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J.P. Zbasnik, T.A. Kozman, D.W. Shimer
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J. P. Zbasnik, T. A. Kozman, D. W. Shimer, and D. R. Hathaway
Lawrence Livermore National Laboratory, University of California
P.O. Box 5511, Livermore, CA 94550

Abstract

We have successfully constructed and tested a pair of high-field coils that is part of the magnet set of the Mirror Fusion Test Facility (MFTF-B) at the Lawrence Livermore National Laboratory. Each coil consists of a multifilamentary Nb_3Sn magnet nested inside a multifilamentary NbTi magnet. During our test, these coils produced a central field of 12 T, with a peak conductor field of 12.5 T. The dimensions of the Nb_3Sn insert coil are: 1.34-m bore, 2.57-m outer diameter, and 1.14-m overall length. These coils were designed to be fully cryogenically stabilized and cooled by pool-boiling liquid helium. The operating current density of the Nb_3Sn coils is 2000 A/cm^2 and 2400 A/cm^2 for the NbTi magnet. In this paper, we present design considerations and details, construction techniques, and operational results of these coils.

Introduction

The Mirror Fusion Test Facility (MFTF-B), commissioned in February 1986 at the Lawrence Livermore National Laboratory (LLNL), consists of 42 superconducting magnets that were configured for plasma physics experiments on tandem mirror fusion machines.[1] The coils, which weigh slightly over 1000 tonnes, are housed in a 58-m long vacuum vessel, which has a volume of ~4000 m^3. The design features and operational details of the overall facility are presented elsewhere in these proceedings[2]; this paper concentrates on the high-field axicell coils. Each of these coils consists of an outer NbTi coil, which generates a 6-T field on the machine axis, and an insert coil of multifilamentary Nb_3Sn, which boosts the on-axis field to 12 T. The relevant coil parameters for these coils are listed in Table 1.

Table 1. High Field Axicell Parameters.

	NbTi Outer	Nb_3Sn Insert
Clear Bore, m	1.34	0.36
Outer Diameter, m	2.57	1.32
Winding Length, m	0.96	0.67
Critical Current, A	>8970	>3200
Operating Current, A	4648	1504
Pack Current Density, A/mm^2	24	20
Peak Field, T	7.5	12.5
Heat Flux, W/cm^2	0.11	0.17
Stored Energy (Alone), MJ	64.2	4.25
Stored Energy (in System), MJ	76.8	11.6
Coil Mass, kg	31,300	6,200

Coil Design

High-Field Insert Coil

A cross section of the high-field insert coil is shown in Fig. 1. The conductor, a monolithic Nb_3Sn composite soldered into a two-piece housing of hardened copper, was wound pancake-style with all the joints on the outer radius. Details of the conductor and its manufacture by the Furukawa Electric Co. were described at an earlier Applied Superconductivity Conference.[3]

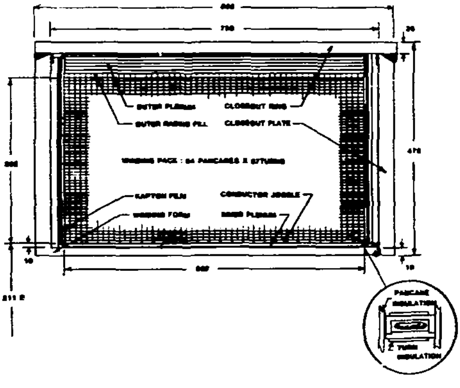

Figure 1. Cross section of the insert coil. Dimensions are in millimeters.

The coil was operated with the bore oriented horizontally. The turn and pancake insulation pieces, fabricated from G-10 CR laminate, are shown in Fig. 2. The flat side of the strip covers 55% of the conductor surface, while the grooved side covers 26%. According to the conductor-pack stress calculations performed for us by General Dynamics-Convair (GDC) using the computer program called STANSOL,[4] the radial pressure was negligible, so there should be no conductor coining. The pancake insulation, also fabricated from G-10 CR laminate, is slotted, and the pieces are arranged so that the slots tend to channel the helium bubbles, primarily caused by nuclear heating, away from the high-field region around the bore tube. The slots allow 43% of the pancake to be exposed to the liquid helium. The maximum axial stress on the conductor at the midplane of the winding pack was calculated to be 25.6 MPa. At this stress level, the conductor coining was negligible.

The ground plane insulation consists of 6 layers of 0.13-mm-thick polyimide film (Kapton strips), with a 50% overlap, which maintains a minimum creepage path distance to ground of 75 mm. The Kapton is protected from damage by G-10 CR sheets. The G-10 CR side plates, which are positioned between the windings and the Kapton strips, are 7.9 mm thick and have 6.4-mm-deep grooves, spaced 6.4 mm apart. The grooves are oriented in the same fashion as the slots in the pancake insulation pieces.

The plenum around the inner bore consists of a grid-like pattern that was machined from G-10 CR

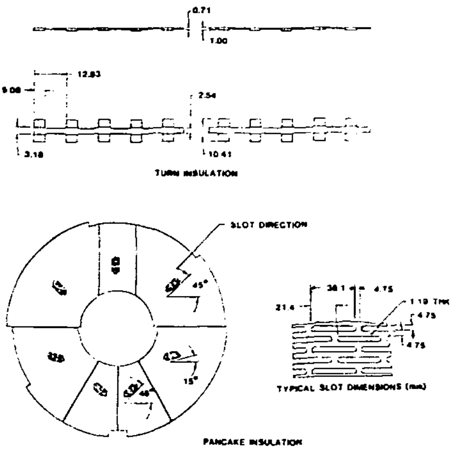

Figure 2. Turn and pancake insulation. Dimensions are in millimeters.

laminate. The plenum has a void fraction of approximately 64%, or a total void volume of approximately 5.6 ℓ. The outer plenum was formed from sheets of G-10 CR, which were slotted in a manner similar to the pancake insulation pieces. The slots are oriented at approximately 45° to the horizontal axis, with the slots of alternate pairs of sheets at 90° to each other, forming a fully permeable structure.

Because of the strain-sensitivity of the Nb_3Sn superconductor,[5] control of stresses and strains in this coil was of great concern. Analysis of the conductor stress from the combined action of winding tension, cooldown, and Lorentz forces was performed by GDC with STANSOL. The input to STANSOL included the winding bobbin, the inner plenum, and 57 conductor-insulation layers. The conductor pack was intended to be self-supporting, so the outer ring was ignored in these calculations. A radial modulus of 2.07 GPa was assumed, based on tests of the radial stiffnesses of other MFTF-B coils. An effective hoop modulus was used, which took into account the initial strain state and the stress-strain behavior of the copper housing. The STANSOL calculations for a 1350-N winding tension yielded a hoop stress that ranged from 75.8 MPa for the first turn to 96.5 MPa at the outer radius for normal operating conditions. For abnormal conditions, in which the current was assumed to peak to 115% of its normal value, the hoop stress on the first turn was approximately 100 MPa. This was well within the capability of the conductor, which has a yield strength of 207 MPa at 4.2 K.

Bending strains from winding were also thoroughly analyzed by GDC. The conductor was reacted on three concentric spools with diameters of 600, 700, and 800 mm in order to maximize productivity. The maximum bending strain from straightening ranged from 0.24% for the 800-mm-diameter spool to 0.32% for the 600-mm-diameter spool. The bending strain from winding onto the 422-mm-diameter core was 0.45%, which was in opposition to the straightening strains. The conductor joggle caused an additional 0.04% bending strain. The most severe cumulative bending strain was 0.25% for the conductor reacted on the 800-mm-diameter spool.

The STANSOL calculations yielded a maximum hoop strain of 0.14% for the abnormal condition of 1730 A. The total maximum operating strain of 0.39% afforded a considerable margin of safety because tests showed that the irreversible damage onset occurred at 0.8% strain.[3]

The stresses in the 304LN stainless steel coil case were also analyzed by GDC, for which they used the 2-D computer program called SOLIDSP.[6] The coil case was loaded by axial forces imposed by the other coils in the MFTF-B set. In normal operation, the insert coil is subjected to a 4710-N axial force, directed away from the machine center, which resulted in a bending stress that peaked at 275 MPa in the closeout weld at the inner bore. Since this was a bending stress, the allowable stress level was 90% of yield, or 620 MPa, which resulted in a generous margin of safety. Fracture mechanics principles were used to determine that a minimum initial flaw size of 5 mm will ensure fracture-free operation for 4-lifetime operation, each lifetime consisting of 490 normal cycles and 10 abnormal cycles. A defect of this size is readily detected by ultrasonic test methods developed for MFTF-B. Further details of the design have been shown by Baldi, et al.[7]

NbTi Outer Coil

The NbTi outer coils presented a significant design challenge because constraints of coil size, field, cost, and schedule resulted in conductor hoop strains of 0.0032 for normal operation and 0.0051 for abnormal operation. The stress and strain calculations were done by GDC, who modified STANSOL to take into account the conductor's plastic behavior. Winding tension and outer case thickness were relatively ineffective in reducing the stress levels, and adding distributed stainless steel reinforcements resulted in a conductor pack that was too large. Manufacturing a new conductor would have caused an unacceptable schedule slippage.

A comprehensive testing program was undertaken, in which static and cyclic mechanical testing demonstrated that the NbTi conductor would survive 4 lifetimes of operation, each consisting of 490 normal cycles and 10 abnormal cycles in which the current peaked to 115% of the normal value. Simulated splice joints survived cyclical loading of tension and compression, corresponding to eight lifetimes of operation.

Fabrication Details

The coil-winding methods and equipment were adapted from our previous work on winding the Nb_3Sn coils for the LLNL High-Field Test Facility.[8] Because the coil was wound pancake-fashion, with joints only on the outer radius, each spool from the Furukawa Electric Co. contained 295 m of conductor, enough to wind 2 pancakes.

The first step was to transfer half of the conductor from the shipping spool to the tensioned payoff spool. We found that the midpoint of every length was marked according to our specification, which we verified with a calibrated roller. The conductor was unspooled while under a 450-N tension.

After the transfer was completed, the shipping spool was then fastened to the swing arm assembly, which was cantilevered from the center of the winding table; the spool orbited as the winder rotated. The swing arm was equipped with mechanisms to control the elevation and tilt of the shipping spool, so that the shipping spool would clear the conductor being wound off the payoff spool.

The conductor joggle and riser pieces, which were fabricated from G-10 CR laminate, were bonded into position with Loctite 414, a cyanoacrylate adhesive. The adhesive was used to hold the items in place only during fabrication; in operation, the pieces are held in place by the conductors.

The first-turn joggle was made by a series of operations in which the conductor was first clamped radially against the bore tube and then pressed axially against the joggle piece by a series of axial screw clamps. While the axial clamping force was applied, the payoff spool was lowered to prevent any localized damage to the conductor. During this procedure, the conductor was under 675-N tension. No overbending was done.

After the joggle was formed, the tension was increased to 1350 N and the 57 turns in the lower (odd-numbered) pancake were applied. The tensioner consisted of a basket filled with 300 lb of lead bricks that pulled on the framework to which the payoff spool was attached. The frame was mounted on linear bearings, which allowed a "back and forth" motion. The required amount of drag to maintain the framework's position was provided by a mechanical disc brake and electric brake motor, which were connected to the payoff spool shaft.

The turn insulation was supplied on reels, which permitted us to automatically feed the insulation into the winding. Axial clamps and cushioned hammer blows were used to ensure a smooth pancake wind. Figure 3 shows the coil being wound.

Figure 3. Winding the Nb_3Sn coil for MFTF-B.

After this lower pancake was completed, radial clamps were used to hold the windings, and the conductor was cut at the appropriate location. The shipping spool, which had been orbiting the winder, was then installed on the tensioner, and the conductor it contained was used to wind the next pancake. After the required number of turns were wound, additional radial clamps on the outside of the coil were used to hold the conductor in place.

After each pancake was wound, conductor resistance measurements, high-potential withstand, and megohm resistance measurements between pancakes were made to ensure electrical integrity. Axial and radial dimensions were recorded to ensure that the coil was not exhibiting excessive buildup.

Considerable scatter was obtained in the individual dimensions, but average values taken over several pancakes indicated that the axial buildup was quite minimal, amounting to less than 0.02 mm per pancake.

Figure 4 shows two of the steps in making the splice joint. Each splice consists of three parts: a copper clamp to which the two conductors are soldered with 60/40 Sn/Pb solder and two flanking stainless steel mechanical clamps. Based on test results, either the stainless steel clamps or the soldered copper clamp is sufficient to react the 9.5-kN tensile load on the conductor with a generous margin of safety. The joint resistance is on the order of 3×10^{-8} Ω. Figure 4a shows the conductors pulled into position in the bases of the various clamp pieces. A tension of 1350 N was used. The black oxide coating was removed from the conductors with fine-grit abrasive paper, and the conductors were tinned with 60/40 Sn/Pb solder. Small clamps were used to prevent the conductor from delaminating during tinning.

The ventilated filler insulation pieces behind the clamps were tailor-made for each pancake, so the splice block would make a uniform contact simultaneously on all four pancakes. Because the splices all stacked up on each other, damage to the lower splices was prevented by inserting between the splices a temporary spacer of leached silica material with an overlayer of Kapton film. Figure 4b shows the assembled clamps in place with the flat-head screws torqued to the proper value. Both copper pieces were tinned and fluxed prior to assembly. Heat was applied with the 750-W flatbar-type heater clamped to the front face. Two thermocouples were inserted into the copper piece, one dedicated to the power controller and the

Figure 4a. Conductors are tinned and pulled into position with a 1350-N tension.

Figure 4b. Space joint ready for heating.

other to give us a real-time readout of the temperature. The joint area was covered with several layers of leached-silica, heat-resistant blanket to prevent heat loss. When the temperature reached 190°C, additional solder was fed through the gap in the top of the splice blocks. The screws were then retorqued, the heater was shut off and removed, and a water-cooled chill bar was attached in its place. The screws were again tightened to their proper torque after the splice had cooled to room temperature. The joint was cleaned and then ultrasonically inspected. We met our criterion to bond 80% of the area.

After all the pancakes were wound, voltage taps were installed on pancakes 14, 24, 26, 28, and 40, using one of the screws in the appropriate splice joint. Voltage taps at each end of the coil were screwed to the conductor terminals. Additional taps were installed on pancakes 6, 7, 46, and 47, so that the voltage across the upper one-eighth turn of each of these pancakes could be used to detect a normal zone that would be caused by a low-helium level. Such a normal zone might not be able to be detected by the quench detector, because if all the pancakes had a similar-sized normal zone, the signals would be cancelled out in the balance circuitry.

The outer radius filler pieces were installed to circularize the coil, and the outer plenum pieces were molded to the proper contour and then installed. The outer layers of Kapton ground-plane insulation were applied, and the 304LN stainless steel closeout plate was clamped in position. Gaps between the closeout plate and the coil pack were filled by a combination of G-10 CR laminate strip and mica-filled epoxy to ensure uniform contact across the entire plate.

Figure 5 shows our technicians installing the outer ring section that contains the tube for the current leads. The coil was protected from the heat of

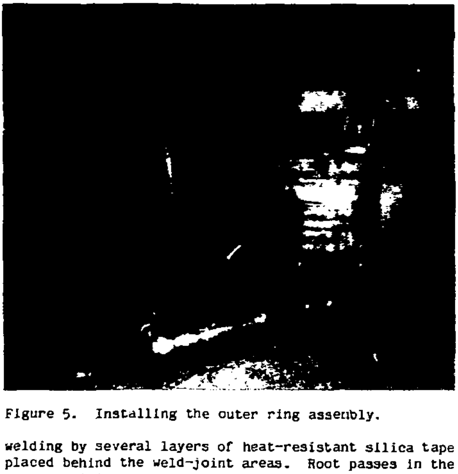

Figure 5. Installing the outer ring assembly.

welding by several layers of heat-resistant silica tape placed behind the weld-joint areas. Root passes in the more sensitive areas were made using gas tungsten arc welding with ER316L electrodes that were specially approved for MFTF-B service. The other areas were done with shielded metal-arc welding (SMAW) with approved E316L-15 electrodes. The root passes were checked with dye penetrant to ensure that they were crack-free. The cover passes were done with SMAW with approved electrodes. The completed welds were examined with ultrasonic techniques to ensure that there were no flaws large enough to present fracture problems.

The coils were then given the final electrical checks to verify that the closeout welding did not cause any problems. Last, every weld area was leak checked to ensure helium leak-tightness. In order to do this, a novel approach was developed in which the coil was pressurized with helium and the weld joints were "sniffed" using form-fitting boots that were connected directly to the leak detector.

Installation and Testing

The Nb_3Sn coil was then installed in the NbTi outer coil. The coils were aligned so that the bore of the two coils were concentric and the midplanes of their winding packs coincided. Twelve 304L shims placed between the outer ring of the Nb_3Sn coil and the bore of the outer coil were used to maintain radial positioning. The main attachment between these coils was via a three-piece ring that was welded in place.

The high-field coil assembly was suspended from the vacuum vessel with a pair of 304LN turnbuckles and from neighboring coils A1 and T1 with 304LN links. The four links to T1 are 34.3 cm wide and 8.6 cm. thick, and the links to A1 are bone-shaped, with a minimum cross section of 16.5 by 8.6 cm. These were fitted with a spherical bearing at each end, located so that coils will be in alignment during operation. The links were pinned with 11.4-cm diameter pins to clevises welded to the coils. Four turnbuckles connect the A2 coil assembly to S6, from which struts extend to reinforced clevises on the vacuum chamber and react the axial forces on this group of coils.

After installing the liquid helium pipes, remaining LN_2 panels, and vapor-cooled current leads, the final leak checks were performed and cooldown was started. A description of the details of the liquid helium flow can be found elsewhere in these proceedings.[9]

The magnet testing proceeded in a planned series of activities during which the coils were first hi-potted. Each coil was then energized to a low level with all other magnets open circuited and slowly discharged using the power cables as a discharge resistor. For these tests, the Nb_3Sn coils were energized to 200 A and the outer coils to 500 A. During the current's decay, the quench-detector self-inductance bridges were balanced, and mutual inductance data were collected for use in the compensated quench detector. Following this calibration, the axicells as a group (A1, A2o, and A2i) were energized to 50% of the operating current and then to 100% operating current. For the axicell coils, the operating currents were: 960 A for A1, 1504 A for A2i, and 4648 A for A2o. The magnets were fast dumped from each of these levels to verify proper operation of the dump resistors and circuit breakers. No quenches occurred during these tests. The only problems were erratic power-supply voltages and blown transient voltage suppressors (MOVs) across the Nb_3Sn coils because their voltage ratings were too low. The peak discharge voltage for the Nb_3Sn coils was 750 V.

After all the groups were tested, the entire array of magnets was energized to the full operating level, again with no quenches. The entire magnet set was tripped at approximately 90% current because the fringing field activated an over-current relay for the solenoids, which automatically fast dumped the entire system. The relay contact was adjusted, and full-current operation was achieved without further incident.

Conclusion

The successful operation of the pair of high-field axicell coils for MFTF-B, which produced a 12-T central field in a 0.36-m clear bore, demonstrated that large, practical, cryostable magnets can be made with multifilamentary Nb_3Sn using the react-and-wind method. In order to achieve this operation, however, the strain sensitivity of the conductor must be understood and respected. Strict quality controls and adherence to procedures based on sound engineering principles must be implemented.

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