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FIRST RESULTS OF THE FULL-ARRAY LCT COIL TESTS*

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Abstract

The international Large Coil Task (LCT) has designed, built, and is testing six different toroidal field coils. Each has a 2.5- × 3.5-m D-shaped bore, a current between 10 and 18 kA, and is designed for stable operation at 8 T. Three coils are bath-cooled; three are cooled by forced flow of helium at supercritical pressure. One uses Nb₃Sn; the others NbTi. The test coils are equipped with voltage, temperature, magnetic field, flow pressure, strain, displacement, and acoustic emission sensors sufficient for penetrating analysis of performance field. Shakedown operation of the test facility and preliminary tests of the first three coils were accomplished in 1984. Tests of the full six-coil toroidal array began early in 1986 and have progressed to the stage of design-current, design-field stability tests. Results to date have elucidated complex structural and electrical interactions in a multicore array and provide gratifying assurance of coil performance.

Introduction

The Large Coil Task (LCT) is a collaborative effort of the United States, EURATOM, Japan, and Switzerland in large-scale development of superconducting toroidal field coils for fusion reactors.^{1,2} The United States provides the test facility at Oak Ridge and three of the six test coils; the other participants, one coil each. Shakedown operation of the International Fusion Superconducting Magnet Test Facility (IFSMTF) and preliminary tests of the first three coils to be delivered were accomplished in 1984.³ Late in 1985, the assembly of the full six-coil toroidal array was completed, and cooldown of the 420-tonne test array was begun. Cooldown was delayed by facility problems, and the rate was limited by cryogenic capabilities.⁴ However, there was no problem with any coil during cooldown, and by the end of February, all were superconducting and ready to be energized. The LCT test program is outlined in Table 1. All preliminary tests, including stable operation of each coil at full current and self-field (6.4 T), were completed by the beginning of June. Since then all six coils have been operated simultaneously and, as of this writing, two coils have been operated stably at full current and 8 T. This paper reports significant findings to date.

Test Coils

All coils were designed to specifications that define basic dimensions and performance but leave choices of conductor, winding, structural, and thermal

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Table 1. Outline of LCT test program

- Startup
 - Tank evacuation
 - Leak tests at room temperature
 - Test stand cooldown
 - Leak tests at cryogenic temperatures
- Preliminary tests
 - Low-current checkout of I&C
 - Single-coil tests to full current, 6 T
 - Multicoil tests to 0.2 full currents
- Design-point tests
 - Full current, 8 T, without pulsed field
 - Test pulse field system to design current
 - Full current, 8 T, with pulsed field
- Extended-condition tests
 - High-field symmetric torus
 - Full current, higher pulsed fields
 - Highest current and field
 - Higher out-of-plane loads

design up to each design team. The coils are about four-tenths the size of coils envisioned for tokamak fusion reactors (bore dimensions are 2.5 × 3.5 m), but conductors are full-size, carrying currents from 10 to 18 kA. Coils by Japan, U.S.-General Dynamics, and U.S.-General Electric (JA, GD, GE) use an atmospheric-pressure bath of helium to cool the conductors. Coils by EURATOM, Switzerland, and U.S.-Westinghouse (EU, CH, WH) use conductors cooled by forced flow of subcooled helium at 1.5 MPa. The WH coil conductor material is Nb₃Sn; the other five, NbTi.

The GD coil is layer wound, with interlayer spacers to direct helium flow produced by boiling to the edge and up to the stack. The GE coil is pancake wound with insulation that blocks interpancake cross flow. The JA coil is also pancake wound, with insulating spacers between pancakes to define cooling channels. Separate cooling channels for the thick stainless steel case are provided in each pool-boiling coil.

The EU coil consists of a monolithic winding block, impregnated with epoxy resin and mounted in two halves of a stainless steel coil case. Epoxy-filled stainless steel bladders transmit forces from winding to case. Both winding and case are actively cooled. The CH coil also is a vacuum-impregnated epoxy-potted monolithic winding enclosed in a bolted box-type stainless steel support structure, with separate cooling for winding and structure. The WH coil has cable-in-conduit conductors fitted in grooves in aluminum alloy plates, which are bolted together. The good thermal conductivity of the plates eliminates the need for separate cooling of the structure.

Each coil has 200 to 300 diagnostic sensors measuring voltage, strain, temperature, magnetic field, flow pressure, acoustic emission, and displacements. In the bath-cooled coils many of the sensor leads penetrate the coil cases. The coils also contain heaters to permit stability and simulated nuclear heating tests.

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Test Facility

The IFSMTF comprises the toroidal array of test coils, with supporting structure in an 11-m-diam vacuum tank, and ancillary electrical, cryogenic, vacuum, control, and data acquisition systems. The test stand is depicted in Fig. 1. Test coils are attached through upper and lower collars to the hexagonal bucking post and are clamped in torque rings at their outer corners.

Fig. 1. IFSMTF test stand.

The copper pulse coils (which have not yet been operated) are mounted on a carriage on a circular track with provisions for moving remotely to each test coil in turn. The "cold wall" consists of panels cooled with liquid nitrogen, with surfaces covered by reflective blankets. During operation, the tank is maintained in the range of 10^{-5} to 10^{-4} torr by two turbomolecular pumps and a diffusion pump.

The facility refrigerator, which is rated at 1.5 kW at 4.2 K, supplies liquid at 4.2 K to three coils and the test stand structure while circulating up to 300 g/s of helium at 1.5 MPa and 3.8 K through the force-flow coils.

Experimental data are acquired through four front-end systems connected to a central processing computer (VAX 780), which in turn is connected to a cluster of computers for data storage and analysis.⁵

Results and Analysis

Test Sequences and Configurations

All major experiments that have been accomplished so far are listed in sequence in Table 2. These experiments are described in detail in other papers at this conference.⁶⁻¹⁰

Table 3 summarizes the design and measured principal coil parameters for the full-array coil tests, and Table 4 lists the measured inductance matrix. It is clearly shown that the LCT full array is highly asymmetrical from both electromagnetic and mechanical point of views.

A computer model based on exact coil parameters and winding geometry was thus developed for full-array field and force analysis. Figure 2 shows the model for the full-array configuration. Along with it, a lumped circuit model¹¹ was also developed for calculations of inductance, currents, voltages, and energy distribution to verify the experimental results.

Table 2. Milestones of the full-array test

Events	Coil	Date	Major accomplishments
Cooldown	WH	2/13/86	Around 15 K, Nb ₃ Sn coil becomes superconducting
	Others	2/18/86	Around 9 K, all NbTi coils become superconducting
Single-coil test	JA	3/24/86	Half-turn recovery plus nuclear heating test
	CB	4/16/86	Simulated nuclear heating
	GD	4/29/86	Full-turn recovery plus nuclear heating test
	GE	5/09/86	Full-turn recovery plus nuclear heating test
	EU	5/21/86	Measurements of current-sharing temperature
	WH	6/05/86	Measurements of current-sharing temperature
Full-array test	All	7/25/86	Symmetric torus at 25% rated current
	GD	8/15/86	Design current reached at 8 T
	JA	8/21/86	Full-turn recovery
		8/25/86	Design current reached at 8 T
		9/19/86	Half-turn recovery plus nuclear heating test

Table 3. Principal coil parameters

COIL	DESIGN CURRENT (KA)	TURNS	AMP-TURN (10^5)	RRR ^a	SELF INDUCTANCE ^a (HENRY)	BUMP RESISTOR (mΩ)	EXPECTED MAXIMUM BUMP VOLTAGE (V)
EU	11.40	588	6.70	108	1.57	220	2506
WH	17.76	424	7.53	333	0.75	102	1812
GE	10.50	622	6.53	121	1.81	55	620
GD	10.20	628	6.41	187	1.81	52 ^a	530
JA	10.22	658	6.72	118	2.00	100	1022
CH	13.00	458	5.95	178	1.00	170	2210

^aMEASURED VALUES.

^aDUE TO LOW BREAKDOWN VOLTAGE TO GROUND, THIS RESISTANCE VALUE WAS LOWERED TO 26 mΩ IN THE STANDARD-1 TESTS.

Table 4. Measured LCT full-array inductance matrix (Henry)

	EU	WH	GE	GD	JA	CH
EU	1.57	0.178	0.079	0.051	0.083	0.200
WH		0.75	0.190	0.055	0.037	0.041
GE			1.81	0.290	0.089	0.040
GD				1.81	0.304	0.063
JA					2.00	0.226
CH						1.00

Coil Energization

Each coil has its own power supply¹² capable of +12 V and currents of 16 or 25 kA. The control system provides for synchronous, coordinated ramping up or down of the coil currents. Figure 3 illustrates two successive controlled energizations of all six coils during the GD design-point stability tests. Note that the maximum total stored energy reached nearly 600 MJ. The V/I curves of simultaneous stable energizing and disenergizing of the test coil (GD) and a neighboring coil (GE) during the GD design-point tests are shown in Fig. 4.

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

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Fig. 3. Successive energizations of six-coils in the GD design-point tests.

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Fig. 4. V/I curves of a test coil (GD) and a background coil (GE).

Quench Protection NOT TEST ABOVE THIS LINE

A unique quench detection system was designed and previously tested for the IFSMTF.¹³ 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 normal-zone voltage. The compensated signals were input to quench detection modules that gives a quench output signal to dump the coil if the signals exceed preset thresholds for preset time durations.

Using the computer automated gain-setting algorithm, preliminary settings of all 120 pickup signals for 40 quench detection channels were started before the coils were cooled down, so that the system could be calibrated with the coil resistive voltages. It was repeated until the coils went into superconducting state. These settings only required minor manual changes during the whole coil test period.

The satisfactory performance of the quench-detection system is illustrated in Fig. 5 for the full-array coil tests. In the insert, a chart-recorded real-time compensated voltage trace was shown for comparison (GD design-point tests). Note that the GD compensated coil voltage is well balanced and quite insensitive to any coil current and voltage changes.

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Fig. 5. Compensated coil voltage waveform during the full-array tests.

The system was fully tested for each coil with intentional offsetting the compensation before its high-current tests. During all the coil experiments, the system worked flawlessly. On several critical occasions, the coil dumps were timely triggered and the coils were properly discharged.

In the EU coil, a novel redundant bridge-circuit quench-detection system was used for every double pancake, along with two channels of the ORNL system.

Coil dumps that were performed intentionally or triggered by the quench-protection system induced currents not only in all six coil-dump-resistor circuits but also inside any nearby metallic components. Measurable energy dissipations have been found in the components such as coil case structure and coil windings.

The induction effects between coil systems are manifested in Fig. 6, which shows the induced currents and voltages waveforms as the WH coil was intentionally dumped from 6440 A. The results are in excellent agreement with calculations by the lumped circuit model.¹¹ In Fig. 7, after all six coils were simultaneously dumped from 10% of design currents, the energy dissipation in each dump resistor is calculated. Also shown in the figure is the list of the initial stored energy in each coil system for comparison.

Fig. 6. Induced currents and voltages in background coils due to WH dump.

Fig. 7. Energy dissipations in dump resistors after LCT full-array dump.

Coil dumps from design current for EU single-coil tests, with stored energy of about 100 MJ, and from 80% current of the test coil (JA) in the full-array test, with a total stored energy of about 400 MJ, have been handled by the system.

Mechanical Behavior

Facility. The Standard-1 (design-point) tests reported herein are rather benign to the facility, basically because of quite low net out-of-plane loads and low net overturning moments on the TF coils and because of zero loads throughout the pulse coil support system. Also, the large net centering forces and the distributions within the windings of the six TF coils are such that all coils are plastered against the bucking post allowing no gaps and producing very little mechanical action in the keeper-keeper slot-collar slot areas or at the coil interfaces to the torque ring system. This effect is clearly shown in Fig. 8 where a typical strain gauge mounted on the lower support collar exhibited high readings of 1200 $\mu\epsilon$ in the GD single-coil full-current tests but minimal in the design-point tests.

Fig. 8. Support collar strains vs the square of the current in the test coil (GD).

Coils. Strains on the three pool-boiling coils were measured on both the winding and the case. All showed similar results.⁸⁻⁹ Plots of strains vs current squared showed roughly linear dependence as expected. The measured strains on the conductors are much higher than those on the case. For the ones that have pre-test analysis, the measured strains are higher than predicted while those on the case are lower than predicted.

Strains on the EU and CH coils were measured on the structure only, whereas on the WH coil they were measured on both the aluminum structural plate and on the conductor. All structural strains showed moderate readings to 100% design currents. The WH coil strains on the plates were higher than on the conductor, consistent with the lower modulus of Al-alloy than the JBK-75 conductor sheath.

The winding displacements from the coil case were also measured on the three pool-boiling coils.⁸⁻⁹ Generally speaking, reasonable behaviors were observed both in single-coil tests and the design-point test performed so far.

Acoustic emissions and motions. Acoustic emissions (AE) were monitored by sensors on the coil case of all except the CH coil. Observation of selected signals indicated distinctive difference between pool-boiling (PB) coils and forced-flow (FF) coils. There were very few AEs on PB coils below about 60% current, and then the increased rather steadily toward higher currents. The AEs on FF coils showed up at lower currents but were generally quieter at higher currents. There was no clear correspondence between AE and compensated coil voltages in PB coils, while the correlation was very good in FF coils.

Both the strain and AE measurements seem to indicate a distinctive feature that the mechanical coupling between the winding and the case of a PB coil is much worse than that in an FF coil.

Internal Heating Tests

Stability. The single-coil stability tests were of two different kinds, depending on whether the magnet was pool cooled (JA, GD, GE) or force cooled (EU, WH, CH). A half-turn (5 m, JA) or a full turn (10 m, GD and GE) of the pool-cooled magnets was driven normal with resistive heaters incorporated in the windings, and the subsequent behavior of the normal zone was studied.

The GD and JA coils⁴⁻⁹ recovered unconditionally at all locations driven normal (JA: straight leg of the inner turn of the middle pancake; GD: edge turn of the innermost layer).

The recovery of the inner turn of the middle pancake of the GE coil was unconditional at some locations but cold-end at others, notably at the top of the coil where the conductor is horizontal.⁸

Current-sharing threshold. The current-sharing thresholds of two of the force-cooled coils (EU, WH) were measured by warming the inlet helium until a voltage was observed. The WH coil⁷ was measured to 63% current corresponding to self-field of roughly 4 T. The measured current-sharing threshold can be analyzed to provide the critical current as a function of field. Results indicate that the WH coil would have enough allowance in current-carrying capability for the operation above design points.

For the EU coil, the current-sharing measurement results up to design current are in fair agreement with extrapolation from single-strand measurements. It was demonstrated that the coil worked outside the cryogenic stability region with well predictable operative limit.

Simulated Nuclear Heating Test. Simulated nuclear heating tests were performed on the three PB (JA, GD, and GE) coils⁸⁻⁹ and the FF (CH) coil. In the tests of the PB coils, heat was produced in several widely distributed heaters over 60 s, resembling a tokamak burning pulse. While the boundary was not surveyed in the tests, the maximum power density in the heated conductor which the coils could sustain was 70 mW/cm³ at I* = 100% for the JA, 42 mW/cm³ at I* = 100% for GD, and 86 mW/cm³ at I* = 70% for GE, in the single-coil test. Also in the full-array test, the JA coil was shown to sustain the heat power of 52 mW/cm³. Clearly, it was demonstrated that the PB coils can sustain a certain level of steady-state local heat power over the conductor in the length of 30-60 m. In the test of the CH coil, an experiment was carried out for two runs in a single coil at different inlet temperatures of the coolant: 3.8 K and 4.2 K. For both runs, total heating power of approximately 259 W was applied during the run to the design current. Results indicate that the coil as single coil is capable of accommodating per

unit winding volume two times the nuclear heating specified for the toroidal field coil of the NET design.¹⁰

Summary

The full-array LCT coil tests have progressed well. Successful experiments performed on all six LCT coils so far have shown that all six coils are likely to meet LCT specifications. Informative results to date have elucidated complex structural and electrical interactions in a multicoil array and provide gratifying assurance of coil performance.

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