Progress of Ultrahigh Field Superconducting Magnets in China

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**CONTENT**

1. Significance of High Field Magnets
2. Key Problems of Science and Technology
3. Progress of HTS-LTS Hybrid Magnets
4. Progress of LTS Magnets
5. Summary
Significance of developing high field magnets

High field magnets are the scientific devices that utilize Ampere’s law to generate high magnetic field. They have made significant contributions to the fields such as physics, chemistry, materials, brain science, life science, and medical health, and produced Nobel Prize level achievements.
Magnet devices that generate high magnetic field include steady-state magnets and pulse magnets;

- Steady state magnets include resistive magnets, superconducting magnets, and hybrid magnets;
- At present, the 32.35 T magnetic field generated by the superconducting magnet in China is a new world record.
Superconducting magnets can generate high-quality and stable magnetic field, with compact volume and low power consumption, and have great development prospects.

- HTS and LTS magnets can be combined to generate ultra-high magnetic field within a small bore, commonly used as ultra-high field NMR magnets;
- LTS magnets can generate a high homogeneity magnetic field within a large bore and are commonly used as human MRI magnets.

Future prospects for superconducting magnets

Superconducting magnet technology changed dramatically with the discovery of high temperature superconductors (HTS) in 1986, an event which drove the development of much higher field magnets;

Higher magnetic field is the eternal pursuit of NMR and MRI magnets.

CONTENT

Ⅰ Significance of High Field Magnets

Ⅱ Key Problems of Science and Technology

Ⅲ Progress of HTS-LTS Hybrid Magnets

Ⅳ Progress of LTS Magnets

Ⅴ Summary
How high is the magnetic field based on superconductors?

High quality superconducting wire ($T_c$, $J_c$, and $B_{c2}$)

Bitter/HTS
4.2K, 45.5T!
2019, Aug.

HTS/LTS
~≥ 40 T?
Steady-state field

YBCO/Bi2212/Bi2223/Nb₃AlGe/Nb₃Sn/NbTi
The 40 T high field superconducting magnet projects in the world

- Now, the U.S., France, and China have each proposed projects for 40T ultra-high field superconducting magnets, and all have adopted structures nested with HTS and LTS magnets;
- In the hybrid structure of HTS and LTS magnets, the magnetic field contribution of HTS magnets is increasing.

Ultra-high field superconducting magnet

Structure of ultra-high field superconducting magnet

Ultra-high field superconducting magnet = HTS magnet + LTS magnet (NbTi, Nb3Sn)

- **Coil structure**
  - Pancake-wound coil
  - Layer-wound coil

- **Insulation method**
  - No-insulation winding
    - Self-protection capability
    - Compact structure
    - High mechanical strength
    - Charging delay
  - Insulation winding
    - Quench protection
    - Low current density
    - Low mechanical strength
    - Quick response

- Partial insulation
- Metal insulation
- Extreme no-insulation
- Smart insulation
- Intra-layer no-insulation
- ……
Charging delay of no-insulation SC magnet

- Radial currents in no-insulation coils cause magnetic field to lag behind the power supply current;
- When the NI HTS magnet and LTS magnet are connected in series, the charging delay is longer.

\[ t_{\text{delay}} = \frac{L_{\text{coil}}}{R_r} \ln\left( \frac{\ln(0.01)}{\ln(1)} \right) - \frac{L_{\text{coil}}}{R_r} \ln\left( \frac{e^{L_{\text{coil}} a}}{a} - 1 \right) - \frac{L_{\text{coil}}}{R_r} \ln\left( \frac{e^{L_{\text{coil}} a}}{0.01L_0} - 1 \right) - \frac{I_0}{a} \]
Quench protection of ultra-high field magnet

- The self-protection ability of the no-insulation HTS magnet is limited;
- For 1.15GHz NMR magnet at IEE, the worst case is a symmetrical quench of the inner and outer coils, which can generate an unbalance force over 400 kN;
- When the background or insert magnets quench, current is induced in the coupling coil, which can help to slow down the flux change and consume the energy.

Asymmetrical azimuthal current produces unbalanced forces

Magnetic dam

Coupling coil model

Insert magnet

Couple coil

Background magnet

Outer coil

Inner coil

Inner coil – outer coil
The no-insulation pancake-wound coil model considering screening current

- The REBCO tape subdivisions are divided into parallel filaments.
- Improved T-A model: the potential difference between two points on any turn along different paths is equal, i.e. $V_{acb} = V_{adb}$.
- Boundary conditions of the original T-A Model:
  \[(T_1 - T_2)\delta = I_{op}\]
- Modified boundary conditions:
  \[(T_1 - T_2)\delta = I_{op} - 2\pi r \int_{z_1}^{z_2} 2\pi r \left( \frac{\partial A_\varphi}{\partial t} + \rho_\varphi J_\varphi \right) d\varphi d\zeta\]
The intra-layer no-insulation layer-wound coil model considering screening current

- The intra-layer no-insulation HTS magnet is equivalent to a circuit network composed of basic electrical components such as local helical inductance and some resistance components;
- Apply the azimuthal current in the helical equivalent circuit model as a constraint to the stacked homogenization T-A model.
Homogeneity and stability of magnetic field

- Screening current causes magnetic field distortion and drift

- Screening current induced field (SCIF) makes the magnetic field show hysteresis relative to the current and results in the reduction of the central magnetic field;

- Flux creep causes the SCIF to drift linearly in logarithmic time, and the position in the hysteresis loop determines the positive or negative drift.

The upper end produces hoop tensile stress, and the lower end produces hoop compressive stress;

Due to the Lorentz force, the superconducting tape will undergo separation and rotation.

Multifilament superconducting tape can effectively reduce the overstress caused by the screening current.
Cryogenics technology for MRI

Operating temperature: 1.55-4.2K;
LTS: $J_C = (1+10\% \text{ or } 30\%) J_C (4.2K)$; HTS: $J_C = 5\sim 6 J_C (77K)$

- Liquid Helium Pool cooling (4.2K-2.2K-1.8K)
- Zero boiling off liquid helium (4.2K-2.2K-1.8K)
- Force flow supercritical helium (4.5K)
- Thermal pipe cooling (signal phase and two-phase helium (4.2K-4.5K)
- Helium-free cooling (2.2K-4.2K)

Adiabatic winding; Cooling channel (All kinds of SCM)
(dB/dt, dI/dt) (Large Scale)
High thermal conduction (small-medium-large)
Quench protection of high stored energy magnet

Quench protection for the whole body MRI

26 *E(1.5T/850mm MRI)=E(134 MJ→9.4T/800mm MRI)

<table>
<thead>
<tr>
<th></th>
<th>Stored E(MJ)</th>
<th>E/M [J/kg]</th>
<th>Average Temperature T2 [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIC 9.4T</td>
<td>27,600</td>
<td>5470</td>
<td>77.65</td>
</tr>
<tr>
<td>IEE 9.4T</td>
<td>23,549</td>
<td>5690</td>
<td>78.75</td>
</tr>
</tbody>
</table>

Quench slice figure at time 0.04000 s
I. Significance of High Field Magnets

II. Key Problems of Science and Technology

III. Progress of HTS-LTS Hybrid Magnets

IV. Progress of LTS Magnets

V. Summary
The 500 MHz NMR HTS-LTS NMR superconducting magnet at IEE CAS

<table>
<thead>
<tr>
<th>Superconducting magnets</th>
<th>Geometrical parameter ((r_1,r_2,z_1,z_2)/\text{mm})</th>
<th>Layers and turns ((n_x \times n_y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS</td>
<td>Coil 1: 42.000, 53.80, -173.075, 173.075</td>
<td>100 \times 112</td>
</tr>
<tr>
<td></td>
<td>Coil 2: 75.000, 90.729, -175.000, 175.000</td>
<td>16 \times 328</td>
</tr>
<tr>
<td></td>
<td>Coil 3: 91.229, 111.649, -175.000, 175.000</td>
<td>24 \times 386</td>
</tr>
<tr>
<td>LTS</td>
<td>Coil 4: 115.271, 141.950, -173.623, -99.108</td>
<td>42 \times 106</td>
</tr>
<tr>
<td></td>
<td>Coil 5: 116.581, 129.1, -15.816, 15.816</td>
<td>20 \times 45</td>
</tr>
<tr>
<td></td>
<td>Coil 6: 115.271, 141.950, 99.108, 173.623</td>
<td>42 \times 106</td>
</tr>
</tbody>
</table>

LNI HTS insert magnet
The 500 MHz NMR HTS-LTS hybrid magnet at IEE CAS

- The final magnetic field homogeneity is strongly dependent on the distribution of the initial values of the magnetic field;
- The LTS magnet may undergo multiple training and warming at high field, which is the problem we need to address next.
The 18 T superconducting magnet at IEE CAS

- The 18 T superconducting magnet adopts a hybrid structure of HTS and LTS magnets;
- The warm bore diameter of the magnet is 60 mm, and the magnetic field homogeneity is about 102 ppm @DSV 10 mm.
The HTS insert magnet of the 18 T superconducting magnet adopts a metal insulation double-pancake coil structure and is connected in series with the LTS background magnet;
The quench protection circuit of LTS magnet adopts a hierarchical strategy.
The ultra-high field superconducting magnet at IEE CAS, bore-size in 43 mm

In 2019, central magnetic field reached 32.35 T, which is the highest magnetic field generated by a full superconducting magnet!
30 T superconducting magnet

- Total field: 30 T
- Insert magnet: 15 T
- Background magnet: 15 T
- Cold inner bore: 35 mm
- Operating current: 140.1 A
- Superconducting tape: YBCO
- Co-wound tape: stainless steel tape
- Coil structure: Double pancake
- HTS conductor length: 9290 m
- Homogeneity: 8 ppm @ DSV 30 mm

30T/Φ35mm user magnet at IEE CAS for SECUF Project: quantum oscillation
30 T superconducting magnet

30T/Φ35mm user magnet at IEE CAS

- The measured and calculated results for the three states of 10 A, 10 A current sweeping cycle (CSC), and 25 A indicate that the non-uniform critical current causes an asymmetric SCIF;
- The designed axial saddle shaped field deforms into an asymmetric single peak field shape.
30 T superconducting magnet

- Bi2223 magnet
- Coupling coils
- Hoop stress in insert magnet without and with coupling coil during LTS magnet quench

Test results of the 30T/Φ35mm user magnet

**Central field:** 30.1007 T

**Field stability:** 2.02 ppm/h

**Field homogeneity:** 31.3 ppm @ 10 mm
Design and fabrication of 1.15GHz NMR(27T)/Φ50mm user magnet at IEE CAS

Illustration of the hybrid magnet

- Central magnetic field: 27 T
- Cold bore: 50 mm
- Clear bore with VTI: 30.5 mm
- HTS tape: Bi-2223
- Nominal tape size: 4.5 mm × 0.3 mm
- HTS DP quantity:
  - Inner coil: 36
  - Outer coil: 38
- Diameter:
  - Inner diameter: 58 mm
  - Outer diameter: 215 mm
- HTS coil inductance: 7.74 H
- LTS coil inductance: 194.13 H

Minimize: \[ \sum v_i \]
Subject to:
\[ \frac{t_{B_z}^{\text{insert}} + T_{B_z}^{\text{back}} - T_{B_z}}{T_{B_z}} \leq \varepsilon \]
The size of the double-pancake coil has a great influence on the homogeneity of the spatial magnetic field, which has been solved by the asymmetric notch coil optimization method;

The proposed optimization method was validated feasibly in our realistic measurement, which was recognized as the critical procedure for the success of the ultra-high field and high homogeneity magnet.
After measuring the initial magnetic field, we applied Z1 and Z2 shim coils in the variable temperature cavity to further reduce the non-homogeneous harmonic components. Using the proposed re-optimization strategy for inconsistent DP coils, we managed to achieve an initial magnetic field homogeneity of 12.5 ppm @ 10 mm, and achieve a homogeneity 6.6 ppm @ 10 mm after shimming.
Test results of the 1.15GHz NMR(27T)/Φ50mm user magnet and spectrometer

Central field: 25.994T
Field stability: 0.83ppm/h
Field homogeneity: 11ppm@10mm
27 T solid state NMR system

VTI
Dilution refrigerator

20mK ~ 300K

All SCM
1.3 GHz liquid state NMR superconducting magnet

- 1.3GHz NMR(30.5T/Φ52mm) magnet design at the IEE CAS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central magnetic field</td>
<td>30.5 T</td>
</tr>
<tr>
<td>Warm bore</td>
<td>52 mm</td>
</tr>
<tr>
<td>HTS tape</td>
<td>Bi-2223</td>
</tr>
<tr>
<td>Homogeneity(peak-peak)</td>
<td>54.2 ppb @DSV10 mm</td>
</tr>
<tr>
<td>Operating current</td>
<td>184 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>2853.67 H</td>
</tr>
<tr>
<td>Magnetic energy</td>
<td>48.3069 MJ</td>
</tr>
<tr>
<td>Height</td>
<td>1403 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>890.6 mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>90 mm</td>
</tr>
</tbody>
</table>

1.3 GHz NMR magnet design
1.3 GHz liquid state NMR superconducting magnet

- 1.3GHz NMR(30.5T)/Ф90mm magnet design at IEE CAS

- NbTi-Bi2223 low resistive joint

- The test coil with two joints

- Magnetic-field decay curves

- The joint resistance vs. the applied field

- The typical joint length is around 60 mm. And the joint resistance was measured using field decay.
- The joint resistance at zero-applied field is $2.2 \times 10^{-9} \Omega$;
- The joint resistance exhibited a linear relationship with the applied field.
Development of 35 T magnet designed at HFIPS CAS

- HTS insert magnet: 20T/Φ17mm, the inner coil is a no-insulation coil, and the outer coil is a metal insulation coil;
- $B_{\text{max}} = 35\text{T} @ 15\text{T}/\Phi 150\text{mm LTS}$

- Inner joint technology is used in the HTS magnet;
- The HTS magnet has successfully risen to 300 A under liquid helium bath, and the central magnetic field can be stably maintained at 24.1T.
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A 7 T animal MRI scanner

- **7T/Φ300mm MRI superconducting magnet**

  ![7T animal MRI magnet](image1)
  ![Shielding coils](image2)
  ![Magnetic field distribution](image3)

  ![Shim coil](image4)
  ![10ppm deviation contour](image5)
Active shimming

The shim coils have the first order coils Z/X/Y, the second order coils Z2/ZX/ZY/X2-Y2/XY, and also Z3.
A 7 T animal MRI scanner

- Passive shimming

Evaluation of the passive shimming effect

An initial magnetic field distribution: 97.8 ppm

Magnetic field distribution simulation after passive shimming: 9.9 ppm
The split superconducting magnet at IEE CAS

- Central magnetic field: 8.8 T
- Operating current: 89.5 A
- Maximum axial magnetic field: 12 T
- Maximum hoop stress: 113 MPa
- Coils inductance: 508.5 H
- Magnetic energy: 2.04 MJ

- The inner coil of the split magnet is made of Nb$_3$Sn wire, and the outer coil is made of NbTi wire;
- The split magnet generates a central magnetic field of 8.8 T at a current of 89.5 A and a saddle shaped magnetic field in the axial direction.
# Main specifications of 9.4T/800mm whole body MRI

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet type</td>
<td>Superconducting magnet</td>
</tr>
<tr>
<td>Field strength</td>
<td>9.4 T</td>
</tr>
<tr>
<td>Magnetic field shield</td>
<td>Iron Yoke-Passive shield</td>
</tr>
<tr>
<td>Field stability vs time</td>
<td>$\leq 0.03$ ppm/h</td>
</tr>
<tr>
<td>Shim style</td>
<td>SC shim + room shim + iron shim</td>
</tr>
<tr>
<td>Shim coils</td>
<td>$\geq 52$ groups</td>
</tr>
<tr>
<td>Room shim coils</td>
<td>$\geq 14$ groups ($z_0$, $z_2$, $z_3$, $z_4$)</td>
</tr>
<tr>
<td>Passive shield</td>
<td>36 group, along the circular</td>
</tr>
<tr>
<td>Three dimension automatic shim</td>
<td>Yes $\geq 2$ order</td>
</tr>
<tr>
<td>Field homogeneity: 22cm DSV</td>
<td>$\leq 0.05$ ppm</td>
</tr>
<tr>
<td>Field homogeneity :30cm DSV</td>
<td>$\leq 0.1$ ppm</td>
</tr>
<tr>
<td>5 G line ($z \times r$)</td>
<td>$\leq 22$ m $\times$ 18 m (non Yoke)</td>
</tr>
<tr>
<td>Length of magnet</td>
<td>$\leq 3.5$ m</td>
</tr>
<tr>
<td>Warm bore</td>
<td>$\geq 800$ mm</td>
</tr>
<tr>
<td>Weight of magnet (100% LHe)</td>
<td>$\leq 50$ ton</td>
</tr>
<tr>
<td>Operation</td>
<td>Near zero boiling off LHe</td>
</tr>
</tbody>
</table>
Ultra-high field 9.4 T/800 mm MRI magnet

- **Superconducting magnet**

  ![Diagram of magnetic field](image)

  The wire and superconducting magnet weights about 30 and 50 tons.

- Precision manufacture of special-shaped structure coils and assembly technology;
- The higher harmonic components of the magnetic field are compensated with iron pieces;
- Sample inhomogeneity was compensated with the room temperature automatic shim coils.
There are totally 13 superconducting shim coils in the 9.4T/800mm whole-body MRI magnet, which include the zonal coils Z1, Z2, Z3, and the tesseral coils X/Y, ZX/ZY, X2-Y2/XY, Z(X2-Y2)/ZXY;

We proposed a field-harmonic superconducting shimming method to restrain the entire magnetic field inhomogeneity and also control individual harmonic component.
We proposed high-performance passive shimming algorithm to realize a highly homogeneous magnetic field distribution with very few iron piece usage.
After several shimming experiments and iterative calculations, the spatial magnetic field homogeneity in the central region is improved from 26.95 ppm to 3.05 ppm in a DSV of 40 cm.
Ultra-high field 9.4 T/800 mm MRI magnet

- Quench protection
  - A passive quench protection circuit, including the coil subdivisions and heater network, was employed to avoid magnet damage during the quench;
  - The whole energization process included four quenches and finally reached the target central magnetic field of 9.46 T with an operating current of 211 A.

Quench protection circuit for the 9.4 T MRI magnet

The current and center magnetic field value of different energization times
Ultra-High field 14 T MRI magnet design

**14T MRI/Φ960mm magnet design at IEE CAS**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central magnetic field</td>
<td>14 T</td>
</tr>
<tr>
<td>DSV</td>
<td>500 mm</td>
</tr>
<tr>
<td>Homogeneity (peak-peak)</td>
<td>25 ppm @500 mm</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>960 mm</td>
</tr>
<tr>
<td>5 Gauss line</td>
<td>10 m(z)×8 m(r)</td>
</tr>
<tr>
<td>Operating current</td>
<td>215 A</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>14.34 T</td>
</tr>
<tr>
<td>Operating factor in coil 1</td>
<td>75.03 %</td>
</tr>
<tr>
<td>Operating factor in coil 4</td>
<td>92.93 %</td>
</tr>
<tr>
<td>Maximum hoop stress</td>
<td>188 MPa</td>
</tr>
<tr>
<td>Coils inductance</td>
<td>23825.2 H</td>
</tr>
<tr>
<td>Magnetic energy</td>
<td>550.7 MJ</td>
</tr>
<tr>
<td>Wire length</td>
<td>Nb$_3$Sn:253.2 km</td>
</tr>
<tr>
<td></td>
<td>NbTi:1567.2 km</td>
</tr>
</tbody>
</table>

Coil pattern of the actively-shielded 14 T whole-body MRI magnet

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CONTENT

I  Significance of High Field Magnets

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It is necessary to study for the quench protection, screening current effect, shimming, HTS-LTS joints, fabrication technology, etc.

The 9.4 T/800 mm MRI magnet for the whole body was developed, and the actual central field is about 9.46 T, and the actual homogeneity is about 3.05 ppm in a DSV of 40 cm after shimming.

Today, China has achieved world leading magnetic field and is to utilize the ultra-high field superconducting magnets. The large-scale scientific device was fabricated with 30 T+ magnets and 27 T NMR magnet. The 35 T/50 mm STM, 1.3 GHz NMR and 14 T MRI magnet will be developed in the next five years. It will significantly promote several scientific R&D in disciplines such as high-energy physics, condensed matter physics, chemistry, materials, life sciences, fusion energy, etc.
Thanks!