Design and Testing of Terminals for REBCO Coils of 32 T All Superconducting Magnet

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***Abstract*—The 32 T all superconducting magnet currently being developed at the NHMFL will contain two REBCO insert coils located within an outsert of several LTS coils. The REBCO coils will experience high stress levels, radial expansion, and axial compression as the coils are energized. Therefore, great consideration has been given to the method by which current enters and exits the coils. Terminals and terminal constraints have been designed to achieve low resistance and high strength, while allowing for necessary movement of the coil and reliable attachment practices. These designs have been fabricated and tested, both as stand-alone tests and on prototype coils, to demonstrate the desired performance characteristics. The general design features are discussed, fabrication procedures are described, and the results of testing at high stress are presented.**

***Index Terms*—High field magnet, terminal.**

I. Introduction

THERE is great interest in the application of REBCO conductors for low temperature, high field magnets. The coated conductor shows exceptional stress and strain properties along the conductor, and good bend tolerance as well. Together with possible additional co-wind and external reinforcement, REBCO conductors are very well suited for high field, high stress solenoid magnet applications. Among the present projects is the 32 T superconducting magnet [1]. In this example, the coil construction of the HTS coils is dry wind, pancake winding. All of the stress is taken on the conductor and additional reinforcement. In addition to the basic mechanical properties of the conductor, the performance of the REBCO coils depend on the connections between conductor lengths, including the in-line joints, the crossover connections between the individual pancakes or disks, and importantly the lead-in and lead-out terminal connections. The difficulty presented by a wide tape conductor is the inability to bend in the wide direction. While a lead transition to a terminal has been demonstrated that relies on bending and out-of plane twisting [2], it remains a difficult construction. For the 32 T magnet, the terminal connections are made in-plane using soldered tabs to change the direction of the current. This paper presents the design requirements for the terminals and the development activity associated with terminal construction and performance.

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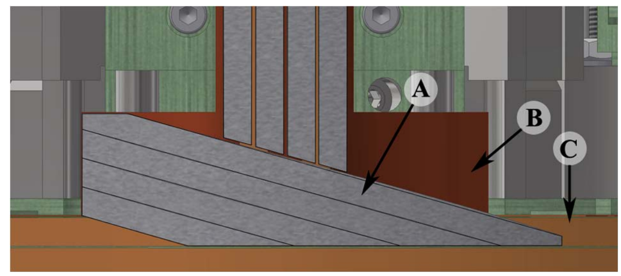

Fig. 1. Scarf structure showing individual pieces of solder-tinned REBCO joining terminal and outer turn of windings. A: Scarf assembly; B: Copper terminal base; C: Outer turn of windings.

II. Design of Terminals

A. Coil Mechanics

When coils are energized, Lorentz forces act on the windings and several conditions are created. The vertically oriented central field causes outward expansion of the windings. Hoop stresses are generated in the coil and the conductors experience significant tensile stress. The radial fields towards the top and bottom of the coil create large clamping forces at the mid plane. These forces cause the coil to compact axially. The terminals are the structures through which the outermost turns of the top and bottom disks are electrically and mechanically connected. The electrical connection completes the circuit and allows current to flow through the coil windings with low resistance in order to minimize helium boil off. The mechanical connection prevents the top and bottom disk from rotating due to the reaction of the tensile forces in the conductor. The terminal must be robust to support the tensile forces, capable of accommodating the radial expansion and axial compression of the coil, all while maintaining minimal resistance by means of a near-superconducting path. To accomplish this, a construction was designed which allows the terminal assembly to move in two axes and remain otherwise fixed. A thin superconducting bridge piece called a scarf, due to its angled ribbon appearance, connects the outer windings to the terminal base.

B. Scarf

The scarf structure, shown in Fig. 1, is a concept that combines two methods of transferring the current into the windings. Conductor that exits the windings by bending in the wide direction provides a continuous load path to transfer the tensile forces. However, this is a difficult operation to perform without encountering out-of plane bending. Tabs oriented perpendicular to the windings may be soldered externally, but lateral forces may adversely affect the unsupported conductor adjacent to the connection. Placing the tabs at an angle combines the strength of the two approaches and eliminates out-of plane bending and adverse lateral loads.

The scarf piece is comprised of four, 4 mm wide pieces of conductor, held together by solder contact with a thin copper foil. It is attached to both the terminal and coil in two separate soldering operations. The conductor pieces are angled 15 degrees above the coil conductor and provide adequate contact area for a solder joint. The construction of the REBCO tape provides a suitable platform for the scarf, as it exhibits high strength and good electrical properties.

C. Superconducting Path

While a continuous superconducting path from coil to leads is not yet a reality under the operating conditions of the 32 T magnet, minimal resistance is maintained by constructing a segmented superconducting path along the terminal connected by solder joints. The coated conductor from SuperPower has REBCO on one side of the Hastelloy substrate. Solder connections must be made between the superconducting sides of two tapes in order to achieve low joint resistance. Therefore, an intermediate piece of conductor must be used to join two tapes that are oriented with the REBCO in the same direction. For our present design, current entering or exiting the coil will encounter three solder joints between the outside coil windings and the superconducting current lead. Adequate surface area in these locations is required to keep the resistance at acceptable levels.

D. Axial Movement

During operation the overall length of the windings may decrease by several millimeters for the 32 T insert coils. Movement occurs towards the mid plane from each end. Therefore, the terminals must move with the ends of the coils. This can be accomplished by a variety of methods. The test configuration chosen for the inner prototype coil required that the terminal be allowed to move axially, independent of the end flange. A constraint was devised to allow axial translation while providing strong lateral restraint. This constraint shown in Fig. 2 incorporates a precision machined slot, in which the terminal assembly is located and shimmed to allow only the desired movement. Belleville springs provide approximately 30 N of preload in the direction of coil compression.

E. Radial Movement

While the scale of the radial movement on the outside of a coil is small, less than 1 mm on the radius, the effect of this movement is potentially damaging for a stiff electrical connection of thin superconductor. To avoid damage, the connection must be allowed to flex or move in such a way, so as to prevent excessive bending strain in sensitive superconducting regions. The constraints shown in Fig. 3 were designed in order to allow the terminal assembly to translate radially with the expanding outer diameter of the coils. This is achieved by attaching the terminal assembly to a slider block, constrained within a slot that is machined into the end flange. The slot is angled so that the terminal is allowed to move in a direction normal to the initial point of contact between the outer winding of the coil and the scarf piece. This constraint is preloaded to approximately 15 N in order to help overcome frictional forces opposing the free radial movement of the terminal.

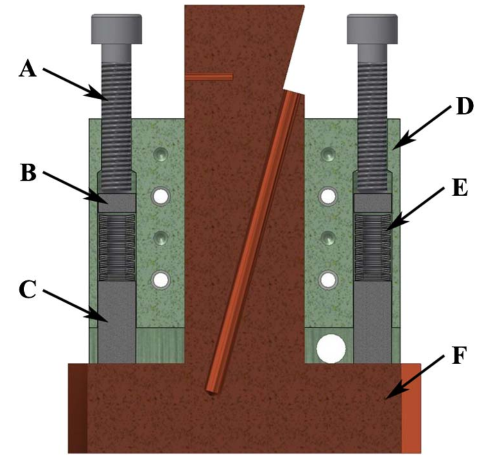

Fig. 2. Cross section through the terminal and terminal support structure showing provision for axial movement. A: Adjustment screw; B: Upper plunger; C: Lower plunger; D: G10 terminal housing; E: Belleville washer stack; F: Copper terminal base.

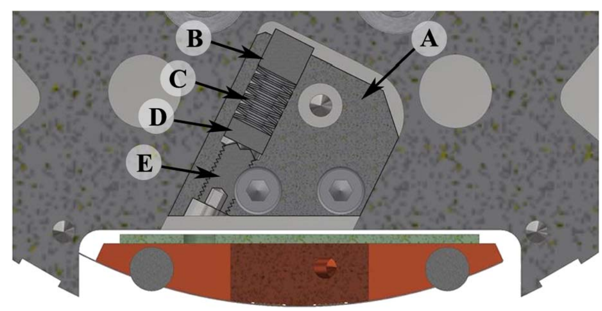

Fig. 3. Cross -section through the terminal and end flange showing provision for radial movement. A: Slider block; B: Back plunger; C: Belleville washer stack; D: Front plunger; E: Adjustment screw.

III. Fabrication of Terminals

A. Terminal Base

The primary electrical path for the current flowing through the terminal structure and into the coil windings is the coated conductor. The small size of the tape makes it difficult to constrain adequately while allowing for controlled movement in the desired directions. Therefore, a base is required to which the conductor is soldered. This structure allows the movement of the assembly to be constrained. The terminal base, shown in Fig. 4, is a block of copper with a flat face on the back and a radius on the front that matches the outer radius of the coil windings. This piece is fabricated using an Electrical Discharge Machining process to provide a precise radius and channels with tight tolerances for conductors. The copper base also serves as an alternate electrical path for the current in the event that the superconducting sections through this region become resistive.

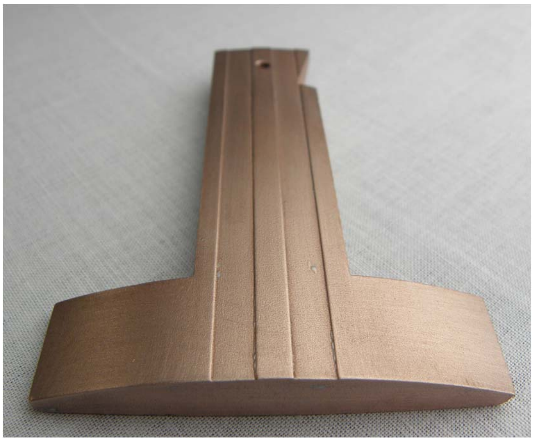

Fig. 4. Picture of the copper terminal base with channels machined for REBCO tape.

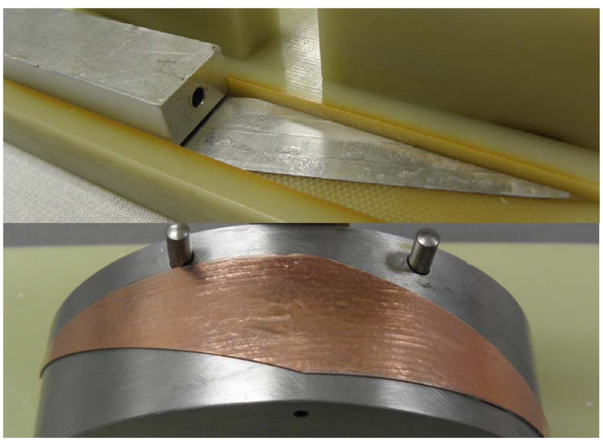

Fig. 5. (Top) Picture of flat soldering operation to connect the four pieces of YBCO tape into a scarf. (Bottom) Scarf is reheated and bent to desired radius.

B. Terminal Assembly

The coated conductor is electrically and mechanically attached to the copper base by a soldering process. The solder chosen was a Kester 63/37 Tin/Lead solder paste. Tin/Lead solder provides a good mechanical connection with low resistance and a low melting temperature. The scarf piece is made in a two-step process shown in Fig. 5. First, four conductors are tinned, cut at the appropriate angles, and soldered together to a thin foil on a flat surface. Then the scarf is re-heated inside a curved fixture to provide a permanent bend, approximately matching the outer radius of the coil windings.

The copper base, conductors, and scarf piece are soldered together inside of an aluminum fixture, shown in Fig. 6, to form the complete terminal assembly. The fixture applies light pressure with the use of springs and is heated by several cartridge heaters. The assembly is held at 195 °C for a maximum of two minutes and then the fixture is cooled with an air flow cooler to minimize the total time that the superconductors are held at elevated temperatures. Once this process is completed, the terminal assembly is ready to be attached to the coil through another soldering process.

Fig. 6. (Left) Picture of terminal showing location of scarf and conductors on copper base. (Right) Terminal assembly soldering fixture with terminal prepared for fabrication.

Fig. 7. Picture of terminal attachment soldering fixture with Nichrome heating strip over the joint area of the terminal.

C. Attachment to Coil

There are a number of considerations that must be carefully addressed in order to produce a satisfactory electrical and mechanical connection between the coil and the terminal assembly. The curvature on the outside of the coil provides a distinct challenge. The joining of two coated conductors through a soldering process is most successful when the two pieces are pressed firmly against each other under uniform heating. This is difficult on a curved surface, especially a surface without a well-defined radius. Though the diameter of a coil can be easily measured with large calipers, the construction of the coil does not assure equal opposing radii. Early attempts with fixed radii soldering fixtures provided some success but were not completely satisfactory. A new method was developed that uses a flexible Nichrome strip to deliver heat and apply pressure against the surface of the solder joint, as shown in Fig. 7. This allows for consistent performance in case of a slightly varying joint radius. The Nichrome strip must be electrically isolated from the conductor and this is done with Kapton tape, which provides a minimal thermal barrier. Measures were implemented to cool the locations where the Nichrome strip comes off of the windings. This area is otherwise susceptible to high temperatures due to the poor thermal conductivity of the Nichrome and lack of contact with the conductor.

IV. TESTING OF TERMINALS

A. Test Fixture

The conditions experienced by the terminal during coil operation are difficult to reproduce in a stand-alone terminal testing setup. However, the expense and difficulty associated with a coil test necessitate the use of such a device. A terminal test

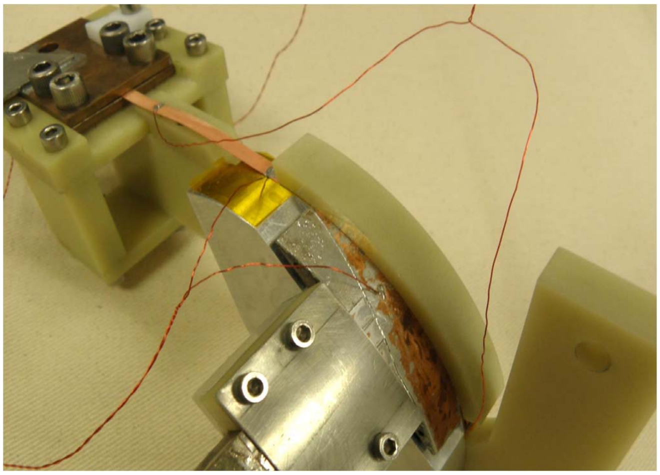

Fig. 8. Picture of the terminal test fixture.

fixture, shown in Fig. 8, has been fabricated that applies a tensile force to a conductor attached to the terminal assembly. Force is transferred through the conductor, the scarf piece, and the terminal base. Performance of the solder connection may be evaluated under a prescribed load. The terminal axial and radial constraints on the test fixture are identical to the constraints of the test coil, though axial and radial translations are not simulated with the test fixture. The fixture contains a curved surface that matches the radius of the outside winding radius of the test coil. This surface simulates the windings underneath the terminal connection. Another structural member is placed on top of the terminal connection in order to simulate the effects of the external reinforcement. The test fixture is connected to a MTS servo-hydraulic test machine for the application of tensile force. All tests were performed at 77 K in self field.

B. Cyclical Testing

The 32 T magnet is being designed as a versatile user magnet system with the ability to sweep between high and low field frequently. All of the structural components are being designed to accommodate 50 000 cycles. Terminals were also tested for fatigue strength over a range of applied stresses. The 32 T magnet will operate near 450 MPa in the high stress regions. Tests of 10 000 cycles at 450 MPa and 500 MPa were performed consecutively on the same terminal with no indication of degradation. Additional cycles at higher stress levels were performed in order to demonstrate the upper limits of the terminal's capabilities. I_C degradation in the terminal joint, as shown in Fig. 9, occurred simultaneously with that to the straight section of the conductor. This indicates that the joint region is equally as strong as the tape itself.

C. Test Coil Experience

A recent test of the inner prototype coil for the 32 T magnet provided useful data on the performance of the terminal design [3]. Damage immediately adjacent to the lower terminal connection limited the capability of the coil. While the exact cause of the damage remains unclear, coil winding procedures and

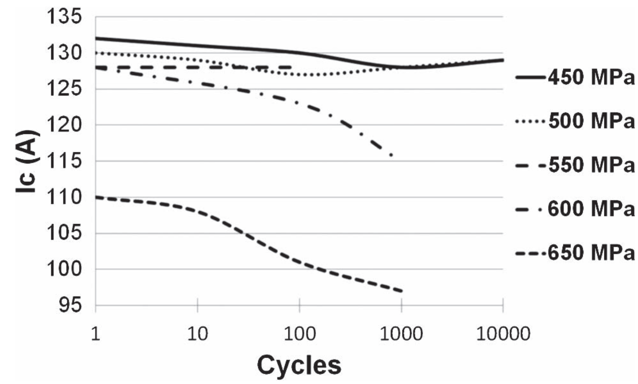

Fig. 9. Plot of critical current versus number of load cycles performed on a test terminal.

terminal design have been revisited and further development is progressing in this area. The top terminal of the prototype coil performed well under the limited operating conditions. The total resistance of the terminal connection was measured to be 125 nΩ. Additional testing of the inner prototype coil will be conducted after repairs have been made. This will provide another opportunity for evaluation of terminal performance.

V. Summary

The terminal design, as tested in both a stand alone configuration and in a prototype coil, appears to provide an acceptable solution to the challenges of connecting to a dynamic coil. However, the response of the terminal to the radial and axial translations of the coil remains somewhat unknown, due to the difficulty of observing these movements. The limited testing of these constraints has not yet proven the fatigue strength of the present design. An additional terminal testing fixture has been proposed and is being designed at the NHMFL. The design will simulate the radial expansion of a coil and allow critical current measurements of the terminal connection. This will also allow high cycle testing without the time and expense of repeated ramping of a coil. Additionally, a modification to the terminal design is being explored which will eliminate the slider block and decrease the radial space needed on the end flanges to accommodate the constraint of the terminal assembly.

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