Design, Fabrication and Test of the React and Wind, Nb$_3$Sn, 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$_3$Sn 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$_3$Sn tape is no longer commercially available, a composite conductor was designed that contains an 18 strand Nb$_3$Sn 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 horizontally 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 plasma center is only 5.3 tesla, a react-and-wind Nb$_3$Sn 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$_3$Sn tape is no longer commercially available, a composite conductor was designed that contains an 18 strand Nb$_3$Sn 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.

II. CONDUCTOR DESCRIPTION

The stringent requirements for the floating coil conductor could be met with 18 strands of high performance Nb$_3$Sn 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.
Fig. 3. A GO coil layer being laid down via our computer controlled winding machine. After winding, this layer had its spaces epoxy and G10 filled, was wrapped with s-glass and cured before winding the next layer.

After each layer was wound we filled the small spaces between conductors with epoxy and the larger gaps, primarily the magnet pole region and any harmonic tuning spacers, with a combination of G10 and epoxy. This epoxy fill was then cured before the layer was wrapped with epoxy impregnated s-glass fiber cord under tension. The s-glass wrap was made to provide coil prestress to minimize conductor motion when the magnet was excited and thereby avoid premature quenches. After applying the s-glass wrap, the layer was cured again so as to have a firm surface for winding the next magnet layer.

In order to help ensure that the coil remained round during curing, each cure was made with the magnet held in four-part clamping fixtures. The machined inner space of this clamping fixture provided a circular reference for curing, typically, the cured surface had radius irregularities less than +0.1 mm. Since the coil leads came from the magnet poles, slots had to be provided in the curing clamps to avoid crushing the leads.

C. Magnet Construction

The coil support tube had end flanges welded to it before coil winding started. Once the coil layers were satisfactorily tested, as described later, an outer jacket was welded to these flanges to form the cold mass. Note that the coil support tube is also the inner helium containment wall.

Large transverse forces are expected at the dipole coil ends, due to the interaction of the dipole coil windings with the solenoidal detector field, when the magnet is energized in H1 and ZEUS. These forces are transferred to the outer cryostat body via stainless steel support keys arranged as shown in Fig. 5. The horizontal keys restrain vertical motion and the vertical keys horizontal motion, differential contraction.
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.

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.

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 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_{0} = 1.41 \times 10^{10} \text{ A} - \text{T}^{-0.5} \text{ m}^{-2}, B_{c0} = 34.2 \text{ T}, T_{c0} = 16.3 \text{ K} 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 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 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.
IV. REFERENCES


