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A Small 1.5 T Persistent Current Operating Test Magnet Using MgB_2 Wire with High j_c Joints

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***Abstract*—Persistent current (PC) operating magnet with bore diameter of about 32 mm was design and developed based on multi- and mono- filament MgB_2 wires. The magnet was in a multi- solenoid structure. One pilot coil was wound and joints were fabricated at both ends, connecting it to a superconducting switch for PC operation tests. The magnet was proposed to demonstrate the high field and high temperature applications at different temperatures. Numerical and experimental results showed a promising future of MgB_2 wires in low cost magnetic resonance imaging (MRI) systems and high field scientific magnets.**

***Index Terms*—joints; MgB_2; magnet; PC operation.**

I. INTRODUCTION

CRITICAL current at high magnetic field was one of the key properties in a practical superconductor. In the past years, the current carrying ability of MgB_2 wire was significantly enhanced via doping and improving the fabrication techniques. Large scale applications, such as MRI systems and high field insert magnets were developed based on the industrialized MgB_2 wire [1 - 8]. Commonly, for a small magnet, the working current was decided by the critical current at the maximum field point. In a comparatively large magnet system, it was possible to divide the magnet into several parts, and decide the working current separately according to the superconductor properties and field distributions. In a PC mode operating magnet, the field and temperature effects on the joints and the switches were also important. Encouraged by the successful attempts of jointing MgB_2 wires using a method in analogy to the powder in the tube (PIT) approaches in wire fabricating [9, 10], a multi-solenoid structured magnet with superconducting joints and switches was designed in this work. Here, two types of MgB_2 wires were used for generating the background field in comparatively large bores and for getting comparatively high field at the center, respectively. Both liquid Helium and conduction cooling conditions were considered in the design and discussions of the magnet. Using a "wind and react" method, pilot coils were prepared and joints were built to form a closed circuit for preliminary tests of PC mode operation.

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II. MATERIAL PROPERTIES AND PREPARATION OF THE JOINTS

The descriptions of the wires used in this work, labelled A to D, were listed in Table 1. Type A wire was "ex-situ" fabricated by Columbus Superconductors Spa. Italy [7], and type B wire was "in-situ" fabricated by Y. W. Ma's group [11]. Wires C and D were specially designed jointers with round and rectangular cross sections, respectively.

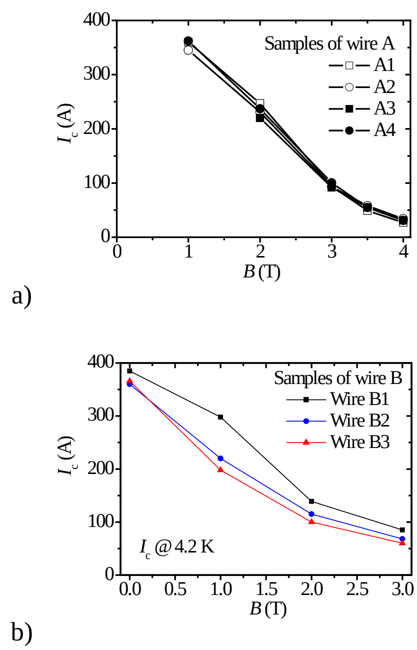

Fig. 1. I_c dependences on the magnetic field in wire A (a) and B (b).

The dependences of transport I_c on the field and temperature in wires A and B were investigated using a typical "four probe" electrical measurement method with the engineering criteria of I_c, at which the voltage across the length of the sample reached 1 μV/cm. The field effect in wire A and B measured at 4.2 K in liquid Helium was shown in Fig. 1. From the results, I_c in wire A was about 350 A at 4.2 K and 1 T, while at 2 T and 3 T, I_c dropped to about 210 A and about 100 A, respectively. Similar results were observed in wire B with comparatively large scattering as shown in Fig. 1b. Tentatively, the scattering was attributed to the fluctuations in pulling and sintering processes.

Critical currents at 20 K and self field in wires A and B were measured in both Helium gas and conduction cooled conditions. From the results, I_c (20 K, self field) in wire A was about 240 A, while in wire B was about 230 A. According to the field dependences of I_c measured at 4.2 K, I_c (20 K, 1 T) and I_c (20 K, 2 T) in wire A was estimated to be about 170 A and about 100 A, respectively, while in wire B, I_c (20 K, 1 T) and I_c (20 K, 2 T) was estimated to be about 110 A and 80 A, respectively.

TABLE I. DESCRIPTIONS OF THE WIRES USED

Label	Cross section (mm^2)	Insulated size (mm^2)	Core type
A	3.65 x 0.65	3.89 x 1.15	Reacted
B	ϕ0.8	ϕ1.1	Not reacted
C	ϕ1.6	ϕ1.9	Jointer round
D	6.50 x 2.88	6.74 x 3.36	Jointer rectangular

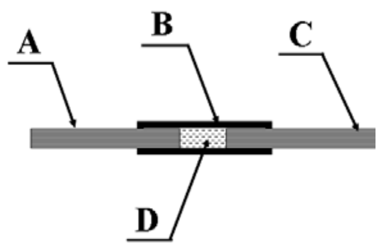

Fig. 2. Schematic of the jointing: A and C, wires to be joined, B, jointer, D, Mg and B powder.

Superconducting joints were made in the wires with the same cross sections using the short jointer wires, labelled C and D in Table 1 as the juncture. Fig. 2 was the schematic of the jointing method. Firstly, powders of Mg and B with the atom ratio of Mg : B = 1 : 2 were packed into the middle part of the jointer, then the wires to be joined, whose sheath metal were peeled off for about 5 mm long, were inserted into the holes in the jointer from the both ends. Afterwards, the joint was compressed with a radial pressure of about 0.6 GPa from the around to form a firm unity and then sintered in an Argon protected furnace for about 1 hour at a temperature of about 1023 K. For the "wind and react" PC operating coils, the joints, the switch and the coil were sintered simultaneously. This was beneficial to the integrity of the joint and consequently to I_c and its field and temperature performance. Besides, the "wind and react" approach was also beneficial to overcoming the cracks and damages in the "in-situ" prepared wires caused by bending and winding in the coil making processes. Thus, a coil of less than 30 mm in diameter could be fabricated using the "in-situ" wires without significantly losing the critical current.

To confirm the feasibility of jointing the "in-situ" and the "ex-situ" wires and forming a PC operating magnet using the method above, joints of short wire samples were fabricated and sintered in advance. The field and temperature dependences of the current carrying capacities in the joints, denoted by the ratio k of the current at which the measured electrical field E across the length of the sample reached 1 μV/cm vs. the virgin I_c in the samples to be jointed, were measured in liquid Helium/Helium gas and conduction cooling conditions.

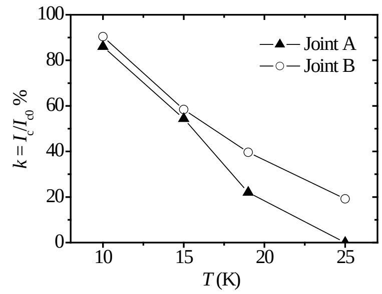

Fig. 3. Temperature dependence of k in the joints at self field.

Fig. 3 showed the experimental results of k in the joints of wire A and B measured at variable temperature and self field. The result demonstrated at comparatively low temperatures, k was nearly 1 in both wires, while was about 37 % for wire B and about 18% for wire A at about 20 K.

On the other hand, possibly because of the comparatively low density and consequently poor connectivity of the granular superconductors, and/or the micro cracks and poor flux pinning conditions in the joints, k dropped quickly to nearly zero with the field rising up to over 1 T at both 4.2 K and 20 K.

Nevertheless, joints and switches were usually installed at the low field part in the magnets, therefore it was still possible to design a feasible PC operating magnet with the "wind and react" prepared coils, joints and switches.

III. DESIGN AND ANALYSIS OF THE MAGNET

Attempting to build and operate an MgB_2 magnet working in the PC mode and generating comparatively high fields, coils, switches and joints made of MgB_2 wires were designed and the parameters of the multi-solenoid structured magnet were listed in Table 2.

TABLE II. DESIGN PARAMETERS OF THE TEST MAGNET

No.	Turns	r_2–r_1 /mm	l /mm	Wire, L/m	I_w/A	B_0/T	I_w/A	B_0/T
					at 20K		at 4.2 K	
1	48x8	26-16	52	B, 50.6		0.619	80	0.581
2	48x12	48-34	190	A,148.3	85	0.301	160	0.562
3	68x26	90-60	266	A,832.7		0.618	240	1.752
4	48x1	7.1-6	52	B,2.11	-	-	100	0.112

As listed in Table 2, in a global design concept, the magnet was divided into 3 coils whose centers were at the same point. The central insert coil, labelled as coil 1, was made of wire B via the "wind and react" approach. The bore diameter, $2r_1$, of coil 1 was 32 mm, while the thickness of winding, $r_2 - r_1$, was 10 mm and the length l of coil 1 was 52 mm. For electrical insulation after sintering at about 1023 K, the wire was firstly wrapped by 2 layers of glass fiber cloth. The thickness of the glass fiber cloth was about 0.07 mm, so the diameter of wire B after insulating was about 1.1 mm. According to the dimension parameters, in the frame of coil 1, 48 turns per layer and 8 layers of wire B would be wound with extra insulation of about 0.1 mm in thickness between the layers. The inner bushing coil, labelled as coil 2, and the outer bushing coil, labelled as coil 3, were made of wire A via a common “react and wind” approach. Wire A was also wrapped by glass fiber cloth for insulation. Besides, for reinforcement and improving the heat conductivity of the windings, two extra layers of nylon clothes were wrapped around each layers of the wire with the addition of epoxy : AlN powder mixture in the weight ratio of 3 : 1 during the winding process. Hence, the average width and thickness of wire A after insulating and winding were about 3.89 mm and 1.15 mm, respectively. Therefore, in the frame of coil 2 and coil 3, whose dimensions were (48 – 34) x 190 mm and (90 – 60) x 266 mm, respectively, there would be respectively 48 x 12 and 68 x 26 turns of wire wound.

Finite element method (FEM) tools were adopted to estimate the field generation ability and decide the working current I_w, and the field distribution results were shown in Fig. 4 to 7.

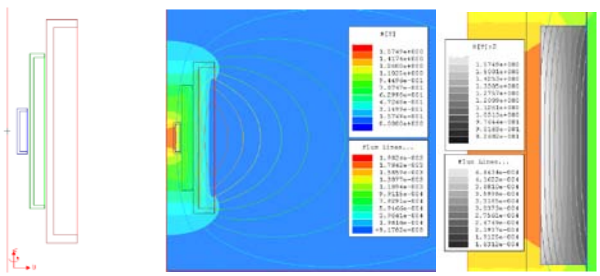
(a) (b) (c)

Fig. 4. a) The model of the test magnet with 3 coils, b) FEM calculated field and flux distribution in the magnet at 85 A working current, c) the field distribution in coil 1.

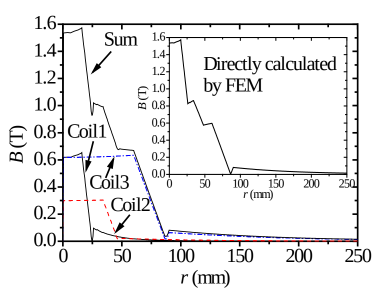

Fig. 5. Estimated field generated by each of the coils at 20 K, and the sum of them, the inset was FEM calculated field distribution along the o-*r* axis.

Fig. 4 and 5 showed the field distribution on the o-*z* surface and along the o-*r* axis from the center at 20 K. According to the field distribution and the field dependences of wires A and B, the working current I_w was designed to be 85 A for each of the coils. This was simple as all the coils could then be series connected, and one PC switch was enough to close the circuit.

From the FEM results, the field at the center of the magnet was about 1.535 T, and the contributions of coil 1, coil 2 and coil 3 were about 0.619 T, 0.301 T and 0.618 T, respectively. The maximum fields at the coils were 1.574 T, 0.862 T and 0.597 T, respectively. It was obvious that I_c in wire B was the limitation of the working current and consequently the field. By supplying the bushing coils with higher working currents, it was possible to enhance the field at the center. However, at 20 K, while the background field contributed by the bushing coils increasing, I_c in wire B dropped quickly, the increase of the background field could only compensate the decrease of the field generated by coil 1, and the sum of the field was not significantly enhanced.

As shown in Fig. 4b, the joints and switches installed at the top of the magnet could work at nearly zero fields. For wire B, the current carrying capability *k* of the joint was about 37%, thus I_c of the joint was about 85 A and enough to carry the working current and form a superconducting close circuit for coil 1. Unfortunately, for wire A, *k* was only about 18% and I_c of the joint was only about 43 A. It was much smaller than the designed working current. Therefore, at 20 K and PC mode, the working current in coils 2 and 3 was limited to 43 A in the best conditions and the field at the center of the nominal 1.5 T magnet was only 1.08 T.

At 4.2 K, however, the critical current of wire B was about 80 A at nearly 3 T, so it was feasible to enhance the field at the center to about 3 T by adjusting the working currents in the bushing coils. The designed working currents in each of the coils at 4.2 K were listed in Table 2. Considering the field effects on the critical current in the inner bushing coil, the working current in it was decided to be 1/3 smaller than that in the outer bushing coil. FEM results shown in Fig. 6 and 7 demonstrated the field of about 2.909 T at the center and the maximum field of about 2.931 T, 2.270 T and 1.735 T in coils 1, 2 and 3, respectively.

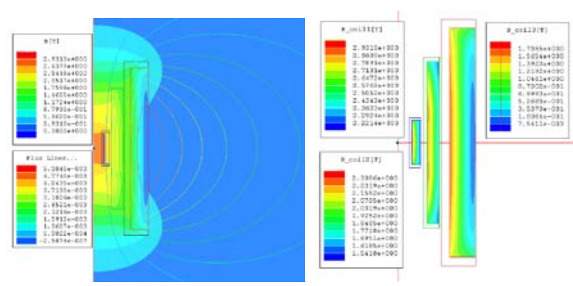
(a) (b)

Fig. 6. a) FEM calculated field and flux distribution in the magnet at 4.2 K with different working currents in different coils, b) the field distribution in coils.

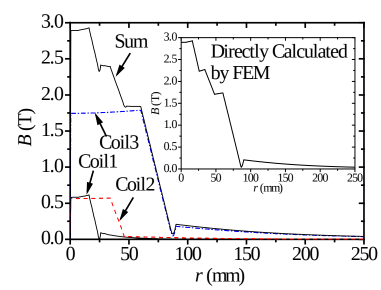

Fig. 7. Estimated field generated by each of the coils at 4.2 K, and the sum of them, the inset was FEM calculated field distribution along the o-*r* axis.

IV. Wind and Preliminary Test

To experimentally demonstrate the feasibility of the design above, the outer bushing coil and the prototypes of the “wind and react” central insert coil were prepared and tested. Due to the fluctuations in the width of the wire and the extra insulation in the practical winding, in total 1754 turns were wound in coil 3 instead of designed 1768. Hence, the field generated by coil 3 at the center was also slightly smaller. At designed 240 A working current, the field contribution of coil 3 at the center of the magnet was about 1.732 T.

The insert coil, labelled as coil 1, was fabricated via "wind and react" process and its properties depended significantly on the conditions of the preparation. Several prototype coils with much fewer turns compared to the design were wound and sintered first for magnetization and PC operation tests. One of the prototypes was labelled as coil 4 and the parameters were listed in Table 2. Fig. 8 showed the photo of two of the prototypes after sintering and wiring.

Fig. 8. Photo of the prototypes of coil 1 after winding and wiring.

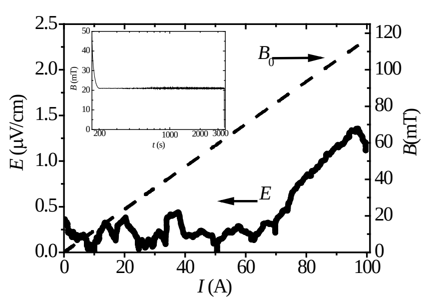

Fig. 9. Load line and *E-I* responses of coil 4, the inset was the one hour field decay test result.

The magnetization load line and the *E-I* responses in coil 4 was shown in Fig. 9. From the load line, the one layer prototype coil with 48 turns of wire B generated about 0.115 T field at the center at 100 A working current, which coincided with the FEM estimation within the error limits. On the other hand, the *E-I* responses showed I_c of this coil was only about 85 A, which was unexpected much smaller than the short sample results of wire B measured at 4.2 K and self field. A tentative explanation to this was the small diameter of only about 12 mm, although in principle the "wind and react" processes could overcome the cracks and damages caused by bending.

The PC mode test was done after magnetizing coil 4 to about 50 A. The circuit was closed by turning off the heater at the switch. The time decay curve of the magnetic field at the center in the following hour was monitored and shown in the inset to Fig. 9. Because the joint and switch were about 10 cm above the liquid Helium and the temperature there was about 15 K, the remaining resistance in the close circuit was large, the captured current quickly dropped to about 17.5 A and the captured field also dropped to about 0.021 T in about 200 s, then became saturated.

In total, the prototype test of the PC mode operation was only partly successful. Although high j_c joints were successfully fabricated with short wire samples, it was still difficult to sinter coils, switches and joints with good quality in one process.

V. CONCLUSION

A 1.5 T magnet using multi- and mono- filament MgB_2 wires was designed. The material properties, especially I_c at variable temperatures and fields were discussed. By lowering the temperature from 20 K to 4.2 K and adjusting the currents in the coils, the field at the center of the magnet could be enhanced to about 2.9 T. Joints connecting the ends of the coils in order to make PC operating close circuits were designed and fabricated. A preliminarily PC operation test was done using one of the prototypes of the insert coil. The results and discussions were referential for the future development of the large scale applications using MgB_2.

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