Insulation system for high temperature superconductor cables

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Abstract. Large-scale superconductor applications, like fusion magnets, require high-current capacity conductors to limit system inductance and peak operating voltage. Several cabling methods using high temperature superconductor (HTS) tapes are presently under development so that the unique high-field, high-current-density, high operating temperature characteristics of 2nd generation REBCO coated conductors can be utilized in next generation fusion devices. Large-scale magnets are generally epoxy impregnated to support and distribute electromagnetic stresses through the magnet volume. However, the present generation of REBCO coated conductors are prone to delamination when tensile stresses are applied to the broad surface of REBCO tapes; this can occur during epoxy cure, cooldown, or magnet energization. We present the development of an insulation system which effectively insulates HTS cabled conductors at high withstand voltage while simultaneously preventing the intrusion of the epoxy impregnant into the cable, eliminating degradation due to conductor delamination. We also describe a small-scale coil test program to demonstrate the cable insulation scheme and present preliminary test results.

1. Introduction

The high energy physics and the thermonuclear fusion communities are actively developing high-current capacity cables using 2nd generation REBCO coated conductor tapes for large-scale, high-field magnet applications. REBCO coated conductors are one of the few high-temperature superconductors (HTS) capable of providing the approximately 20 T peak magnetic flux that may be required by these devices and the only one presently available in large scale production. Potential applications include the LHC Energy Upgrade [1], with peak magnetic flux density in the range from 16 T to 20 T, and compact fusion devices like ARC [2], with peak magnetic flux density in the range from 20 T to 22 T. The REBCO cable types under development include: conductor on round core (CORC) [3], twisted, stacked-tape cable (TSTC) [4] and Roebel bar [5]. In addition to operating in a high electromagnetic stress environment, the conductors will also be exposed to ionizing radiation. The anticipated radiation dose on the ITER magnets is 1x10⁻²³ neutrons/m² [6], while the dose rate on subsequent fusion magnets will likely be up to an order of magnitude higher.

A principal risk factor for HTS coils is the low through-thickness tensile strength of present generation REBCO tapes. Therefore, it is necessary to control the thermo-mechanical stress transmitted to the conductor when a large, high-field REBCO-based coil is cooled to cryogenic
temperatures and energized [7]. The thermo-mechanical stresses develop in part because of the different thermal contractions and mechanical stiffnesses of typical epoxy potting compounds and the REBCO tapes. The through-thickness thermal contraction of typical fiberglass/epoxy insulation is about 1%, whereas the thermal contractions of the REBCO tapes and steel former are on the order of 0.25% [8, 9]. Large differential stresses develop as the coil is cooled to low temperatures, and these stresses can potentially delaminate the REBCO tapes. Through thickness delamination of the REBCO tape has been reported at tensile stresses as low as 10 MPa, and has been cited as the cause of degraded performance for several epoxy impregnated small coils [10]. One approach to address delamination due to differential thermal contraction during cooldown has focused on the use of filled epoxies [11, 12].

To support the development of next-generation, high-field magnets, we sought to develop a reliable means to electrically insulate and epoxy-impregnate high-current capacity cables using presently available REBCO coated conductor tapes. Our approach was to develop a combination of epoxy potting and barrier insulation materials that, when combined in a magnet, can absorb most of the through-thickness tensile strains applied to the REBCO tapes when a magnet is cooled and energized. The high dielectric strength barrier insulation we selected can be tightly sealed to the surface of the REBCO cable to prevent the intrusion of epoxy in direct contact with the tapes. The candidate epoxy impregnant was selected based on its anticipated high radiation resistance. The epoxy impregnant also provides suitable stiffness, structural strength, low thermal expansion, and relatively high thermal conductivity to react the mechanical and thermal loads applied to a magnet, while preventing delamination due to differential thermal contractions during resin curing and magnet cooldown. Our criterion for success was to demonstrate negligible degradation to the cable’s superconducting performance following insulation, epoxy impregnation, cool-down, and operation.

2. Test configuration

We utilized an inductive charging method to evaluate the performance of the cable samples to eliminate the need for high-capacity current leads. Figure 1 shows a solid-model image of the arrangement. The cable sample was in the form of a small, partially slit-tape coil [13]. The upper-most, water-jet-cut aluminum plates used to shape and support the coil were suppressed in Figure 1 to emphasize the conductor shape. The coil was also equipped with a small AISI 1018 iron pole piece to increase the magnetic flux density captured by the coil.

To form each test coil, a set of between twenty and thirty, 305 mm long by 12 mm wide REBCO tapes from SuperPower, Inc. was laser slit along the tape centerlines over most of their length, leaving a short section of full width tapes at each end. The tapes were then stacked together to form an approximately 2 kA current capacity cable and installed in the aluminum support plates, with the top halves of the tapes deformed to a roughly semi-circular shape in one direction, and the bottom half of the tapes deformed in the other direction to form a continuous closed loop. Two types of SuperPower HTS tapes were used during the project. The first sample used SuperPower type SCS-12050-AP tapes with 10 µm thick electroplated copper applied to each side, while the second sample used SuperPower type SF-12050-AP tapes with 2 µm thick electroplated silver applied to each side. The minimum 77 K self-field critical current for copper-clad tape was 328 A, while that for silver-clad tape was 298 A.
A slit-tape coil geometry was used to permit direct comparison of cable performance both before and after application of the barrier insulation and epoxy impregnation. Energization of the coil was performed by flux trapping, during which the coil was placed at room temperature in an energized background field coil, cooled to 77 K by liquid nitrogen transfer, and subsequently energized by removal of the background magnetic field. The coil configuration and test procedure were selected to minimize confounding effects such as stress concentrations at current lead breakouts, and variation in the distribution of current among cable tapes from one test sequence to the next. The conductor’s critical current is easily determined by applying external field before cooldown greater than the sample’s anticipated, maximum self-magnetic field. After the sample is cooled and the external field is removed all conductor tapes are at their critical condition, with zero applied external magnetic field. The expected critical current for each sample was determined using a COMSOL Multi-Physics [14] model of the test setup. The model investigated the distribution of magnetic flux density over the cable cross-section near the ends of the slits, where the upper half of the cable loop passes directly over the lower, and near the center of each half of the cable. The cable critical current at each location was iteratively determined by: imposing a cable current at zero background field in the COMSOL model, determining the distribution of magnetic flux density over the cable cross-section, evaluating the effect of local magnetic flux density (intensity and direction) on expected critical current density, integrating over the cross-section to determine the expected cable critical current, and adjusting the applied current in the model until the applied and expected current matched. In our model, we relied on Takayasu’s recent low-field, 77 K measurements on SuperPower advanced pinning site tapes [15] to model the effect of magnetic flux density on the local critical current density in the cable. The COMSOL model also calculated the expected magnetic field across the surface of the sample’s iron pole piece. The surface of the pole piece was equipped with F.W. Bell model BHT-921 Hall probes mounted at the center and near the edge as a means to indirectly determine the sample current.

Several samples were fabricated during the development of the insulation scheme. Because of the high cost of superconductor, development began using a surrogate material, namely 22 mm wide by 50 µm thick Inconel tape. The first conductor sample was made using the copper-plated REBCO tapes, while the second sample was made using silver-plated tapes. Copper-plated tapes are more relevant for large-scale magnet applications, where the copper provides an alternative current path in the event of superconductor quench. However, the copper-plated tapes were more prone to the development of a significant, built-up edge of rapidly resolidified material during laser slitting, which interfered with the regular stacking of the tapes during sample fabrication. The switch to silver-plated tapes, which do not demonstrate this effect to an appreciable extent, was made, because the primary focus of the study was on the development of the insulation scheme. All tape samples were partially laser slit at Laser Edge Technology in Merrimac, MA.

During processing of the REBCO conductor samples, the critical current of the uninsulated sample was first determined at the Plasma Science and Fusion Center at MIT. The sample was transferred to Composite Technology Development, Inc. for insulation application. The sample was returned to MIT for re-evaluation of its critical current and finally returned to CTD for sectioning and visual examination of the insulation quality.

3. Insulation scheme

Various approaches have been developed to electrically insulate individual REBCO coated conductors, including the application of electrodeposited polyimide [16] or encapsulation within heat shrunk tubing [17]. The insulation would be applied to the conductor before magnet winding and epoxy impregnation. The objective of both approaches is to surround the conductor with a continuous, tight-fitting but poorly adhering insulating layer that would electrically insulate but mechanically decouple the conductor from tensile stresses which might be applied to the REBCO layer. The approach presented here is conceptually similar, but intended for use on high-current capacity cables fabricated from multiple REBCO tapes. Our proposed approach for insulating long-length REBCO cables is to continuously wrap them with thin polyimide shrink tape and then pot with a highly-filled
epoxy for enhanced mechanical strength and radiation resistance. A significant advantage of the approach described here is its compatibility with continuous manufacturing processes that might be used during cable production.

3.1. Material Selection
We selected polyimide tape because of its known high dielectric strength and radiation resistance. Tape wrapping was chosen because the processing method can be performed on long lengths using an automated system. Shrink tape was chosen rather than adhesive-backed tape because of the known radiation sensitivity of the acrylic adhesives and the tendency of adhesive tapes to wrinkle during wrapping, forming gaps through which resin could flow.

The polyimide shrink tape used in this study is capable of up to 13% shrinkage when processed at 350 °C. However, the tape was processed at lower temperature in this study to accommodate the maximum recommended processing temperature for the REBCO conductors. Our results show that when the tape is applied with high tension initially to form a snug wrap, the 8% shrinkage that can be achieved at 150 °C is acceptable for forming a tight barrier.

CTD-101G resin was chosen as the potting material in the test samples based on its relatively low cure shrinkage, high cryogenic strength and stiffness, and anticipated high radiation resistance. CTD-101G is an anhydride-cured, bisphenol-A based resin with a high concentration of filler added to reduce shrinkage and improve thermal conductivity. For a 5 hr cure at 110 °C, followed by 1.5 hr at 135 °C, the linear cure shrinkage is 0.55±0.04% when evaluated per ASTM D 2566. The resin viscosity during processing at 60–80 °C ranges from 200 cP to 1000 cP when measured using a Brookfield viscometer, which is low enough to be used for potting coils. Its pot life of 1.5–3 hr is long enough for processing small coils, but may need to be optimized for use in large-scale magnets. When tested per ASTM D 638 at 77 K, the neat resin (without fiberglass) has a tensile modulus slightly above 19 GPa and a tensile strength exceeding 95 MPa. All resin properties were determined at CTD.

3.2. Preliminary Irradiation Testing
For fusion magnet applications, radiation stability of the insulation scheme is critical. To evaluate the radiation resistance of the selected materials, polyimide shrink tape tension specimens and CTD-101K and CTD-101G short-beam-shear specimens were irradiated at the Massachusetts Institute of Technology Nuclear Reactor Laboratory in their 2PH1 facility. The particular tests conducted were chosen as they most dramatically demonstrate any material property changes that arise from radiation exposure. The short-beam-shear specimens were fabricated with S2-glass. Radiation exposures of two and four times the ITER design fluence were used in this work, which equates to $2 \times 10^{22}$ and $4 \times 10^{22}$ neutrons/m$^2$, respectively. The specimens were returned to CTD for film tension testing at 295 K (per ASTM D882) and short-beam-shear testing at 77 K (per ASTM D2344). The test results are shown in Figure 2, where it can be seen that the polyimide film retains 79% of its tensile strength.

![Figure 2](image_url)

Figure 2. Pre- and post-irradiation test results. a) Polyimide shrink tape tensile test at 295 K and b) resin/S2-glass short-beam-shear test at 77 K.
after exposure to 4x the ITER design fluence. The CTD-101K and CTD-101G specimens had a higher degree of strength reduction after exposure to the high irradiation levels, but future work will focus on improving the potting compound radiation stability.

3.3. Insulation of test coils

Figure 3 shows initial efforts to apply the polyimide shrink tape to a stack of 32 partially slit Inconel strips. This effort was performed to develop the process that would subsequently be used to insulate the significantly more expensive superconductor coils that were subjected to critical current evaluation. The Inconel strips were stacked and held together with clamps while the polyimide shrink tape was tightly wrapped with a ½ lap around the strips (Figure 3a). The ends of the shrink tape were held in place with Kapton tape. Once the conductor loop was completely wrapped with polyimide, it was reinserted into the aluminium support plates and heated in an oven to 150 °C for 30 minutes to shrink the polyimide and form a tight wrap around the Inconel strips. The polyimide-insulated sample is shown in Figure 3b. Unlike the processing for a continuous cable length, the complex geometry near the ends of the slits prevented straightforward wrapping of the polyimide tape. Our ability to successfully seal these regions in the final test sample (to be discussed below) confirms the robustness of the proposed approach. The insulation process was similar for each succeeding sample, however, slight improvements were made as we gained experience.

Figure 3a Polyimide shrink tape winding procedure, and b) polyimide-insulated sample reinserted in its aluminium support plate (right).

To complete the test sample fabrication, the polyimide-wrapped conductor was removed from the aluminum plates, which were then used as a potting mold to apply and cure the resin. The machined slot in the aluminum plate was sealed at the bottom using a 2.5 mm thick silicone sheet as a gasket. The slot was half filled with resin, warmed to 80 °C, and degassed in a vacuum oven. The lower half of the conductor was reinstalled in the plate and additional resin was applied to completely fill the slot. The resin was cured using the following schedule: 3 hr ramp to 110 °C, soak at 110 °C for 5 hrs, 1.5 hr ramp to 135 °C, soak at 135 °C for 1.5 hrs, 2 hr cool to 22 °C. The upper half of the coil was then potted by adding a second sheet of silicone between the upper and lower plates. For the second half of the coil, pre-warmed, degassed resin was injected into the gap between conductor and plate using a syringe to completely fill the slot. The resin cure cycle was then repeated for the resin applied to the second half of the coil. The thermal process cycle was verified by Super Power to have no detectable impact on expected critical current of their REBCO conductors [18]. The silicone sheet gasket between the aluminum support plates was not part of the original sample fabrication plan and was not present during critical current testing of the uninsulated samples.

Figure 4 shows results from the sectioning analysis of the sample made using a stack of 20 partially laser-slit copper-plated REBCO conductors. The locations of the cuts are shown in Figures 4a and 4b, while representative microscopic images of conductor cross-sections are shown in Figures 4c and 4d. Figure 4c shows a conductor cross-section taken at sample location 1 in Figure 4a. The free surface of the sample is to the right, while the silicone gasket between support plates is to the left. The conductor
The stack is not well aligned and has a slightly trapezoidal shape due to the presence of the built-up edge along the edge of the laser cut slit. The conductor stack shows considerable resin infiltration, most likely due to the irregular packing on the stack which introduces gaps between the polyimide tape wraps. The approximately 20% reduction in measured critical current for this sample from the uninsulated to insulated conductor tests (discussed below) is attributed to the presence of resin within the conductor stack, which may have damaged some of the tapes. Figure 4d shows the conductor cross-section taken at sample location 3 in Figure 4b. The silicone gasket between the plates is towards the right in this figure. It shows similar trapezoidal shape, but is well compacted, with resin intrusion limited towards the periphery of the stack.

Figure 4. Section views of the sample made using the copper plated REBCO conductors. a) and b) location of sample section lines. c) and d) representative cross-section views.

Figure 5 shows results from the sectioning analysis of the sample made using a stack of 29 partially laser-slit silver-plated REBCO conductors. The locations of the cross-sections are the same as those shown in Figures 4a and 4b. Figure 5a shows the conductor cross-section taken at sample location 3, while Figure 5b shows the conductor cross-section taken as sample location 5. The microscopic images at these locations show well compacted, neatly arranged conductor stacks, with near rectangular shape. No resin flow can be seen between tapes within the conductor stack and only negligible resin can be detected within the polyimide wrap towards the left hand side of Figure 5a.

Figure 5. Representative cross-section views of the sample made using the silver-plated REBCO conductors. a) Section at sample location 3, and b) section at sample location 5.
4. Critical current measurements

Figure 6a shows the minimum excitation sequence needed to determine the critical current of our slit tape conductor samples. The data trace shows the magnetic flux density measured on the surface, near the center of the sample pole piece vs. the excitation current applied to the background field magnet for the uninsulated sample fabricated using the silver-plated REBCO tapes. The thin, solid black line shows the initial current upramp, with the room temperature (RT) sample installed in the bore of the magnet. The sample was then cooled to 77 K by liquid nitrogen transfer into the sample cryostat. The magnet current down ramp following cooldown is shown by the thick, dashed black line. The small vertical downward drop at zero external magnet current is attributed to flux creep in the sample as the induced current in the sample decreases from just over critical to below critical current. The thick dotted line shows a current upramp towards the end of the test sequence during which the liquid nitrogen is allowed to boil away at constant background field. The vertical upward portion of this curve is due to quench of the sample current as the sample temperature increases due to heat leak into the cryostat. The solid black curve shows a set of external magnet current sweeps following sample quench. The trace shows negligible change in the Hall probe calibration and offset with temperature and minimal magnetic hysteresis in the background magnetic field.

Figure 6b compares the magnetic flux density trapped by the sample fabricated using 29 silver-plated REBCO conductor before and after application of the cable insulation. The vertical axis shows the magnetic flux density measured by the Hall probes mounted near the center and near the edge of the sample pole piece vs elapsed time following the end of the external magnet current downramp with sample immersed in liquid nitrogen. The thick lines show measurements for the uninsulated sample, while the thin lines show measurements for the insulated sample. The solid lines show measurements taken near the edge of the pole piece, while the dashed lines show measurements taken near the center. The slight reduction in the Hall probe readings for the insulated sample are due to the introduction of a 2.5 mm gap (corresponding to the silicone gasket) between the pole pieces during application of the cable insulation. The COMSOL models of the test arrangement indicate that all asymptotic Hall probe readings in Figure 6b are consistent with a sample current of 1720±20 A, compared with the estimated sample current of roughly 1830 A based on the magnetic field distribution across the cable cross-section near the ends of the slits, which is slightly lower than that near the center of the sample loop. The agreement is reasonable given inherent uncertainties in the COMSOL modeling, the assumed uniformity of critical current density across the width of each REBCO tape, and the position of the laser slitting line relative to the REBCO tape centerlines.

Figure 6. a) Flux-trapping test sequence, and b) comparison of flux creep portion of the test sequence before and after polyimide tape wrapping and epoxy potting of the silver-plated conductor stack.

Figure 6b compares the magnetic flux density trapped by the sample fabricated using 29 silver-plated REBCO conductor before and after application of the cable insulation. The vertical axis shows the magnetic flux density measured by the Hall probes mounted near the center and near the edge of the sample pole piece vs elapsed time following the end of the external magnet current downramp with sample immersed in liquid nitrogen. The thick lines show measurements for the uninsulated sample, while the thin lines show measurements for the insulated sample. The solid lines show measurements taken near the edge of the pole piece, while the dashed lines show measurements taken near the center. The slight reduction in the Hall probe readings for the insulated sample are due to the introduction of a 2.5 mm gap (corresponding to the silicone gasket) between the pole pieces during application of the cable insulation. The COMSOL models of the test arrangement indicate that all asymptotic Hall probe readings in Figure 6b are consistent with a sample current of 1720±20 A, compared with the estimated sample current of roughly 1830 A based on the magnetic field distribution across the cable cross-section near the ends of the slits, which is slightly lower than that near the center of the sample loop. The agreement is reasonable given inherent uncertainties in the COMSOL modeling, the assumed uniformity of critical current density across the width of each REBCO tape, and the position of the laser slitting line relative to the REBCO tape centerlines.
By comparison, results for the earlier sample, fabricated using 20 copper-clad REBCO tapes, were consistent with a sample current of 1150±10 A prior to insulation, which was close to the anticipated value, and a current of 940±10 A during retest following insulation. These results are for the poorly aligned sample that showed significant resin intrusion between the conductor tapes in Figure 4c.

5. Summary
We have tested a method for electrically insulating and epoxy impregnating high-current-capacity cables formed from REBCO tapes, using radiation-resistant materials suitable for use in large-scale superconducting magnet applications. The method combines a heat shrinkable polyimide tape, which acts as a barrier insulation, followed by impregnation with a low shrinkage resin, CTD-101G. Tight wrapping, followed by shrinkage of the polyimide tape effectively compacts the cable stack, potentially enhancing tape-to-tape current transfer, while sealing the cable stack perimeter to prevent resin intrusion between tapes during potting. The method was demonstrated using a series of small, slit-tape conductor samples. The results for the cable sample fabricated using silver-plated REBCO conductors shows that, when properly applied, the proposed insulation scheme effectively prevents critical current degradation during cooldown and subsequent operation.

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