Design, Fabrication and Test of the React and Wind, Nb3Sn, LDX Floating Coil

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***Abstract*—The Levitated Dipole Experiment (LDX) is an innovative approach to explore the magnetic confinement of fusion plasma. A superconducting solenoid (floating coil) is magnetically levitated for up to 8 hours in the center of a 5-meter diameter vacuum vessel. The floating coil maximum field is 5.3 T, and a react-and-wind Nb3Sn conductor was selected to enable continued field production as the coil warms from 5 K during the experiment up to a final temperature of about 10 K. The coil is wound using an 18-strand Rutherford cable soldered into a half-hard copper channel, and is self protected during quench. The coil is insulated during winding and then vacuum impregnated with epoxy. The impregnated coil is tested with 2 kA operating current at 4.2 K, and then a single, low resistance joint is formed at the outer diameter of the coil before the coil is enclosed in its toroidal helium vessel. This paper presents details of the coil design and manufacturing procedures, with special attention to the techniques used to protect the coil from excessive strain damage throughout the manufacturing process.**

***Index Terms*—coil fabrication, levitated dipole, Nb_3Sn, quench protection, react-and-wind, soldered joints**

I. INTRODUCTION

THE Levitated Dipole Experiment (LDX) seeks to investigate steady state, high beta plasma operation with near-classical magnetic confinement through the use of a superconducting solenoid which is levitated inside of a large vacuum vessel. Levitated coils for plasma research are not new [1], [2]. LDX, however, focuses on maximizing magnetic flux expansion, and this sets the experiment apart from earlier devices. As a fusion device, it is based on a concept first proposed by Hasagawa [3]. An overview of the experiment is available [4], and details on other aspects of the experiment, including the floating coil conductor fabrication [5], the BSSCO-2223 levitating coil [6], and the NbTi charging coil [7] are being published. The floating solenoid coil (F-coil) will operate inside a helium pressure vessel that is itself surrounded successively by a lead thermal shield and an outer vacuum vessel, all of which form a toroidal structure capable of taking up to 10 g crash loads. Details of the cryostat design are published [8]. This entire 580 kg structure will be levitated inside a 5-meter diameter vacuum vessel during the experiment. This paper describes the details of the completed floating coil fabrication and test activities prior to the assembly of the coil into the helium vessel.

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II. FLOATING COIL OVERVIEW

The floating (F) coil (Fig 1) is a 0.4 H solenoid winding that operates persistently through a low resistance lap-solder joint formed at the winding outer diameter (OD). When the F-coil is charged to full current, the peak field on the winding is about 5.3 T. Prior to daily operation, the coil is cooled in the charging station to about 5 K via retractable helium transfer lines which connect into extensions from the F-coil heat exchanger tubing (Fig. 1). The F-coil is charged to full current by the simultaneous discharge of the charging coil. During an experimental run, the coil is expected to slowly warm from about 5 K to close to 10 K over the course of about 8 hours. At full current of 2070 At 5.3 T the F-coil current sharing temperature is about 10.8 K.

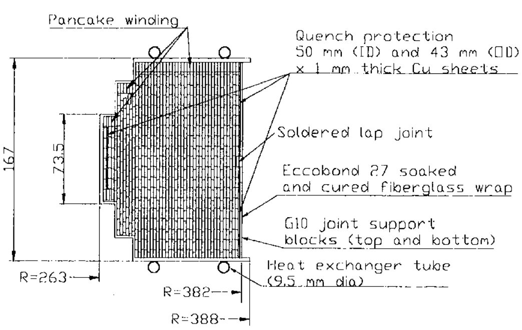

Fig. 1. Floating coil winding (dimensions in mm) is contoured to fit into a toroidal shell. Heat exchanger tubes for recooling are also shown. Finished coil has about 720 turns.

The coil is wound from a continuous length of about 1500 m of conductor (Fig. 2) comprised of an 18-strand, Nb3Sn Rutherford cable which has been heat treated and soldered into a half-hard, RRR=80 copper channel. The index (n-) value for the soldered conductor was measured in the range of

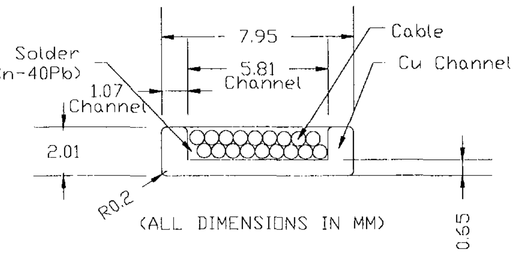

Fig. 2. Floating coil conductor cross section

20-30 [5]. A single pancake from the ID to the OD brings the start lead to the OD for joint formation, and the balance of the coil is layer wound. Copper sheets, 1 mm thick and perforated to allow epoxy passage during later impregnation, are formed around the outer diameters of the innermost and outermost winding layers. These act as eddy current heaters during quench to ensure more rapid and uniform quench propagation.

The coil form an a separate mandrel (Fig 3) were fabricated by Ability Engineering in South Holland, IL, from aluminum alloy to provide support for the thin (2-3 mm) stainless steel coil form during winding and later testing. The coil form was sprayed with mold release prior to assembly into the mandrel, and the edge between the form and the mandrel was sealed with RTV to prevent epoxy from bonding the form to the mandrel during impregnation and cure.

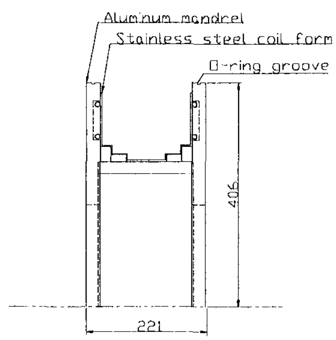

Fig. 3. Coil form in winding mandrel (upper half only)

To prevent strain degradation to the reacted Nb_3Sn strand, strict observation of the minimum bend radii (270 mm and 1000 mm, easy and hard way, respectively) had to be observed throughout all manufacturing steps.

III. Winding Line Arrangement and Operation

Coil winding and impregnation were performed by Everson Electric in Bethlehem, PA. The winding line consisted of a friction-drag payoff to keep conductor tension at 110-130 N, a 2 m-long, carriage-mounted, dual reel, automatic insulation taping head, and a horizontal-axis winding machine with a foot-operated on-off switch and a 0.1-turn resolution electronic turns counter. The total length of the line was about 12 m, with about 6 m between the payoff reel and the taping head carriage bed, and about 4 m between the taping head carriage bed and the winding. Distances were set to maintain small horizontal-plane angles between the line of the carriage, the payoff and coil, thereby limiting "hard-way" bending strain in the conductor. The dual taping head applied a half-lap of 0.1 mm-thick x 6 mm-wide fiberglass tape over a half lap of 0.025 mm-thick x 6 mm-wide Kapton tape.

The inside corners of the stainless steel coil form were taped with Kapton and the insides were lined with a thin layer of Mylar film to act as a slip plane between the winding and the form. Because the maximum voltage in the winding during quench was calculated to be about 200 volts, no additional ground insulation was considered necessary.

The taping head was initially set up to run while winding. Early in the winding process, however, a jam of the tape in one of the tape dispensers caused a break in the conductor. This unfortunate event forced several changes in the line and the need to start over. Fortunately, the break occurred near one end of the conductor length, and there was sufficient spare conductor on the spool to complete the winding after several modifications to the winding line.

Line modifications included the addition of a set of redundant up-down-left-right limit switches which detected the displacement of the conductor as it passed through the orbiting head and tripped both the orbiting and advance drives on the taping head machine. Displacement limits were set based on solution of the beam equations for the conductor to limit strain to about 0.4% in the worst case. This had to include the additional displacement after a trip due to rotational inertia of the orbiting head. The orbiting speed was reduced to about 100 rpm and a power-off spring brake was added to the orbiting head drive motor shaft. These actions limited the additional rotation of the head after power interruption to about 16°. Idler wheels in the tape dispensing paths were provided with side flanges. An interlock was added to prevent winding while taping. Tape tension was set to about 10 N via spring-loaded clamps on the dispensing wheel flanges. It was necessary to check that the width of the cardboard hub on each fiberglass tape roll was no greater than the width of the tape itself for the friction clutch on the tape payoff to work properly. With modifications in place, several static and dynamic tests on dummy conductor confirmed that simulated tape jams did not overstrain the conductor, and the entire winding was restarted from the beginning.

The pancake portion of the coil was wound first. About 120 m of conductor was de-reeled from the main spool onto a separate 0.9 m diameter payoff. The balance of the conductor remained coiled on the delivery reel, which was co-mounted with the coil on the axis of the winding machine. Care was taken in this initial setup to support 3 or 4 turns of conductor in a graceful, spiral pattern, transitioning from the main winding reel to the coil form. These turns stayed fixed relative to one another during the pancake winding process. All winding was done with the cable side of the conductor facing outward. The entire pancake was wound plus about 11 extra turns for later use in the formation of the coil shorting joint.

G10 winding transitions were machined and fabricated in sets in advance to enable low-strain transitions of the conductor from one layer to the next. Each set consisted of a short, 75 mm-long ramp and a long (nominally 2πr-75 mm) taper, glued-up as a laminate on a cylinder. A long and a short element were placed end-to-end at each winding layer end. Nine different long lengths were made for the 44 layer coil.

Once the pancake portion of the winding was complete, the main conductor reel had to be de-mounted from the winding machine axis and moved back to the payoff station. This delicate operation had to be performed without imparting excessive strain on the spiraled conductor loops between the winding and the reel. This was accomplished by keeping the loops of conductor large and smooth between the winding and the reel as the reel was crane-lowered to a floor-level dolly. Turns were then de-reeled from the main reel as it was rolled back to the payoff station and mounted. The long straight length of conductor was lifted manually into the taping head.

After winding the first layer in the layer-wound portion, the inner copper quench protection sheet was installed. The jointed ends of these sheets were carefully designed after several initial soldering attempts with other designs yielded cold solder joints. The successful design employed narrow copper fingers with solder introduced on both sides to ensure good surface wetting. Each sheet end is milled to ½ of the 1-mm thickness over a length of 50 mm and one end was additionally milled for 4-mm-wide fingers separated by 1-mm-wide slots containing 2.5-mm-diameter holes spaced at 8-mm intervals. The ends were carefully clamped and marked in place before machining so that when re-clamped for final soldering, the laps were aligned. Both ends were pre-tinned with Indalloy 1E solder (melting temperature 118 C, well below 173 C for 60Sn-40Pb solder in the conductor). Three thermocouples, one for heater control and two for monitoring the temperature of the joint area while soldering, were 60Sn-40Pb soldered to the edge of the copper sheet in three corners of the joint lap region. The prepared copper sheet was first clamped hard with band clamps to the inner winding layer. Once clamped, a stainless steel wire clamp, which remained in place during soldering, was tightened over the central finger of the joint and the band clamps were released. Ribbons of Indalloy 1E solder were laid in the finger slots and then the joint region was covered with a silicone rubber sheet and a special clamping jig (Fig. 4). The clamped joint was thermally insulated and heated under control until the solder was confirmed melted by the monitoring thermocouples. The completed joint is shown in Fig. 5. The spaces between the sides of the copper sheet and the coil form were filled with Nomex strips built up to 1-mm thickness.

The balance of the layer winding proceeded to the OD of the coil. The last layer winding contained 6 turns which were wound toward the axial center of the winding plus additional turns to form the joint. Seven of the extra 11 turns from the pancake were wound from the pancake side toward the center, leaving a center channel about 50 mm wide with no outer-layer turns. The extra pancake turns were temporarily stacked in the center channel while the two outer copper sheet joints were added around the outermost winding layer in a similar fashion as was done on the inner sheet. The OD of the coil, exclusive of the central channel, was tension wrapped with 0.5 mm-thick fiberglass tape.

Fig. 4. Inner perforated copper sheet clamped with heater block for solder lap joint with stainless steel band clamps

Fig. 5. Inner copper sheet joint after soldering. The strain relief detail keeps excessive strain away from soldered joint. Copper perforations provide for epoxy flow during later impregnation.

IV. Epoxy Impregnation

After completing the winding, the coil's dc resistance was measured at 2.47 Ω, the coil was hi-pot tested to 500 V with leakage current less than 0.1 μA, and the 60 Hz ac impedance was measured at 17.2 + j35.8 Ω, agreeing reasonably with the calculated value of 13.3 + j38.8 Ω for the coil inside the aluminum mandrel.

The 50-mm-wide central channel at the OD had to be kept clear during the epoxy impregnation process for later arrangement of the F-coil shorting joint. The area was protected with a combination of release tapes to keep epoxy from entering this region. The fiberglass tapes over the two outer copper sheets were covered with Tedlar tape wound around the coil circumference but interleaved with fiberglass tape to allow wicking of the epoxy into the winding pack. The radial gap between the winding OD and the OD of the mandrel was filled with Tedlar-wrapped copper bars to prevent this region, except near the fill and vent ports, from filling with epoxy. The OD of the mandrel was sealed by a cylindrical steel shell clamped against the mandrel OD o-rings. The shell was fitted with an epoxy fill port and baffles at the bottom and a vent stack with baffles at the top. The two coil leads penetrated the steel cylinder at the top and were sealed with RTV. Special, Tedlar wrapped wedges were placed under the leads as they emerged radially away from the winding pack.

The impregnation resin was CTD-101K, but with a special mix (100 parts Part A, 90 parts Part B, and 0.3 parts Part C) and cure schedule (gel 85 C for 16 hours, cure 110 C for 30 hours) to help minimize exotherm and keep the maximum cure temperature below the melting point of the Indalloy 1E. This mix was achieved through dummy impregnation trials and with special assistance from Dick Reed[1]. The coil and impregnation fixture were installed inside the VPI vacuum tank with the coil winding axis horizontal. The tank was evacuated to about 1 mTorr. Mixed and degassed resin was introduced through a fill line into the fill port at the fixture bottom. Filling, followed by 3 atmosphere-to-vacuum cycles of the VPI tank, took about 4 hours. When filling was complete, 7.2 l of resin had been introduced into the coil volume. The VPI tank was let up to atmosphere, and the coil and fixture were transported to the curing oven.

During cure, an additional 1.05 l of degassed resin was manually added at the resin vent port. There was no measurable exotherm in the epoxy. Total resin volume in the coil was 8.25 l, in line with calculations. After cure, epoxy removal from the area around the leads and vent port was facilitated by having pre-inserted several Mylar strips, in egg-carton fashion, to provide epoxy breakaway planes.

V. Floating Coil Test

After impregnation, the coil was prepared for testing in a bucket dewar at MIT. A 25 and 50 cm long test joint was formed using LDX F-coil conductor (Fig. 1), one per coil conductor end. From each of these jointed leads, another joint was made to a flexible NbTi cable which attached to the cryostat current leads. Voltage taps were connected across the joints, and Hall probes were mounted in the bore of the coil.

The coil was cooled to 4.2 K in liquid helium and current was ramped to 2200 A, or 106% of full operating current in accordance with Fig. 6. Most importantly, the coil did not quench at any time, despite ramp rates up to 12.5 A/s--an order of magnitude higher than the planned operating rate. Joint voltages were measured at 2200 A to be 2.3 nΩ and 4.6 nΩ at the 50 and 25 cm lengths, respectively. Field measurements in the coil bore agreed well with calculations.

VI. Final Joint Fabrication

Based on the performance of the test joints, the F-coil persistence joint was soldered with Indalloy 1E solder to a lap length of 800 mm through the use of a special clamping fixture. This length was a tradeoff between lower joint resistance and higher ac losses during charging.

VII. Conclusions

The wind-and-react fabrication of a Nb_3Sn Rutherford cable-in-channel conductor has been described giving special

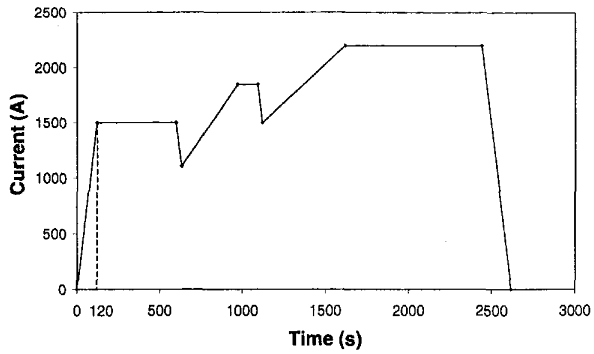

Fig. 6. First current ramp sequence of the floating coil to 2200 A or 106% of full planned operating current. Additional ramps were made, also. The coil never quenched.

attention to strain control during winding, especially by using displacement limit switches on the conductor at the taping head. Fabrication of the quench protection copper sheets has also been described. The coil was successfully impregnated with an new formulation and cure schedule for the epoxy to avoid any measurable exotherm and to prevent melting the Indalloy 1E solder which is used in the copper sheet joints. Sample joints were tested which formed the basis of the production shorting joint in the F-coil. The coil was ramped without quenching at 12.5 A/s from 0 to 1500 A, and then on to 106% of full operating current in a bucket dewar test.

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