TESTS ON LARGE DIAMETER SUPERCONDUCTING SOLENOIDS DESIGNED FOR COLLIDING BEAM ACCELERATORS*

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ABSTRACT

Two prototype large diameter thin coil solenoids which use the mechanical structure to moderate quenches, have been built and systematically tested. The solenoids are cooled by two phase helium flowing in tubes which form a part of the coil structure. The coils have been tested by inducing a series of quenches at various currents. The results of these tests are given in this paper.

1. INTRODUCTION

Experiments on the electron-positron colliding beam machines now under construction in the United States and Germany will require a new generation of magnetic spectrometers for charged particles. There is an advantage from a radiation standpoint in having thin coils (for example coils which are 0.25 to 0.4 radiation lengths thick). It is hoped that one can build such a solenoid magnet for a PEP detector which has a central induction of 1.5 Tesla in a cylindrical volume 4 m long and 2 m in diameter.¹ In a magnet of this size and induction, the use of superconductivity is justified by electric power savings alone.

Superconductors which operate at high current densities are required in order to meet the 0.25 to 0.4 radiation length (including the cryostat) limit needed. It is clear that ordinary bath cooled-cryogenically stable magnets are not suitable for such a spectrometer. The approach considered here permits one to operate large solenoids at current densities around 10^5 A cm^{-2} without burning up the coil during a quench.^{2,3} This paper discusses the results of experiments on two one-meter diameter prototype magnets which operate at current densities as high as $1.17 \times 10^5 \text{ A cm}^{-2}$ with stored energies larger than 300 kJ.

II. TWO LBL TEST MAGNETS

Two one-meter diameter test solenoids which were built have an inside diameter of 1021 mm with a coil thickness (including liquid helium cryostat) of 24.5 cm. The overall length of the magnets is 500 cm. The magnet assembly consists of three parts: 1) a low resistance aluminum bore tube, 2) a high current density coil wound with modern multifilament intrinsically stable superconductor, and 3) a tubular cooling system carrying two phase helium at 4.7°K (see Fig. 1).

The low resistance bore tube is the key element for controlling a magnet quench with the stored energies of the magnitude encountered here. Without the bore tube the test coils could have burned up either from hot spot formation or from transient voltage problems. The low resistance aluminum bore tube (aluminum was chosen because of its high conductivity and low radiation thickness) performs three functions: 1) the bore tube absorbs most of the coil during a quench; 2) the bore tube drives the entire coil normal in a short time (this process we refer to as "quench back") and; 3) the bore tube reduces the effective magnet inductance at high rates of current

change and therefore it reduces the transient voltage problem.

The tubular cooling system takes the place of the liquid bath cryostat. Two phase helium is used as a coolant. The advantages of the tubular cooling system are: 1) the magnet cool-down is well controlled; 2) the mass and radiation thickness of the cryostat is minimized; and 3) the amount of liquid helium in direct contact with the magnet is minimized. The magnet coil, its bore tube and the tubular cooling system are cast into a single integrated unit.

The two LBL solenoids were wound with two different 1 m diameter superconductors. In each case two layers of the superconductor were first wound on the aluminum bore tube; next the aluminum cooling tube was wound over the coil; and finally the whole assembly was vacuum impregnated with epoxy (see Fig. 1). Each magnet has a radiation thickness of 0.24 radiation lengths.

Figure 2 shows the two magnets assembled for testing. The A magnet is above; the B magnet is

Fig. 1. A cross section of the thin solenoid.

Fig. 2. The two solenoids assembled for an experiment.

Manuscript received August 17, 1976

* This work was done with support from the U.S. Energy Research and Development Administration.

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below. Table 1 presents the electrical characteristics of the two magnets. The LBL tests which are described here served two primary purposes: 1) the tubular cooling system was to be tested on a closed cycle refrigerator; and 2) the role of the bore tube in controlling the quench of the magnets at their operating currents was to be verified. The latest series of tests were successful on both counts.

TABLE I

The Physical and Electrical Characteristics of the Two LBL Test Coils

	A Magnet	B Magnet
Number of Superconductor Filaments	2300	2700
Matrix Copper to Superconductor Ratio	1.8	1.0
Superconductor Critical Current at 2 T and 4.2 K (A)	900	1360
Coil Diameter (mm)	1035	1035
Coil Length (mm)	461	464
Number of Turns	835	832
Magnet Inductance (H)	0.75	0.74
Magnet Design Current (A)	700	880
Design Current Density in Matrix (Am^{-2})	0.91×10^3	1.12×10^3
Magnet Stored Energy at Design Current (J)	1.83×10^5	2.88×10^5
Peak Current Achieved in Test (A)	804 ^a	920 ^{aa}
Peak Current Density Achieved (Am^{-2})	1.02×10^3	1.17×10^3
Peak Stored Energy Achieved (J)	2.42×10^5	3.12×10^5

^a Last training quench for the A magnet. Previous training quenches occurred at 597, 654, 696, 733 and 773 A.

^{aa} Peak current was limited by the power supply. There was no evidence of training.

III. REFRIGERATION SYSTEM TESTS

The July 1976 test involving the simultaneous operation of both test magnets showed that the tubular cooling system would operate on a closed cycle refrigerator. A CRI model 1400 refrigerator was used for the test. The machine is capable of delivering 55 W of refrigeration or 0.54 g s^{-1} of liquid helium. The measured liquidification-refrigeration coefficient is 125 J g^{-1} (4.4 W per liter per hour). The estimated heat load into the magnet was about 10 W. In addition, about 0.18 g s^{-1} of helium gas was required for the three 1000 A current leads and a gas bleed on the control dewar. With a combined load of 10 W plus 0.18 g s^{-1} , the refrigerator liquified at the rate of 0.27 g s^{-1} into the control dewar.

The experimental apparatus, which has a cold mass of 220 kg, cooled down from 300°K to 4.7°K in less than two days. Pressure drops as high as 2.2 bar were recorded across both magnets. (Each magnet has 117 m of 10.8 mm ID tube.) At 5.2 K, the single phase pressure drop across the two units was as low as 0.2 bar. The start of two phase flow was announced by a dramatic decrease in the pressure drop by at least a factor of 2 across the two magnets. Pressure drops across the two magnets during two phase flow varied

from 0.03 to 0.08 bar depending on the gas content of the helium flowing in the tubes. Sustained two-phase flow was easily obtained; the two magnets operated at between 4.6 and 4.8°K. The tubular cooling system was well behaved during a quench even though transient pressures as high as 13 bar were measured.

IV. TESTS ON THE MAGNETS

The A magnet has been tested on three different occasions (Nov. 1975, March 1976 and July 1976). The B magnet was tested only once in July of 1976. The A and B magnets were also tested together during the July test. The basic electrical properties of the magnets were measured, confirming the theoretical calculations of inductance. Quenches were induced in the magnets to study the properties of the magnet during quenching.

Ten millimeter diameter copper coils in which a 1000 nF capacitor was discharged were used to induce the quenches. These coils are called quench coils. The A magnet has one such coil. The B magnet has four coils at different locations. The electrical data was recorded on storage oscilloscopes. The most important signals analyzed were the voltage across the main current shunt (this voltage is proportional to the coil current) and the voltage generated by flux changes inside the coil. The signals were recorded on pictures of the storage scope screen. The pictures were measured and the digital information was then processed by the LBL, CDC 7600 computer.

Quench tests of the coil were made in graduated steps.⁶ Quenches were induced at low currents first. It was established that the quench should do no damage to the coil at the next current level before a quench of that current level was tried. The object of this procedure was to get as much data about the coil as possible before anything happens to the coil. (Both coils were quenched at current densities in excess of 10^3 Am^{-2} without apparent damage.)

The quench tests demonstrated that much of the current in the coil is shifted to bore tube during the quench. Figure 3 shows the magnetic flux in the magnet which was generated by the coil itself, by the bore tube, and the sum of both. The currents in coil and bore tube are proportional to the first two. From Fig. 3 one can see that the current in the coil is shifted to the bore tube. As much as

AA01. TEST 6, LOG 2, RUN 47.

Fig. 3. The current shift from the coil to the bore tube during a quench.

75 percent of the magnet stored energy is dissipated in the bore tube as a result of this current shift. Quenches at high currents happen on a shorter time scale than quenches at low currents. This is shown in Fig. 4 which is the normalized current i/i_0 as a function of time for various starting currents i_0 .

The sudden drop of the current shown in Fig. 4 is evidence of "quench back." Further evidence is shown in Fig. 5 which is a plot of coil and bore tube time constants τ_c and τ_{AI} as a function time after the quench.

$$\tau_c = L i_c / \frac{d\phi}{dt}$$

$$\tau_{AI} = M i_{AI} / \frac{d\phi}{dt}$$

where ϕ is the flux in the coil; L is coil self inductance; M is mutual inductance between the coil and bore tube; i_c is current in the coil; i_{AI} is the

Fig. 4. Normalized current vs time for various starting currents during a quench.

AA01. TEST 6. LOG 2. RUN 47.

PAGE 76 $i_0 = 700$. $U_0 = 18$

Fig. 5. Coil and bore tube time constant as a function of time after quench initiation.

current in the bore tube; and τ is time. Just after the quench is induced, the normal region grows. The resistance of the coil increases approximately as the time squared. This resistance drives the current from coil to the bore tube. The bore tube current heats the bore tube which in turn heats up adjacent sections of superconductor driving them normal. This may be one of the causes of "quench back." It should be noted that other causes may contribute to "quench back." However, there are theoretical reasons to believe that heating is the dominant cause of quench back at low currents.

Quench back starts when the current in the coil drops to around 70 percent of the original current in the coil. Once quench back has started, the coil current drops very quickly so that when quench back is complete there is only around 30 percent of original current in the coil. Figure 6 shows the quench back time as a function of current in both the A and B magnets. The hand represents the time over which the coils are going normal through the quench back process. At low currents the A magnet requires more time to quench back than does the B magnet. An explanation for this is that the normal resistance of the B magnet due to its smaller copper to superconductor ratio is higher than for the A magnet. Quench back appears to occur only after the magnet resistance reaches a specific value. The B magnet reaches this value sooner than the A magnet. We observed that when quenches were induced at two separate points in the B magnet the quench back time was reduced.

Strain gages mounted on the bore tube measured the bore tube strain due to magnetic forces. The first A magnet test (in Mar, 1975) showed that the magnet and its bore tube strained as a single unit when magnetic forces were applied. The B coil behaved the same way as the A coil during its first test. Subsequent tests of the A magnet showed that the coil bore tube epoxy bond had broken. The strain gages showed that a portion of the A magnet coil moved away from the bore tube. It is felt that this is the cause of training observed in the A magnet. During the second test of the A magnet (in March 1976) spontaneous quenches occurred at 597, 654, 696, 733, and 733A; the training was progressive. The third A magnet test (in July 1976) showed the first training quench at 804A (the magnet was not trained beyond this point). Future LBL thin

Fig. 6. Quench-back time versus current in the coil.

solenoids will be designed to prevent movement of the coil away from the bore tube as was observed in the A magnet. The B magnet showed no evidence of straining. A peak current of 920 A was reached, a limit due to our power supply not the magnet. The only time that the B magnet was driven normal spontaneously was when it was charged so fast that large eddy currents were induced in the bore tube.

The A and B magnets were powered together in the July 1978 test. The two magnets were thermally isolated from one another. The only coupling (at short time scales) was electrical. A quench artificially induced in the A magnet would cause quench back in the B magnet and vice versa. The quench back time for the two magnets in series was longer than the quench back time for either magnet alone. Quench back occurred when the current in both coils dropped to about 70% of its starting value. An explanation for this is the larger inductance of the two coils in series. The length of a coil does not have an effect on its quench performance.

V. RESULTS OF THE QUENCH STUDY

Quench back divides the quench process into two distinct periods. In the first period, the current in the bore tube increases as the coil current decreases. Period I ends with the sharp increase in the bore tube current that we call quench back. The analysis shows that during period I the coil resistance increases quadratically with time until quench back takes place. Before quench back only a portion of the coil turns normal. The low coil resistance is evidence of this. After quench back, when the coil is entirely normal period II starts. This period is characterized by a decay in the coil and bore tube currents which can be characterized by the time constants of the coil and bore tube.

The duration of period I is important since it is the most likely period in which local overheating of the coil may occur. In both the A and B magnets, the duration of period I was found to decrease approximately as $I_0^{-1/2}$, where I_0 is the initial value of current in the coil. There is a maximum amount of energy per unit volume that can be deposited in a section of the coil in a given time by a given amount of current. An upper limit temperature T_{LH} can be computed assuming there is no heat transfer from the coil section.⁶ At 920 A in Magnet B, a T_{LH} of 460°K is calculated over the time of period I. Since there is no evidence of coil deterioration, the maximum temperature actually reached is probably lower than this value.

SUMMARY

Recent tests of the LBL thin solenoids showed that superconducting magnets can be cooled using a two phase helium tubular cooling system connected to a refrigerator. Electrically the two magnets behaved as expected. The current was shifted from the coil to the bore tube during a quench. Thus, the magnets can be safely quenched even when the superconductor matrix current density is greater than 10^4 A/cm^2 and the magnet stored energy is in excess of 300 kJ. The LBL experimental program has contributed to our understanding of the quench process in high current density magnets.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of the following individuals: A. Barone, C. Covey, C. Gibson, E. Green, A. Kiehl of LBL and D. Andrews of Cornell University. We thank U. Ciliberto and the ESCAB group for providing us with a refrigerator and a place to perform our experiments.

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