

Development and Testing of HTS Coil with Ceramic Coated REBCO Conductor for High Radiation Tolerance

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Abstract—High temperature superconductors (HTS) are being considered for use in future accelerator projects where they will be subjected to high levels of radiation. Development of coated conductor HTS magnets has been undertaken at the High Energy Accelerator Research Organization (KEK). This paper presents the fabrication and testing of seamless double pancake racetrack-type HTS coils wound with EuBCO tape coated with a ceramic insulation material which has a higher radiation tolerance than organic materials. The coils are instrumented with voltage taps and Hall sensors, and an excitation test at 77 K in self-field was completed. The preparation for excitation tests in the background field (~ 10 T) are currently in progress at Brookhaven National Laboratory (BNL).

Index Terms— Superconducting magnets, EuBCO, HTS, radiation resistant.

I. INTRODUCTION

SIGNIFICANT progress has been made in recent years in advancing the maturity of high-temperature superconductors (HTS) for use in high field magnets for fusion applications [1-3]. This progress involves prototyping and testing of HTS cables and model coils relevant to fusion at privately funded startup companies such as the ST40 reactor at Tokamak Energy [4] and SPARC at Commonwealth Fusion Systems [5]. To seamlessly integrate magnet design into high radiation environments, challenges related to shielding and insulation must be addressed. Ongoing studies in laboratories in both the U.S.A and Japan are dedicated to this endeavor.

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At the Japan Proton Accelerator Research Complex (J-PARC), applied studies of HTS conductors for a muon source are being conducted as part of the development of the 2nd target (TS2) at the Materials and Life Science Experimental facility (MLF). In the initial stage of the design study, alternative options were explored, transitioning from low-temperature superconductors (LTS) to HTS magnets, to optimize magnet size by reducing the shield and increasing the operating temperature. This transition suggests a high potential for radiation-resistant muon source applications [6]. In a subsequent design study, assuming a beam power of 1 MW at 3 GeV for an actual MLF, a large radiation shield made of tungsten was placed inside the HTS coil with an internal diameter of 1300 mm to minimize radiation effects. Nevertheless, the estimated absorbed dose on the coils over 10 years was projected to reach 130 MGy [7].

In the past, research at CERN led to the development of radiation resistant normal conduction magnet. Currently mineral insulated magnets based on magnesium oxide are operated at J-PARC in environment close to 100 MGy [8][9]. This research is an attempt to apply similar method to superconducting magnets, and high radiation-resistant HTS coils are crucial for establishing technologies related to radiation-resistant magnets for future accelerator projects.

Among the critical components in the superconducting magnet system, insulation materials stand out as one of the most radiation-sensitive component. It is imperative to select the appropriate insulation material capable of withstanding radiation levels exceeding 100 MGy. Additionally, in the selection of insulation material, it is important to consider the curing temperature. Rare-earth barium copper oxide (REBCO) conductors, when exposed to high-temperature environments, can experience degradation in the critical current (I_c) of the conductor due to the oxygen diffusion, making coating and curing temperature as a critical parameter. In this paper, defined temperature upper limit to maintain conductor performance is 180 °C.

At KEK, a study for coating HTS tapes with inorganic insulation with a thickness of approximately 20 μm using gel-sol technology was undertaken. As lower heat load due to coating and impregnation can minimize the thermal effects, coating temperature conditions were optimized to 100 °C for 20 min to successfully form a coating on the surface of the REBCO conductors. Subsequently, a small circular double pancake test coil has been developed with the insulated

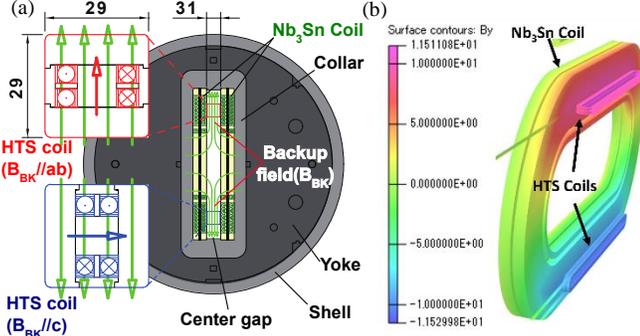


Fig. 1. (a) Schematic view of BNL DCC017 and orientation of HTS test coils. (b) Magnetic field distribution using OPERA 3D FEA.

conductor using the wet winding technique, involving the application of a commercially available ceramic adhesive, Aron Ceramic Type C, sourced from Toagosei Co. Ltd. (curing temperature 150 °C) on the coated tape surface [7]. The small coil showed no degradation in the superconductivity at 77 K. As a next step, it is necessary to realistically verify the feasibility of mineral-insulated coils by testing in varying conditions of temperature, magnetic field, and transport current, this technique was applied to a racetrack coil configuration.

In this study, the focus is on designing, fabricating, and testing mineral insulated HTS coils at 77 K, and upcoming plans of testing these coils in a backup field (B_{BK}) of around 10 T using the DCC017 common coil test facility at Brookhaven National Laboratory (BNL). The DCC017 consists of racetrack coils, operating in series, placed on the left and right of the aperture, producing fields of the same magnitude but in opposite directions as shown in Fig. 1(b). This configuration allows two HTS coils to be tested independently in different orientations (B_{BK} // ab axis and B_{BK} // c axis), as shown in Fig. 1(a) [10][11]. This paper describes the double pancake racetrack coil fabrication using ceramic-coated conductors with a wet winding process and testing at 77 K. The goal is to establish a new HTS coil technology and verify its feasibility.

II. RACETRACK COIL DESIGN

A. Design parameters

To assess the performance of the HTS coils within the confined central space of 31 mm in the DCC017 magnet system, as shown in Fig.1(a), a design featuring a double pancake racetrack-type coil geometry was selected. This design prioritizes compactness, seamless transition between layer 1 and layer 2, and a minimum bending radius of 5.5 mm. The coil configuration is constrained by a maximum outer dimension of 29 mm, leaving a 2 mm gap between the test coil and the DCC017 system. This gap accounts for installation

TABLE I
PARAMETERS OF THE TAPE AND COILS

Parameter	Coil#1	Coil#2	Coil#3
HTS tape width (mm)	4	4	4
HTS tape thickness (mm)	0.16	0.16	0.16
Ceramic Coating each side (mm)	0.025	0.025	0.025
Adhesive thickness each side (mm)	0.05	0.05	0.05
Coating Solution	G92-5	G92-5	G92-5
Layer 1 turns	20	20	21
Layer 2 turns	20	20	20
Turn-turn insulation	OK	OK	OK

tolerances and allows for the incorporation of electrical insulation and mechanical reinforcement.

The final assembly consists of a 323 mm long coil, placed in a stainless steel (SS) support structure with outer dimensions measuring 29 mm x 29 mm x 370 mm.

B. Wire Type and Length

The 4 mm wide EuBCO tapes with a substrate thickness of 50 μm (FESC-SCH04) produced by Fujikura Ltd., are adopted for the insert coil, considering the 5.5 mm bending radius required for the innermost layer of the insert coils. Although Fujikura Ltd. guarantees a minimum allowable bend radius of 10 mm for FESC-SCH04, published data indicates no deterioration in I_c even with a bend radius of 5 mm [12]. Three reels each of 45 m long tape, adequate for winding three coils, were delivered. The conductor average I_c , measured at a temperature of 77 K in a self-magnetic field during factory shipping inspection, was 208 ± 1 A, 202 ± 2 A, and 201 ± 2 A respectively. At KEK, after achieving the target coating thickness ($<50 \mu\text{m}$), spools of insulated tapes were used for fabricating the test coils. The required length for seamless double pancake coils with 20 turns is less than 40 m, as the coil's maximum width including support structure is 29 mm, due to the DCC017 space limitation. Details on the cable and coil are provided in Table I.

The tapes were insulated with G92-5 (Nikken Co. Ltd), a 1:1 sol-gel formulation of SiO_2 and Al_2O_3 . An automated spray process was integrated into the reel-to-reel continuous coating system, and the coating temperature conditions were optimized at 100 °C for 20 minutes. This process resulted in the formation of a 25 ± 4.7 (σ) μm thick ceramic coating over a 40-meter length on both sides of the FESC-SCH04 tapes.

III. FABRICATION OF COIL

A. Coil Winding

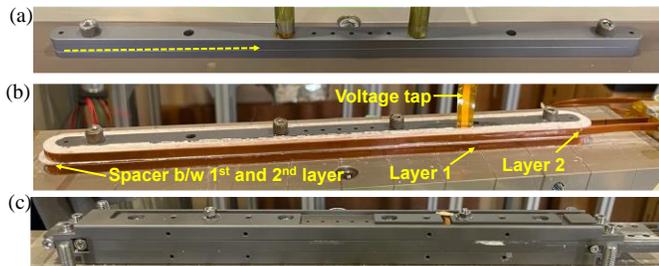


Fig. 2. (a) Photograph of SS central island. (b) details of double pancake racetrack coil with voltage tap and spacer between 1st and 2nd layer. (c) Complete assembly of coil and support structure.

The coil winding is centered on the SS central island, as illustrated in Fig. 2(a). At KEK, a specialized 360-degree rotating platform was devised to facilitate the winding process. Winding of these coils was conducted at a controlled pace, with a speed of 5 turns per hour, regulated manually. A constant tension of 4.5 N was maintained through the application of a controlled feeder machine, including an HTS tape spool securely affixed to the shaft. A wet winding approach was used, with the commercially available ceramic adhesive, the same one used in the small circular coil described in section I. As detailed in Table I, the coated conductor has a thickness of 0.21 mm (0.16 mm HTS tape, and 0.025 mm ceramic coating on each side of HTS tape), with the central SS island measuring 11 mm in width. The average thickness of the first and second layers combined across all coils was approximately 6.1 mm. This resulted in a ceramic adhesive layer of 0.1 mm (0.05 mm on each side of the HTS tape).

While winding in the radial/bending section, it was observed that the ceramic coating slightly peeled from one side (facing outward/substrate side of HTS tape), with no delamination observed on the inner side of the tape (superconductor side). To ensure the integrity of turn-to-turn insulation, the coil resistance was meticulously measured using a four-probe method after every turn.

Three units were fabricated, comprising two units designated for testing in the BNL common coil magnet and one serving as a spare. By employing a uniform manufacturing method for all three units, we aimed to enhance quality control and validate the reproducibility of the manufacturing process.

B. Impregnation and Heat Treatment

Following the completion of the coil winding process, stainless steel side support plates were attached in position. The surfaces of all support parts in contact with the coil, including the central island, were roughened by shot blasting and then coated with a ceramic of the same material as the FESC-SCH04 tape surface.

During this installation, noticeable gaps became apparent between the outermost coil turn and the support plates. To address this, we initially used glass fiber packing within these gaps, followed by the application of the same ceramic adhesive previously used between turns during the wet winding. To ensure thorough filling of leftover voids within the inner layers, excess adhesive is applied. Subsequently, any surplus adhesive was cleaned after the final assembly. Filling

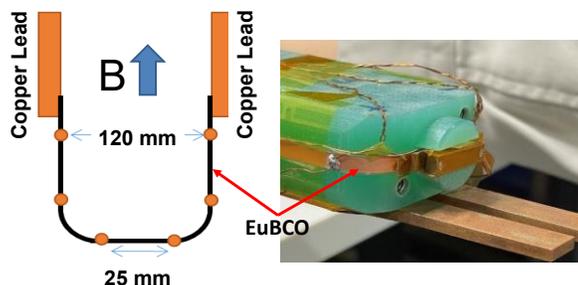


Fig. 3. Detailed schematic of voltage taps and soldered EuBCO sample on the U-shaped sample holder.

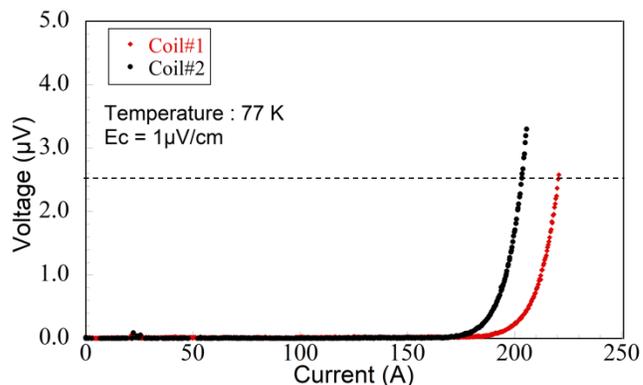


Fig. 4. I-V characteristics of short sample test result at 77 K of spool 1 and 2 used for coil #1 and coil #2 respectively. Voltage tap distance is 2.5 cm.

gaps not only helps to increase the cooling efficiency for conduction-cooled magnets but also helps to reduce the movement of the coil due to electromagnetic forces.

Adhering to the Aron Ceramic Type C adhesive manufacturer's recommendations, the assembled coil was left to naturally dry at room temperature for a duration of 16 – 24 hours. Following this initial drying period, the coil underwent a controlled curing process involving exposure to temperatures of 90 °C for 2 hours and 150 °C for 1 hour, staying well below the allowed upper-temperature limit of 180 °C. Subsequently, the coil was allowed to naturally cool down to room temperature. Following impregnation and heat treatment, the outer dimensions of all three coils were measured, aligning with the maximum allowed margin for the BNL common coil insert slot.

IV. CRYOGENIC TESTING

A. EuBCO tape performance validation

To establish the safe operational parameters for the test coil positioned within the common coil environment with a background magnetic field of 10 T, an assessment of the I_c is imperative. For the performance validation of HTS tapes, samples of 125 mm length were extracted from all three spools of EuBCO conductor, supplied by Fujikura. The length of these test samples is inherently constrained by the limitations within the high magnetic field bore. Within the scope of this study, the samples were soldered onto U-shaped

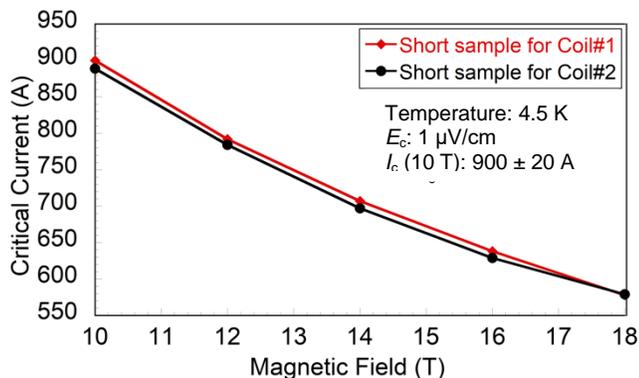


Fig. 5. Critical current as a function of applied external field (B/c).

sample holders, as per [13], with six voltage taps connected to facilitate voltage monitoring across radial and linear segments of the test samples. A schematic depiction of the test setup configuration used at the National Institute for Materials Science (NIMS) 18 T magnet facility is shown in Fig. 3. All samples were tested at the Tsukuba Magnet Laboratory of NIMS under two different temperature conditions: 77 K and 4.2 K. The tests at 77 K were conducted under no external field, and at 4.2 K, the background magnetic field strength varied between 10 T-18 T. I_c measurements were specifically conducted within a 25 mm segment of the sample, aligning the applied magnetic field parallel to the c -axis of the HTS tape.

Adhering the recognized standard, the electrical criterion (E_c) of $1 \mu\text{V}/\text{cm}$ was employed as the benchmark for I_c measurements. The resulting data derived from the 25 mm voltage tap are presented in Fig. 4 and Fig. 5. Notably, the critical current for the wire samples was observed to reach approximately 200 A with a variation of ± 10 A at 77 K, aligning closely with the manufacturer's stipulated test results.

Under the high magnetic field test conditions, I_c at 4.5 K and 10 T exhibited a stable performance, with a critical current of approximately 900 A and a variation of ± 20 A. It is imperative to emphasize the significance of these 10 T results, as they correspond directly to the testing conditions that will be encountered within the BNL common coil configuration, where a background magnetic field generated by the common coil is around 10 T.

B. Coils Testing at 77 K

The cryogenic system used for testing the coil at 77 K was an in-house setup, fully equipped with instrumentation dedicated to measuring crucial parameters such as temperature, resistance, and voltage. To supply power to the coil, an existing power supply system was utilized, consisting of eight units capable of delivering 20 A each, connected in a parallel configuration, thus yielding a cumulative current capacity of 160 A.

Each coil assembly was outfitted with four voltage taps as shown in Fig. 6, two taps to measure the voltage across the seamless transition area are soldered on the innermost turns of the 1st and 2nd layers named as L1_T1_VT and L2_T1_VT, to measure the total coil voltage two taps are soldered on the extended section (20th turn) of the 1st and 2nd layers named as L1_T20_VT and L2_T20_VT respectively. Furthermore,

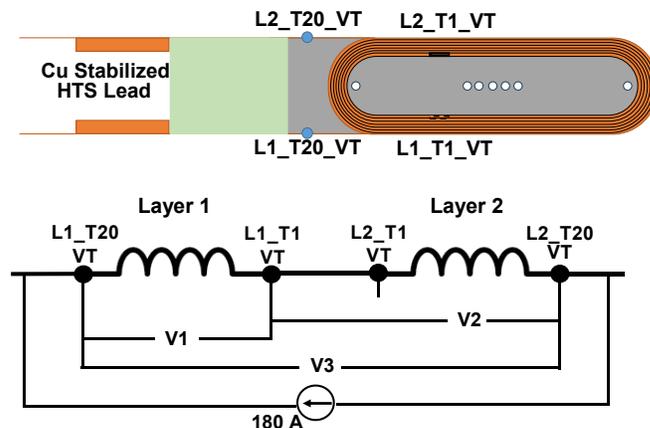


Fig. 6. Test coil schematic and circuit diagram of the voltage taps used for 77 K measurements at KEK.

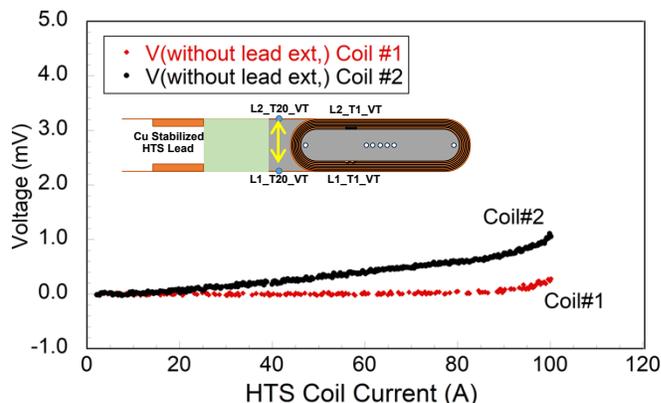


Fig. 7. Voltage as a function of coil excitation current of two test coils in LN2, the voltage is measured 20th turn of Layer 1 and Layer 2.

seven Hall sensors precisely installed along the straight and radial sections, to be used for magnetization measurements at the 4.2 K test in DCC017 at BNL.

Before initiating the cryogenic cool-down process, electrical assessments were conducted on the fabricated coils. During these assessments, the electrical resistance of several megaohms between the conductor and the outer support of the HTS coils was measured by a common multimeter. For ground insulation reinforcement, polyimide tapes are wrapped twice around the surface of the coil units, and 2 mm thick Glass Fiber Reinforced Plastic (GFRP) plates are sandwiched between the support frame for DCC017 installation and the coil units. Furthermore, a GFRP plate was inserted between the support frame and the fixed part of DCC017. There are no direct metal contacts between the coil unit and ground-level fixtures due to the use of GFRP collars on all bolted connections.

The insulation between individual turns was measured during the winding process and post-final assembly, with no noticeable changes in resistance observed. Resistance measurements were consistently monitored throughout the cooldown phase, revealing a continuous decline in resistance for all three coils until it eventually disappeared, indicative of the superconducting behavior at around 90 K.

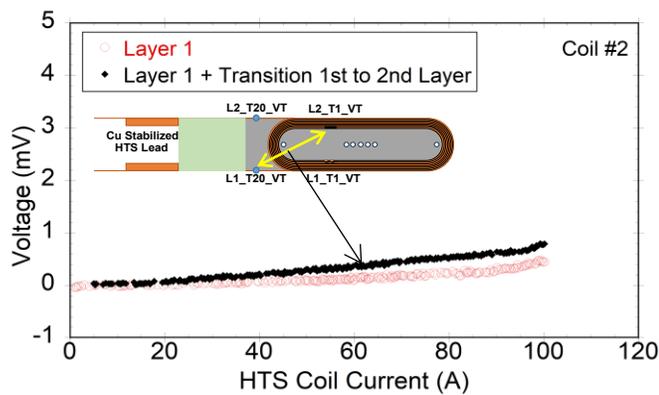


Fig. 8. Influence of the transition region of coil #2 on the overall output voltage.

Following the cooldown, an energization test was executed, incrementally ramping the applied current with ramp rate of 1 A/sec. This incremental current application was performed in 20 A steps, followed by reduction to zero, with this cycle repeating until a clear increase in voltage due to normal conduction transition was confirmed. In one of the three tested coils (spare coil), a current-dependent voltage rises up to 5 mV was observed in the second layer of the coil when current was applied up to 5 A. This suggested that there was a normal conducting part remaining in the coil due to damage caused by the winding or assembly, and the excitation test for that coil was discontinued. Fig. 7 shows the excitation results for coil #1 and coil #2. Signs of a rapid voltage increase corresponding to a clear normally conducting transition are observed in both coils around 100 A. It means that the coil exhibited a 17% reduction in I_c compared to the anticipated value of 120 A.

While coil #1 exhibited good performance, with all sections displaying a healthy state and no evidence of degradation, coil #2 presented a linear rise in output voltage. Further investigation revealed that this behavior was attributed to current sharing within the transition area, the innermost turn transitioning from layer 1 to layer 2, as shown in Fig. 8. The phenomenon of current sharing within coil #2 may impose limitations on the maximum operating current achievable during testing with the DCC017 at BNL.

Potential factors contributing to this degradation include aspects related to the handling and winding process. As detailed in sections I and II, due to space constrain in the DCC017, a small bending radius and twisting between the innermost layers can be major reasons for such damage. This issue is less likely to occur in larger-scale models of the solenoid. To address damages in the transition area, a potential solution involves connecting two single pancakes instead of adopting a seamless transition approach, which may prove effective in future applications. Delamination issues can also be mitigated by avoiding small bending radii. Notably, no delamination issues were observed in small circular coil.

V. SUMMARY AND FUTURE PLANS

In the ongoing research and development of ceramic-insulated radiation-resistant coils utilizing REBCO conductors for future accelerator projects, we have completed the fabrication of seamless double pancake racetrack-type coils through a wet winding process and testing at 77 K temperature

These coils were fabricated using EuBCO conductors coated with ceramic insulation.

To assess the impact of the winding process on the coil performance, we conducted energization at 77 K. This investigation aimed to understand any deterioration resulting from the winding process, particularly considering the differences in geometry between the long racetrack coil with a small bending radius and the previously tested small circular coil. The data collected from these initial tests will be important for upcoming tests at 4.5 K and 10 T at BNL.

The preliminary results of these tests are promising and suggest the feasibility of employing mineral-insulated coils in practical applications. However, a more comprehensive investigation into the performance of these test coils under high magnetic field conditions is crucial before drawing conclusive findings. Excitation tests in the BNL common coil are scheduled for winter/spring 2024.

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