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PRELIMINARY RESULTS OF THE PARTIAL ARRAY LCT COIL TESTS*

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Abstract

The Large Coil Task (LCT) is a collaboration between the US, Euratom, Japan, and Switzerland for the production and testing of 2.5 × 3.5-m bore, superconducting 8-T magnets. The definitive tests in the design configuration, the six coils arrayed in a compact torus, will begin in 1985. Partial-array tests are being done in 1984. In January the initial cooldown of two coils was aborted because of helium-to-vacuum leaks that developed in certain seal welds when the coil temperatures were 170 to 180 K. In July three adjacent coils (designated JA, GD, CH) were cooled and in August two were energized to the limits of the test facility. An overview of the results are presented, including facility, cooldown (warmup has not yet begun), energization, dump, recovery from intentional normal zones, strain, and displacement, for operation up to 100% of design current but below full field and stress. These initial results are highly encouraging.

Introduction

The Large Coil Test Facility (LCTF) in Oak Ridge will contain six test coils, but for various reasons three were available for early partial testing and facility shakedown.¹ Coil CH, provided by Switzerland, was completely installed except for the electrical bus.² Coil JA, provided by Japan, is the only one previously cooled and energized.³ Coil GD, manufactured by General Dynamics/Convair Division,⁴ was provided by the US. The coils are 60° apart, with JA in the middle, forming half of a six-coil compact toroidal array.

Operation

The first cooldown of the LCTF for two-coil tests started Jan 10, 1984. Helium gas cooled with LN was circulated through the test stand bucking post, upper and lower torque rings, GD winding, GD structure, and the JA coil. The cooldown criteria allowed an average ΔT between the outlet and inlet helium to the coils of 50 K, but caution in the face of instrumentation problems resulted in using only 19 K ΔT during the first 3.5 days of cooldown. On Jan 14, at 230-250 K range, LN was introduced to the cold walls. This and the smoother, higher average ΔT (up to 41 K) of the helium almost doubled the cooldown rate to 0.6 K/h. On Jan 17, at 160-180 K, large helium leaks developed inside the vacuum vessel and cooldown was halted. On Jan 19 helium flows were re-established to warm up the system. It went smoother than cooldown, though the average rate was about the same as that of cooldown

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(0.6 K/h). On Jan 25 the tank was let up to air; the next day the lid was removed with temperatures ranging from 255 to 275 K.

The leaks proved to be in the GD coil, at ports earlier used for urethane filler injection, and it was necessary to remove the coil from the tank to gain access for repair. During that time its inside-tank cabling and associated connectors were reworked for higher voltage-withstand capability. Evacuation of the tank started on June 14 and cooldown (Fig. 1) on July 3. Above ~100 K, the cooldown rate was limited by the available GHe mass flow and the particular cooldown criterion limiting the GHe ΔT to 50 K. Below 100 K, where LN heat exchanger cooling lost effectiveness, ΔT was less than 20 K, limited by the refrigerator turbine. In the final stages of cooldown (Fig. 2), the resistances of the coils dropped abruptly at the expected 9.2 K critical temperature.

High-voltage tests on the upgraded GD system were repeated when the coil and lead dewar contained LHe, the tank pressure was $\sim 10^{-5}$ torr, and all electrical systems were attached. The conductor-to-ground withstand capability, 600 V, was disappointing, so the dump resistor taps were changed to give a dump voltage (from 10.2 kA) of 530 V rather than 745 V. Prior to the magnet charging tests, a comprehensive series of low-current (500-A) tests were performed to insure the proper function of power supply, dump resistor, breaker circuit, Programmable Logic Controller (PLC) interlock

Fig. 1. History of the cooldown starting July 3, 1984 for (a) the facility structure and (b) the three coils.

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system, and quench detection circuits. The coils were then run extensively (Fig. 3) to shakedown the facility and test the GD and JA coils. One test remains, sub-atmospheric operation of the refrigerator, before warmup begins on Sept 15.

Fig. 2. Winding temperature and resistance of one coil (JA) in the final stages of cooldown. Typical of all three coils.

Fig. 3. History of coil currents during the partial-array tests. Downward arrows represent dumps. Hold points and energizations below 5% (500 A) are omitted.

Test Results

Quench Detection. In the LCTF, an asymmetric multi-coil array, a conventional single-bridge detection circuit would be ineffective due to mutual coupling effects. Thus a unique pickup coil compensation scheme² was used to cancel the inductive signals caused by the coil and its neighbors so that a resistive (normal zone) voltage could be detected. The pickup coils, each consisting of 64-turn shielded cable distributed around the outside surface of the coil case, provide inductive signals for compensation modules of self coil and neighboring coils. For each coil, eight quench detection modules were provided to cover different portions of the coil redundantly. Appropriate gains in the compensation modules were set manually for both coils just before they went into superconducting state ($T \sim 15$ -20 K). It was not necessary to change the gain settings during the test period.

Each module provided high-level quench signal (0.5-V threshold with 0.8-s delay) and low-level quench signal (0.25-V threshold with 8-s delay) to the PLC for coil protection. Note in Fig. 4 that while two coils were simultaneously charged with about 4 V, the residual compensated voltages stayed well below the 100-mV level.

Coil Dumps. Several coil dumps were performed from appreciable current levels (Fig. 3) showing that the associated facility systems worked well to 10.2 kA. The GD terminal voltage was balanced with respect to

Fig. 4. Total voltage, current, and compensated voltage while two coils are simultaneously charged. ground within $\sim 7\%$, and a 100-k Ω center-tap ground resistor was added to help insure this balance. Also, a series of single-coil dumps were attempted while the other coil was held at constant current to demonstrate that the quench detectors would not dump the adjacent coil. This was successful, giving promise of great savings of time and helium in the six-coil testing by using selective rather than simultaneous dumping. In one test (Fig. 5), the JA coil was first set into a persistent mode with coil current at 7010 A and then the GD coil was dumped from 4100 A. Figure 5 also shows an increase in the JA current of about 490 A, due to the magnetic coupling of the coils.

Refrigerator Operations. After the successful cooldown of the coils and facility the refrigerator was operated continuously to maintain system temperatures and liquid helium levels. Pressure on the pool-boiling

Fig. 5. Single-coil dump with both coils energized. JA coil in persistent mode.

coils was maintained at 14.5-15.0 psi $\bar{a}$ corresponding to a bath temperature of 4.2-4.3 K. The flow through the CH coil was maintained at $\sim$ 4.4 K by flow through a bath-cooled heat exchanger.

Operational disturbances were few. The large compressors were inadvertently tripped off several times, resulting in time loss of 1-2 h per event. The most serious event was the loss of vacuum in the 19,000-L storage dewar, costing about one week's time and several thousand liters of LHe.

Heat Losses. After cooldown was completed and the system thermally stabilized ($\sim$ 22 days after the coils were first filled), 4.2-K refrigeration heat loss measurements were performed on isolated sections of the system by observing liquid depletion rates in each component while the rest of the system was held at a nearly constant helium level. The major components of the system at 4.2 K are the three coils (45-50 W per pool-boiling coil, nearly independent of current), the bucking post and associated structure (low), the four vapor-cooled lead dewars and bus ducts (at $I = 0$, $\sim$ 60 W cold gas plus six SCFM warm gas), the two external LHe storage dewars (1 W for the 2,000-L dewar, 2 SCFM warm gas for the 19,000-L dewar), and the vacuum jacketed liquid and vapor lines connecting them.

Magnetic Field Surveys. During the coil tests, periodic stray-field surveys were made to confirm that personnel and equipment in the building were not being exposed to excessive magnetic fields. The results confirmed earlier calculations. With 10.2 kA in the GD coil and 4.1 kA in the JA coil, the highest field outside the fenced area was 227 Gauss; the highest field in an occupied office was 65 Gauss. Computer monitors were upset, personnel were not.

Coil Power Supplies. The power supplies used during the coil tests were $\pm$ 12 V, $\pm$ 16 kA, 12-phase, SCR units manufactured by PWR Inc. The negative voltage gives an adjustable, convenient way to slowly ramp down the coil current. The usual problems in commissioning large feedback type power supplies were aggravated by the fact that they had not been previously tested with a 2-H, 10-kA inductive load. As debugging progressed, the supplies ran smoothly in the voltage control mode at currents to 10 kA with 4 kA in the adjacent coil.

Single-Coil Heater Tests. Several of the JA heaters were energized successfully reproducing the earlier tests in Japan. Two of the GD heaters were energized using several combinations of heater power, pulse duration, and coil current. Figure 6 shows voltage traces taken when a half-turn heater adjacent to the coil case sidewall and spanning the outer leg of the D was energized at full coil current (10.2 kA). The flat tops of the voltage traces show that the heater drove the conductor fully normal. This conclusion is confirmed by the agreement of the measured flat-top voltage with that inferred from the measured normal-state resistance at zero field corrected for the magnetoresistive effect.

Recovery is rapid (a few hundred ms) and occurs simultaneously over the length of the heated half-turn, indicating that recovery was from the sides rather than from the ends. The normal-state heat flux at 10 kA in the self-field of 5.3 T near the heater is 0.12 W/cm 2 . To this must be added an uncertain contribution from the outflow of heat deposited by the hot heater; we estimate this to be not more than $\sim$ 0.1 W/cm 2 . Being in the Stekly regime means that this heat flux is smaller than the minimum film boiling heat flux, the measurement of which Christensen⁶ indicated to be about 0.18 W/cm 2 for a similar heat transfer environment.

Rapid as recovery is, it is still much slower than expected for this conductor with no heater embed-

Fig. 6. Results of pulsing half-turn heater on outer vertical leg with GD coil at full current. (a) Voltage across upper one-sixth turn. (b) Temperature at center of lower one-sixth turn, on the narrow side of the conductor opposite to the heater. (c) Heater current.

ed in it (recovery time $\sim$ 10 ms). The resolution of this discrepancy lies in the fact that the nichrome heater wires are driven to high temperatures (100 K or more) and leak heat slowly into the conductor. This is borne out by the comparison (Fig. 7) of the measured response timing of the heated half-turn with the predicted response times made for a conductor with a heater embedded in it, times are based on GD Conductor Cooling and Heater Verification Test (CCHVT) data analysis.⁷ Agreement is good except for one pulse which was just enough to drive the conductor into the current sharing regime. There is no reason to think that a normal zone accidentally created, would not recover in milliseconds.

Acoustic Emission (AE). The GD coil with its adjacent structures was fitted with 30 low-noise AE sensors.⁸ The JA coil had four such sensors and four of another kind. Data for off-line analysis, now underway, were

Fig. 7. Comparison of GD prediction with measured response timing of heated half-turn.

recorded on multichannel tape recorders, continuously at first and later only when AE signals were expected. Two channels (sensor #16 on the outer leg of GD,⁸ and bobbin at the smallest radius of JA³) were also observed in real time on a scope. Preliminary results are:

- (1) Large and frequent AE signal bursts were observed whenever either coil was charged to a new current level for the first time. Smaller and much less frequent bursts were seen on subsequent runs of GD.
- (2) Some bursts coincided with spikes in the compensated voltage, these originated with conductor motion; more occurred without such coincidence, implicating the structure.
- (3) Few bursts were seen on GD for current discharge or dump, more for JA, especially as lower currents were reached.
- (4) Only a few small bursts were seen when the current was held steady, unless the other coil was charging; for JA, spikes in the compensated voltage also appeared.
- (5) No AE signal was actually observed when one-half turn of the coil winding was driven normal by heater.
- (6) For GD, AE activity seemed to die down after the current was raised above 7.5 kA, indicating the (unbonded) winding was tightly bedded at that load. For JA, AE activity continued to increase with current, probably indicating that some glued bonds in the winding were cracking.

Mechanical Behavior. From an engineering mechanics viewpoint, three distinct Lorentz force loading conditions occurred during the testing. These were (1) a single coil at 100% of design current, (2) two coils simultaneously at 40% of design current, and (3) one coil at 40% while the other was at 100% of design current. The first two of these loading conditions were approximated within a finite element model⁹ (FEM) for the originally proposed two-coil test. Calculated values obtained from this FEM are the basis for the comparison presented below. For various reasons, this FEM contained only two coils, both of which were modeled identically to reflect the gross mechanical aspects of the GD coil. The third loading condition was not treated.

When a single coil is energized to 100% of its design current, the magnetic forces tend to make the coil become more nearly circular. Changes in bore dimensions were monitored by specially designed Moving Coil Displacement Transducers.¹⁰ The horizontal bore increase for the GD coil was 100 to 109 mils compared to a calculated value of 91. The vertical bore decrease for the GD coil was 37 to 47 mils compared to a calculated value of 40. Values for the JA coil were slightly higher. The winding displacements within the coil cases were measured. Figure 8, for an unbonded

winding (GD), shows outward motion for the bobbin and toward the OD ring, compaction from the ends, and significant bedding-down, all as expected. Curves taken with both coils energized are more complicated, but also understandable. Similar data from the JA coil shows much less displacement and bedding-down, presumably reflecting its turn-to-turn bonding. As the winding pack model was extremely crude in the FEM, comparison of calculated values with these data await an updated and more refined model.

When both coils were simultaneously energized to 40% of their design current, the out-of-plane magnetic forces towards each other tend to squeeze the torque rings out from between the two coils. The torque ring spokes, which hold the torque ring in place, restrain this motion and thus develop large loads. The torque ring bending strain for this loading condition was measured to be 200 $\mu\epsilon$ which compares favorably to a calculated value of 227 $\mu\epsilon$. The spoke strain was 340 $\mu\epsilon$ which compares to a calculated value of 333 $\mu\epsilon$. Both calculated values were obtained by applying I^2 scaling to the FEM values because the only loading condition in the FEM that applied was that of 100% of design current in both coils.

A red-line strain limit of 1500 $\mu\epsilon$ was in effect during the 40%-100% simultaneous coil testing. This value was nearly reached in the spokes. Comparison with the FEM awaits completion of an analogous loading condition.

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Fig. 8. GD winding movement away from the coil case.

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