TESTING ELECTRICAL INSULATION OF LCT COILS AND INSTRUMENTATION*

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ABSTRACT

Three of the superconducting test coils in the Large Coil Task (LCT) use conductors cooled internally by forced flow of helium. In the other three coils, the conductors are cooled externally by a bath of helium. The coils and facility are designed for rapid discharges (dumps) at voltages up to 2.5 kV, depending on coil design. Many coil sensors are connected electrically to the conductors. These sensor leads and signal conditioning equipment also experience high voltage. High-potential tests of ground insulation were performed on all components of the International Fusion Superconducting Magnet Test Facility (IFSMTF). Coil insulation was also tested by ring-down tests that produced voltage distributions within the coils like those occurring during rapid discharge. Methods were developed to localize problem areas and to eliminate them. The effect on breakdown voltage near the Paschen minimum of magnetic fields up to 2 T was investigated.

1. INTRODUCTION

The Large Coil Task is an international effort under International Energy Agency auspices for development of superconducting magnets for fusion. Six 8-T, 2.5- x 3.5-m-bore coils were designed and constructed by six teams and were installed in the IFSMTF for testing as a compact torus [1,2]. The high stored magnetic energies (up to 200 MJ per coil) require discharges at voltages up to 2.5 kV to avoid overheating should a nonrecovering transition to normalcy occur. The dielectric strength of the coils, instrumentation, feedthroughs, superconducting busses and vapor-cooled leads (see Fig. 1) must be maintained in the presence of large and changing magnetic loads, large temperature differences, and unpredictable changes in helium conditions. All components in the magnet system using the dielectric strength of helium must be carefully designed in view of its changing state during operation modes. Solid insulations in LCT must also withstand the mechanical and thermal stresses. During fabrication, assembly, and operation many nondestructive tests and remedial measures were developed to identify and improve weak points.

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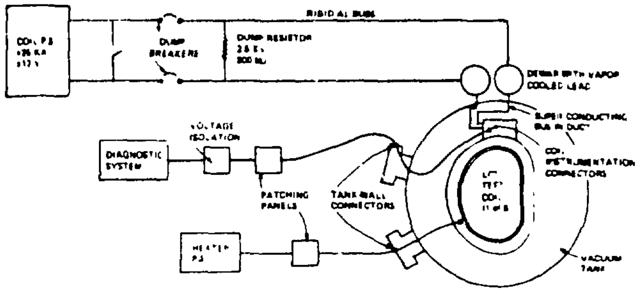

Fig. 1. *Simplified electrical schematic for one coil, emphasizing difficult insulation points*

2. INSULATION OF THE POOL-BOILING (PB) COILS

The three PB coils (GD, GE, and JA [3-5]) [illegible] windings cooled by immersion in liquid helium. Thus, their conductor insulation can cover only a fraction of the conductor surface, typically about 30%. Since the helium and the insulator edge surfaces are electrically in parallel with the solid insulator and are not able to withstand as high a voltage as the solid, the voltage rating of the PB coils is limited. For our PB coils the design dump voltages are about [illegible] V between turns, 50 to 150 V between "pies" or layers, and 1 kV between terminals. The two coils wound in spirals ("pancakes" of 2 pies each) used solid insulation about 0.5 mm thick between turns and had no extra precaution at the conductor edge. The coil wound in helicies (layers), GD, had interturn gaps of 1.9 mm for helium flow. The GD and JA coils depend on intermittent solid insulation about 3 mm thick for the layer or pie voltage, but GE has solid sheets of G-10 laminate for this purpose. All three coils have solid insulation for the groundwall, but perfect coverage is difficult.

Each PB coil has heaters for raising the local conductor temperature during testing, and 200 to 300 sensors, about half of which are attached to the conductor. For JA, instrumentation cables for sensors are routed in Teflon tubes, out through a guide duct to room-temperature ceramic-sealed feedthrough connectors, whose air side connects to the facility cabling. Supplemental Kapton film insulation was applied to the cables at specific locations where the dielectric strength was suspect.

Kapton-insulated sensor cables in the GD coil were inserted in Teflon tubes and routed in grooves to geometrically convenient locations on the coil case, where the penetration from liquid helium to tank vacuum is made through standard feedthrough connectors (Fig. 2). In the tank, each cable was placed in a Teflon tube that was then heat-shrunk, and the Stycast 2850 epoxy potting on the vacuum side of the Deutsch connectors was extended to embed the tube ends. Cables of similar voltage were then inserted in semirigid Teflon tubes, tested to 8 kV with an electrode wire and *helium in the tube, and* routed to the tank wall connector shown in Fig. 2. Sensor cables (Kapton insulated) in the GE coil were routed in grooves in the G-10 interpie spacers and then up to

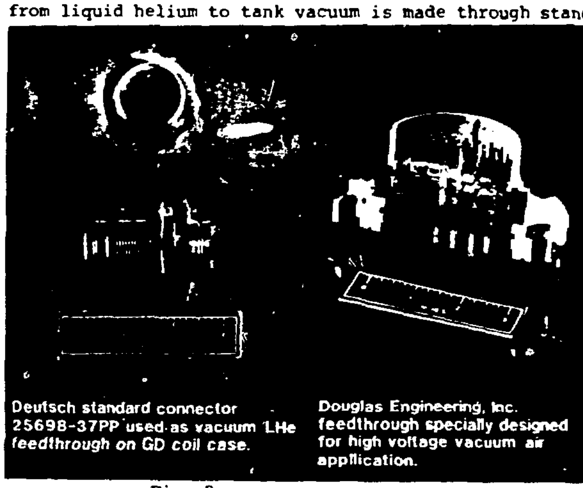

Fig. 2

TABLE I

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

terminal boards in the vapor-filled "stack" area. Two layers of Teflon tubes were heat-shrunk or individual cables in the stack and in the guide duct from the stack to the tank wall. The feedthrough connector of Fig. 2 was used for the room-temperature helium-to-air transition at the tank wall.

3. INSULATION OF THE FORCED-FLOW (FF) COILS

The conductors of the three FF coils (CH, EU, and WH [6-8]) are completely covered with insulation, and no intentional use of helium as an insulator is made except inside the fiberglass tubes used as electrical breaks connecting helium tubes at conductor potential with grounded ones. In all three, much effort was expended to ensure complete coverage with solid insulation in the vacuum region also, since coil dump and degradation of the vacuum could be parts of the same chain of events. Details of insulation usage in the coils and facility are given in Table I.

The CH coil consists of of 22 pies, each wound from solder-filled NbTi square cable, with supercritical helium circulating in a copper tube in the center of the conductor. The bare cable was insulated with dry fiberglass tape, and the interpie and winding-to-case insulation was made of fiberglass cloth. The pies are connected electrically in series by internal and external crossover joints, situated at the inner radius and on the top of the D, respectively. These joints were also insulated with fiberglass tape. The coil was wound on the D-shaped inner ring of the structure. Finally, the casing was installed around the winding and the whole assembly vacuum-impregnated with epoxy and potted. The box-type support structure of the winding is not vacuum tight. The winding is equipped with 35 diagnostic voltage taps, but to maintain the integrity of the monolithic winding no other sensor is attached to the conductor. The winding is equipped with 11 full-turn heaters and three pulsed heaters, each of Constantan wire. These Kapton-insulated heaters are placed between the pies at the inner radius of the winding. Cables from the coil to the tank wall were treated as described previously for the GD coil.

The pancakes of the EU coil were wound "two-in-hand." Thus, the length of the flow path was halved, the in-process insulation tests were eased, and a bridge-type quench detector in an asymmetrical coil array could be used. The penalty, inconsequential for a FF coil, is that the voltage across the turn insulation is nearly equal the pancake voltage. The conductor was wrapped with dry glass tapes (total thickness, 0.45 mm) and wound into a two-pie pancake. The pancakes were stacked and epoxy-potted, and the monolithic winding was installed in a leaktight structural case, which provided a guard vacuum. As for CH, sensors were placed on the surface of the winding but not inside. The cables, which had substantial Kapton insulation, were run in the guard vacuum and guide duct to a feedthrough box at the tank wall, and to fuses.

The WH conductor was bent to shape and inserted in grooves in aluminum structural plates in such a way that the turn insulation was simultaneously the groundwall insulation. The conductor was wrapped with six Kapton tapes having a total thickness of 0.4 mm and was finally wrapped with one tape of Mylar for ease of insertion into the groove. There are inductive heaters, a resistive heater, and many sensors in the coil, but none of these penetrates the conductor's steel sheath that contains the helium. The heated turn was epoxy-potted in its groove. The Kapton-insulated cables were treated like those of the GD coil except that the small Teflon tubes were full length to the tank wall rather than being overlapped and heat-shrunk.

4. FACILITY SYSTEMS

The high current is brought to the coils by 12 superconducting busses, each immersed in helium in a duct that penetrates the tank wall to join a separate dewar containing the vapor-cooled lead (VCL). At the top, each VCL assembly utilizes a machined fiberglass (G-10) plate to seal air against vacuum and to electrically isolate the lead from its dewar. The high-current busswork attached to the top of the VCL consists of four or five 2.5- x 25-cm aluminum bus bars, supported by fiber-composite bolts and maple-wood blocks. The entire bus system is enclosed in a grounded cage constructed of aluminum angle and expanded aluminum sheet. The main power supplies are transformer isolated, three quadrant, and water cooled. During normal operation the resistance to ground is typically 1 MΩ with demineralized cooling water having a resistivity of 6 MΩ-cm. (Since, on dump, the power supplies are isolated from the magnets by breakers in each bus (Fig. 1), this value of ground resistance is acceptable.) All high-voltage signals are routed from the vacuum vessel to the control room by using commercially available high-voltage cables and connectors having continuous voltage ratings well above the maximum expected voltages. All high-voltage signals are electrically isolated from personnel and from grounded data acquisition hardware by special electronics that incorporate optical isolation. The Burr-Brown 3650K, with a continuous 2000-V rating, is incorporated into all the high-voltage isolation amplifiers and current sources used to condition high-voltage signals. Each of the high-voltage conditioners was subjected to numerous bench tests as well as installed system tests. The design of the modules is inherently safe because of the large current-scaling resistors installed in the front-end circuitry. This limits the breakdown currents to an acceptable level in the event of an instrument failure.

5. VERIFICATION TESTS

Various bench tests were done to see that proposed or existing designs had sufficient insulating capabilities. One such test of general interest measured the effect of magnetic

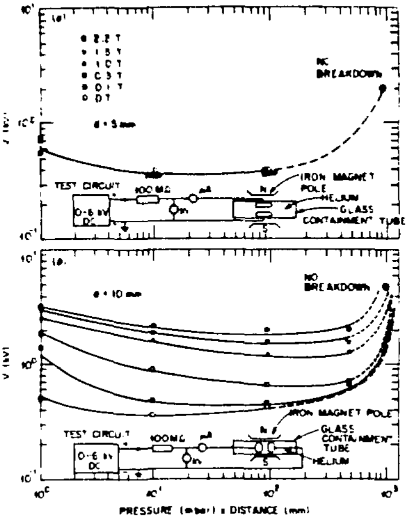

Fig. 3. Breakdown voltage in the range of the Paschen minimum as a function of pressure times distance, for helium at 20°C. (a) Magnetic field parallel to electric field. (b) Fields perpendicular.

fields on helium breakdown. The dielectric withstand of helium decreases rapidly with increasing temperature [9]. This must be taken into account for all components during testing and operation. It is a characteristic of gaseous insulation that, if the product of gas density and electrode spacing is varied, the breakdown voltage goes through a minimum

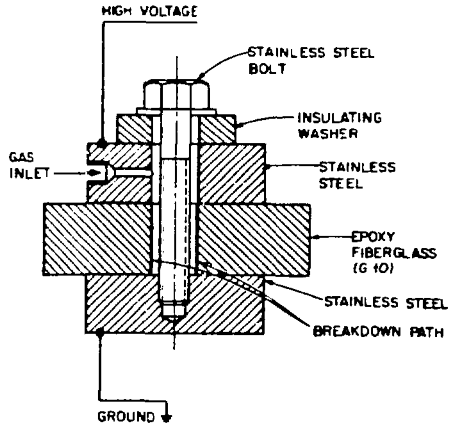

Fig. 4. Test specimen for VCL flange bolt

(Paschen minimum). Because this effect is correlated with the movement of ions and electrons, a change could be expected if a magnetic field were present. For a simple parallel-electrode geometry, the shifting of the Paschen minimum was investigated up to 2.2 T parallel and perpendicular to the electric field. The effect for perpendicular fields was found to be noticeable but not large enough to use in component design (Fig. 3).

For a large facility with many components, economic views and time schedule must be considered. Sometimes the original design has to be changed, or new aspects make other measures necessary. The VCL flange bolting system has such a history. Even after several steps were taken to reduce degradation by moisture, the space around the bolts could be contaminated by helium if an O-ring leaked. A 1:1 test specimen was fabricated (Fig. 4) in which the critical space could be filled with any mixture of nitrogen and helium. Breakdown measurements with up to 50% helium showed breakdown voltages of 25 kV, but for pure helium breakdown occurred at 4.5 kV.

6. INSULATION TESTS

Table II summarizes the high-voltage tests done on the test coils and facility. The dc tests, suitable for testing groundwall insulation, used Meggers for survey work. For the definitive work, equipment was used which gave accurate values of voltage and current and which limited leakage current on breakdown to a value that would not cause surface damage to Kapton or G-10 [10]. Terminal-to-terminal tests were done with the ring-down method described in the following section.

TABLE II

Overview of high-voltage tests[a]

System	Design dump voltage	Coil tests[b]: After fabrication	Coil tests[b]: After installation (IFSMTF)	System tests[c] (coils cold tank evacuated)	Component or in-fab tests
EU	2600	12,000	7600	2200	2-in-hand cond., 1000 Stacked pancakes, 1000 Other components, ≤12,000
CH	2600	10,000	7600 2200[d]	2200	≤15,000
JA	1020	3000 1000 AC	1000	1000	≤3000
GD	745	3000	1800 Bd 1000[d] in He	260[e] Bd	Cables, 7000 in He
GE	905	2100 2100 in He	2100	1000	Cables, 8500 in He
WH	2500	3500	2000	2200	First plates, 16,500
Pulse coils	2000	3000	3000 2200[d]	Not yet tested	Main feedthrough, 8000
Facility	2500			2500	≤10,000

[a]Unless otherwise indicated, voltage is winding to ground, dc in volts

[b]At room temperature unless otherwise noted with air or N_2 in the coils

[c]Originally planned at 1.5 times dump voltage, but limited by rating of electronic instrumentation to 2200 V

[d]Peak of short pulse applied across coil terminals during ringdown tests

[e]Present breakdown value. As a result of this low value, the operating voltage has been reduced, by reducing the dump resistance to 26 mΩ

7. RING-DOWN TESTS

A test method was desired to develop the required terminal-to-terminal test voltage while limiting the energy that would be dissipated if an electrical breakdown did occur during the test. The procedure was to charge the coil at a very low current and then to break the current with a switch, allowing the open-circuited coil to "ring-down" at its self-resonant frequency, determined by its inductance and distributed internal capacitance. This provided maximum voltage with minimum stored energy. Each set of tests began with a charging current of a few milliamperes, which was then increased on successive shots until the desired terminal-to-terminal voltage was reached or careful examination of the waveforms indicated breakdown. The latest tests used a second-generation electronic switch designed especially for the purpose [11]. The voltage peaks were of short duration and should not be equated directly to dc values.

Two of the instrumentation feedthrough connectors on the GD coil had adjacent pins connected to leads from sensors mounted on the conductor at opposite ends of the coil. A primary objective of the test was to determine if there would be an electrical breakdown between these pins in the event of a coil dump. To prepare the coil for testing, all the external instrumentation leads were laid out on an insulated table and their ends separated. The coil was pumped out and backfilled with helium to slightly above atmospheric pressure. On ring-down, two distinctly different periods were observed, one superimposed upon the other. The low-frequency component was attributed to the decay rate of eddy currents in the case. A charging current of 90 mA produced an initial peak of 95 V with no indication of breakdown. At slightly higher currents, initial peaks between 106 and 270 V that became slightly clipped and wider indicated that some breakdown was taking place. However, at even higher voltages, up to the predetermined

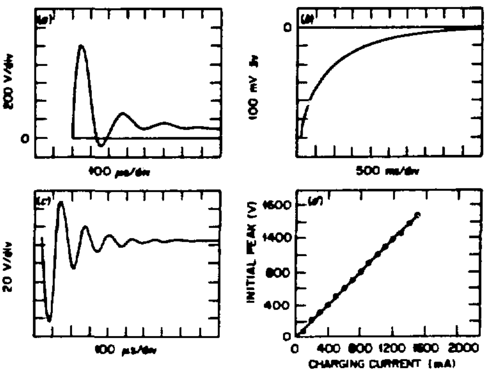

Fig. 5. Typical results of ring-down tests. (a) GD coil—ringdown from 1075 mA charging current. No breakdown. (b) WH coil—characteristic decay. (c) Upper pulse coil—from 50 mA. (d) GE coil—initial peak voltage vs charging current. (Straight line is characteristic of other coils tested.)

limit of 1000 V, no clipping was observed [Fig. 5(a)]. The test was repeated at a later date, but the anomaly never reappeared.

The ring-down characteristics of the WH coil are quite different from the others. It is heavily damped by eddy currents in the aluminum plates, which act as a shorted secondary, and large test voltages could not be reached. Figure 5(b) shows the characteristic voltage decay of the ambient-temperature coil.

Charging currents for the CH coil were begun at 1 mA and were raised in steps until an initial peak of 2200 V was reached after interruption of 2.23 A. The upper and lower pulse coils were tested in the same manner as the test coils, up to a peak of 2000 V, without breakdown [Fig. 5(c)]. The coil and leads for GE were prepared as for GD. The charging current was increased from 10 mA in increments of 100 mA while the oscilloscope was observed for any sign of breakdown. Figure 5(d) shows a plot of the peak voltage as a function of charging current. The linear plot indicates that there was no breakdown.

8. BREAKDOWN LOCALIZATION

With such large and complicated systems, locating breakdowns was often difficult and time-consuming. Therefore, where feasible, components were tested beyond the system test voltage before being connected. Repeated subdivision of a system was the standard technique for localization, but sometimes an indivisible residue still contained an unlocated breakdown. It was shown that acoustic emission (AE) techniques could detect breakdowns a few meters away and, by triangulation and time-of-flight measurements, could locate within about 5 cm [9] breakdowns occurring during dc high-voltage tests. The breakdown at the GD coil connector J21 was located in this manner, and the grinding, repairing, and rewelding were successful.

9. EXPERIENCE

Besides the items mentioned previously, several other electrical flaws were uncovered in the testing. During coil fabrication, WH had two breakdowns deeper than the top plate and was unstacked, repaired, and rewound. One EU pancake was discarded after winding. The JA coil had Teflon wiring in the duct cut through. The GD coil had the first four layers unwound and rewound to allow strengthening of the cable insulation. The GE coil eventually developed five unstable shorts, each by fine lead wire across several turns; two were removed by cutting, two were burned out electrically, and a minor one was unmolested. The Kapton cabling as originally installed in the tank was too fragile and was reinforced as previously described. The maple and micarta supports for the rigid bus were susceptible to moisture, and ground resistances of ≈6-10 MΩ were not consistently achieved without various improvements. The only system that is presently derated is GD; its breakdown voltage has fallen from as much as 2 kV previously (helium, ambient) to 260 V presently (helium, cold, vacuum). The difficulty is thought to be at the coil case instrumentation connectors, a location that is inaccessible unless the tank lid is removed.

10. CONCLUSIONS

Verification tests are invaluable in guiding the design of complicated and demanding insulation systems. The actual environment should be considered carefully. During fabrication and installation, high-voltage electrical tests uncover flaws that cannot be detected by other means. During this time components and systems should be exposed to a series of tests. These test voltages should decrease as the work progresses, and the final voltage on the completed system should give a quite substantial margin over the working voltage.

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