FABRICATION AND TESTING OF CURVED TEST COIL FOR FRIB FRAGMENT SEPARATOR DIPOLE*

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Abstract

A critical element of the fragment pre-separator of the Facility for Rare Isotope Beams (FRIB) is the 30° dipole bend magnet. Because this magnet will be subjected to extremely high heat loads, operation at 4.5 K would is not be practical. High Temperature Super-conductors (HTS) can be operated at 40 K which is more effective for heat removal. An efficient design for this magnet would make use of coils that follow the curvature of the magnet which requires windings to have a negative curvature on one side. In this paper we demonstrated that HTS coils with negative curvature can be wound. However, winding curved coils with negative curvature are difficult as the coil tends to unwind during the process. As part of an R&D effort for this magnet we wound a quarter scale test coil with and without negative curvature for this magnet with YBCO conductor and measured their performance at 77 K. This paper will discuss the winding process and the test results of the study.

INTRODUCTION

The FRIB facility will provide isotope beams for physics research with intensities not available elsewhere. A crucial element of the FRIB fragment pre-separator beam line is the 30° bend dipole magnet. There are two such magnets in the fragment pre-separator. The basic design is a sector bend superferric magnet where the coils magnetize the iron yoke and the magnetized iron provides the desired field quality. Because these magnets are in a high radiation environment they will be subject to a high heat load. We propose to build this magnet with YBCO. In earlier studies [1,2,3], it has been shown that YBCO is highly radiation resistant.

In order to accommodate the large heat loads, we propose that this magnet operate at 40 K. HTS, unlike NbTi and Nb_3Sn superconductors, can operate at 40 K where the heat capacity of the coolant is large enough to remove the heat load in an efficient manner. Although Bi-2212 conductor could be used for this application, we have chosen YBCO because it is currently available in the large quantities that would be necessary for the prototype coil. YBCO is only available in tape form. In order to wind the coil and preserve the 2D transverse cross section at different positions in the magnet, the inner segment of the coil will have a concave geometry with negative curvature. This geometry is shown in Figure 1a. Winding coils in this configuration is more difficult as the conductor tends to unwind during the process. An alternate coil geometry shown in figure 1b avoids the negative curvature segment however the magnetic field in the good field region may show some dependence on location in the magnet. A comparison of the field properties for these two configurations is given in another paper [4]. The field calculations showed that the maximum difference inside the good field region was 1.5% which occurred near the inner edge in the longitudinal center of the magnet where the coil geometry differences are the largest.

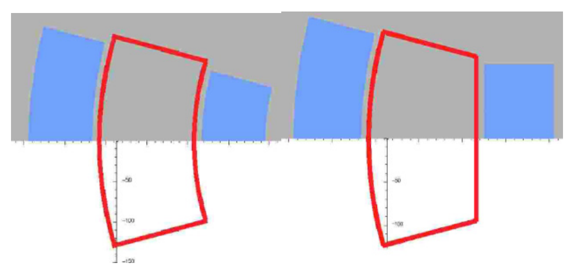

Figure 1: Two coil configurations examined. a) The left diagram uses a curved inner radius segment which was wound with negative curvature. b) The right diagram uses straight conductor for that segment.

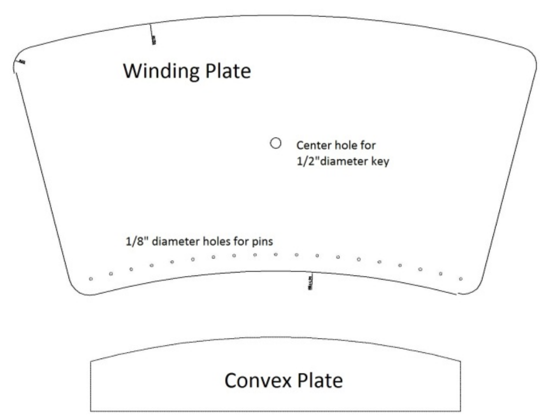

Figure 2: Winding tools used to wind coil with concave segment.

WINDING PROCEDURE

In this study we wound two coils, one of each for the two configurations shown in figure 1. The coils are scaled to one quarter the size of the coils needed for the fragment pre-separator magnet. The prototype magnet

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has a bending radius of 4 m. The radius of the inner segment is 3.4 m. The inner radius of the 1/4 -scaled test coil is 0.85 m resulting in much greater curvature for the test coil. We used SuperPower SCS4050-AP YBCO wire [5] to wind these coils. Muons, Inc. had designed and manufactured a tool for the winding of these coils. A sketch of these tools is shown in Figure 2. The conductor is wound around the edge of the upper plate which is rotated around the center hole. A back plate shown in Figure 3 is attached behind the winding plate to support and register the conductor as it is wound. The holes near the concave surface of the winding plate hold pins that are used to anchor Kevlar string to hold the conductor in place as it is wound around that segment of the plate. The slots in the back plate accommodate the string that holds the conductor. This technique was originally developed to wind curved coils with NbTi conductor. The photograph in Figure 4 shows the first several turns on the concave segment being held in place with the Kevlar string. Since the Kevlar string left bend marks on the conductor with a potential to damage the conductor, we abandoned this technique. We had initially hoped to wind the coil without any epoxy, but it was not possible for a coil of this size and geometry. Instead we held each conductor in place by painting epoxy on the narrow edge of the conductor with the convex plate shown in the lower part of Figure 2 with the fast setting epoxy holding the conductor in place when dried. It may be pointed out that the coils are not epoxy impregnated (and hence wide face of the HTS tape not exposed to direct contact with epoxy) but are only held together with epoxy painted on the surface. This technique is a variation of the one used in other HTS tape wound coils at BNL and has not been found to create any degradation. Figure 5 shows this process. A similar approach was applied to the coil without a curved inner segment (shown in Figure 1b). An insert piece was placed on the concave side of the winding tool to support the conductor during the winding.

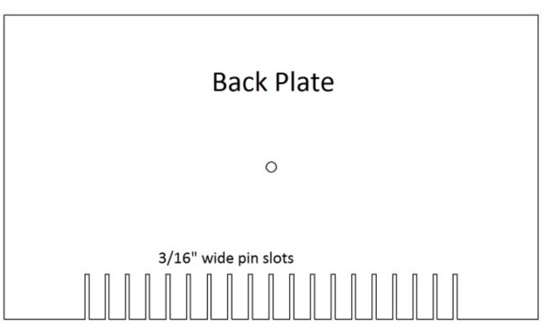

Figure 3: Back plate to winding plate shown in Figure 2.

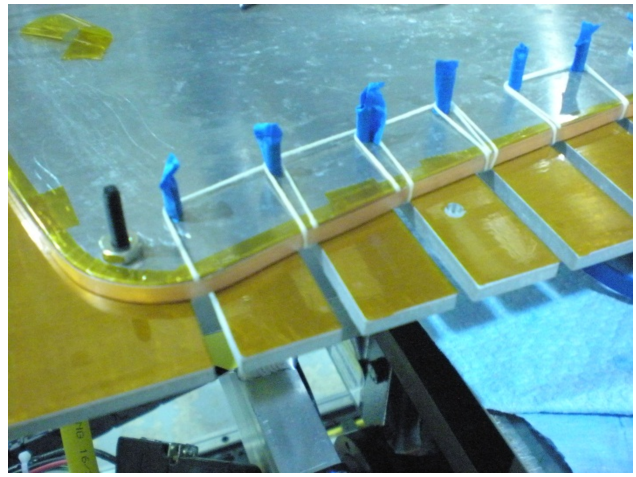

Figure 4: Winding YBCO coil with inverse curvature segment using Kevlar string to hold the conductor in place.

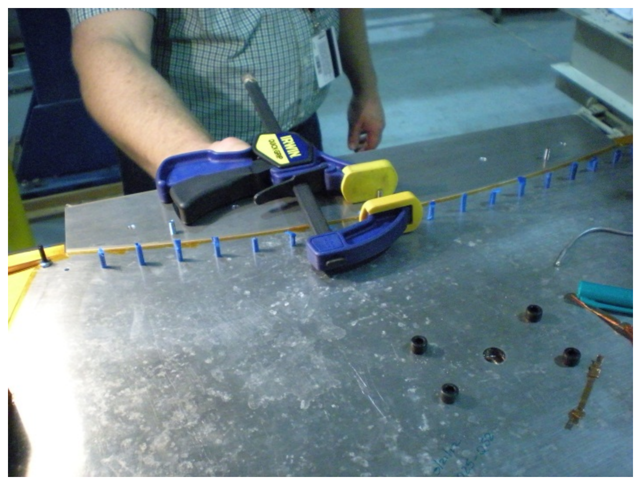

Figure 5: Conductor being held in place in negative curvature section of the coil while epoxy is drying.

COIL TESTING

As the coils were wound, a large number of voltage taps were inserted every several turns for detailed measurements during testing. This allows determination and localization of performance degradation during the course of this complex winding. The voltage taps provide diagnostic information during the testing as the onset of pre-mature resistive voltage during the testing will indicate a defect or degradation in conductor performance. Also power supply electrodes were soldered to the beginning and end of the coils. The coils were placed in a cryostat box cooled to 77 K with liquid nitrogen. Figure 6 shows the voltage vs. current (V vs. I) curve for the coil with the straight inner coil segment as shown in Figure 1b. The initial testing of this coil showed a resistive voltage at the 11th turn, limiting the current to 5 amps. To continue testing the defective portion of the conductor was removed and the coil was retested with 11 turns. The three curves correspond to voltage drop between specified turns. A resistive voltage was first observed in the inner turns, as expected due to higher field at coil inner radius. This coil showed a critical current of ~55 amps before a part of the coil went normal. This performance is consistence with the expectation. The actual construction technique, however, would be modified for large scale production. It is more likely to follow the procedure that has been used in winding a large number of coils at BNL.

The second coil with the geometry shown in Figure 1a with the negative curvature on the inner segment of the coil was tested. The first several turns were wound using the Kevlar string technique, however local pressure points from the string were observed and it was felt that there could be damage to the conductor. The rest of the coil was wound with epoxy at strategic places and held in place with the winding tool shown in Figure 5. The initial test was made with the whole coil including the turns which were suspected to have been damaged by the Kevlar string. In fact, the first test of this coil did not even reach 10% of the expected performance and the voltage taps indicated that the failure was in the turns where the Kevlar string was used. We removed the first five turns (which included those where the Kevlar string was used) and retested the coil. Figure 7 shows the V vs. I plot for this coil with the negative curvature segment. This coil had 17 conductor turns and achieved ~55 amps. This demonstrates that the coil with reverse curvature can indeed be wound successfully.

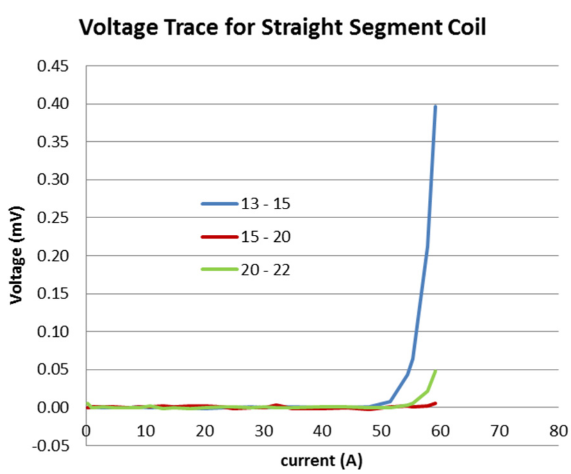

Figure 6: V vs. I trace for the coil with the straight inner segment.

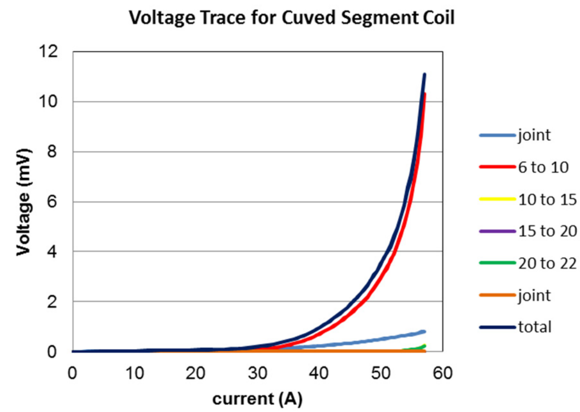

Figure 7: V vs. I trace for the coil with the curved inner segment.

CONCLUSIONS

We have demonstrated that the curved coils for FRIB dipoles with or without reverse curvature can be successfully wound. The winding of the coil configuration shown in Figure 1b with the straight inner segment was easier and faster to wind than the coil with the concave curved inner segment (Figure 1b). As the field from the curved configuration [1] is only marginally better, the straight inner segment configuration will be preferred for its ease in fabrication.

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