Design, Fabrication and Test of the React and Wind, Nb_3Sn, LDX Floating Coil Conductor

Bradford A. Smith, Philip C. Michael, Joseph V. Minervini, Makoto Takayasu, Joel H. Schultz, Eric Gregory, Tae Pyon, William B. Sampson, Arup Ghosh, and Ronald Scanlan

***Abstract*—The Levitated Dipole Experiment (LDX) is a novel approach for studying magnetic confinement of a fusion plasma. In this approach, a superconducting ring coil is magnetically levitated for up to 8 hours a day in the center of a 5 meter diameter vacuum vessel. The levitated coil, with on-board helium supply, is called the Floating Coil (F-Coil). Although the maximum field at the coil is only 5.3 tesla, a react-and-wind Nb_3Sn conductor was selected because the relatively high critical temperature will enable the coil to remain levitated while it warms from 5 K to 10 K. Since pre-reacted Nb_3Sn tape is no longer commercially available, a composite conductor was designed that contains an 18 strand Nb_3Sn Rutherford cable. The cable was reacted and then soldered into a structural copper channel that completes the conductor and also provides quench protection. The strain state of the cable was continuously controlled during fabrication steps such as: soldering into the copper channel, spooling, and coil winding, to prevent degradation of the critical current. Measurements of strand and cable critical currents are reported, as well as estimates of the effect of fabrication, winding and operating strains on critical current.**

***Index Terms*—superconducting cables, superconducting coils, magnetic levitation**

I. Introduction

THE Levitated Dipole Experiment (LDX) is a collaborative project between Columbia University and the Massachusetts Institute of Technology to develop a new approach for the study of magnetically confined plasmas. It is based on the study of high-beta plasmas in a dipole magnetic field [1]. This configuration ideally requires the dipole to be magnetically levitated in the center of a large vacuum chamber, without current leads or cryogenic connections extending through the plasma volume. This floating coil (F-Coil) will be charged inductively in a self-contained cryostat, and should remain superconducting with a near constant operating current for several hours per experimental run. The weight of the floating coil and its cryostat should be minimized to reduce the strength of the levitating field for minimal distortion of the dipole magnetic field. These restrictions require use of Nb_3Sn superconductor with a high critical temperature and high critical current density at moderate magnetic fields [2].

A reasonably high current is selected to minimize internal coil quench voltages. Ideally this could be achieved with a flat, relatively large Nb_3Sn tape conductor, which would be easy to react and wind while minimizing any strain degradation. Unfortunately, we could not find such a tape produced commercially. The moderate current requirement led then to selection of a flat Rutherford-type cable comprised of 18 multifilamentary, 0.6mm diameter Nb_3Sn strands.

Since the flat, Rutherford cable of superconducting wires would be put through the reaction heat treatment and then wound into the coil, it would not have sufficient mechanical strength to withstand the electromagnetic stress resulting from coil energizing. The cable was therefore soldered into a copper channel, which provides the structure to carry the mechanical loads and also provides a low resistance shunt for quench protection.

Proper handling of the reacted cable was critical during all fabrication steps including soldering into the channel, take-up spool winding and unwinding, and during coil winding, to avoid irreversible strain degradation of critical current. Details of the design, fabrication and test of the F-coil are given in [3], and details of the Charging Coil (C-Coil) in [4].

II. Conductor Description

The stringent requirements for the floating coil conductor could be met with 18 strands of high performance Nb_3Sn multifilamentary wire cabled into a flat Rutherford cable geometry and soldered into a high purity OFHC copper channel. The cable was designed to have an operating current of 2070 amperes at a peak magnetic field of 5.3 tesla. The F-Coil conductor will begin operation at a temperature near 4.5K, but during operation of the LDX experiment, the temperature in the sealed cryostat will rise to about 10 K. Once the coil reaches maximum temperature, the experiment will be stopped, the coil inductively de-energized and then prepared for another experimental run.

A. Strand

The selected superconducting strand was developed by Intermagnetics General Corp.-Advanced Superconductors (IGC-AS) for enhanced performance for fusion applications which generally require the highest possible critical current density at magnetic fields above 12T, while also exhibiting relatively low or moderate hysteresis losses for bipolar field cycles. Although the LDX F-Coil will not operate at such

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B. A. Smith, P. C. Michael, J. V. Minervini, M. Takayasu, and J. H. Schultz are with the Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, MA 02139 USA (telephone: 617-253-5503, e-mail: minervini@psfc.mit.edu).

E. Gregory and T. Pyon are with Intermagnetics General Corp-Advanced Superconductors, Waterbury, CT 06704 USA (telephone: 203-753-5215, e-mail: gregory@ct1.nai.net).

W. B. Sampson and A. Ghosh are with the Brookhaven National Laboratory, Upton, NY 11973-5000 USA (telephone: 631-344-3974, e-mail: ghosh@bnl.gov).

R. Scanlan is with the Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA (telephone: 510-486-7241, e-mail: rmscanlan@lbl.gov)

TABLE I
CHARACTERISTICS OF THE SUPERCONDUCTING STRAND

PARAMETER	VALUE
Superconductor material	Nb_3Sn
Wire design	Internal Tin – 19 subelement
Wire diameter	0.598 mm
Wire density	9.05 g/cm^3
Barrier material	Tantalum
Non-copper fraction	0.609
Filament twist pitch	0.95 cm/right

high magnetic fields, nor will it be bipolarly cycled, we chose this strand to serve as a developmental benchmark for future high field fusion magnet applications. Details of the strand design are given in Table I.

B. Cable and Reaction Heat Treatment

The 18 strand Rutherford cable was fabricated at Lawrence Berkeley National Laboratory (LBNL) with the aid of Mobile One® as a lubricant, some of which was left on the cable during the reaction heat treatment. The Mobile One® provided sufficient lubricant during the heat treatment to prevent substantial sintering between the bare copper surfaces in adjacent strands.

The cable was delivered in a single piece length of 1600 meters. It was prepared for reaction heat treatment by helical winding 7 layers on a 750 mm diameter drum. A single layer of woven glass cloth was placed between each cable layer to prevent sinter bonding of the layers. The coil was heat treated in a large furnace at the Brookhaven National laboratory (BNL), and the reacted cable was returned to IGC-AS where it was soldered into a finished conductor. Details of the cable and reaction heat treatment parameters are given in Table II.

C. Soldering Cable into Copper Channel

A half hard, OFHC copper channel is provided for mechanical strength. The cable had to be soldered into the copper channel after the reaction heat treatment. This step required very critical control of the strain state of the cable to prevent irreversible strain degradation. The dimensions of the cable-in-channel are shown in Fig. 1.

The overall arrangement of the soldering line is shown in Figure 2. The heat treatment spool was used as the cable

TABLE II
CHARACTERISTICS OF THE CABLE

PARAMETER	VALUE
Number of strands	18
Cable pattern	Flat Rutherford
Twist pitch	44 mm/left
Cable width (avg.)	5.49 +/- 0.010 mm
Cable height (avg.)	1.193 +/- 0.005 mm
Reaction drum diameter	750 mm
Reaction atmosphere	Vacuum, 10^{-6} torr
Reaction heat treatment conditions	Ramp up at 6C/hr to 185C / 100hrs Ramp up at 6C/hr to 460C / 144hrs Ramp up at 6C/hr to 570C / 220hrs Ramp up at 6C/hr to 650C / 175hrs Ramp down at 25C/hr

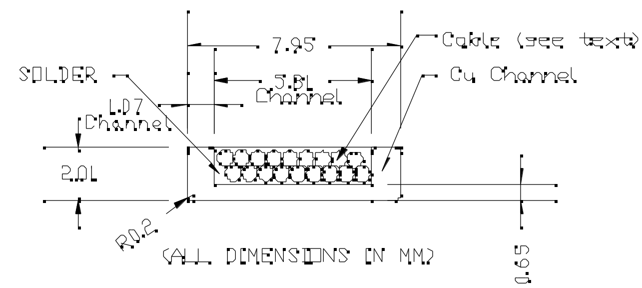

FIG. 1. LDX FLOATING COIL CONDUCTOR.

payoff spool. The spool unfortunately had a polygonal-shape to its ID, causing "bumps" as high as ~0.5 mm in the finished conductor, where the cable was above the channel, despite all the other good efforts on the soldering line itself. These bumps did affect the critical current performance and had to be repaired as discussed later.

The spool axle had a simple weight, rope and pulley arrangement for keeping about 3-4 kg of tension on the cable as it was drawn through the line by the caterpillar drive at the take-up end of the line. Since the cable still had residual material from the lubricant after heat treatment, it was pre-wiped with sponges soaked with the soldering flux (Ecosol DGS 2). The channel payoff spool was set up in parallel with the cable payoff. Special supports of simple paper-covered plywood tables were arranged to provide support as needed along the length of the line. The reacted Nb_3Sn cable was kept as straight as possible throughout the entire line, with the goal of keeping the minimum bend radius everywhere to more than 1 meter in the easy bending direction.

The copper channel was brought into co-alignment with the cable in the vertical plane using horizontal guides, with the cable above the channel. The channel and the cable entered the flux spraying station one above the other (cable on top). The cable and the channel were individually wiped with rubber wipers to remove excess flux prior to entering the solder bath.

The bath was prepared ahead of time by melting 60/40 PbSn solder. The solder pump was energized to keep the solder level above the entrance and exit ports in the inner tank. These ports also acted as spillways to the outer tank where the solder was recycled. Slag-like material was continuously removed from the surface of the bath to keep

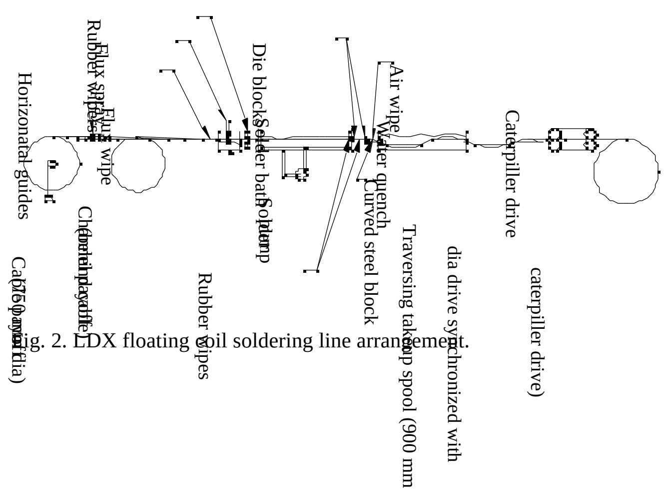

Fig. 2. LDX floating coil soldering line arrangement.

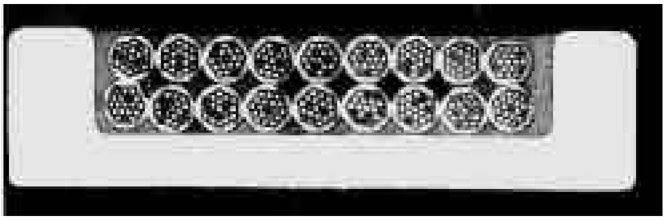

Fig. 3. Photograph of a polished section of the soldered conductor

oxides and other build-up from contaminating the conductor. Inside the bath, a number of guides kept the cable above the channel.

A set of rubber wipers were installed around the conductor immediately at the exit of the bath, prior to entering the first die. A second set of wipers and a second die were placed after the first, with about 150 mm spacing between the two dies. The second die and wipers were required to help remove excess solder from outside the desired envelope of the finished conductor. Both dies had an inner envelope matching the finished conductor. Immediately after the second die, the conductor was forced over a curved steel quench block, where the excess solder on the conductor was simultaneously wiped by two directed compressed air streams. The curved steel block worked in tandem with a set of curved guides in the water quench tank to keep the cable in the channel. After some trial and error in the positioning of the quench block on dummy cable, the cable was reliably seated in the channel at the proper level. An additional set of curved guides were used to align the conductor with the caterpillar drive.

The 900 mm diameter take-up spool was mounted on a traversing carriage so as to minimize any bending of the finished conductor in the hard direction. The drive mechanism of the traversing carriage was directly synchronized with the rotational drive of the take-up spool, and these both were synchronized with the drive of the caterpillar so as not to place excessive strain on the conductor from either over-tension or over-bending.

A magnified photograph of the finished conductor is shown in Figure 3. The finished soldered conductor length was 1600 meters in a single piece. A second, shorter conductor length of 230 meters was soldered, originally to be used for a secondary co-axial, series-connected shaping coil. This coil was eliminated from the final F-Coil design, but the shorter piece length was used for winding and joint trials.

III. Conductor Tests

Conductor tests were made to determine the critical current of the single strand and the finished, soldered cable. Comparison of the results was made to determine if there was any significant degradation of the critical current of the finished conductor due to strain damage beyond that expected from estimation of the elastic strain state due to conductor fabrication and spooling.

A. Single Strand Measurements

Measurement of critical current was made by IGC-AS on a representative strand co-reacted with the production cable. Critical current measurements were made at 4.2 K using the electric field criterion of 10 microV/m. A voltage range of 10~100 μV/m was also used to estimate the n-values which were evaluated at 32-36 in the magnetic field range of 7-10 tesla. The Lorentz force was applied inward into the mandrel for all measurements. These results were used for comparison with critical current measurements made on samples from the reacted and soldered production conductor.

B. Cable-in-Channel Conductor Samples

The critical properties for three samples of LDX F-coil production conductor were measured at the cable test facility at Brookhaven National Laboratory. The first pair of cable-in -channel samples contained a few short wavelength, large amplitude (~0.5+ mm) ripples in the height of its pre-reacted cable above the nominal conductor thickness; hereinafter referred to as the "bumpy" sample. The second sample contained only a few cable ripples where the cable protruded 0.1~0.12mm above the nominal conductor thickness; hereinafter referred to as the "smooth" sample. The third sample initially contained a variety of cable ripples which were "repaired" by remelting the solder and pressing the cable firmly into the channel. The largest of these ripples had a height of 0.5~0.55mm and was located near the mid-point of one of the sample legs. We believe the bumps in the production cable were introduced during the reaction heat treatment. The suspected source of these short wavelength ripples has been traced to the construction of the reaction spool. The drum for this spool is reinforced with ribs that run from one flange to the other. Some of these ribs protrude slightly, with the result that the drum surface is not entirely smooth. When the cable was wrapped on the drum, these protrusions produced corresponding ripples that were set into the cable during its reaction, mostly in the first layer.

The effect of these ripples on conductor performance was observed during the first test of the "bumpy" sample where severe degradation of the conductor's critical current relative to the single strand data was measured.

C. Cable-in-Channel Conductor Test Method

The 1.2 meter long samples for the cable-in-channel test were mounted in a compression fixture that supports the Lorentz forces on the conductors. The sample fixture was inserted into a dipole magnet which provided the background field. Tests were conducted in a bath of liquid helium at temperatures of 4.435-4.45 K, depending on the sample under test. Temperature variation for each test sample was typically within 2 mK. The two conductor samples were joined at the bottom and tested at the same time with current in series. The typical joint resistance is about 10^{-9} ohm. The V-I curves were determined simultaneously for each member of the bifilar pair using a resistivity criterion of 10^{-14} ohm-meter. In the event that one member has a low quench current its partner may not be measurable in the set-up. The broad faces of the conductor are aligned parallel to the background field direction. By altering the current direction through the sample, the sample self-field in the space between the two legs of the hair-pin either adds to the background field (high-field configuration) or subtracts from the background field (low-field configuration). Measurements were made for both current directions.

D. Conductor Test Results

Figure 4 shows the measured critical currents vs. peak field for the LDX conductor samples. Included are two critical current estimates for the cable obtained by multiplying the single strand data measured at IGC by 18 strands. The first estimate assumes an intrinsic strain of –0.002 in the superconductor filaments of a single strand with very low copper fraction. This value was used to estimate Summer's parameter values from the single strand data. [5]. The second estimate assumes an intrinsic strain of –0.0045 for the strain state of the flat conductor sample in the test fixture. All critical current values have been reduced to a common 4.2K operating temperature using a Summer's fit of the data with C_o=1.41 x 10^{10} A-$T^{1/2}m^{-2}$, B_{c2om}=34.2T, T_{co}=16.3K with the intrinsic strain adjusted for each test configuration to give a closest fit to the measured data. Conductor test data was also adjusted for the peak field at the cable including self-field generated by the samples. The self field adjustment ranged from 0.0595 T/kA to 0.145 T/kA depending on sample current direction. The n-values were calculated at 7-8 in the field range 5-7 tesla for the bumpy conductor sample, and at 20-30 in the field range 6.5-8.0 tesla for the repaired and smooth conductor samples.

E. Discussion

The critical current of the "smooth" conductor sample tested about 5% higher than anticipated for a simple 18-strand scaling of the strand witness sample data. The reason for this may be due to several factors including: different criterion for evaluating the critical currents of the strand and conductor, possible variations in the critical current of the individual cable strands compared to that of the witness sample, or light stretching of the cable as it was soldered into the channel (which tends to reduce the intrinsic strain in the conductor because net compression is reduced).

The repaired sample's critical current was roughly 15% lower than that of the "smooth" sample. This indicates that the critical properties of the conductor are slightly degraded by the repair process. This result seems reasonable because the protruding conductor volume in the repair region is likely subject to compressive strains as it is pushed down flush with the copper channel. Despite its degradation from the ultimate conductor performance, the measured results for the repaired sample are consistent with an initial assumption of approximately –0.45% intrinsic superconductor strain estimated by tracking the final strain state of the strand from cable reaction, spooling/straightening operations, conductor soldering, and then cooldown of the short sample [6]

The critical current for the "bumpy" sample is roughly half of that originally anticipated. The severity of strain degradation in this sample is likely enhanced by the high degree of strain localization near the bumps produced by firmly clamping the relatively soft conductor/solder/channel arrangement into the rigid test fixture. The use of masking tape as a compliant padding material, and the use of lighter clamping pressures during subsequent measurements most likely resulted in the much more favorable results observed for the smooth and repaired test samples.

These cable test results were used to estimate the final performance of the conductor during F-Coil operation at full current and 4.5 K. The estimated strains in the superconductor filaments are 0.27% tensile on the outward facing surface of the cable, and 0.08% tensile on the surface of the cable facing into the channel. These strain estimates were developed for the inner diameter of the F-coil winding. Using the maximum 0.27% strain value, a 2070A operating current, and a 5.33 T peak field, the conductor fitting parameters deduced from these short sample tests give an estimated current sharing temperature of ~10.8 K for this high field location.

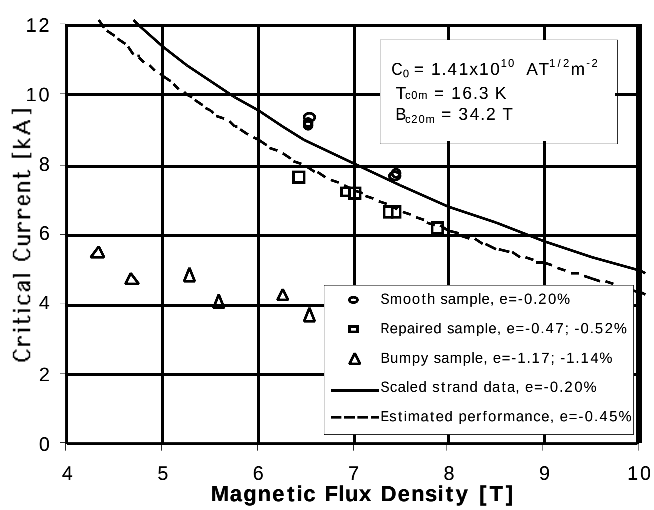

Fig. 4. Measured and estimated critical currents vs. peak magnetic flux density (including self-field) for three production LDX F-coil conductor samples.

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