HIGH FIELD MAGNETS
FROM PARTICLE PHYSICS TO MEDICAL APPLICATIONS

1990s

LHC Experiments

ATLAS Barrel Toroid

30 years of history

Iseult 11.7 T MRI Magnet

CMS Solenoid

2010s
Incredible machines for very large research instruments
the children of Athena and Hephaestus...
the marriage of the Science and Technique....
The instruments are the constants partners of the researchers
to explain the origin of the Universe and the brain functions.

**NEW MYTHOLOGIES FOR THE 21ST CENTURY**

Incredible machines for very large research instruments
the children of Athena and Hephaestus...
the marriage of the Science and Technique....
The instruments are the constants partners of the researchers
to explain the origin of the Universe and the brain functions.
Brief introduction on challenges using superconducting high field magnets

From the first bubble chambers to ATLAS and CMS detector magnets

The long road to human 11.7T MRI system
CHALLENGES USING SUPERCONDUCTING HIGH FIELD MAGNETS
MAGNETS ARE EVERYWHERE!!!

The very first magnet!

0.5 Gauss / 5.10^-5 T in Wuhan

Permanent magnet (NdFeB, 0.5T)

Resistive magnet (2T)

MRI magnet (Siemens 3T)

VNIIEF MC-1 (Russia) 2.8 kT

ISSP (Japan) (750 T)

NHMFL Tallahassee Hybrid magnet (40 T)

Bruker 1 GHz NMR (23.5T)

LHC Dipole (8.3T)
AND SUPERCONDUCTIVITY HAS A LOT OF APPLICATIONS!
Possibility to generate **very large volumes** of **(high) magnetic field** using superconductors.

\[ E_{\text{beam}} \propto B_{\text{dipole}} R \]

Circular Collider

\[ \frac{\Delta p}{p} \propto \frac{p}{BL^2} \]

Particle Detector

\[ \frac{S}{N} \propto B_0^{\frac{3}{2}} \]

NMR/MRI systems
RELEVANT PARAMETERS FOR MAGNET DESIGN

- **Main parameters for the specification**
  
  - Field $B$, length $L$, radius $R$
  
  - Field shape and homogeneity, field stability, radiation thickness, interaction length, etc…

- **Parameters relevant for the physics**
  
  - $B$, $BL^2$ (sagitta), $BL^2$ (momentum resolution), …

- **Parameters relevant for the magnet designer**
  
  - $B^2 R$ (mechanical forces)
  
  - $B^2 R/e$ with $e$ coil thickness (stresses, protection in case of quench)

- **Parameters relevant for the ressource manager**
  
  - Cost: $C = \alpha (RL)^{0.8} + \beta (B^2 R^2 L)^{0.7}$ (from A. Hervé)
    
    $C(M\$) = 0.5(E_s MJ)^{0.662}$
    
    $C(M\$) = 0.4(B(T)V)^{0.635}$ (from Green and Lorant)
- **High magnetic field** $B$ : intrinsic value : $B_c$ 
  $\sim 10$ T for NbTi 
  $\sim 20$ T for Nb$_3$Sn

- **High mechanical forces/stresses**
  - Forces must be held by the conductor and/or the external support structure
  
  \[(\text{coil thickness} \propto RB^2/ (E/M) \propto RB^2 \rho/\sigma_h \ (\rho = \text{density}))\]
  
  - Electrical insulation must also withstand the stress (shear stress in particular)

- **Protection in case of quench**
  - Importance of the value of the stored energy per unit of cold mass (E/M ratio)
  
  peak temperature at homogeneous energy dump ($E = 0.5\mu_0\int B \cdot dV ; E/M=H=\int C_p dT$)

  - Necessity of fast quench propagation (active/passive propagation techniques, high RRR in stabilizer, energy extraction by external dump)

- **Dimensions:**
  - Manufacturing dimensions and tolerances, handling
  
  - Road transportation $R_{max} \sim 3.5$ m

- **Enabling technologies** : SC Conductor, Electrical insulation, cooling, manufacturing techniques
Jeng in LTS and HTS conductors at 4.2K and 1.9K

- Conductor Source: http://fs.magnet.fsu.edu/~lee/plot/plot.htm

Applied Magnetic Field (T)

Whole Wire Critical Current Density (A/mm², 4.2K)

- Nb-Ti
  - 4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
  - Maximal Jc at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in Jc for Nb-Ti

- Nb-Ti 1.9 K

- Nb-Ti 4.22 K High Field MRI strand (Luwoto)

- MgB₂: 2nd Gen. AIMI 18+1 Filaments, The OSU/ HTRI, 2013

- Nb₃Sn: High Jc

- Compiled from ASC’02 and ICMC’03 papers (J. Parrell Ol-ST)

- 4543 filament High Sn Bronze-16wt.%,Sn-0.3wt.%Ti

- Nb₃Sn: Bronze Process

- Bi-2212: 50 bar OP

- Bi-2223: B∥ Tape Plane

- Bi-2223: B⊥ Tape Plane (prod.)

- Bi-2223: B⊥ Tape Plane (carr. cont.)

- Bi-2223: B⊥ Tape Plane (prod.)

- REBCO: B∥ Tape Plane

- REBCO: B⊥ Tape Plane

- Bi-2212: 50 bar OP

- Bi-2223: B∥ Tape Plane

- Bi-2223: B⊥ Tape Plane

- Bi-2223: B⊥ Tape plane (carr. cont.)

- Bi-2223: B⊥ Tape plane (prod.)

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- Bi-2223: B∥ Tape Plane

- Bi-2223: B⊥ Tape Plane

- Bi-2223: B⊥ Tape plane (carr. cont.)

- Bi-2223: B⊥ Tape plane (prod.)

- Nb₃Sn: Internal Sn RRP*

- Nb₃Sn: High Sn Bronze

- Nb-Ti: LHC 1.9 K

- Nb-Ti: LHC 4.2 K

- Nb-Ti: High Field MRI 4.22 K

- MgB₂: 18+1 Fil. 13 % Fill

April 2018
A LARGE CHOICE OF SC WIRES AND CABLES…

MRI is biggest user of NbTi SC wire

**NbTi**
- *Dominant commercial superconductor*
- MRI is biggest user of NbTi SC wire
- Bendable, ductile, low cost ($1/kA.m)
- \( T_c=9.3\, \text{K}, \, B_{c2}=11.4 \, @ \, 4.23\, \text{K} \)

**Nb3Sn**
- *Primary high field SC*
- Brittle
- \( T_c=18\, \text{K}, \, B_{c2} \approx 23-29\, \text{K} \)
- Higher cost (x 5 price of NbTi)

**MgB2**
- Brittle
- \( T_c=39\, \text{K}, \, B_{c2}=40\, \text{T} \)
- Higher cost (x 5 price of NbTi)

Technology based on **ReBCO** and **BSCCO** super expensive ($50-100/kA.m) and not mature enough for large industrial applications
DETECTOR MAGNETS
MAGNET OPTIMISATION IS A COMPLEX PROBLEM…

How physicists depict the CMS detector…

How engineers built it…
Two main types of large, superconducting detector magnets:

- **solenoids** (e.g., ALEPH and CMS at CERN) and **toroids** (e.g., ATLAS at CERN).

\[
\begin{align*}
B_x &= 0 \\
B_y &= 0 \\
B_z &= B_0 \\
B_r &= 0, \\
B_\theta &= B_0 \\
B_z &= 0
\end{align*}
\]

+ Very good momentum resolution at large angle, compact and efficient structure.

- Requires an iron yoke, inefficient for small-angle particles.

+ No field along the axis, magnetic field always transversal to the particle momentum, low fringe field, best momentum resolution at low angle.

- Very inhomogeneous magnetic field, high peak field on the conductor, complicated magnet structure.
BRIEF DETECTOR SC MAGNETS HISTORY

BEBC (CERN 1972)

CMS (CERN 2006)

ATLAS (CERN 2006)
First superconducting bubble chamber magnet constructed at Argonne National Laboratory by John Purcell 1968

Split pair solenoid with vertical axis and gap to allow beam entry

Bath cooled coils – NbTi copper stabilised conductor operated in cryostable mode

Low current density ~ 8A/mm^2

<table>
<thead>
<tr>
<th></th>
<th>Argonne 12 ft BC</th>
<th>Fermilab 15 ft BC</th>
<th>Cern BEBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1968</td>
<td>1972</td>
<td>1972</td>
</tr>
<tr>
<td>Field (T)</td>
<td>1.8</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Winding ID (m)</td>
<td>4.8</td>
<td>4.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Stored Energy MJ</td>
<td>80</td>
<td>400</td>
<td>800</td>
</tr>
</tbody>
</table>
BEBC cooling power at 4K ~ 900W equivalent to ~ 0.5MW at 300K
Corresponding power for a resistive version ~ 60MW

BEBC - BIG EUROPEAN BUBBLE CHAMBER

20 pancakes, NbTi conductor 3 x 61 mm,
200 untwisted filaments 200 μm 5700 A

Inter-layer insulation with slots to allow boiling He flow

BEBC magnet 1967-1972
750 MJ
Co-extruded monolithic conductor – Al alloy support cylinder – (shrink fit or) internal winding without mandrel

Conductor joints formed by welding between aluminium sections

Indirect Cooling Circuit
Welded to Al5083 Cylinder
ALUMINUM STABILIZED CONDUCTORS

Example

**ATLAS Conductor**

65 kA at 5 T

1.25mm dia. NbTi/Cu strand,

2900A/mm² at 5T, 4.2 K

40 strands Rutherford cable,

Co-extrusion with high purity Al (RRR>1500)

(AI for low density and high RRR)

Inter-metallic bonding Cu-Al necessary

size 57 x 12 mm², 56 km
## DETECTOR MAGNETS IN THE 1980S

<table>
<thead>
<tr>
<th>Name</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>CLEO2</th>
<th>ZEUS</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accelerator Laboratory</strong></td>
<td>LEP CERN</td>
<td>LEP CERN</td>
<td>CESR Cornell</td>
<td>HERA DESY</td>
<td>HERA DESY</td>
</tr>
<tr>
<td><strong>Designed by</strong></td>
<td>Saclay</td>
<td>RAL</td>
<td>Cornell Oxf.</td>
<td>Milan Un.</td>
<td>RAL</td>
</tr>
<tr>
<td><strong>Manufactured by</strong></td>
<td>Saclay</td>
<td>RAL</td>
<td>Oxford Inst.</td>
<td>Ansaldo</td>
<td>RAL</td>
</tr>
<tr>
<td><strong>Inner Bore (m)</strong></td>
<td>4.96</td>
<td>5.2</td>
<td>2.88</td>
<td>1.72</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>Outer Bore (m)</strong></td>
<td>5.98</td>
<td>6.2</td>
<td>3.48</td>
<td>2.22</td>
<td>6.08</td>
</tr>
<tr>
<td><strong>Winding Length (m)</strong></td>
<td>6.35</td>
<td>6.8</td>
<td>3.48</td>
<td>2.5</td>
<td>5.16</td>
</tr>
<tr>
<td><strong>Overall length (m)</strong></td>
<td>7</td>
<td>7.4</td>
<td>3.78</td>
<td>2.8</td>
<td>5.75</td>
</tr>
<tr>
<td><strong>Conductor (mm²)</strong></td>
<td>35 x 3.6</td>
<td>24 x 4.5</td>
<td>16 x 5</td>
<td>15 x 4.3</td>
<td>26 x 4.5</td>
</tr>
<tr>
<td><strong>Stabiliser</strong></td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
</tr>
<tr>
<td><strong>Cold Mass (t)</strong></td>
<td>25</td>
<td>25</td>
<td>7</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td><strong>Conductor mass (tons)</strong></td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>2.4</td>
<td>7</td>
</tr>
<tr>
<td><strong>Current (A)</strong></td>
<td>5000</td>
<td>5000</td>
<td>3300</td>
<td>5000</td>
<td>5500</td>
</tr>
<tr>
<td><strong>Design field (T)</strong></td>
<td>1.5</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Stored energy (MJ)</strong></td>
<td>137</td>
<td>108</td>
<td>25</td>
<td>16</td>
<td>120</td>
</tr>
<tr>
<td><strong>Cooling method</strong></td>
<td>Thermo siphon</td>
<td>Forced flow pumps</td>
<td>Thermo siphon</td>
<td>Forced flow pumps</td>
<td>Forced flow pumps</td>
</tr>
<tr>
<td><strong>Radiation length (X0)</strong></td>
<td>2</td>
<td>7.4</td>
<td></td>
<td>0.9</td>
<td>4</td>
</tr>
</tbody>
</table>
14 TeV proton-proton collider:
Installed in the LEP 27 km tunnel, to produce the events needed to study the "Standard Model" of particles, to understand the "Mass", Higgs boson and more..

Exploration and discovery machine
2 general ATLAS and CMS detectors, each checking the results of the other. Can look beyond the “Standard Model” and perhaps discover a "new physics"
LHC DETECTOR MAGNETS…THE GIANTS!

CMS
Largest Solenoid
4T, 2.7 GJ, 7m dia, 12m long

ATLAS TOROIDS
Largest field volume – 8200 m³ self contained field (no yoke) open structure
4T peak field, 1.55 GJ, 20 m dia, 25 m long
ATLAS AND CMS DETECTORS

The graph shows a comparison of stored energy (MJ) against E/M (kJ/kg) for various detectors. The detectors included are:

- ATLAS
- CMS
- ALEPH
- DELPHI
- H1
- CDF
- VENUS
- ZEUS
- TOPAZ
- CLEO2

The graph highlights the performance of these detectors in terms of stored energy and E/M efficiency.
On 4 July 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider announced they had each observed a new particle in the mass region around 125 GeV.

On October 8, 2013, Peter Higgs and François Englert won the Nobel Prize in Physics for their work on the Higgs boson.
ATLAS SUPERCONDUCTING MAGNETS

Barrel Toroid + End Cap Toroids + Central Solenoid

System of 4 magnets provides magnetic field for the inner detector (solenoid) and muon detectors (toroids)

20 m diameter x 25 m long
8200 m³ volume
  170 t superconductor
  700 t cold mass
1320 t total mass
  90 km superconductor
  20.5 kA at 4.1 T
1.55 GJ stored energy
conduction cooled at 4.8 K
8 years construction 98-06

It is still the largest superconducting magnet in the world!
ATLAS EXPERIMENTAL AREA @ CERN

- Two underground caverns
- 2 main shafts give access to a 50,000 m$^3$ main cavern for the detector

Length = 55 m  
Width = 32 m  
Height = 35 m
June 2003, bare cavern given to ATLAS
SEPTEMBER 2003, WALL STRUCTURES ERECTED
MARCH 2004, FEET PUT, READY FOR THE TOROID
ATLAS COILS

Barrel Toroid
(8 coils, 4 T peak, 1080 MJ)

End Cap Toroid
(8 coils, 4 T peak, 250 MJ)

Central Solenoid
(2 T, 39 MJ)
# ATLAS TOROIDS PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>End Cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torus inner bore (m)</td>
<td>9.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Outer diameter (m)</td>
<td>19.3</td>
<td>10.6</td>
</tr>
<tr>
<td>Overall length (m)</td>
<td>26</td>
<td>5.6</td>
</tr>
<tr>
<td>Number of coils</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Total Amp x turns (MA)</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>Stored Energy (MJ)</td>
<td>1200</td>
<td>350</td>
</tr>
<tr>
<td>Operating current (kA)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Peak field (T)</td>
<td>3.8</td>
<td>4</td>
</tr>
<tr>
<td>Total Weight (t)</td>
<td>800</td>
<td>240</td>
</tr>
<tr>
<td>Conductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall size (mm²)</td>
<td>70 x 11</td>
<td>70 x 7</td>
</tr>
<tr>
<td>Type</td>
<td>Rutherford cable + pure Al coextruded</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>Indirect cooling with flow of pressurized supercritical helium 4.5 K</td>
<td></td>
</tr>
</tbody>
</table>
Barrel toroid lay-out

- 8 coils of size 25x5 m\(^2\); 20 kA, 4.0 T peak field
- Assembled as toroid and mounted on ..
- 18 feet and 6 bedplates in cavern floor
- Current & Cryogenics are connected via a top feedbox and the cryoring

A coil has 2 double pancake coils glued in an Al casing, suspended by radial Ti tie rods and tangential cryo-stops, Al thermal shield & MLI, in a SS vacuum vessel
Barrel and End Cap Toroids Conductor : 65 kA at 5 T

1.25mm dia. NbTi/Cu strand, 2900A/mm² at 5T

40 strands Rutherford cable, ~1700 A / strand

Co-extrusion with high purity Al (RRR>1500)
(Al for low density and high RRR)
Intermetallic bonding Cu-Al necessary

BT: size 57 x 12 mm², 56 km

ECT: size 46 x 12 mm², 25 km
MECHANICAL CHALLENGES OF THE SUPPORTING STRUCTURE

Weight supported by the structure:
1300 tonnes - dead weight, cold mass, muon chambers, services, etc..

• Magnetic forces:
  - radial forces: 1100 tons / coil
  - axial forces: 240 tons /on each side

• Atmospheric pressure

• Deformations and thermal constraints

• In accidental situation:
  - "fault magnetic scenario"
  - seismic incident
  - other risks

• Bolted connections
Model of the barrel toroid final coil with the same section but a length reduced to 9 m.

Same technical concepts to validate the design and manufacturing technologies of the final coils.

The manufacturing and testing of B0 proved to be fundamental in optimizing final coils's production cycle.
B0 MANUFACTURING AND TESTING 1996 - 2000
PICTURE OF ONE FULL SCALE INDIVIDUAL COIL

25 m

5 m
56 km of superconductor

16 coil windings

8 coil casings

8 vacuum vessels

8 col masses

8 thermal screens
- Tie rods Ti 5Al 2.5 Sn ELI
- Head 304 L
- Cryo stops fiber Glass-epoxy
Forged aluminum warm voussoirs

Connecting pieces

Wedge assembly + permaglide©
ATLAS BARREL TOROID MANUFACTURING

BT coil manufacture at Ansaldo

BT coil encasing at CERN

Cryostating at CERN

Cold test of individual BT coil at CERN

Last coil finished in July 2005
INTEGRATION & TESTS FROM 2002 TO 2005
IN CERN ASSEMBLY HALL 180

- B4
- B6
- B3
- B5 test
- B7 welding
- B8 cold mass integration
THERMAL SHIELD INTEGRATION – HE PIPES LAYOUT
INSERTION OF THE COLD MASS INTO VACUUM VESSEL
INSERTION OF THE COLD MASS INTO VACUUM VESSEL
INDIVIDUAL COIL TEST 4,5 K 22 KA
Each coil has been individually cold tested at 22 kA and 4.5K

2 weeks cool-down
PREPARATION THE INSTALLATION
TILTING OF THE COIL
DEPARTURE FOR THE CAVERN
Difficult handling – tight tolerances

Use of two lifting frames

190 t load capacity hydraulic jack to tilt the coil
THE FIRST COIL ARRIVING IN THE CAVERN....
CAVERN ASSEMBLY

- Installation of the 4 bottom coils
- ...with temporary supports
THE BEAUTY OF A TOROID
LAST COIL INSTALLED...

Descent of 8th Barrel Toroid coil (4 August 2005)

Barrel Toroid completed (September 2005)
Installation of ATLAS magnet system (BT & CS) at the bottom of CERN pit (November 2005)
BARREL TOROID COOLING DOWN

BT cooling curve

Temperature [K]

Start up of the LHe pumps: 10 L/s
Cooling by LHe forced flow

- Start cooling with Shield Refrigerator
- Start cooling with Main Refrigerator
21 KA: 18 OCT – 10 NOV 06

Ramp

≈ 4 hours

Fast discharge

20.5 = nominal
END OF THE NIGHT SHIFT AFTER THE TEST!
### ATLAS END CAP TOROID

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal Magnetic Field</td>
<td>4.1 T</td>
</tr>
<tr>
<td>Current</td>
<td>20 500 A</td>
</tr>
<tr>
<td>Temperature</td>
<td>4.8 K</td>
</tr>
<tr>
<td>Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Internal Radius</td>
<td>1.7 m</td>
</tr>
<tr>
<td>External Radius</td>
<td>11 m</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>250 MJ</td>
</tr>
<tr>
<td>Weight</td>
<td>240 tonnes</td>
</tr>
<tr>
<td>Conductor Length</td>
<td>13 km</td>
</tr>
</tbody>
</table>
ATLAS CENTRAL SOLENOID IN THE PIT...
ATLAS CENTRAL SOLENOID

- Diameter 2.4 m  5.3 m long
- 2.0 T & 38 MJ
- 9 km of conductor
- Weight 6 t

Excitation to full field: 8 kA on 1 Aug 06

High strength pure aluminium stabilizer Al-0.1wt%Ni alloy
cold work of around 20 - 2.5% in area reduction after co-extrusion
RRR > 500, YS > 85 Mpa
Al-strip quench propagator
ATLAS MAGNET SYSTEM INSTALLED IN 2008
CMS SOLENOID

Yoke
(Barrel: 6000 t, End Cap Disks: 2x2000 t)

Solenoid
(4 T, 2.7 GJ, 220 t)
CMS SOLENOIDAL COIL

Central field: 4 T
Nominal current: 20 kA
Stored energy: 2.7 GJ
Length: 12.5 m
Internal diameter: 6 m
Weight: 220 t

Conductor

- Pure Al + high strength alloy 6082
- YS > 250MPa @ 4K
- RRR 1400

4 layers reinforced conductor
CMS COIL WINDING

Conductor manufacturing

Winding mandrel
CMS COIL WINDING
VACUUM IMPREGNATION
CMS SOLENOID ASSEMBLY at CERN
- **5 modules connected in series:**

- **Electrical test:**
  - Mass insulation: 54 MΩ at 2 kV.
  - Connections checked with 2 A (3.75 Gauss)

- **Piping:**
  - Alumibum and stainless steel welding

- **He leak testing:**
  - Local
  - Global
END OF THE MODULE ASSEMBLY

Feb. 2005
THERMAL SHIELD AND MULTILAYER INSULATION ASSEMBLY
COLD MASS TILTING – 350 T –INSERTION IN BARREL YOKE
Yoke reception at CERN (June 2002)

Magnet insertion into barrel yoke (Fall 2005)

Lowering of the central part of the CMS detector to the bottom of its CERN pit (Feb. 2007)
FUTURE DETECTORS

ILC

4 $T$ - 6.5 m

3 $T$ - 7.2 m

4 $T$ - 10 m
HIGH FIELD MAGNETS
FROM PARTICLE PHYSICS TO MEDICAL APPLICATIONS

ATLAS Barrel Toroid

Iseult 11.7 T MRI Magnet

CMS Solenoid
The long road to human 11.7T whole body MRI system

Iseult project
**MRI MILESTONES**

- **1937** Rabi (1944) - resonance method for recording magnetic properties of atomic nuclei
- **1940** Zavoyski – discovery of electron paramagnetic resonance
- **1946** Block, Purcell (1952) – nuclear magnetic precision measurements, related discoveries
- **1973** Lauterbur (2003) – First MR images on samples
- **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
- **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

Rabi (1944): Nobel prize in Physics
Lauterbur and Mansfield (2003): Nobel Prize in Medecine
Field uniformity and stability
- Design Uniformity: 10 parts-per-million (ppm) in ~50 cm diameter volume
  - Multiple-coil configuration
  - Shimming strategy with coils and iron pieces
- Field decay:
  - short-term decay: 1 ppb during sequence (EMI, vibration)
  - Long-term decay: less than 0.1 ppm/hour on average, less than 0.1% per year

Shielding
- Magnetic field outside of the scanning suite shall be less than 5 gauss (industry standard)
MAGNETIC COMPONENTS OF A MRI SYSTEM

- Shielding coil
- EIS coils (External Interference Shield)
- RF Antenna
- Main coil
- Gradient coils
- Warm-shims
- Cryo-shims

Courtesy L. Scola
EARLY NMR IMAGING MAGNETS 1977 - 1981

- Aberdeen 0.03T resistive magnet - 1977
- John Woodgate and the first 0.3Tesla NMR Imaging Magnet for EMI
- 0.15T Resistive magnet - 1980
- First 1.5Tesla magnet (STAR)

Courtesy G. Gilgrass
FAST EVOLUTION: X 5 WITHIN 20 YEARS FOR ACTIVELY SHIELDED MAGNETS

1985 - First 1.5 Tesla 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
### Whole Body MRI Magnet Typical Sizes

<table>
<thead>
<tr>
<th>Field</th>
<th>1.5 T</th>
<th>3 T</th>
<th>7 T</th>
<th>11.75 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>GE-SHFJ/CEA</td>
<td>Siemens</td>
<td>Siemens</td>
<td>Iseult</td>
</tr>
<tr>
<td></td>
<td>1.25 - 1.7</td>
<td>1.6 - 1.8</td>
<td>~ 3</td>
<td>4</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td></td>
<td>1.90 - 2.1</td>
<td>&gt; 2.50</td>
<td>4.6</td>
</tr>
<tr>
<td>Mass (tons)</td>
<td>~ 5</td>
<td>~ 8</td>
<td>~ 25</td>
<td>~ 135</td>
</tr>
</tbody>
</table>
SNR gain $\propto B_0$

SNR $\propto B_0^{1.65}$

**Better resolution !!!**

*Example of a rat hippocampus image
 Courtesy Neurospin/CEA*
WORLD UHF MRI PARK EVOLUTION 2001-2018

2003
- 3T : ≈ 100 systems
- 2 systems 7T WB
- 1 system 8T WB

2007
- 3T : ≈ 700 systems installed
- 7T : ≈ 30 systems installed
- 1 system 8T WB, 3 systems 9.4T WB
- 4 projects at 11.7T WB
(NeuroSpin, Tokyo, Berkeley, Bethesda)

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

2018
- 3T : >12000 systems installed (25% of the overall MRI park)
- 7T : ≈ 70 systems installed
- 1 system 8T WB, 4 systems 9.4T WB
- 1 system 10.5T WB in Minneapolis:
  First images on human volunteers since beginning 2018
- 2 projects at 11.7T WB:
  - NIH (Bethesda): Delivery expected in Dec. 2018
  - NRI (Seoul): Delivery in May 2019
- Emerging projects
  14T: Heidelberg, Boston (MGH), Stanford
  15T: China, 20T: USA
Neurospin
CEA Saclay, France

Project partners: *CEA*(F), *GE – ex Alstom* (F), *Guerbet* (F), *Siemens Healthcare* (G), *Friburg University*(G), *Bruker Biospin* (G)

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

*for developing brain science*
ISEULT 11.7 T MRI MAGNET
BACK TO 2005…

An original idea

Pr. Denis Le Bihan CEA Neurospin

The initial specification

$B_0$  
Useful bore  
Homogeneity $Ø10cm$  
Stability  

10 gauss line inside magnet room

A very preliminary magnet concept a few months later…

Size  
Superconductor  
DP weight  
Cold structure  
Warm structure  
Whole system

Length 5m, Diameter 4m  
64t (47t main coils, 17t compensation)  
232kg (for main coils)  
38t  
48t  
153t
When art meets science: the arches of Neurospin

Claude Vasconi, French architect 1940-2009

T Park Hong Kong
sludge incineration plant
STRONG R&D AND PROTOTYPING ACTIVITIES 2006-2009

Manufacturing techniques, mechanics, cryogenics, quench analysis, electrical engineering…
Iseult 11.7 T MRI Magnet

- 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 MRI magnet

- 220km of NbTi large superconductor
- 170 wetted double pancakes for the main coil
- 2 shielding coils to reduce the fringe field
- Cryostat for liquid helium at 1.8 K, 1.25 bars

- Dedicated refrigerator 80 l/h + 40 W à 4.2 K
- Two 1500 A power supplies for redundancy

<table>
<thead>
<tr>
<th>Stored Energy</th>
<th>338 MJ</th>
</tr>
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<tbody>
<tr>
<td>Inductance</td>
<td>308 H</td>
</tr>
<tr>
<td>Current</td>
<td>1483 A</td>
</tr>
<tr>
<td>Length</td>
<td>5.2 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>5 m</td>
</tr>
<tr>
<td>Weight</td>
<td>132 t</td>
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ARTISTIC VIEW OF THE ISEULT 11,7 T WB MRI SYSTEM

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</tr>
</tbody>
</table>

B0 / Aperture 11.75 T / 900 mm
Homogeneity < 0.5 ppm sur 22 cm Ø

- Cryostat
- Shielding coils
- Main magnet
- Caloduc
- Cryogenic satellite
- Vacuum
- Helium vessel
- RF Antenna

Stored Energy: 338 MJ
Inductance: 308 H
Current: 1483 A
Length: 5.2 m
Diameter: 5 m
Weight: 132 t
Combination of Cryogenic satellite, Vacuum, Caloduc, and Helium vessel creates the Cryostat, which is essential for cooling the MRI system to extremely low temperatures. The Main magnet produces the magnetic field of 11.75 T, ensuring high-quality MRI images. Shielding coils are crucial for minimizing external magnetic interference, ensuring the MRI machine operates efficiently and safely.
Cryostable magnet design (“Stekly” criteria)
- NbTi @ 1.8 K (pressurized helium bath)
- Development of a dedicated code to evaluate the pressure increase in case of quench in the system

Double pancake winding technique (x170 DP)
- Innovative winding method
- No winding mandrel
- DP directly wetted by the superfluid helium

Active shielding with 2 coils to reduce the fringe field
- Saving of 750 tons of iron compared with a passive shielding technique

Magnet operated in driven-mode / external power supply
- Field stability of 0.05 ppm/h using a current limiter
Specific design → Main coil made of "wetted" double-pancakes
→ Shielding coils vacuum impregnated with epoxy resin

• Double pancake stacking
The objective is to design a magnet theoretically intrinsically homogeneous

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

Method and device for generating a homogeneous magnetic field in an area of interest, especially for NMR imaging

Design proven on a prototype
System requirement: Field must be within <0.1% peak-peak

Options:
1. Driven operation
   - Expensive driver, permanently installed
   - Lead losses

2. Persistent operation: average decay <0.1 ppm/hr
   - Typical MRI/NMR configuration
   - Lower cost. Better performance
   - Driver is not on site
   - Requires very low circuit resistance
   - Retractable leads
   - Risk: unstable SC components
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

CEA Patent WO/2009/063150: System for creating a magnetic field via a superconducting magnet

Validated on prototype magnets

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

A design with 2 power converters to increase the availability of the magnet
ISEULT MAGNET MANUFACTURING STEPS
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,

- 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
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

CIC NbTi
Position of each DP checked with laser tracker
Overall length of the main coil achieved within 1mm tolerance
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

Final pulping and leak tests

Cryostat assembly
2 WEEKS OF TRANSPORT FROM BELFORT TO SAACLAY

ARRIVAL AT SACLAY

May 19th, 2017
MAGNET INSTALLATION – JUNE 2017
A DEDICATED COMPLEX INSTALLATION TO OPERATE THE MAGNET

- Power supplies
- Cryo-lines
- 48 V Batteries
- Control room
- Vacuum circuit
- MCS/MSS/DAQ
- Dump resistor
POWER SUPPLY SYSTEM TO ENSURE 24 HOURS OPERATIONS

Redundancy of all key equipments

48V batteries in case of power failure

Building equipped with a diesel generator
The reliability of MSS is always based on voting redundancy.

Detects the voltage rise due to a quench.
GENERAL SCHEME OF THE CRYOGENIC EQUIPMENT

Proximity cryogenics:

- Make the magnet and cryogenics «independents»
- Use reliable technologies and redundancy of equipment
- Continuous operation in case of failure of cryoequipment

External cryogenics:

- Gas buffers
- He compressors
- He pumps
- Cryogenic transfer line
- Cold Box
- LHe dewar (5000 l)
- He liquefier

Magnet room:
- Magnet cryostat 11.7T (1.8 K)
- Caloduc (superfluid He thermal drain)

Machine room:
- Heaters 5/300 K
CRYOGENICS EQUIPMENTS

LHe Dewar - 5000 l (Cryotherm)

Compressors

Air Liquide Refrigerator:
40W@4.5K & 80l/h at rising level & 900W@44K

He gasbag (recovery circuit)
135 m3 – (ATIC)

Vacuum and helium pumps
MAGNET COMMISSIONING – START SUMMER 2017

- Quench line installation
- Scaffolder installation
- Magnet electrical and insulation tests
- First magnetic measurements in situ (0.1 A, flux gate)
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 < mm
  To take into account the thermal shrinkage during cool down (copper/aluminum)
CALODUC ASSEMBLY – OCT 2017- OCT 2018

Helium vessel and inner cooling tubes leak tests

wiring

MLI

Thermal shield

Vacuum vessel welding
COOLING DOWN NOVEMBER 2018

-5ppm/62ppm/-190ppm

Maximum amplitude in direction X/Y/Z

-10ppm/63ppm/-88ppm
SHIMMING STRATEGY

Improve uniformity from ~max 500 ppm in magnet as-built to 10 ppm

• Passive shimming
  • Precisely-positioned pieces of iron in the warm bore. Improves overall uniformity (not individual harmonics)
  • Lowest cost option
  • Cons: Good for specified field/location only. Re-shim requires Service. Temperature drift

• Active superconducting shimming (SC and resistive shims)
  • Adjustable. Trade off convenience vs performance. Compensates harmonics
  • Cons: Higher cost. Performance limitations. Need re-shimming if moved to a different location or even re-ramped. Interactions with magnet

• Active resistive shims to improve uniformity in a sweet spot
  • Compensates effects of human body (magnetic susceptibility local inhomogeneity). Adjustable for individual patients
  • Compensates field harmonics
  • Cons: Low strength. Time-consuming shimming. Interactions with magnet and gradient coils
FINAL COOLING DOWN

Cooldown beginning on Nov. 20th 2018

1.8K since March 3rd, 2019
TODAY WE ARE HERE... 8.3 T
IN SUMMER 2019, WE SHOULD BE THERE…

- Magnetic Field: 11.75 Tesla
- Temperature: 1.8 °K
- Current: 1489 A
After 15 years of development, the first image !!!
MRI magnet
low field
HTS
1-3 T
Cryogen free
Low electrical
consumption

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

MRI magnet
high field
> 11 T
Whole body

R&D Nb3Sn
HTS > 16 T
Warm thanks to all the people involved in these crazy adventures !!!