Construction and Testing of Curved ReBCO Coils

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***Abstract*—In many applications dipole magnets with coils having significant curvature are needed. This is particularly challenging for high temperature superconductors (HTSs) as they are brittle. One possible application for curved HTS coils was the fragment separator dipole magnets for the Facility for Rare Isotope Beams (FRIB). For this application these magnets would operate in a high radiation environment and would be subject to a high heat load. Removal of heat generated in magnets in this environment using conventional Ni–Ti and Nb_3Sn superconductors, which generally operate at ∼4.5 K, is difficult. However, an HTS conductor can be used to permit operation at 40 K where heat removal is significantly more efficient. As these coils are curved, one side of the coils has a reverse curvature requiring the development of special technology to wind the coils. As part of an STTR grant to develop and demonstrate a super-ferric design for a 2.2 T magnet, two curved coils were fabricated with a 12-mm-wide SuperPower ReBCO conductor and first tested in liquid N_2 at 77 K. Afterwards the coils were installed into a cryostat and cooled to the design temperature of 48 K with cryocoolers. This paper presents the construction details and test results for these coils.**

***Index Terms*—Accelerator magnets, high-temperature superconductors (HTS), superconducting coils, superconducting magnets.**

I. Introduction

THIS DOCUMENT describes the fabrication and testing of curved HTS coils designed to operate at 40 K. This study addresses the issues for dipole magnets subtending large bends. There are difficulties associated with winding a curved coil. The inner curved side of the coil has a negative curvature that will tend to unwind during the winding process. We will describe our approach to fabricate these coils. Muons, Inc. and Brookhaven National Laboratory (BNL) were awarded an STTR grant to develop the curved dipole technology using HTS conductor that could be used for the fragment separator dipole magnet at the Facility for Rare Isotope Beams (FRIB).

Although Ni-Ti and Nb_3Sn are robust conductor material in radiation, they generally operate at 4.5 K which is less practical because of the heat deposited from the radiation is difficult to remove at that temperature. Magnets built with Nb_3Sn, with higher critical temperature than NbTi, may operate up to ∼10 K, but with significantly reduced performance. HTS conductors can carry significant current at 40–50 K where the Carnot efficiency is greater making heat removal easier and are reasonably resistant to radiation. Also at the higher temperature the coils can be cooled using cryocoolers instead of helium refrigerators.

These magnets operate in a high radiation environment and are subject to a high heat load that must be removed. The radiation seen by the first quadrupole after the target is estimated to be 10 MGy/year. The deposited power will drop by an order of magnitude before reaching the first dipole. The magnet design and the choice of materials used must be compatible with the high radiation. Organic materials such as epoxy must be avoided in the fabrication of the coils.

BNL has been involved in an R&D program to develop the quadrupole magnets for the fragment separator at FRIB [1]–[4] using HTS conductor. A design of the fragment separator dipole magnet using HTS was previously published [5]–[7]. The FRIB project has decided not to use HTS magnets for the fragment separator dipole magnets [9]. We have adjusted our program to develop curved HTS coils cooled with cryocoolers for broader applications in accelerators and beam lines.

TABLE I
Geometric Coil Parameters

Parameter	Value
Height	190.58 mm
Width	396.09 mm
Thickness	12.7 mm
Coil Curvature	850 mm
Corner Curvature	51.79 mm
Number of Turns/Pancake	145
Total Conductor Length	320 m

II. Demonstration Coil Design

The goal of this project was to develop HTS coil technology in support of a radiation tolerant dipole magnet design suitable for an extremely high radiation environment such as that present at FRIB. The advantage of using HTS is that the magnet coils can be operated at 40–50 K where heat removal is more efficient. As this is a proof-of-principle demonstration, we have taken advantage of using an existing cryostat that was previously used at BNL for an earlier project. Also, cryo-coolers existing at BNL were used to cool the coils without using liquid helium. The geometry of the coils was chosen to fit into the existing

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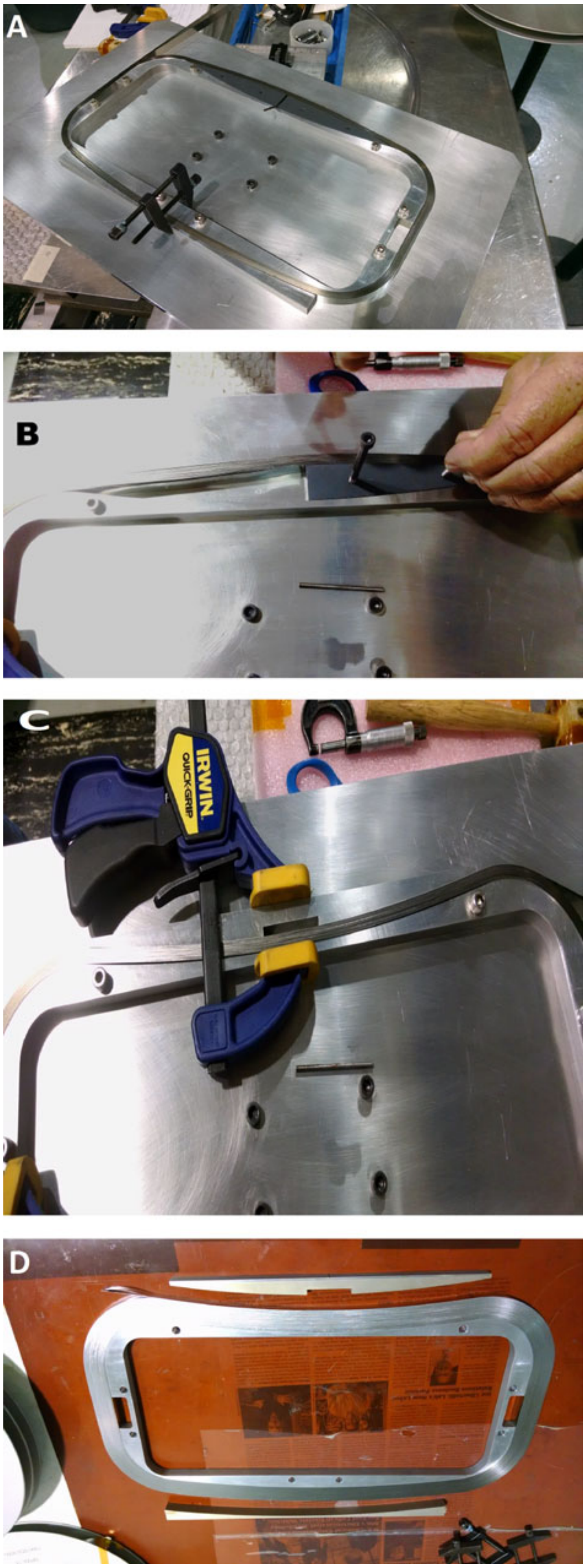

Fig. 1. Winding bobbin and tooling used for the practice wind with stainless steel tape. (a) Tape is wound with positive curvature on all sides of the bobbin using the special tooling. (b) The tooling is being removed before the practice coil is pressed into position on the negative curvature section. (c) The coil is clamped into place. (d) The completed practice coil with tooling used during winding is shown.

cryostat. Table I lists the dimensions of the bobbin used to wind the coil. As the coil is curved there is a segment of the coil that has negative curvature which will tend to unwind during the winding process. For the demonstration, we wound two single pancake coils and then assembled them as a double pancake. Each pancake required 145 turns of conductor. The coils were wound using Super Power 12 mm (SCS 12050-AP) conductor. This conductor has 45 μm of copper for stabilization. The conductor specifications were to carry 450 A in the presence of 3 T at 40 K. The conductor is co-wound with 2 mil stainless steel tape which acts as an inter-turn insulation.

A. *Practice Winding*

We initially performed a practice winding using stainless steel tape instead of conductor to develop the techniques for winding coils with negative curvature. Fig. 1 shows photographs of the practice winding used to fabricate the coils. Fig. 1a shows the tape wound on the bobbin with a tooling piece placed on the concave segment so that the tape is wound with positive curvature on both sides. The inserted piece is designed to keep the conductor length the same after the conductor is pressed against the mandrel when the filler piece is removed. Fig. 1b shows the practice coil when it is pressed against the bobbin and Fig. 1c shows the coil clamped into place. Fig. 1d shows the completed practice coil on the bobbin along with the tooling used for the winding.

B. *Winding with HTS conductor*

The HTS coils are wound on a computer controlled machine which supplies constant tension during the winding. A filler piece is placed in the negative curvature segment of the bobbin to provide a positive curvature of the same magnitude as is shown in Fig. 2a. The coil is wound with HTS tape interleaved with the stainless steel tape. After the coil is wound the filler piece is removed (Fig. 2b) and the coil in that section is pushed into a negative curvature position (Fig. 2c). The filler piece is designed so as not to change the tensile strain on the individual turns. The negative curvature coil section is clamped to hold it and epoxy is applied to the surface of the coil to hold its shape during winding (Fig. 2d). Stainless steel pieces are placed on the outside of the curved sections to provide structural support when energized.

III. Coil Testing

The two coils that were wound are shown in Fig. 3. Each coil has 145 turns of the 12 mm conductor. The coils are fitted with voltage taps to monitor where quenches might occur. Fig. 4 shows the test results for each coil operated at 77 K. The two coils show similar V-I profiles. The coils do not show any evidence of degradation. This means that the procedure used in generating reverse curvature did not cause any measurable damage.

IV. Cooling and Cryostat Design

We chose to use an existing cryostat and cryocoolers at BNL to build and test curved coils at 40–50 K within the limited

Fig. 2. Stages of the winding with HTS conductor. (a) Using filler piece to wind with positive curvature. (b) With filler piece removed. (c) Pushing inner side for negative curvature. (d) Clamping negative curvature side.

Fig. 3. Two single coil pancakes that will make up a double coil pancake.

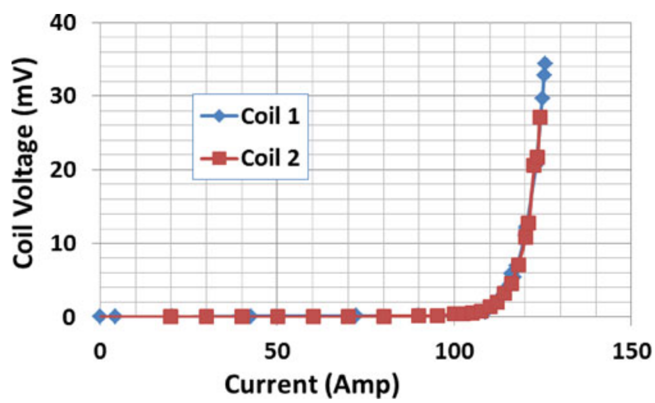

Fig. 4. V-I plot for coils individually operated at 77 K.

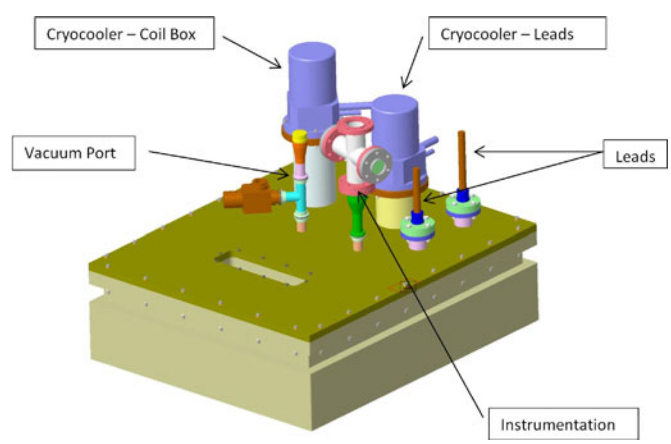

Fig. 5. Exterior view of the cryocooled system design.

budget of the grant. Two cryocoolers were mounted on top of the cryostat to provide the refrigeration – one to HTS coils and the other to the HTS leads. Fig. 5 shows an illustration of the outside of the cryostat with the cryocoolers attached. The interior of the cryostat is shown in Fig. 6. Modifications were made to the existing support structure, leads and test setup to accommodate the double-pancake structure of this magnet. The temperature of the copper leads varies from 248 K as it enters the cryostat to 42 K where they are connected to the HTS leads. The design of the cryogen-free cryostat and specifications of the cryocoolers are given in [10].

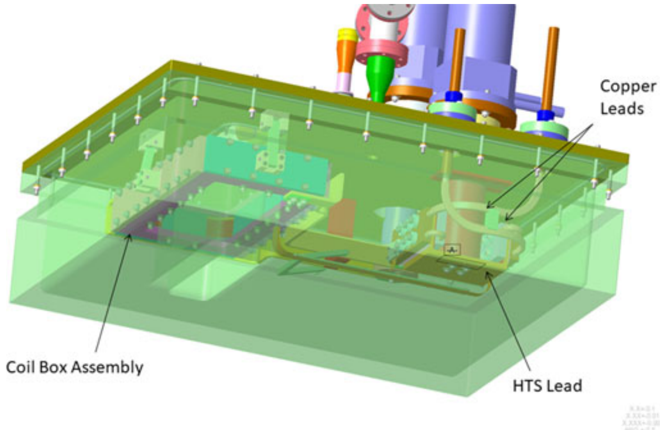

Fig. 6. Layout of the interior of the cryocooled system design.

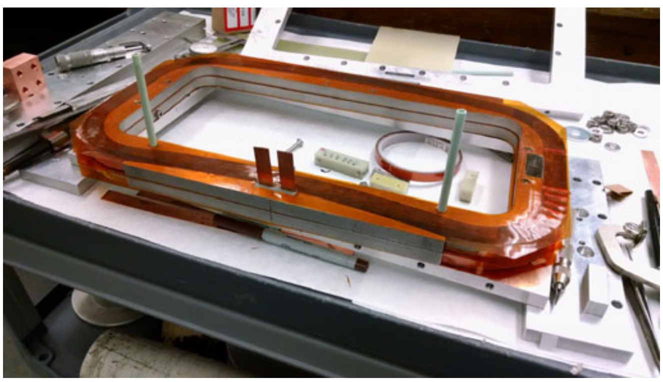

Fig. 7. The two coils wrapped in insulation and assembled together.

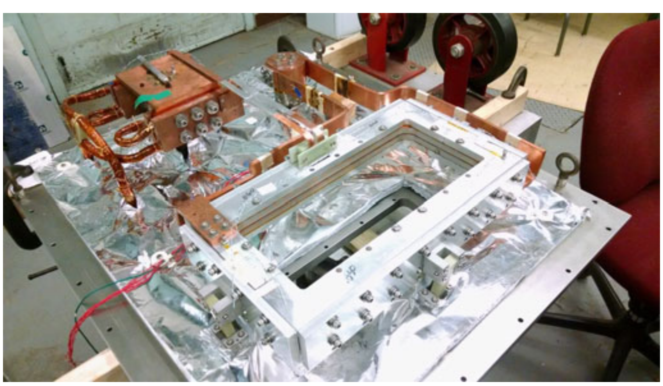

Fig. 8. HTS coils are installed into the cryostat.

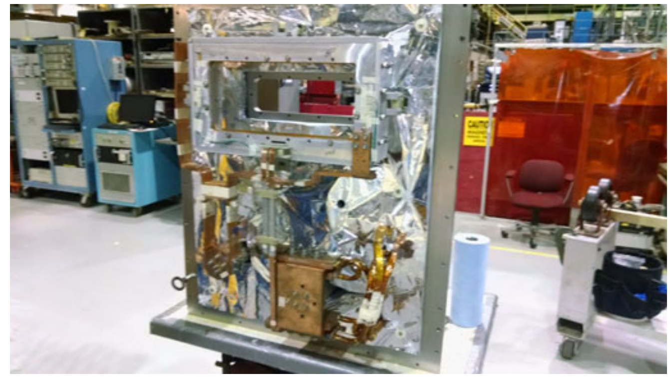

Fig. 9. Cryostat before closing with all internal structures assembled.

Fig. 10. Cryocooled magnet coils being tested.

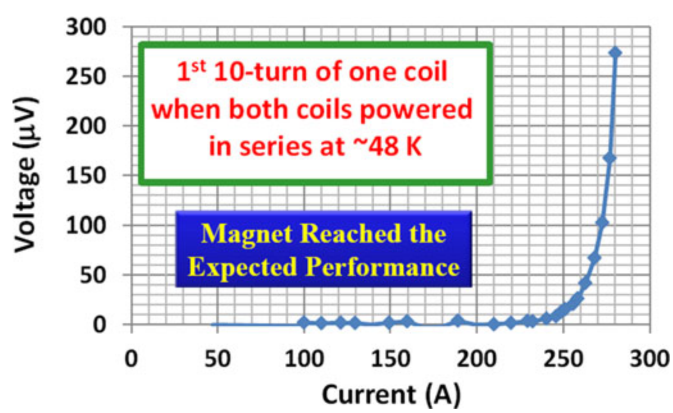

Fig. 11. Test results for magnet cooled to 48 K.

A. Assembly of the HTS Coils inside the Cryostat

The two wound coils are assembled into a double coil pancake. For this test, Kapton sheets were used between the coils as insulation. If the coils were to be used in a radiation environment Nomax sheets would have been used instead of Kapton. Fig. 7 shows the insulated coils being assembled. The coils are installed into a stainless steel support structure and placed into the cryostat (Fig. 8). HTS leads are attached to the coils and copper cooling fins are installed. Fig. 9 shows all internal structures in the cryostat before it was closed.

V. Cryogenic Testing

Fig. 10 shows a photo of the testing setup for the magnet. The photo shows the cryostat on left of photo, cryocooler on the bottom and data recording equipment on the right. The coil was cooled to 48 K with the coils powered in series. The coil is ramped very slowly ramping effects. Fig. 11 shows the V-I plot for the coils. The coils are subject only to their self-field. The peak field on the conductor at 225 A is 1.2 T which occurs at the coil corners. The field is largely parallel to the coil surface. The ratio of critical current at 48 K to that at 77 K is consistent with the data provided by the conductor manufacturer. An incident occurred with one of the coils during the test that precluded testing at lower temperatures.

VI. Conclusion

Curved HTS magnet coils have been built and tested using cryocoolers. The fabrication techniques that were used to wind the coil with positive curvature and press the HTS conductor to the negative curvature configuration did not cause observable degradation. This technology that was developed should be useful for other accelerator applications.

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