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MgB₂ Coils for MRI Applications

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Abstract—In this paper, we report our progress in the development of a low cost, liquid-helium-free MgB₂ superconducting MRI magnet. Several technical issues related to the construction of such a magnet to operate in persistent current mode are discussed, namely, the performance consistency of long length MgB₂ conductors, the fabrication of superconducting joints and persistent current switches. Quench detection and protection of such magnets operated in solid nitrogen environment are also discussed.

Index Terms—HTS/LTS magnet, MgB₂ superconductor, NMR magnet, persistent mode.

I. INTRODUCTION

EIGHT years after the discovery of MgB₂ superconductivity, long length conductors in an order of km have become commercially available [1], [2]. The critical temperature (T_c) of MgB₂ \sim 40 K promises some advantages, compared with those of the low-temperature superconductors (LTS) currently used in all superconducting MRI magnets, \sim 10 K (NbTi) and \sim 18 K (Nb₃Sn). Owing to the higher T_c , an MgB₂ magnet will have its stability considerably enhanced and cryogenic system substantially simplified. In Francis Bitter Magnet Laboratory at MIT, we have been developing the technologies to build low-cost, liquid-helium-free, whole-body MRI magnets. To demonstrate the feasibility of the MgB₂ conductor in such applications, we are building a prototype whole-body MRI magnet of 0.5 T. Some technical issues—cryogenics; stability; protection; temporal stability; and spatial homogeneity of field—will be addressed and investigated through the construction of this real size prototype. In this paper, we report the present status of the work.

II. SOLID N₂ SUBMERGED MAGNET

Fig. 1 shows a schematic drawing of the prototype magnet and the cryogenic system. Instead of being submerged in liquid helium, the MgB₂ coils are surrounded by solid nitrogen and maintained at an operating temperature between 10 K (nominal) and 15 K with a two-stage cryocooler. The philosophy behind this design approach is the following.

- No regular cryogen replenishing is required since the solid will not evaporate after the initial filling.
- Solid nitrogen will render a uniform temperature within 1 K over the entire magnet.

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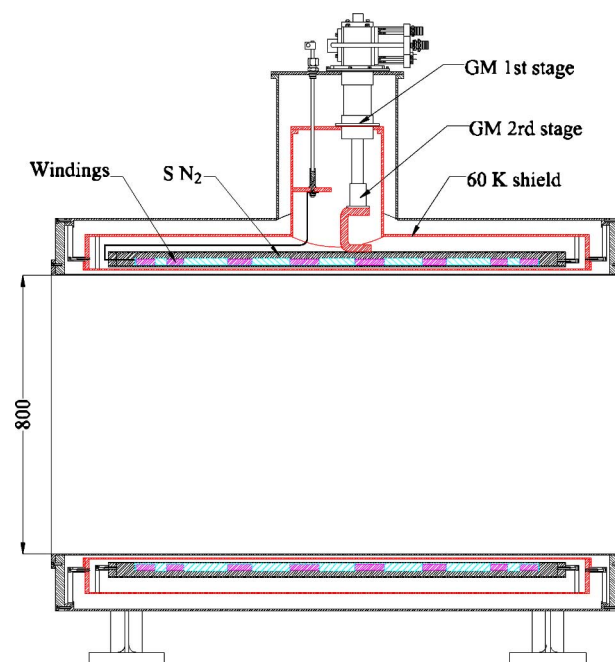


Fig. 1. In-scale sketch for the magnet system under construction.

- Owing to the relative large heat capacity of solid nitrogen around 10 K, it will sustain the working temperature of the magnet even during a short period of power disruption when the cryocooler is not functioning. Assuming there is a 2 W heat load to the magnet from various sources, it takes 5 hour for the magnet to warm up from 10 K to 15 K if it is surrounded by 50 liter of solid nitrogen, while it takes less than 5 minutes if the magnet is attached to the same volume of copper.

III. TEST COILS IN SOLID NITROGEN

Prior to the current project, a “demonstration” magnet (DEMO magnet) was built and tested [3] to verify the viability of long-length MgB₂ conductor in the application of MRI magnet and the feasibility of using solid nitrogen in the cryogenic system. The multi-filament MgB₂ wire used for DEMO magnet, known as “18+1 Nb/Cu/Monel”, was developed and fabricated by Hyper Tech Research [1]. This round conductor consists of 18 filaments embedded inside Cu and Monel matrix (see Fig. 2). There are two forms of the conductor from the manufacturer, reacted and un-reacted. For the un-reacted conductor, the material in the filaments is in the form of magnesium and boron in stoichiometric ratio. Such wire must go through heat treatment at a high temperature so that the precursor reacts and forms MgB₂ filaments. After the heat treatment, the conductor is superconductive at low temperature and is called reacted wire. Twelve coils were made using reacted wire, each

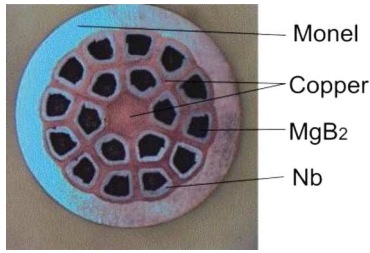


Fig. 2. Photograph of the cross section of 0.84-mm diameter 18 + 1 multifilament MgB₂ wire, with key components identified. [1]



Fig. 3. Photograph of a splice assembly to join two multifilament MgB₂ wire inside Cu alloy matrix. [8].

with conductor of 1 km long and wound on a copper bobbin of 773 cm in diameter and 25.4 cm in vertical winding length. After tested individually below 15 K at a current of 100 A, ten of them that passed the tests were stacked and clamped with tie rods to make DEMO magnet.

The magnet was enclosed inside an aluminum chamber which was thermally attached to the second stage of a GM cryocooler. By filling the chamber with liquid nitrogen, the magnet was submerged in the liquid and cooled to 77 K. The operation of the cryocooler would further lower the temperature of the chamber. The liquid nitrogen would first solidify at 62 K and then the solid was cooled to below 15 K. The DEMO magnet tested at a temperature of 13 K and a current of 87.7 A, produced a center field of 0.54 T.

IV. JOINT FABRICATION AND PERFORMANCE

One important technique for the application of MgB₂ conductor in MRI magnets is to splice MgB₂ wires superconductively. A typical superconducting magnet consists of several coils. In order to operate the magnet in a persistent mode, the joints between the coils must be superconducting. There are mature techniques in making superconducting splices among NbTi and Nb₃Sn wires. The temporal stability of a typical MRI magnet requires that the overall resistance from the contribution of all joints should be in the order of $< 10^{-10} \Omega$ [4]. Techniques to splice MgB₂ wires are still under development [2], [6], [7]. In an earlier paper, we reported our success in the fabrication of superconducting joints (see Fig. 3) using un-reacted wire supplied by Hyper Tech Research [8]. Fig. 4 shows the critical current I_c as a function of temperature in self field. At 11.2 K, the joint appears to be superconducting up to 200 A. With a field-decay

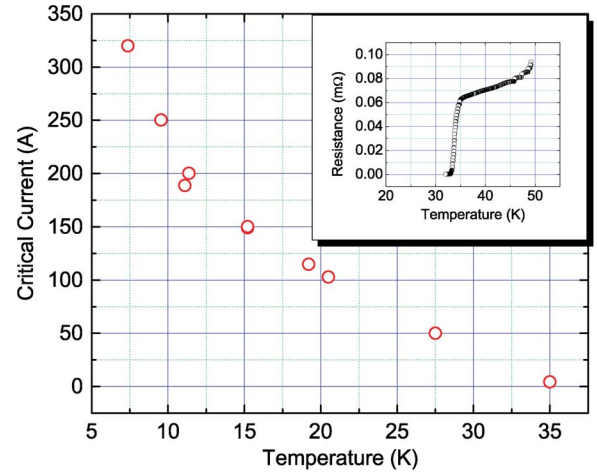


Fig. 4. I_c vs. T data for an MgB₂ splice in self field. Inset: resistance vs. temperature data of the splice, showing the superconducting transition.

TABLE I
REFERENCE DESIGN FOR 0.5-T WHOLE BODY MRI MAGNET

Coils	M1	M2	C1	C2
Conductor diameter	0.84 mm (bare)			
$2a_1$ (mm)	860	860	860	860
$2a_2$ (mm)	877.6	877.6	894.9	894.9
$2b$ (mm)	84	71	50	53
z (mm)	± 94	± 279.5	± 279.5	± 549.5
Turns/layer	83.5	70.5	49.5	52.5
Layers	10	10	20	20
Wire length (km)	2.29	1.94	2.74	2.92
Operating current	97.83 A			
Total Inductance	25 H			

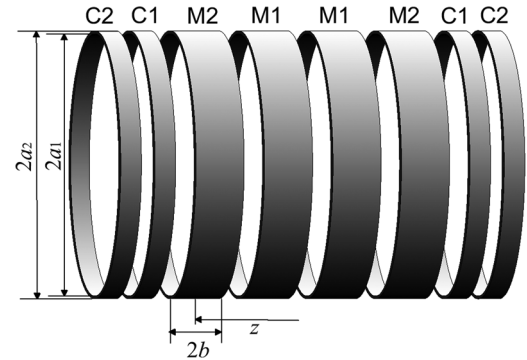


Fig. 5. In-scale coil arrangement of Phase II whole-body MRI magnet, consisting of MAIN COIL (M1 and M2) and CORRECTION COIL (C1 and C2).

method, a joint can be evaluated to a resistance level less than $10^{-14} \Omega$ [5]. The superconducting splice techniques for reacted conductors are still underdevelopment in our laboratory.

V. A 0.5 T WHOLE-BODY MRI MAGNET UNDER DEVELOPMENT

We designed the 0.5 T whole-body MRI magnet based on the conductor from Hyper Tech Research which we had used in the previous work in the construction of DEMO magnet. The main winding parameter is listed in Table I. The magnet consists of 8 coils modules, which can be grouped into 4 pairs, specified as M1, M2, C1, and C2 (see Fig. 5). As shown in Fig. 6, each module will be made of a single piece of conductor. At

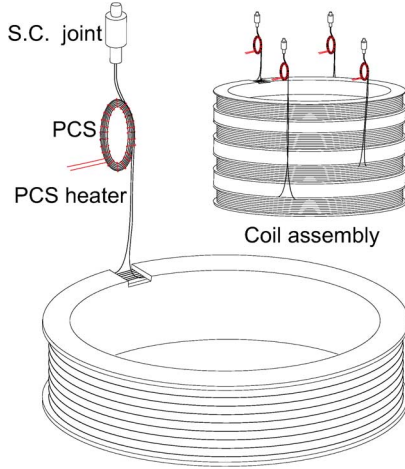


Fig. 6. Coil configuration: a single coil module and an assembly with 4 modules.

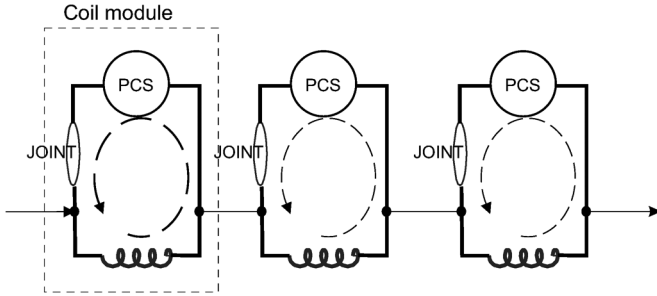


Fig. 7. Interconnections between coil modules. The thick lines represent superconducting loops and the thin lines are non-superconductive interconnections.

the current stage, we will choose the un-reacted wire to wind the coils. After a coil is wound, the two ends of the conductor will be joined together using the splice technique we have developed. In this wind-and-react approach, a whole module has to go through the heat treatment procedure so that the precursor in the filaments and in the joint assembly will react and become MgB_2 at the same time and each module will behave as a closed superconducting loop at low temperatures. A small section of the conductor in the loop will be wrapped with a heater and becomes the persistent-current switch (PCS) as shown in Fig. 6.

After low temperature tests to verify that the critical current and temporal stability of each individual module meet the requirements, the eight modules will be assembled together as illustrated in Figs. 6 and 7. The modules will be interconnected via soft solder which is low resistive but not superconducting. At low temperature, when the PCS is not heated, each module forms a superconducting current loop; the currents in the loops may not be identical. When the current in the loops needs to be ramped up or down, one can either apply heat to all PCSs so that the current flows through each coil in series or apply heat to a particular PCS to modify the current in the corresponding coil and bypass the rests. Due to mutual inductance, charging one coil may also influence the current in other coils. Instead of connecting the eight coils in series and shunting the whole magnet with a single PCS, a typical method for almost all LTS magnets, we choose to make modular coils based on the following considerations.

- The conductor length currently available from manufacturer is around 3 km.

- Each module can be tested individually before and after assembled into the magnet. If a module fails at any stage of the test, either due to the resistive joint or conductor, it can be replaced without any influence to other modules.
- At the moment, we have only managed to superconductively splice MgB_2 from un-reacted conductor. This means that after heat treat of the coils modules, we would not be able to remake any superconducting splice. If the coils were all series-connected with superconducting splices, the whole magnet must be discarded even if only one coil or splice failed to perform.

VI. QUENCH DETECTION

During the test of the DEMO magnet, some short circuits produced excessive local heating and induced a quench in the magnet which caused damages in some coils. Although the HTS conductor improves the stability margin of a magnet substantially, which makes quench due to small disturbance less likely to happen, it also significantly suppresses the normal zoom propagation velocity to 1/10 of the value for a typical LTS conductor [9]. When a quench does happen, the energy will be focused in the initial normal zone where the temperature rises substantially that it may damage the winding. In the following part of the paper, we will discuss the minimum size of a normal zone which can cause a quench, the time needed for a hot spot to reach 300 K, and a protection scheme to be used in the 0.5 T MgB_2 magnet.

In a composite superconducting conductor like the MgB_2 we use, when a normal zone appears, the heat generated at the spot will propagate along the conductor through the matrix material (copper in our case). If the length of the normal zone is short, hence the heat produced is small, the normal zone will shrink and eventually return to superconducting state. There exists a minimum length for a normal zone, l , beyond which its length will grow with time and a quench can happen. l is given by,

$$l = 2\sqrt{\frac{3k_m(T_{cs} - T_{op})}{\rho_m J_m^2}} \quad (1)$$

where, k_m and ρ_m are the thermal conductivity and resistivity of copper matrix at the operating temperature $T_{op} = 10$ K. $T_{cs} = 30$ K is the current sharing temperature for MgB_2 and J_m is the current density when current flows in copper matrix instead of MgB_2 . At an operating current $I_{op} = 100$ A, we get $l \sim 5$ cm calculated from the conductor geometry shown in Fig. 2.

Next we estimate when a normal zone longer than the minimum length appears, how long it takes for this section of conductor to reach 300 K due to the joule heating. Assuming adiabatic condition, we can write

$$A_{cd}C_{cd}(T)\frac{dT}{dt} = \frac{\rho_m}{A_m}J_{op}^2(t) \quad (2)$$

where, A_{cd} and C_{cd} are the cross section and specific heat of the overall conductor (Cu, MgB_2 , Monel). ρ_m is the resistivity of the wire when it is in normal state. We take $\rho_m = 0.017 \mu\Omega\text{cm}$, the resistivity of copper around 10 K since other materials in the conductor are highly resistive. A_m is the cross section area of copper matrix. Using the conductor parameter shown in Fig. 2,

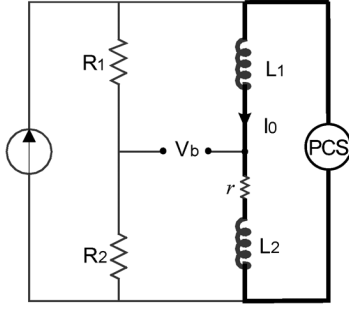


Fig. 8. Bridge circuit voltage detection when the module is being charged. In persistent mode, a supply is not in the circuit.

we estimate that it takes ~ 1 s for the conductor to reach 300 K. In this estimation, we assume that $I_{op} = 100$ A and it does not change within this period of time.

A quench detection mechanism must be adapted to detect the appearance of a normal zone. Fig. 8 shows a bridge circuit applied to a coil module, where a center voltage tap is attached to the coil. In a balanced bridge, where $L_1/L_2 = R_1/R_2$, the inductance voltage due to the current ramping and/or due to the voltage ripples of the power supply will cancel across the bridge, $V_b = 0$. When a normal zone is initiated in the winding, a resistance r appears in one arm of the bridge which results in an unbalanced voltage V_b ,

$$V_b = (L_2 - L_1) \frac{dI_0}{dt} + \frac{R_1}{R_1 + R_2} I_0 r \quad (3)$$

In this circuit, the detection of r isn't influenced by the status of the PCS whether it is in a superconducting or a resistive state. A detection circuit will be attached to each module and they will function independently. Normally $L_1 \simeq L_2$, so $V_b \simeq 1/2 I_0 r$. For a normal zone of 5-cm long, it gives $V_b = 5$ mV when $I_0 = 100$ A.

VII. QUENCH PROTECTION

In order to avoid a localized hot spot, an active protection technique has to be used to quickly expand the normal zone so that the energy store in the magnet will be dissipated in a large volume. Such a technique, also used in many large LTS magnets [10], is applicable for persistent-mode magnets. In this method, upon the detection of a hot spot, a portion of the winding is driven normal with a protection heater, planted in the winding. The normal portion must be large enough to absorb the entire magnet energy and still keep the hot spot and heated portion of the winding below 300 K [4]. As one can see from the following discussion, it is necessary to heat only a few percent of the entire winding to satisfy the 300-K requirement. Also note that this protection heater may be planted in a "convenient location" in the winding, irrespective of the size and the location of a hot spot. As indicated in Table I, when the magnet is fully charged, a total of 120 kJ is stored at an operating current of 97.83 A. If we allow the resistive zone to reach a final temperature of 260 K, its enthalpy density increases by 577 J/cm^3 . The total winding volume required to absorb 120 kJ is thus 208 cm^3 . For a 0.84-mm diameter wire, this volume requires a wire length of

~ 375 m, i.e., only $< 2\%$ of the total wire is needed to absorb the entire energy and still limit the hot-spot temperature to 260 K. In the current design, a heater will be attached on top of the outmost layer of the superconducting winding on each coil. To warm up 208 cm^3 of copper conductor to 30 K, it requires 360 J heat input. Since it takes ~ 1 s for a hot spot to reach 300 K, the activation of the protection heater should be in a fraction of one second, which should be easily achievable with a power supply.

VIII. CONCLUSIONS

Our goal of the project is to build a prototype for commercially viable low-cost, easy-to-operate (e.g., LHe-free) whole-body MRI magnets. Through the program, we will demonstrate the feasibility of several design and operation approaches for HTS magnets, 1) using MgB₂, to keep the HTS magnet low-cost; 2) operating in the range 10–15 K for enhanced stability; 3) liquid-cryogen-free "dry" environment; 4) persistent-mode operation for good temporal stability and ease of operation; 5) protection from quench damages. The long MgB₂ conductor performance is still improving in the aspects of the critical current and field. Some key techniques like superconducting splice of reacted wire is still under development in our laboratory and elsewhere. The technologies accumulated in the project will help to promote the application of MgB₂ in the future for MRI magnets of even higher field, competitive to the current state-of-the-art NbTi magnets, but with substantially lower costs and enhanced stability.

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