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1.8K CONDITIONING (NON-QUENCH TRAINING) OF A MODEL SSC DIPOLE*

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Abstract

The accepted hypothesis is that training quenches are caused by heat generation when conductors move under Lorentz force. Afterwards no conductor motion will occur until a higher field and greater Lorentz force acts. If superior heat transfer and/or greater temperature margin is provided by operating at lower bath temperature, one might expect that the heat generated by conductor motion will not cause a runaway temperature increase, or quench. To test this hypothesis, the central dipole field in SSC model magnets was ramped at 1.8 K to 7.1 tesla without the magnets' quenching. The bath was then raised to 4.4 K and the magnets quenched at their short sample limits of 6.6 tesla or higher. Comparison with similar magnets trained in He I at 4.4 K is made and the significance of the non-quench training on system operation is discussed.

Introduction

It is generally accepted that training in high current density magnets, such as the SSC guide field or "ring" dipoles, is caused by heat generation when conductors move rapidly under Lorentz force. The SSC dipoles use fine NbTi filaments in a small wire strand, so those instabilities associated with flux motion are not considered to be a problem. After a training quench, no conductor motion will occur until a higher field is reached and greater Lorentz force acts on the windings.

The time and refrigeration capacity required for recooling the coil after it has quenched are the major expense items associated with the training process. A method is needed for testing/training coils in which the various internal effects that cause a quench occur while the quench itself, and thus the expensive after-effects, are avoided. If superior heat transfer and/or greater temperature margin is provided by operating at lower bath temperature, one might expect that the heat generated by this conductor motion will not cause a runaway temperature increase, or quench.[1]

The precise nature of the training behavior depends on conductor design, coil prestress (which is dependent on the mechanical structural details), and the nature of friction at the various surfaces that separate the magnet components. Friction is important since rapid, "stick-slip" motion is thought to be one possible source of small scale heating that initiates the quenches. Friction also affects the degree to which training is retained (memory) or lost (amnesia) on temperature cycling between room and operating temperatures. Additional potential causes for training in some magnets are the bonds, either glue or solder, between the various components of the winding package, that can break under the Lorentz force. Training in coils of this type is thus associated with the breaking of stronger and stronger bonds at higher and higher currents/fields. If epoxy bonds are broken, it would be a permanent change and the magnet would be expected to have a good memory, on cycling to room temperature for example. Because energy is deposited at the site of the broken bond, it is likely that broken bonds between insulation and conductor, or between two conductors, are the source of training. The bonds between two insulators are thermally isolated from the conductor and are thus not likely to be the culprit. As might be expected for a subspeciality with such broad implication for accelerator commissioning and operation, there is a small but fiercely involved band of training aficionados with strong opinions as to the cause and prevention of quenches.

Low-Temperature Conditioning

To minimize the materials in the magnet, and hence the cost, the dipoles that have been designed for the SSC have minimum possible size based on beam quality considerations (inner coil bore is 4 cm diameter) and maximum coil current density. For the specified 6.6 tesla central field, the peak field is close to 7 tesla and the coil current density is some 46,000 A cm^{-2} overall. The Lorentz forces are large, the ratio of stabilizing copper to superconductor is low (1.3) and at the operating temperature of 4.35 K, the temperature margin is only ~0.3 K. Therefore, some training is usually observed, with 3 or 4 quenches to full field being typical for the developmental magnets produced so far. The best magnets have achieved full field on the first or second quench, and the worst have required as many as eight quenches and started at 85% of full field.

Low temperature "conditioning" basically consists of two steps. First, the magnet is cooled in a helium bath to a temperature well below the operating temperature. Second, the current/field in the magnet is ramped to above the nominal operating values. Ideally, this current is reached without a quench and, ipso facto, it is conditioned. It will reach the operating current/field when rewarmed to 4.35 K without quenching. Obviously, it takes longer and costs more to cool to lower and lower temperatures; thus, we would like to condition the magnets at as high a temperature as possible.

Because there is little quantitative data on the energy releases that lead to training, it is not possible to predict the highest effective conditioning temperature.

Two factors are known to be important in the ability of a conductor/coil to resist quenching. These are the temperature or enthalpy margin and the dynamic heat removal capability of the fraction of the helium bath in immediate contact with the conductor. The margin of the conductor is a monotonically increasing function as the temperature decreases. However, as the specific heat is proportional to T^3, the enthalpy available between the test temperature and quench temperature of say 4.6 K will double as the temperature is decreased from 4.35 to 4 K, will increase to 3 times the original value by 3.5 K, and finally at about 2 K

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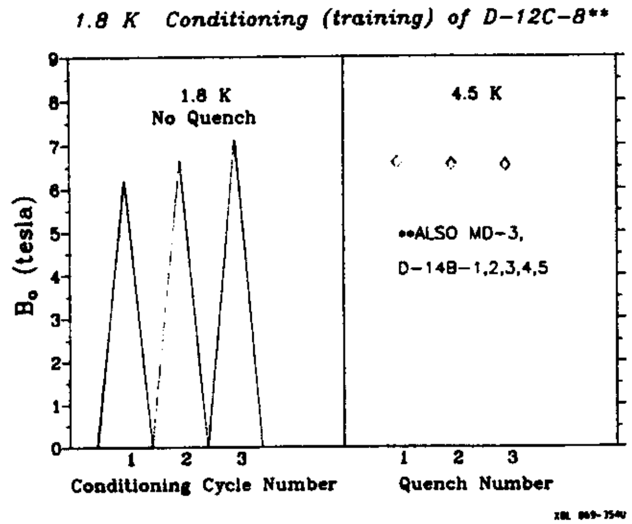

Fig. 1. Low Temperature Conditioning of D-12C-8

increase to 4 times the original value. Transient heat transfer of helium has been studied extensively, but it is not clear that geometries relevant to the SSC dipole windings have been considered. From the general data on subcooled helium at atmospheric pressure, one concludes that, quantitatively, heat transfer changes only slightly (decreases) between 4.3 K and 2.16 K (T_λ) and then rises sharply to a peak near 1.8 K. This result is a major reason for choosing 1.8 K as the operating point for these tests.

Example of 1.8 K Conditioning Dipoles D-12C-8 and D-12C-7

Since magnet training usually is thought of as quenches at successively higher currents, we suggest the term "low-temperature conditioning" to refer to non-quench training. Figure 1 illustrates the process and results achieved. The SSC model dipole magnet D-12C-8 was first cooled to 1.8 K and then the current was cycled to 7200 A, some 10% above the expected 4.4 K quench current of 6600 A. The magnet did not quench at the 7200 A level because the critical current is raised well above this value at 1.8 K and the superior heat transfer of superfluid helium at 1.8 K carries away heat associated with small conductor motions under Lorentz force loading more quickly than does normal helium at 4.35 K. Since the loading at 7200 A operation is greater than that at the 6600 A level at 4.4 K, we expect that there will be no quench inducing conductor motions when at 4.4 K the magnet is subsequently charged to 6600 A. Figure 1 shows that this is indeed the case. An identical model magnet, D-12C-7, was trained in He I at 4.4 K and its behavior is compared with the low temperature conditioned D-12C-8 in Fig. 2.

Further Example - MD-3

The low temperature conditioning should work even for a magnet with poor inherent training behavior if the energy release in the motion is small enough. Results of tests of a matched pair of dipoles with underclamped ends are shown in Fig. 3. MD-2 was trained at 4.4 K; its first quench was at a current 15% below its plateau value, which took twenty quenches to reach. Its twin, MD-3, which was conditioned at 1.8 K, was within 2% of its plateau on its first 4.4 K quench. Two percent is within the usual scatter for plateau quench values.

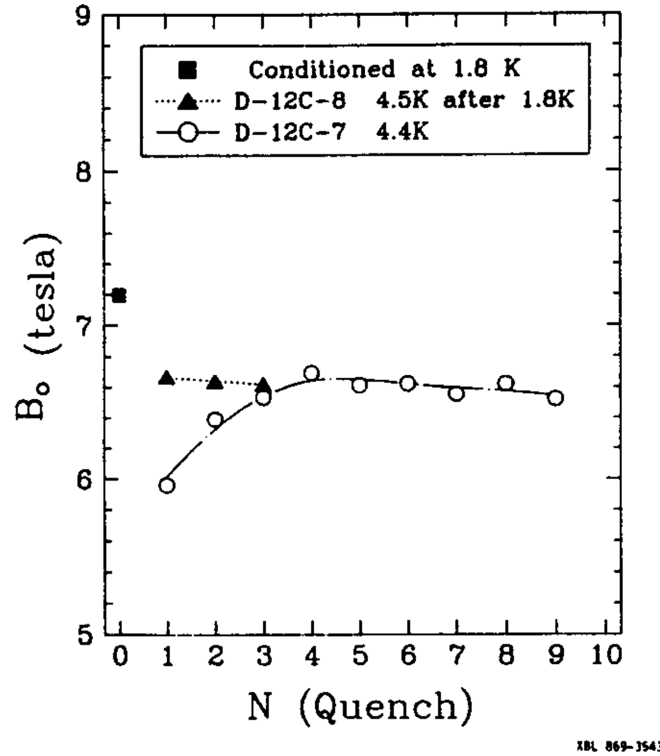

Fig. 2. Training at 4.4 K vs. 1.8 K Conditioning

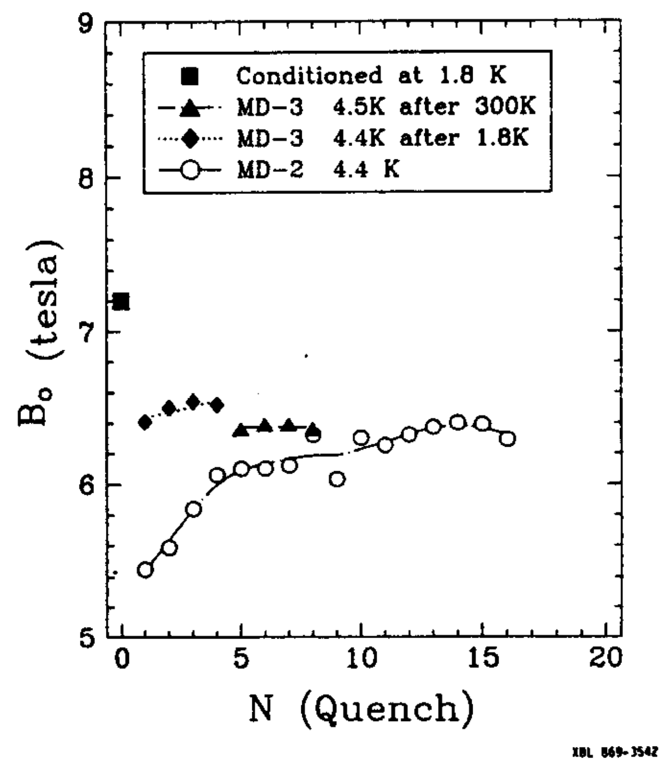

Fig. 3. Training of MD-2; Conditioning of MD-3

Training Results for LBL-SSC Dipole Magnets

Twelve one meter long dipole models have been tested in the past year and their training results are shown in Fig. 4. Five magnets were trained in He I at 4.4 K and seven were low-temperature conditioned to 7200 A. Model dipole D-14B-5 is the only conditioned magnet that did not reach its short

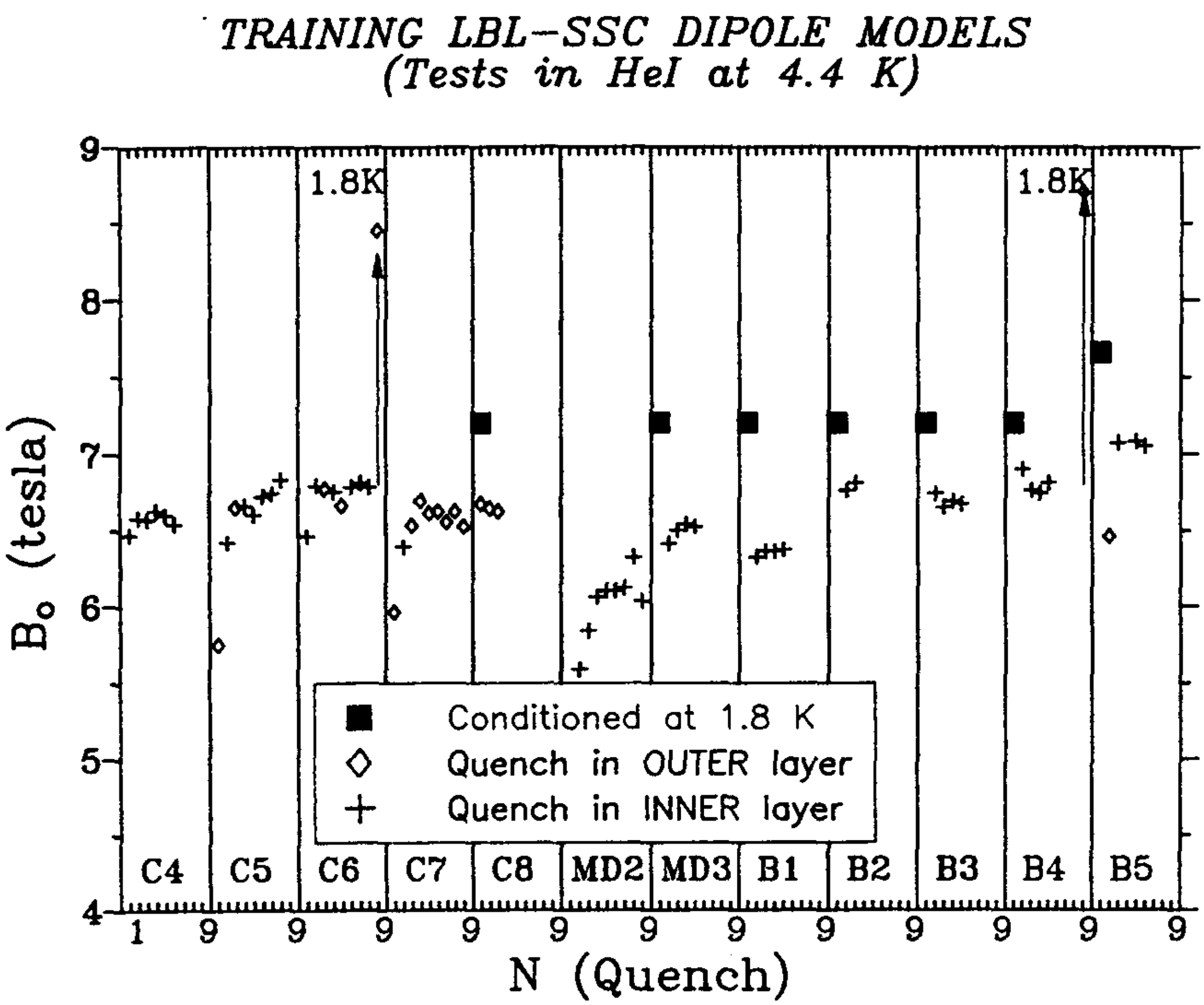

Fig. 4. Training of 12 LBL-SSC Dipole Models

sample limit on its first 4.4 K quench, and it did reach it on its second.

<u>First Quench Current at Various Temperatures</u>

As discussed above, six magnets that were conditioned by cycling the current to 7200 A between 1.8 K and 2.0 K achieved short sample performance at their first excitation in He I at 4.4 K. A natural question arises as to whether a different low temperature, and a different cycle current, might be as effective and yet more convenient than those used to date. Since each test presumably requires a new untrained magnet, a test of the two variables independently would not be a simple process. To shed more light on the process, however, we tested four of the conditioned magnets for their first quench currents at several temperatures during a second cooldown from 4.4 K to 1.8 K, i.e., after testing at 4.4 K. One expects that, on cooling, the quench current should follow the short sample curves until, at some lower temperature, the short sample value is above the 7200 A conditioning value. For higher currents, the magnet is not conditioned and may require a training series of quenches to reach its short sample limit. We make only one quench at each of several intermediate temperatures and then continue to lower the temperature toward the target 1.8 K. These data are shown in Fig. 5 and suggest

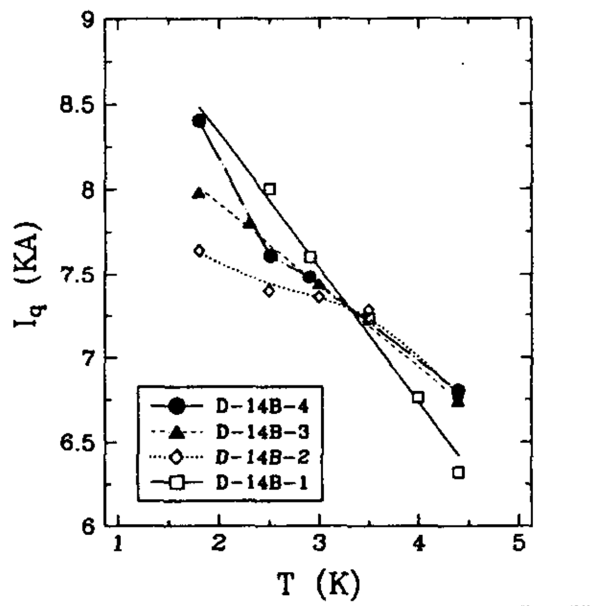

Fig. 5. Reduced Temperature Conditioning Training LBL-SSC Dipole Models

that the conditioning temperature, for 7200 A, could be raised to between 3.0 K and 3.5 K, and perhaps simplify the cryogenic problems as compared with 1.8 K. A reasonable conjecture is that if any conditioning temperature had been chosen, the first quench current would be that shown in Fig. 5. Then, at a given temperature, any conditioning current below the first quench current could be used for non-quench training. Once the final structure for the SSC dipoles has been decided upon, these experiments should be repeated to determine the best conditioning parameters. Of course, identical magnets will not all be truly identical; thus, some additional temperature or current margin must be included to accommodate the extreme variations.

Retention of Training, Memory and Amnesia

We have discussed the mechanical movements of the superconductors responsible for the phenomenon of training. Implicit in the magnet's quenching at successively higher current levels is that sufficient friction is present to prevent the conductor, which has moved, from returning to its previous location when the current and Lorentz force are reduced. Usually, the conductors stay in their trained location if the magnet is kept at liquid helium temperature; but when the magnet is warmed to room temperature, the various magnet components expand at different rates and amounts. Internal stresses and frictional forces may be reduced enough to allow some superconductors to recede from their final trained positions, and some or all of the training may have to be repeated.

If no retraining is required, and full field performance is demonstrated on the first excitation on recooling to 4.4 K, we use an anthropomorphism and say that the magnet has a good memory. Operationly, such a magnet is satisfactory since it only has to be trained once and can then be expected to perform properly at another place and later time. However, if the magnet requires retraining after a thermal cycle to reach operating field, it is unsatisfactory since one would have to retrain it after warmups. One also is concerned with long term relaxation due to creep and trauma associated with transportation shocks.

Two magnets exhibited perfect memory at 4.4 K upon thermal cycling and one, assembled with low prestress, had its first quench 5 percent below its previously achieved short sample value. Overall, this class of magnets retained the training that had been effected by the low temperature conditioning procedure.

System Implications of Conditioning and Retention of Training

The SSC will contain some 7600 dipoles in an 83 km circumference. Ten refrigerators will be distributed around the ring and the helium cooling circuits are each about 4 km long. For safety reasons, when one magnet quenches, the other four dipoles in the half cell are driven normal with pulse heaters. Several megajoules of stored magnetic energy are dumped into the helium and, because of the pressure drops in the long feed lines, times of the order of an hour are required before the dipoles are cooled and ready to run again. If there are relatively few unexpected quenches, there is no particular problem. But, if many of the magnets required retraining in place, at the operating temperature of 4.35 K, and they averaged one or two quenches each, it might be impractical to train the entire ring up to full field. Low temperature conditioning (reconditioning in thiscase) would entail special auxiliary refrigeration units that could subcool sections of the ring in sequence, and these shorter sections could be conditioned as needed.

Without the low temperature conditioning option available, the SSC prototype dipoles would have to demonstrate acceptable retention of memory under one or more of the various lengthy and costly modes mentioned in the section above.

Conclusions

Low temperature conditioning, or non-quench training, has been demonstrated in a number of high current density, small bore, SSC accelerator model dipoles. This behavior supports the accepted hypothesis that magnet training is associated with rapid conductor movement as the Lorentz force exceeds some frictional restraint. The exact nature of these frictional restraints are not well understood, but are intimately related to retention of training.

The advantages of quench training reduction or elimination are so great from the system's standpoint that consideration should be given to incorporating temperature capability below 4.3 K in magnet test facilities.

Acknowledgements

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References

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