A Homogeneous Superconducting Magnet System for EBIT

Jiawu Zhu, Yong Ren, Futang Wang, Wenge Chen, and Zhiyou Chen

***Abstract*—A homogeneous magnetic-field superconducting magnet with a room-temperature bore of 75 mm and a central field of 4.5 T was designed, manufactured, and tested. As a result of magnetic-field homogeneity considerations, the magnet is composed of a pair of split coils. Both coils are connected in series and charged with a single power supply. A bobbin with TA2 Ti alloy material was employed for reducing the effect of material permeability. The magnetic-field homogeneity is better than ±200 ppm from −10 to 10 mm in the axial direction. The magnet can be operated in persistent mode with a superconducting switch. In this paper, the magnet design, manufacture, mechanical behavior analysis, and the test results of the magnet are presented.**

***Index Terms*—Electron beam ion trap (EBIT), magnetic-field homogeneity, mechanical behavior analysis, superconducting magnet.**

I. INTRODUCTION

SUPERCONDUCTING magnets with high magnetic-field homogeneity and zero liquid helium boil-off are of increasing interest in various applications, including magnetic resonance imaging, microwave applications, electron beam ion trap (EBIT) devices, etc. [1]–[3]. The EBIT is a device that produces, traps, and excites very charged ions by means of a high-current-density electron beam [4]. The electron beam is magnetically compressed by a high magnetic field with high homogeneity from a pair of split coils. We have developed a 4.5-T NbTi superconducting magnet with a room-temperature bore of 75 mm and a magnetic-field homogeneity that is better than ±200 ppm from −10 to 10 mm in the axial direction for an EBIT cooled by liquid helium at an operating temperature of 4.2 K. This paper presents the magnet design, manufacture, mechanical behavior analysis, and the test results.

II. MAGNET DESIGN AND FABRICATION

The superconducting magnet consists of a pair of split coils in order to improve the magnetic-field homogeneity. The magnet can generate a central magnetic field of 4.5 T at an operating current of 55 A. The maximum magnetic field of the superconducting coils is 5.592 T located at the inner surface of the first coil with a displacement of 37 mm from the midplane, as shown in Fig. 1. The total inductance of the magnet is 18.5 H, and the stored magnetic energy is 27.94 kJ at a rated current of 55 A. A bobbin made of TA2 titanium alloy is employed. The magnet has a magnetic homogeneous region with an axial length of 20 mm. The homogeneity of the magnetic field is better than ±200 ppm. The multifilament NbTi superconducting wire with a diameter of 0.538 mm was adopted. Table I lists the main parameters of the superconducting magnet. Fig. 2 shows the load lines of the two superconducting coils. Fig. 3 shows the layout of the superconducting coils. The NbTi superconducting magnet was impregnated with a filling material of paraffin wax to prevent the turns from moving during operation. Both coils are connected in series and charged with a single power supply for easy operation.

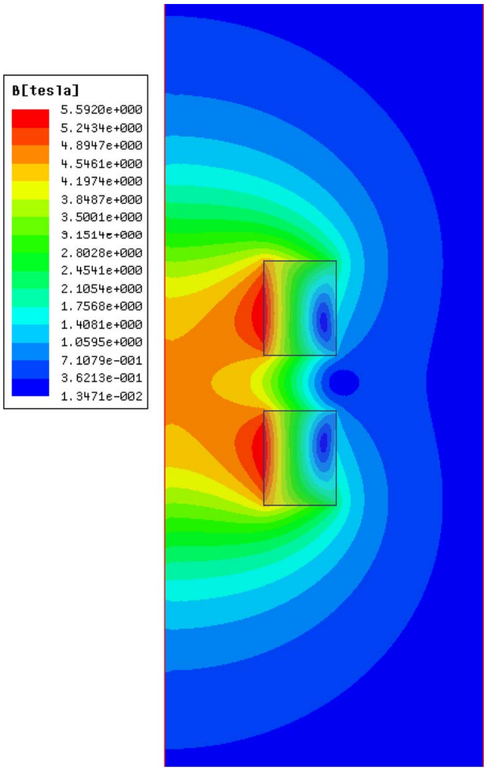

Fig. 1. Magnetic-field distribution of the superconducting magnet.

A pair of Bi-2223 high-temperature-superconducting current leads was employed to reduce the heat leak. The heat loss of the current leads is less than 0.1 W at a rated current of 55 A. The recondensing magnet cryostat is designed to be cooled by a two-stage Gifford–McMahon cryocooler with a cooling

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TABLE I
MAIN PARAMETERS OF THE SUPERCONDUCTING MAGNET

		S1 coil	S2 coil
Strand		NbTi	
Strand diameter	mm	0.538	
Cu/Sc ratio		1.3	
Twist pitch	mm	42 ±10	
Insulator		Formvar	
Inner diameter	mm	110	110
Outer diameter	mm	192	192
Mid-plane	mm	41.2	-41.2
Height	mm	52.3	52.3
Turns		7376	7389
Operating current	A	55	
Inductance	H	18.5	
Stored energy	kJ	27.94	
Central field	T	4.57	

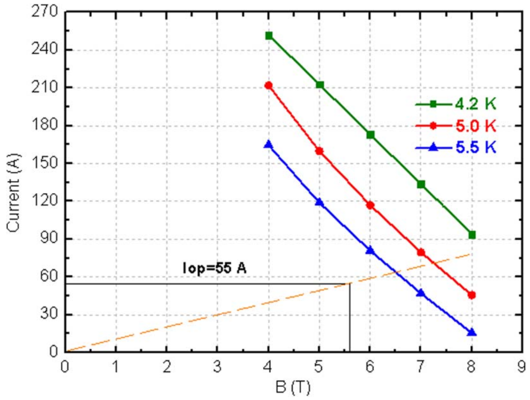

Fig. 2. Load lines of the superconducting magnet.

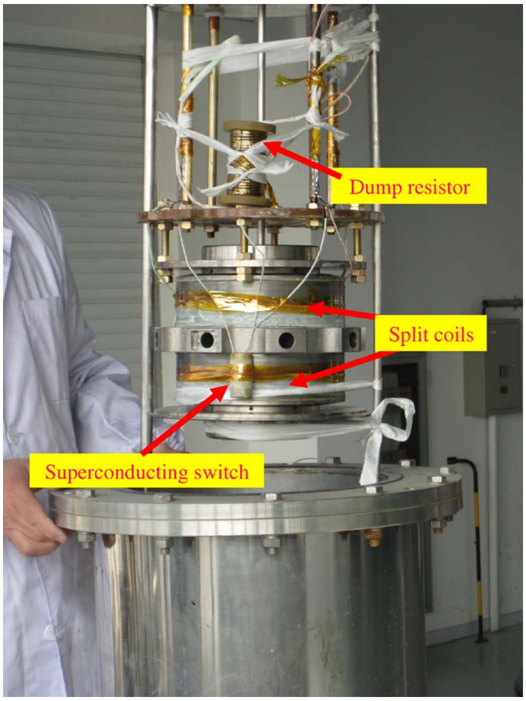

Fig. 3. Layout of the superconducting magnet for the EBIT.

capacity of 1.5 W at 4.2 K (45 W at 50 K). The evaporated helium was cooled by the second stage of the cryocooler, and the radiation thermal shield and the relevant support structure were cooled by the first stage of the cryocooler.

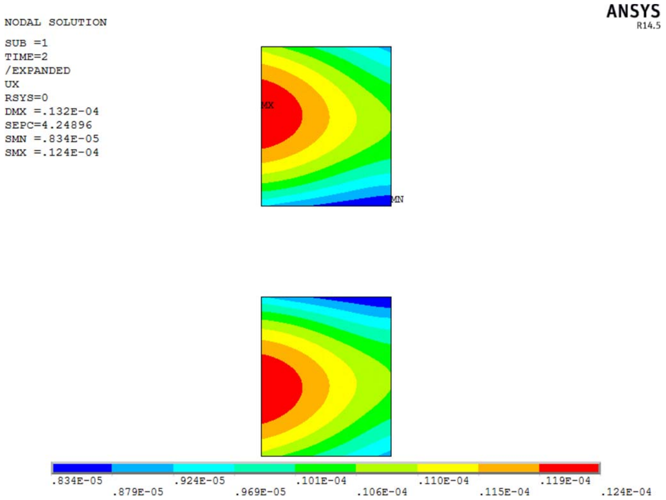

Fig. 4. Radial displacement of the superconducting magnet during excitation (without pretension and reinforcement).

In a persistent-mode superconducting magnet system, a switch with NbTi/CuNi and MnCu wires is generally used [5]. The self-inductance of the persistent switch is approximately zero by bifilar winding the wires on a bobbin. To reach the desired magnetic field, the superconducting switch was first driven into the normal state by a heater. Once the rated magnetic field is reached, the current will be introduced into persistent mode with the switch heater off.

Quench protection of the superconducting magnet is an important issue during a quench in order to avoid excessive heating or the terminal voltage. The superconducting coils are protected by subdividing them into two sections with a dump resistor and diode protection circuits.

III. MECHANICAL BEHAVIOR ANALYSIS

Premature quench of a NbTi compact superconducting magnet is often caused by the mechanical disturbance results from the electromagnetic force [6], [7]. Therefore, it is important to evaluate the mechanical behavior of the superconducting magnet during excitation. A large attraction force of 59.7 kN in the axial direction exists between two split coils at an operating current of 55 A.

A 2-D nonlinear finite-element model with ANSYS was used to analyze the mechanical behavior of the superconducting magnet [8]. Fig. 4 shows the radial displacement of the superconducting magnet during excitation (without pretension and reinforcement). The analysis results show that there is not always compressive contact between the innermost layer and the bobbin. To reduce the mechanical disturbance results from the Lorentz force, the TA2 wires were first used to reinforce the superconducting coils. However, the superconducting coil can be only charged with 36 A. The mechanical strength of the TA2 wires is less than that of the steel wires. Then, the TA2 wires were replaced with the stainless steel wires. Fig. 5 shows the hoop stress, deformation, and strain distribution of the superconducting coils when the superconducting magnet is ramping up to the rated field. The calculated results indicated that the superconducting coil is under compression during

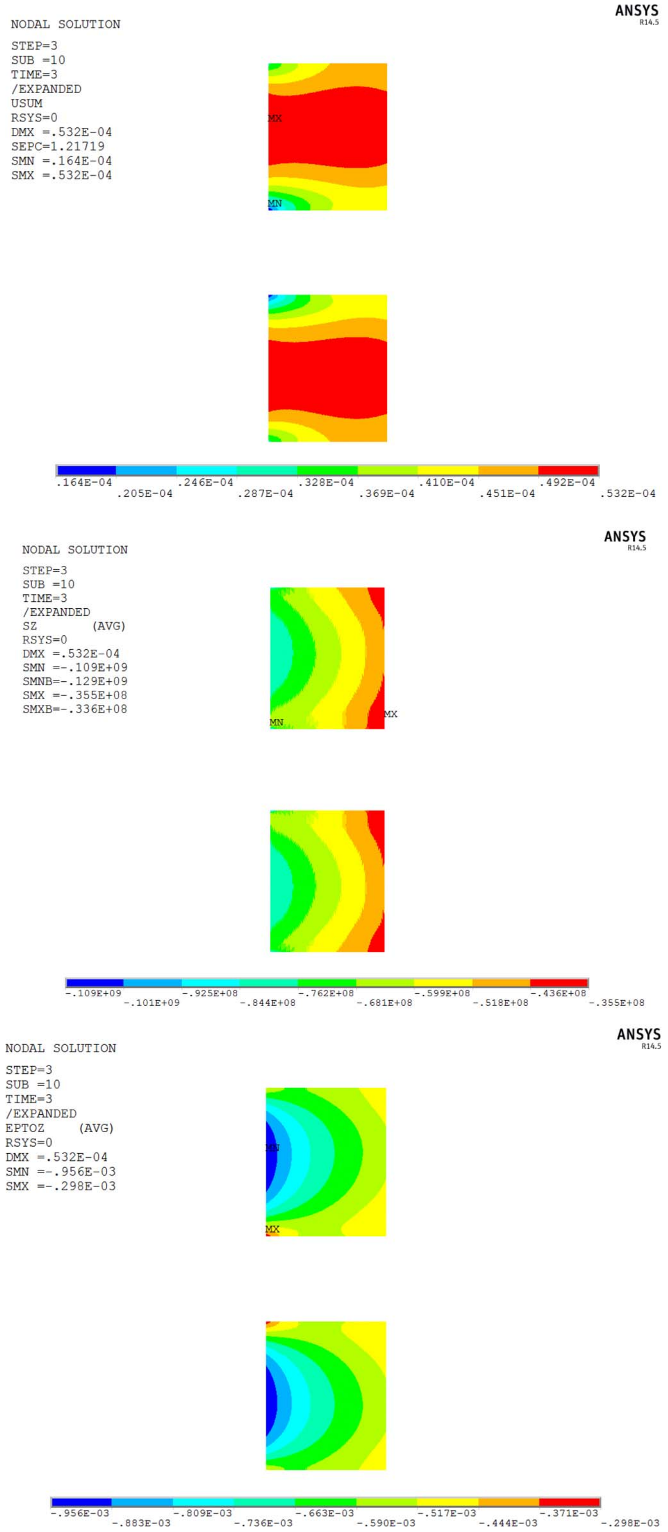

Fig. 5. Deformation, stress, and strain distribution of the superconducting magnet during excitation.

excitation. The maximum deformation and the hoop stress of the superconducting coils are about 0.525 mm and 108 MPa, respectively. Our calculated results also show that the superconducting coils are always closely in contact with the bobbin during excitation conditions.

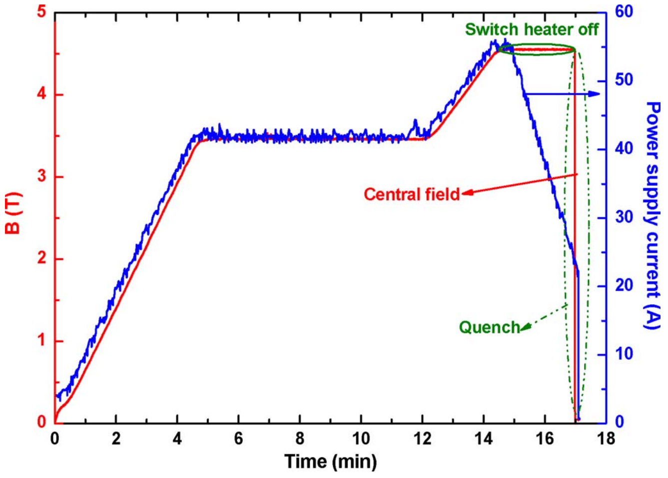

Fig. 6. Dependence of the central magnetic field and the power supply current as a function of time.

IV. EXPERIMENTAL RESULTS

After completing the winding of the superconducting coils, the superconducting coils were immersed in liquid helium to evaluate the superconducting performance of the coils, as shown in Fig. 3. A 150-A 6-V dc power supply was employed for the magnet performance tests.

In the first design stage, the TA2 wires were used to reinforce the superconducting coils. Both coils were independently tested to evaluate their performance. Each coil can be charged with 5 T without any quench. However, the superconducting magnet can be only charged with 36 A (i.e., 3 T) when both coils are connected in series, as suggested in Section III. The premature quench of the superconducting magnet may be caused by the strand movement due to the attraction force in the axial direction. Then, we decided to replace the TA2 wires with stainless steel wires to reinforce the structure.

After updating the reinforcement, the superconducting magnet was then retested. The superconducting magnet with the new reinforcement was quenched at 58 A in the first test. The superconducting magnet was successfully ramped up to 4.5 T in the second test. Once the rated field was reached, the current was introduced into persistent mode with the switch heater off. Unfortunately, a quench was triggered by a superconducting switch, as shown in Fig. 6. The persistent current switch was solidified with epoxy resin to resist the electromagnetic force and to reduce the heat leak to the liquid helium.

The third test showed that the superconducting magnet with the new reinforcement can realize a 4.5-T central field. Fig. 7 shows the dependence of the central magnetic field as a function of time. The test results also show that the magnet can realize a static operation with persistent mode at 50 and 55 A, respectively.

The magnetic-field homogeneity of the superconducting magnet for a special region can be expressed as

$$\Delta B/B = \frac{B}{(B_{\max} + B_{\min})/2} - 1 \qquad (1)$$

where $B_{\max}$ and $B_{\min}$ are the maximum magnetic field and the minimum magnetic field, respectively, for a special region. Fig. 8 shows the magnetic-field homogeneity along the axial length for the calculation and experimental results. The field

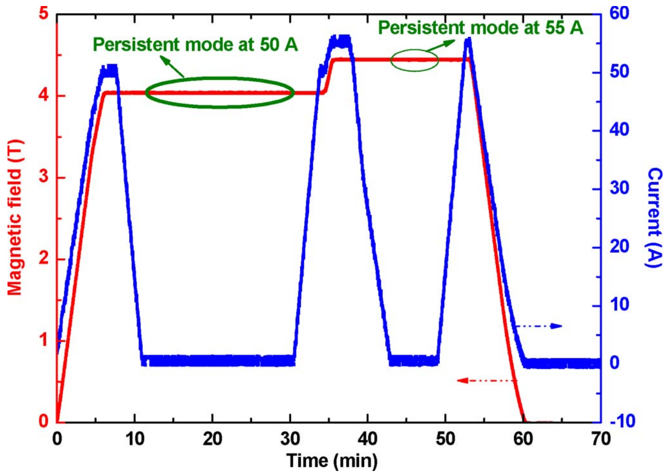

Fig. 7. Dependence of the central magnetic field and the current as a function of time.

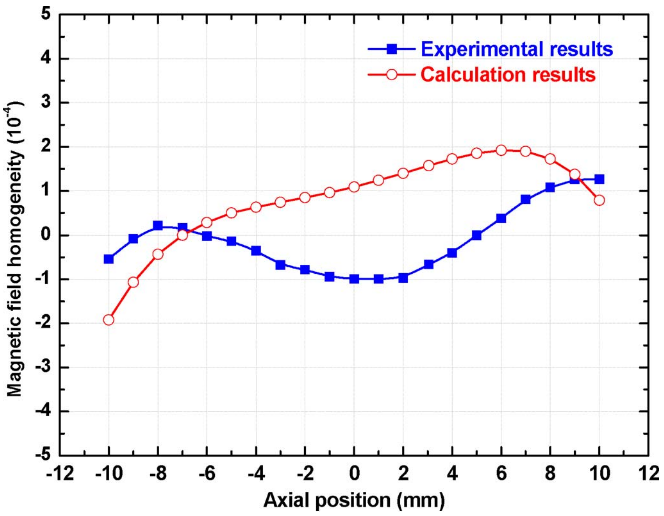

Fig. 8. Magnetic-field homogeneity distribution along the axial length.

homogeneity measured satisfies the requirements for the EBIT. The difference on the field homogeneity between the calculation results and the experiment results may be caused by an inaccurate position of the Hall probe in the magnet bore.

V. CONCLUSION

A 4.5-T superconducting magnet with a homogeneous region of 20 mm in axial length was designed and constructed for EBIT application. The superconducting magnet was impregnated with a filling material of paraffin wax to prevent the turns from moving during operation. Large Lorentz force exists in the axial and radial directions when the magnet is charged to the full operational current. The reinforcement structure of the superconducting magnet is required. Two reinforcement materials of steel and TA2 wires were used. The mechanical strength of the TA2 wires is less than that of the steel wires. Therefore, the prestress exerted on the reinforcement material of the TA2 wires is less than that of the steel wires. The first design with TA2-wire reinforcement can be only charged with 36 A due to the attraction force in the axial direction. By modifying the reinforcement with the stainless steel wires, the superconducting magnet can reach a 4.5-T central magnetic field. The magnetic-field homogeneity of the magnet satisfies the requirements for EBIT application. The detailed finite-element analysis was used to predict the performance of the magnet. The performance test of the zero liquid helium boil-off will be performed in the future.

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