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Letter

World record 32.35 tesla direct-current magnetic field generated with an all-superconducting magnet

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Abstract

We have successfully reached the world record 32.35 T direct-current magnetic field by using a homemade all-superconducting magnet. The magnet has consisted of a 15 T low temperature superconductor outsert coil and two high temperature superconductor no-insulation (NI) insert coils using a conductor tape coated of REBCO ($REBa_2Cu_3O_x$, where RE = Y, Gd). This result proves the feasibility of reaching a strong magnetic field up to 32 T by using the NI process as well as the superconductor magnet with insulation. This magnet is one of the essential parts of the 'Synergetic Extreme Condition User Facility' project, which provides expertize, instrumentation, and infrastructure for investigating matter science under extreme physical conditions. We thought that such a strong superconductor magnet would bring the possibility to explore more mystery in physics, medicine, pharmacy, etc.

Keywords: superconducting magnet, no-insulation coils, HTS magnet, very high-field

(Some figures may appear in colour only in the online journal)

1. Introduction

The Chinese government commenced the Synergetic Extreme Condition User Facility (SECUF) project in 2017, which provides expertize, instrumentation, and infrastructure for investigating matter science under extreme physical conditions. This project aims to bring together physical sciences related experiment techniques and push them to the limits of ultra-low temperatures (T), ultra-high pressures (P), strong magnetic fields (B), and ultrafast time resolution. The Strong magnetic fields are required in many fields, such as medicine (magnetic resonance imaging MRI), pharmacy (nuclear magnetic resonance NMR), particle accelerators (such as the Large Hadron Collider LHC) and fusion devices (Tokamak or stellarator), as well as for other diverse scientific and industrial uses.

Up to now, the world record dc magnetic field is 45.5 T, obtained at the National High Magnetic Field Laboratory (NHMFL USA), with a 14.4 T REBCO insert in a 31.1 T resistive magnet [1]. The insert composed of 12 pancake coil was a test coil, had an inner winding diameter of 14 mm, an outer winding diameter of 34 mm, and a height of 53.1 mm. The winding current density amazingly reached 1260 A mm^{-2} before it quenched. In the all-superconducting magnet, specificly the REBCO insert coil, and there are two primary techniques process: no-insulation (NI) and insulation. For the

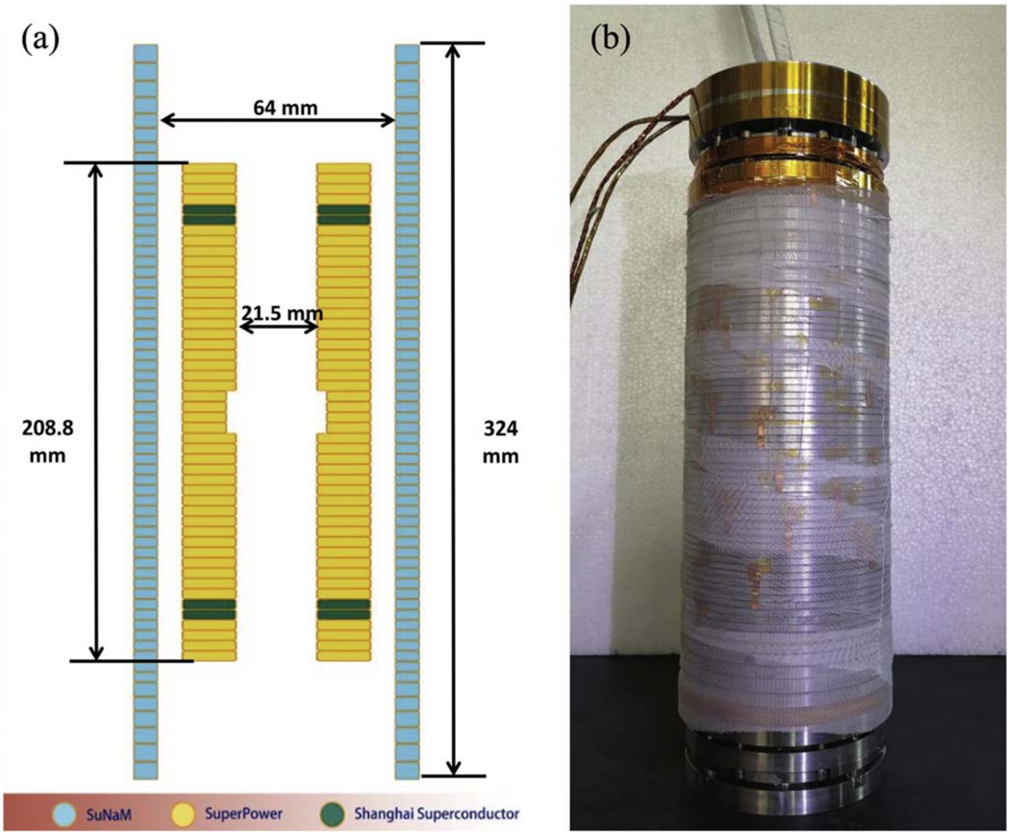

Figure 1. Design and construction of REBCO insert coil. (a) Construction design of REBCO insert coil (not to scale). (b) Right, photograph of REBCO insert coil.

insulation process, the NHMFL successfully reached 32 T after several intentional quenches in 2017, which was the world record at that time [2]. Due to the self-quench-protection ability, the NI process attracted more attention worldwide [3, 4]. The RIKEN obtained the highest magnetic field of 30.5 T in NI process, with a 12.8 T lay-wound Bi-2223 coil and small REBCO test coil in a 17.2 T LTS background magnet [5]. A 26.4 T all REBCO magnet was also developed at SuNAM based on NI process [6].

We, Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS), contracts to build the high-field superconducting magnet with a center field up to 30 T. In order to achieve this goal, IEECAS has carried out a series of high-field REBCO insert magnet programs based on a 15 T LTS outsert coil, and we obtained 25.7 and 27.2 T successively in 2017 [7–10].

In this paper, we briefly introduced our latest progress of the all-superconducting magnet, which successfully reached 32.35 T at the end of 2019. It reveals the feasibility of reaching a strong magnetic field up to 32 T by using the NI process as well as the insulation process.

2. Design and fabrication

Our project target is to build a 30 T superconducting magnet based on a 16T-φ 160 mm LTS magnet. Considered the small bore size of the background magnet, NI technology was employed to increase the engineering current density (J_e) of the 15 T REBCO insert. The insert consists of two coils. There are 24 double-pancake (DP) coils in the inner coil, also named REBCO Coil 1, and 36 DPs in the outer coil, named REBCO Coil 2.

As for a REBCO insert, the critical current is mainly limited by critical currents of the most vulnerable conductors, since the unsophisticated magnet assembly technology dramatically reduces the critical current of the magnet. However, this is very hard to quantify during the magnet design. So in most cases, we increase the electromagnetic operation margin to compensate for the reduction of the critical current of the magnet. The most effective method to increase the electromagnetic operation margin in local regions is to reduce the current density in these areas. There are two approaches that can meet this requirement, the first is to increase the conductor width, and the other is to wind the DPs with double-winding technology. Here 'double-winding' means co-winding two REBCO conductors at the same time. One thing worthy of knowing is that due to the thicknesses of pieces of conductors were slightly different, stainless steel tapes were used to co-wind with the coated conductors at the outermost layers of the DPs. So the current densities in those regions were slightly different.

Figure 1 shows the design and construction of the REBCO insert coil. The specification of the 15 T REBCO

Table 1. Parameters of the REBCO insert.

Parameter	REBCO Coil 1				REBCO Coil 2			
IR/OR/height (mm)	21.5(23[a])/54/208.8				64/75/324			
The thickness of REBCO (μm)	95 $\pm$ 5 Super power			90$\pm$10 SSTC	130 $\pm$ 15 SuNAM			
DP Type (m)	4 mm	4 mm	4 mm * 2	4 mm	4 mm	6 mm	7 mm	8 mm
Piece length (m)	~162	~156	~80	~130	~75	~75	~75	~75
Turns per DP	680	640	330	580	166	130	160	148
DP height (mm)	8.7	8.7	8.7	8.7	8.7	12.7	14.7	16.7
DP quantity	16	2	4	2	26	2	2	2
J_e (A/mm^2)	334.6	334.6	167.3	281.3	246.5	170.6	147.9	130.5
I_o (A)	137							
Peak hoop stress (MPa)	515				308			
B_r (T)	4.18				3.90			
B_z (T)	12.48				2.52			
Conductor length (m)	~3900				~2500			

[a] Notch coil.

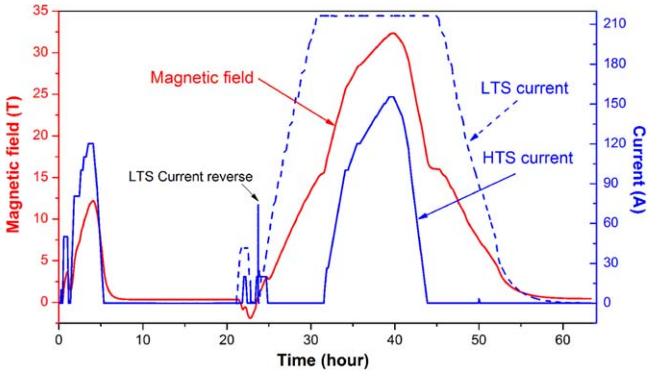

Figure 2. Test of the REBCO insert under 15 T background magnetic field at 4.2 K.

insert can be seen in table 1. There are eight types of DPs for the REBCO insert, the arrangement of these DPs is shown in figure 1. The designed operation current for the REBCO insert is 137 A, at which it can generate 15 T field under 15 T background field. REBCO Coil 1 contributes 12.48 T for the center field, while REBCO Coil 2 contributes 2.52 T.

3. Results

The REBCO insert was then tested in a 15 T LTS magnet in liquid helium bath. First, the REBCO was excited to generate a central field of 12 T to check whether the test system was healthy and then was discharged, as shown in the peak between 2 and 6 h in figure 2. The primary excitation of the LTS magnet showed that the direction of the generated magnetic field was in the negative direction of the magnetic field generated by HTS insert. Hence the current direction of the LTS magnet was inversed, as pointed as 'LTS current reverse'. When the center field reached 30 T, the terminal voltage of the REBCO insert was quite low, which indicated the insert was quite stable and had much operation margin to go. Then the current of the REBCO insert was excited to 155 A and maintained for half an hour, and the center magnetic field finally reached 32.35 T.

Based on the calculation results, the peak hoop stress in the REBCO coil 1 reached 610 MPa, in the middle plane of the innermost layer in the REBCO coil 1. The peak hoop stress in the outer REBCO coil reached to 350 MPa.

The maximum engineering current density, also the engineering current density for most DPs in the inner REBCO coil, was 378.2 A mm^{-2}. The peak perpendicular fields in the inner and outer REBCO coils, all located at the bottom of the coils, increased to 4.6 T and 4.1 T, respectively. For the generated 17.35 T center field, the inner coil contributed 14.43 T, and it was 2.92 T for the outer REBCO coil.

Since the test took too much time and rapid excitation speed resulted in massive consumption of liquid helium, the REBCO insert was then discharged in case of running out of liquid helium, as shown in figure 2. No quench happened during the test, which showed the REBCO insert functions well under such a high magnetic field and hoop stress. The details of the magnet will be analyzed and reported soon later.

4. Discussion

The achieved 32.35 T center field by the all-superconducting magnet is currently the world record dc magnetic field ever achieved by all-superconducting magnets. Thanks to the NI technology, the highest current density of the REBCO insert can reach 378.2 A mm^{-2}, which brings more technical feasibility to achieve a 32.35 T center field with a 15T-φ160 LTS magnet. The calculation showed that the peak hoop stress in the insert increased amazingly up to 610 MPa, which was a big challenge for the coated conductors since the allowable tensile stress is only around 650 MPa. The most vulnerable region is the DP–DP splice joints, which should be adequately protected. There are two main reasons account for this. First, the tremendous hoop stress appears as the shear stress in the splice joint region, whereas the allowable shear stress for coated conductors is only around dozens of MPa, far smaller than the actual value. Hence, high strength overbending was employed to ease the shear stress problem. The other reason is that the enormous axial compressive stress due to the Lorenz force will compress the DPs, so folds on the conductors which electrically connect two adjacent DPs will damage the splice joints permanently. To deal with this problem, proper axial pretention devices were fabricated to compress the DPs before soldering the splice joints, to make sure the relative displacements between DPs within a controllable range during the excitation process.

The main disadvantage of the NI coils is the large unbalance force in case of a quench. High strength supporting system was fabricated for the REBCO insert since there was no quench during the test, we cannot evaluate the performance of the supporting system yet.

Another disadvantage of the NI coils is the long charge time, even for the LTS magnet. The change time from 0 to 32.35 T is around 16 h, which is unacceptable for a condensed matter physics magnet, even though the magnetic field strength and cold bore size meet the requirements of the SECUF project. While for NMR application, the fields usually hold for years, the finished 32.35 T magnet with a cold bore of 35 mm could be a better option. With the increased signal strength and improved resolution, this magnet can provide a brand-new research platform, which is of considerable significance to the development of basic science and the development and application of new technologies and materials.

5. Conclusion

In this paper, we successfully fabricated an all-superconducting magnet with 15 T LTS outsert coil and two NI REBCO HTS insert coils. The current grading method was used to fabricate the REBCO magnet, so as to increase the overall operating margin of the REBCO coils. To solve the mechanical problem—Achilles' Heel of REBCO coil, unique supporting structures were designed to ease the stress concentration problem in the REBCO magnet. Finally, a world record center field of 32.35 T was obtained without a quench. With a cold bore of Φ35 mm, this all-superconducting magnet can be directly used as an NMR user magnet.

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