MAGNETIC CONDITIONING IN SUPERFLUID

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Publication Date
1988-08-01

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Presented at the Japan–U.S. Seminar on Basic Mechanisms of Helium Heat Transfer and Related Influence on Stability of Superconducting Magnets, Fukuoka, Japan, August 29–September 2, 1988

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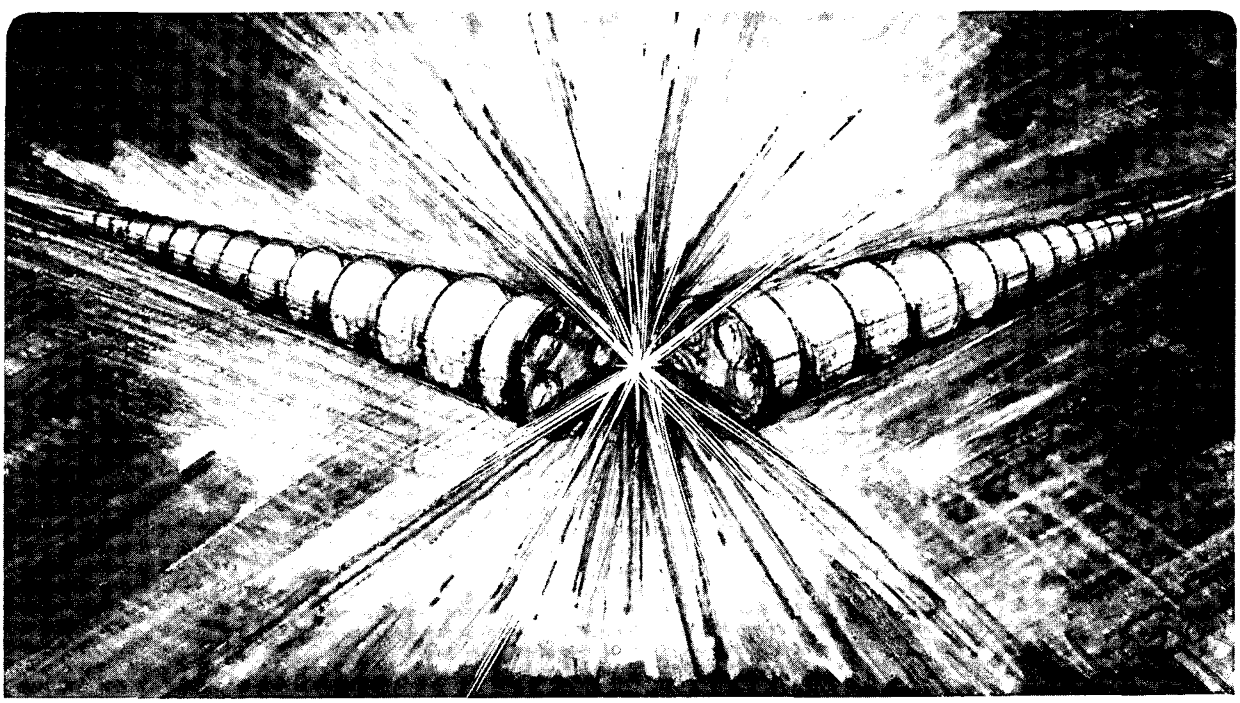

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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SSC-MAG-215
LBL-25795

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76F00098.

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ABSTRACT

Improvements in superconducting magnet technology have reduced to a handful the number of training quenches typical of dipole magnets. The number of training quenches in long (17 m) and short (1-2 m) SSC magnets are now about the same (operating at 6.6 tesla and 4.4 K). Yet the steps necessary to totally eliminate training are in the future R&D plans for magnet construction and conductor motion prevention. The accepted hypothesis is that Lorentz forces and poor mechanical properties of superconducting cables are the cause of conductor motion. Conductor motion reduces the stored energy in the cable by converting it into heat. The small amount of heat generated (millijoules) during motion is usually enough to quench the magnet when it is close to short sample. During training, the magnet performance normally improves with the number of quenches. It is not the quench itself that improves magnet performance but rather the fact that once conductor motion has occurred it will probably not repeat itself unless subjected to higher forces.

Conditioning is a process that enables the magnet to reduce its stored energy without causing a premature quench.[1] During the conditioning process the magnet is further cooled from its operating temperature of 4.4 K to 1.8 K by converting He I into He II. As a result the magnet is placed in a state where it has excess stability as well as excellent heat transfer capabilities.[2] Although this does not eliminate motion, if the magnet is now cycled to ~10% above its operating field at 4.4 K (which is above short sample) the excess stability should be enough to prevent quenching and reduce the probability of conductor motion and training once the magnet has been warmed back up to its operating temperature of 4.4 K.

INTRODUCTION

Training and premature quenching have always been a part of superconducting magnet technology. A naive way of looking at the performance of a high field superconducting magnet is to assume that it is a simple thermodynamic system that approaches its critical values B, J, T (field, current density and temperature) in a quasistatic way. This way, a magnet is

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superconducting or not depending on its thermodynamic state. In this sense the concept of stability is as simple as an on-off device with a quench occurring in a predictable manner, usually at short sample values. Once a quench has occurred, two different approaches may be taken to protect the magnet from the high temperatures associated with its normal state. The first is the concept of cryostability, where a large amount of copper is used to shunt the current when joule heating occurs. During the quench of such a magnet, sufficient cooling is normally available to slow the quench propagation and even reverse it without a need to turn off the power supply. This type of design is usually associated with fusion magnets where the stored energy is high (megajoules). The second approach is more typical of accelerator magnets. In these magnets, once a quench occurs it cannot be stopped and protection can only be achieved by spreading the stored energy over a large volume, reducing the density of heat production, while at the same time inverting the power supply and extracting the energy. In such magnets, the quench velocity is usually high (10 to 100m/s) and the Cu/SC ratio low (1.3-2:1). In this manner, only a fraction of the stored energy will dissipate into the helium.

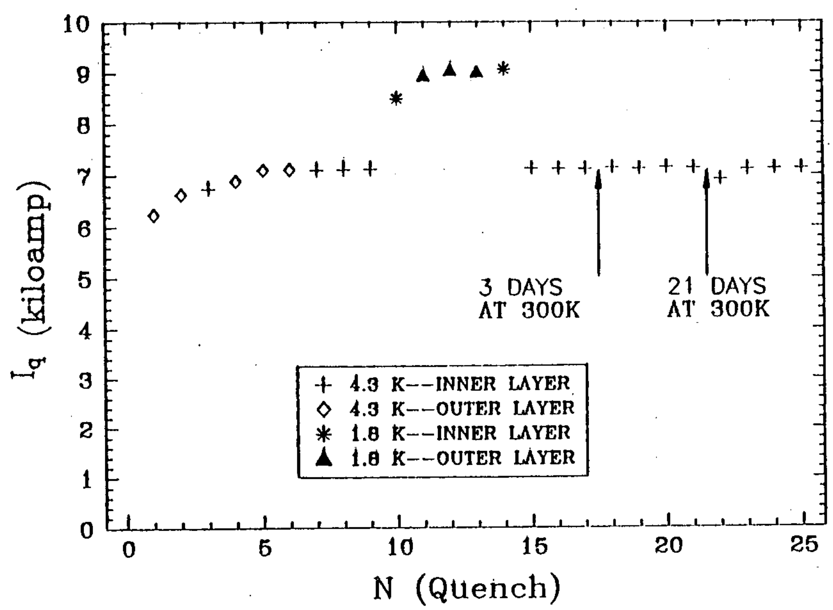

Figure 1. A typical training curve for 1m long SSC dipole (magnet D-15A-4F).

In both types of magnets - cryostable and high current density - the concept that a quench always occurs at short sample is false. In a process called training (Fig. 1), a magnet quenches prematurely; however, with each subsequent current cycle, it exhibits an increase before quenching again until it finally reaches short sample performance. The process of training is not always guaranteed nor is there an assurance that it will retain its training after a warm-up cycle. Experience has shown that most magnets do exhibit training and that some suffer amnesia and require additional training after a warm-up cycle.

In training magnets, the approach to short sample performance is done in a nonquasistatic way. The combination of high Lorentz forces, poor mechanical properties, and the use of cryogenic temperatures make an ideal environment for conductor motion and cracked epoxy. As a result, small amounts of energy (order of millijoules) can easily be released, raising the local temperature and resulting in a quench. An SSC dipole at 6.6 T produces a sideways force of Fx=8000 lb for each inch in length.[3] The cable modulus is typically $1.5 \cdot 10^6$ psi.

TRAINING AND CONDITIONING

In Figure 2 and 3, the training curves of 21 magnets have been plotted. These magnets are 1m long SSC dipole models that have been designed and built at the Lawrence Berkeley Laboratory. The two layer magnets are made from superconducting cable with 23 strands and 1.3:1 Cu/SC, and 30 strands and 1.8:1 Cu/SC in the inner and outer layers, respectively. To apply prestress to the coils, interlocking collars have been used and the entire assembly was placed inside iron yokes.

In magnet series C (Fig. 2), stainless steel collars were used. Aluminum collars were used in series B and A (Fig. 3). The amount of prestress in these models varied, and, in extreme cases, the stress was as low as to be practically nonexistent and as high as 10 Kpsi. The magnet's cables were from different manufacturers and were of different dimensions as well as having different short sample values.

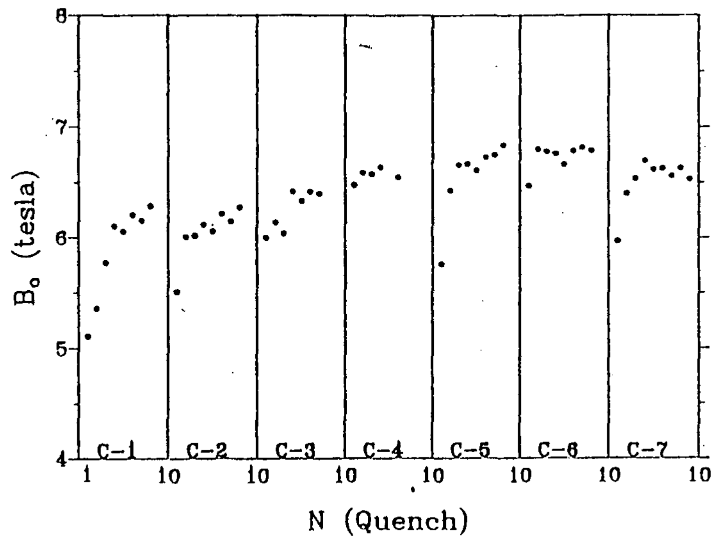

Figure 2. Training curve of 1m SSC dipole models with stainless steel collars — C series.

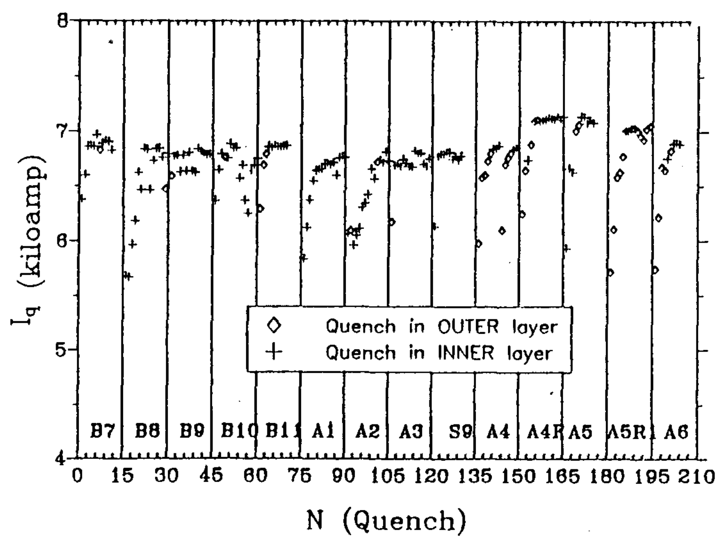

Figure 3. Training curve of 1m SSC dipole models with aluminum collars — B and A series.

These magnets provide a limited but useful statistical base for the evaluation of training. The most common parameter, the prestress, focused upon in association with training, does not reveal a great deal of sensitivity. Attempts to correlate the prestress in these magnets with training performance were proven unsuccessful. Regardless, all of the magnets have trained, the best of them having a single training quench. The magnets have shown low sensitivity to prestress, the Cu/SC ratio, and the margin of stability. A fairly significant number of training quenches occurred in the outer layer which has a higher Cu/SC ratio than the inner layer, as well as a higher safety margin.

It is, therefore, natural that, when a magnet behaves differently in this environment, it is noted; when it happens again, we realize we are on to something. When the first magnet conditioned in He II exhibited no training, we were hopeful; when the second magnet repeated the behavior, we knew that conditioning had something to offer. The magnet was conditioned by being cooled to 1.8 K before it was charged. Then the magnet was cycled 3 times to about 10% over its 4.4 K short sample level. During the conditioning process, the magnet reached 7.2 tesla, but did not quench since it was way below the ~9 tesla short sample performance expected at 1.8 K. Following this process, the magnet was warmed up to 4.4 K and ramped to a quench.

The conditioning process, although seemingly curing the magnet training, does not shed any light on where motion occurred, if at all, and what could be done to prevent it in the first place. On the other hand, it points out that magnets do not have to train.

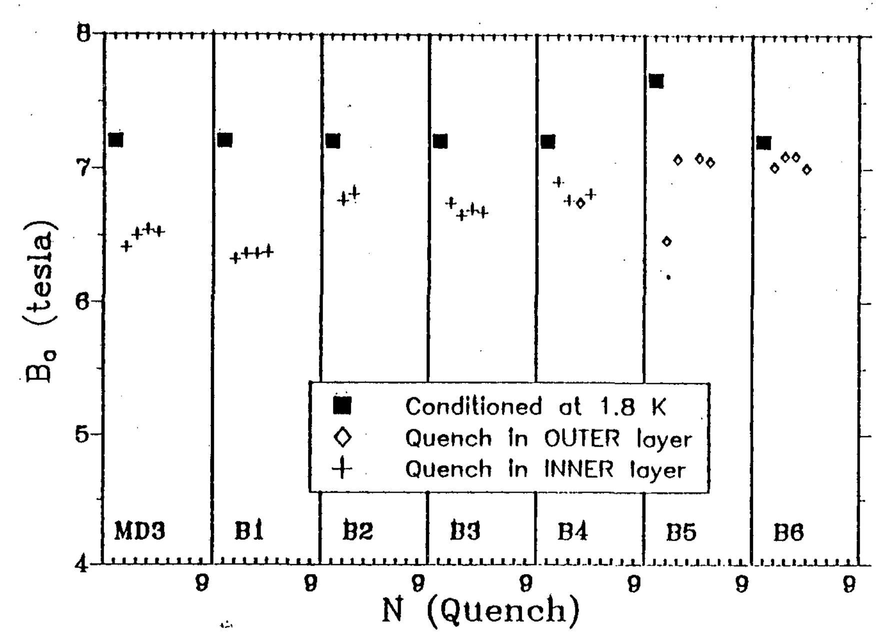

Figure 4. Training curves of 1 m SSC models after 1.8 K conditioning — B series.

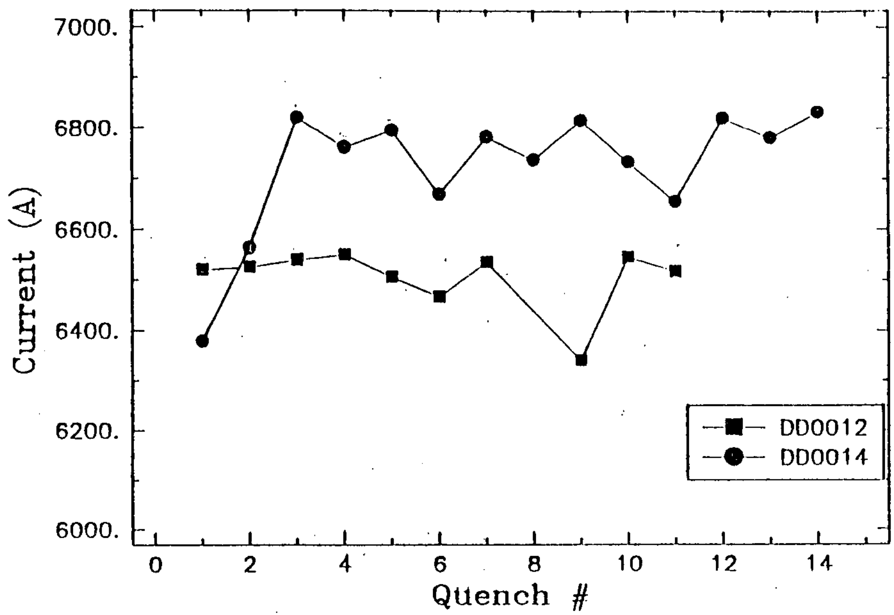

Figure 5. Training curves of recent 17m long SSC dipoles.

CONCLUSION

About half a dozen long SSC dipole magnets have now been built and tested. Although the training performance of the first few models were rather disappointing, the results from the last two models have been very encouraging (Fig. 5). Nevertheless, magnet training is still an open question and with the prospects that about 8000 long magnets will have to be built, magnet conditioning is a real possibility. In anticipation of such a possibility, reduced temperature capabilities have been incorporated into the Fermi National Accelerator Laboratory test facility where the SSC long magnets are being tested.

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