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A 0.6 T/650 mm RT Bore Solid Nitrogen Cooled MgB_2 Demonstration Coil for MRI—a Status Report

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Abstract

Aiming to demonstrate feasibility and practicality of a low cost superconducting MRI magnet system targeted for use in small hospitals, rural communities and underdeveloped countries, MIT-Francis Bitter Magnet Laboratory has developed a 0.6 T/650 mm room temperature bore demonstration coil wound with multifilament MgB_2 conductor and cooled via an innovative cryogenic design/operation. The coil is to be maintained cold by solid nitrogen kept in the solid state by a cryocooler. In the event of a power failure the cryocooler is automatically thermally decoupled from the system.

In this paper we present details of the MgB2 conductor, winding process, and preliminary theoretical analysis of the current-carrying performance of the conductively cooled coils in zero background field and over the 10–30 K temperature range.

Index Terms

Conduction cooled; MgB2; MRI; solenoids

I. Introduction

In the early 1990s General Electric initiated a trend toward “dry” (no liquid cryogens) superconducting MRI magnets by introducing an all Nb_3Sn magnet/cryocooler MRI system. The magnet operated at 10K, the practical upper temperature with Nb3Sn. Despite the popularity of its dry magnet, because of its high cost compared with that of a “wet” (liquid helium cooled) NbTi system, the dry 10 K Nb_3Sn magnet could not compete against the wet 4.2 K NbTi magnet. Clearly, the key to market penetration for dry MRI systems is an HTS (High Temperature Superconductor) that in cost and performance can excel NbTi. We believe that such an HTS is Magnesium Diboride (MgB_2), discovered in January 2001. Fig. 1 presents field vs. temperature plots of MgB_2 and two staples of conductor for superconducting magnets, NbTi and Nb_3Sn [1]. The MgB_2 plot makes it clear that the applicable field range of MgB_2 extends into the 10–30 K temperature range, impossible with NbTi and Nb_3Sn.

Also, its critical current density in the temperature range 10 – 15 K in low fields (see Fig. 2) is well above the minimum level to formulate MgB_2 into a composite conductor that must include not only MgB_2 but also normal metal to make the composite meet strength, stability and protection requirements of a working magnet.

II. Our Approach

The Magnet Technology Division at MIT-FBML, has developed a demonstration system that introduces two important firsts to MRI superconducting magnet technology, both benefiting the operation of the next generation of low-cost MRI magnet systems: 1) a trend–setting MgB_2 for the next generation of MRI magnets; and 2) an innovative cryogenic design/operation concept that introduces a volume of solid nitrogen in the magnet housing. The presence of solid nitrogen in the system, maintained by a GM cryocooler, enhances the magnet’s heat capacity enormously (Fig. 3) [2] enabling the magnet to maintain its operating field over a limited time period even with its cryocooler shut off as would be the case of a power outage, an event not rare in rural communities and underdeveloped nations. Only during this shut off period, the magnet and the solid nitrogen, otherwise kept at a nominal operating temperature of 10 K by its cryocooler, will warm up to a design limit of 15 K over a period of one day.

Volumetric heat capacity data for representative coil materials, as well as, for solid neon and solid nitrogen are presented in Fig. 3.

III. Demonstration Magnet

A. Conductor

The conductor for this demonstration coil is a multifilament MgB2 conductor developed by Hyper Tech Research, Corp. (HTR). MgB2 wire is generally processed using the powder-intube (PIT) route. At HTR MgB2 PIT strand is made continuously by Continuous Tube Filling/Forming (CTFF) process in which powder is dispensed onto a strip of metal as it is being continuously formed into a tube. The result is an overlap-closed tube, the powder being enclosed in a sheath. The monofilament wire may be enclosed in a second tube to aid wire drawing, or a bundle of them may be re-stacked to form a multifilament strand. The sheath material must not only contain the powder but also be chemically compatible with it, the reason why Fe is preferred, although HTR has made wire with Nb and Cu. They have been successful in fabricating FeCu wires up to 7 filaments, NbCu up to 19 filaments and all Cu sheathed wires up 19 filaments. Fig. 4 shows microscopic cross sectional views of some of these wires.

Recently HTR was able to successfully produce a 1 km of multifilament MgB_2 wire [3].

B. Demonstration System

Table I lists the basic specifications of the 0.6 T/650 mm demonstration magnet and its cryogenics. The magnet will operate nominally at 10 K with its cryocooler running. The presence of 15-liter solid nitrogen, also at 10 K, permits the magnet to maintain its operating field at 0.5 T even during a period of power outage, assumed to be 1 day for this system.

The magnet is comprised of 10 coils connected in series. Each coil is wound on a copper former with 1000 m of unreacted multifilament MgB_2 wire which is glass braided insulated. The copper former has a winding pocket 26 mm wide × 20 mm deep, on a 770 mm diameter. Details of the winding pocket are shown in Fig. 5.

The main parameters of the demonstration magnet are presented in Table II.

As mentioned before, the coils are wound with unreacted MgB_2 conductor and then sent for heat treatment. A typical heat treatment profile is shown in Fig. 6.

C. Experimental Procedure

After winding and heat treatment each coil is tested for its current-carrying capabilities. To that effect, the coil is conductively cooled and in the absence of solid cryogen. The test setup is shown in Fig. 5. In order to provide an isothermal environment for the coil during testing, it is placed between two copper plates which are then connected, via a flexible copper strap to the second stage of the cryocooler. The entire system is then surrounded by an aluminum radiation shield, thermally connected to the cryocooler first stage.

The cryocooler is a Sumitomo Model RDK-408S running on an air cooled compressor. At 60 Hz it provides with 35 W of cooling capacity at 45 K on the first stage, and 6.3 W at 10 K on the second stage.

To control the coil temperature, a 50Ω heater is wound on the second stage of the cryocooler. Power to the heater is through a CryoCon Model 32B Temperature Controller.

The coil is instrumented with several Cernox temperature sensors to monitor its cooldown and warm-up. A Hall probe, located at the geometric center of the coil serves to measure magnetic field strength at the various coil temperatures and currents.

Fig. 7 shows a photograph of the experimental setup for the conductively cooled single coil.

After each of the 10 coils has been tested for their current-carrying capabilities in the configuration just described, they will be assembled into a single, series connected coil, thus forming the full MgB_2 MRI demonstration magnet.

In the final configuration this coil, placed in a 650 mm RT bore cryostat, is surrounded by a volume of 15 liters of solid nitrogen.

D. Operational Issues

1) Nitrogen Safety—Of the several important cryogenic issues for our system, the one on safety is particularly important, and addressed here. Solid nitrogen melts at 64 K and under atmospheric pressure liquid nitrogen boils at 77 K.

The total enthalpy required to raise the temperature of solid nitrogen from 10 K to 64 K is 72.2 J/g, which assuming an average density of 0.9 g/cc for solid nitrogen over this temperature range, translates into a volumetric enthalpy of 65 J/cc.

A solid nitrogen volume of 15 liters stored in magnet housing requires an energy input of ~1,000 kJ to heat up the cold body from 10 K to 64 K. As stated in Table II, the total magnetic energy stored in this demonstration magnet is 89.3 kJ. Thus, even if all of this stored energy were to be dissipated into the solid nitrogen, it would be heated up to ~30 K.

Fig. 8 shows a theoretical temperature evolution of the system in the event of a long period of power outage.

2) Field Inhomogeneity Due to Thermal Expansion—The co-efficient of linear thermal expansion, α(T), is defined by

$$\alpha(T)=\frac{1}{L_0}\left(\frac{\partial L}{\partial T}\right)_P \quad (1)$$

α(T)varies with Tas

$$\alpha(T)=aT+bT^3 \quad (2)$$

Based on an experimental α(T)plot of copper [4] in the range $0 \le T \le 50$ K, we find $a = 5\times10^{-9}$ K^{-2} and $b = 3 \times 10^{-11}$ K_{-4}. For ΔT = 5K, between 10 K and 15 K, we may compute $\Delta L/Lo$ for copper by integrating (1).

$$\left(\frac{\Delta L}{L_0}\right)=\int_{10K}^{15K}(5\times10^{-9}T+3\times10^{-11}T^3)dT=0.62\times10^{-6}$$

Because copper is a pure metal, ($\Delta L/L_0$) over this temperature range is likely to be considerable greater than corresponding values for winding materials, therefore a linear change of 0.62 ppm, although it does not translate directly to a spatial field inhomogeneity of 0.62 ppm, it does not present a real concern.

E. Present Status

One coil, with 400 m of multifilament MgB_2 conductor from Hyper Tech Research was wound and heat treated.

Fig. 9 is a photograph of the coil before its heat treatment.

IV. Future Work

1. Characterize the coil already wound and heat treated for its current-carrying capabilities at different temperatures. Coil will be conductively cooled for that purpose.
2. Wind and react the additional coils to build the demonstration magnet.
3. Perform a preliminary test without solid nitrogen to verify that the magnet can indeed generate a central field of 0.6 T in the temperature range 10–15 K.
4. Perform a similar test in the presence of a 15 liter volume of solid nitrogen.

Acknowledgments

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References

1. Larbalestier, DC. MgB_2 —a large scale applications perspective. APS March Meeting MgB2 Press Brief; Mar. 12, 2001;
2. Iwasa, Y. A ‘permanent’ HTS magnet system: key design & operational issues. Adv. Supercond. X, Proc. 10th Int. Symp. Superconductivity (ISS’97); Tokyo. 1998;
3. Rindfleisch, M. Private communication. Columbus, OH: Hyper Tech Research, Corp; 2005.
4. Reed RP, Clark AF. American Society for Metals. Materials at Low Temperature. 1983

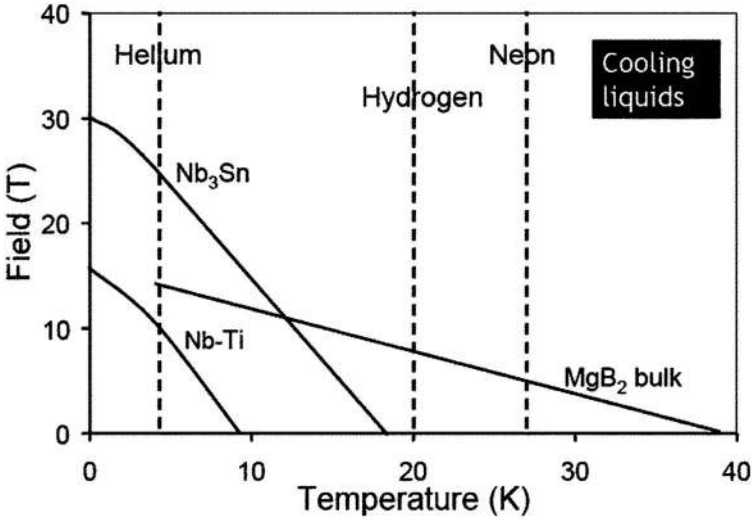

Fig. 1.

Field vs. temperature plots for NbTi, Nb_3Sn and MgB_2.

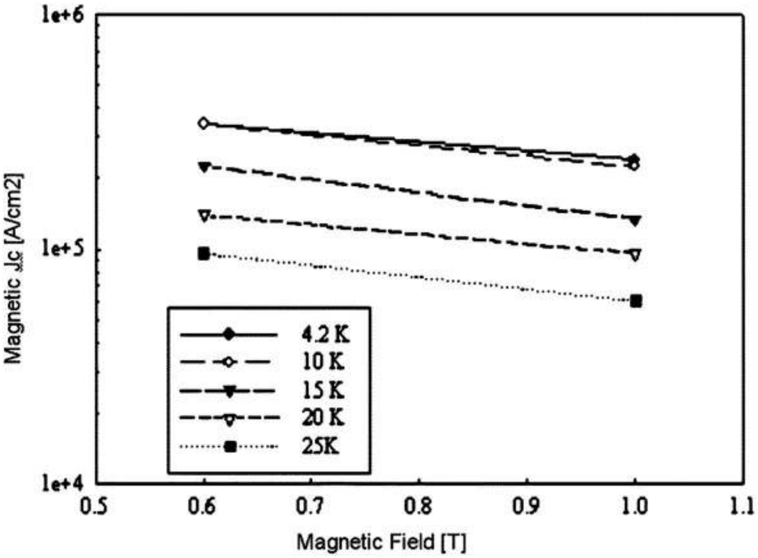

Fig. 2.

Magnetic J_c results for a 30 min/700° $CMgB_2$ sample.

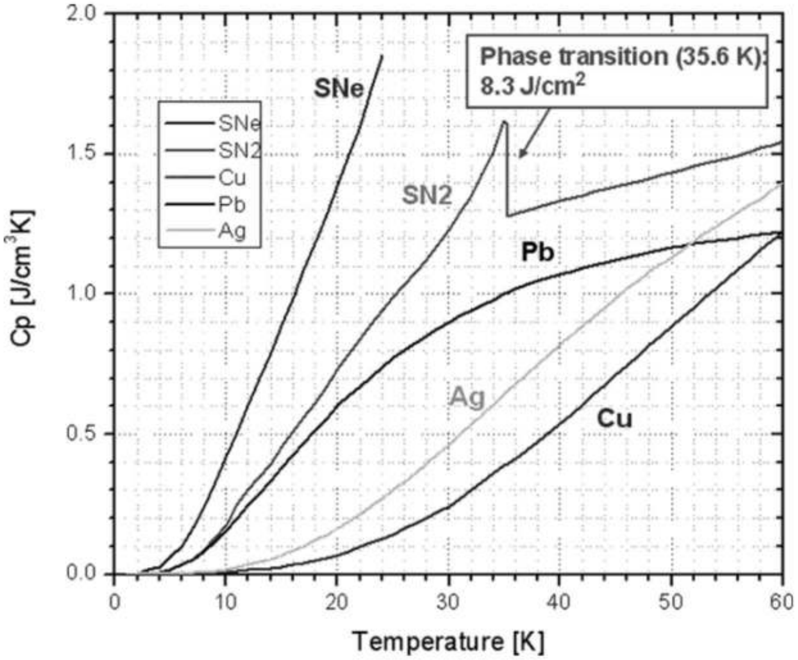

Fig. 3.
Heat capacity data.

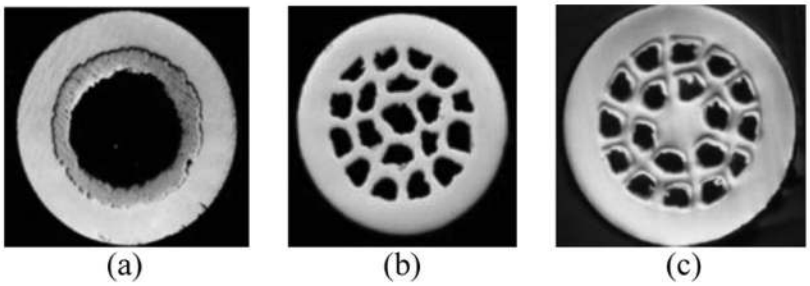

Fig. 4.

Cross sectional views of MgB_2 wires: a) 1.0 mm diam. All Cu sheathed wire; b) 19-filament Cu monofilaments restacked in Cu; c) 19-filaments (12 × 6 × 1) single Nb-CTFF in Cu restacked in Monel.

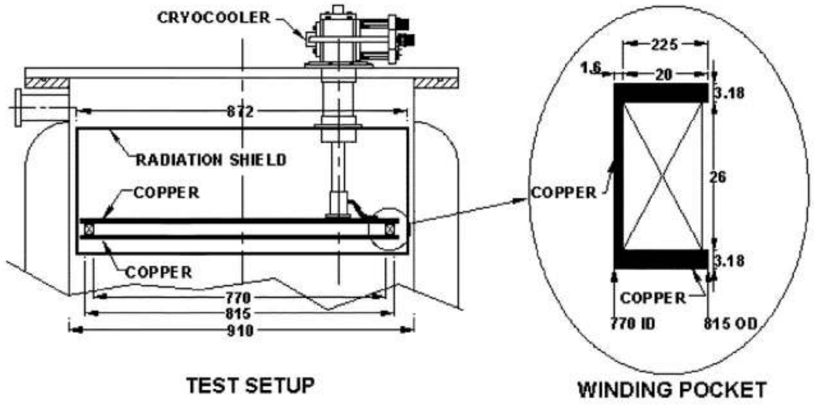

Fig. 5.

Cross section of the experimental setup showing detail of the winding pocket.

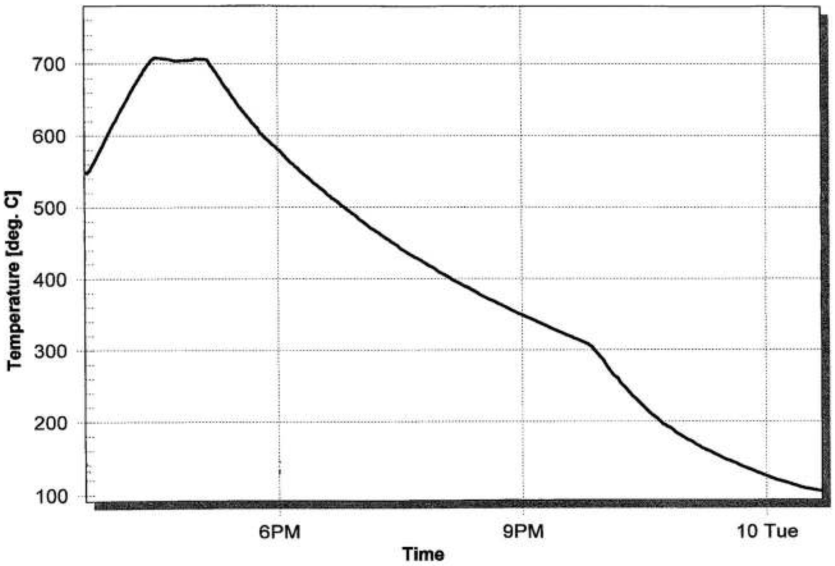

Fig. 6.

Typical heat treatment profile of an MgB_2 coil.

Fig. 7.
Experimental setup for a single, conductively cooled, coil.

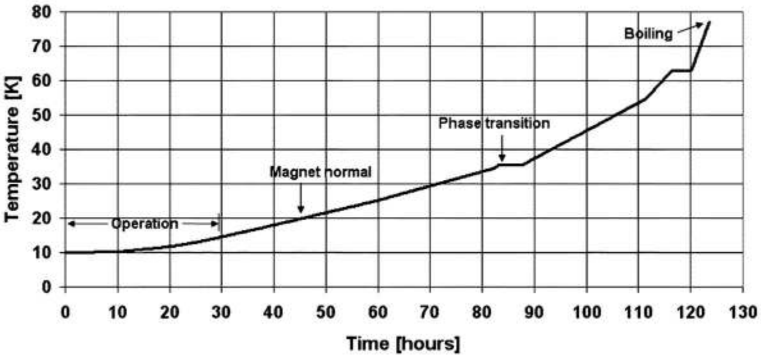

Fig. 8.

Warm-up time function during a long period of power outage.

Fig. 9.

Pre-heat treatment, single 770 mm ID coil wound with 400 m of unreacted multifilamentary MgB_2 conductor.

TABLE I

Magnet and Cryogenics Specifications for the Demonstration System

Parameter	Specification
Central field/room temperature bore	0.6 T/650 mm
Magnet operating temperature	10 K (nominal); up to 15 K (during power outage)
Temporal stability	≤0.01 ppm/h
Cryocooler: 2nd stage/1st stage capacity (GM type)	6 W @ 10K/35 W @ 45 K
Total solid nitrogen volume	15 liters
Warm-up periods:	24 h
10→ 15K/15→64K(solid)/64→77K (liquid)	29 h/82 h/4 h
Recooling time from 15 K	≤1h

TABLE II

Parameters of Demonstration Magnet

Parameter	**Value**
Winding I.D. [mm]	773
Winding O.D. [mm]	814
Winding length/coil [mm]	26
Wire diam. (insulated) [mm]	0.96
# layers	16
Turns/layer/coil	25
Total turns/coil	400
Total wire length/coil [m]	1000
Operating current [A]	93.8
Inductance [H]	20.3
Stored energy [kJ]	89.3
B_{max} (central field) [T]	0.6