CONF-840937-16

EBT-P MAGNET DEVELOPMENT PROGRAM SUMMARY*

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CONF-840937--16

DE85 002486

Abstract

The ELMO Bumpy Torus Proof-of-Principle Magnet Development Program, which began in 1979, has fabricated and tested three NbTi superconducting magnets. The magnets are metastable with a maximum winding pack current density of 10,000 A/cm² at a peak field of 7.4 T. Each magnet has been installed in a close-fitting dewar with a warm bore. Previous publications have reported successful tests of the first two windings in a large dewar, tests of the first complete magnet in its own dewar, and construction details of the dewars. This paper gives procedures and results for the test of the third winding in an open dewar, the test of the second single magnet in its own dewar, and two tests in which two magnets were run in series to generate a 73,000-lb side load at 5 T. The last tests verified the mechanical integrity of the design and qualified two of the magnets for use in the National Radio Frequency Test Facility.

Introduction

The ELMO Bumpy Torus Proof-of-Principle (EBT-P) Magnet Development Program has designed, fabricated, and successfully finished testing three high-current-density superconducting magnets. Oak Ridge National Laboratory (ORNL) wound the first two coils (D1 and D2) in 1980^{1,2} and tested them in a large open dewar. These coils were then shipped to General Dynamics, Convair Division (GDC), where they were installed in close-fitting individual dewars with warm bores designed in cooperation with McDonnell Douglas Astronautics Company (MDAC) and ORNL. The first test of a single completed magnet was successful, as reported in Ref. 4. The third coil (D3) was wound by GDC as part of the plan for technology transfer. The D3 coil was tested in a large dewar at ORNL and then returned to General Dynamics, where it was also installed in a close-fitting dewar.⁵ While D3 was being fabricated, the completed D2 magnet was tested at ORNL. The D1 and D2 magnets were next tested in series to 5.1 T with a 73,000-lb out-of-plane load. As reported here, these tests were successful. When D3 arrived at ORNL it was installed in place of D1 and tested in a two-magnet test. Again, as reported here, the tests went well, with no training. The D2 and D3 magnets will now be used for the National Radio Frequency Test Facility (RFTF).⁶

Magnet and Open-Dewar Test Comparison

Table 1 compares the physical characteristics of the three magnets. The D3 magnet also differed from D1 and D2 by including five voltage taps within the windings to allow the protection system to discriminate against induced voltage signals caused by plasmas.⁷ Further details may be found in Refs. 1-5.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Manuscript received September 10, 1984

The D2 magnet used a single grade of conductor primarily because magnetization tests showed it to have a significantly smaller effective filament diameter than the high-field compacted bundle⁸ and because it had adequate critical current properties.

Open-dewar tests were accomplished on all three magnets.^{3,5} The design criteria required a 1-A/s charge rate and toleration of 10 W of X-ray heat at 7.4 T. In the tests, the X-ray heat load was simulated by applying a 0.5-Hz sine wave on the base current and varying the amplitude. The principal results are given in Table 2.

In the open-dewar testing the D3 magnet performed best, tolerating 20 W at 7.5 T without quenching. Higher heating rates were not tested. It should be noted that none of the magnets quenched without either an applied X-ray heatload or very high charge rates, satisfying the requirement to exhibit no training.

Single-Magnet Tests

The EBT-P magnet test program changed when the EBT-P project was cancelled. During this time the RFTF project, which proposed using the development magnets, was approved. RFTF did not require the X-ray heating capability but did require steady-state operation at 5 T with an out-of-plane load, which EBT-P did not. Single-magnet tests were performed on D1 and D2 to demonstrate operation at 5 T and 7.4 T and to establish as-built heat leaks. The D1 test results are given in Ref. 4, and Table 3 gives a summary of results for D1 and D2.

These tests showed that both magnets worked reliably, charging to design field levels without training or quenching. This was done with helium transfer to the bottom of the winding pack at up to 17 psia (~4.4 K). The helium boiloff rates were approximately 14 L/h, which was lower than predicted.

Two-Magnet Tests

The primary objectives of the two-magnet tests were to verify the mechanical integrity of the magnets and to demonstrate that the magnets could be charged to 5 T with an appreciable out-of-plane load. Some question was raised early in the magnet program that an axially tight winding pack might not be achieved with a U-shaped bobbin. If the pack was not tight, some void space would be produced by the single-magnet tests, and the out-of-plane force could cause the pack to shift within the bobbin. It was known from the first open-dewar tests that the windings do lift off the bobbin due to self-field and relaxation of the applied prestress. Since very small energy inputs were predicted to produce current sharing or normal excursions, such motions would cause quenching or training. It was felt that this would not be a problem, however, because the wedges in the windings produced significant axial compression, as shown by spreading of the side walls, and the closeout weld tended to axially compress the windings even more.

For the D1-D2 and D3-D2 tests the magnets were mounted 60 cm apart, centerline to centerline, as shown in Fig. 1. With this configuration the design

Applied Superconductivity Conference
September 9-13, 1984, San Diego, CA

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Table 1. Magnet comparison

	D1		D2	D3
Conductor type	Compacted bundle ^a (bare, two grades)		Compacted bundle (bare, one grade)	Uniformly distributed monolithic (Ebanol-C coated)
Critical current, A, at 7.5 T	3730	2835	3020	3040
Copper-to-superconductor ratio	2.4:1	3.2:1	3.1:1	2.8:1
Resistivity ratio	110	194	190	140
I_{op}/I_{crit} (1830 A)	0.49		0.61	0.60
Number of turns	1225		1240	1218
Winding pack ID, cm	46		48	48
Winding pack cross section (width × radial height), cm	21.1 × 10.7		21.1 × 10.8	21.1 × 10.8
Inductance, H	0.86		0.86	0.86
Dewar warm bore ID, cm	41.9		41.9	41.9
Dewar superinsulation	Aluminized Mylar		Aluminized Mylar	Aluminized Kapton

^aS. O. Hong et al., IEEE Trans. Magn. MAG-17(1), 916 (1981).

Table 2. Open-dewar test comparison

	D1	D2	D3
Maximum ramp rate tested without quench to 7.4 T ^a (A/s)	32	25	12
Maximum heat tested with- out quench, 7.5 T (W)	12	≤10	20
Heat tested to cause quench, 7.5 T (W)	14	10 (delayed)	Not tested
Heat tested to cause quench, 5 T (W)	68	60	Not tested

Table 3. Single-magnet test

	D1	D2
Maximum charge rate tested to 5 T (A/s)	12	12
Maximum charge rate tested 5 T to 7.4 T (A/s)	2.1	2
Maximum X-ray heat tested at 5 T (W)	20	Not tested

out-of-plane load of 73,000 lb was generated at 5 T (1200 A). The coils were run in series with a 0.24- Ω dump resistor "hardwired" across each magnet and the primary circuit breaker between the coils, as shown in Fig. 2. This configuration limited the coil voltage to ground to 290 V for a dump. A current shunt and pickup loop for each magnet were used for quench protection in the same manner as described in Ref. 4.

One of the primary objectives of the two-magnet tests was to verify the mechanical integrity of the design by applying the maximum design out-of-plane load while monitoring the strains on the cold mass supports and the coil bobbin. Figure 3 shows the coil cold mass with its three titanium supports before insertion into its dewar.

Fig. 1. EBT-F magnets D2 and D3 mounted for two-magnet test.

Predictions of the strains in the cold mass supports vs current were made based on the finite-element model analysis performed by GDC. The bobbin was also monitored by strain gages, including the inner bore corner, which was predicted to be the high-stress region. The test was accomplished by charging to predetermined current hold points. At the hold points a data scan of the strain gages was made. These values were then compared to the predicted values before going to the next higher level. In addition, four gages were selected to be displayed on strip charts vs current. The charts were monitored to detect any sudden slippage during a current ramp. For safety, a spare quench protection module was also used as a current limiter by monitoring the current shunt voltage. This was set to dump the magnets at 1300 A.

Typical results for cold mass support strains vs current are shown in Fig. 4. These data are for the first chargeup for the D3-D2 tests. Because of the symmetry of the supports and loading, all the gages, which were on different supports, were predicted to

Fig. 2. Two-magnet test electrical schematic.

Fig. 3. D2 magnet cold mass and Ti-6Al-4V cold mass supports.

have the same strains. The agreement between predicted and measured strains was excellent. For the first D1-D2 tests, nine cold mass support strain gages were monitored, including at least one on each of the six supports, and the mean values agreed to within 6% of prediction. Figure 5 shows a typical chart recorder record from the first D1-D2 test. Except at the current hold points, the traces were smooth, indicating no sudden slippage or hysteresis. The calculated

Fig. 4. Typical cold mass support strain vs current data. Each gage is on a difference support leg.

Fig. 5. Chart record of a D1 cold mass support strain vs current for the first ramp up and back down.

strain in the corner on the inner bore of the bobbin was 383 $\mu\epsilon$ (11.1 ksi), and the measured value was 366 $\mu\epsilon$ at 1183 A.

At the end of the D1-D2 test, the D1 magnet was allowed to run out of helium while at 1200 A. The quench protection system was set to discharge the magnets when the compensated voltage exceeded 2 V for more than 270 ms. It performed as required, and Fig. 6 shows a strip chart display of the discharge. The compensated voltage appears to go to zero when the magnets are dumped because the amplifier goes into an attenuate mode and divides the output by ten. These data were recorded on an FM tape recorder and played back after the event.

One significant problem occurred during the D1-D2 testing. The D1 magnet developed a leak from the stack region into the vacuum space during cooldown.

This caused a higher heat leak but did not prevent testing. Before any use in RFTF, however, the magnet must be repaired.

The D2-D3 test encountered no significant problems. The magnets were operated for nearly an hour at 5 T with a 73,000-lb out-of-plane load, demonstrating long-term stability. Heat leaks and vapor-cooled lead gas flow requirements for D2 and D3 were within design predictions.

Fig. 6. Strip chart record of a D1 magnet quench caused by a lack of helium.

Conclusions

1. The basic magnet design has been shown to meet or exceed all major design goals. The magnet operates stably and reliably at 5 T and can be charged up to field without training at reasonably fast rates (2 A/s). In fact, throughout the entire program of open-dewar and completed magnet tests at up to 7.4 T and 10,000 A/cm², no magnet has quenched during normal operation (without simulated X-rays or much higher than design charge rates).
2. Very good agreement was demonstrated between test results and design predictions for cryogenic usage and mechanical response.
3. A rigorous quality assurance program made a significant contribution to a successful program and testing. Many problems were identified early and solutions found. A few examples follow.
 - Testing demonstrated that the original vapor-cooled leads specified were inadequate. A larger capacity was substituted before fabrication.

- Weld-sample testing by GDC showed that the D3 bobbin contained a brittle sigma phase in the welds. Annealing the bobbin corrected it.
 - While winding D3, a weak splice was found by resistance measurement made with a proof load on the splice. Investigation discovered that a procedural etching step had been missed. The splice was gone without any problem.
4. Both Oxford-Airco and Intermagnetics General demonstrated the capability of reliably fabricating conductor that fully met the EBT-P magnet development design specifications.
 5. The excellent operation of the D3 magnet, which was constructed entirely by GDC as part of a cooperative effort by ORNL, MDAC, and GDC, represents a successful technology transfer from ORNL to industry.
 6. Sufficient data and experience were developed to allow GDC to proceed with fabrication of 39 of the magnets, had the EBT-P program proceeded to the construction phase.

Acknowledgment

The authors wish to thank Robert Dannenmuller of MDAC for his valuable contributions throughout the program.

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