel)
Leak rate of 5.10^{-9} mbar.l/s
on all the internal cooling circuits

A Complex Installation to Operate the Magnet



COOLDOWN – 19 NOV. 2018 – 7 MARCH 2019

- Huge mass to cool down: cold mass (105 tons @ 1.8K) + thermal shield (3.4 tons @ 55K)
- Cooling 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

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CRYOGENIC BUDGET

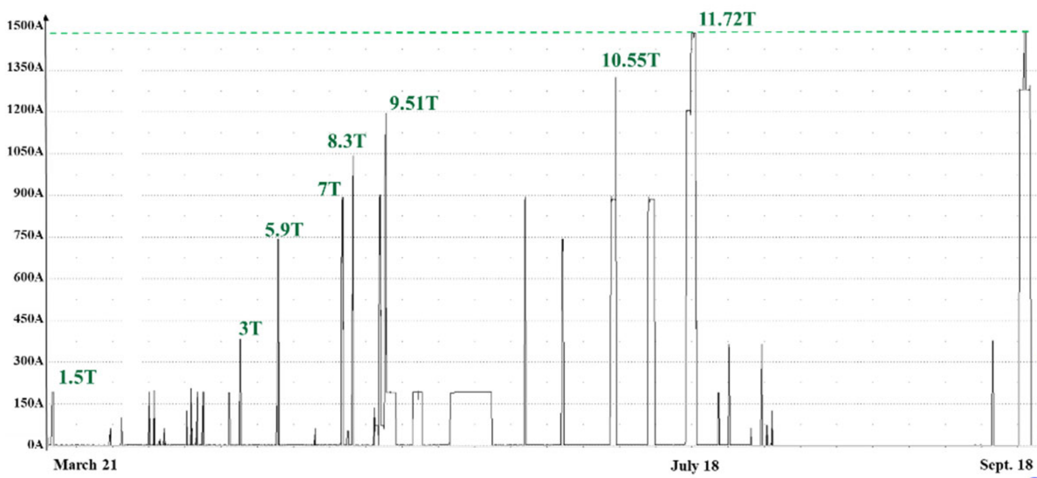
	Measured values
Liquefier parameters	**900W @ 55K (transfer lignes + satellite)**
	40W @ 4.5K
	72 l/h @1.8K

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 (they are too difficult to measure accurately)

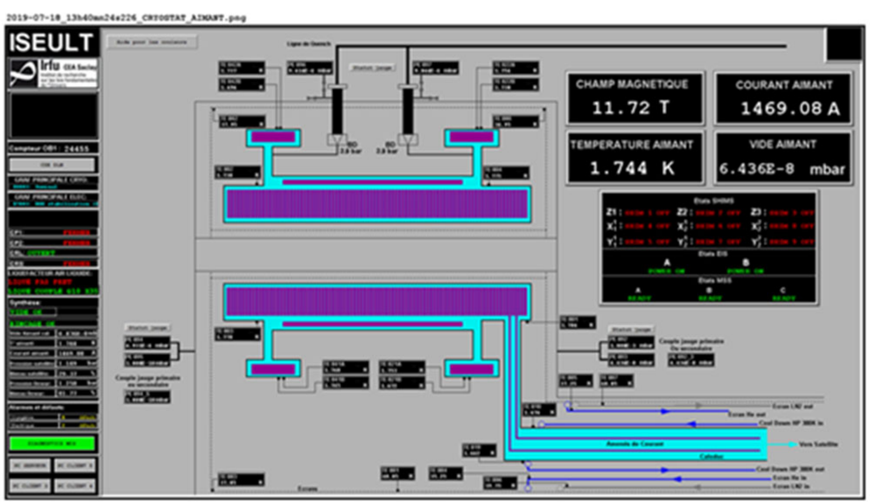
The cryoplant should be able to handle safely the additional thermal losses deposited when all the imaging system is in operation (especially during the gradient coil sequences in DC mode).

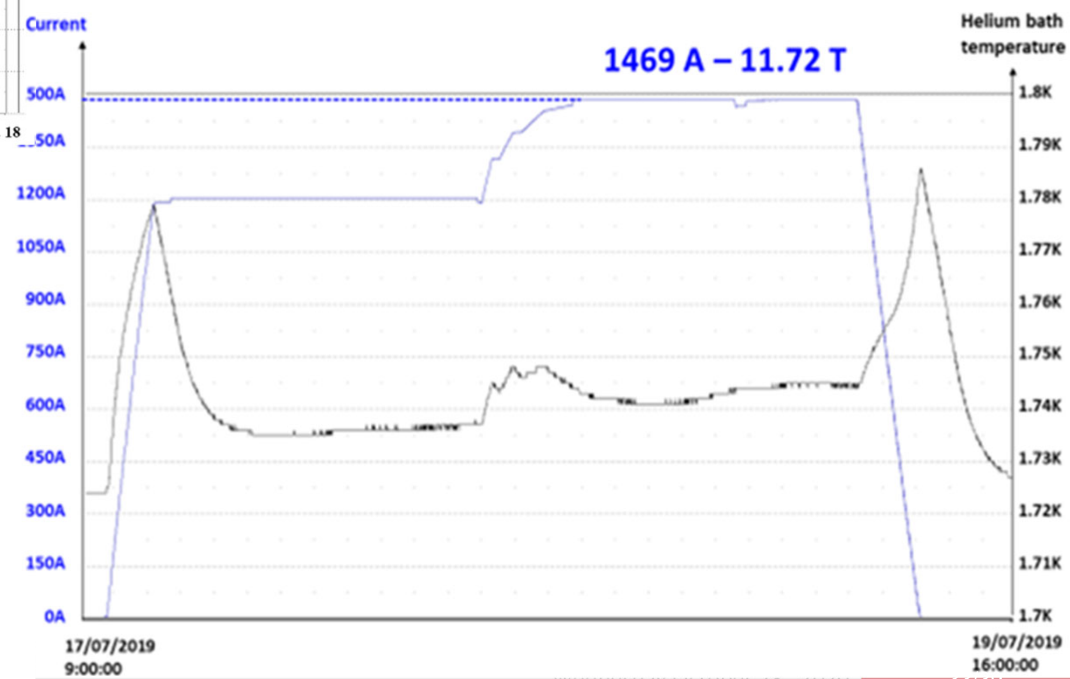
STEP BY STEP ENERGIZATION 11.72T – MARCH - JULY 18TH 2019



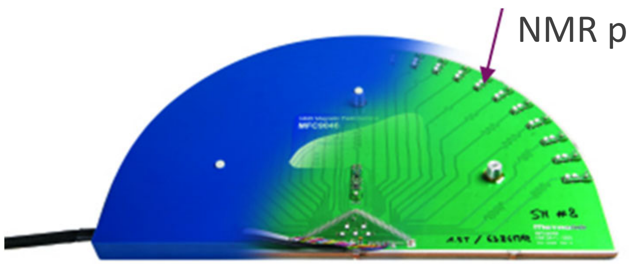
Test duration of 2 days

- Ramp-up in 30 hours
- Switching test between the two power supplies
- Plateau of 18 hours @ 11.72T
- First magnetic measurements (homogeneity and drift)
- Slow discharge in 3 hours to unload the magnet



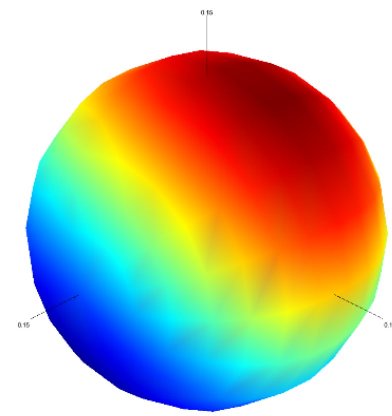


FIELD HOMOGENEITY MEASUREMENTS



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

	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

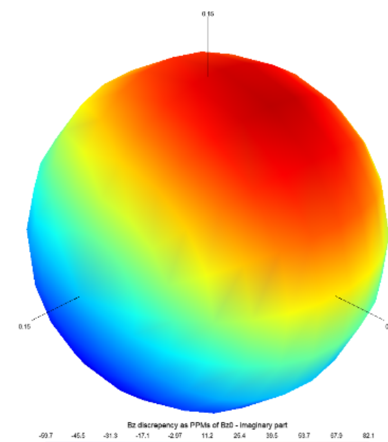


1.5 T

$\Delta|\vec{B}|_{pk-pk}$ = 142 PPM

7 T

$\Delta|\vec{B}|_{pk-pk}$ = 128 PPM



- **Very good agreement between the measurements (1.5T, 3T, 7T, 11.7T)**

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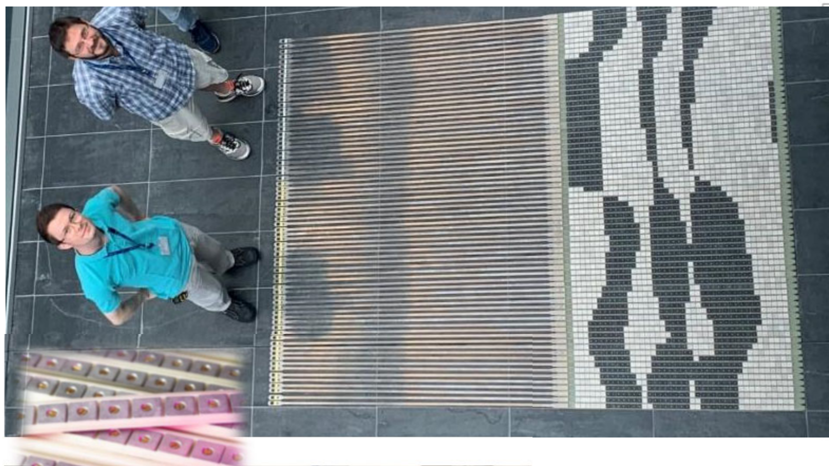
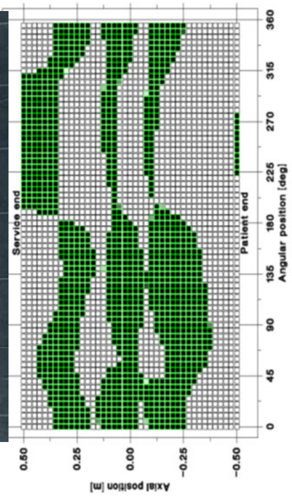
PASSIVE SHIMMING AT 3 T AND 7 T (JUN – JUL. 2020)

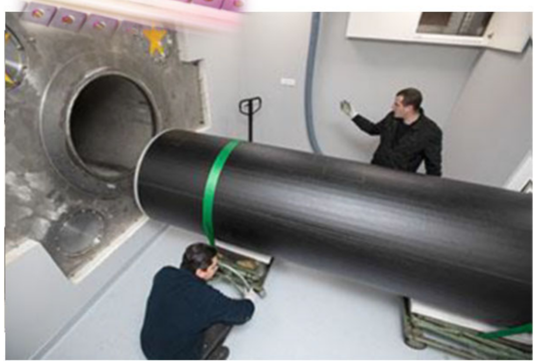
- **Implementation of the additional iron shims**
- Optimization of shim pattern (27kg of iron)
- Assembly of the 72 rails (41 aluminium/iron parts per rail)

- **Magnetic measurements at 3T and 7T**
- Validation of the homogenization method and the additional shim effect; several more iterations will be needed to reach the 0.5ppm spec





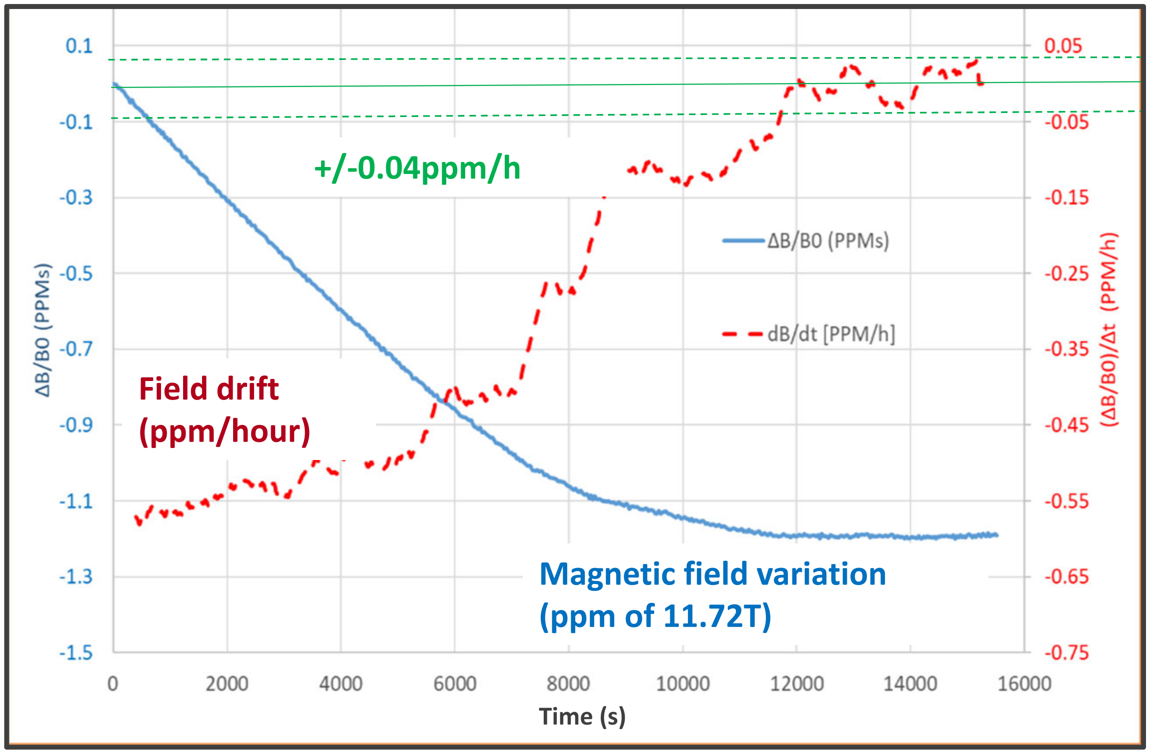
DHS	11,7T w/o iron	3T measurements extrapolated at 11,7T with iron	7T measurements extrapolated at 11,7T with iron
Z_0 [T]	*11,7*	*11,7*	*11,7*
Z_1 [ppm]	*-5,6*	*0,2*	*11,9*
Z_2 [ppm]	*-16,9*	*0*	*-1*
Z_3 [ppm]	*3,6*	*0,1*	*-0,8*
Z_4 [ppm]	*1,3*	*1,3*	*1,5*
Z_5 [ppm]	*-0,1*	*-0,1*	*-0,1*
X_1^1 [ppm]	*23,2*	*0,8*	*-2,9*
Y_1^1 [ppm]	*64,5*	*-0,4*	*2,5*
X_2^1 [ppm]	*2,6*	*-0,4*	*0,5*
Y_2^1 [ppm]	*-7,1*	*-0,1*	*-0,1*
X_2^2 [ppm]	*-0,6*	*-0,4*	*-0,6*
Y_2^2 [ppm]	-1,2	-0,5	-0,4

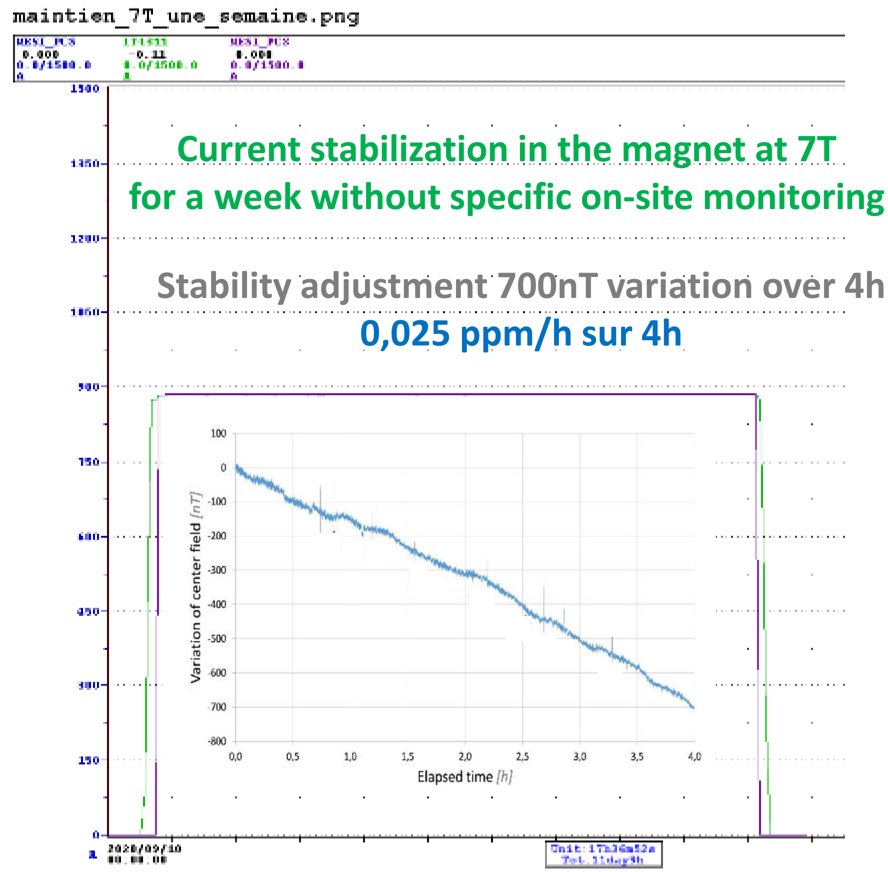


- **Confirmation at 7T of the 3 T results** (slight variations due to disassembly / reassembly of the bench between the two measurements)
- Final adjustment to be made after setting up the gradient.

FIELD STABILITY

- Magnetic field drift adjusted using the fault current limiter
- **0.04 ppm/h obtained after only 4 hours of tests @ 11.72T (vs. spec 0.05ppm/hour)**





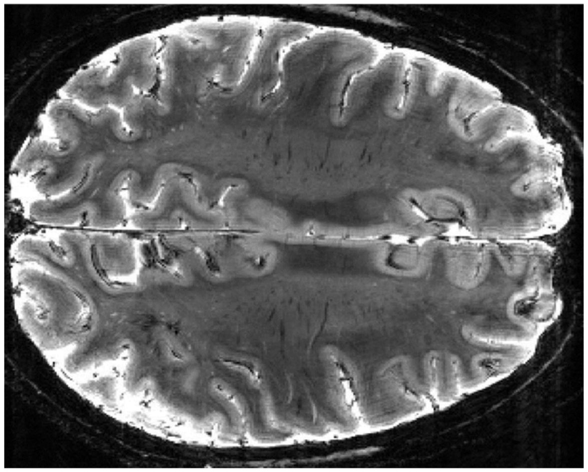
MRI System Equipment (Oct. 2019 – Oct. 2020)

- Covers
- Room walls
- Patient bed
- Faraday cages
- Gradient coils
- Consoles

SIEMENS Healthineers

Final Commissioning Steps of The Iseult MRI System and First Image in 2021

- Installation of the MRI equipment (Gradient Coils, RF antenna, …)
- Final commissioning steps until mid-2021 :
  - *Final commissioning of the high-availability control and protection systems*
  - *Final adjustment of the field homogeneity (iron shims – cryoshims)*
  - *Final adjustment of the field stability*
  - *Tests of the impact of the gradient coil operations on magnet operations (He consumption, eddy currents etc..*



Brain image at 7T (courtesy of Neurospin)

After 20 years …..the start of a new adventure

PERSPECTIVES FOR THE FUTURE

Extremely High Field MRI Magnet

> 14 T

Whole body

(80 – 90 cm)

R&D Nb3Sn HTS

Driving parameters

Higher forces and stored energy

Technology changes : *NbTi -> Nb_3SN and/or HTS*, quench management, structural materials for conductor, cooling solution and operating temperature

Higher risks : high stresses, manufacturing issues (brittle nature of the materials, ..), volume of materials, ..

Higher investments costs : several tens of millions euros …

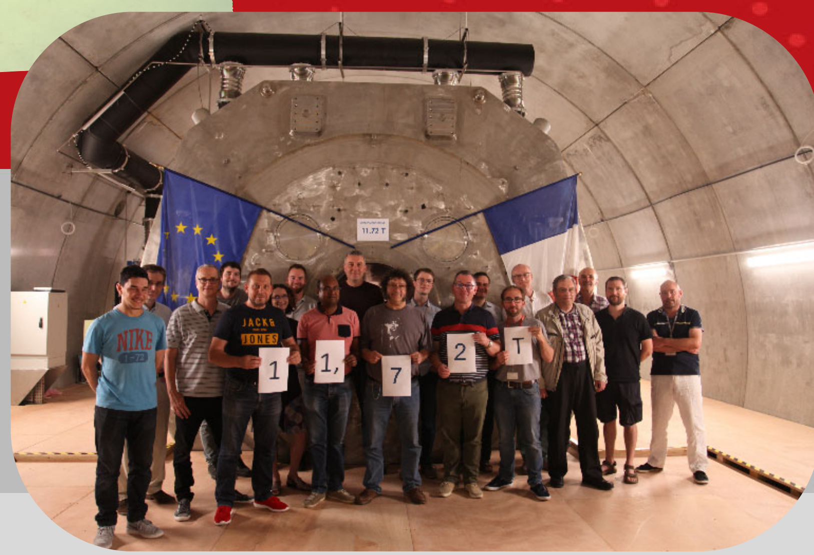
….

Benefits for MRI images ?

International collaborations with academics and industries to develop MRI magnets for the future

Rendezvous in 20 years!

Thank you for your attention



Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr