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Active Protection of an MgB₂ Test Coil

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Abstract

This paper presents results of a study, experimental and computational, of a detect-and-activate-the-heater protection technique applied to a magnesium diboride (MgB₂) test coil operated in semi-persistent mode. The test coil with a winding ID of 25 cm and wound with ~500-m long reacted MgB₂ wire was operated at 4.2 K immersed in a bath of liquid helium. In this active technique, upon the initiation of a “hot spot” of a length ~10 cm, induced by a “quench heater,” a “protection heater” (PH) of ~600-cm long planted within the test coil is activated. The normal zone created by the PH is large enough to absorb the test coil’s entire initial stored energy and still keeps the peak temperature within the winding below ~260 K.

Index Terms

Active protection; MgB₂ magnet; persistent mode; quench detection

I. Introduction

Recently magnesium diboride (MgB₂) superconducting wires have been developed for a variety of applications including magnetic resonance imaging system (MRI), fault current limiters, and accelerator applications. Since MgB₂ has a critical temperature (39 K) higher than those of low temperature superconductors (LTS) and it is not compromised by weak-link problems associated with other high temperature superconductors (HTS), it is promising for magnet applications such as low-field (<3 T) MRI operating in a temperature range 10–20 K [1], [2]. For reliable and successful operation of any superconducting magnets, protection is one of the most crucial issues. In our first attempt to build an “MRI-size” MgB₂ magnet, we successfully operated a solid-nitrogen-cooled MgB₂ “Demonstration” magnet, comprising a stack of 10 MgB₂ coils and operated in a 10–15 K range. During subsequent operation of the magnet, due to a short with a coil support, some of the coils were prematurely quenched, *unprotected*, and damaged [3].

A driven mode magnet generally relies on a *detect-and-dump* protection method which is not applicable to a persistent-mode magnet. To protect itself from overheating, a persistent-mode magnet of a “modest” size relies chiefly on “fast” normal zone propagation (NZP) velocities to dissipate most of its stored energy nearly over its entire winding—the so-called self-protecting magnet [4]. A “large” persistent-mode MgB₂ whole-body magnet being developed now at Francis Bitter Magnet Laboratory is not self-protecting [5]; it will be

protected by an active protection method, specifically by the detect-and-activate- the-heater (DAH) method applied to this test coil.

This paper presents results of a protection measurement performed on an MgB₂ test coil, wound with reacted MgB₂ wire and operated in semi-persistent mode at 4.2 K in a bath of liquid helium (LHe). For this DAH protection, a “protection heater” (PH), planted at the outermost layer of the test coil, drove a 6-m long MgB₂ wire that is large enough to absorb the entire coil energy and still keep the hot spot (a 10-cm long section driven by a “quench heater”) below 260 K. Protection tests were performed at operating currents of 100, 125, and 150 A. The paper presents an analytical method to compute the hot-spot temperature and test coil resistance after the initiation of a hot spot. The analytical results are then compared with experimental results.

II. MgB₂ Wire & Analytical Method

A. MgB₂ Wire

The MgB₂ wire was manufactured by Hyper Tech Research, Inc. It is designated as “18+1 Nb/Cu/Monel” multifilament wire. Eighteen mono-filament strands and one center copper filament are stacked into seamless Monel tube and then drawn into the final size, 0.84 mm. Reaction is done through heat treatment in 700° C for 20 to 40 minutes [6]. With a critical bending strain of 0.4%, the minimum bending diameter of the 1-mm insulated wire is estimated 25 cm. Table I shows the specifications of the MgB₂ wire.

B. Analytical Method

Temperature-dependent thermal and electrical properties of the wire for analytical calculation were estimated with the mixture rule of constituent property values.

Hot spot temperature increase and consequent resistance growth in Fig. 1 was calculated by a combination of a power density equation applied to a unit length of the MgB₂ wire in the test coil and an equation governing the test coil circuit, respectively, (1) and (2) [4]

$$\begin{aligned} C_{cd}(T) \frac{\partial T}{\partial t} &= \rho_m(T) J_m^2(t) - q(T) \\ L \frac{\partial i(t)}{\partial t} + i(t) R(t) &= 0, \end{aligned} \quad (1)$$

where

$$R(t) = \frac{1}{A} \int_0^{u_{NZP} \cdot t} \rho_m(T) ds \quad (2)$$

where C_{cd} is the specific heat capacity, ρ_m is the equivalent resistivity, J_m is the matrix current density, and q is the cooling term which is ignored, i.e. an adiabatic condition, in this analysis. L is the inductance of the test coil and $i(t)$ is the coil current. $R(t)$ represents the normal zone resistance which depends on the time evolution of the hot spot. The normal zone expands in size at NZP velocities, u_{NZP} : ~5.5, 11, 32 mm/s corresponding, respectively, to 100, 125, and 150 A at 4.2 K, self-field in a single wire [7].

III. Experimental Setup

A. Configuration

The semi-persistent MgB_2 test coil consists of a main coil and a persistent current switch (PCS). A continuous piece of MgB_2 wire, ~500-m long wire, is used to wind both the test coil and build the PCS. Two terminals of this coil/PCS unit, each ~20-cm long, were soldered. Specifications of the test coil and PCS are given in Table II. Three heaters are required: 1) PCS heater; 2) quench heater; and 3) protection heater. For the MgB_2 wire operating at ~100 A and 4.2 K, a non-recovering hot spot length in the winding was calculated to be about 10-cm long [8]. Thus, a 10-cm long quench heater with a few turns of polyimide tape and epoxy was planted in the outermost layer of the coil for thermal insulation from LHe. Manganin wires were used for the PCS heater and the quench heater. An equivalent circuit and a photo of the coil are shown in Fig. 2.

B. Quench Detection

In the active protection, the first critical step is quench detection. For this, a bridge circuit was used with the test coil divided in two nearly equal sections by a center tap, as shown in Fig. 2(a). A balanced bridge circuit, where $L1/R1 = L2/R2$, cancels the inductive voltages of charging and discharging of the test coil as well as the power supply ripples. Thus the bridge voltage, V_d , = 0 unless a quench occurs in the winding. When a resistance r , assumed to be constant with initial non-recovering hot spot resistance, appears in one arm of the bridge at operating current, I_{op} , an unbalanced voltage, the detection voltage, V_d , is generated which is given by

$$V_d(t) = \frac{R1}{R1+R2} r \cdot I_{op}(t) \quad (3)$$

Because $L1$ and $L2$ are nearly the same, $R1$ and $R2$ are each set to 500 Ω , sufficiently large for the bridge circuit. V_d from the initial hot spot is calculated to be 11.25 mV at 150 A.

C. Protection Heater Activation

A portion of the winding is driven normal with the PH. The length and the power required by PH were determined from enthalpy considerations. The enthalpy of the MgB_2 wire at 4.2 K (operating temperature), 30 K (current-sharing temperature, T_{cs} , at 100 A), and 260 K are 0.005, 2, and 520 J/cm³, respectively. The total energy stored in the test coil at 150 A is ~1800 J. If we assume that the total energy of 1800 J will be adiabatically dissipated in the winding, a wire length of only 6.3 m is required (~1% of the total wire) to keep the initial hot zone below 260 K. Thus, a ~6-m long protection heater was planted in the outermost layer of the test coil.

Heater material and energizing method should be determined from energy balance. In the case of large scale magnets, for example, a few hundred or a thousand meter long heater would be required to protect a whole magnet, and thus a low-resistive heater energized by a capacitor circuit may be preferable, in general, to a power supply. For the test coil, a bare copper wire of 0.15 mm in diameter was used for the PH. The PH requires a minimum energy input of ~15 J to heat the insulated MgB_2 wire of at least ~6-m long to a current sharing temperature, T_{cs} , of ~30 K. The total energy of 30 J is provided by a 25-mF capacitor energized at 49 V consideration of excessive cooling by LHe. Since the resistivity of copper varies with temperature above ~30 K, the current and the temperature of the PH were computed numerically by combination of a power density equation in an adiabatic condition and an equation governing $R - C$ discharging circuit. Fig. 3 shows the numerical

calculation results. Almost all the energy stored in the capacitor is discharged within 30 milliseconds which is fast enough to protect the magnet. The capacitor firing circuit includes an isolation amplifier, a comparator, an insulated-gate bipolar transistor (IGBT) switch and its driving circuit. The detection voltage is amplified and compared to the reference voltage of an op-amp based comparator. The output signal from the comparator triggers an IGBT switch through its driving circuit.

IV. Results and Discussion

A. Charging and Persistent Mode

All the tests were performed at 4.2 K with the coil immersed in a bath of LHe. For charging the test coil, power applied to the PCS heater was 15 W. The coil was charged and operated successfully up to maximum 150 A in the semi-persistent mode. A current ramp rate was 0.5 A/s. Fig. 4 shows power supply current and the current through the coil which is converted from a Hall sensor attached on the center of the main coil for 100-A operation. The coil current slightly lagged behind the power supply current during charging process because of both, a relatively low PCS resistance and a fast ramping rate. The semi-persistent decay time constant is 7.5 hours, long enough for this test. From this current-decay time constant, the joint resistance at 4.2 K is calculated to be $0.6 \mu\Omega$.

B. Protection Results

Protection tests were carried out at 100, 125, and 150 A. Each test was repeated with and without firing the PH and the respective hot-spot temperatures were compared. The energies applied to the quench heater and the PH were ~ 5 J and 30 J, respectively.

Fig. 5 compares two sets of data, one experimental and the other numerical, at 100, 125, and 150 A when the PH was not activated. The respective observed maximum temperatures, 168, 220, and 302 K, could be estimated from the stored energy, the NZP velocities, and cooling on the coil. Although the resistance data agree well with each other as shown in Fig. 1, hot-spot temperature data do not agree quite well. This is perhaps because of the time delays of both the temperature sensors respond and heat diffusion, transverse NZP, and cooling effects. Test results with and without PH activation at 125 A are shown in Fig. 6. The hot-spot temperature was reduced to 67 K by the activated PH, whose temperature reached 118 K. The effective coil resistance during current decay may be estimated from the $I(t)$ plot. When the PH was activated, the coil resistance rose rapidly, causing the coil current to decay quickly.

Fig. 7 shows the test results at 150 A. The maximum hot-spot temperature rise without protection was $302 \text{ K} > 260 \text{ K}$. The detection voltage, which was amplified and compared to a reference, triggered IGBT switch. There was a delay of tens of milliseconds from the initial voltage detection to the capacitor firing. The energy stored in the capacitor, 30 J, is discharged and injected to the PH within 30 ms, heating the PH fast. The first peak in the PH temperature curve is a result of the initial heat input from the capacitor. Then, this energy is diffused, within ~ 0.1 s, into “protection portion” (MgB_2 winding adjacent to the PH). The hot-spot temperature was heated to 92 K, while the protection portion was heated to 134 K.

In these tests, although the maximum temperature rise was only 302 K with this coil due chiefly to a combination of its relatively small size and stored energy as well as, perhaps, its fast NZP velocities, our active protection technique was performed successfully. An overheating problem would be a more critical issue and a DAH protection method, as demonstrated here, is a viable, perhaps the only, option for persistent-mode large MgB_2 magnets [5].

V. Conclusion

This paper has presented results, experimental and analytical, of a DAH protection method applied to a small MgB_2 test coil operated in semi-persistent mode at 100, 125, and 150 A. Design, fabrication, and test of the active protection system were all performed successfully. The voltage detection and capacitor firing by the IGBT switch were reliably operated. With a “protection heater” activated, it was possible, at 150 A, to limit the hot-spot maximum temperature to 92 K, which otherwise reached 302 K. With these results we may conclude applicability of a DAH technique to a “large” MgB_2 coil such as for a whole-body MRI. Our analysis also predicted quite accurately the coil resistance and hot-spot temperature time functions. The improved analytical tool should lead to an optimized code for a DAH technique in designing the key DAH parameters and improving quench detection technique, particularly quench voltage amplitude and time scale.

Acknowledgments

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Fig. 1.

Calculation results of a hot spot temperature and resistance at 125 A without protection: solid lines and scattered circles represent numerical and experimental results of normal zone resistance in the coil, respectively and the scattered symbols with x-center the hot spot temperature.

Fig. 2.

(a) An equivalent circuit of the test, (b) a photo of the test coil and PCS.

Fig. 3.
Numerical calculation results of capacitor discharge current and protection heater temperature.

Fig. 4.
Charging and semi-persistent characteristic of the test coil.

Fig. 5.

Hot spot temperature profiles without protection at 100, 125, and 150 A.

Fig. 6.

Test results at 125 A: The current decaying and temperature of the coil.

Fig. 7. Test results at 150 A: The temperature of the coil and detection voltage from the bridge circuit.

TABLE I

MgB₂ Wire Specifications

Diameter of a bare/insulated wire	[mm]	0.84/1
Insulation material		S-glass
Critical bending strain	[%]	0.4
Minimum bending diameter	[m]	0.25
Critical current, I_C (4.2 K, self-field)	[A]	1000
Critical temperature, T_C	[K]	39
NZP velocities range *	[mm/s]	15–1000
	Cu	0.29
	MgB ₂	0.17
	Monel	0.39
Cross-sectional area ratio		
	Nb	0.15

* Transport Current Ranges From $0.15I_C$ to $0.9I_C$ at 4.2 K, Self-Field [7]

TABLE II

Specification of the Test Coil and PCS

<i>Test Coil</i>		
Operating temperature, T_{op}	[K]	4.2
Winding ID/OD/height	[mm]	250/292/25
Turns per layer/# of layers		25/24
Total wire length	[m]	500
Operating current	[A]	100, 125, and 150
$B_z(0,0)/B_{max}$ at 100 A	[T]	0.271/1.07
Self inductance, L_{Coil}	[mH]	160
<i>PCS</i>		
Turns per layer/# of layers		2/2 (non-inductive)
Total wire length	[m]	3.15
Manganin heater length	[m]	3
PCS-test coil joint resistance at 4.2 K	[$\mu\Omega$]	0.6
Current decay time constant	[s]	2.7×10^5 (75 hour)