Published in final edited form as:
IEEE Trans Appl Supercond. 2012 June ; 22(3): . doi:10.1109/TASC.2012.2185472.

MgB_2 for MRI Magnets: Test Coils and Superconducting Joints Results

Dong Keun Park,
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Jiayin Ling,
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Matt Rindfleisch,
Hyper Tech Research Inc., Columbus, OH 43228, USA

John Voccio,
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Seungyong Hahn,
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Juan Bascuñán,
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Michael Tomsic, and
Hyper Tech Research Inc., Columbus, OH 43228, USA

Yukikazu Iwasa
Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract

Among key design and operation issues for MgB_2 relevant to MRI magnets are: uniformity of current-carrying capacity over long lengths (>2 km) of wire; and reliability of a splicing technique. This paper presents experimental results of current-carrying capacities of a small test coil and joints, both made from MgB_2 round wires, multifilament and monofilament (mono), manufactured by Hyper Tech Research, Inc. The test coils were wound with 95-m long unreacted, C (carbon)-doped MgB_2 multifilament wire, sintered at 700°C for 90 min. The critical currents were measured in the 4.2 K–15 K and 0 T–5 T ranges. We have modified our original splicing technique, proven successful with unreacted, un-doped MgB_2 multifilament wire sintered at

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dk_park@mit.edu.

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570°C, and applied it to splice both un-doped and C-doped mono wires sintered at 700°C. Most consistently good results were obtained using the un-doped mono wires. Also presented are results of a small joint-coil-PCS assembly of mono wire, operated in persistent mode at 50 A at >10 K.

Keywords

MgB_2 coil; monofilament MgB_2 wire; MRI magnet; persistent current mode; superconducting joint

I. INTRODUCTION

MAGNESIUM diboride (MgB_2) superconductor offers a promising option for low-field (<2 T) magnets, including MRI applications [1], [2]. With a critical temperature of 39 K MgB_2 can operate at temperatures, unlike Nb-Ti, well above liquid-helium (LHe) temperatures, an important advantage for stability and cryogenic issues. Due to its simple chemical structure and improved manufacturing techniques, MgB_2 wires in over kilometer-lengths are now available [3]. However, to apply MgB_2, to-date untested in magnets such as for MRI that require > 10 km of wire, uniformity of its current-carrying capacity over long lengths, up to ~5 km, must be demonstrated. Another important challenge to develop MgB_2 MRI magnets is to consistently make superconducting joints, essential elements for persistent-current-mode operation.

At the MIT Francis Bitter Magnet Laboratory, we are engaged in a 2-phase project to complete a 0.5-T MgB_2 whole-body MRI magnet [4]. In the current Phase 1 program, the main Coil of this MRI magnet will be completed, comprising four MgB_2 coils, MgB_2 – MgB_2 joints, and MgB_2-based persistent-current-switches (PCS's), all prepared with unreacted MgB_2, manufactured by Hyper Tech Research, Inc. The entire assembly will be later heat-treated. This paper presents experimental results of: 1) current-carrying capacities of test coils; 2) joints of various round MgB_2 wires; and 3) a small coil, equipped with a joint and a PCS, all prepared from a single length of unreacted monofilament (mono) MgB_2 wire.

II. CONDUCTORS

We used two types of unreacted Hyper Tech MgB_2 round wires: C (carbon)-doped multifilament (#2314); and un-doped mono (#2221). Fig. 1 shows the cross sectional views of two round wires of ∅0.83 mm. The filament sizes and total MgB_2 fractions are 54 μm and 8% (#2314) and 0.44 mm and 28% (#2221). Fig. 2 shows J_C(B, 4.2 K) and J_C(B, 4.2 K) plots, supplied by Hyper Tech, of #2314 (squares) and #2221 (circles) wires, heat treated at 700°C for 60 min.

III. TEST COIL RESULTS

A. Experimental Setup for Test Coils

To confirm that Hyper Tech MgB_2 wire has uniform IC (B,T) performance over its "long" length, test coils, wound with 95-m long #2314 wire, were tested. The parameters of both coils are given in Table I. Coils were sintered at 700°C for 90 min., identical with our new joints sintering condition. Fig. 3 shows a schematic drawing of the coil cryogenic system housed in a 280-mm OD cryostat, which is inserted in the bore of a 5-T/300-mm room-temperature bore superconducting magnet which provides field errors <3% within the within the ∅49 mm × 76.2 mm cylindrical volume. Each test coil, enclosed in a copper can, was at a uniform temperature. A heater was wound on the outer surface of a copper can. To achieve adiabatic condition, as shown in Fig. 3, the open space was filled with Styrofoam, which helped to minimize LHe consumption over the operating temperature range 4.2 K–15 K. HTS current leads between the coil chamber and copper current leads further reduced LHe consumption.

B. Results and Analyses

Fig. 4 shows experimental results of one of the test coils: $I_C(B,T)$ plots in the temperature range 4.2 K–15 K and 0 T–5 T. The other coil had defects at the current terminals. Each open symbol is an estimated from the Fig. 2 data for a peak field that includes the coil self field (Table I): it matches well to the measured one (solid). For example, a measured I_C of 205 A at 4.2 K with no external field (solid circle in Fig. 4) is close to 200 A of the Fig. 2 data for a calculated peak self field of 2.34 T in the coil. We may therefore conclude that $I_C(B,T)$ performance is uniform over a length of ~100 m and consistent with that of short samples.

IV. Superconducting Joints

A. Joint Fabrication

We have been modifying our original joint technique which proved successful with unreacted multifilament MgB_2 wires sintered at 570°C for 2400 min [5]. The reasons include: 1) even with unreacted wires, the reaction conditions of joints should be the same with those for coils, 700°C for 90 min., because a coil sintered at 570°C/2400 min. will not have its $I_C(B,T)$ performances as shown in Fig. 5; 2) to achieve consistency; and 3) to make the joint technique applicable to reacted wire, because even if the entire magnet system can be built with unreacted wire, e.g., our 0.5-T MRI magnet, it is still likely that some joints will have to be remade after reaction: a splicing technique should ideally work with reacted wires even if its primary use is for unreacted magnet systems.

The original joint technique, sintering at over 650°C, the Mg melting point, proved unsuccessful, chiefly because of excessive loss of Mg vapor from the joint housing. To succeed with temperatures >650°C, we tried hermetic seals to minimize Mg vapor loss. Fig. 6 shows a modified joining fabrication process (a) and a photograph of a joint (b).

This joint fabrication essentially uses the same original procedure [5], except the last few steps: i) press the stainless steel plug (0.6 GPa–0.8 GPa) to make powder into an *ingot* under an Ar gas atmosphere; ii) press a copper plug to seal the billet top; iii) use ceramic paste to seal the billet bottom holes; iv) sinter the joint at 700°C for 90 min. which gave better results than those sintered at 700°C for 60 min.

B. Results and Analysis

Table II shows a summary of the joint results. I_C was measured by a four-probe method. First, both un-doped and C-doped multifilament wires were joined with the original technique, 570°C/2400 min. Since each Nb-encased Mg+B filament is exposed to Mg+B mixture ingot only at the tip, the total Mg+B/Mg+B contact area in 18-filament wire is quite small. Magnified views inside some splices of 18-filament wires reveal bent and/or broken filaments, probably when the Mg+B powder is compressed against the filaments. These damage-prone fragile filaments may be responsible for inconsistent results of our original splicing technique.

Joints of both C-doped and un-doped wires filled with C-doped powder mixture were non-superconducting even at 4.2 K. Next, using the modified technique, we tried with un-doped mono wires (#2221), sintering the joint at 700°C. The results (Fig. 7) were: $I_C \approx 270$ A (10 K) and 140 A (20 K). For joints with C-doped mono wires the results were: $I_C \approx 100$ A (un-doped powder) and 16 A (C-doped powder) at 10 K. One clear physical difference between C-doped and un-doped powder mixtures is their densities: ~ 0.7 g/cm^3 and ~ 0.3 g/cm^3, respectively. C-doped powder is less dense: it has more voids, which may be filled with air and/or Ar gas, impeding formation of a solid powder ingot. Also, for the same pressure applied to the powder, the less dense powder is deformed more severely. We are still working on splicing C-doped mono wires with un-doped and C-doped powder mixtures.

C. Mono MgB_2 Wire for our 0.5-T MRI Magnet

A consistency (5 successive joints having an average IC of 140 A at 20 K) achieved with un-doped mono wires (#2221) motivates us to consider using mono wire for our 0.5-T MRI magnet—coils, joints, PCS's. Because joints will be placed at low-field (<0.3 T) regions of the magnet, their self-field IC >140 A at <20 K is surely acceptable.

Note that the difference in I_C between #2314 and #2221 is minimal in a field of <2 T. From the data in Figs. 2 and 4, the I_C(B, 15 K) of #2314 is estimated >140 A at 1.5 T, which meets the target operating condition of our 0.5 T MRI magnet, 100 A in the range 10 K– 15 K with a peak field of <1.5 T. Unlike mono Nb-Ti wire (> ∅0.2 mm) which will surely be hampered by flux jumping, mono (up to ∅0.5 mm) MgB_2 wires will be immune from flux-jump-induced instability because of its large enthalpy in the range 10 K–15 K [6]. However, the copper fraction must be increased from zero as in #2221 to a level that keeps a matrix (copper) current density, at operating current, below ~ 930 A / mm^2 for active protection [7].

V. SMALL PERSISTENT-CURRENT-MODE TEST COIL

Using a current-decay technique on a small persistent-mode coil, we have successfully confirmed a good #2221 joint, which terminates the coil, equipped with a PCS. Table III shows parameters of the coil. Fig. 8 shows a photograph of the joint-coil-PCS assembly. A Hall probe, placed in the coil center, monitored the field decay with time. The experimental procedure is as follows. Initially, place the entire assembly into the LHe reservoir of a wide-neck storage dewar. Next, lift the assembly, after energized at 4.2 K, above the liquid level to keep, during persistent-mode operation, the joint at 10.5 K, the coil at 14.4 K, and the PCS at 17.2 K, with a temperature variation of <1% for 30 min. Fig. 9 shows the center field, external current, and coil voltage all vs. time plots. In Regime (a), with the PCS "open" the coil was charged up to 50 A, and in (b) the PCS was closed. In (c) the external current was reduced to zero and the center field dropped by 0.07%, chiefly due to dissipation of magnetic energy stored in the PCS, and the coil subsequently settled down to a persistent current of 49.54 A. The peak field applied to the joint at 50-A operation was negligible, 4 mT. The field was measured for a period of 20 min. From a measured field decay rate, we calculate a total circuit resistance of $<10^{-12}\Omega$, which may be attributed to both the joint resistance and the temperature-dependent Hall measurement error (−0.07%/K). The joint resistance is small enough for an MRI magnet of mono wire MgB_2 to operate in persistent mode. To date we have not been able to increase the coil current above 50 A due to overheating at the current-leads-to-coil-terminals connections.

VI. CONCLUSION

Two important issues for application of MgB_2 to persistent-mode MRI magnets, specifically our 0.5-T whole-body magnet—uniform current-carrying capacities over long length of wire and reliability of a superconducting joint technique—were investigated. Small coils, wound with ~100-m long C-doped multifilament MgB_2 wire, were tested for their $I_C(B,T)$ performance. The measured I_C values matched well with those expected from short-sample values. Modifications made to our original MgB_2 splicing technique have proven that more consistent joints are achievable with unreacted, un-doped mono wires. To date we have consistently produced superconducting joints with mono wires capable of carrying 270 A at 10 K in self field. A small joint-coil-PCS assembly was built with un-doped, mono MgB_2 wire and successfully operated in a persistent-current of 49.54 A at > 10 K.

Acknowledgment

The authors thank the National Institute of Biomedical Imaging and Bioengineering of the NIH for continued support of this project.

This work was supported by the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health, and in part by General Electric Company.

REFERENCES

[1]. Iwasa Y, Larbalestier DC, Okada M, Penco R, Sumption MD, and Xi XX, "A round table discussion on MgB_2 toward a wide market or a niche production? A summary," IEEE Trans. Appl. Supercond, vol. 16, no. 2, pp. 1457–1464, 6 2006.

[2]. Li XH, Du XJ, Qiu M, Ma YW, and Xiao LY, "Design and experimental demonstration of an MgB_2 based 1.5 T MRI test magnet," Physica C, vol. 463–465, pp. 1338–1341, 10 2007.

[3]. Tomsic M, Rindfleisch M, Yue J, McFadden K, and Phillips J, "Overview of MgB_2 superconductor applications," Int. J. Appl. Ceram Technol, vol. 4, pp. 250–259, 6 2007.

[4]. Yao W, Bascuñán J, Hahn S, and Iwasa Y,"MgB_2 coils for MRI applications," IEEE Trans. Appl. Supercond, vol. 20, no. 3, pp. 756–759, 6 2010.

[5]. Yao W, Bascuñán J, Hahn S, and Iwasa Y, "A superconducting joint technique for MgB_2 round wires," IEEE Trans. Appl. Supercond, vol. 19, no. 3, pp. 2261–2264, 6 2009. [PubMed: 20671806]

[6]. Iwasa Y, Case Studies in Superconducting Magnets: Designs and Operational Issues, 2nd ed. : Springer, 2009, pp. 354–355.

[7]. Park DK, Hahn S, Bascuñán J, and Iwasa Y, "Active protection of an MgB_2 test coil," IEEE Trans. Appl. Supercond, vol. 21, no. 3, pp. 2402–2405, 6 2011. [PubMed: 22081754]

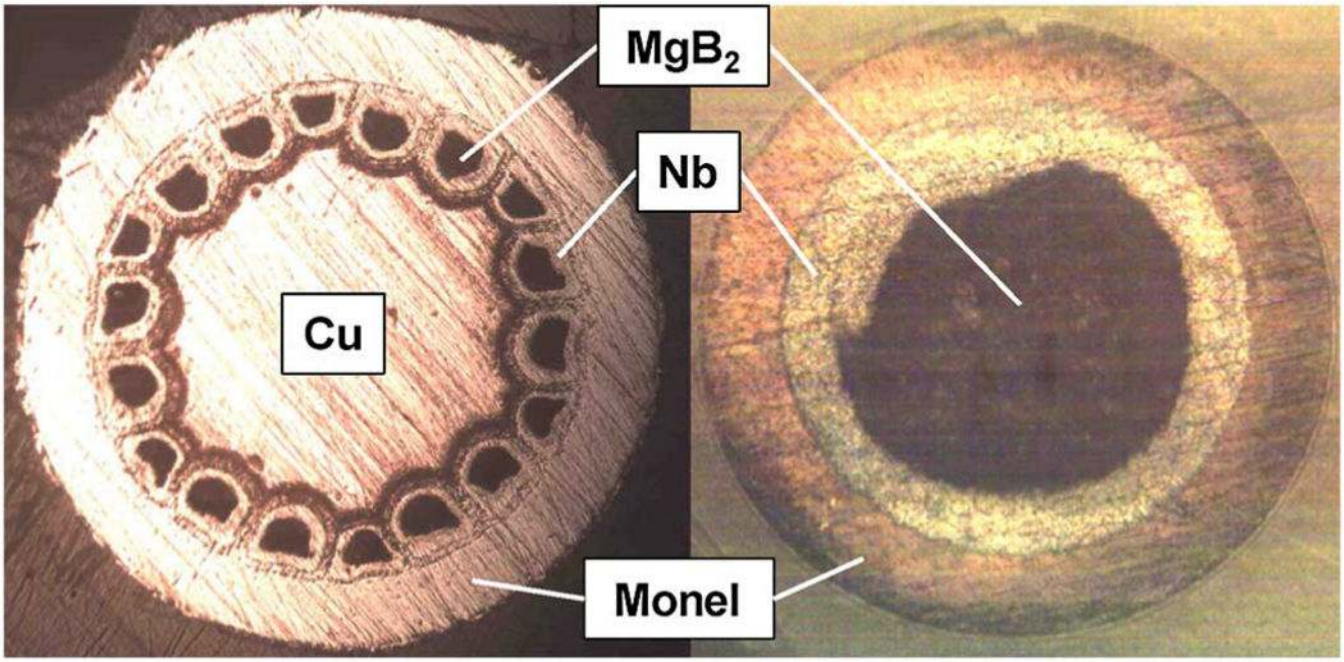

Fig. 1.

Photographs of the cross sections of MgB_2 round wires with key components identified: (left) #2314; (right) #2221.

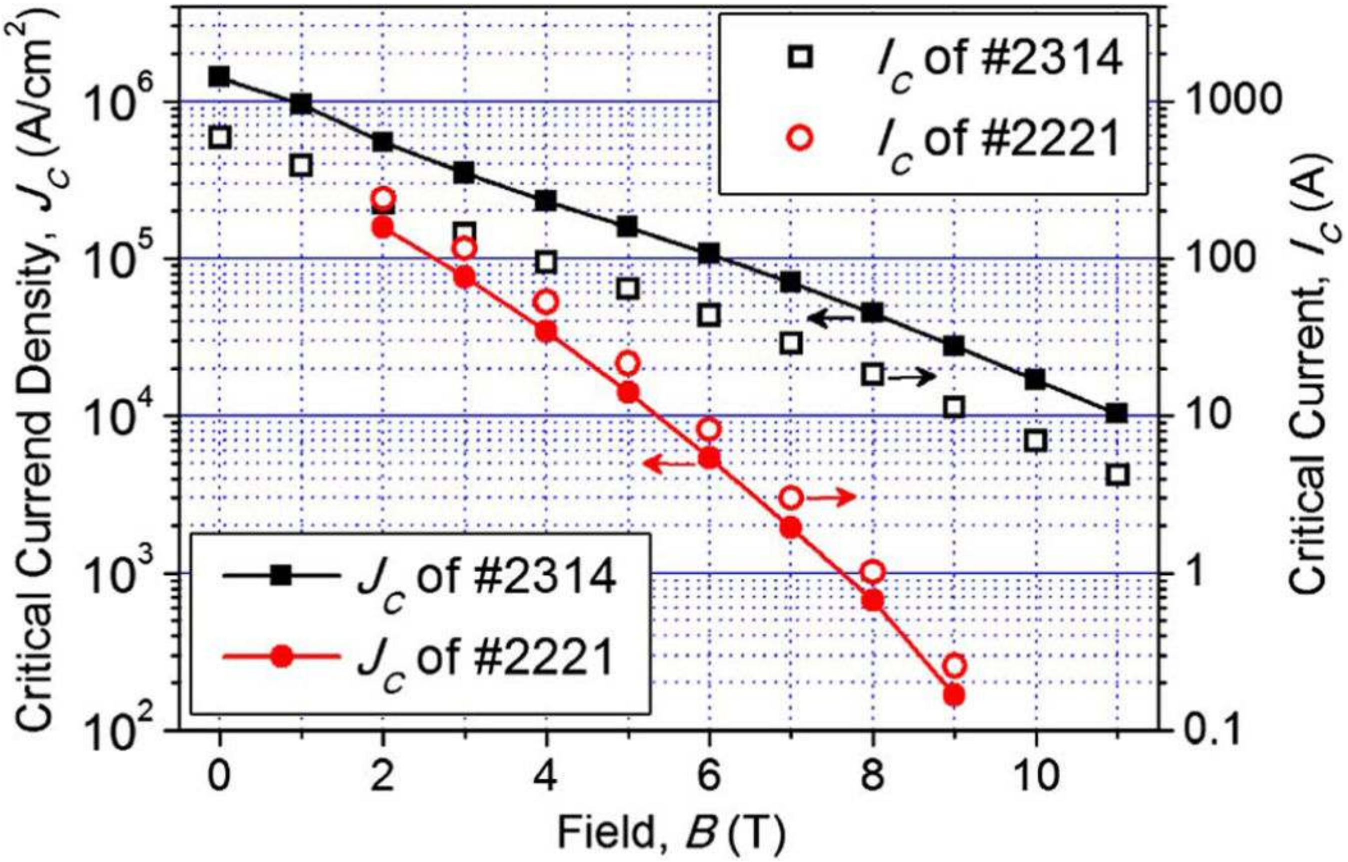

Fig. 2.

$J_C(B)$ and $I_C(B)$ plots of #2314 (multi) and #2221 (mono) wire at 4.2 K, measured by Hyper Tech Research, Inc.

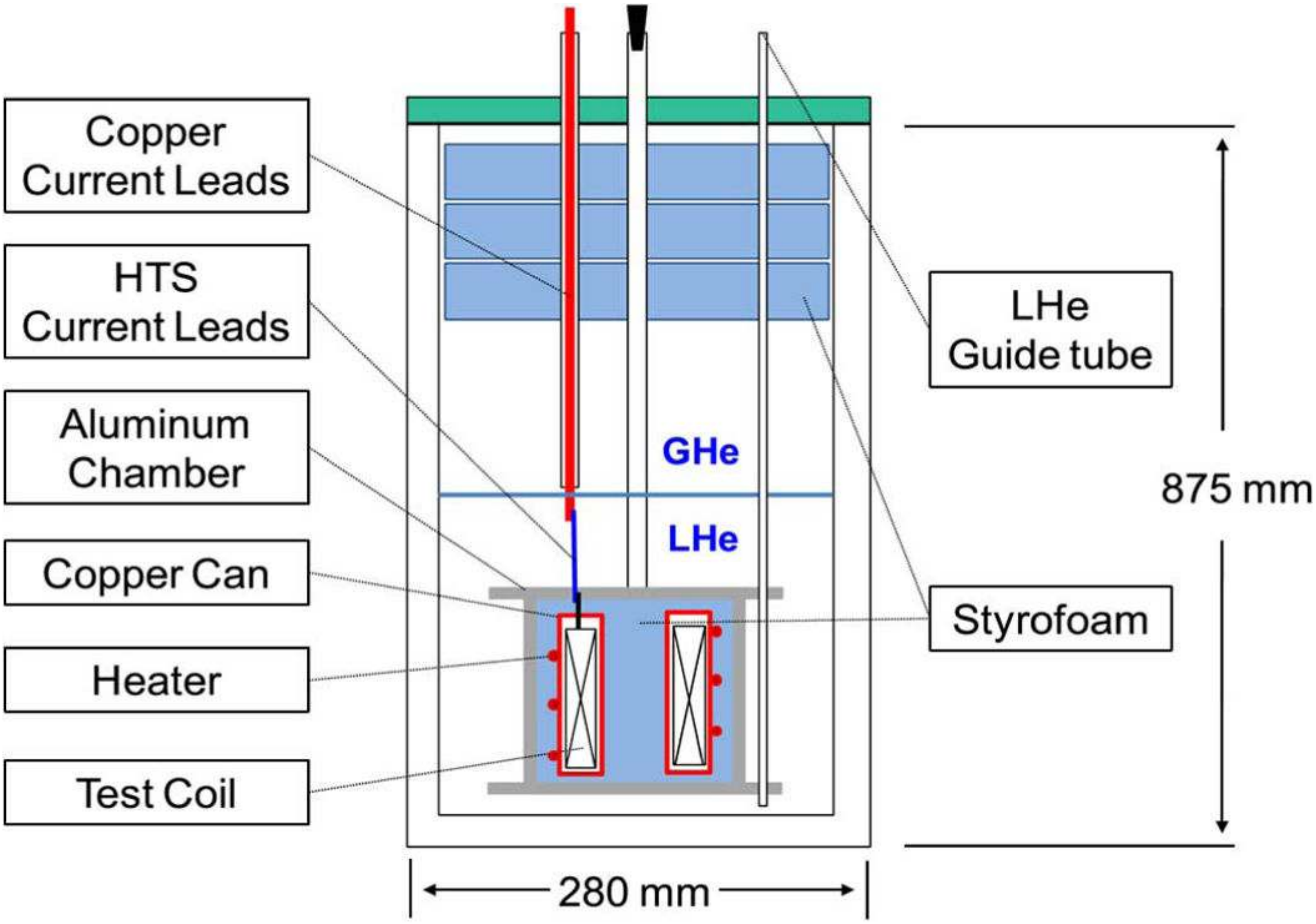

Fig. 3.
Schematic drawing of the test coil cryogenic chamber.

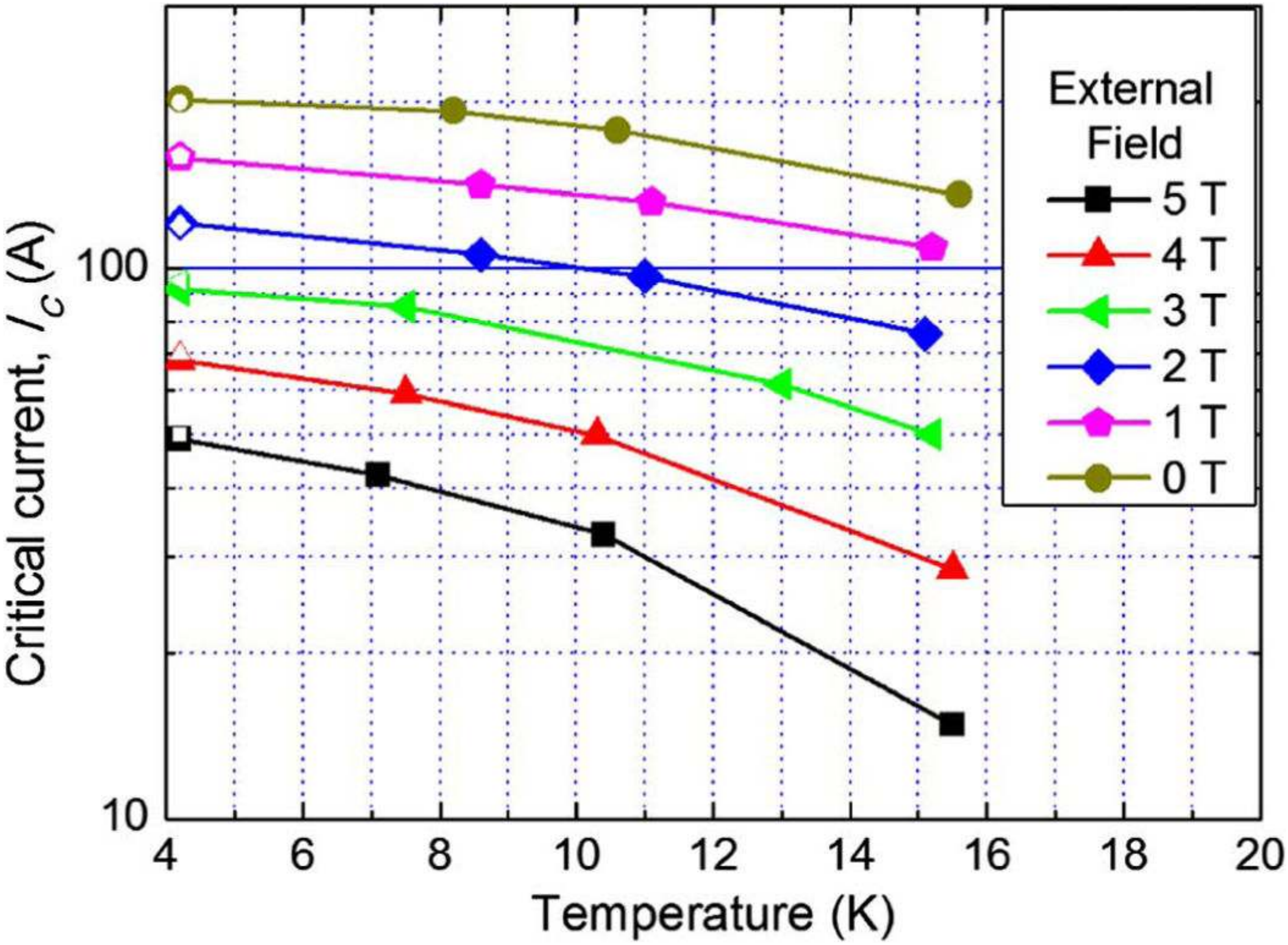

Fig. 4.

Measured $I_C(B,T)$ plots of a test coil. Open symbols at 4.2 K represent the expected coil I_C based on $I_C(B,T)$ plots of short sample shown in Fig. 2.

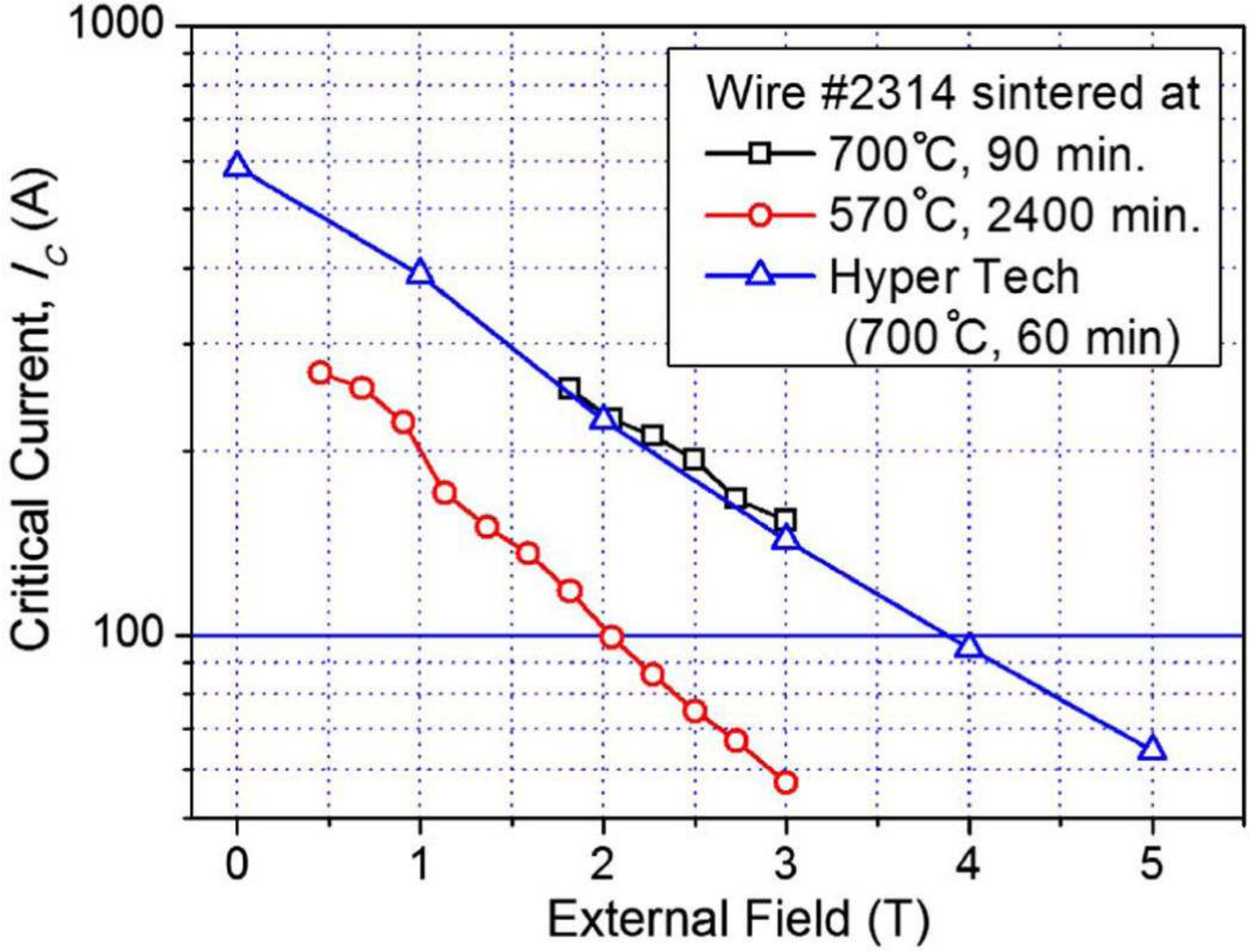

Fig. 5.

I_C and field plots of in-field performance at 4.2 K between #2314 wire short samples sintered at 570°C and 700°C , respectively.

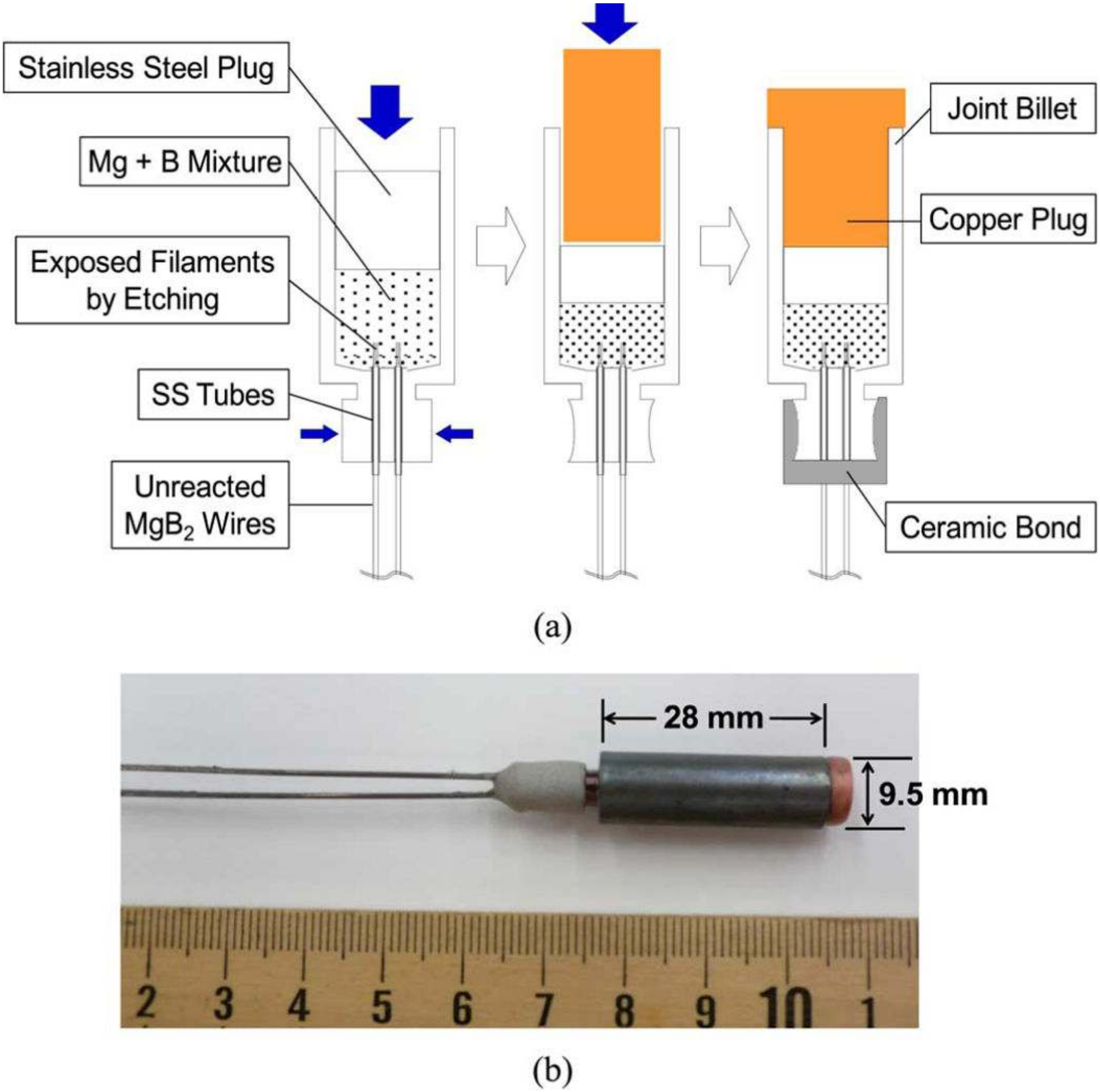

Fig. 6.

Splicing MgB_2 round wires: (a) fabrication process and (b) a photograph.

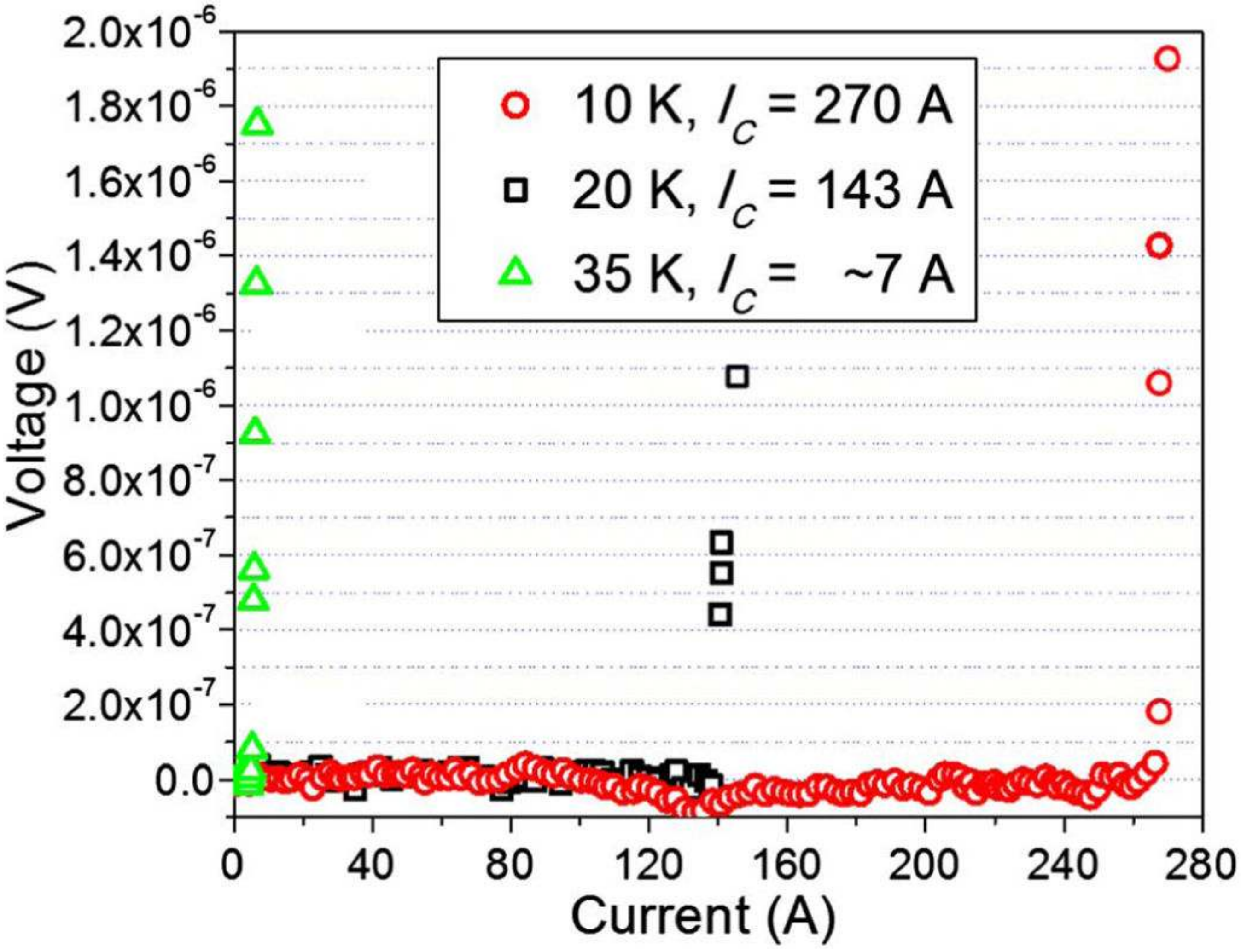

Fig. 7.

I–V curve of a mono wire joint at selected temperatures.

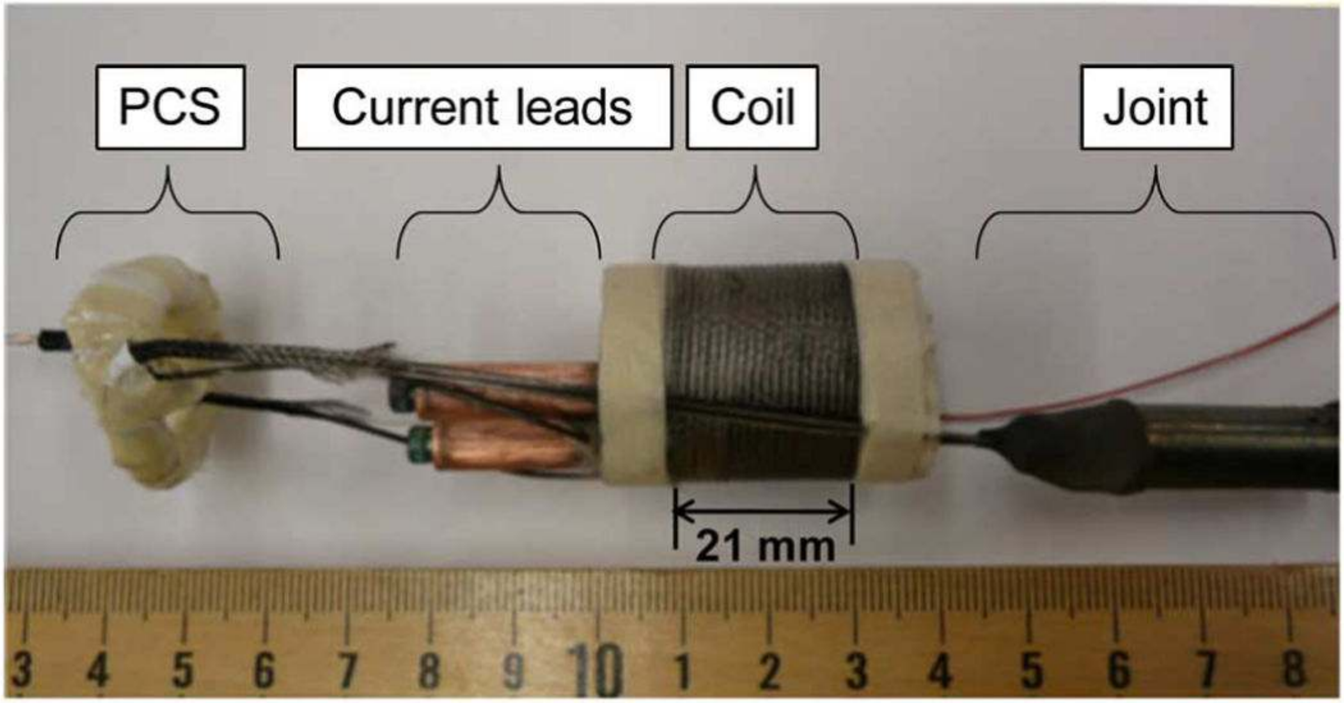

Fig. 8.
Photograph of a joint-coil-PCS assembly.

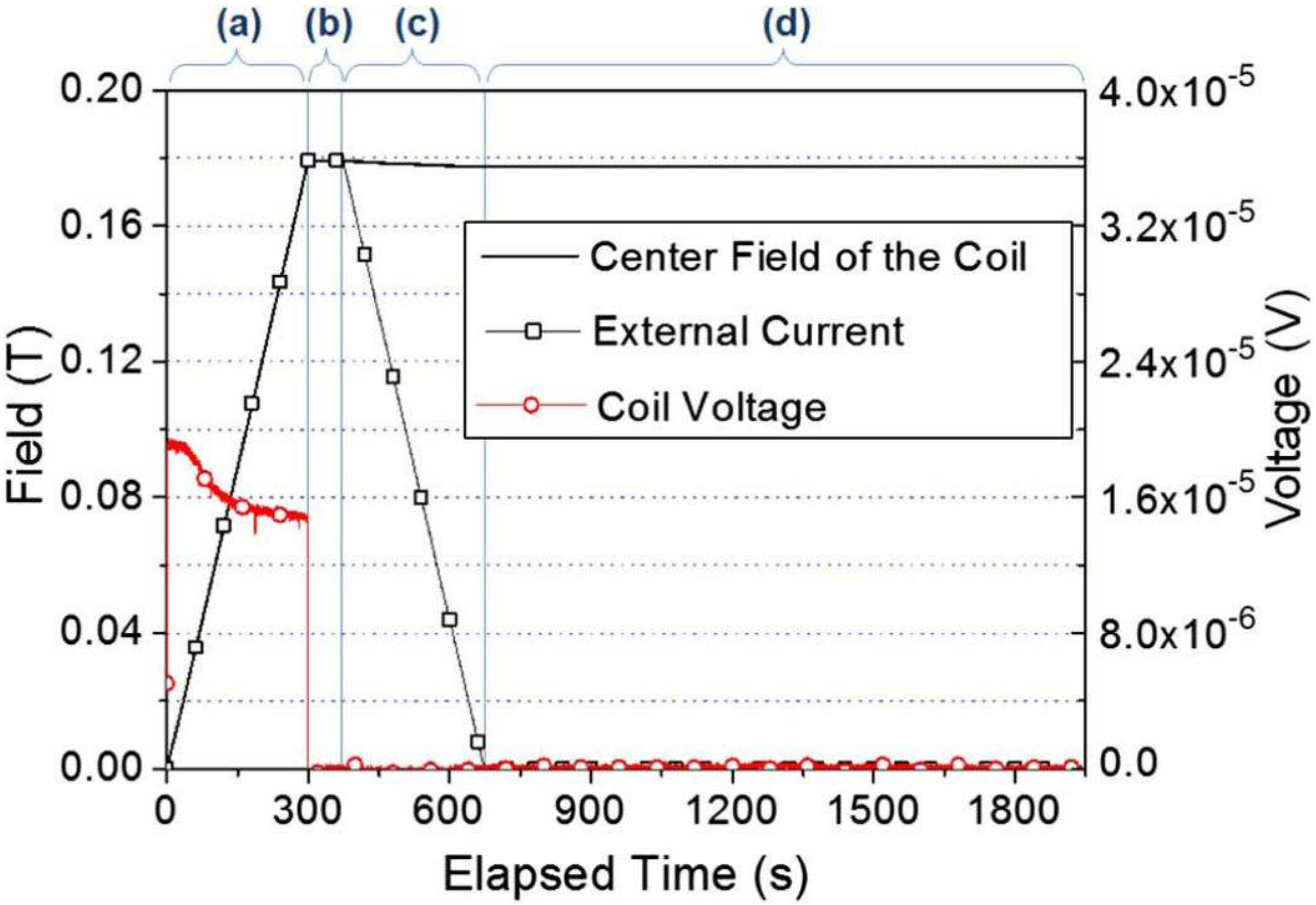

Fig. 9.

Current, voltage, and coil-center field vs. time plots for a small persistent-mode test coil, initially energized at 50 A.

TABLE I

PARAMETERS OF TEST COILS

Parameters		**Values**
Conductor		C-doped multifilament (#2314)
ID; OD; height	[mm]	31.8; 49.0; 76.2
Number of turns		750
Total wire length	[m]	95
Inductance	[mH]	8.16
Heat treatment condition	[°C; min.]	700; 90
Magnet constant, Bzc, @ 1 A	[mT]	10.92
Coil peak field constant @ 1 A	[mT]	11.14
Operating temperature range	[K]	4.2 – 15
External field range	[T]	0 – 5

TABLE II

Superconducting Joint Results Summary

Sintered at 570 °C for 2400 min. in vacuum			
Wire (# of filaments)	**Powder**	**I_C at 4.2 K [A]**	**I_C at 10 K [A]**
Un-doped (18)	Un-doped	123 – 390	6.5 – 103
Un-doped (18)	C-doped	0	0
#2314 (18)	C-doped	0	0
Sintered at 700 °C for 90 min. in 1-atm Ar atmosphere			
Wire (# of filaments)	**Powder**	**I_C [A] @ selected temperature**	
#2221 (1)	Un-doped	>230 A @ 10 K; 120–160 A @ 20 K (270 @ 10 K*; 140 @ 20 K*	
C-doped (1)	Un-doped	100 @ 10 K; 42 @ 20 K	
C-doped (1)	C-doped	110 @ 4.2 K; 16 @ 10 K; 11 @ 16 K	

[*] Average values of 5 joint samples from different batches

TABLE III

PARAMETERS OF A SMALL COIL

Parameters		**Values**
Conductor		Un-doped Mono (#2221)
ID; OD; height	[mm]	17.9; 25.0; 21.0
Number of turns		84
Total wire length	[m]	~6.5
Inductance	[μH]	89.8
Heat treatment condition	[°C; min.]	700; 90
Magnet constant, Bzc, @ 1 A	[mT]	3.52
Coil peak field constant @ 1 A	[mT]	3.95
Temperature at join	[K]	10.5