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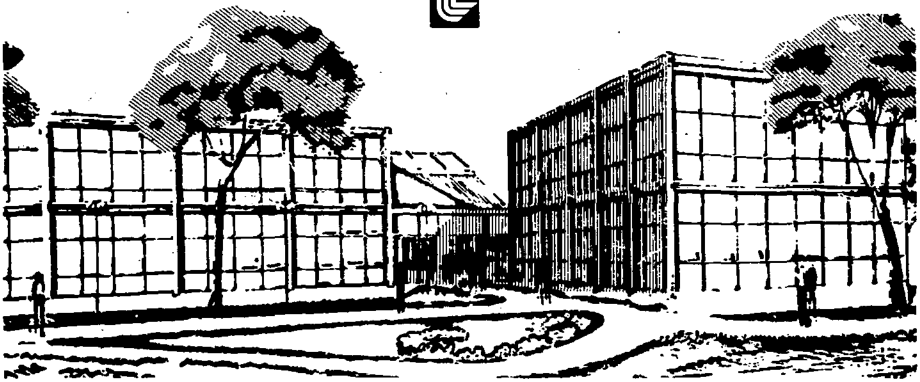

MFTF TEST COIL CONSTRUCTION AND PERFORMANCE

D.N. Cornish, J.P. Zbasnik, R.L. Leber, D.G. Hirzel, J.E. Johnston, and A.R. Rosdahl*

ABSTRACT

A solenoid coil, 105 cm inside and 167 cm outside diameter, has been constructed and tested to study the performance of the stabilized Nb-Ti conductor to be used in the Mirror Fusion Test Facility (MFTF) being built at Lawrence Livermore Laboratory. The insulation system of the test coil is identical to that envisioned for MFTF. Cold-weld joints were made in the conductor at the start and finish of each layer; heaters were fitted to some of these joints and also to the conductor at various locations in the winding. This paper gives details of the construction of the coil and the results of the tests carried out to determine its propagation and recovery characteristics.

I. INTRODUCTION

The plasma confinement field for the Mirror Fusion Test Facility (MFTF) being constructed at Lawrence Livermore Laboratory will be generated by a pair of large Nb-Ti superconducting coils in a yin-yang configuration.[1] For these coils, a cryostatically stabilized conductor incorporating internal, liquid-helium-cooled surfaces has been developed.[2] To determine the performance characteristics of the conductor, we fabricated and tested a 105-cm i.d., 167-cm o.d. solenoid made from this conductor.

The insulation system between the pancakes and turns of the test coil is identical to that envisioned for the MFTF coil so the conductor environment in the solenoid is representative of that in the final coil. Normal zones were created by pulsing heaters attached to the conductor: a study of the behavior of these zones has established a stability criterion for the conductor in a representative environment.

II. DESCRIPTION OF COILS AND EQUIPMENT

Figure 1 shows the solenoid being wound. The winding was done in pancake fashion; the G-10** epoxy-fiberglass dots that provide turn-to-turn insulation and coolant passages were wound in with the conductor and the interpancake insulation was slotted to give 50% bearing surface. Joints in the conductor were made by first stripping off the outer copper stabilizer, then cold-welding the core, and finally soldering the stabilizer back on. To stagger the discontinuity at the joint, the stabilizer was replaced in two L-shaped pieces, 23 and 43 cm long. Joints were made alternatively at the inside and then at the outside diameter between neighboring pancakes as the winding progressed. Table I lists parametric values for the conductor and test coil.

Fig. 1. Various operations in winding the test coil

TABLE I
Conductor and Coil Parameters

Parameter	Value
Conductor:	
Overall dimensions	12.45 x 12.45 mm
Cu/superconductor ratio (9th & 10th pancakes)	6.41
Cu/superconductor ratio (11th pancake)	4.42
Effective Cu area (9th & 10th pancakes)	105.7 mm^2
Effective Cu area (11th pancake)	101.7 mm^2
Mass per unit length	1.05 kg/m
Available external cooling surface	0.0225 m^2/m
Available internal cooling surface	0.0592 m^2/m
Total available cooling surface	0.0817 m^2/m
Coil:	
Thickness of interturn insulation	1.2 mm
Thickness of interpancake insulation	1.7 mm
Inside radius	523.2 mm
Outside radius	834.6 mm
Winding length	256 mm
Total conductor mass	2080 kg
Winding tension	900 N

Figure 2 shows the location of the heaters, potential taps, and strain gages on pancake 10. Pancakes 9 and 11 were similarly equipped, but did not have strain gages.

The heaters were fabricated in three steps: (1) A sheet of 0.025-mm-thick stainless-steel foil was laminated to a 0.076-mm-thick polyimide film using M-Bond 600 adhesive, which was cured at 93°C for 2 h with an applied pressure of 1.4 MPa (200 psi). The resultant glue line was about 0.002 mm thick. (2) The stainless-foil was then photochemically etched to form the individual, arc-shaped heaters. (3) Finally, a top layer of polyimide film was glued onto the shaped foil with the M-Bond 600. This top layer had holes near the ends of each heater through

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* University of California, Lawrence Livermore Laboratory, Livermore, CA 94550.

** Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

which connections could be made. This process yielded a sheet of enough heaters for one pancake.

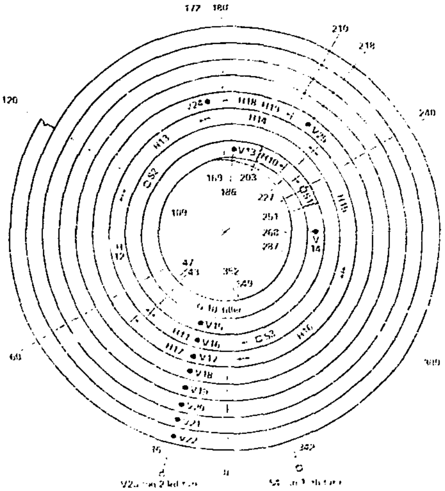


Fig. 2. Locations of the heaters (H), potential taps (V), and strain gages (S) on pancake 10.

The heaters and strain gages were bonded to the top face of the conductor with AE-10 adhesive, cured at 24°C for a minimum of 6 h with an applied pressure of 0.14 MPa (20 psi). The thickness of this glue line was approximately 0.01 mm.

A coating of Volan A glass cloth impregnated with PR-1660-L polyurethane was applied to all exposed terminals (heaters, strain gages, and potential taps) for mechanical strength, insulation, and moisture protection. A 12-h cure at 24°C and 14 kPA (2 psi) was used for this bonding.

Each main heater spanned a 60° arc and was about 60 cm long and 3.2 mm wide. These heaters were located 3 to 4 turns out from the bore tube so as to be in a thermal environment representative of that experienced by the bulk of the conductor bundle and also to be close to the peak field. A 30-cm-long heater was also fixed to the high-field joint between pancakes 13 and 14. By simultaneously energizing several heaters, e.g., those on different pancakes, we could create a variety of normal zones in the coil.

To measure the stability of the conductor at more than one field, and at the same time to obtain a higher field than was possible with the test coil alone, we mounted an additional backing-field coil on each side of the test coil. These coils, which are part of another facility, were connected in series and powered independently of the test coil. Figure 3 shows the coil assembly being connected to the suspension tubes before being lowered into the cryostat.

Each coil had a protection system consisting of a quench detector, a circuit breaker, and a water-cooled, stainless-steel resistor. Upon sensing a quench, the detectors tripped the circuit breakers and discharged the coils through their resistors.

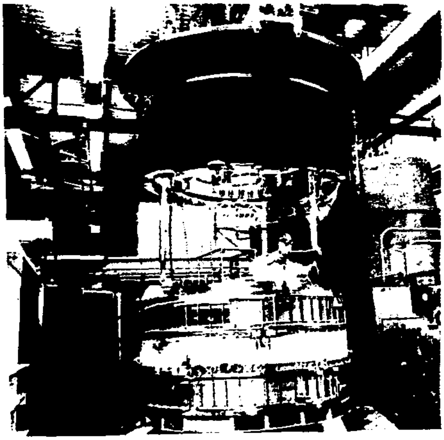


Fig. 3. Coil assembly being connected to the suspension tubes before being lowered into the cryostat.

In addition, the breakers would open automatically upon loss of a.c. power or an overcurrent from the power supplies, or manually with a push button.

The voltage drops across the main, current, vapor-cooled leads were monitored by a warning/trip chassis. A buzzer sounded if the voltage drop exceeded the warning level; if the voltage exceeded the trip level, the circuit breakers would open automatically.

With the breakers open, the discharge voltages developed were [illegible] V (0 to 450) V and [illegible] V ([illegible] to >300 V) across the test and backing coils, respectively. All diagnostic leads were routed through relays that opened just before the circuit breakers to prevent these voltages from entering the control panels and instrumentation.

III. TEST PROCEDURES AND RESULTS

For each series of test runs, the current in the backing coils was held constant at either zero or at the full design value, the current in the test coil was set at some value, a certain combination of heaters was pulsed for a preset time, and data, including voltages across potential taps, were recorded on a multichannel recorder. The voltage applied to each heater in all the tests reported here was 40 V, and the resistance of each 60-cm-long heater was about 10 Ω (i.e., 160 W/heater). The duration of the pulse could be accurately controlled; for a given test, we increased the test-coil current in steps until either the normal zone propagated or the heater on-time reached the arbitrary limit of 200 ms. If this limit was reached without normal-zone propagation, we then increased the test-coil current and applied another series of pulses to the heaters.

Figure 4 shows the recovery and propagation velocities as a function of $I^2\rho$ heating in the stabilizer. Data for various 60-cm-long heater arrangements are presented. The velocity is almost independent of the length of the initial normal zone (over this range), and the critical heat generation is 1.5 W/cm. This corresponds to a heat flux, averaged over all cooling surfaces, of 0.19 W/cm².

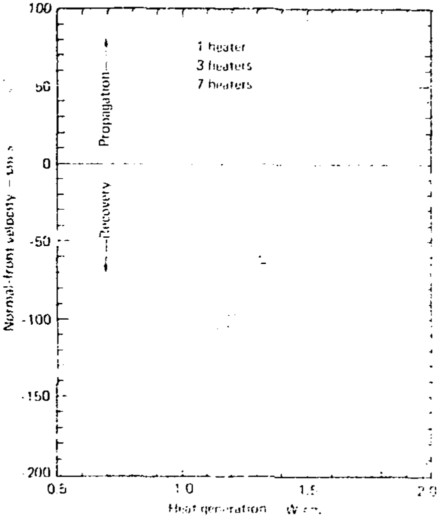
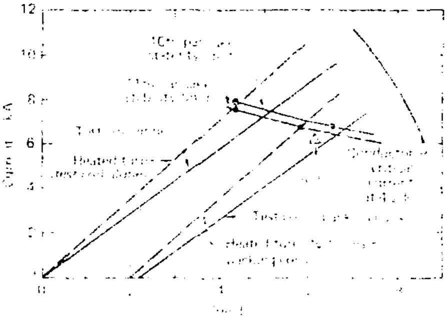


Fig. 4. Relationship between heat generation and normal front velocity for various heater arrangements.

Figure 5 shows the peak-field and heated-turn load lines for the test-coil field alone and also with the field increased by the backing coils. The condition of zero propagation velocity defines the stability limit; the extrapolation (dashed line) assumes a constant critical heat generation of 1.5 W/cm and allows for the effects of magnetoresistance. The lower stability limit of the 11th pancake can be explained by the smaller amount of copper in the core. The MFTF conductor is similar to that used in pancake #10.

The behavior of the test coil can be explained using this stability limit (critical heat generation). For example, in one experiment the heaters were pulsed when the current was slightly above the stability limit. The normal region propagated in one direction only, spirally inwards towards the high-field region. After the normal region had propagated about a turn, the coil current was ramped down, and soon thereafter recovery started from the low-field end of the normal zone and proceeded inward. By the time the current at the peak-field point had dropped to the stability value, the coil had fully recovered. This sequence took 67 s. In another experiment, the heater was pulsed when the current in the heated turn was well above the stability limit. In this instance, propagation was in two directions: outward (i.e., towards the low field) propagation stopped after 17 s when the heat generation fell to the critical value; inward propagation continued into the adjacent pancake, and after [illegible] s the [illegible] two pancakes caused the [illegible] normal at the rate of a [illegible]. The [illegible] heat generated at this time was approximately [illegible] kW.



[illegible]

[illegible] was taking [illegible] conductor. [illegible] towards. [illegible] propagated [illegible] because pancake [illegible] monitored [illegible] this period [illegible] caused by [illegible].

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To investigate the coil behavior above the stability limit, the backing-coil current was adjusted to the desired level, and as the current in the test coil was slowly increased, a single, 60-cm-long heater was pulsed. Approximately [illegible] were dissipated in the heater during each of these 60-ms pulses. The coil quenched three times, but they were spontaneous quenches not initiated by the heater. The quenches were not always in the same pancake, and as shown in Fig. [illegible] the field was a little higher each time. The maximum conductor field was 7.55 T.

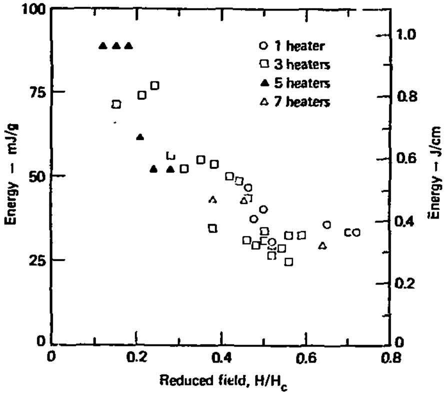

Fig. 6. Energy required to create a fully normal zone.

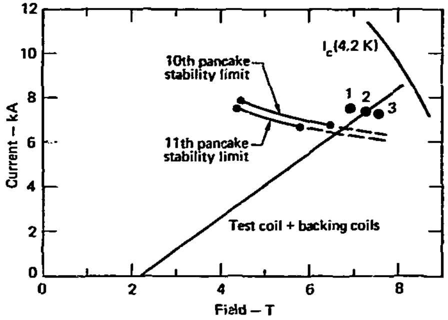

Fig. 7. Operation of the test coil above the stability limit.

A 30-cm-long heater attached to the inner (high-field) joint between pancakes 13 and 14 was used to study the stability of a joint. At 6.2 T and 6200 A, the joint did not recover to the full superconducting state. The equivalent of 23 cm remained normal until the current was reduced to 6110 A, at which time the current rapidly returned to the superconducting core. This 23 cm is the same length as the shorter piece of stabilizer replaced after the joint was made. While the inner joints were being wound onto the coil, they were bent to a 50-cm radius, and there was a tendency for the solder bonding of the replaced stabilizer to give way at the ends. This could explain the lower recovery current at this point.

Strain gages were attached to the top face of the conductor. The strain caused by magnetic loading was very reproducible, and the maximum attained was on the first turn and amounted to 0.18% at 7.5 T. During each test, the measured strain at zero-field did not return to its initial value. The cumulative zero field strain measured by the first-turn strain gage increased by 0.32% during this series of tests. It must be emphasized that in this work a single strain gage was used. To define the strain field in the conductor, i.e., to separate the tensile and bending strains, an additional gage would be needed on the opposite face.

The axial compression of the test coil under load was also of considerable interest. During the winding process, we had kept a careful record of conductor and insulation thickness at six points around the coil. The actual final coil length was measured and found to be 6 mm greater than the sum of all these dimensions. The coil was compressed between steel end plates by a ring of bolts around the inside and outside diameters of the coil. However, an excess of about 1.5 mm was left in the coil, and linear potentiometers were attached to the end plates to measure any displacement during operation. Readings from these did in fact confirm that the coil contracted and relaxed by this 1.5 mm as the system was energized and de-energized.

Conclusions

Fabrication of the MFTF Test Coil was of great value in determining the handling properties of the conductor and insulation and the problems of making *in situ* joints, and in obtaining preliminary data on coil buildup.

The conductor stability was within the expected range and was both determinate and reproducible. The conductor was docile in that above the stability limit the velocity of propagation was relatively slow and a reduction in current caused it to recover if it were not too far above this limit. Propagation was limited to that along the conductor for 10's of seconds, and propagation to the layers above did not occur until several kilowatts were being dissipated. A great deal of detailed information on the behavior of both the conductor and the test coil was obtained.

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