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RAMP RATE SENSITIVITIES OF SEVERAL SUPERCONDUCTING DIPOLE MAGNETS
OPERATED IN HE I AND SUPERFLUID HE II*

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Abstract

The quench current of a superconducting dipole magnet decreases from its slow-ramp value as the current ramp-rate is increased, due to heat buildup in the coil winding. This ramp-rate dependence has been measured for several superconducting dipoles in both normal He I and in superfluid He II. The heat generated by changing fields has been measured for several magnets in He II, where particularly sensitive and accurate measurements can be made of any heat input to the essentially isothermal helium bath by its temperature rise. Previously measured values of heat transfer are applied to the data from one magnet to explain its observed behavior.

The conclusion is drawn that at a given cycle rate, a superfluid He II-cooled superconducting accelerator can operate closer to the short-sample limit of the magnet's superconductor than can a corresponding He I-cooled machine.

Introduction

A series of short dipole magnets has been built and tested at LBL to evaluate various parameters pertinent to the construction of full-scale high-field superconducting magnets for particle accelerators. The general features of these magnets are described in reference 1. Briefly, they are 1 m long, with an open internal diameter of 76 mm. The coils are wound with a 23-strand Nb-Ti composite cable in two layers, similar in cross section to the Fermilab Energy Doubler/Saver magnets.² The cable is insulated with overlapping layers of 25 μ m Kapton and 50 μ m Mylar tapes. Coil winding and some pre-compression are done on a mandrel mounted on a coil-winding turntable. When the winding is complete, the mandrel is removed and the full desired pre-stress is imposed on the coil by means of a tapered collet and structural ring assembly, installed over the coil in a press. The mechanical properties of all construction materials have been well characterized in advance, to permit prediction of dimensions and pre-stress levels in the operating magnets.

The experimental test apparatus consists of a helium refrigerator-liquifier rated at 200 watts at 4.2 K, a 7000 A magnet power supply, a control and instrumentation console, a large helium vapor pump for temperature reduction capable of 30 watts at 1.8 K, and the 400 liter liquid helium cryostat containing the horizontal magnet, which is operated at 1 atmosphere pressure and at temperatures ranging from 4.4 K to 1.75 K. The description and operation of an earlier version of this apparatus can be found in reference 3. Extensive temperature instrumentation is placed throughout the cryostat. The magnet is instrumented for the particular tests being conducted, and is externally monitored and quench protected. Instrumentation readout is computer controlled for storage, display and manipulation.

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General

The current at which a superconducting magnet quenches is not only a function of the field and transport characteristic of the conductor, but is also dependent on temperature. The current can be assumed to be constant throughout the magnet winding, and the peak field depends on conductor location, but the peak temperature depends on local heat generation in and removal from the superconductor itself. Factors which influence these last items are examined below.

Fast Ramps to Quench

After a magnet is trained to operate consistently at its design field at a slow (~ 0.01 T/s) field ramp rate, more rapid ramps are imposed and the resulting decrease in field/current at quench is observed. Figure 1 shows results for several magnets operated in normal He I at about 4.4 K, normalized to their slow-ramp fields. An idealized curve, Fig. 2, can be made of the results from any one magnet at a

Fig. 1. Field at quench vs. field rate-of-rise normalized to slow-ramp fields

Fig. 2. Idealized ramp-rate sensitivity curve

given starting temperature and divided into three regions which are characterized below.

Region I. In this region ramp rates are slow, heat generation is small and potential heat removal rates are greater than input rates. There will be a small temperature difference between the interior of the conductor and the accessible helium bath, and this will degrade the level of field attainable to a small extent.

Region II. In this region we have both a higher rate of heat generation and a faster-rising current and field. The rates of heat transfer to the helium bath are smaller than the swept-field induced heat in the superconductor. The temperature of the winding consequently rises, leading to lower quench currents than at slow ramp rates.

Region III. This region is characterized by an almost constant quench current as the rate of rise is increased. The heat generation is now high enough so that practically all of it goes to increase the enthalpy of the conductor, the insulating materials and the small amount of entrained helium, with negligible heat transfer out of it. The temperature rises quickly, and to an almost constant value.

Magnet Evolution

Six magnets were made in the D-7 series with increasing coil pre-stress, as a means of increasing coil rigidity to reduce training. Rutherford cable conductor with Kapton and Mylar film insulation is used in all these magnets. We increased the coil pre-stress by heating the assembled coil (to 100C) under high pressure (above 10,000 psi). This causes the composite strands in the cable to yield. The plastic film insulation also deforms to fill gaps in the cable-to-cable interface. Bringing the cable strands into more intimate contact has the undesired effect of increasing the electrical coupling between the strands, which leads to increased heat generation during ramped or cyclic operation. The deformation of the insulation tends to close up the small helium passages between strands, reducing the heat transfer from the cable to the helium bath.

There is also a tensioned, helically-wound wrap of Nylon monofilament over each coil layer, employed to retain the initial take-up pre-stress during coil assembly and to provide circumferential helium passages. Under high pressure and prolonged heating, this Nylon wrap also deforms, tending to close the helium passages between turns. So, as a result of measures taken to decrease the training of these magnets, their ramp-rate sensitivity has been increased. Let us now examine the six magnets in this series, to explain qualitatively the behavior seen in Fig. 1.

D-7A

This was the first magnet of the series. It was relatively lightly compressed and had no heat treatment to "creep" the coil insulation and winding. The film insulation was 25 μ m Kapton with about 80 percent coverage, skip-overwrapped with 25 μ m Mylar. The 25 μ m Mylar was found to be overly fragile and was replaced with 50 μ m Mylar in subsequent magnets. This magnet had the lowest ramp-rate sensitivity of the series, as can be seen in Fig. 1. The heat generation was also the smallest as determined by cyclic heating calorimetry done in He II.

D-7B

This magnet uses a "zebra" cable with copper oxide insulation on alternate strands which greatly reduces the heat generation. There is virtually no ramp rate dependence in the field rate range used in testing the other magnets in the D-7 series.

D-7C

The major changes from D-7A were the thicker (50 μ m) Mylar insulation and the multiple "creeping" of the coil package through moderately high pressure and elevated temperature (100C). The coupling loss in the cable (interstrand current paths) is larger than in D-7A as measured in the cyclic heating experiments. The thicker and more heat-deformed insulation reduces the heat transfer from the conductor to the cooling bath, resulting in a higher ramp-rate sensitivity than that of D-7A.

D-7D

The only change from D-7C is that an extremely thin layer of B-stage epoxy was applied to the Mylar insulation. The measured heat generation during cyclic heating was the same as in D-7C. The heat transfer, however, was severely reduced, as can be seen in its effect on ramp-rate sensitivity shown in Fig. 1.

D-7G

This magnet differs from D-7C in superconducting cable used. The Nb-Ti filaments were approximately twice as large, and the coating on the strands is copper-nickel instead of Stabrite. The large filaments increased the hysteresis loss, and the resistive coating tended to reduce the coupling loss, so the net cyclic heating loss is approximately twice that of D-7C. No epoxy was used in this magnet. Inspection of Fig. 1 shows the increase in ramp rate sensitivity compared to D-7C. Interestingly, the sensitivities of D-7D, with epoxy, and D-7G, with doubled heat input, are almost the same. We can conclude that the small amount of epoxy used in D-7D decreased the governing heat transfer by half.

D-7H

This magnet has the standard conductor, has epoxy on the Mylar wrap over the conductor, and was squeezed and heated over many cycles. The measured heat generation was some 50 percent greater than D-7C and D-7D, but still below that of D-7G. The ramp rate sensitivity is the largest of the series and is attributed to having the poorest heat transfer, because the measures used to compact and stiffen the structure also closed up most of the available helium passages in and around the coil winding.

Initial Temperature

The variation of quench current/field with initial temperature at slow ramp rates is dominated by the improvement in the Nb-Ti conductor's critical current and field at low temperatures. The heat generated in the three regions, discussed above, has an influence that is now determined by heat transfer between the interior of the superconducting coil, where the heat is generated, and the main helium bath, where it is dissipated. Each temperature regime has its own rate and mechanism for transporting heat once it is transferred to the surrounding fluid. For a superconducting coil in a real magnet, these

parameters are strongly modified by the geometry, materials and methods of construction.

The last magnet, D-7H, was subjected to single ramps to quench at various rates starting from three different temperatures; 4.4 K (in normal He I), 2.25 K (normal He I near the lambda point), and 1.85 K (superfluid He II). Figure 3 displays the

Fig. 3. Magnet D-7H, field at quench vs. field rate-of-rise at three starting temperatures.

results. Qualitatively, the shapes and trends of the curves follow the analyses we have given above, i.e., at very slow ramp-rates the quench current/field is dominated by the improvement of the critical field and current in the Nb-Ti superconductor at lower temperatures. The curve for the 1.85 K starting temperature shows that higher heat transfer can permit higher ramp rates before the quench current begins to fall off. The curve of 2.25 K starts higher, but quickly falls to the same values as that taken at 4.4 K.

If we now normalize each curve to its slow-ramp value, we obtain the curves of Fig. 4. The 4.4 K and 2.25 K curves are now quite similar but not quite identical, and the 1.85 K curve still shows a considerable improvement in field for a given ramp rate. For comparison, the 1.85 K curve for one of our less rate-sensitive magnets, D-7A, is shown on Fig. 4 also.

Fig. 4. Magnet D-7H, fields normalized to slow-ramp fields.

Correlation with Measured Heat Inputs and Heat Transfer

The heat generated in these magnets has been measured, usually in He II, where it is possible to use the entire volume of superfluid helium as a calorimeter, deducing the heat input directly from the physical properties of the helium and its temperature rise, as reported in reference 4. These measurements show cyclic heating losses up to 30 watts at 0.5 tesla per second. A portion of this cyclic heat is generated in the aluminum alloy structural rings of the magnet. If we take the remaining heat, divide by the coil surface exposed to the liquid helium bath, which is taken to be 100% of the inner layer and 15% of the other three surfaces touching the compacted Nylon wrap, we will come up with an average heat flux density, some 1 to 20 milliwatts per square centimeter. We have also measured the heat transfer coefficients for a bare copper surface in various orientations, with both open and restricted geometries.⁵ It is noted also in reference 5 that these results compare well with data taken by others. If these data are now compared to the effective heat transfer coefficients for one of our magnets, they are seen to differ by more than an order of magnitude.

Conclusions

In a series of almost identical magnets, relatively minor changes in materials and construction techniques result in large changes in sensitivity to fast ramp-rates. These magnets are moderately lossy, (30 watts at 0.5 T/s), due to the low resistance of the Stabrite strand coating that governs the inter-strand coupling. Serious ramp-rate effects are observed in these accelerator dipole magnets in the heat generation range of 1-10 watts/meter. Significant differences are observed for changes in insulation and ventilation details. Improved heat removal is desirable and can be obtained by changing the relevant constructional details.

The enhanced heat removal capabilities of He II result in a reduced ramp-rate sensitivity for magnets pulsed or cycled in superfluid He II. At a given rate of field change, magnets operated in He II can operate closer to their (higher) short sample limit than can the same magnets operated in normal He I.

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