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THE IEA LARGE COIL TASK TEST RESULTS IN IFSMTF*

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Abstract

The Large Coil Task (LCT) is an international collaboration of the United States, EURATOM, Japan, and Switzerland to develop large superconducting magnets for fusion reactors. The testing phase of LCT was completed on September 3, 1987. All six coils exceeded the design goals, both as single coils and in six-coil toroidal tests. In addition, a symmetric torus test was performed in which a maximum field of 9 T was reached in all coils simultaneously. These are by far the largest magnets (either in size, weight, or stored energy) ever to achieve such a field.

Introduction

The Large Coil Task (LCT) is an international collaboration under the auspices of the International Energy Agency (IEA) among the United States (US), EURATOM (EU), Japan (JA), and Switzerland (CH) to develop large superconducting (SC) toroidal field magnets for tokamak fusion reactors. Six 2.5- × 3.5-m bore coils capable of producing 8 T were fabricated, three by the US [General Dynamics/Convair Division (GD), General Electric Co./Oak Ridge National Laboratory (GE/ORNL), Westinghouse Electric Corp. (WH)] and one each by the other participants, and assembled in a toroidal array in the International Fusion Superconducting Magnet Test Facility (IFSMTF) in the Oak Ridge National Laboratory (ORNL). The coils were widely different in design with three (GE, GE/ORNL, JA) cooled by pool-boiling (PB) helium at atmospheric pressure and three (EU, CH, WH) cooled by forced-flow (FF) helium at supercritical pressure (1.5 MPa). The WH coil was the only one to use Nb_3Sn conductor (wound after reaction) and aluminum for the structure; all the others used NbTi conductor and stainless steel structures. The GD coil was the only one layer wound; all the others used pancake winding. All the magnets were heavily instrumented, and thus detailed information on the electrical, thermal, and mechanical behavior of the coils was obtained, some for the first time on SC magnets of any size.

This paper describes the various single-coil and six-coil array tests to the design point and beyond and also the symmetric torus tests that were performed. Only a brief summary is given of the specific thermal and mechanical experiments because they are reported elsewhere in these proceedings and in previous review articles [1,2,3].

Facility and Instrumentation

The test coils with their supporting structure are enclosed in an 11-m-diam vacuum tank that is about 15 m high. The six coils are attached through upper and lower collars to a hexagonal bucking post that supports them. The outer corners of the coils are clamped in torque rings at top and bottom. The bucking post has internal chambers filled with liquid helium (LHe) during operation, but the torque rings are cooled by conduction to the coils. The bucking post rests on a "spider frame," which in turn rests on rollers on pedestals cooled with liquid nitrogen (LN_2) to intercept heat flowing up from the tank. Superconducting buses from each coil run through the vacuum tank wall to dewars where the transitions to room-temperature conductors are made. Two copper "pulse coils" are mounted on a carriage on a circular track, with provisions for moving remotely to each test coil in turn. Nitrogen coolant for the copper conductors of the pulse coils is supplied through flexible stainless steel hoses. The carriage, track, and pedestals are not actively cooled. The "cold wall," closely enclosed by the vacuum vessel, consists of stainless steel panels supplied with LN_2; their surfaces are covered with reflective blankets. The total cold mass is about 350 tonnes near LHe temperature and about 100 tonnes near LN_2 temperature.

The facility refrigerator has a capacity of 1.5 kW at 4.2 K. During coil test operations it must simultaneously supply liquid at 4.2 K and atmospheric pressure to many components and helium at 3.8 K and supercritical pressure (15 atm) to the FF coils. Although the refrigeration system is marginal for such a large facility, with many "minor" modifications and careful attention to operating parameters and extraneous heat loads, it has proved adequate.

There are more than 900 sensors for the test stand and refrigeration system. Each coil has 200 to 300 diagnostic sensors measuring voltage, strain, temperature, and magnetic field. Most have displacement transducers to measure movement of the winding pack, pickup coils to measure the pulse fields, acoustic emission sensors, and the FF coils have pressure transducers for flow measurements. All the coils contain resistive heaters to permit some heat perturbation experiments (stability, simulated nuclear heating, or current sharing temperature). The WH coil also has inductive heaters for recovery tests. A unique quench detection system was designed and previously tested for the IFSMTF. The scheme was based on analog subtraction of self and neighboring pickup winding voltages from the coil voltage to yield a compensated signal proportional to a resistive (normal-zone) voltage. The compensated signals were input to quench detection modules that give a quench output signal to dump the coil if the signals exceed preset thresholds of voltage and duration.

Coil Tests

On October 24, 1985, the last of the six coils was installed and the vacuum tank lid was put on for the pumpdown. After leak checking and repairing of the room-temperature leaks, the preliminary cooling was started to find and repair the cryogenic leaks that invariably occur in such a complicated system. All repairs were completed and pumpdown was started early in January 1986. Cooling commenced on January 18, and the first coil [the Nb_3Sn (WH) coil] was superconducting one month later. In early March the test program was started and was carried out over an 18-month period, ending on September 3, 1987, with a maximum field torus test in which all of the coils were energized simultaneously to a 9-T magnetic field. During this testing period the system remained continuously at cryogenic temperature. Occasionally, there were excursions in temperature with some as high as liquid nitrogen temperature due either to problems with the cryogenic system or to coil dumps of the full array from high current. At such times it took between two days to a few weeks to cool the facility back to helium temperature.

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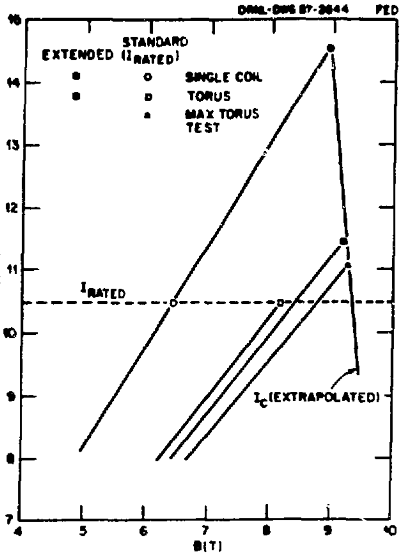

Fig. 1. Load lines for the GE/ORNL coil. See tables for values.

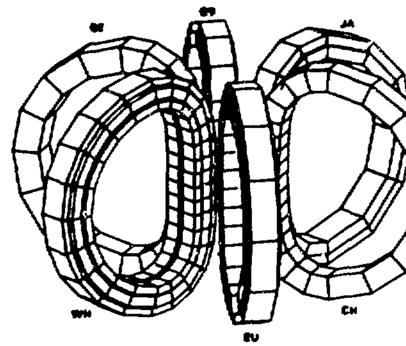

Fig. 2. LCT full-array model for field and force analysis.

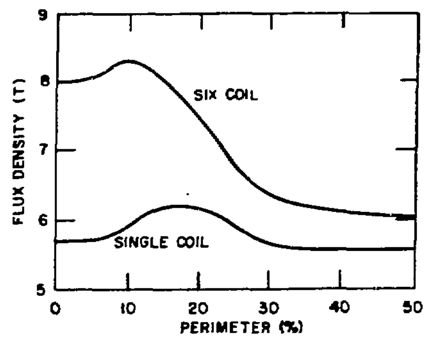

Fig. 3. Field variation from inside turn in middle of straight section of outside perimeter for WH coil.

Single-Coil Design-Point Tests

The coil tests were arranged in a sequence of increasing severity with the electrical and thermal tests performed first, followed by pulsed field experiments and ending with the mechanical tests. The data on the GE/ORNL coil contained in Fig. 1 illustrate the sequence of current and field tests that were performed for each of the six coils. First, the coil was tested by itself to full design current (which in the case of the GE/ORNL coil is 10,500 A). In this test (sometimes called Standard test), the solenoidal forces on a D-shaped coil lead to severe deformation of the structural case, with the horizontal bore increasing and the vertical bore decreasing. The calculation of these dimensional changes by a relatively simple finite element model agreed very well (within 10%) with the measurements made on the GD and JA coils by MCDT's placed in the bore of the coils [4].

Summary of Single-Coil Design-Point Test

- All six coils reached 100% design current at $B_{max} = 6.4$ T on the first try without any quenches due to bedding down of the winding or training.
- WH coil was energized to 100% design current at helium inlet temperature of 8 K.

Six-Coil Design-Point (Standard-1) Tests

The next series of tests were the design-point tests (Standard-1), wherein each coil was tested in turn to full rated current at a reference field of 8 T. For these tests the other five coils were treated as background coils and energized to about 80% of their rated current. A special synchronized reference signal drive was constructed to control each power supply so that all coils could be charged to a different percent of their rated current simultaneously. The settings were continuously variable from 0 to 140% of current ratings. Four of the power supplies delivered 16 kA±12 V, and two were rated at 25 kA±12 V. The reference field is calculated for the innermost turn at the midplane of the straight section of the D-shaped coil. The special computer program FANDF [5], which was written for this calculation, takes into consideration the differences of each of the coils in current density, amp turns, and geometry (see Fig. 2). Thus, for each coil to make a reference field of 8 T, different sets of currents were required for the other five background coils. These ranged from 72% for the CH coil test to 91% for the test of the WH coil. The test of the other four coils used background coil currents close to 80%. For the last of the six coils tested, the WH coil, the background currents and thus the reference field were already so high that we decided to perform this test as the so-called symmetric torus test. In this test the currents were adjusted in each coil in such a manner that all six coils achieved an 8-T reference field simultaneously. To accomplish this, the WH coil actually had to be run at 101.4% of rated current, while the other five were energized between 88 and 95% of their rated current (average was 91%). This test could be performed with confidence since each coil already had achieved 8-T reference field at 100% design current. Each manufacturer of the coils also provided a calculation for the ratio of the maximum field in the corner region to the reference field. For a coil by itself (single-coil test) this ratio is accurately calculated, but for operation in the six-coil torus the ratio is not accurately calculated and a program similar to FANDF is being prepared. The inaccuracy is due to the fact that each coil manufacturer assumed all the "other" coils were identical to its own when performing the torus calculation. For this reason all tests are performed for the *reference field*. In Fig. 3, the field distribution around the circumference of the inner turn is shown for the WH coil for both single-coil (solenoidal) and six-coil toroidal operation. This is typical of all the coils. The difference between the maximum field in the corner region and the reference field is 20.5% and 3% for the single-coil and toroidal configuration, respectively. Note that the angular variation is much less in the solenoidal operation and the minimum in the toroidal operation is similar to the maximum field value of the single-coil operation.

Summary of Six-Coil Design-Point Test

- All six coils achieved 100% design current at a $B_{ref} = 8$ T without any training, including the EU and CH adiabatically stabilized coils.

Single-Coil Extended-Current (Alt-C) Tests

After completing all the electrical and thermal tests (described later) at the design point (100% rated current and 8-T reference field), we returned to single-coil extended tests (Alt-C tests) with the aim of determining the *maximum current* above rated current that each coil would carry (with the maximum

Table 1. Single-Coil Extended Current Tests

Coil	Cooling[a]	Operating/ Rated I_{op}/I_{rated} (%)	Operating Current I_{op} (A)	Inlet temp. T_{in} (K)	Outlet temp. T_{out} (K)	Reference field[b] B_{ref} (T)	Max/Ref B_{max}/B_{ref} (%)	Max field B_{max} (T)	Stored energy E_s (MJ)
EU	FF	140	15,949	3.73	3.97	7.76	115.3	9.01	200
WH	FF	131	23,200	3.90	5.50	6.83	120.5	8.23	202
GE/ORNL	PB	139	14,591	4.33	4.33	7.70	115.5	8.89	193
GD	PB	120	12,240	4.33	4.33	6.79	113.6	7.72	136
JA	PB	138	14,061	4.30	4.30	7.73	113.9	8.81	198
CH	FF	120	15,600	3.72	3.94	6.92	113.5	7.86	123

[a]FF stands for force-flow, PB for pool-boiling.
[b]Innermost turn at midplane of straight section.

being set at 140% because of design limit on deformation of the structure).

The results of the single-coil extended tests are shown in Table 1. Three of the experiments resulted in a quench of the test coil. The EU coil was the only one to achieve the 140% of rated current, and this resulted in a maximum field of 9 T. The stored energy was 200 MJ, or about twice the stored energy of the coil at the design point (Standard test).

The GE/ORNL coil reached 139% of rated current without undergoing a quench, but the current drive was stopped when it became evident the onset of current sharing was observed. To verify that this was the reason for the increase in the coil compensation voltage, the current was reduced until the voltage decreased to zero and then slowly increased stepwise until the exponential voltage rise was reached. It was a pleasant surprise to encounter current sharing well above the cryostable limit.

The JA coil achieved 138% of rated current, at which point the critical current in the high-field-grade conductor was exceeded and the coil quenched. The actual critical current in the conductor, which was at a temperature between 4.3 and 4.4 K according to the pressure inside the coil, was very close to the short sample data extrapolated to 4.4 K. The coil was too stable in all the experiments to have quenched for any other reason.

Before the start of the test of the GD coil, we decided to limit the current to 120% of the rated current because a higher dump voltage could not be tolerated. The breakdown voltage to ground had slowly decreased with time for this coil and, as a result, the dump resistor was lowered to 26 mΩ, the minimum safe value (dump voltage = 265 V). In the actual test the coil was brought to 120% and, when the current ramp was stopped to permit a flattop for data acquisition, the coil quenched. A study revealed that the quench originated in the grade-III conductor (low-field grade). The critical current had been exceeded. The current in this conductor was not as high as one would have expected from short sample measurements, even compensating for the higher temperature operation. The performance of this coil in subsequent experiments was not in jeopardy, because the field distribution for operation in a toroidal test was actually lower for the grade-III conductor than in the solenoidal test, even when the reference field was more than 2 T higher. Unlike similar braided conductor used in both GD and JA coils, similar monolithic subelements used in both EU and GE/ORNL coils exceeded short sample expectations. The conductors are shown in Fig. 4.

The CH coil also had a limit of 120% rated current, which was set by the fabricator (Brown Boveri & Cie) to avoid excessive deformation of the structure. During the later stages of the testing program for some thermal experiments, the CH coil was charged to 120% of rated current without a quench. However, during the extended tests the coil exhibited some sort of training effect for two successive charging attempts which ended in quenches at 111% and at 119%, respectively. Both quenches originated in the end pancake, possibly an indication

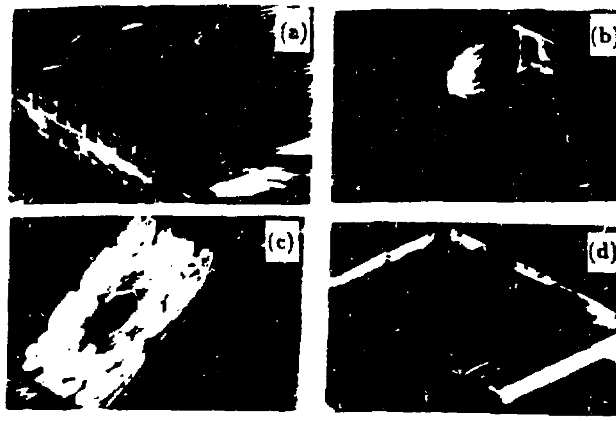

Fig. 4. Photographs of (a) GE, (b) JA, (c) CH, and (d) EU conductors.

of delamination of potted conductor or motion between the winding and structure.

The WH coil was energized to 131% of rated current, at which point the resistive power dissipation in the coil was over 600 W, and it quenched. The cryogenic system could not handle such an additional load, and the output temperature continuously increased throughout the experiment, as shown in Fig. 5. The resistive power dissipation was calculated resistively from the compensation voltage across the coil (clearly discernible above the noise at 12 kA), as well as thermodynamically from temperature and mass flow measurements. For the latter measurement, steady-state conditions have to be established, and the first point taken was at 11 kA. In Fig. 6 a plot of the power dissipation vs current for the WH coil would indicate the onset of resistance is about 10 kA or at 56% of the rated current and approximately only 30% of the expected critical current. It is remarkable that the coil could be operated some 13 kA above the first appearance of resistance.

Summary of Single-Coil Extended-Current Test

- All six coils achieved at least 120% design current.
- EU, GE/ORNL, and JA achieved 140%–9 T, 139%–8.9 T, and 138%–8.8 T, respectively.

<u>Six-Coil Extended-Field (Alt-A) Tests</u>

After the single-coil extended tests were performed, these results, along with knowledge of the critical current, enabled us to design the six-coil extended tests. The purpose of these tests was to achieve the *maximum field* for each test coil without exceeding the limits of the background coils. For example, the GE/ORNL single-coil extended test achieved 14,591 A at a maximum field of 8.9 T. Since current sharing was reached, this point is the critical current. With known empirical rules[6], the current was extrapolated to higher fields. A six-coil extended

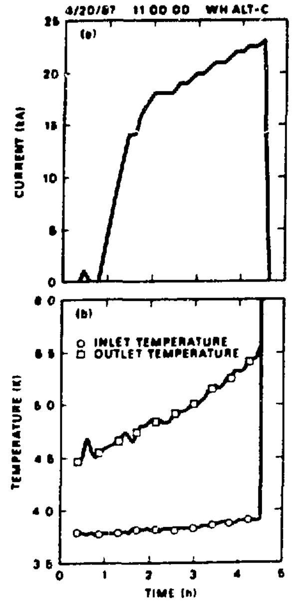

Fig. 5. Current and temperatures for WH single-coil extended test.

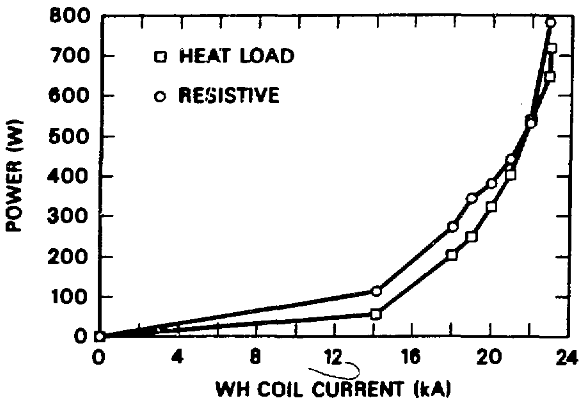

Fig. 6. Resistive power dissipation in WH coil measured resistively and thermodynamically in single-coil extended test.

test was designed to reach a 9-T reference field, which was successfully performed with the five background coils set at various currents, which averaged out to 94% of their rated current. A maximum field of 9.2 T was achieved stably without a quench, although the final current 11,447 A was close to the critical current limit.

Similar type tests were done one after the other for all six coils. The results are summarized in Table 2. All the NbTi coils achieved a 9-T maximum field. The Nb_3Sn WH coil reached 8.9-T maximum field and quenched when the resistive power dissipation was close to 600 W. The CH coil results were reached after the current ramp was stopped, but the system continued to drift up in current (until the voltage decreased to almost zero). After a few minutes another 5 A and 40 G were added to the CH coil, and it quenched. There was movement in the toroidal array due to the very substantial out-of-plane forces as well as the central forces that were present in all six-coil tests. These movements are seen by all the coils (simultaneously measured by the compensated voltage across all the coils), but only the CH coil end pancakes received enough motion to develop a normal region, resulting in a quench. The coil was not designed to be cryostable. Frictional heating external to the conductor is removed by the helium only after passing through the conductor (see Fig. 4). The EU conductor, which also is operated above the cryostable limit, is designed so that the helium intercepts any externally generated heat before it reaches the superconductor.

The results for the other four coils were achieved without a quench. The PB coils are operated at a higher average temperature, 4.3 K, than the two NbTi FF coils, 3.83 K, so it is all the more pleasing that they achieved the same maximum field.

Summary of Six-Coil Extended Field Tests

- All three NbTi pool-boiling coils achieved 9 T at 4.3 K.
- Both NbTi force-cooled coils achieved 9 T at <3.8 K>.
- The Nb_3Sn force-cooled coil achieved 8.9 T at <4.7 K>.

Symmetric Torus Test

Near the end of the program, after all the six-coil extended field tests were completed, we intended to repeat the symmetric torus test, but with the aim of achieving 8.5 T simultaneously on all the coil in much the same manner as the earlier 8.0-T symmetric torus test. This was done after all the mechanical and safety tests were completed, and it was so successful that we were encouraged to try for a torus test in which a maximum field of 9 T could be achieved, at least on some of the coils.

Table 2. Six-Coil Extended Field Tests for Each Coil[a]

Coil	I_{op}/I_{rated} (%)	Operating current I_{op} (A)	Av. current in background coils (%)	Ref field B_{ref} (T)	B_{max}/B_{ref} (%)	Max field[b] B_{max} (T)	Stored energy E_s (MJ)
EU	114	13,000	<91>	9.01	101	9.1	788
WH[c]	112	19,827	<94>	8.64	103	8.9	829
GE/ORNL	109	11,447	<94>	9.03	102	9.2	827
GD	100	10,230	<99>	8.78	102	9.0	858
JA	107	10,958	<97>	8.85	102.2	9.1	858
CH[d]	110	14,303	<87>	8.85	101.3	9.0	630

[a]The inlet and outlet temperatures for FF coils and the bath temperature for the PB coils are similar to the values in Table 1.

[b]Probably only one figure should be considered significant for B_{max} until the toroidal field calculation is completed.

[c]The test ended in a quench.

[d]These are values when current ramp was stopped. The system drifted up by some 40 G and the test ended in a quench.

Table 3. Current Distributions and Forces for the Maximum Field Torus Test (E_s = 944 MJ)

	EU	WH	GE/ORNL	GD	JA	CH
Rated current (A)	11,400	17,760	10,500	10,200	10,220	13,000
I_{op}/I_{rated} (%)	106	108	106	98	106	99
Inlet temperature (K)	3.80	3.90	4.26	4.26	4.26	3.80
Outlet temperature (K)	3.95	5.10	4.26	4.26	4.26	4.20
Reference field (T)	9.09	8.75	9.06	8.78	8.90	8.98
Maximum field (T)	9.2	9.0	9.2	9.0	9.1	9.1
Out-of-plane force (MN)*	-11	1.2	10	-0.15	1.6	-1.1
Central force (MN)	57	66	53	51	53	46

Negative sign indicates clockwise direction looking down on torus.

Finally, on the last day of experimenting, we ran the symmetric torus test again with some adjustment in the current settings so that, while the symmetry was lost with regard to the reference field, the highest maximum field could be obtained on each coil. This test was also successful, and every coil reached 9.0 T or higher, simultaneously. The load line for the GE/ORNL coil is indicated in Fig. 1 and is labeled "maximum torus test." We ran the test right to the extrapolated critical current value. The reason we could do this was that the pressure in the pool-boiling coils was reduced to 15 psi for this test and thus we did not expect to reach current sharing in the GE/ORNL coil or exceed the critical current in either the JA or the GD coil. The settings are shown in Table 3. After stopping the current ramp and taking data, the inlet and outlet temperatures of the WH coil continued to rise, and the whole system quenched from a total stored energy of 944 MJ. Subsequent examination seemed to indicate that all coils were all right and that no damage occurred as a result of the full-torus dump from such a high setting.

Summary of Maximum Field Torus Test

- All six coils simultaneously attained a maximum field of at least 9 T. The total stored energy was 944 MJ.

Additional Comments

Facility

Despite the fact that the refrigerator was marginal, the test stand was maintained at cryogenic temperature throughout the 20-month period of cooling and testing.

Subatmospheric operation of the auxiliary cold box over an extended period has been verified to be practical. The inlet temperature to FF coils can be at 3.7 K.

Cooling and warming of the test stand was carried out expeditiously and smoothly. No large thermal stresses or displacements were noted. No flow distribution problems were observed for any of the PB coils.

The remainder of the facility (vacuum pumps, power supplies, electronics, data acquisition system, computers, etc.) worked reliably with very good overall availability.

The diagnostic sensors on both the facility components and the coils held up remarkably well, with fewer than 5% becoming unusable over the course of the experiment.

Coils

Residual resistivity ratio (RRR): The WH conductor had an extremely high value, indicating that the diffusion barrier was effective and that the copper was annealed during the heat treatment for the formation of the Nb_3Sn. The GD conductor also had a high RRR value, showing the advantage of separate fabrication of the cable and matrix.

Sensors: There was never any indication that the sensors on any of the coils created any shorts. This was also true of the GE/ORNL coil, which had shorts that were eliminated before the experimental program began.

Joint Losses: The joint losses for all six coils were low and agreed closely with calculations.

System Dumps: The effects of coil dumps (induced current and voltages and changing out-of-plane loads) could be accurately calculated. About 96% of the stored energy was removed by the dump resistor for four of the coils. Only 77% could be removed from the WH coil because of the large eddy currents induced on the shorted aluminum structure. Similarly, only 88% was removed from the CH coil because of a copper cooling tube on the structure which provided a path for induced eddy currents.

Hot Spot Measurements: Hot spot measurements were made for a PB coil (GE) and a FF coil (WH), and they were less than the adiabatic calculation, lending encouragement for extrapolation to reactor-size magnets.

Stability Tests: The PB coils were all cryostable at the design point. The energy needed to drive a half (5 m) or whole (10 m) turn normal was one to two orders of magnitude larger than one would calculate on the basis of known enthalpy. The WH coil was extremely stable (stability margin between 1 and 1.9 J/cm^3, depending on the location of the heater) at the design point, even though it was operating well above current sharing.

Simulated Nuclear Heating: The PB coils were stable at the design point with power densities of 50 mW/cm^3 sustained for 60 s over 50 m of conductor. The nominal EPR requirement was 10 mW/cm^3. The FF CH coil could handle continuous heating of 300 W with local dissipation exceeding the NET requirement by a factor of 2.

Current Sharing (CS): For the first time current sharing measurements were carried out on large coils (EU and WH). The CS measurements could be performed on the EU coil above the cryostatic stability limit without initiating thermal runaway. The CS measurements on the WH coil indicated severe degradation of the conductor current.

FF Cooling Requirement: For the EU coil the flow was stopped at the design point for 1 min, and then the coil was ramped down without a quench being initiated. In all, the coil was without active cooling for 1 h.

AC Losses: The magnitude of the losses measured on three coils was low (18±3 W) and within expectations. However, the lack of any field (and current) dependence is not fully explained, but analysis is still in progress.

Acoustic Emission (AE): The AE noise emanated mostly from movement of the winding, but there was some from the structure. The PB coils had more AE than the FF potted EU or the WH (conductor contained in grooves) coils. The virgin runs were always noisier than subsequent charging, indicating compacting (bedding down) of the winding pack. There was better correlation between AE and compensated voltage for the FF coils than for the PB coils, indicating that the winding and structure do not communicate as well in PB coils.

Mechanical Loads: The mechanical structure of all the coils under the extreme central loads (46 to 66 MN) during the toroidal tests and the out-of-plane loads (19 to 27 MN) during the Alt-B (five coils energized and one off) tests was excellent.

Winding Motion: Motion exists in all the coils, but it did not affect the performance of any of the coils except the CH coil, which quenched on some occasions when it was energized to very high currents.

Displacement Measurements (DM): Displacement measurements are qualitatively as expected, but the magnitudes are not well predicted and the differences among the coils are not fully understood. Bore displacements have behavior and magnitude as predicted. The three PB coils show surprising differences in winding pack displacements. None of the coils are elastic, and some hysteresis was found. The FF potted EU coil deforms more like a solid body than the PB coils. In the Alt-B or out-of-plane load test, the DM of the winding pack showed differences between the two sides when the same total net force was reversed, which results from the different field distribution that each coil experiences on each side.

Strain Measurements: Our ability to calculate the magnitude of the strains is not very good. The strains on the PB conductors are higher and the case strains lower than anticipated. This, along with the AE data, would tend to indicate that the transmission of forces between the winding and the structure is poor. The only strain data on the conductor of the FF coils is the WH conductor, which had lower strains than the PB conductors, indicating good coupling to the grooves in the plates. Case strains for the EU and CH potted coils were also higher than for the PB coils, again indicating that transmission of the forces from the windings was good. Some nonlinear strains were noted on the subelements of the GE/ORNL conductor, but not on the core of the conductor, which behaved similarly to the other PB conductors. This may be an indication of delamination of some subelements. However, this did not affect the stability or performance of the coil.

Conclusions

All six LCT coils exceeded their design goals.

The NbTi coils performed as well as, or better than, the Nb_3Sn WH coil. Substantial improvement is needed in the performance of the Nb_3Sn conductor to meet the ITER requirements of winding pack current density and field level.

The LCT results would indicate that either a FF or a PB design could be extrapolated to a reactor-size magnet.

The advantages usually ascribed to FF potted magnet designs (ease in providing very high discharge voltages, transmission of the winding forces to the structural case, and cooling of the conductor) were supported by the results.

Four state-of-the-art advances were made:

The advantages usually ascribed to PB magnets (exceptional cryostability, ability to absorb large nuclear heating, and ease in cooling) were verified.

Four state-of-the-art advances were made:

- These are the largest coils (in size, weight, or stored energy) to ever produce 9 T or, for that matter, 8 T.
- The EU and CH coils are the largest adiabatically stabilized coils ever made.
- The WH coil is the largest Nb_3Sn coil ever made.
- The WH coil is the largest coil to be operated at full design current at 8 K.

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