IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

PERFORMANCE OF DIPOLE MAGNETS IN HELIUM II*

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Abstract

Data from tests in He II of four 1-meter-long magnets are presented. The maximum quench current is increased up to 30 percent, compared with tests in He I. Data from calorimetric measurements of heat generated during cyclic operation are presented. Quenches were induced by heaters placed near the conductor, and the energy required to induce quenches in He II and in He I are compared.

Introduction

Degraded performance and subsequent training of pulsed accelerator dipole magnets is often attributed to coil mechanical motion and associated local heat generation. We and others, have conjectured that the enhanced heat transfer to superfluid helium would remove this heat without quenches. In addition, the increased current capacity of superconductors at 1.8K should allow magnet operation at increased fields, subjecting the windings to stresses of ~1.5 to 1.7 times greater than the normal operating stress at 4.2K thereby accelerating or circumventing the training process.

The Superfluid Test Facility

A facility for testing superconducting accelerator magnets in a pressurized bath of helium II has been constructed and operated [1,2]. The cryostat accepts magnets up to 0.32 m diameter and 1.32 m length with current to 7000 A. In initial tests, the volume of helium II surrounding the superconducting magnet was 90 liters. Minimum temperature reached was 1.7K at which point the pumping system was throttled to maintain steady temperature.

A two reservoir system, similar in principle to that of Claudet[3] and Bon Mardion[4,5], is used. The lower vessel, which contains the magnet and is completely filled with liquid, is pressurized to slightly over one atmosphere by contact with an upper saturated helium bath. This 28-liter bath also intercepts the major conduction heat loads from the vessel supports, current leads, and instrumentation leads, and supplies coolant to reduce the lower vessel temperature below T_λ. This coolant for the lower vessel is withdrawn as a liquid at 4.4K from the upper vessel, cooled in a counterflow heat exchanger, expanded across a JT valve to a low pressure and temperature, vaporized in a coil immersed in the lower reservoir, and warmed in the counterflow heat exchanger before exhausting to the vacuum system. This apparatus is shown in Figure 1.

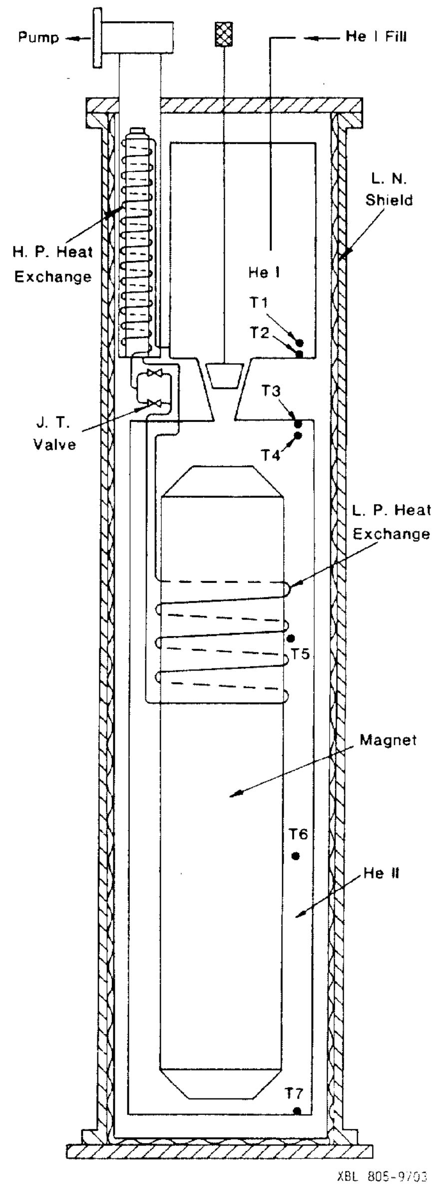

Figure 1: Schematic of pressurized helium II apparatus, showing locations of temperature sensors.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48

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behavoir of dry windings is quite non-linear; the winding fixture has been designed to allow for the initially large strain required to assemble the conductors. At high pre-stress 10,000 to 15,000psi, the compresive modulus is 2-3 x 10^6psi. This final compression is accomplished with the ring-collet system. The coil pre-stress can be significantly reduced by long term creep of the insulation at room temperature.

The D-7 Series of Dipole Magnets

As stated above, these magnets have approximately the same winding cross-section as the FNAL doubler magnets. They are 86.4 cm long overall, with an open 7.6 cm diam. bore. The compression rings that cover the magnet have an O.D. of 17.8 cm, with end plates and longitudinal tie rods outside of them. The coil windings are in two layers of insulated cable described above. The first layer of D-7A had 74 turns; D-7B, 78 turns. The second layer of both totaled 50 turns. Non-coil azimuthal and end space was filled with aluminum spacers in D-7A, NEMA G-10 in D-7B. The completed, nylon-wrapped coil O.D. was 11.9 cm. The central field at a 5000A current level is 4.6 T in D-7A, 4.75 T in D-7B with no iron.

Tests

For testing, these magnets were vertically mounted, without an iron shield, in our pressurized helium-II test facility, which is described elsewhere[1].

Magnet instrumentation included quarter-coil voltage taps, strain gauges on outside structural rings and on a caliper in the bore, and quench-inducing heaters adjacent to the inner coil windings.

Cryostat instrumentation included temperature and pressure sensors and a coil adjacent to the magnet for use in quench detection. External electrical energy extraction was provided.

The primary goal of these tests was to see how elimination of epoxy effects magnet training. A secondary goal was to investigate the training behavior in pressurized He II[3].

In general, the instrumentation and test plans were set up to observe and obtain data on training in He I and He II, ramp-rate sensitivity, heat generation in cyclic operation, magnet deformation, and energy required to quench, using pulsed heaters on coils.

Test Results, Magnet D-7A

1) Training. The initial quenches at 4.4K were caused by electronic problems and an extreme rate sensitivity. Later examination of these runs shows that no real transitions (quenches) occurred at slow ramp rates. In the belief that transitions had occurred, the magnet was next run in helium II to 6500A, which is 30 percent higher than the 4.4K short-sample current. All subsequent slow-ramp quenches at 4.4K were at conductor short-sample current, 5000A at 4.6T central field (B_o), 5.2T field on the conducter in the straight sections, and 5.7T maximum field (B_{max}). Although no real training behavior was observed in this magnet we cannot know whether the magnet would have trained if it had been initially energized with slow charge rate at 4.5K.

2) Rate sensitivity. Sensitivity of the magnet to heat buildup produced by rates of change of field from 10^{-3}T/sec to 5T/sec were obtained both in normal helium at 4.4K and in helium-II at temperatures from 1.8K to 2.0K. An initial extreme sensitivity to field ramps greater than 10^{-3}T/sec, (possibly due to a short) became less severe during the course of these tests. Ramp rates of 0.2T/sec to 5000A at 4.4K and 1T/sec in superfluid helium were achieved during the later stages of the tests.

3) Heat generation. The unique properties of superfluid helium allowed us to use the entire helium-II volume as a sensitive calorimeter. The magnet current was cycled with a triangular wave-form having several amplitudes, rates and base-current offsets. The measured temperature rise of the bath was converted to heat input in watts and joules/cycle, given in more detail in reference (3). These runs were made after the rate sensitivity referred to above had stabilized at reasonably low values.

4) Pulsed heater on the D-7A coil. Small heating strips-adjacent to the inner turns of the coil were used to induce quenches. The uncorrected observations were that for heater pulses shorter than 250ms the energy required to quench the coil at 4000A is about 120mJ at 4.4K and 250mJ at 1.8K. The full test results are given in Refernce 3.

5) Deformation. Strain gauges were mounted on the periphery of one of the central compression rings; the rings deformed as expected.

6) Thermal and mechanical cycling. As part of the first series of tests, the magnet was warmed to room temperature and re-cooled in the cryostat. The first transition at 4.4K was at 4990A and the first at 1.9K reached 6500A, showing that one thermal cycle had not affected the magnet's properties. Then the magnet was warmed up, the compression rings were removed, the magnet was inspected and measured, and the rings were reinstalled. A further short test sequence at 4.4K confirmed the retention of full field capability without training, but with the return of the original poor rate sensitivity, presumably a short.

Tests of Magnet D-7B

1) Training. This magnet trained. The first quench was at 3650A, proceeding to 4650A after 23 quenches, where it levelled off. (The Fermilab "Zebra" cable used in this magnet is expected to have a short-sample current limit in this vicinity). The magnet was then run in helium II at several temperatures, reaching 5465A. Returned to 4.4K, current limits were at 4700A. After warm-up and re-cooling, two more quenches at 4.4K were at the 4700A level, showing retention of full training.

2) Rate sensitivity. The magnet was run up to full field at rates as high as 0.3T/sec with no reduction of maximum field attained. A cyclic heat generation experiment was not performed, nor were the pulsed heaters used to induce quenches.

3) Deformation during excitation. This magnet was monitored for deformation of the compression rings during magnet excitation by strain gauges on two rings and by strain gauge instrumented calipers monitoring the polar and side axes of two other rings. A calculation of the expected deformation using a realistic distribution of Lorentz forces fits the data well after the first 5 quenches.

Table II

I	Helium I <250 ms	Helium I 1sec	Helium I Cont.	Helium II <250 ms	Helium II 1sec	Helium II Cont.
2000A	220 mj	1200 mj				
3000A	180 mj	750 mj				
4000A	120 mj	390 mj	0.45W	220 mj	1000 mj	1.3W
4500A	90 mj	270 mj				

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