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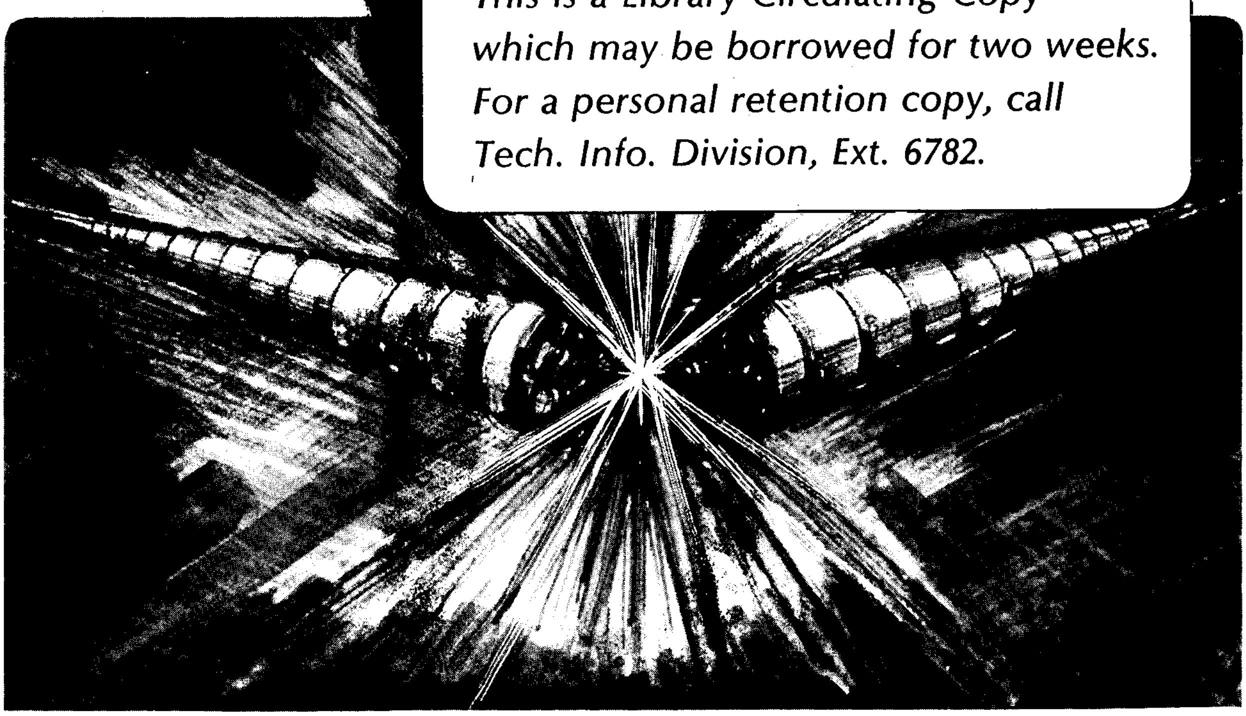

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Introduction

An eight-pancake Nb-Ti dipole magnet, with bent up ends, called D-10B has been built and tested, see Figure 1. This magnet is a Nb-Ti version of a Nb_3Sn magnet designed to produce a 10-tesla dipole field in a 40 mm diameter aperture. The pancake design is used for the heavy 12,000 ampere Nb_3Sn cable because of the mechanical difficulty in winding such a heavy cable into the conventional nested cylindrical shell configuration with a 2" inner winding diameter. The Nb-Ti version operates at 1.8K, in He II, has superconducting cable half as thick as the Nb_3Sn cable, and operates at half the operating current: 6,000 A rather than 12,000 A at 10 tesla. Both magnets are approximately one meter long.

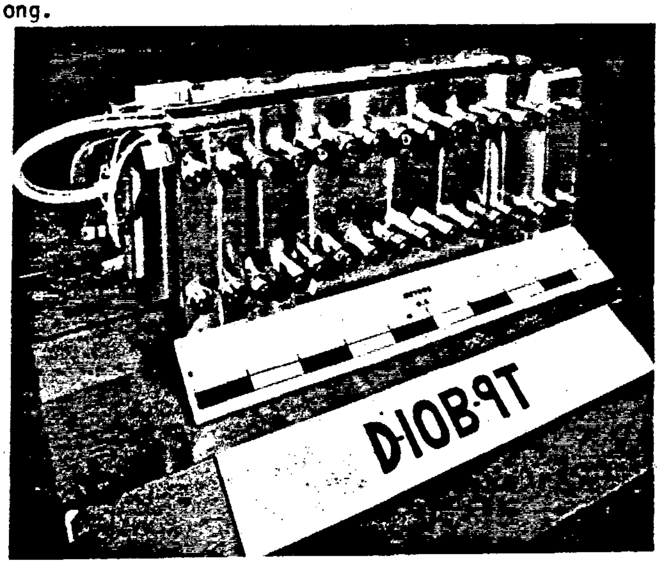

Figure 1. D-10B magnet

D-10B was tested from January 26 to February 2, 1983 and reached short-sample performance in both He I and He II after moderate training. The central field at 4.3K is 7.0 (± 0.1) tesla, and at 1.8K is 9.1 (± 0.2) tesla. Ramp rate sensitivity and cyclic heating data were also measured.

Magnet Description

Construction

The block, or flat pancake, coil geometry of this magnet can be seen in Figure 2, which shows the D-10B cross section. The coil sections are wound from heavy rectangular cable in flat pancake pairs, commonly called racetrack windings. The particular geometry was chosen to enable heavy Nb_3Sn Cable to be wound into a small aperture dipole.

While waiting for the experimental Nb_3Sn cable to be fabricated, we built a model with Nb-Ti cable to test the new geometry for fabrication practicality and also to test the magnet for training and other pertinent behavior. This Nb-Ti magnet is called D-10B and is reported here.

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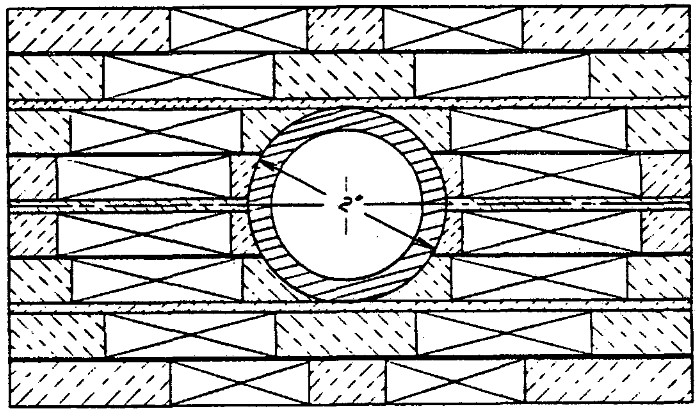


Figure 2. Coil cross section

The target pressures to be achieved at final assembly were based on code results from "Poisson" and "SAP4" which show that horizontal pressures on the outside of each layer due to 10 tesla central field, when the inside turns are kept under minimum compression, will be approximately 8700 psi for layers 1, 2, and 3 and 17,000 psi for layer 4. Layer 1 is nearest to and layer 4 is farthest from the midplane. Vertical pressure averaged about 1000 psi. The magnet structure and assembly clamps were designed to produce 7000 psi prestress horizontally and 5000 psi vertically.

The superconducting cable is wrapped with 1 mil (25 micron) thick overlapped Kapton, which is coated with B-stage epoxy except for the inner four turns of each pancake. The pancakes are wound in pairs and assembled, with their inner NEMA G-10 islands and outer G-10 spacers, into the top and bottom half magnets in a clamping structure in which the half units are baked to 120°C to cure the B-stage epoxy. The two halves are then re-assembled in the final clamping structure, and the magnet is pre-stressed using shims and external bolts. Strain gauges are used in the G-10 spacers within each pair of pancakes to adjust the pre-stress through the use of shims. Room temperature pre-stress in the range of 6000 psi was achieved. Details of the clamping structure, pre-stress required, and strain gauge measurements appear in Reference 1. Figure 3 shows a cross-section of the coil in its aluminum and stainless steel bolted structure. More details of the design are given in Refences 2 and 3.

Nb-Ti Cable

A Rutherford rectangular cable of 27 strands of 31.8 mil (0.81 mm) diameter is used. For highest current density, a low copper-to-superconductor ratio of 1:1 was specified, and possible problems with conductor stability were anticipated. The actual Cu:S.C. ratio turned out to be even lower, 0.86:1. The strand contains 409 Nb-Ti filaments, each approximately 29 microns in diameter. Each strand was insulated with Stabrite.

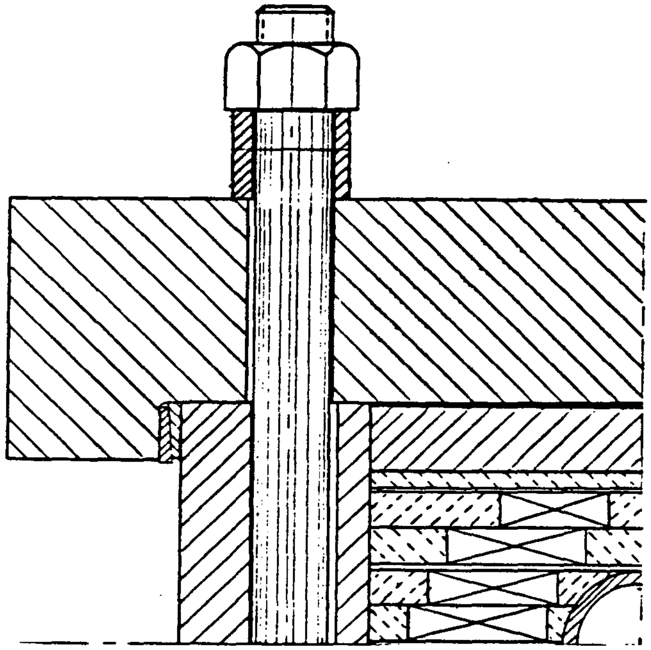


Figure 3. Magnet cross section

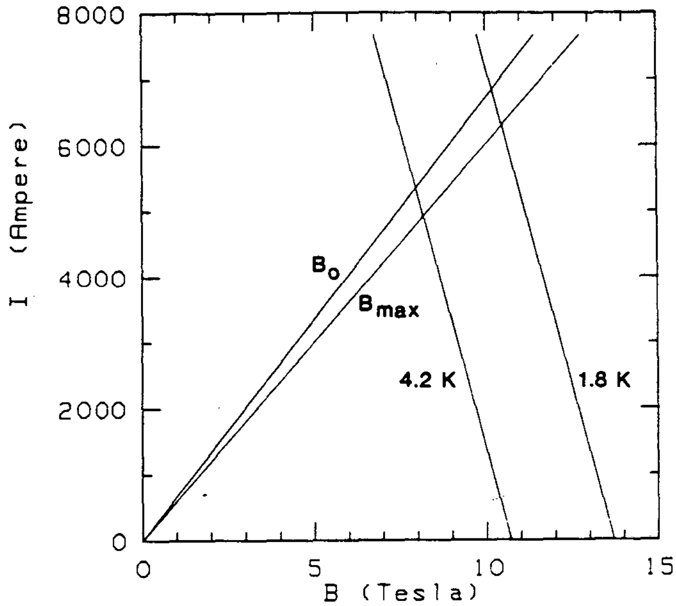


Figure 4. Load lines and short-sample curves

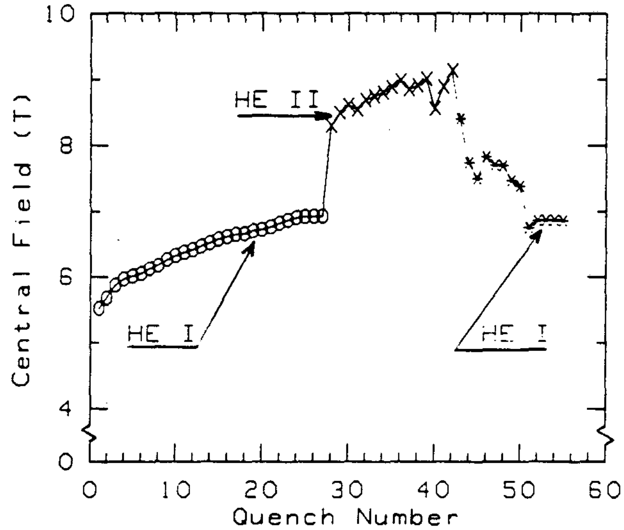


Figure 5. Training history

The cable dimensions, without insulation, are 0.056" x 0.446" (1.42 mm x 11.33 mm). The manufacturer (the superconductin strands were fabricated by Magnetic Corporation of America and the cabling was done by New England Electric Wire Corporation) had considerable trouble in supplying this cable due to wire breakage during cabling. Various repairs of sections of cable had to be done at LBL to complete the magnet. Therefore we have no information on how uniform the cable might be throughout the magnet.

The load lines for the central and maximum fields are graphed on Fig. 4 together with the short-sample curves. Short sample measurements were made at the MIT Francis Bitter Magnet Lab by Yuki Iwasa and were also checked by A.D. McInturff of FNAL. We, at LBL, extended the 4.2K curve test to the 9 to 11 tesla range. The 1.8K short sample curves were constructed from the 4.2K curve by assuming that the 4.2K current line is translated 3.0 tesla to the right for the 1.8K values. This relationship was previously measured at MIT for a different Nb-Ti sample.

Test Results

Training

Figure 5 shows the training history of D-10B. The first quench at 4.3K was about 80 percent of its short sample value, or some 5.5 tesla central field. The training was moderately slow, some twenty five (25) quenches to short sample. It is not clear whether this slow training is due to a superconductor stability problem, structural and pre-stress problems, or due to some particular defect in one pancake pair from conductor or manufacturing defects. 69 percent of all quenches occured in pancake 4 bottom, and 87 percent of all quenches occured in the pancake pair 3 and 4 bottom. The maximum field reached at 4.3K is 7.0 (± 0.1) tesla and we believe it to be short sample performance because the same current is reached before and after operation, at higher currents, in He II. Also the character of the quenches, which is quite reproducible, is that of conductor operating at short sample. Fig. 4 suggests that true short sample behavior would be a few percent higher but there may be some portion of the cable that is a bit lower in performance than the samples that were measured.

The He II data, at 1.8K, show the initial large increase in magnet current that we expect, but then some 10 to 15 quenches are needed to attain short sample performance. Again, the reason for this slow training is not clear. From quench 42 to quench 51, the helium bath is being raised from 1.8K to 4.3K. The magnet, though lossy, could be ramped faster than 1 tesla per second. Extended cyclic heating experiments were carrried out up to 0.5 tesla per second.

Pulsing Losses, Cyclic Heating

a. Calorimetric Loss Measurement In He II one can measure the heat generated by magnet cyclic heating through monitoring the bath temperature movements. Inspection of the curve (Fig. 6) shows that the D-10B behavior is linear, which means the loss is hysteretic in nature, occuring in the superconductor itself.

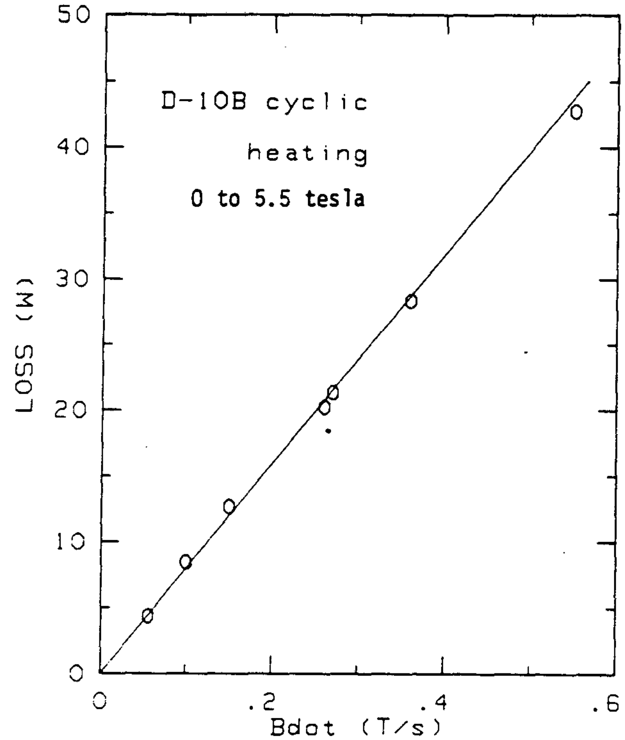
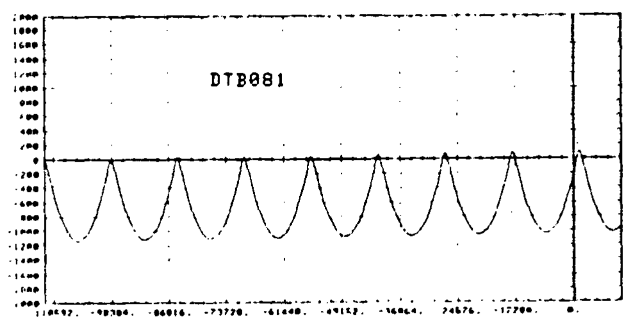


Figure 6 . Losses during cyclic heating — calorimetric

b. Electrical Loss Measurement An electrical loss measurement technique was also used to measure cyclic heating. Voltage and current signals were sampled and converted to digital data in the 12 bit A to D converter built into a Le Croy data logging system. The data is then multiplied and summed in our HP-1000 computer. A typical run output is shown in Fig. 7 where the integrated power vs. time is displayed together with an expanded scale for the successive minimums.



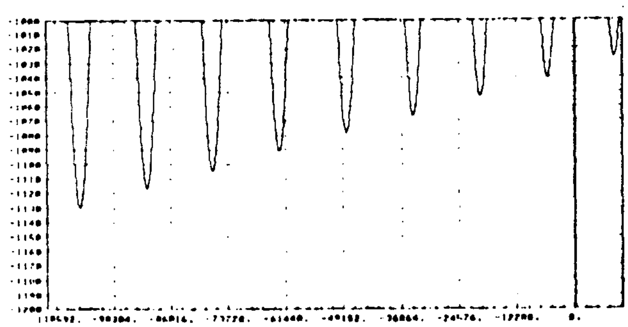


Figure 7. Integrated power vs. time - electrical

The data for the electrical loss measurements in He II display a constant power offset compared to the calorimetic data. We attribute this to an inadequate number of bits in our present A to D converter, and a new converter with 15 bits is being procured. Electrical loss measurements in He I were also made and, with the constant power term subtracted, the data is in agreement with the calorimetric data and what one expects when operating in He I rather than He II. More extensive experimental data appear in Ref. 4 and 5.

Conclusions

1. It is possible to achieve high dipole fields, greater than 9 tesla, with small (50 mm) apertures, with a high-current-density, flat-pancake geometry as incorporated in this magnet design. Nb-Ti operating in both He I (4.3K) and He II (1.8K) reached its short-sample limit. Training was somewhat slow but regular; the reasons for this are not understood.

2. It is possible to use very little copper on the Nb-Ti superconductor (Cu:SC = 0.86) and still achieve a very high field and to protect the magnet against damage upon quenching. The overall quench propagation velocities were similar to cylindrical-shell-geometry magnets with Cu:Nb-Ti ratios in the range of 1.5 to 1.8:1.

3. 87 percent of all quenches occured in just two of the eight layers, so a defect may have been responsible for the slow training.

4. A mechanical support structure has been developed which allows the pre-stress in both the horizontal and vertical directions to be controlled during fabrication and the operating stress to be monitored during operation.

5. Heat removal up to 45 watts over extended periods of current pulsing was observed. Cyclic heating experiments were done up to a rate of 0.6 tesla per second.

Acknowledgments

Appreciation is expressed to the builders of this magnet: Roy Hannaford, Jim O'Neill, Al Borden, Tom Young, Fred Perry and Larry Parsons. Not only was a new winding and assembly method successfully carried out on the first attempt, but scores of special parts had to be rapidly machined, fitted and sometimes invented on the spot. Damaged superconducting cable had to be laboriously repaired with strand by strand splicing. The efforts of Rob Althaus in getting and keeping all the electric and electronic components operative are gratefully acknowledged. Experimental operations, including operation of the cryogenic and refrigeration systems were ably and cheerfully carried out by Bruce Heppler.

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