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Program of ACASC Asian ICMC 2023

Progress of Ultrahigh Field Superconducting Magnets in China

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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

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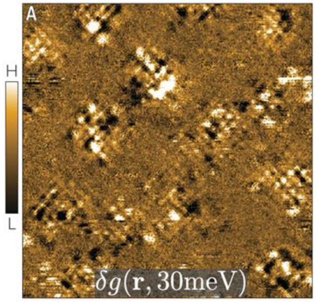
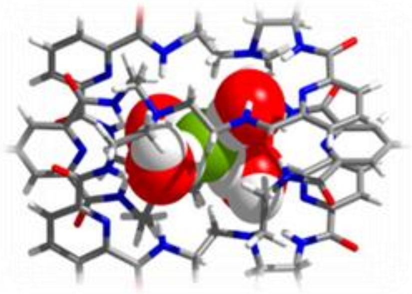
Significance of developing high field magnets

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.

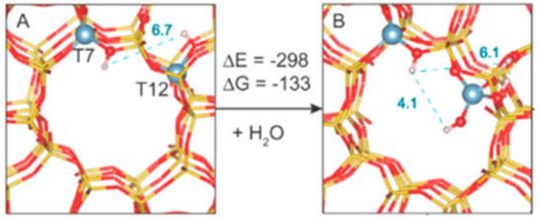
Physics



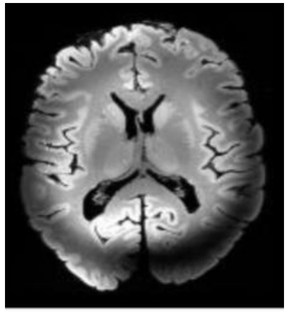
Chemistry



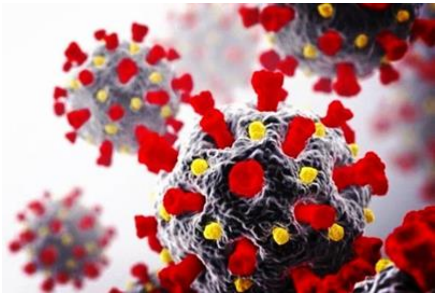
Materials



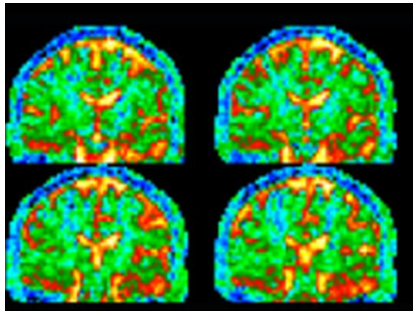
Brain science



Life science



Medical health



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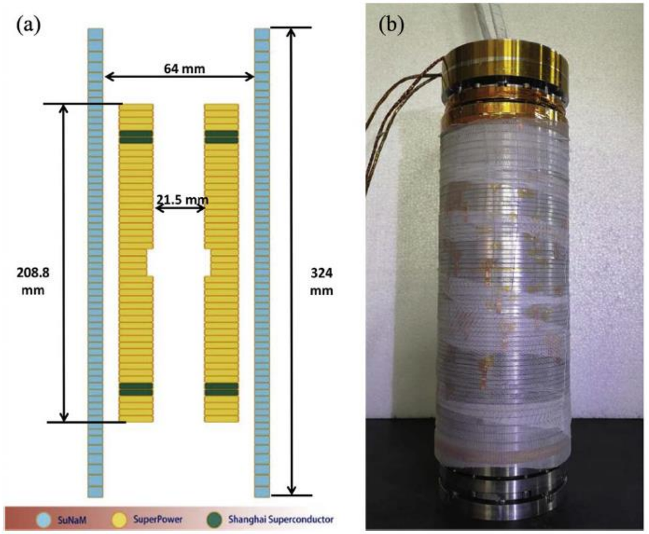
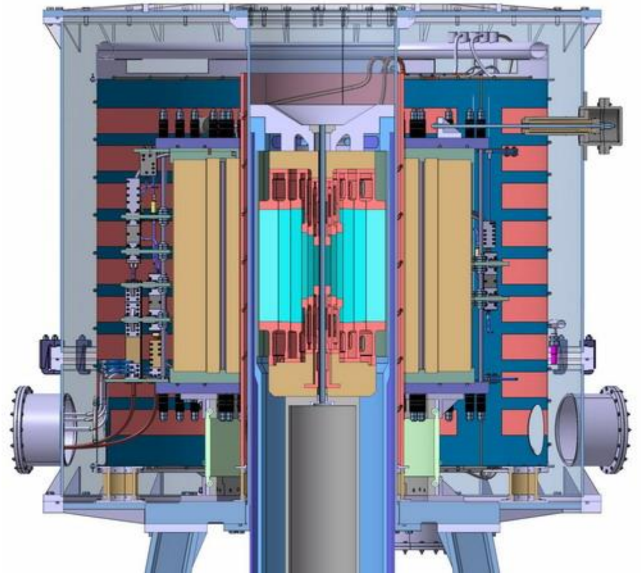
High field magnets technology

□ High field magnets

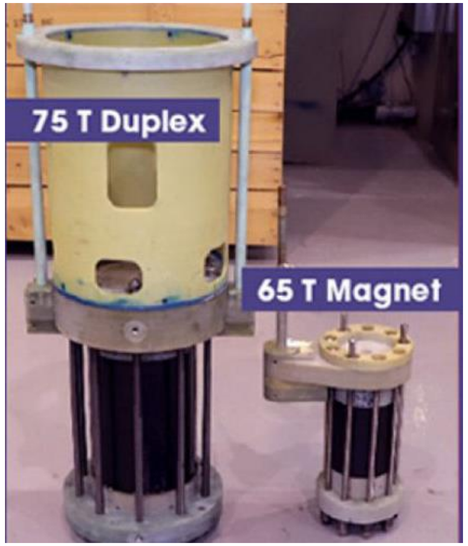
Resistive magnet



Superconducting magnet



Hybrid magnet



Pulse magnet

- 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.

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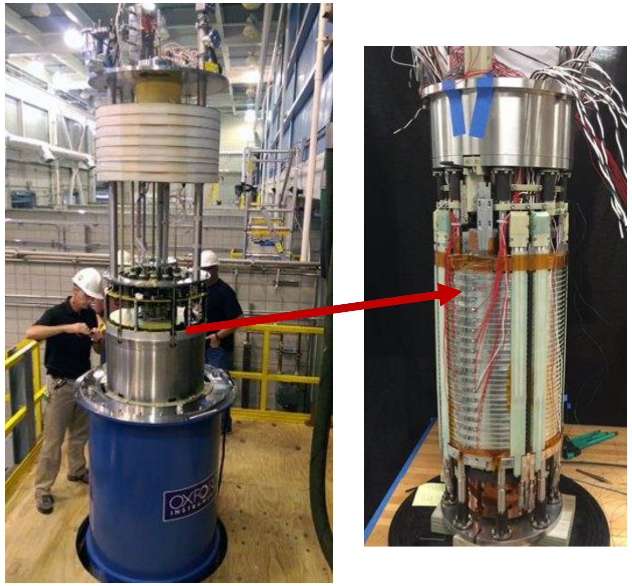
Superconducting magnets technology

- Superconducting magnets can generate high-quality and stable magnetic field, with compact volume and low power consumption, and have great development prospects.



32 T superconducting magnet

1.2 GHz NMR magnet

500 MHz MRI magnet

- 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.

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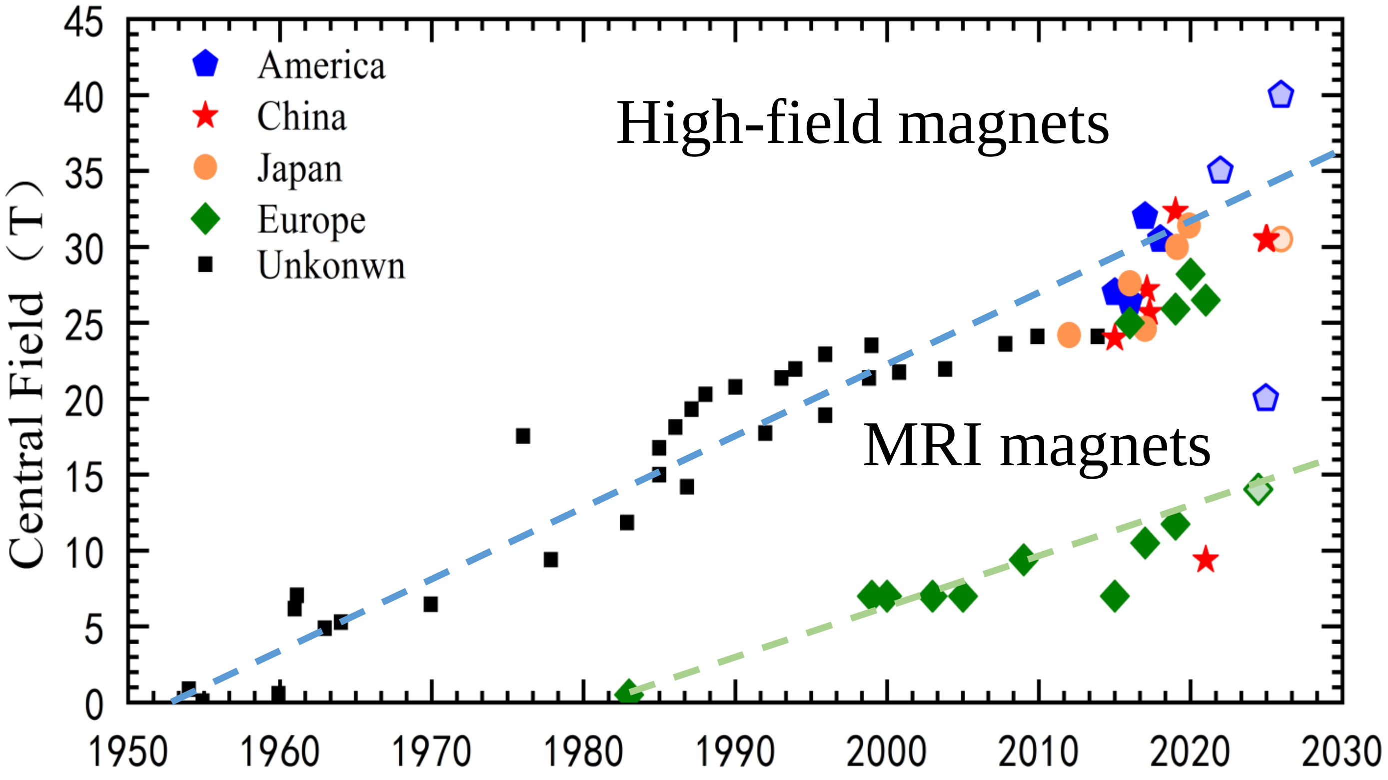
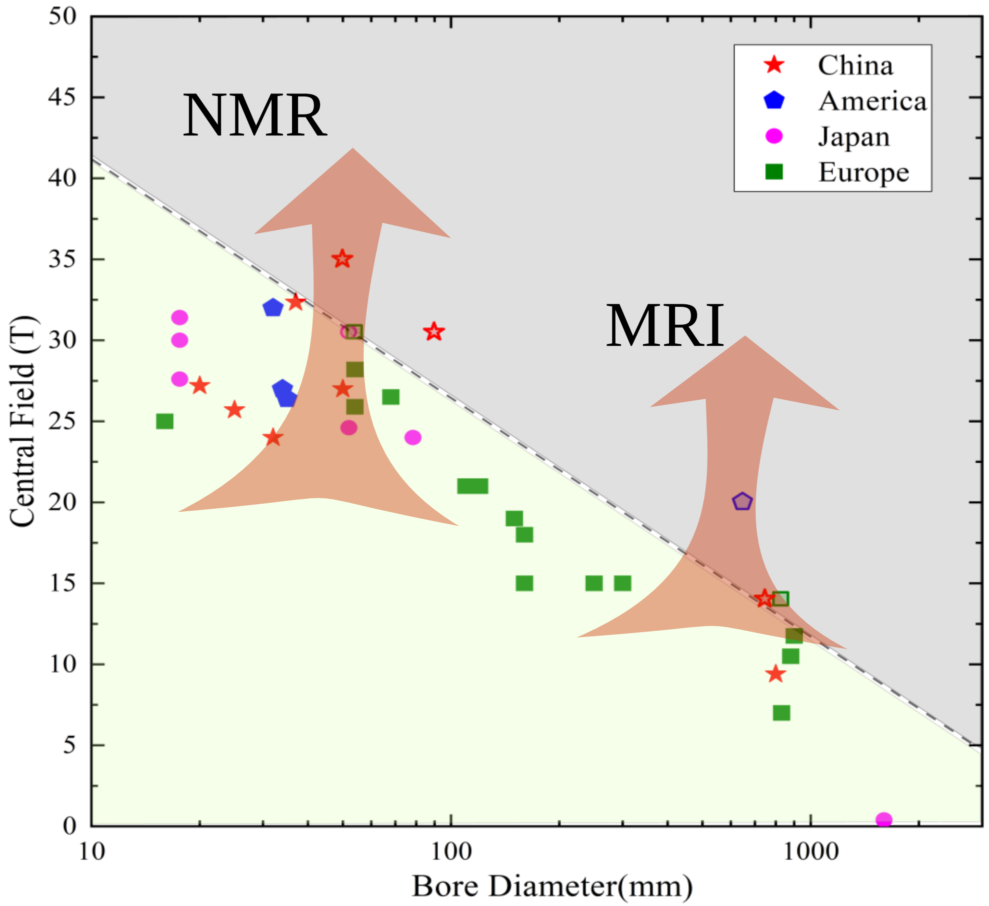
Future prospects for superconducting magnets



The history of 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.

Hma, B , etc.Journal of Magnetic Resonance 306(2019):80-85.

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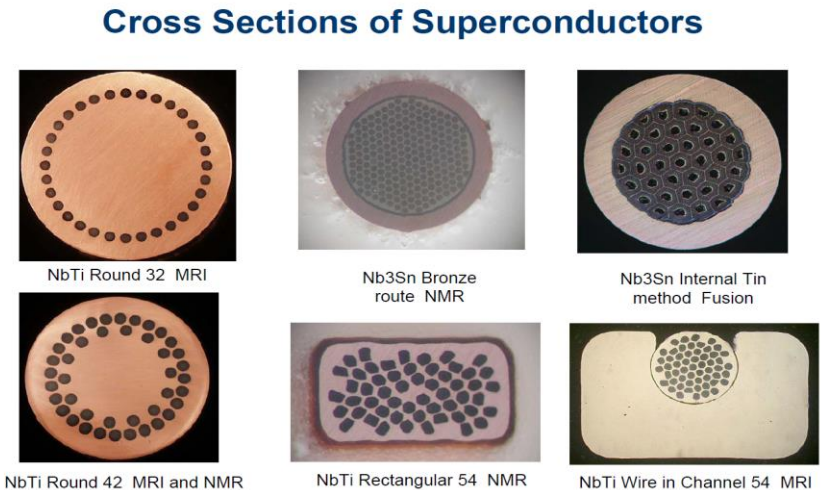
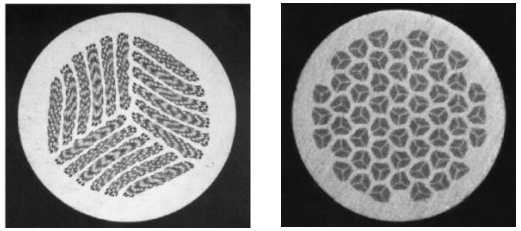
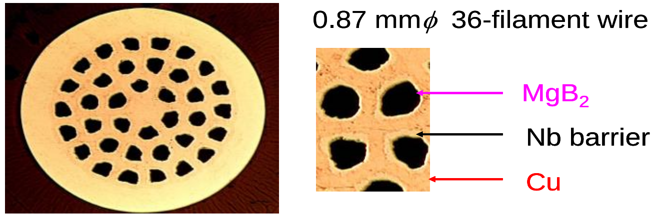
Superconducting magnet

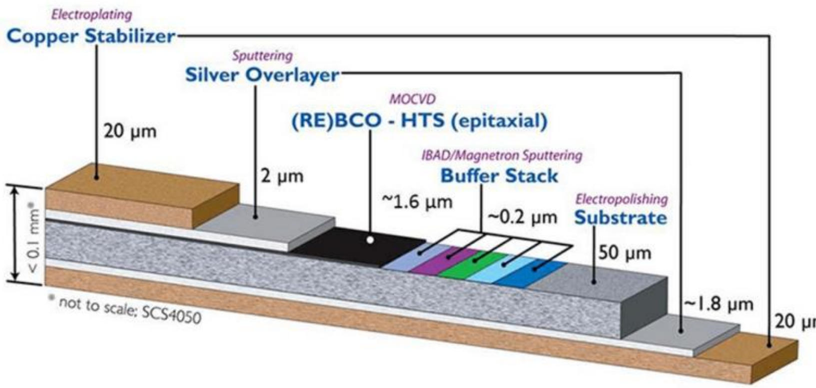
☐ How high is the magnetic field based on superconductors?







[Mike Tomsic (Hyper Tech) (2006)]



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/Nb$_3$AlGe/Nb$_3$Sn/NbTi

www.superpower-inc.com/content/2g-hts-wire

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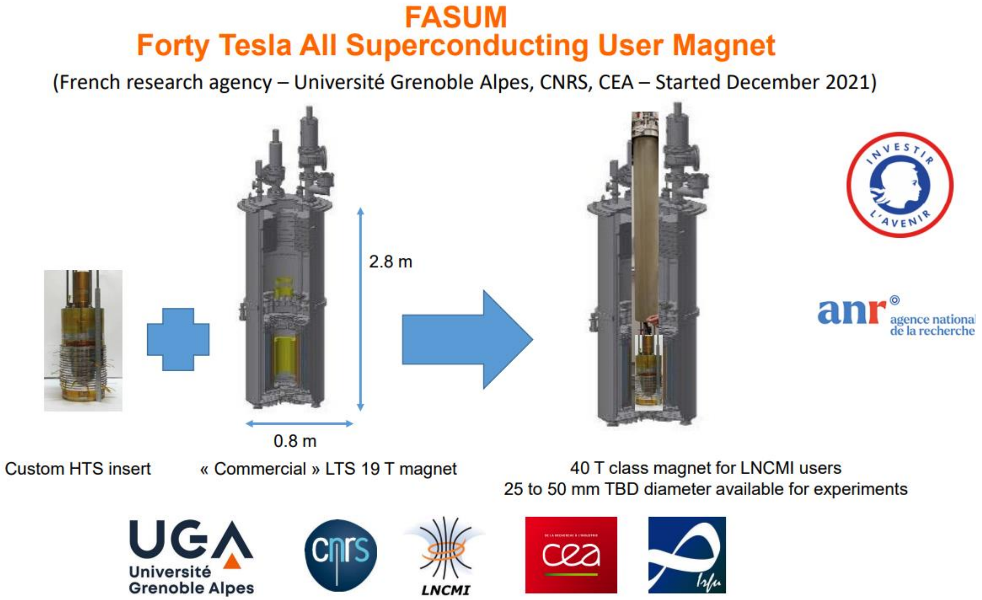
40 T superconducting magnet project

☐ The 40 T high field superconducting magnet projects in the world

The MAGLAB in U.S.



CNRS-LNCMI

3. 面向40T高场全超导磁体研制的关键科学问题研究（申请代码1选择A20的下属代码）

面向物理、材料、生命健康科学等领域对高性能全超导磁体的迫切需求，针对40T高场全超导磁体构建的关键基础科学问题，深入研究REBCO高温超导带材在强磁场和高应力等综合极端条件下的关键临界参数演化与调控规律，发展高温超导磁体尽限设计理论，提升高温超导内插磁体磁场强度，解决高均匀磁场构造、屏蔽电流抑制等关键科学技术问题。核心指标包括：获得REBCO铜基高温超导带材在40T磁场下应用的关键临界参数指标和安全边界；实现均匀性优于100ppm@1cm³，稳定性优于10ppm/h，磁场强度高于26T的高温超导内插磁体。

研究内容包括：

（1）复杂极端条件下高温超导带材的性能表征研究

针对REBCO铜基超导带材在复杂极端条件下服役特性不明问题，结合强磁场、大应力和极低温等综合极端条件，利用电输运、磁扭矩、磁光等精密测量手段，开展REBCO铜基高温超导带材综合性能测试和性能调控，获得其在超过40T磁场下的临界性能和安全边界，为磁体设计提供数据支撑。

（2）高温超导内插磁体的尽限设计理论与方法研究

针对高温超导磁体尽限设计理论缺乏问题，发展多物理场非线性耦合分析和多目标与多参量优化解算技术，明晰高温超导磁体内屏蔽电流的精准分布规律和失超传播机制，实现极高场内插高温超导磁体的尽限设计。

（3）内插超导磁体精准构造理论与匀场方法研究

针对高温超导磁体在极端复杂应力环境下空间精准定位难、屏蔽电流难以消除等难题，开展内插高温超导磁体精准构造理论和匀场方法研究，实现在26T时均匀性优于100ppm@1cm³，稳定性优于10ppm/h的高均匀高温超导磁体，为未来发展40T级全超导磁体提供基础。

本集成项目的申请应同时包含上述3个研究内容，紧密围绕项目主题“面向40T高场全超导磁体研制的关键科学问题研究”开展深入和系统研究，预期成果应包含原理、方法、技术、器件以及专利等。

NSFC in China

- 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.

https://nationalmaglab.org/news-events/news/nsf-grant-funds-new-40t-superconducting-magnet-design/

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Ultra-high field superconducting magnet

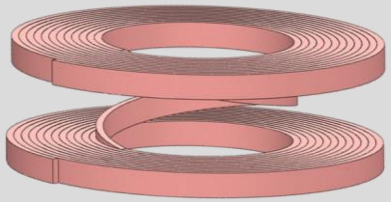
☐ Structure of ultra-high field superconducting magnet

Ultra-high field superconducting magnet = HTS magnet + LTS magnet (NbTi, Nb_3Sn)

HTS magnet

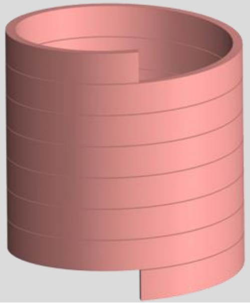
Coil structure

Pancake-wound coil



- Convenient winding
- Low production risk
- Many joints

Layer-wound coil



- High homogeneity
- Few joints
- High production risk

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
- ……

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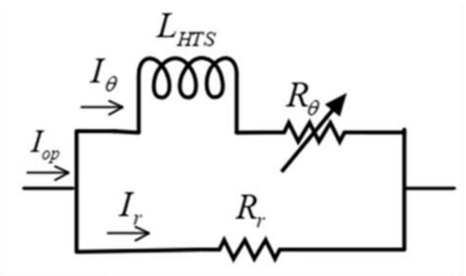
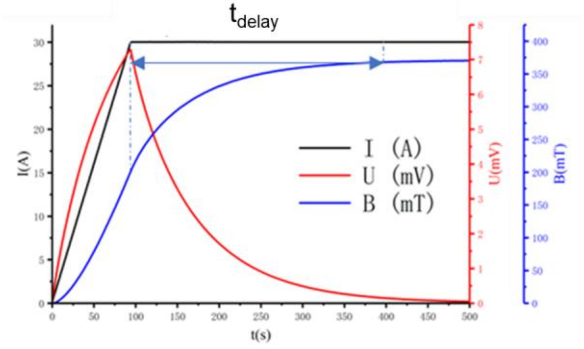
Charging delay of no-insulation SC magnet

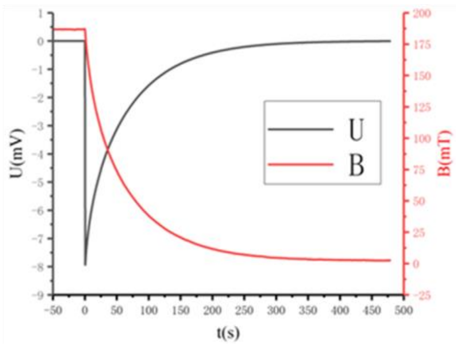
☐ Charging delay



$$I_\theta + I_r = I_{op}$$

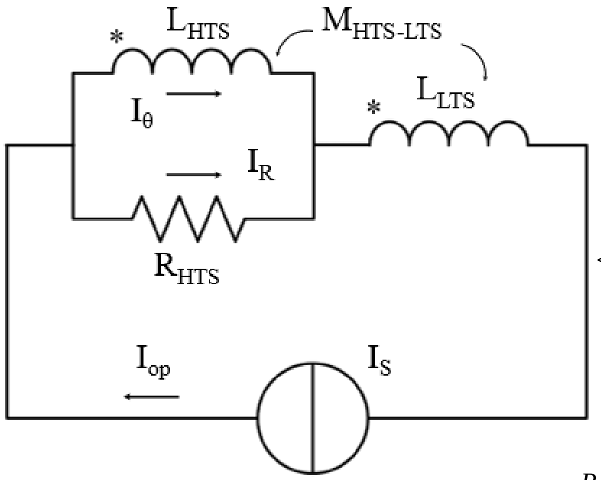
$$L_{HTS}\frac{dI_\theta}{dt} + I_\theta R_\theta = I_r R_r$$





Charging process of NI coil Sudden discharging process

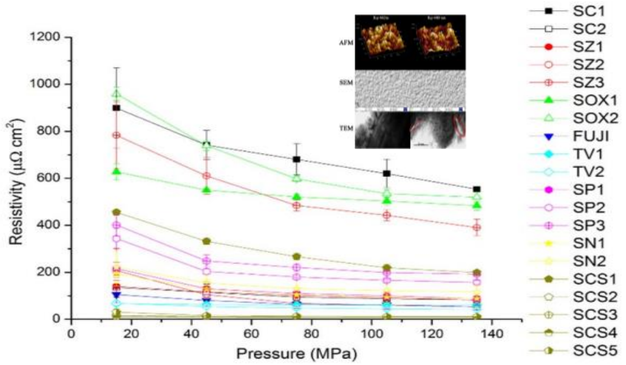
$$t_{delay} = \frac{L_{coil}}{R_r}\ln\left(a\frac{L_{coil}}{R_r}\left(e^{\frac{R_r I_0}{L_{cil}\,a}} - 1\right)\right) - \frac{L_{coil}}{R_r}\ln(0.01 I_0) - \frac{I_0}{a}$$



$$\begin{cases} I_\theta + I_R = I_{op} \\ L_{HTS}\dfrac{dI_\theta}{dt} + M_{HTS-LTS}\,a = I_R R_{HTS} \end{cases}$$

$$t_{delay} = \frac{L_{HTS}}{R_{HTS}}\left(\ln\left(a\frac{L_{HTS}+M_{HTS-LTS}}{R_{HTS}}\left(e^{\frac{R_{HTS}}{L_{HTS}}\frac{I_0}{a}} - 1\right)\right) - \ln(0.01 I_0)\right) - \frac{I_0}{a}$$

Adjust the surface micro condition



- 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.

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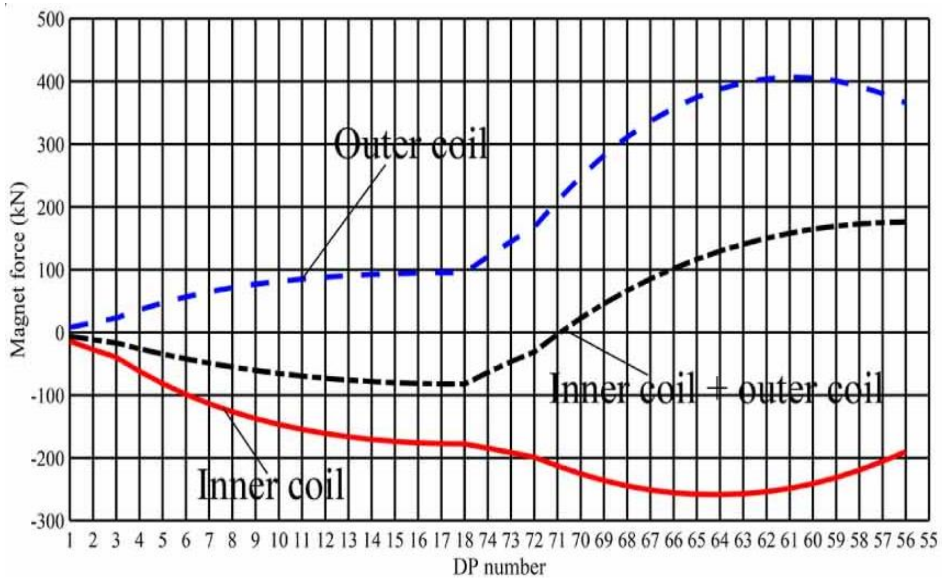
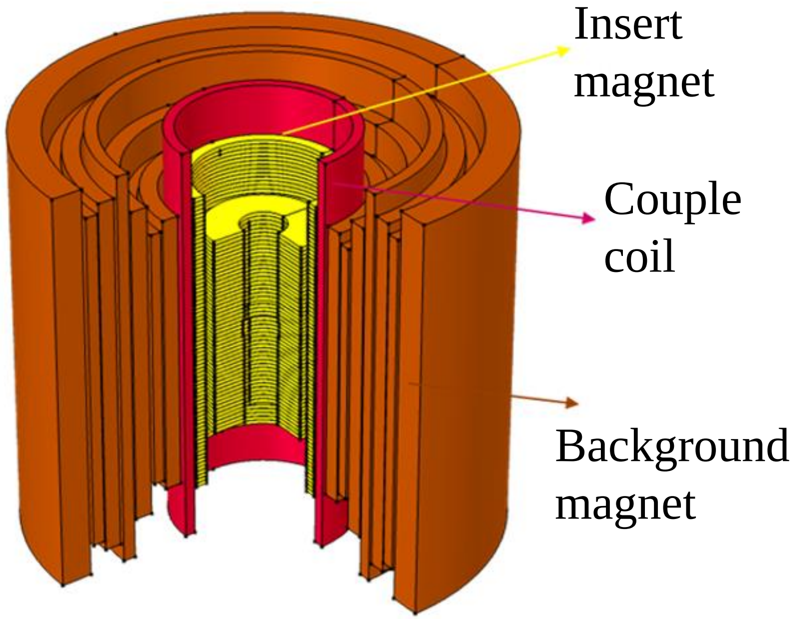
Quench protection

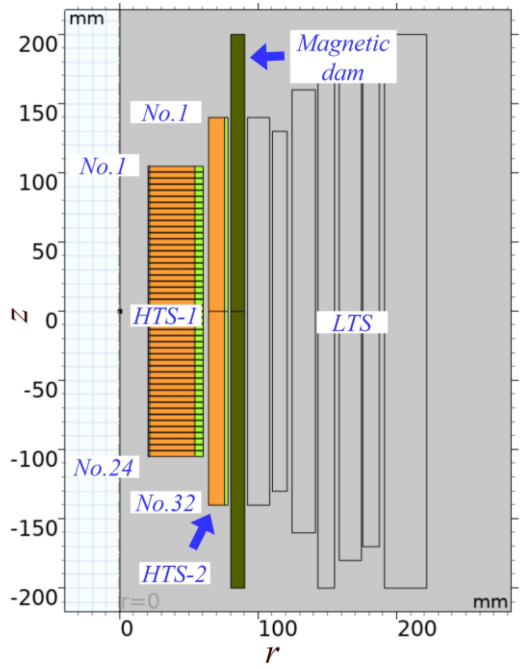
□ Quench protection of ultra-high field magnet



Asymmetrical azimuthal current produces unbalanced forces



Magnetic dam



Coupling coil model

- 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.

Qin, L., Liu, J., Wang, L. et al. J Supercond Nov Magn 35, 1483–1489 (2022). https://doi.org/10.1007/s10948-022-06199-4

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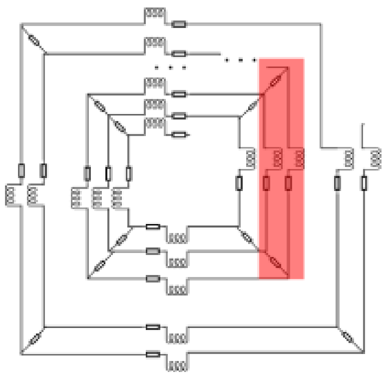
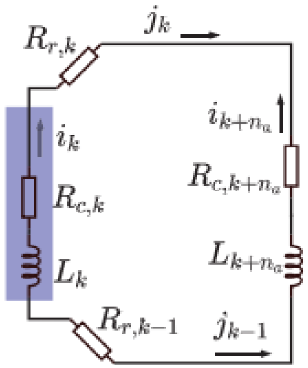
Circuit and FEM model

□ The no-insulation pancake-wound coil model considering screening current

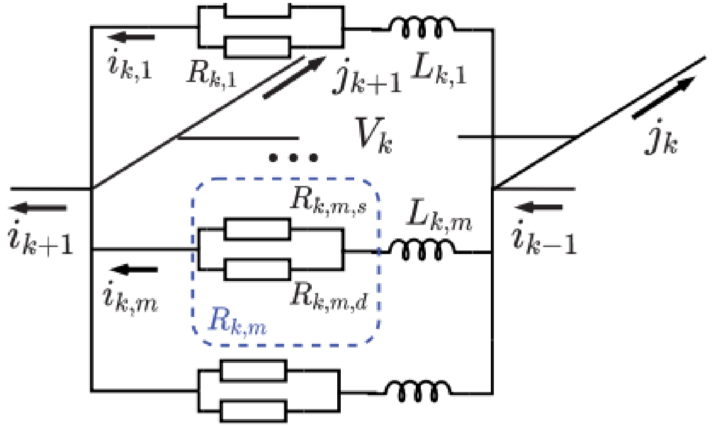
- The REBCO tape subdivisions are divided into parallel filaments.



(a) Grid circuit.

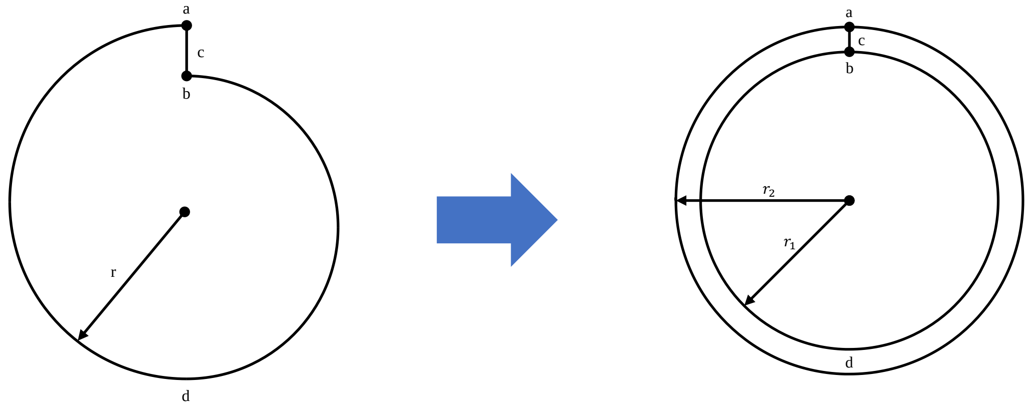


(b) Subdivision circuit.



The refined circuit model

- Improved T-A model: the potential difference between two points on any turn along different paths is equal, i.e. V_{acb}=V_{adb}.



Spiral ring Concentric ring

Boundary conditions of the original T-A Model：

$$(T_1 - T_2)\delta = I_{op}$$

Modified boundary conditions：

$$(T_1 - T_2)\delta = I_{op} - 2\pi r \int_{z_1}^{z_2} \frac{2\pi r(\frac{\partial A_\varphi}{\partial t} + \rho_\varphi J_\varphi)}{d \cdot \rho_r} dz$$

Lang Qin et al 2021 Supercond. Sci. Technol. 34 075002

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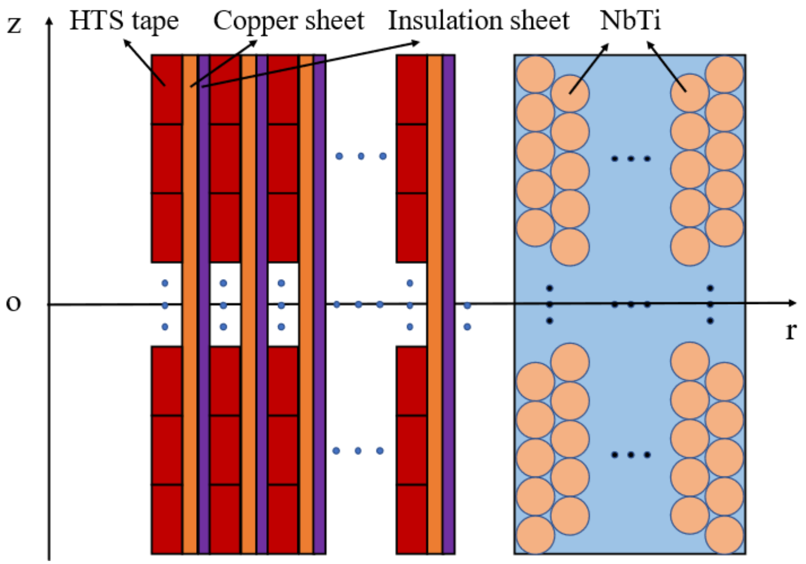
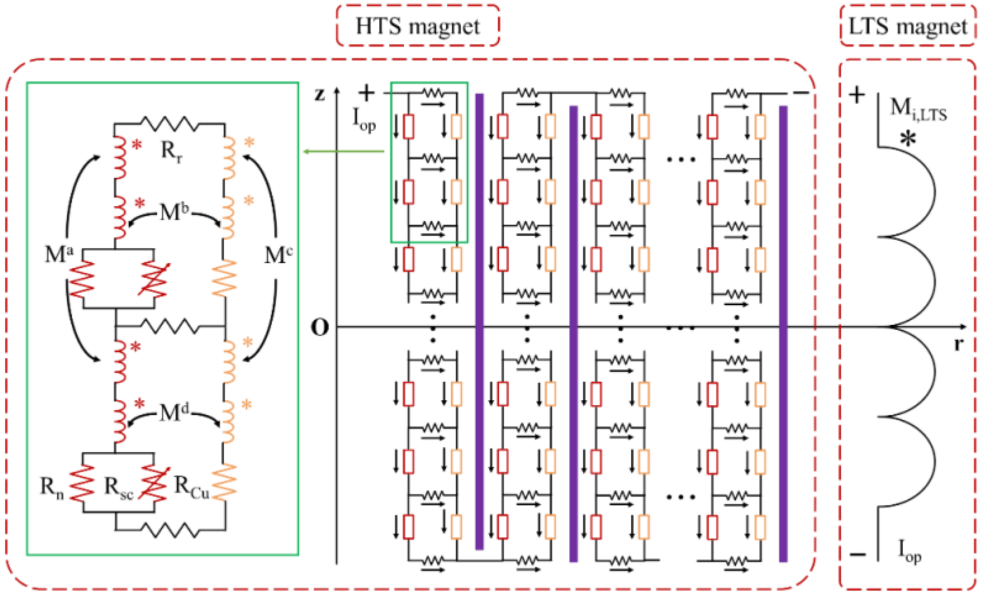
Field circuit coupling method

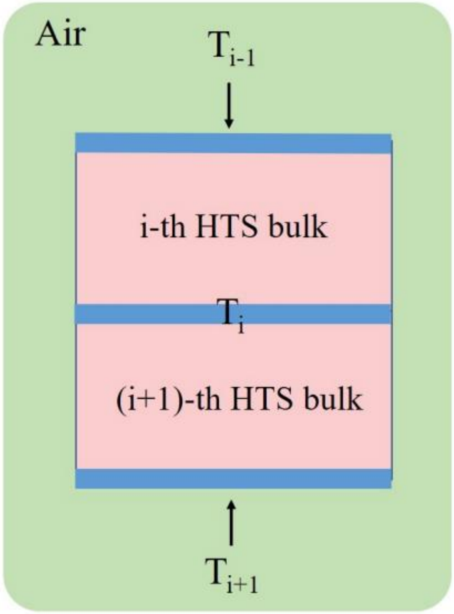
□ The intra-layer no-insulation layer-wound coil model considering screening current



HTS-LTS hybrid magnet



Helical equivalent circuit diagram



Stacked homogenization T-A model

- 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.

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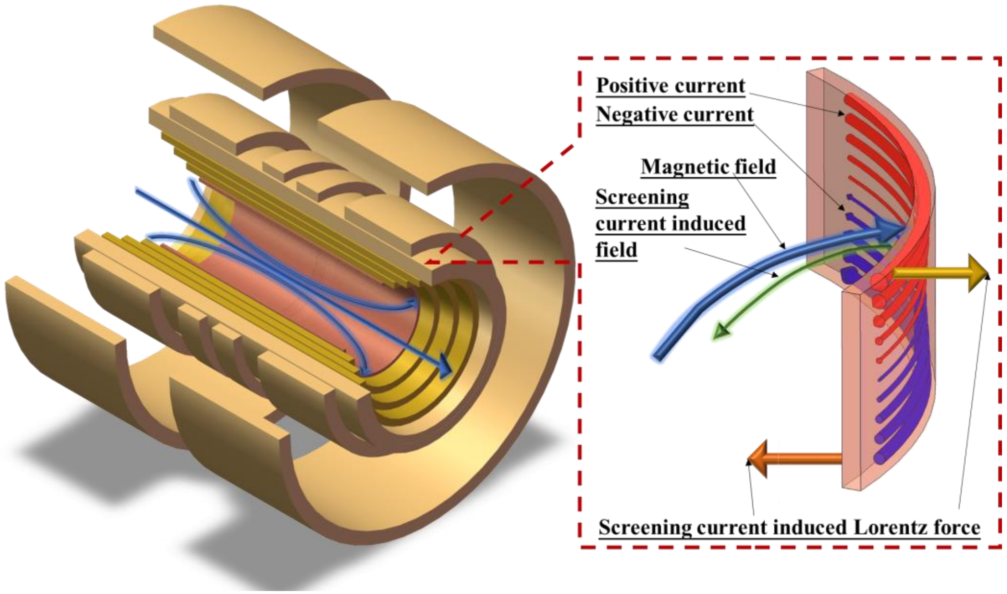
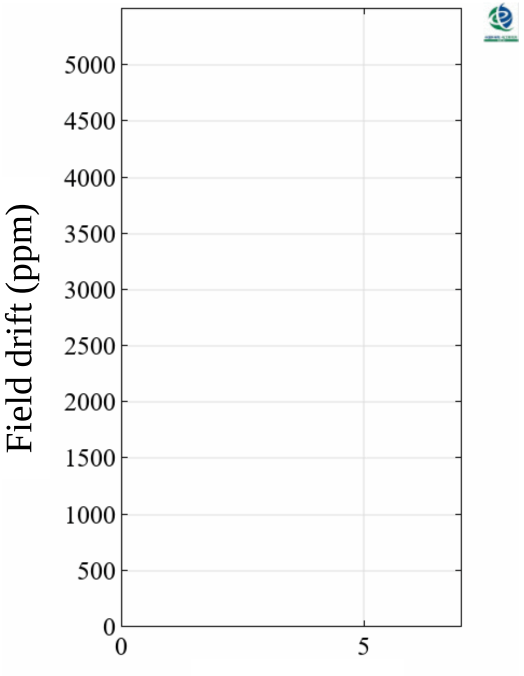
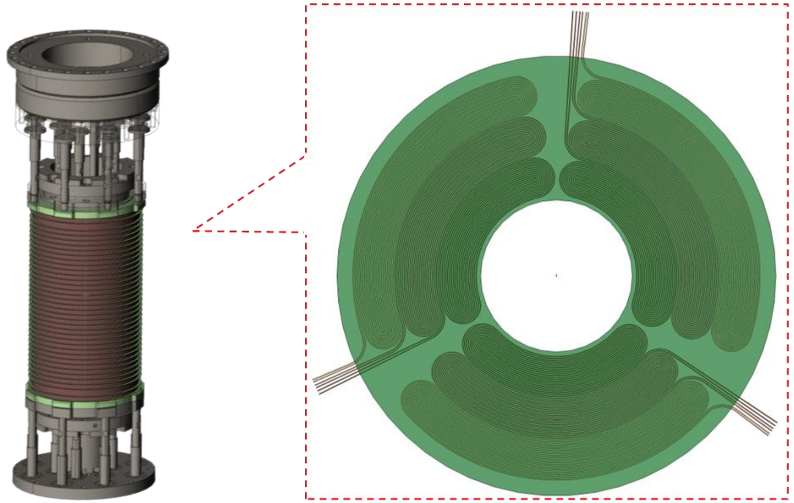
Homogeneity and stability of magnetic field

□ Screening current causes magnetic field distortion and drift



Screening current





Heat to eliminate screening current

- 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.

Wang L , Wang Q , Qin L ,et al. Journal of Superconductivity and Novel Magnetism . https://doi.org/10.1007/s10948-019-05414-z.

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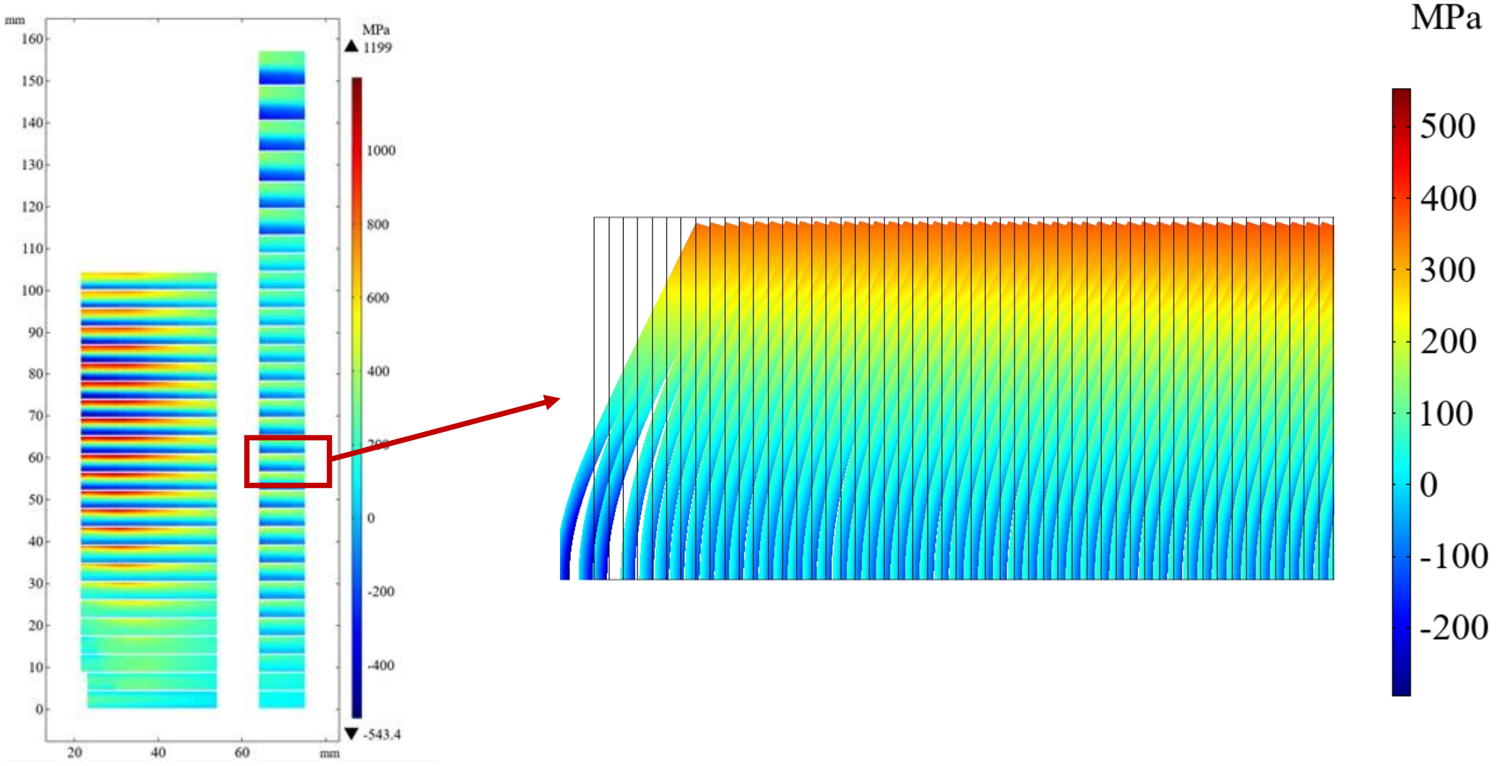
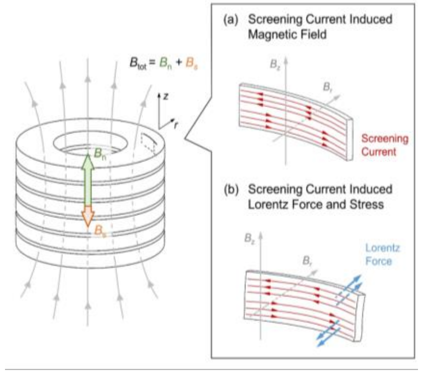
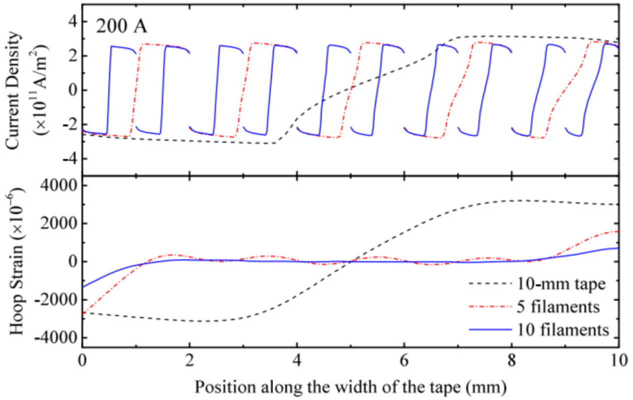
Screening current induced stress

□ Screening current induced stress







- 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.

A C Wulff et al 2021 Supercond. Sci. Technol. 34 053003

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

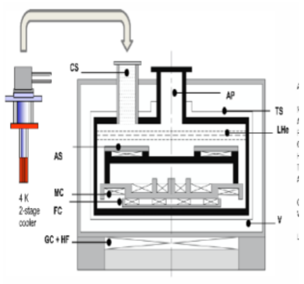
Cryogenics and cooling technology

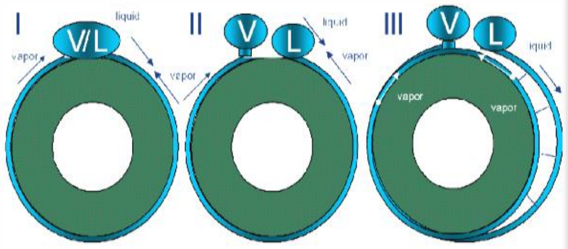
□ Cryogenics technology for MRI

Operating temperature : 1.55-4.2K;

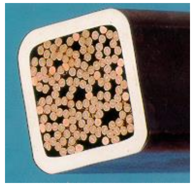
LTS：J_C=(1+10% or 30%) J_C (4.2K)：HTS: J_C =5～6 J_C(77K)

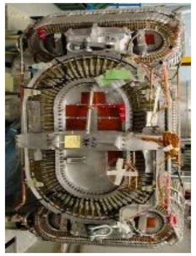
Liquid Helium Pool cooling (4.2 K-2.2K-1.8K)



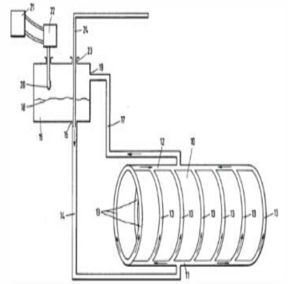


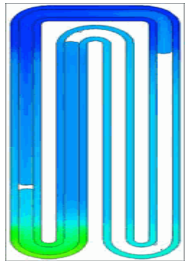
Zero boiling off liquid helium (4.2 K-2.2K-1.8K)



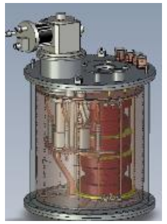


Force flow supercritical helium (4.5K)





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)

Yuri Lvovsky *et al* 2013 *Supercond. Sci. Technol.* 26 093001

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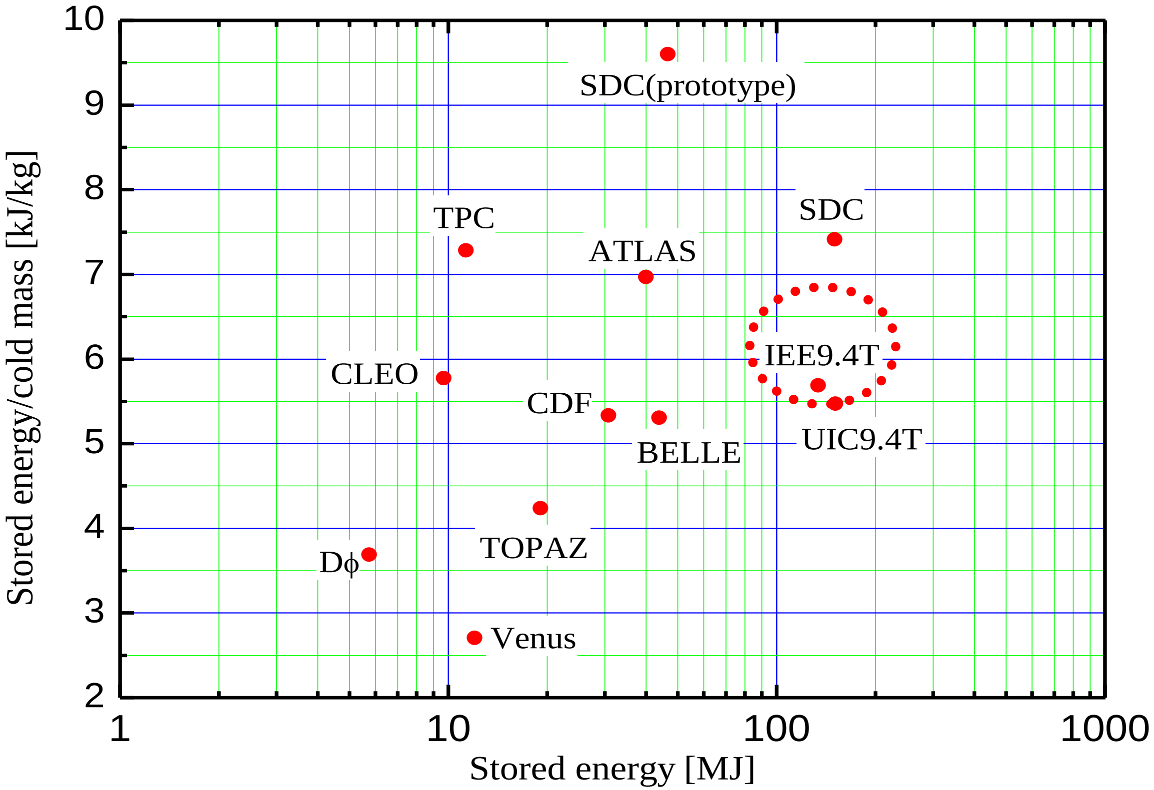
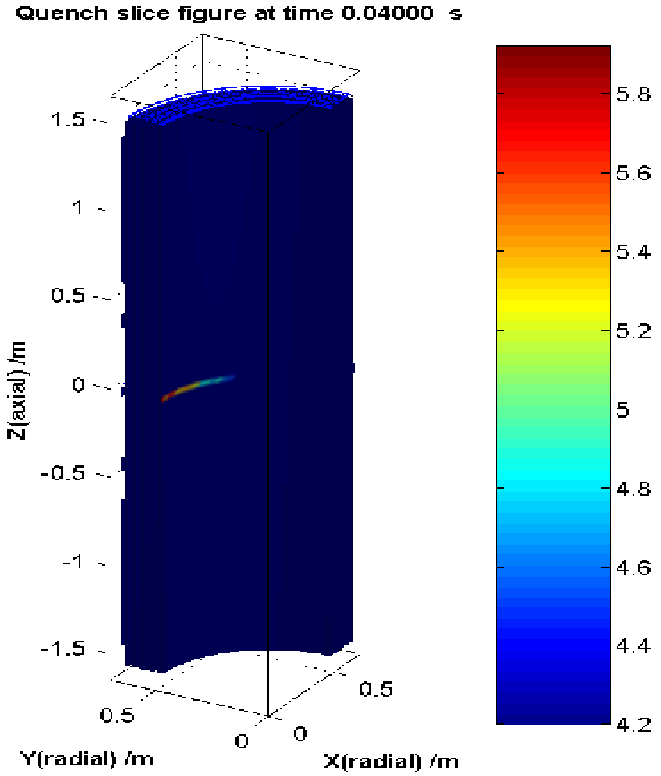
Quench protection of high stored energy magnet

□ Quench protection for the whole body MRI

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





	Weight（kg)	Stored E(MJ)	E/M [J/kg]	Average Temperature T2 [K]	
UIC 9.4T	27,600	151	5470	77.65	<100K
IEE 9.4T	23.549	134	5690	78.75	<100K

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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

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500 MHz NMR superconducting magnet

□ The 500 MHz NMR HTS-LTS NMR superconducting magnet at IEE CAS

LNI HTS insert magnet

Superconducting magnets	Geometrical parameter (r_1,r_2,z_1,z_2)/mm	Layers and turns (n_r×n_z)
HTS	Coil 1: 42.000,53.80,-173.075,173.075	100×112
LTS	Coil 2: 75.000,90.729,-175.000,175.000	16×328
	Coil 3: 91.229,111.649,-175.000,175.000	24×386
	Coil 4: 115.271,141.950,-173.623,-99.108	42×106
	Coil 5: 116.581,129.1,-15.816,15.816	20×45
	Coil 6: 115.271,141.950,99.108,173.623	42×106

Kangshuai Wang, et al. Physica C: Superconductivity and its Applications. https://doi.org/10.1016/j.physc.2023.1354372.

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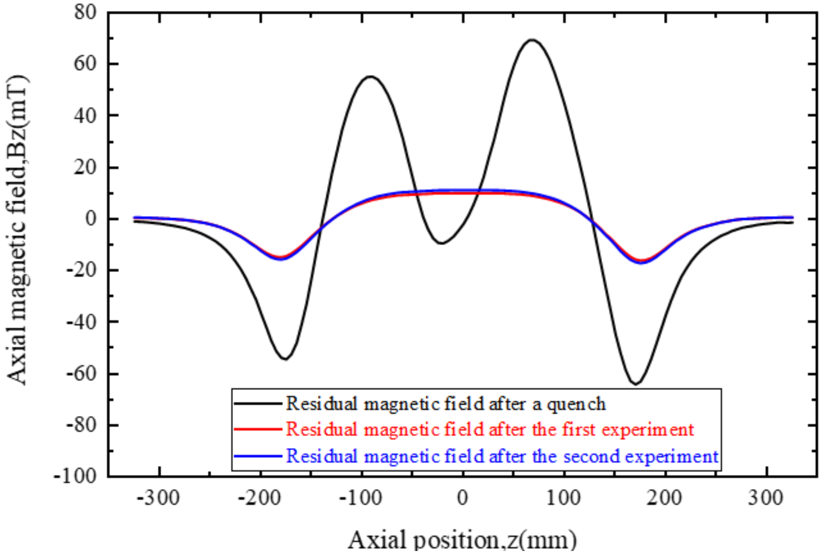
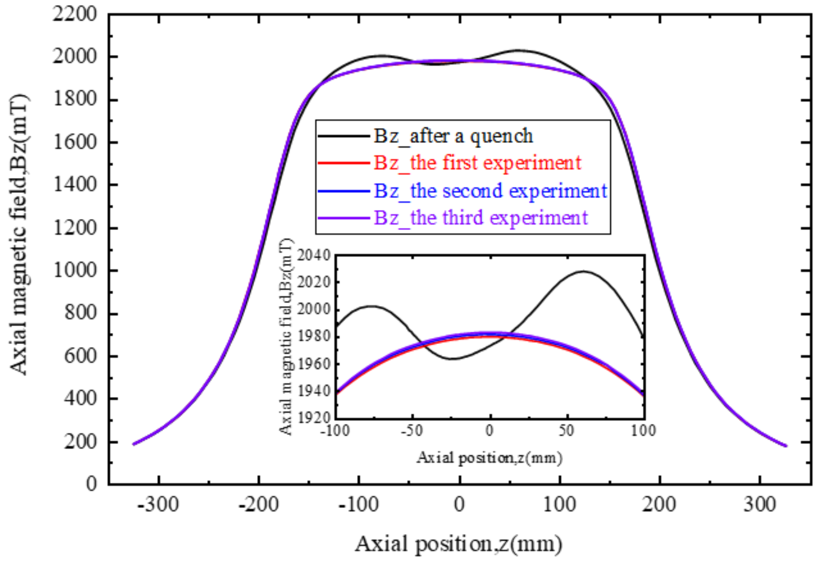
500 MHz NMR superconducting magnet

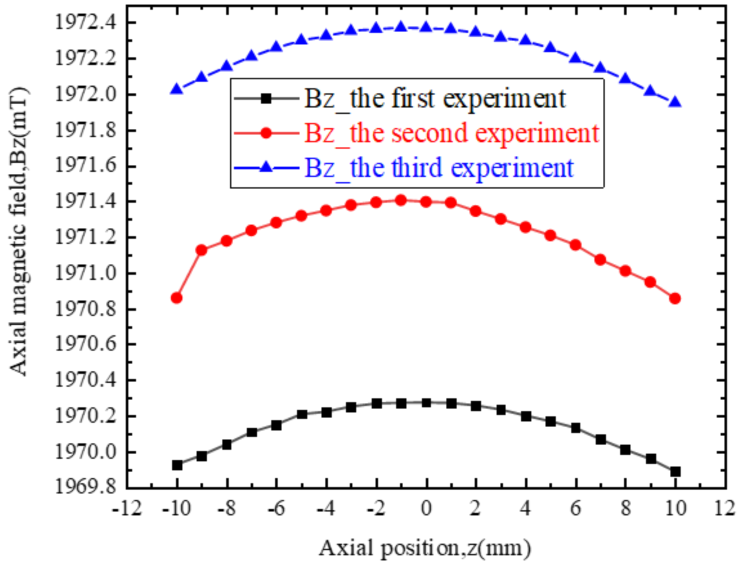
□ The 500 MHz NMR HTS-LTS hybrid magnet at IEE CAS



Axial residual magnetic field distribution on the center axis of the magnet



Axial magnetic field distribution on the center axis of the magnet at 20 A



The axial magnetic field on the center axis of the magnet

- 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.

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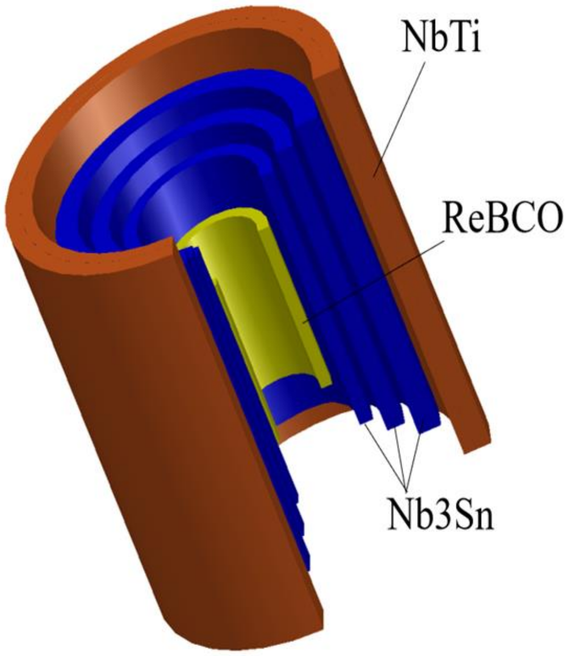
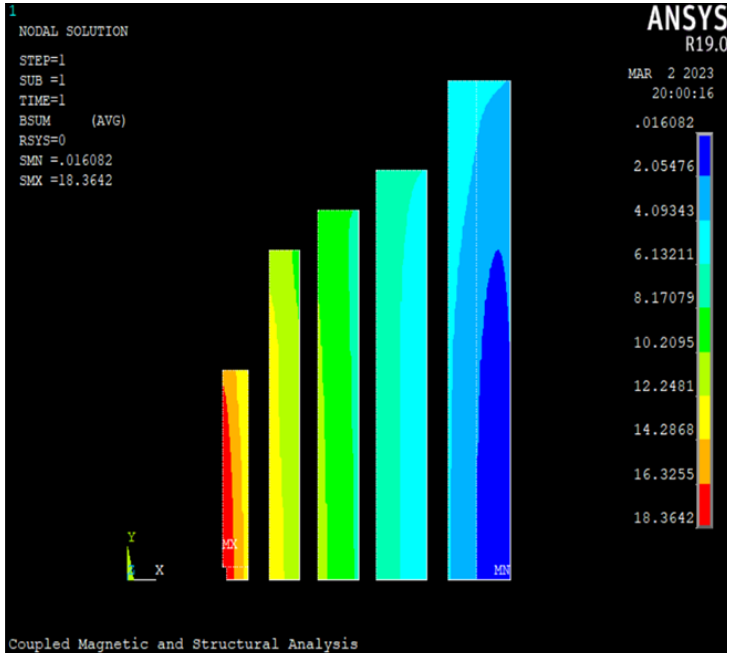
18 T superconducting magnet

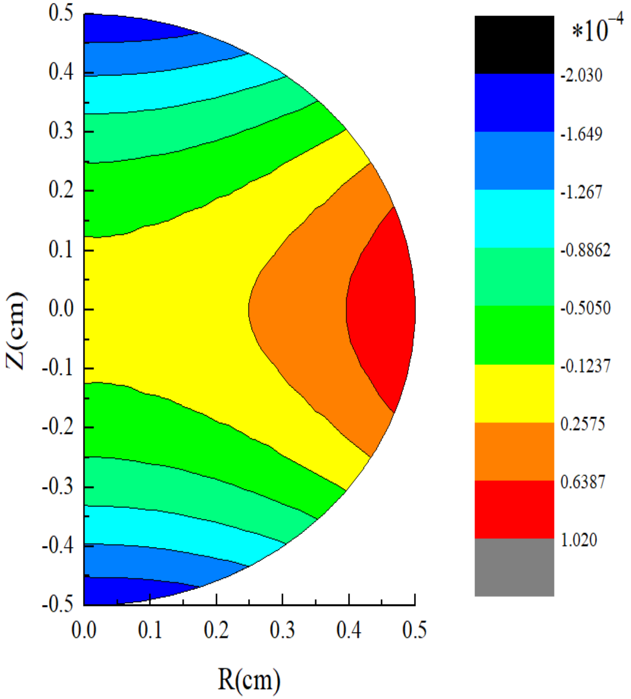
□ The 18 T superconducting magnet at IEE CAS



Coil configuration



Magnetic field distribution



Magnetic field homogeneity

- 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.

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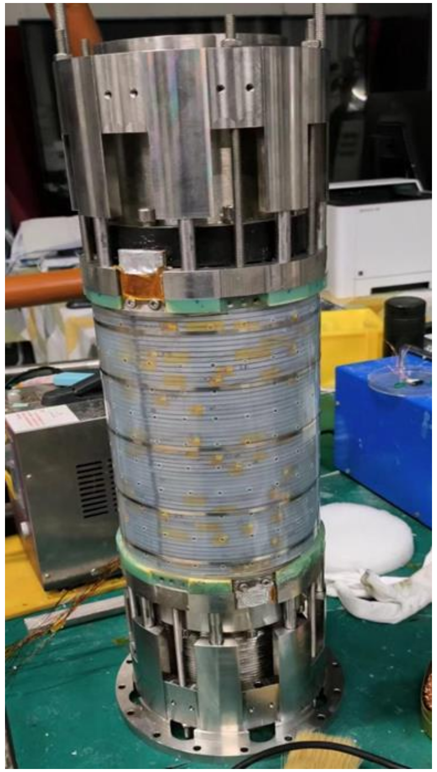
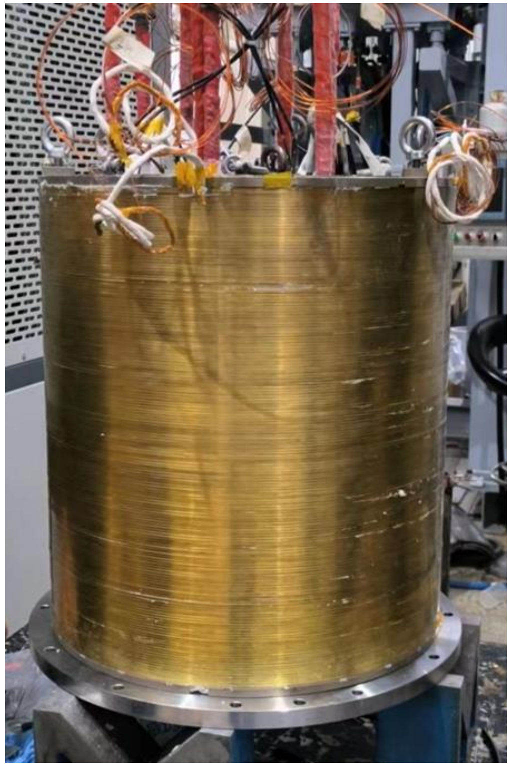
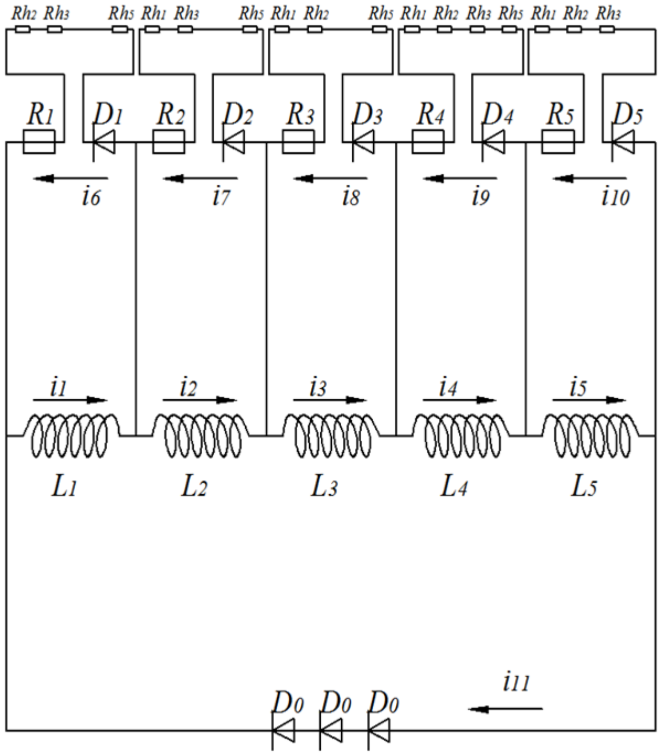
18 T superconducting magnet

□ The 18 T superconducting magnet at IEE CAS


HTS insert magnet


LTS background magnet



Quench protection circuit

- 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.

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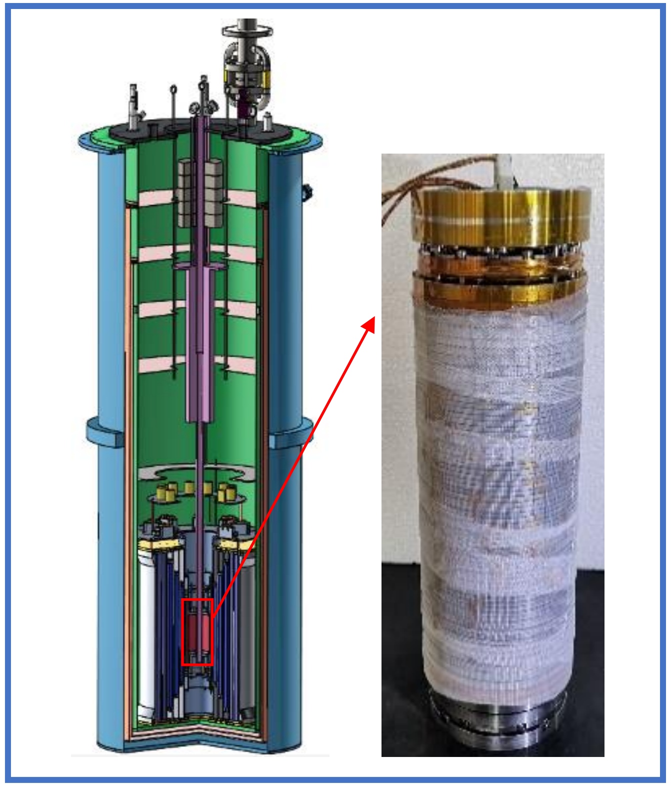
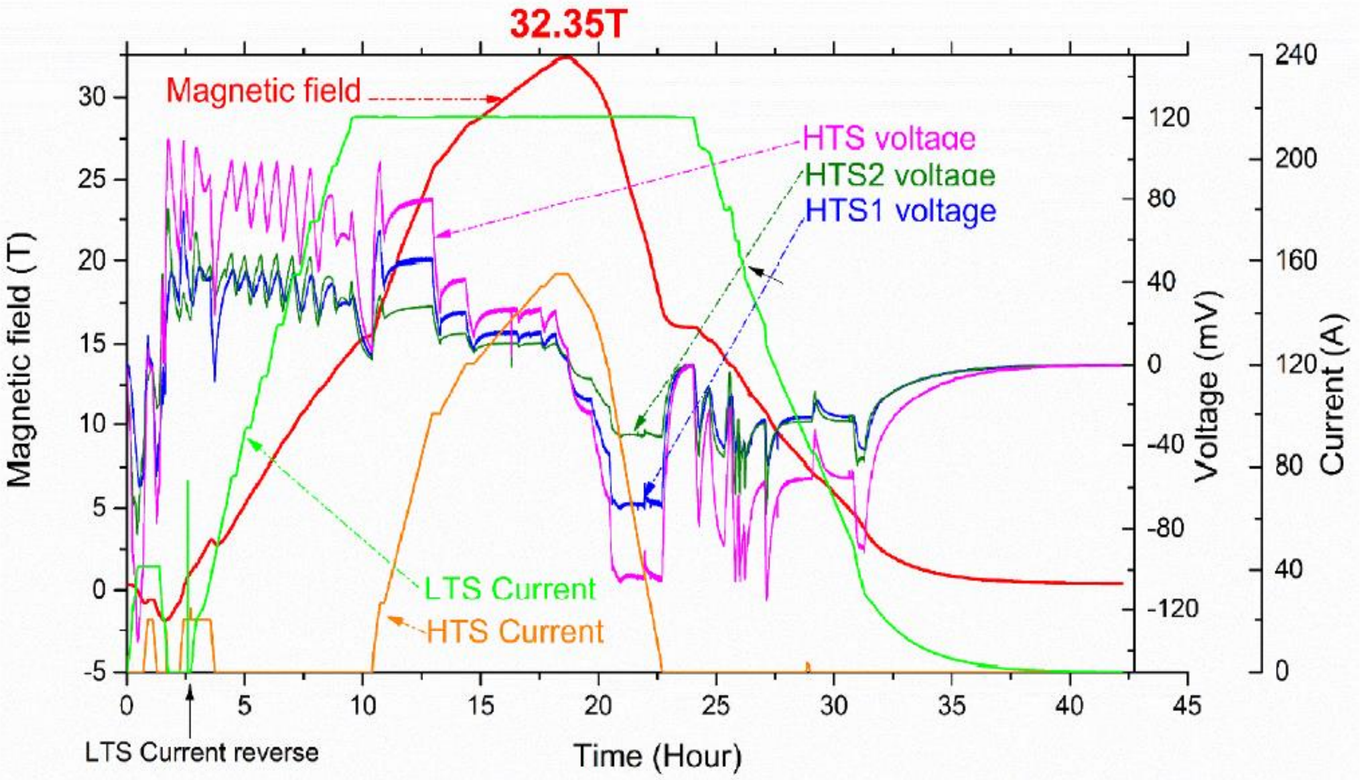
32.35 T superconducting magnet

- The ultra-high field superconducting magnet at IEE CAS, bore-size in 43 mm



32.35 T superconducting magnet



Test results of the magnet at 4.2 K

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

Qiuliang Wang et al 2022 Supercond. Sci. Technol. 35 023001

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

30 T superconducting magnet

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

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

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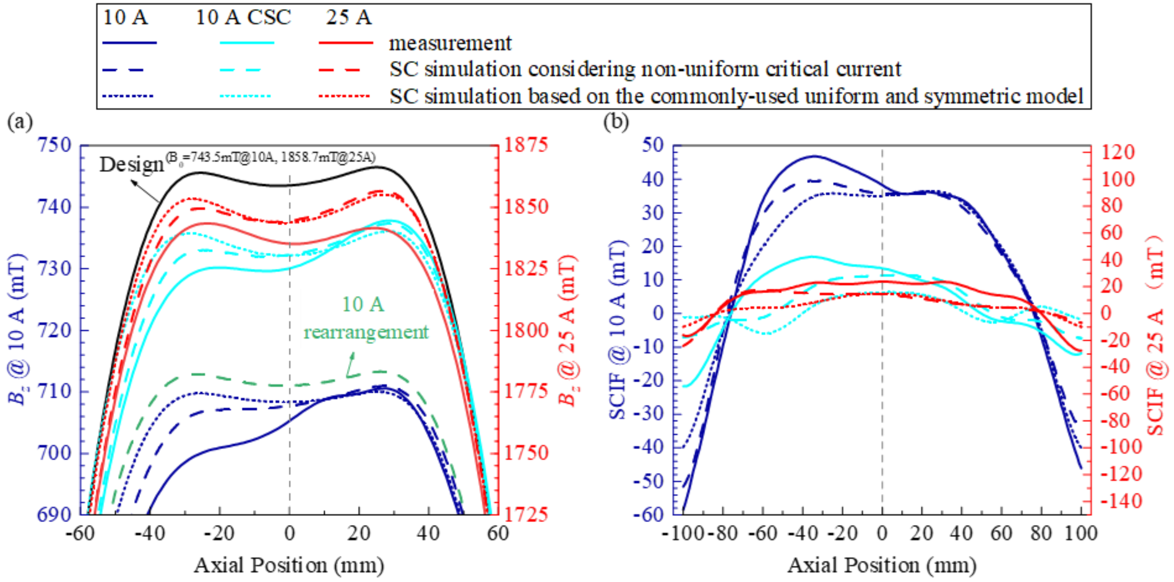
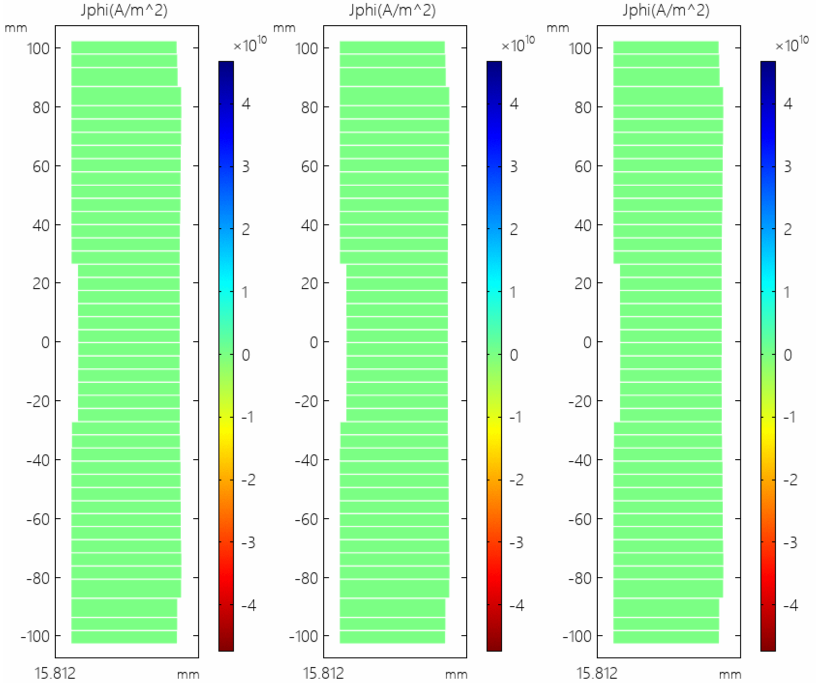
30 T superconducting magnet

☐ 30T/Φ35mm user magnet at IEE CAS

Inner magnet



Experimental and simulated magnetic field and SCIF distribution along the axial position



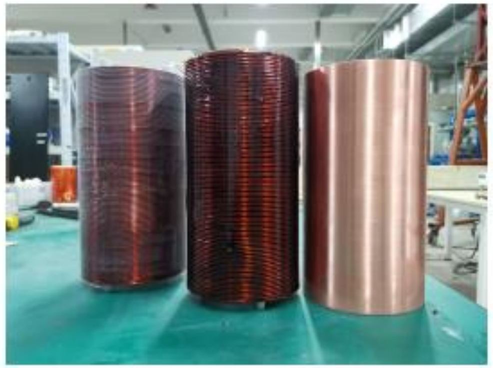
Simulated current density distribution of the inner insert for 10 A, 10 A CSC, and 25 A

- 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.

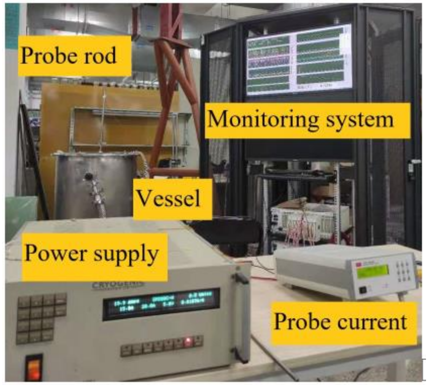
30 T superconducting magnet

☐ 30T/Φ35mm user magnet at IEE CAS

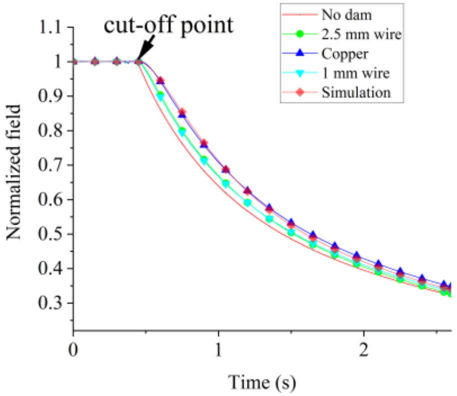
Bi2223 magnet



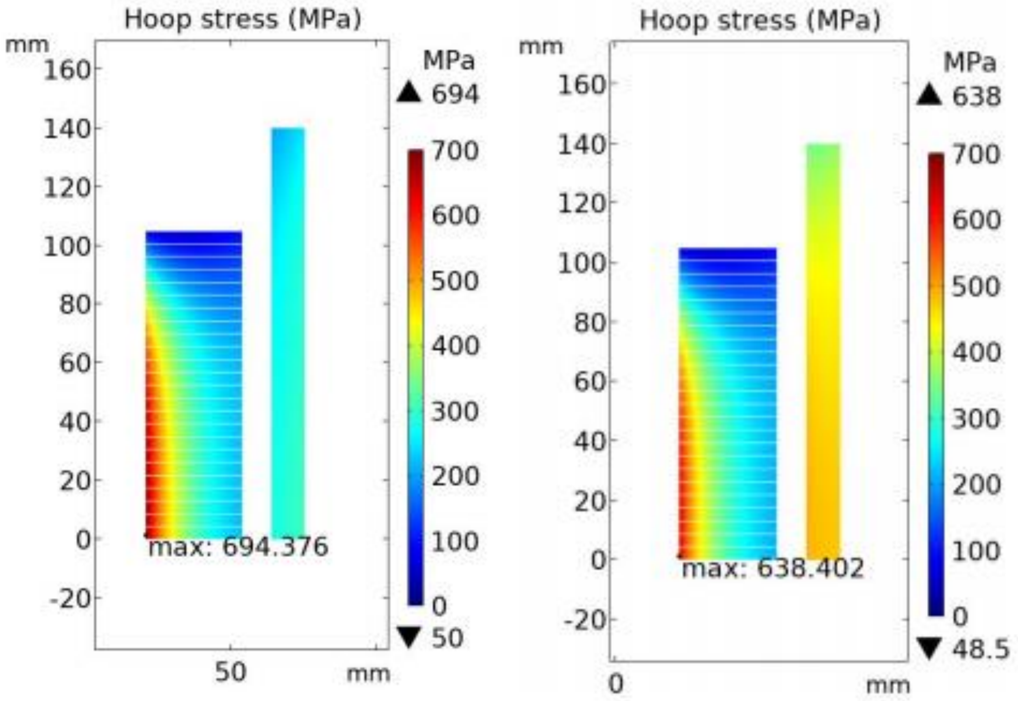
Coupling coils



Test system



Magnetic field



Hoop stress in insert magnet without and with coupling coil during LTS magnet quench

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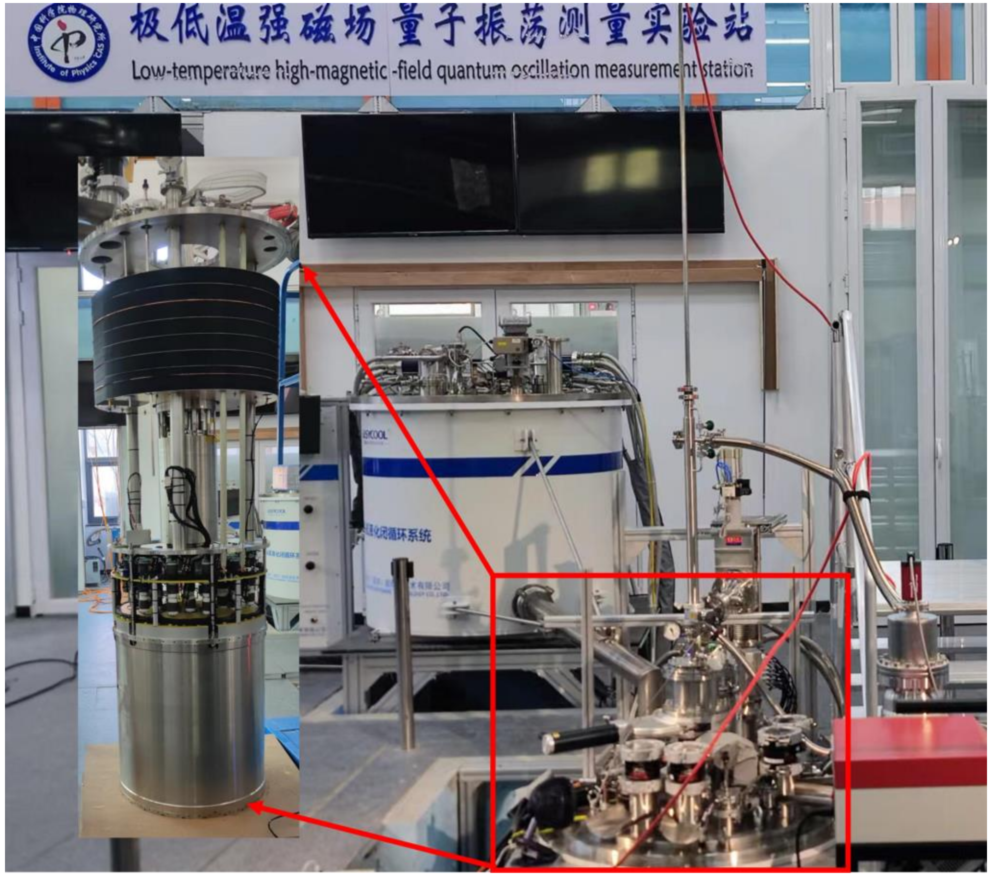
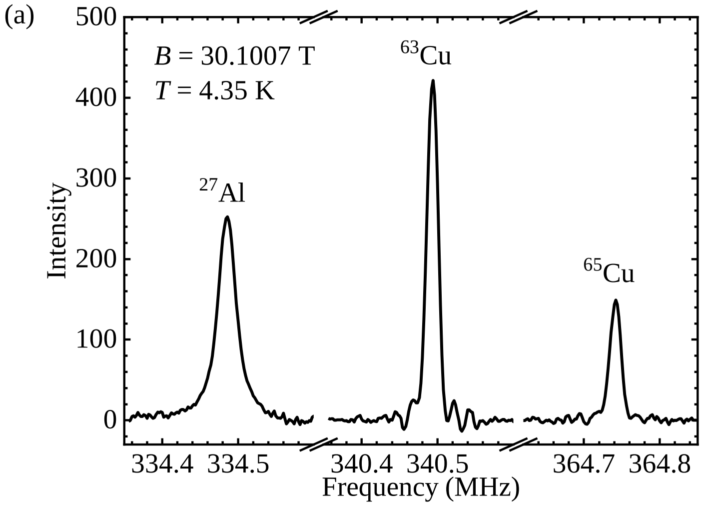
30 T superconducting magnet

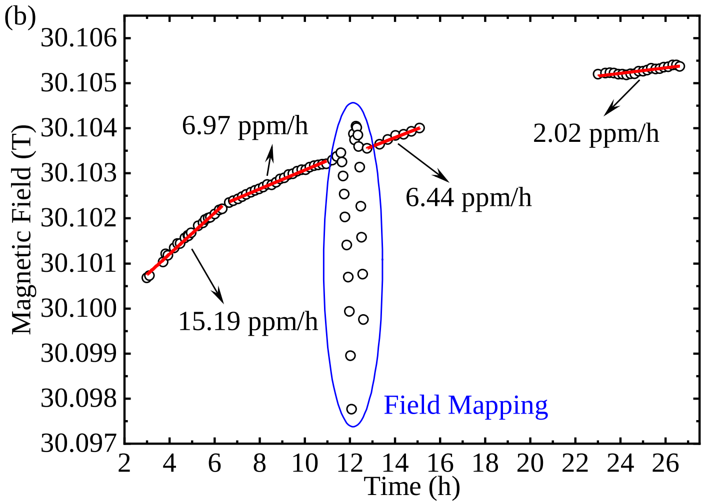
□ Test results of the 30T/Φ35mm user magnet



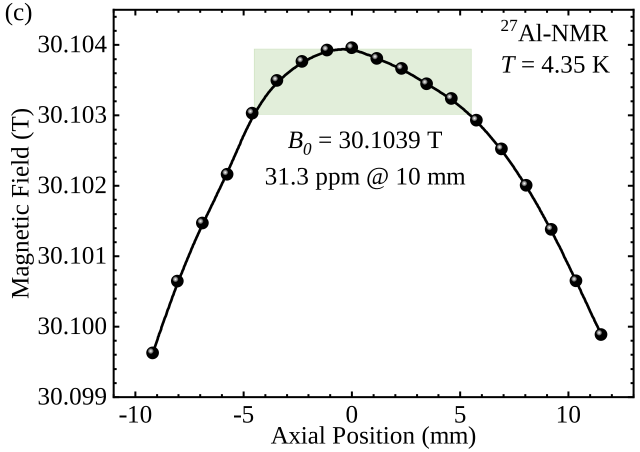
30 T superconducting magnet



Central field: 30.1007 T



Field stability: 2.02 ppm/h



Field homogeneity: 31.3ppm@10mm

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27 T solid state NMR superconducting magnet

□ Design and fabrication of 1.15GHz NMR(27T)/Φ50mm user magnet at IEE CAS

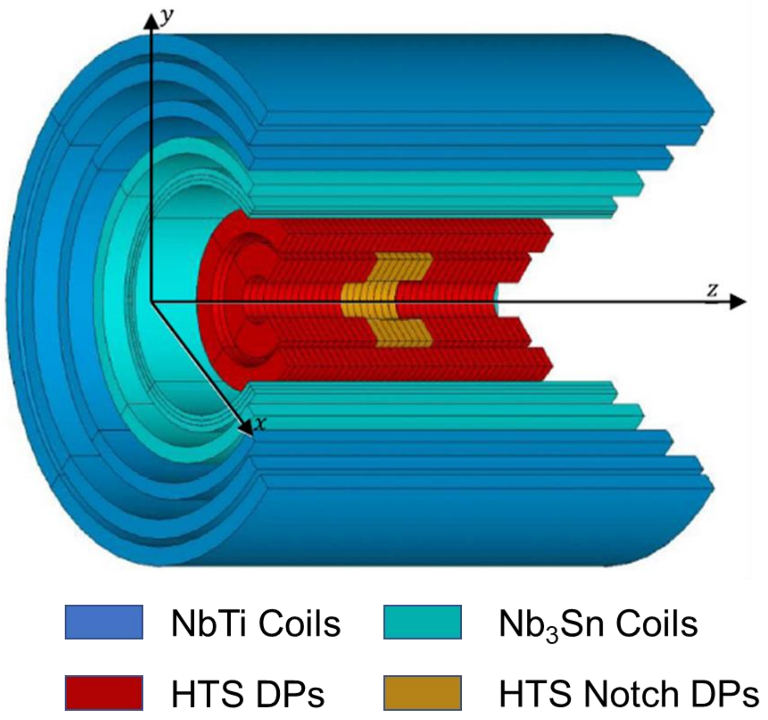
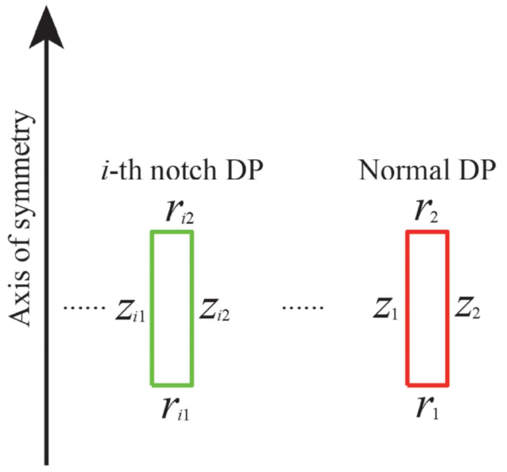


Illustration of the hybrid magnet



Minimize: $\sum v_i$

Subject to:

$$\frac{\left|t_{Bz}^{insert} + T_{Bz}^{back} - T_{Bz}\right|}{T_{Bz}} \le \varepsilon$$

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

[1]Yaohui Wang et al 2020 Supercond. Sci. Technol. 33 064004;[2] Yaohui Wang et al 2023 Supercond. Sci. Technol. 36 115028

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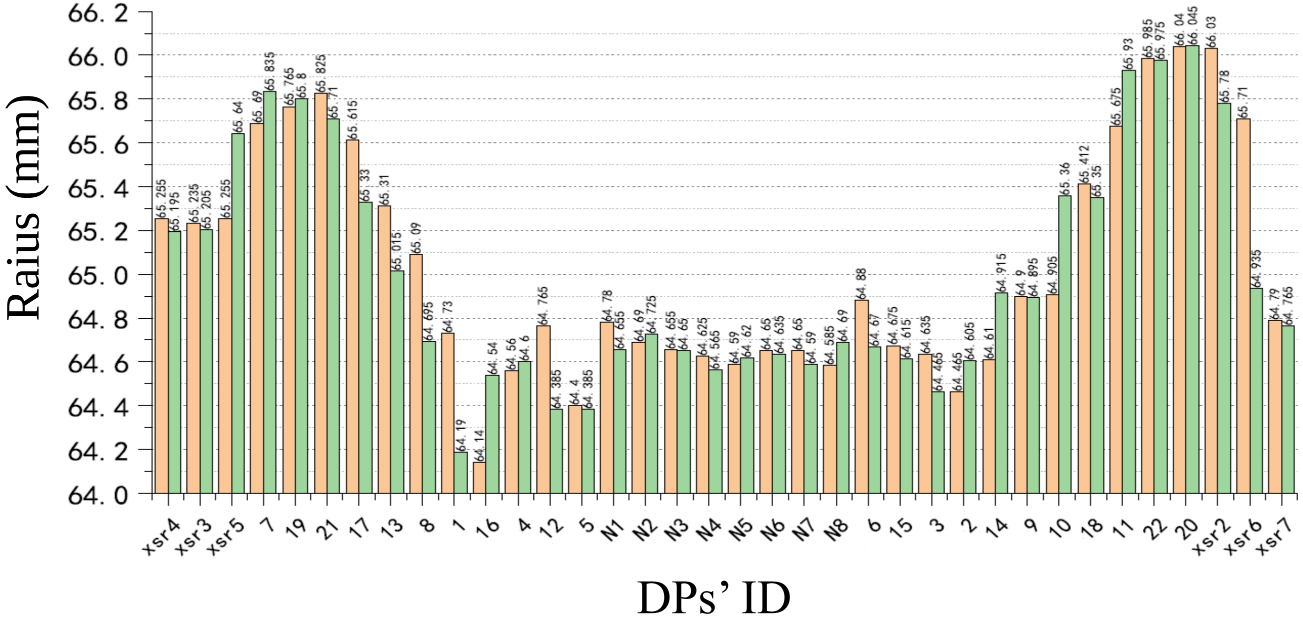
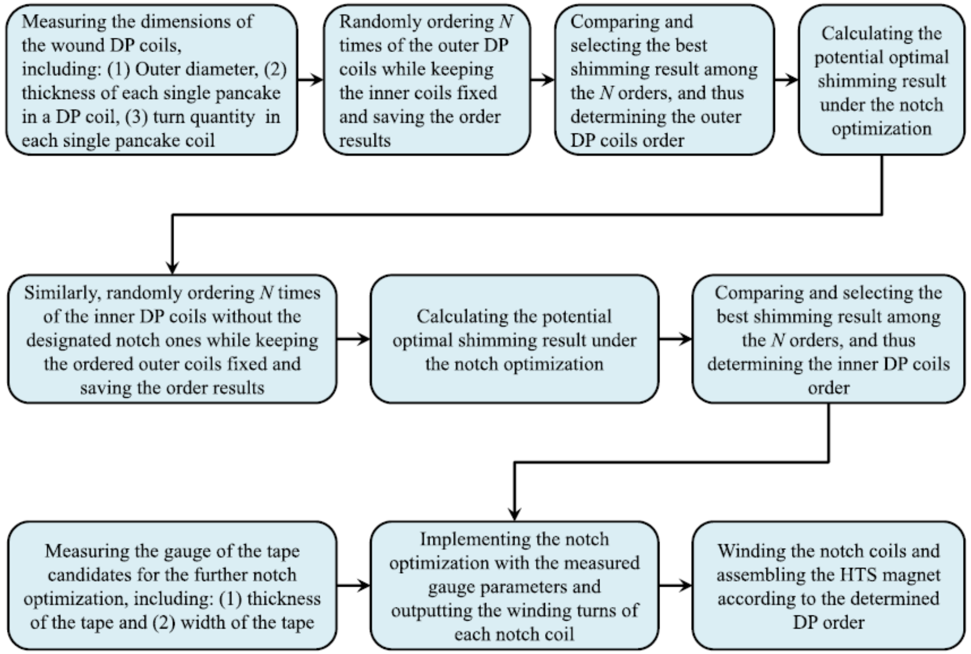
27 T solid state NMR superconducting magnet

□ 1.15GHz NMR(27T)/Φ50mm user magnet at IEE CAS



The size of the double-pancake coil



Optimization procedure of non-homogeneous HTS coils

- 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.

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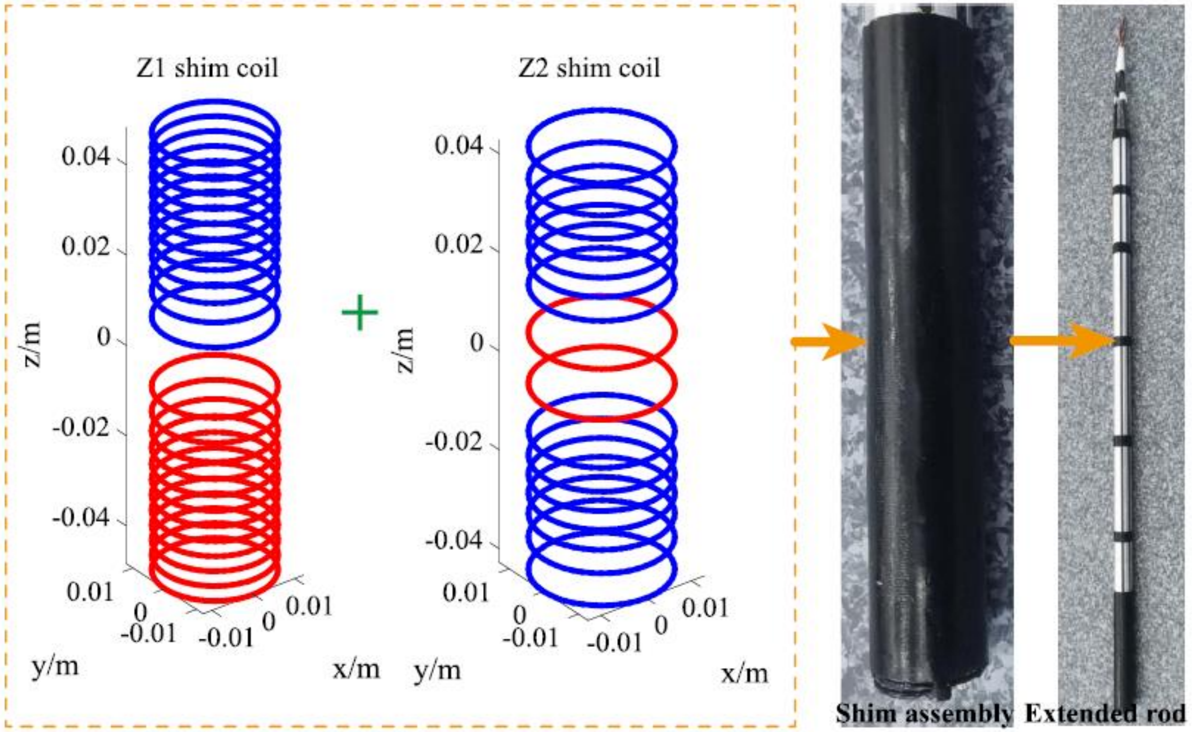
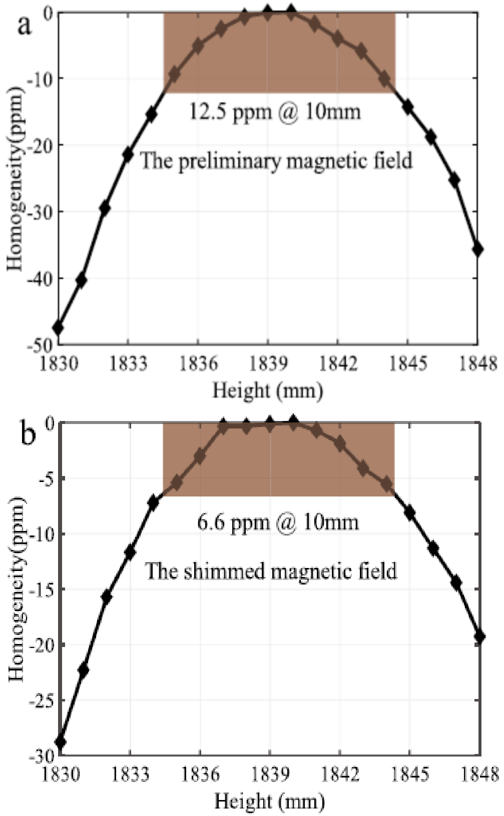
27 T solid state NMR superconducting magnet

□ 1.15GHz NMR(27T)/Φ50mm user magnet at IEE CAS



Shim coil design and fabrication



Preliminary and shimmed magnetic field.

- 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.

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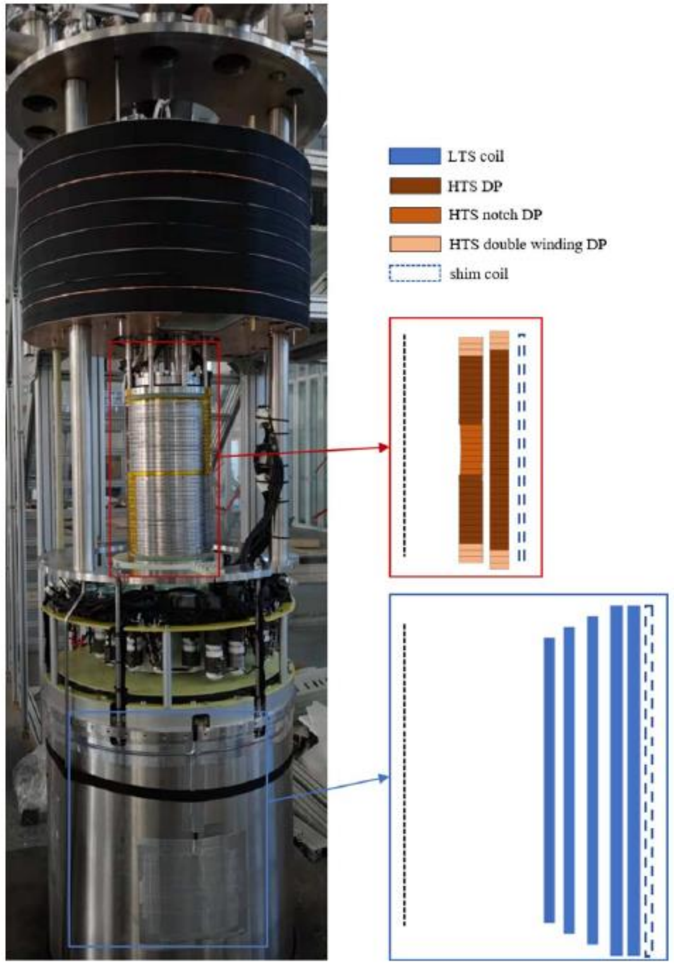
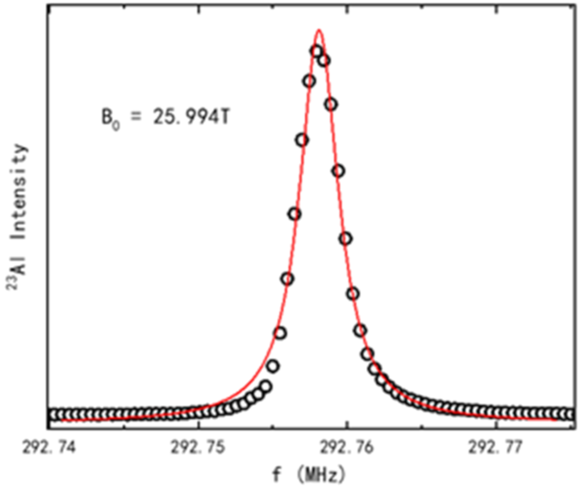
27 T solid state NMR superconducting magnet

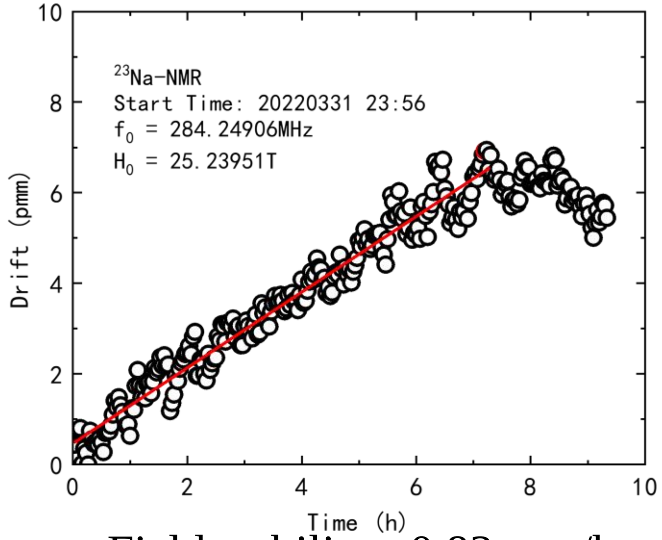
□ Test results of the 1.15GHz NMR(27T)/Φ50mm user magnet and spectrometer



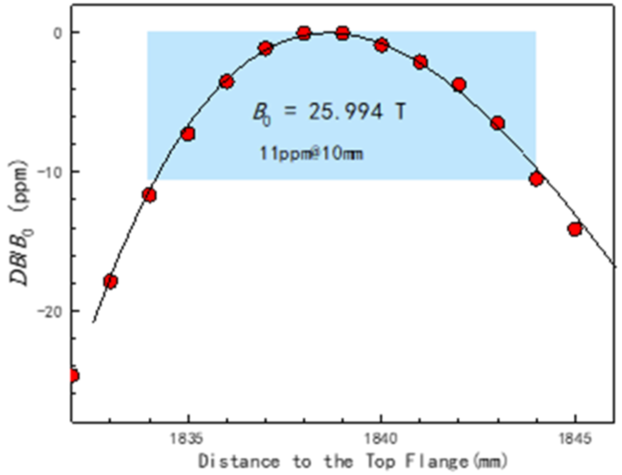
1.15GHz NMR magnet



Central field: 25.994T



Field stability : 0.83ppm/h



Field homogeneity:11ppm@10mm

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27 T solid state NMR system

VTI

Dilution refrigerator

20mK ~ 300K

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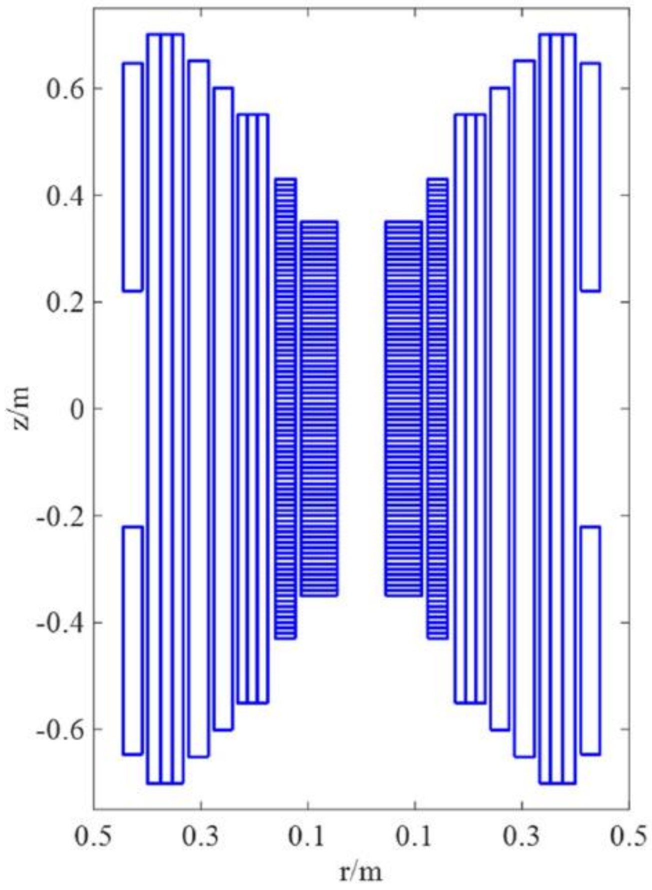
1.3 GHz liquid state NMR superconducting magnet

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



1.3 GHz NMR magnet design

Central magnetic field	30.5 T
Warm bore	52 mm
HTS tape	Bi-2223
Homogeneity(peak-peak)	54.2 ppb @DSV10 mm
Operating current	184 A
Inductance	2853.67 H
Magnetic energy	48.3069 MJ
Height	1403 mm
Outer diameter	890.6 mm
Inner diameter	90 mm

Wanshuo Sun et al 2023 Supercond. Sci. Technol. 36 075011

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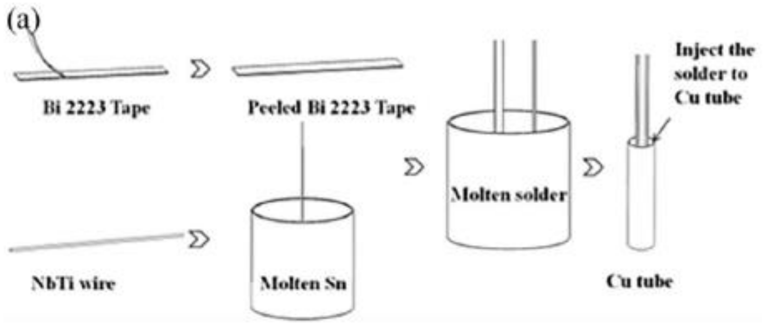
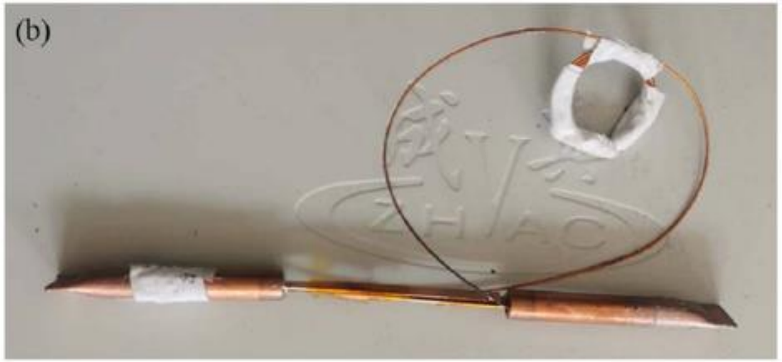
1.3 GHz liquid state NMR superconducting magnet

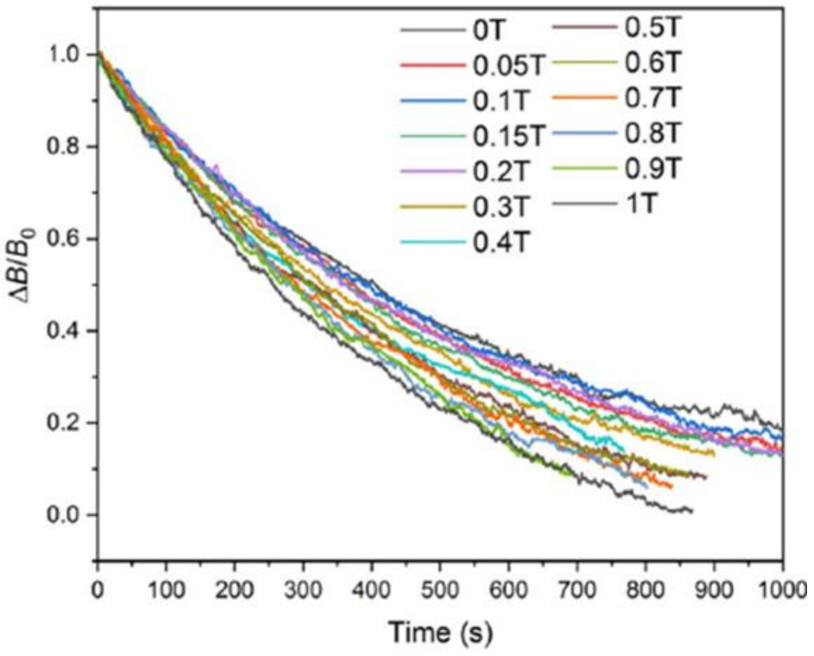
□ 1.3GHz NMR(30.5T)/Φ90mm magnet design at IEE CAS



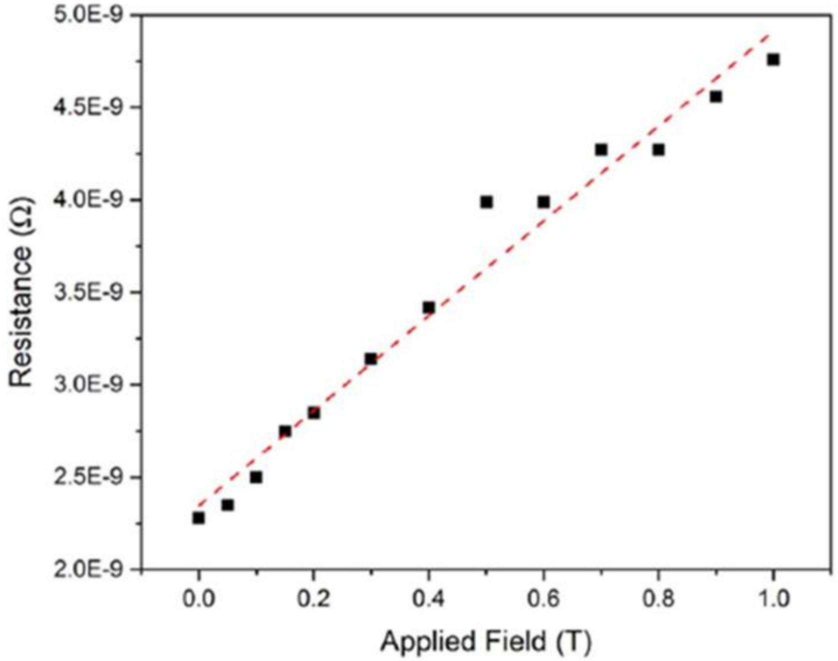
NbTi-Bi2223 low resistive joint



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.

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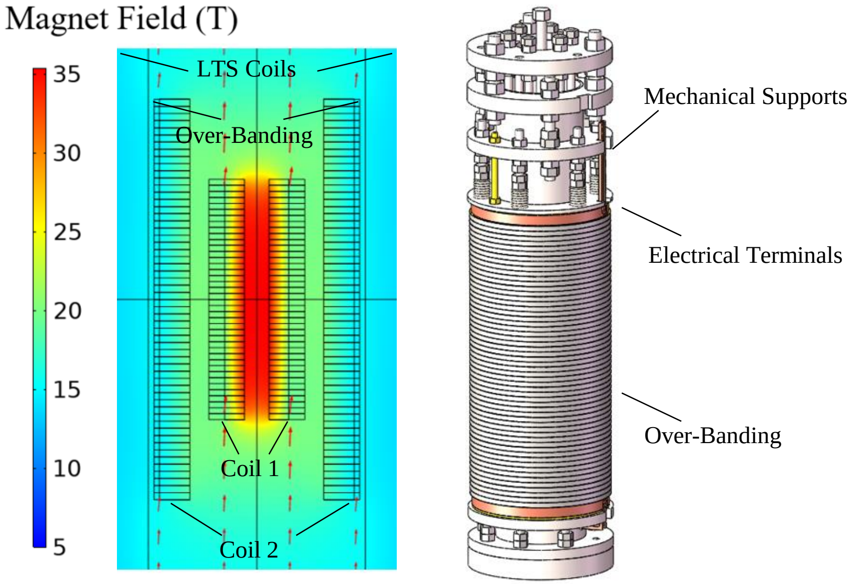
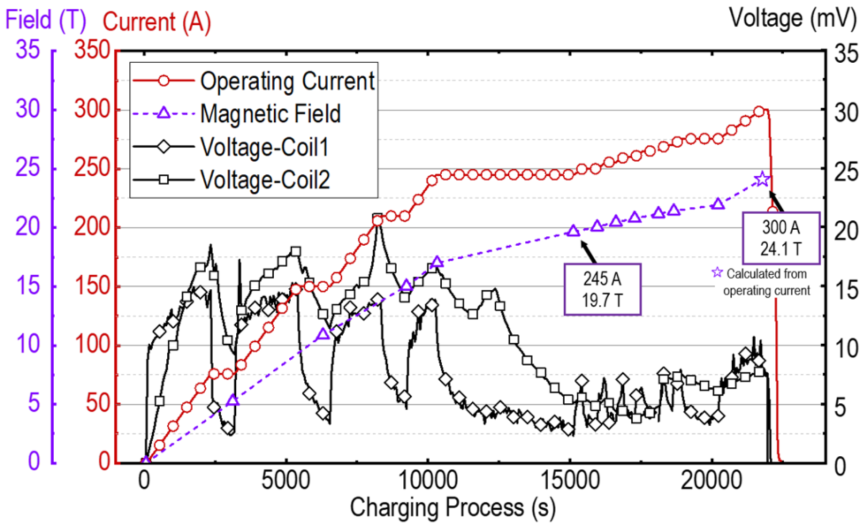
HTS-LTS hybrid superconducting magnet

□ Development of 35 T magnet designed at HFIPS CAS



(a) (b)



HTS insert magnet

- HTS insert magnet: 20T/Φ17mm, the inner coil is a no-insulation coil, and the outer coil is a metal insulation coil;
- B_{max}=35T @15T/Φ150mm 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.

Qiuliang Wang *et al* 2022 *Supercond. Sci. Technol.* 35 023001

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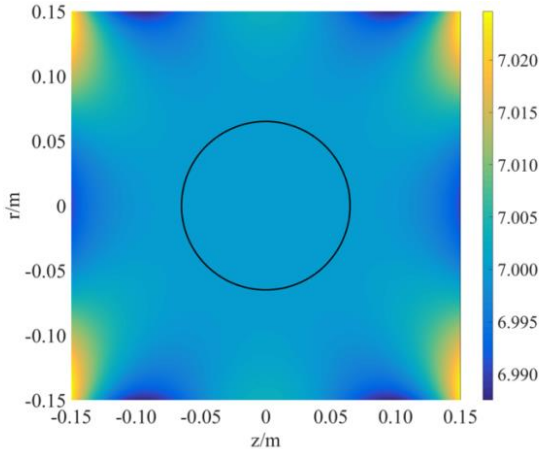
A 7 T animal MRI scanner

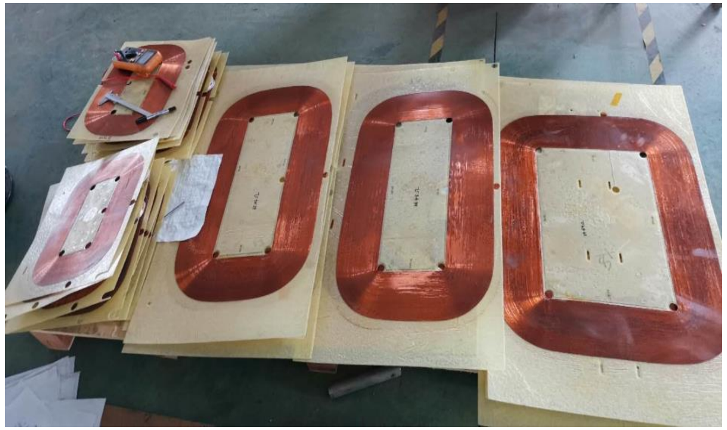
□ 7T/Φ300mm MRI superconducting magnet

7T animal MRI magnet

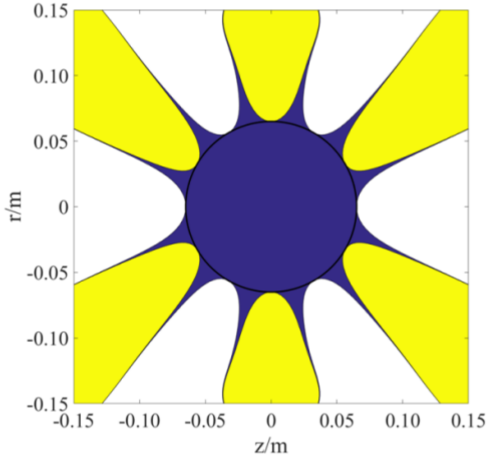
Shielding coils



Magnetic field distribution



Shim coil



10ppm deviation contour

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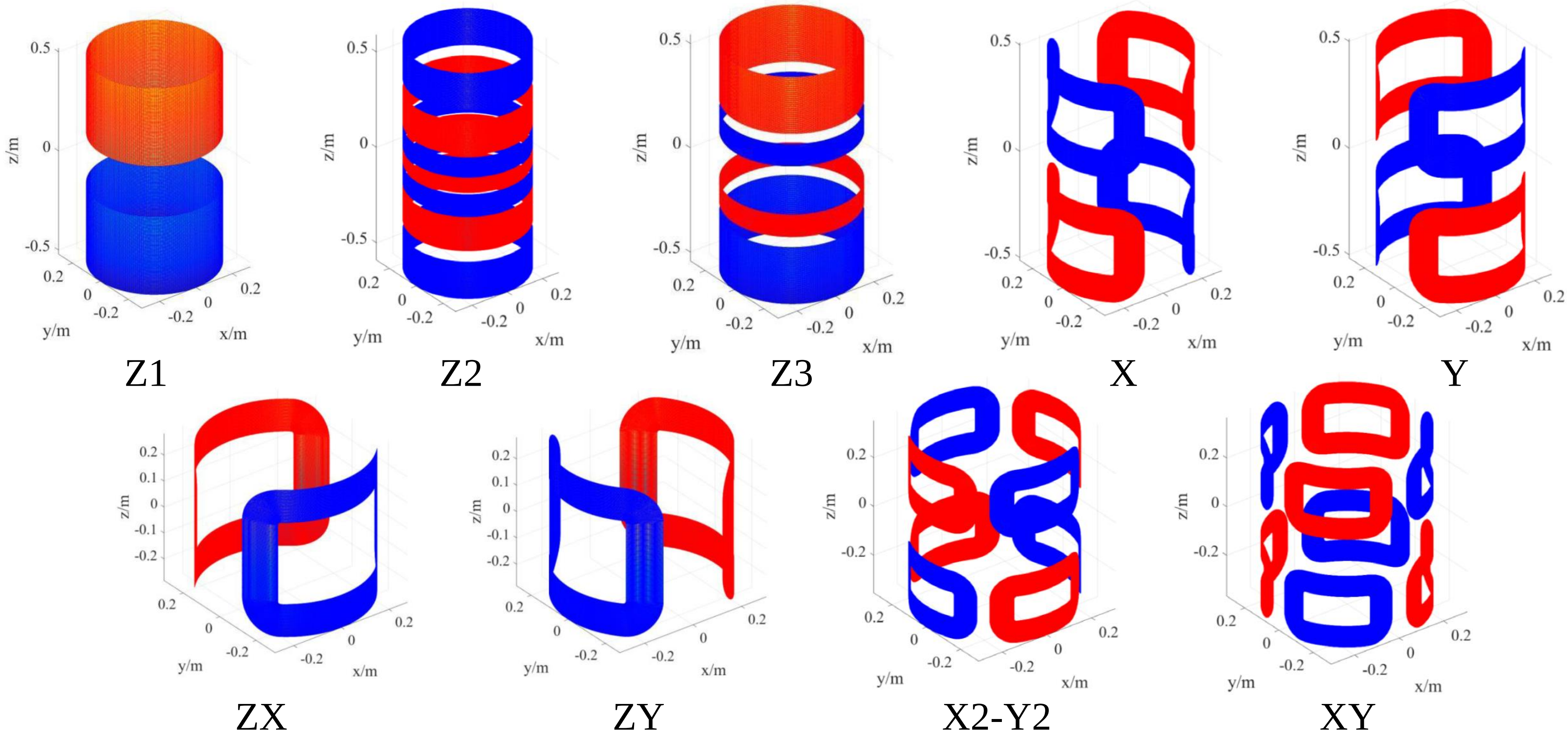
A 7 T animal MRI scanner

☐ 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.

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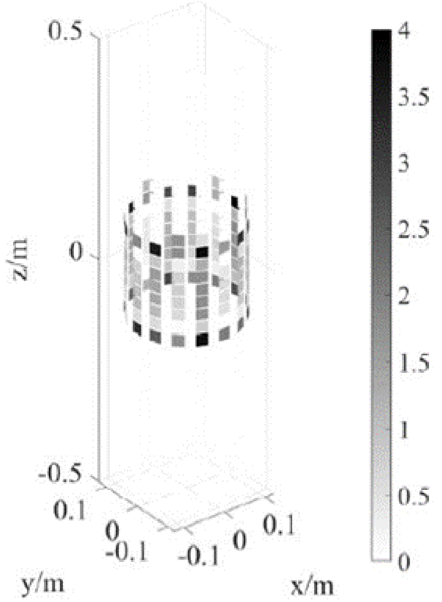
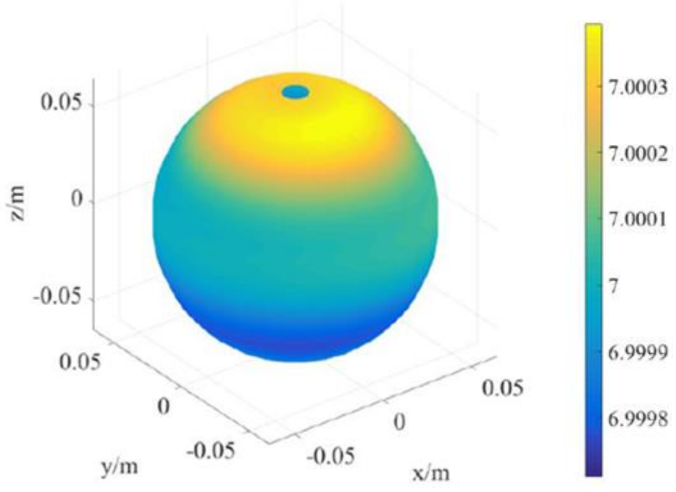
A 7 T animal MRI scanner

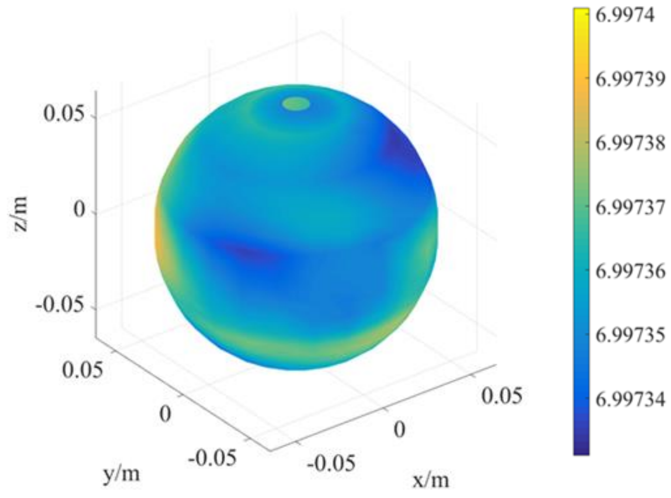
☐ Passive shimming



Evaluation of the passive shimming effect



An initial magnetic field distribution:97.8 ppm



Magnetic field distribution simulation after passive shimming:9.9 ppm

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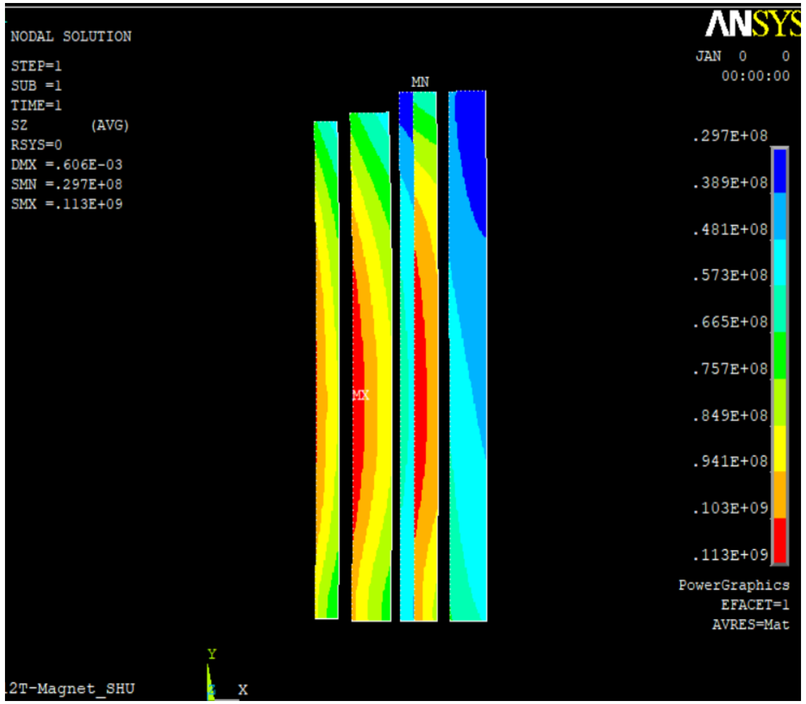
Split superconducting magnet

☐ 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



Assembly of split magnet

Hoop stress distribution

- The inner coil of the split magnet is made of Nb_3Sn 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.

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Ultra-high field 9.4T/800mm MRI magnet

Main specifications of 9.4T/800mm whole body MRI

Magnet type	Superconducting magnet
Field strength	9.4 T
Magnetic field shield	Iron Yoke-Passive shield
Field stability vs time	≤ 0.03 ppm/h
Shim style	SC shim + room shim + iron shim
Shim coils	≥ 52 groups
Room shim coils	≥ 14 groups (z0 , z2 , z3, z4)
Passive shield	36 group， along the circular
Three dimension automatic shim	Yes ≥ 2 order
Field homogeneity: 22cm DSV	≤ 0.05 ppm
Field homogeneity :30cm DSV	≤ 0.1 ppm
5 G line (z x r)	≤ 22 m x 18 m (non Yoke)
Length of magnet	≤ 3.5 m
Warm bore	≥ 800 mm
Weight of magnet (100% LHe)	≤ 50 ton
Operation	Near zero boiling off LHe

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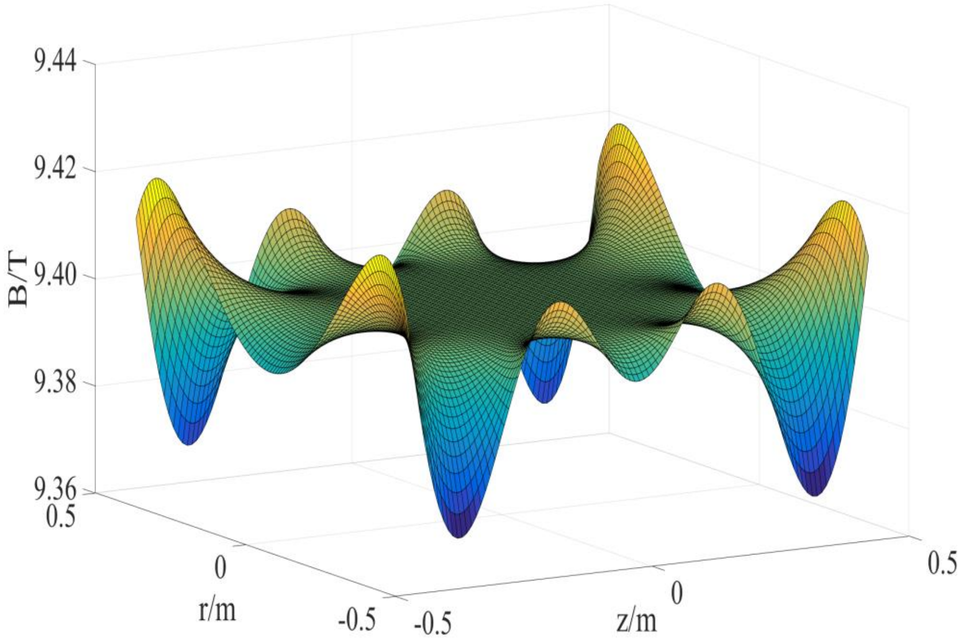
Ultra-high field 9.4 T/800 mm MRI magnet

☐ Superconducting magnet



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.

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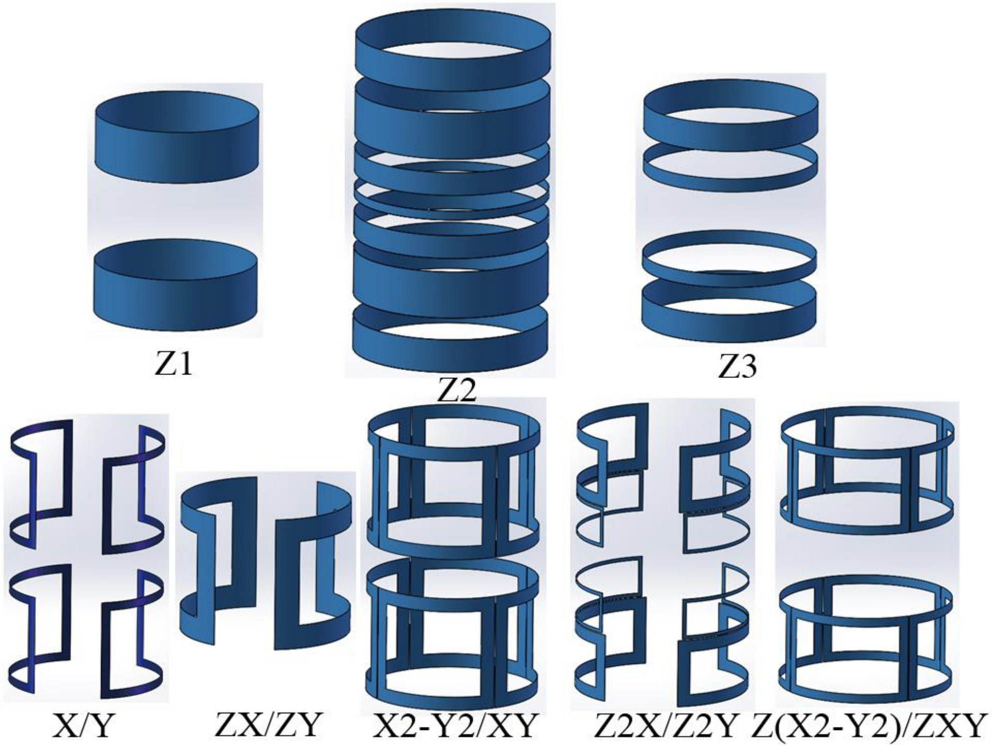
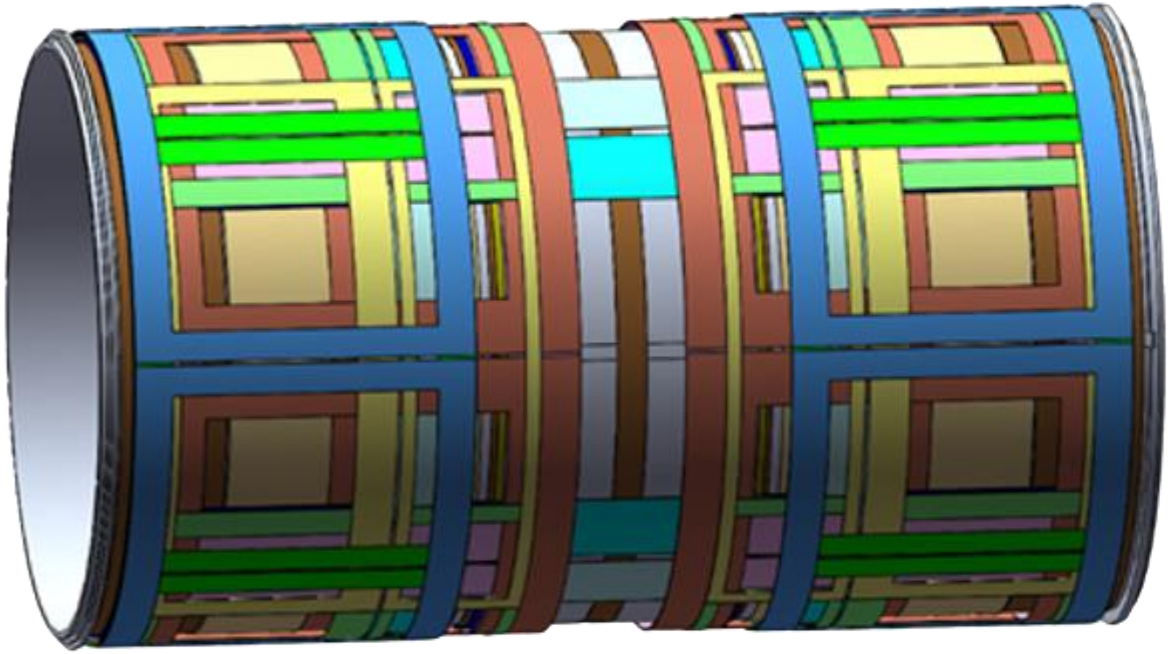
Active shimming ultra-high field magnet





- 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.

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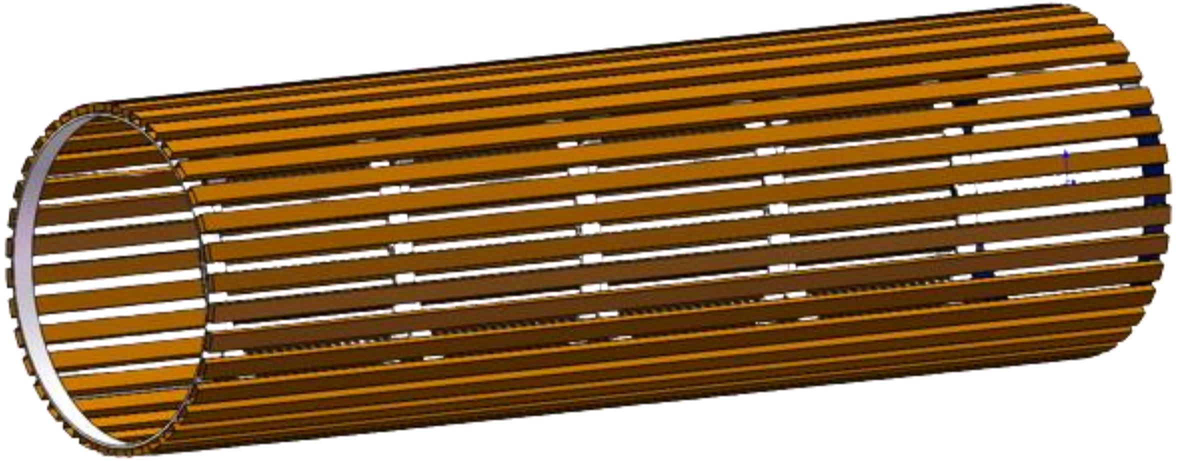
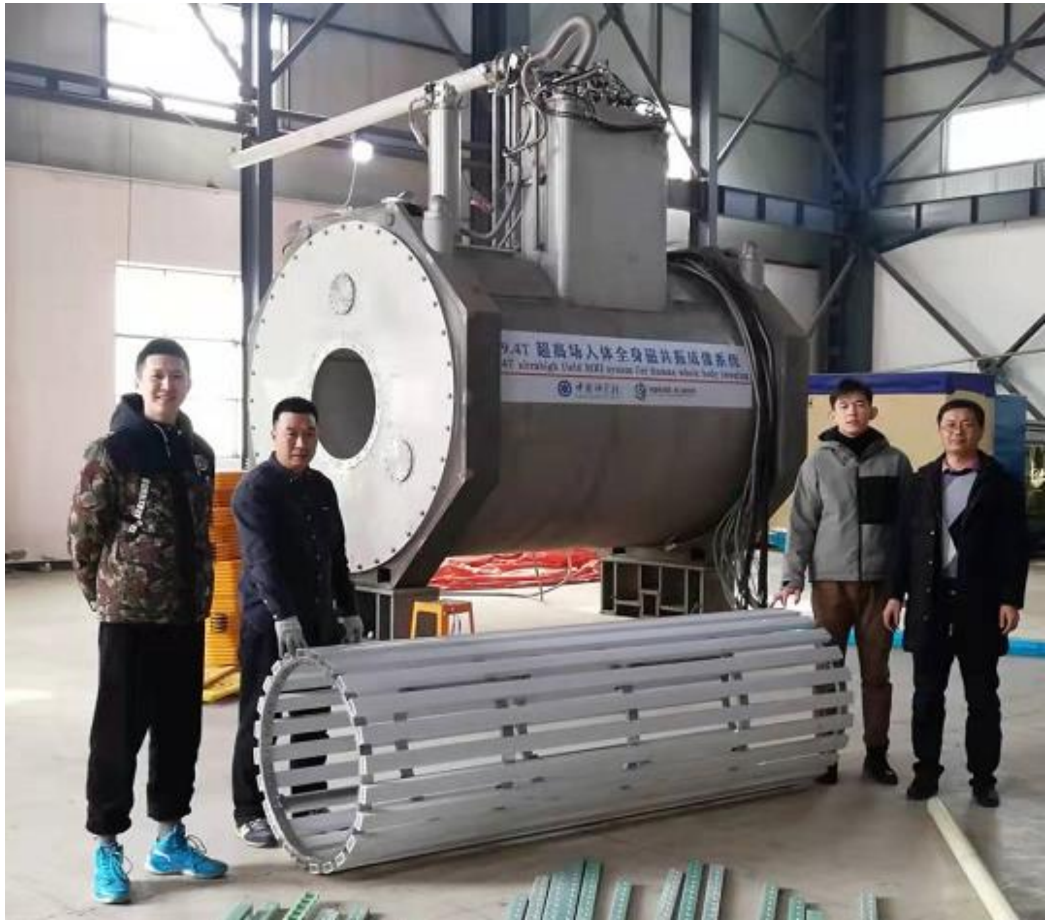
Passive shimming ultra-high field magnet





We proposed high-performance passive shimming algorithm to realize a highly homogeneous magnetic field distribution with very few iron piece usage.

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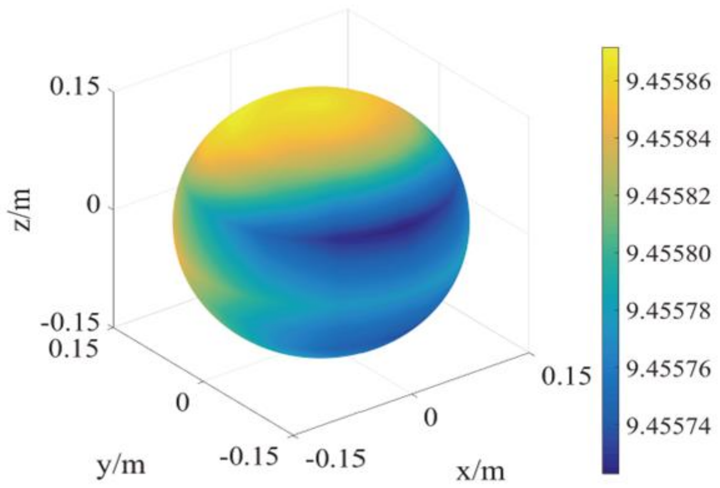
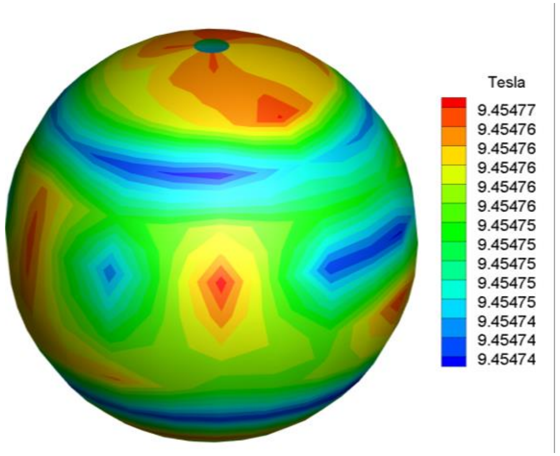
Ultra-high field 9.4 T/800 mm MRI magnet

Shimming results



After active shimming
26.95 ppm@40 cm



After passive shimming
3.05 ppm@40 cm

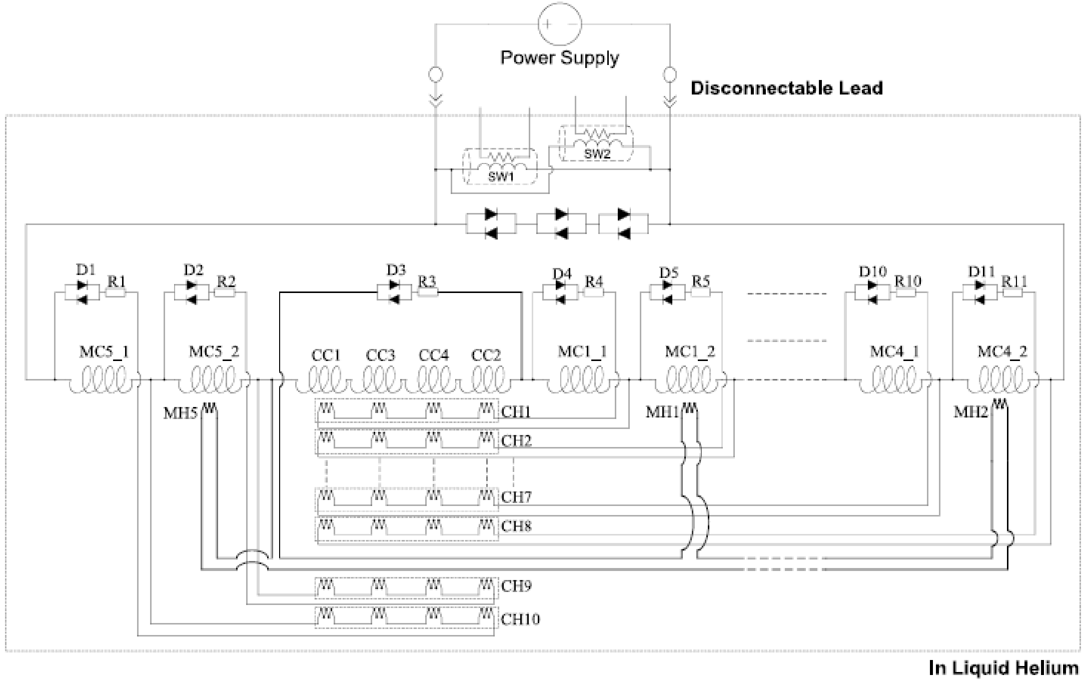
Testing results

Central field	9.46 T
Stability of field	0.02 ppm/h
With active shimming	26.95 ppm (p-p)@ 40 cm DSV
With passive shimming	3.05 ppm(p-p)@40 cm DSV
Vapor rate	Zero
Room bore size	800 mm
Length	3662 mm

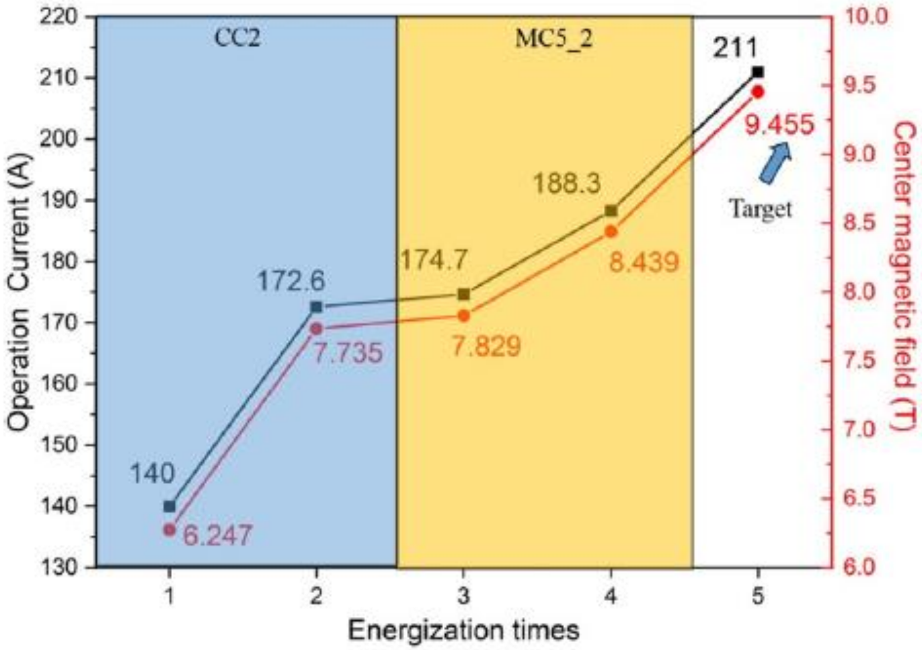
After several shimming experiments and iterative calculations, the spatial magnetic field homogeneity in the central region is improved from 26.95 ppm to 3.05 ppm in a DSV of 40 cm.

Ultra-high field 9.4 T/800 mm MRI magnet

☐ Quench protection



Quench protection circuit for the 9.4 T MRI magnet



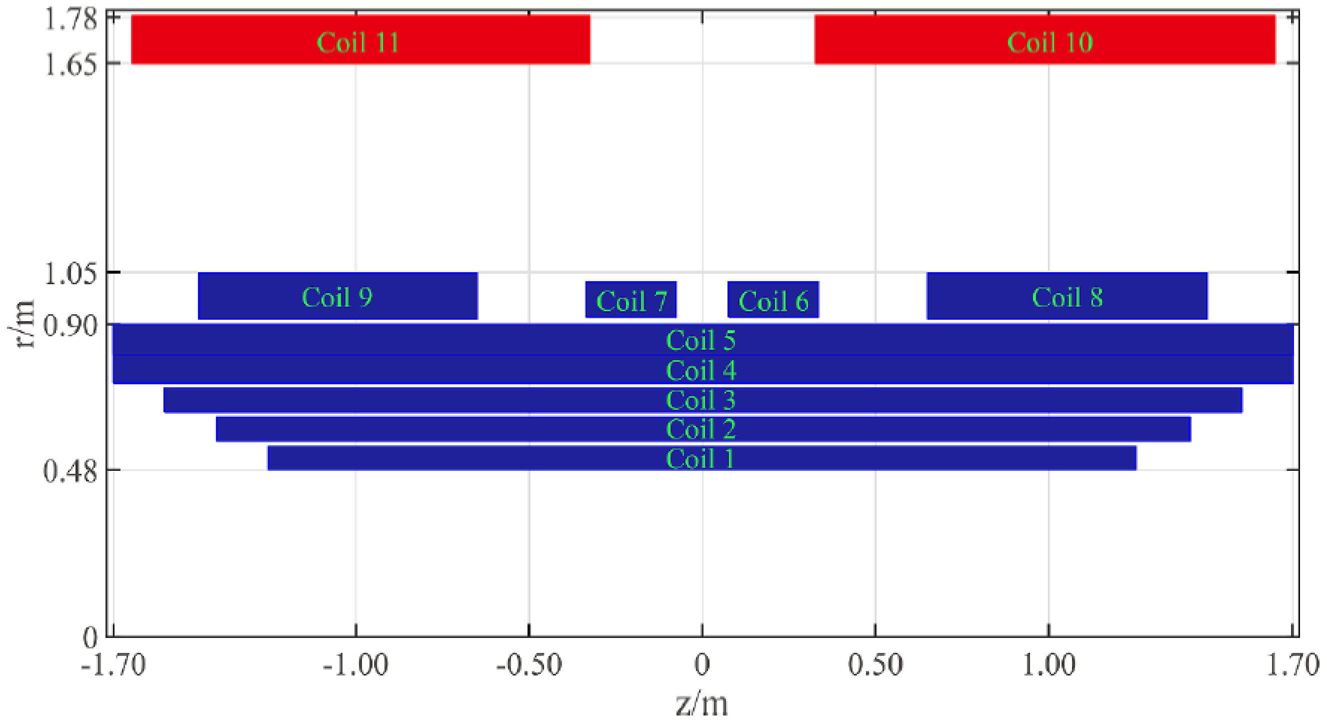
The current and center magnetic field value of different energization times

- 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.

Shunzhong Chen et al 2023 Supercond. Sci. Technol. 36 045007

Ultra-High field 14 T MRI magnet design

□ 14T MRI/Φ960mm magnet design at IEE CAS



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

Central magnetic field	14 T
DSV	500 mm
Homogeneity(peak-peak)	25 ppm @500 mm
Cold inner bore	960 mm
5 Gauss line	10 m(z)×8 m(r)
Operating current	215 A
Maximum magnetic field	14.34 T
Operating factor in coil 1	75.03 %
Operating factor in coil 4	92.93 %
Maximum hoop stress	188 MPa
Coils inductance	23825.2 H
Magnetic energy	550.7 MJ
Wire length	Nb_3Sn:253.2 km NbTi:1567.2 km

Yaohui Wang et al 2022 Supercond. Sci. Technol. 35 014001

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Summary

- 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!