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PARTIAL-ARRAY TEST RESULTS IN IFSMTF*

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ABSTRACT

Preliminary performance tests of two large superconducting magnets have been carried out in the International Fusion Superconducting Magnet Test Facility (IFSMTF). Each of the Japanese (JA) and General Dynamics/Convair (GD) coils was operated up to its full design current of 10.2 kA with the other serving as an adjacent background coil at 40% of design current. Cryostatic stability was demonstrated for both coils by noting recovery from a full half-turn (5 m) driven normal. A new pick-up coil compensation scheme was successfully used for the quench detection system. Each coil remained superconducting when the other was dumped. Unique instrumentation was used to measure changes in bore dimensions and displacement of the winding from the coil case. Agreement between structural analysis and measurement of bore dimension changes resulting from magnetic loads is good. The Swiss (CH) coil underwent only a cryogenic test. The forced cooling worked well and an inlet temperature of 3.8 K was demonstrated.

INTRODUCTION

In the International Fusion Superconducting Magnet Test Facility (IFSMTF), previously called the Large Coil Test Facility (LCTF), six D-shaped coils of 2.5 × 3.5-m bore will be tested in a compact toroidal array starting in 1985.[1,2] Facility shakedown and partial coil testing were performed from July to September of 1984, using three coils set at 60° apart to form a half torus. The objectives of this partial-array test were set by a Large Coil Task (LCT) Project Officers' agreement in September 1983, in which the accomplishment of the following objectives was deemed necessary to prepare properly for operation in the subsequent six-coil tests:

1) Cool down the test stand in a controlled fashion, in a reasonable time, and without excessive temperature differences.
2) Fill at least one coil with liquid helium, then maintain the coils and test stand (including bucking post, torque rings, superconducting buses, and vapor-cooled leads) at about 4 K.
3) Operate at least one coil at full current, thereby proving operation of the power supply, vapor-cooled leads, superconducting bus, dump system and data acquisition system.
4) Operate two coils so as to prove satisfactory operation of the quench detection system and power supplies with magnetically coupled coils.
5) Operate for a substantial period of time with simulated forced-flow coils, to check all operating modes of the helium system.

All objectives but the last were accomplished or exceeded during the partial-array test. This test consisted of cooling two bath-cooled coils (JA and GD), one forced-flow coil (CH), a forced flow simulator and the test stand to liquid-helium temperature, and electrically testing the two adjacent bath-cooled coils. These two coils were operated both separately (single-coil tests) and simultaneously (two-coil tests in which one is considered the test coil and the second serves as the background coil). The effect of magnetic coupling ($k = 0.15$) on the quench detection system, power supply, and instrumentation and its influence on mechanical strain were investigated. This paper summarizes the essence of the partial-array test and reports details on selected topics.

COOLDOWN AND WARMUP

Cooldown of the three test coils and the

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test stand started on July 3, 1984. Helium gas was circulated through the system by the refrigerator compressors in a fashion shown by the schematic of Fig. 1. The refrigeration coldbox has a LN_2-cooled rapid cooldown heat exchanger (RCHX) to precool part of the incoming stream to about 80 K and mix it with the remainder to control the inlet temperature. The mixed 15-atm gas was then split into two streams. One stream passed through the bath-cooled coils and the test stand (bucking post and upper and lower torque rings), while the other stream flowed through the forced-flow coils (CH coil and simulator). Both streams then returned to the coldbox and passed through part or all of the heat exchangers in counter-flow against the stream coming in from the compressors. Thus, a bootstrapping effect was achieved. The incoming gas temperature decreased as the test component and returning gas got colder. At about 100 K, the flow through the RCHX was stopped, and turbine 1 was turned on. Below 20 K, turbine 2 was also turned on to increase the cooling power of the coldbox. At this time the helium supply to both torque rings was valved off. At 4.2 K, the flow path was further changed to fill the bucking post and both bath-cooled coils with LHe. The four lead dewars were filled with LHe from the 2000-L storage dewar. To liquefy helium into the bath of the heat exchangers in the auxiliary cold box, flow was established through the JT-valve. Warmup was accomplished by essentially the same helium route except bypassing part of the returning gas around the coldbox heat exchangers.

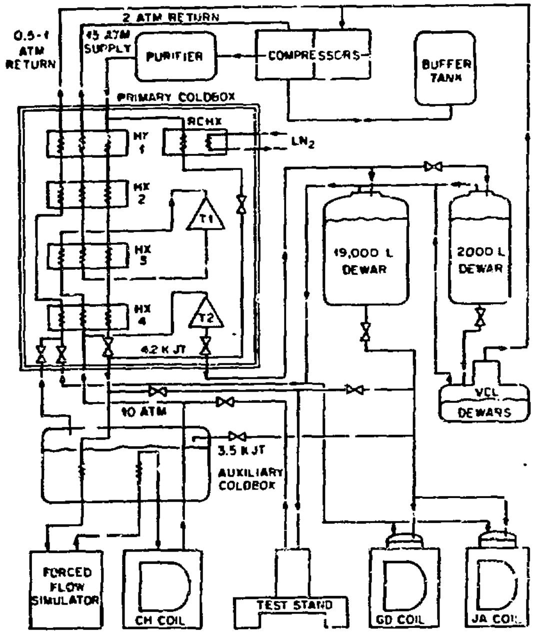

Fig. 1. Simplified schematic of the cryogenic system for the partial-array test.

Above 100 K, the cool-down rate was limited by the available helium mass flow and by the cool-down criteria established prior to the test. The criteria specified maximum temperature differences ($\Delta T = 50$ to 100 K) in the components and between different components at their mating surfaces to prevent excessive thermal stresses. To facilitate a continuous check, a cool-down computer program was used. It periodically compared the actual temperature differences with the established limits and printed out the result, with warnings if any limit was surpassed. This information was used to fine tune the helium flow into the different components. Thus, for instance, the mass flow between the winding and the structure of the CH coil was controlled in such a way that the latter stayed at least 20 K cooler than the winding during the whole cooldown.[3] This assured that the epoxy-filled winding remained in compression. It also helped to determine how to regulate the mass flow through the test stand in order to have all components in a narrow temperature band. Below 100 K, the width of the temperature band was limited by the efficiency of turbine 1. The temperature history of the facility and coils during the cooldown and warmup are shown in Figs. 2(a) and (b). It can be seen that cooldown of the 200-tonne test facility lasted about 24 days (580 h) and the warmup a week longer (770 h). The difference was mainly due to the desire to avoid frost or condensation when air was admitted to the tank, and to the fact that there was no provision for warming the incoming gas above room temperature. The frequent interruptions in the helium inlet temperatures were the result of compressor trip-offs.

COIL TEST SEQUENCES

Electrical charging tests of the GD and JA coils took place over a 21-day period. Tests were ordered in a sequence of increasing relevance to shakedown of facility, checkout of instrumentation, extent of risks, and importance of information to be gained for later full-array tests. Table 1 summarizes the major achievements of these tests.

Each pool-boiling coil was individually charged to its full design current of 10.2 kA. This produced a maximum field of 6.4 T on the conductor. (The design field for six-coil operation is 8 T.) There was neither quenching nor training in any test sequence. There were, however, three unintentional dumps of the JA coil. On one occasion, a thunderstorm shut off the refrigerator compressor. This stopped the gas flow from the vapor-cooled-lead dewars, which caused an automatic dump of the JA coil from 2.1 kA. On a second occasion, a power supply fault tripped the breaker and dumped the

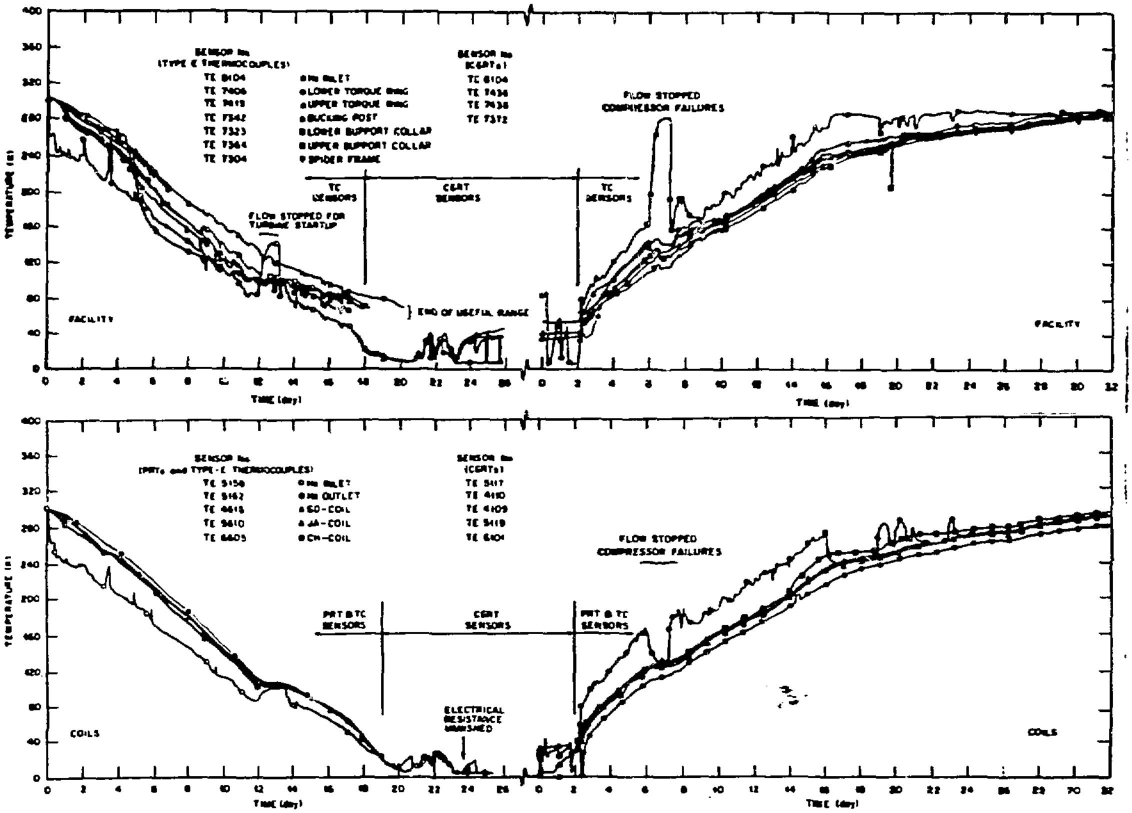

Fig. 2. Temperature history of the cooldown and warmup for (a) the facility test stand and (b) the three coils.

coil from 6.4 kA. On a third occasion, during stability testing of the JA coil, the heater-induced normal zone remained longer than the preset duration of delay and the quench detection circuit triggered an automatic dump of the coil from 8.2 kA. No damage was caused by any of these incidents. They did, in fact, prove the effectiveness of the automatic protection system.

To learn the influence of charging and discharging of a neighboring coil and to test the mechanical integrity of the test stand, three separate two-coil tests were performed. Additional spikes in the inductively compensated voltage and acoustic emission signals not present in the individual tests abundantly indicated conductor motion caused by the lateral mechanical load by the charging neighboring coil. To exemplify the mutual coupling effect, each coil was put into (nominal) persistent mode before the neighboring coil was dumped. (In a persistent mode, the shorted bus resistance of about 0.2 mΩ gave a time constant of about 3 hours.) Significant terminal voltages and sizable increases in persistent current were observed whenever the neighboring coil was dumped, but no quenching of the coil in persistent mode occurred. This showed that the future array can probably remain superconducting when a single coil quenches.

Many intentional dumps and recovery tests were performed on each coil. These tests are described in the next two sections.

DUMP TESTS

In order to check the coil protection circuitry and to make sure a coil can withstand an unexpected quench without damage, both the GD and the JA coils were dump tested at successively higher currents. (See Table I. Pre-test dumps of 500 A or less to check out instrumentation were omitted from the table.) Different methods were used to initiate the dumps. These included simulated quench detector signals (i.e., low helium gas flow and low LHe level in the vapor-cooled-lead dewars, and high lead resistance, etc.) and manual dump switches.

Table 1. Test Sequences

Dates	Test Objective	Major Achievements
8/14-8/15	Preliminary GD single-coil test	Ramped to 40% I_{GD}
		Dumped from 25% I_{GD}
8/16-8/23	JA single-coil test	Dumped from 25% and 50% I_{JA}
		Ramped to 100% I_{JA} (10260 A)
		Dumped from 63% I_{JA} unintentionally
8/26-8/27	Preliminary two-coil test	Ramped both coils to 40% I_{GD}
		Dumped GD from 25% I_{GD} with JA at 25% I_{JA}
		Ramped GD to 40% I_{GD}, JA to 65% I_{JA}
8/28	GD single-coil test	Dumped from 40% I_{GD}
		Ramped to 100% I_{GD} (10210 A)
8/29-8/30	GD coil recovery test	Recovery test to 100% I_{GD} with one heater
		Recovery test to 85% I_{GD} with three other heaters
8/31	Two-coil test with GD as test coil	JA to 40% I_{JA}, GD to 100% I_{GD}
		Dumped JA from 40% I_{JA} with GD at 40% I_{GD}
9/1	JA coil dump test	Dumped from 87% and 100% I_{JA}
9/2	JA coil recovery test	Recovery test to 100% I_{JA} with three different heaters
9/3	Two-coil test with JA as test coil	Dumped GD from 40% I_{GD} with JA at 70% I_{JA}
		GD to 40% I_{GD}, JA to 100% I_{JA}
		Recovery test on JA at the above conditions

A measurement of voltage withstand done at the end of the coil cooldown with both coils and vapor-cooled-lead dewars filled with liquid helium showed a breakdown voltage of the GD coil system of only 600 V, while that of the JA coil system passed the 1500-V test. To be sure that no damage would be done, the maximum current for deliberate dump of the GD coil was limited to 4.1 kA ($V_D \leq 220$ V). No adverse effects or appreciable LHe boiloff from the coil reservoir were observed when the coil was dumped.

A complete dump test was performed on the JA coil from 25 to 100% of the design current, I_{JA}. Helium boiloffs from the coil reservoir were measured in dumps up to 63% of I_{JA}. The results shown in Fig. 3 are in good agreement with the expected eddy current loss $I^2\tau$ dependence. The JAERI domestic test results are also shown in Fig. 3. At 87% and 100% I_{JA}, the coil pressure rose to 2.4 atm and more than 3.0 atm, respectively. In both cases, a relief valve and a vent valve to a dump tank were opened temporarily, making loss measurements impossible. Carbon thin-film temperature sensors on the conductor and coil voltage traces showed that eddy current heating caused part of the coil to go normal temporarily during discharge. Except for the undesirable loss of helium to atmosphere, the facility proved to be capable of handling a coil quench from full current (corresponding to stored energy of about 100 MJ).

Since the GD and JA coils were mounted side-by-side they were strongly coupled. The measured mutual inductance was about 0.3 H. Charging or discharging of one coil produced a noticeable terminal voltage on the other. A significant current was induced in the latter, especially when it was in persistent mode. However, since the discharge time constants were quite different, the induced current and the energy transfer were quite different. When the JA coil was dumped from 4090 A, with a time constant of 19 s, the GD coil current increased from 3890 A to 4490 A, a ΔI of 600 A. Nearly all of the initial mutual inductance energy was transferred to the GD coil. When the GD coil was dumped from 4040 A, with a time constant of 36 s, the JA coil current increased from 7020 A to 7500 A, a ΔI of 480 A. Only about 85% of the initial mutual inductance energy was transferred to the JA coil. Fifteen percent of the energy was dissipated in the bus. Figure 4 shows the current and voltage history of the latter dump.

RECOVERY TESTS

Recovery tests were performed on both the GD and JA coils up to 100% of their design currents. Different sections of half-turn

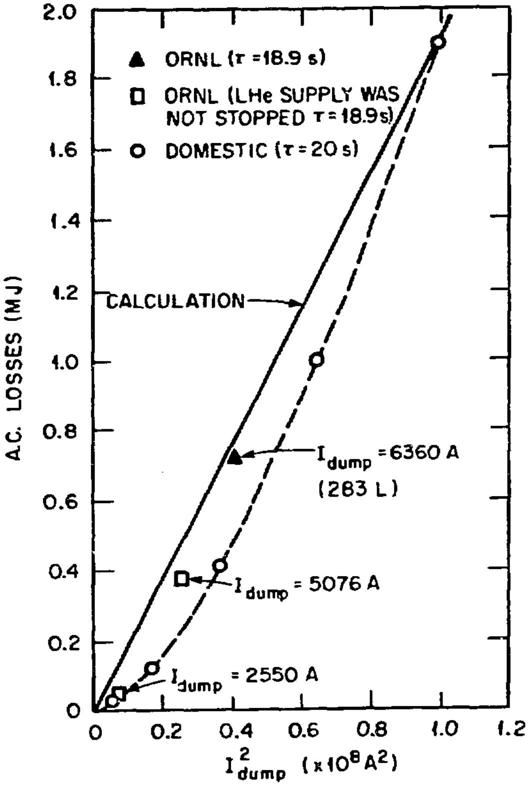

Fig. 3. Measured LHe boiloffs from JA coil dumps as compared to ac loss calculation.

(5-m-long) heaters were energized using various combinations of heater power, pulse duration, and coil current. Thin-film carbon thermometers on the conductor, as well as heated-zone conductor voltages, were monitored to observe the growth and recovery of normal zones. Heater pulse energies on the order of kilo-Joules were required to drive the conductor normal. Recovery to the superconducting state was observed under all test conditions.

The most severe test condition for the GD coil was when it was charged to full current (10.2 kA) and a heater on the first layer next to the sidewall and spanning the outer curved sector of the D was energized. The results are shown in the traces of Fig. 5. The flat tops of the voltage traces show that the heater drove the conductor fully normal, a conclusion confirmed by the agreement of the measured voltage with that expected from the normal-state resistance (measured at zero field and corrected for the magnetoresistive effect). Recovery is rapid (a few hundred ms) and occurs in the same way in the middle third of the normal zone as in the end thirds. This shows that recovery was from the sides (Stekly regime) rather than from the ends (Maddock-James-Norris regime). 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 we must add an uncertain contribution from the outflow of heat sequestered in the heater. Being in the Stekly regime means that the total heat flux is smaller than the minimum film boiling heat flux, which measurements of Christensen and Peck[5] indicated to be about 0.18 W/cm^2 for identical conductor in a similar heat transfer environment.

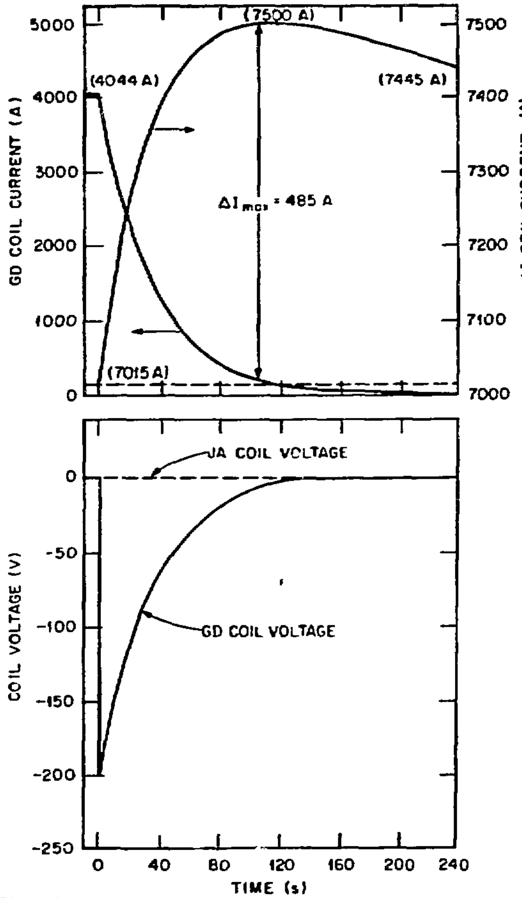

Fig. 4. Coil current and voltage histories after GD coil was dumped from 40% design current when JA coil was in persistent mode at 70% design current.

Recovery tests on the JA coil included both tests as a single coil and tests with the GD coil as background at 40% current. The additional 0.2 T magnetic field imposed by the GD

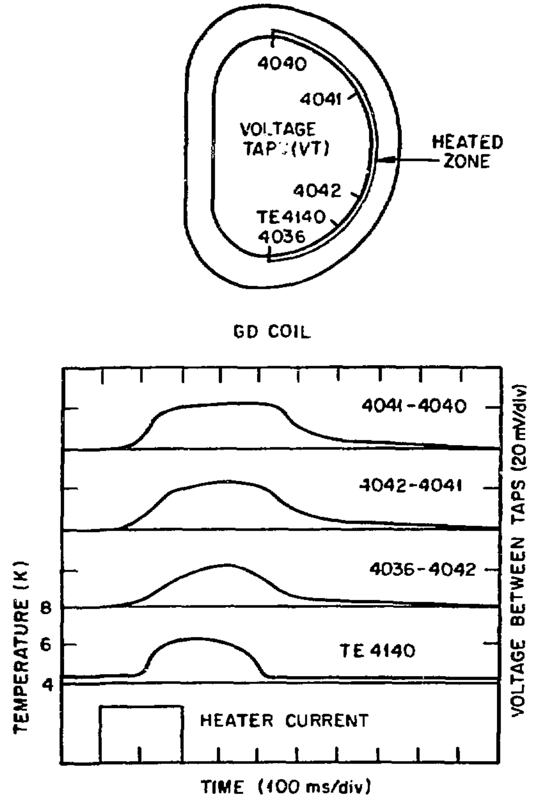

Fig. 5. Conductor heated zone voltage and temperature due to a heating pulse on GD coil at full current.

coil did not make much difference in the recovery data. The results of 100% I_{JA} charging with and without the GD coil energized are shown in Fig. 6. The heater was on the central pancake, innermost turn and spanned the straight leg of the D.

Although both coils showed full recovery, the recovery times were much slower than expected for these conductors with no heater embedded in them (recovery time $\leq$ 1 ms). The resolution of this discrepancy lies in the fact that the heater wires are driven to very high temperatures (100 K or more) and leak heat slowly into the conductor. The JA coil heaters have thicker electrical insulation than do GD's, and comparison of the recovery time and pulse heating required confirmed that the JA heaters are not so well thermally coupled to the conductor as those on the GD coil. In the examples shown in Figs. 5 and 6, a 400-ms, 1.9-kJ pulse was applied to the heaters in the JA coil to create a normal zone, whereas it took only a 200-ms, 0.4-kJ pulse applied to the heaters in the GD coil to do the same. These recovery test results lead us to believe that either coil would recover in milliseconds from a normal zone accidentally generated.

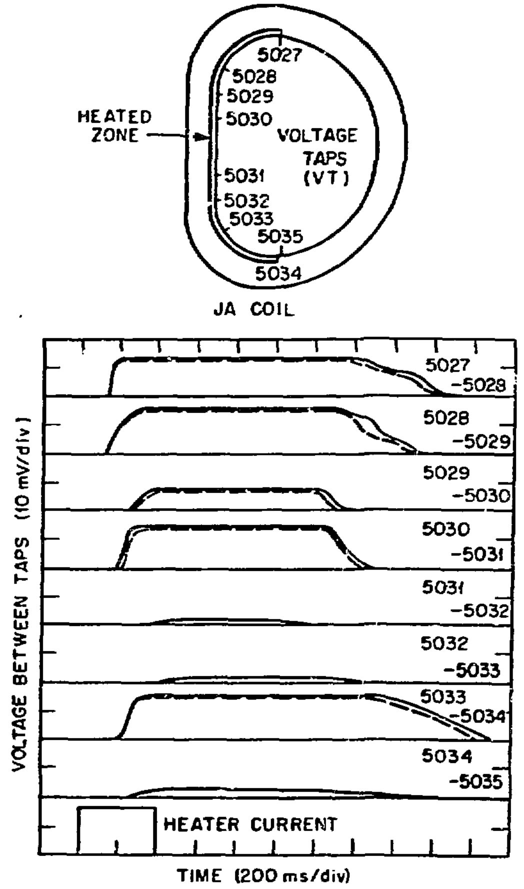

Fig. 6. Heated zone voltage profiles due to heating pulse on JA coil with (solid line) and without (dashed line) GD coil energized.

QUENCH DETECTION

The function of the quench detection system is to detect normal zone voltage and remove the coil energy quickly and safely if the normal zone grows beyond certain limits. Traditionally, in a single-coil test, a single-bridge circuit is used to compensate the inductive voltage. The compensated voltage thus represents resistive voltage, or a normal zone. In IFSMTF this technique is not effective because bridge circuits cannot simultaneously cancel out inductive voltages caused by a coil itself and strongly coupled neighboring coils on separate electrical circuits.

In the partial-array tests, we tested a unique pick-up coil compensation scheme[6] for multi-coil operation. In this scheme, the self- and mutual-inductive voltages are subtracted from each of the voltage tap signals. Two pick-up coils, each consisting of 64 turns of shielded cable distributed around the outside surface of the coil case, provide inductive signals generated by the coil and its neighbors for the compensation modules. For each coil, eight quench detection modules were provided to cover redundantly different portions of the coil. Appropriate gains in the compensation modules were set manually for both the GD and JA coils just before they went into the superconducting state ($T \leq 15$-20 K). No other adjustments were necessary. These same settings were used during the whole test period.

Each module provided to the Programmable Logic Controller (PLC) for coil protection a dump signal for a high-level quench (initially set at 0.5-V threshold with 0.8-s delay) and a low-level quench (set at 0.25-V threshold with 8-s delay). The high-level quench threshold was subsequently increased to 1.5 V for the JA coil after the unintentional heating-induced dump mentioned previously.

The test results were quite satisfactory. Figure 7 shows a typical compensated coil voltage, when both coils were charged. Note that it is very insensitive to the inductive coil voltage, indicating the compensation scheme is indeed effective.

MECHANICAL BEHAVIOR

The mechanical behavior of the GD and JA coils and of the test stand was monitored by strain gauges directly attached to the conductor surfaces, the coil cases, and the coil support structures, by displacement transducers installed across the bore and between the windings and coil cases, and by acoustic emission sensors attached to the coil cases.

The two coils experienced distinct electromagnetic loading conditions during the partial-array test:

(1) a single-coil test, in which one coil alone is energized up to 100% of its design current, and
(2) a two-coil test, in which a test coil is charged to its rated current in the background field provided by the adjacent coil charged to 40% of its rated current.

The current limit of 40% rated current on the background coil prevented too high a stress on the spoke that holds the torque ring to the bucking post. This limitation will not exist in the full six-coil test. A strain limit of 1500 με in the spoke was set by a preliminary finite element calculation, and therefore spoke strain caused by out-of-plane forces was carefully monitored during the testing.

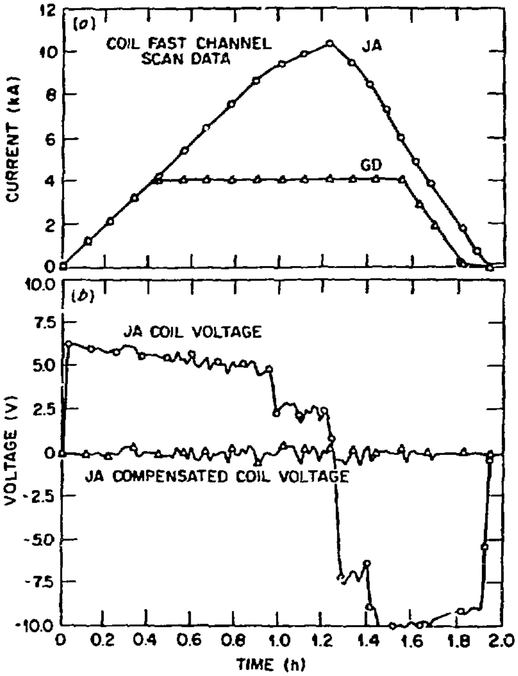

Fig. 7. Simultaneous charging and discharging of both GD and JA coils, showing the insensitivity of the compensated voltage to the changes in applied coil voltage.

The GD coil was energized steadily up to its full design current without quenching or training. Figure 8 shows the strains in the innermost layer of the GD conductor measured in the single-coil test. The tensile strain in the tangential direction increases roughly in proportion to the square of the current. The strain gauge attached at the top of the winding behaved differently from the others because of a nearby conductor joint.

When a single coil is energized to its rated current, the electromagnetic forces tend to expand the coil in the radial direction and make it become more circular. The changes in bore dimensions were monitored by specially designed Moving Coil Displacement Transducers. Measurements of the GD coil bore are shown in Fig. 9. They show an increase of 2.55 mm in horizontal bore and a decrease of 1.19 mm in vertical bore. These results are in good

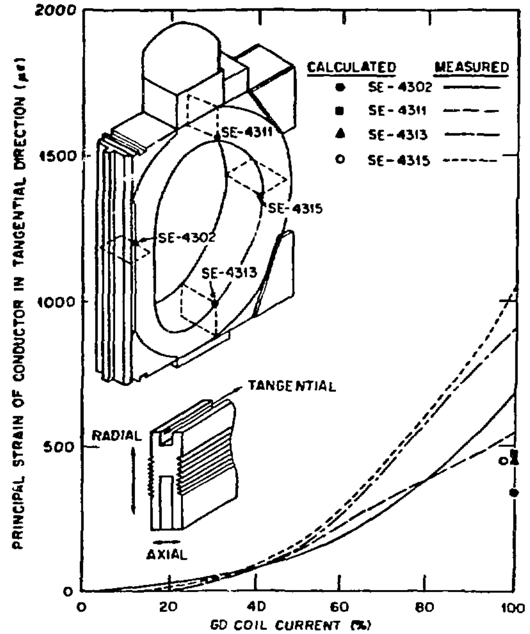

Fig. 8. Measured strain characteristics of the GD coil conductor in the innermost layer.

agreement with predicted values of 2.31 mm and 1.02 mm.[8]

A major purpose of the single-coil test for the JA coil was to confirm the strain data obtained in the domestic test[4] at JAERI and thus demonstrate mechanical integrity after shipment and installation. It is important to verify that large superconducting magnets can be fabricated in industry and shipped to a fusion plant without damage. The conductor strain and coil-case strain obtained in the single-coil test were in good agreement with the domestic test results. However, the winding displacement from the coil case measured at IFSMTF showed noticeable differences from those measured in the domestic test, since the coil support structure in ISFMTF was quite different from that at JAERI. The comparison of the relative displacements of the winding is shown in Fig. 10. The winding shows outward radial motion from the inner ring toward the outer ring as expected, but the relative displacements at the rated current were much larger than those in the domestic test results. In neither test is it well understood why the conductor pulled away less in the straight leg than in the return leg. The changes of the inner bore were also monitored by the displacement transducers. The measurements of the JA coil bore showed an increase of 3.1 mm in horizontal direction and a

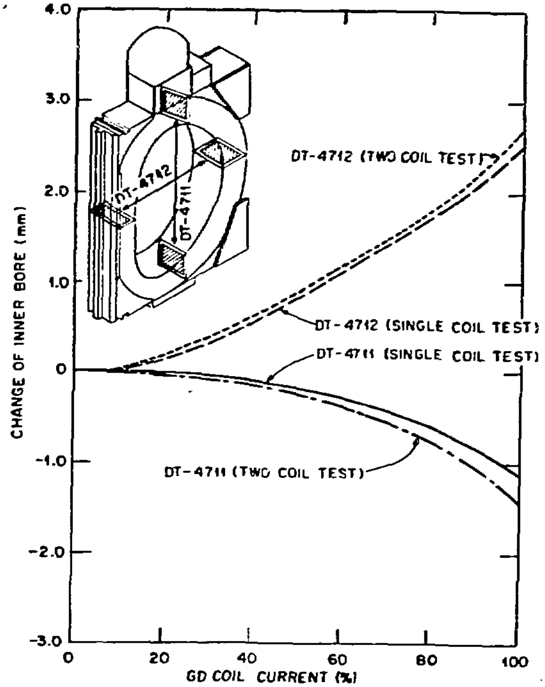

Fig. 9. Changes in the bore dimensions of the GD coil in single- and two-coil tests.

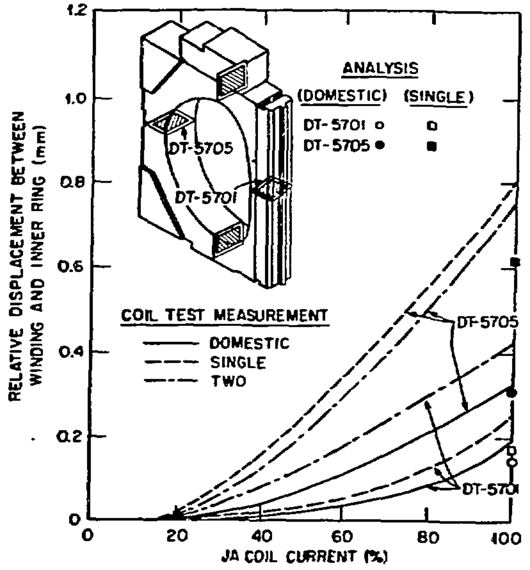

Fig. 10. Relative displacements between the winding and the inner ring of the JA coil in the partial-array and the domestic tests.

decrease of 2.0 mm in vertical direction. Based on mechanical behavior, the dump test, and the recovery tests, it is concluded that there is no damage to the JA coil due to shipment and installation.

The two-coil test (100%-40% simultaneous charge of nearest neighbors) gave the most severe loading condition in the partial-array test. When both coils were simultaneously charged, out-of-plane forces act on the coils and the torque rings. Conductor strains and displacements in both coils compared well with the single-coil test results. Only the coil case strain at the corner of the helium vessel differed significantly from the single-coil test result. Figure 11 compares the case strain at the coil corner. The compressive strain measured in the two-coil test was 550 με compared to a calculated value of 750 με. From this result, it is expected that in the future six-coil operation, both test coils will have the mechanical integrity to remain in operation against out-of-plane loads resulting from an adjacent coil being dumped.

With one coil at 4.1 kA and the other at 10.2 kA, a maximum strain of 1420 με was developed in the spoke connecting the torque ring to the bucking post. This was close to the 1500 με limit set for the spoke for safe operation.

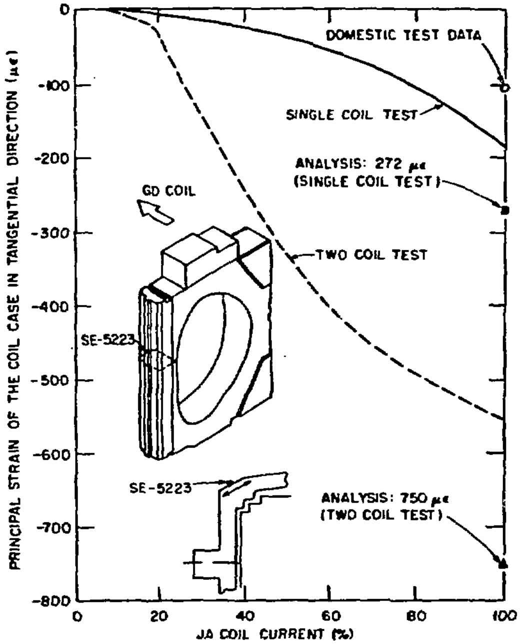

Fig. 11. Strain in the torus equatorial plane, at the corner of the JA coil case, in single- and two-coil tests.

CRYOGENIC PERFORMANCE

The cryogenic system performed satisfactorily in cooling down the test facility and the three test coils, maintaining the facility and the CH coil at operating temperature, maintaining the liquid helium level in the two bath-cooled coils and the four vapor-cooled-lead dewars during coil tests, and warming up the test facility and test coils in a controllable fashion. Inadvertent refrigerator compressor trip-offs, though annoying, did not cause much disturbance in the operation.

As a part of the test program, tests were also performed to check the capability of the cryogenic system to handle the loads anticipated in the six-coil full-array test, in which the three forced-flow coils are to be cooled with a helium mass flow of 300 g/s at a temperature of 3.8 K, and the three bath-cooled coils and the 12 vapor-cooled-lead dewars are to be filled with liquid helium at atmospheric pressure. For the present test, the additional bath-cooled coil and vapor-cooled-lead dewars were simulated by a heater in the JA coil and the additional force-flow coils were simulated by a coil simulator mounted in the vacuum tank.

The simulation of the standby mode for the six-coil test was performed under steady-state conditions for about 12 hours. The pressure in the auxiliary coldbox was about 1 bar and therefore the temperature in the forced-flow system was 4.2 K. The test showed that the refrigeration capability is sufficient for six coils and 12 vapor-cooled leads at 4.2 K and that the pressure drop in the forced-flow system can be maintained. Unfortunately, additional liquefaction of helium in this test mode was not possible. Therefore, it will be necessary in the full-array test to reduce the pressure drop and consequently the heat load in the auxiliary coldbox during standby. This can be done by increasing the mass flow through the coil cases and decreasing it in the windings, thereby reducing the total pressure drop in the forced-flow circuit.

The test with a pressure of 0.5 bar in the auxiliary coldbox and a helium inlet temperature of 3.8 K in the forced-flow system could not be performed in steady state because helium leakage in the high-pressure part of the auxiliary coldbox depleted the inventory and prevented steady-state conditions from being reached. We would have repeated this test, but were prevented by leakage of air into the subatmospheric pressure system and the heat exchanger. The test did show that the refrigeration system and especially the auxiliary cold box are able to cool the three forced-flow coils with helium flow of 300 g/s at a temperature of 3.8 K. However, the remaining cooling capacity was not sufficient to maintain the helium level in the two pool-boiling coils and the vapor-cooled lead system.

Other problem areas in the cryogenic system to be repaired prior to the six-coil test included inconsistent and anomalously high heat losses in the vapor-cooled lead system, especially at high currents or with very low helium flows; inability to calculate accurately heat losses in the helium transfer lines because sensors were attached on the outside of the pipes and did not give accurate enough temperature readings; and helium leakage into the vacuum jacket. These and the previously mentioned problems have prompted an extensive study and component tests to determine how to upgrade the cryogenic system within practical constraints of time and money.

CONCLUSIONS

While it was gratifying to charge the two pool-boiling coils (JA and GD) to full operating current (10.2 kA) and demonstrate cryostatic stability (albeit at 80% of design field), the main reward of the partial-array test was the knowledge gained in operating the entire facility and testing all the individual subsystems. Thus, we learned about some deficiencies, e.g. in the power supplies, and can address them while the remaining three coils are being received and installed.

The refrigerator/liquefier was quite adequate for the partial-array test but its total performance was still less than anticipated. This fact, coupled with higher than expected losses in the vapor-cooled leads, compels us to upgrade the cryogenic system prior to the full six-coil tests. Although leaks in the subatmospheric system impeded a thorough testing of the forced-flow capability, an inlet temperature of 3.8 K to the CH coil was demonstrated with adequate flow.

Many subsystems performed as well as or better than expected. These include the diagnostic equipment used to measure changes in bore dimensions and displacement of winding pack within the coil case, the test stand, the nitrogen cold wall, the controls of the cryogenic system, the diagnostic system including the acoustic emission sensors, the data acquistion system, and the vacuum tank. The vacuum pumping system, consisting of Roots blowers, turbomolecular and diffusion pumps, was able to maintain the vacuum tank (10^6 liter volume) in the 10^{-5} torr range even in the presence of small helium leaks. The nitrogen cold wall worked extremely well and the total heat leak into the coil and structure from gravity supports, bus lines, and instrumentation leads was about what was estimated and reasonably low (~50 W/coil). The modifications made to the refrigerator instrument and control system after the January cooldown were effective and the control of the July cooldown was easy and smooth.

The quench detection system performed well. We now have more assurance that if one coil is dumped or undergoes a quench, it will be possible to maintain current in the other coils, thus reducing the load on the refrigerator. The heater experiments verified that both the JA and GD coils were extremely stable to heat perturbations. Finally, we note that once superconductivity was established in the coils the experimental program was carried out within 21 calendar days, slightly fewer than had been planned.

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