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

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


- 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 ($\omega = \gamma B_0$)

$\omega$ is the precession frequency (Hz)

$\gamma$ is the gyromagnetic ratio

Spin precession around $B_0$ 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
One of the best tool to study the human brain

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

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

*Neurosciences ... structures & functions of the brain*
In recent decades neuroscience made extraordinary progress.

Human brain singularity
- Cognitive Neurosciences

Pathological brain singularity
- Clinical Neurosciences

Neuroimaging

- Physics, Electronics
- Medicine & Biology
- Mathematics & Statistics
- Image Processing
- Psychology & Sociology
SNR Gain $\propto B_0$: Clinical Research Applications

Example of a human hippocampus image - Courtesy Neurospin/CEA

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

⇒ High accuracy segmentation of the hippocampus becomes possible!
⇒ Highly interesting information for clinical research: Alzheimer’s Disease, epilepsy, schizophrenia…
SNR GAIN AND FUNCTIONAL SENSITIVITY $\propto B_0$: NEUROSCIENCE APPLICATIONS

Anatomical 7T MRI (T2*)

Zoom on the cortical layers

Cortical layers observed in histology

7T functional MRI: 800 $\mu$m isotropic

Voxel distribution over the three gray matter layers.


At 7T: first cortical layer-specific cognitive studies, at 11.7T: towards 500 $\mu$m 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**

**1985 - First 1.5T Active Shield Test Bed**

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

*Courtesy G. Gilgrass*
EXAMPLES OF EXISTING ULTRA HIGH FIELD MRI MAGNETS

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

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

10.5 T 88 cm Passively Shielded
in operation, CMRR, Minneapolis, USA
**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, human brain images since 2018
- 3 projects WB 11.7T:
  - Iseult: 90cm/active shielding, NIH/Bethesda: 68cm/passive shielding,
  - NRI (Seoul): 68cm/passive shielding

Future projects @ 14T: USA (Boston, Stanford), China (Beijing, Shenzhen), Netherlands (Nijmegen), Germany (Heidelberg)
The original idea

Pr. Denis Le Bihan CEA Neurospin

The initial specification

- \( B_0 \) \hspace{1cm} 11.7436T
- Useful bore \hspace{1cm} 900mm
- Homogeneity \( \varnothing 10\text{cm} \) \hspace{1cm} <0.1ppm
- Stability \hspace{1cm} 0.05ppm/h

10 gauss line inside magnet room

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

- Size \hspace{1cm} Length 5m, Diameter 4m
- Superconductor \hspace{1cm} 64t (47t main coils, 17t compensation)
- DP weight \hspace{1cm} 232kg (for main coils)
- Cold structure \hspace{1cm} 38t
- Warm structure \hspace{1cm} 48t
- Whole system \hspace{1cm} 153t
NEUROSPIN: A UNIQUE FACILITY FOR NEUROSCIENCE RESEARCH

When art meets science: the arches of Neurospin

Claude Vasconi, French Architect 1940-2009

Neurospin was opened at CEA Saclay in 2007
Facility equipped with several commercial MRI systems

3 teslas Siemens
7 teslas Siemens
11.7 teslas

Hospital area
(8 beds, consultation rooms, EEG, MEG)

3T clinical MR scanner
7T clinical MR scanner
11.7T clinical MR scanner

Site authorization for Biomedical Research since 2007

Accreditation for animal experimentation since 2008

Facility equipped with several commercial MRI systems:
- 3 teslas Siemens
- 7 teslas Siemens
- 11.7 teslas

Claude Vasconi, French Architect 1940-2009
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

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
ISEULT PROJECT - SCIENTIFIC GOALS

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

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

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

Ultra High Field MRI:

- Signal increase
- New contrasts
⇒ New discoveries

Exploration of the brain at the mesoscopic scale:

- Non-invasive imaging
- Whole human brain
- In vivo
QUEST FOR HIGH FIELD MAGNETS IN FRANCE
FROM PHYSICS TO MEDICAL APPLICATIONS

1980s

Tore Supra Fusion Magnets

1990s

LHC Experiments

CMS Solenoid

ATLAS Barrel Toroid

2000-2010s MRI

Iseult 11.7 T MRI Magnet

LNCMI 8 T Solenoid

40 Years of History of Large SC Magnets
The ISEULT Magnet

A challenging specification:
- \( B_0 / \text{Aperture} \quad 11.75T / 900mm \)
- 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

![Diagram of windings and cryostability](image)

- Double pancake stacking

---

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

---

**Main coil structure (real size)**

- 170 Double-Pancakes
- 82 turns
The objective is to design a magnet theoretically **intrinsically** homogeneous

$$B_z(r, \theta, \varphi) = B_0 + \sum_{n=1}^{\infty} r^n \left( X_n P_n(\cos \theta) + \sum_{m=1}^{n} \left( X_m \cos m\varphi \right) + X_m \sin m\varphi \right) W_n^m P_n^m(\cos \theta)$$

- **Block design**

- **SPECIAL PANCAKE LAYOUT**

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

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

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

External cryogenics:

- Magnet cryostat 11.7T (1.8 K)
- Caloduc (superfluid He thermal drain)
- LHe dewar (5000 l)
- Cryogenic transfer line
- He compressors
- He pumps
- He liquefier
- Cold Box
- Gas buffers

Proximity cryogenics:

- Make the magnet and cryogenics «independents»
- Use reliable technologies and redundancy of equipment
- Continuous operation in case of failure of cryoequipment
**STRONG R&D AND PROTOTYPING ACTIVITIES 2006-2009**

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

- Critical current above the specification +10 %
- No cabling degradation
- Good dimensional reproducibility +/- 15 \( \mu \)m
- Yield strength > 250 MPa
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
2 WEEKS OF TRANSPORT FROM BELFORT TO SACLAY – MAY 2017
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**

**Vacuum vessel welding**

**Final leak tests**

(inner cooling circuits and vacuum vessel)

Leak rate of $5 \times 10^{-9}$ mbar.l/s

on all the internal cooling circuits
A Complex Installation to Operate the Magnet

- Power supplies
- MSS/MCS racks
- Compressors
- Vacuum Circuit
- Dump Resistor
- Cryogenic plant
- 48 V batteries
- Magnet control room
- Air Liquide Refrigerator
- LHe Dewar - 5000 l
- He gasbag (recovery circuit) - 135 m³
- Refrigerator
- Compressors
- Vacuum and helium pumps
• 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)

**COOLDOWN – 19 NOV. 2018 – 7 MARCH 2019**

- **Cold mass temperature**
- **190 ppm max inhomogeneity sur Ø 22 cm**
- **250 000 L liquid nitrogen**
- **18 500 L helium (filling and cooling down)**
- **150 kW of electrical power to operate the cryoplant**

- Cooldown with nitrogen (thermal shield and cold mass) **7 weeks**
- Turbo expander pumps activation
- Cooldown with helium (thermal shield and cold mass) **5 weeks**
- Pumping units activation
- Cold mass filling with helium
- Cooldown from 4.2K to 1.8K **4 weeks**
- Power outage

**88 ppm max inhomogeneity**

$4K \downarrow 2.17K \downarrow 1.8K$
## CRYOGENIC BUDGET

<table>
<thead>
<tr>
<th>Liquefier parameters</th>
<th>Measured values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>900W @ 55K (transfer lignes + satellite)</td>
</tr>
<tr>
<td></td>
<td>40W @ 4.5K</td>
</tr>
<tr>
<td></td>
<td>72 l/h @1.8K</td>
</tr>
</tbody>
</table>

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

(*) 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

<table>
<thead>
<tr>
<th></th>
<th>300K</th>
<th>1.8K 1.5T</th>
<th>1.8K 3T</th>
<th>1.8K 7T</th>
<th>1.8K 11.7T</th>
<th>Cryoshim power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1$ [ppm]</td>
<td>-132</td>
<td>-16</td>
<td>-7</td>
<td>-5</td>
<td>9</td>
<td>+/- 300</td>
</tr>
<tr>
<td>$Z_2$ [ppm]</td>
<td>-105</td>
<td>-22</td>
<td>-16</td>
<td>-15</td>
<td>-17</td>
<td>+/- 70</td>
</tr>
<tr>
<td>$Z_3$ [ppm]</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>+/- 10</td>
</tr>
<tr>
<td>$X_1^1$ [ppm]</td>
<td>-1</td>
<td>22</td>
<td>21</td>
<td>22</td>
<td>24</td>
<td>+/- 32</td>
</tr>
<tr>
<td>$Y_1^1$ [ppm]</td>
<td>59</td>
<td>63</td>
<td>59</td>
<td>60</td>
<td>62</td>
<td>+/- 32</td>
</tr>
<tr>
<td>$X_2^1$ [ppm]</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>+/- 14</td>
</tr>
<tr>
<td>$Y_2^1$ [ppm]</td>
<td>-</td>
<td>-6</td>
<td>-6</td>
<td>-6</td>
<td>-7</td>
<td>+/- 14</td>
</tr>
<tr>
<td>$X_2^2$ [ppm]</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td></td>
<td>+/- 10</td>
</tr>
<tr>
<td>$Y_2^2$ [ppm]</td>
<td>-</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+/- 10</td>
</tr>
</tbody>
</table>

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

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

1.5 T

7 T

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

- 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.

<table>
<thead>
<tr>
<th>DHS</th>
<th>11,7T w/o iron</th>
<th>3T measurements extrapolated at 11,7T with iron</th>
<th>7T measurements extrapolated at 11,7T with iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z₀ [T]</td>
<td>11,7</td>
<td>11,7</td>
<td>11,7</td>
</tr>
<tr>
<td>Z₁ [ppm]</td>
<td>-5,6</td>
<td>0,2</td>
<td>11,9</td>
</tr>
<tr>
<td>Z₂ [ppm]</td>
<td>-16,9</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Z₃ [ppm]</td>
<td>3,6</td>
<td>0,1</td>
<td>-0,8</td>
</tr>
<tr>
<td>Z₄ [ppm]</td>
<td>1,3</td>
<td>1,3</td>
<td>1,5</td>
</tr>
<tr>
<td>Z₅ [ppm]</td>
<td>-0,1</td>
<td>-0,1</td>
<td>-0,1</td>
</tr>
<tr>
<td>X₁₁ [ppm]</td>
<td>23,2</td>
<td>0,8</td>
<td>-2,9</td>
</tr>
<tr>
<td>Y₁₁ [ppm]</td>
<td>64,5</td>
<td>-0,4</td>
<td>2,5</td>
</tr>
<tr>
<td>X₂₁ [ppm]</td>
<td>2,6</td>
<td>-0,4</td>
<td>0,5</td>
</tr>
<tr>
<td>Y₂₁ [ppm]</td>
<td>-7,1</td>
<td>-0,1</td>
<td>-0,1</td>
</tr>
<tr>
<td>X₂₂ [ppm]</td>
<td>-0,6</td>
<td>-0,4</td>
<td>-0,6</td>
</tr>
<tr>
<td>Y₂₂ [ppm]</td>
<td>-1,2</td>
<td>-0,5</td>
<td>-0,4</td>
</tr>
</tbody>
</table>
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)

Current stabilization in the magnet at 7T for a week without specific on-site monitoring

Stability adjustment 700nT variation over 4h 0.025 ppm/h sur 4h
MRI SYSTEM EQUIPMENT (OCT. 2019 – OCT. 2020)

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

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

Brain image at 7T (courtesy of Neurospin)
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: \( \text{NbTi} \rightarrow \text{Nb}_3\text{Sn and/or HTS}, \)
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