EXPERIMENTAL STUDIES OF HELICAL SOLENOID MODEL BASED ON YBCO TAPE-BRIDGE JOINTS

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ABSTRACT

Helical solenoids that provide solenoid, helical dipole and helical gradient field components are designed for a helical cooling channel (HCC) proposed for cooling of muon beams in a muon collider. The high temperature superconductor (HTS), 12 mm wide and 0.1 mm thick YBCO tape, is used as the conductor for the highest-field section of HCC due to certain advantages, such as its electrical and mechanical properties. To study and address the design, and technological and performance issues related to magnets based on YBCO tapes, a short helical solenoid model based on double-pancake coils was designed, fabricated and tested at Fermilab. Splicing joints were made with Sn-Pb solder as the power leads and the connection between coils, which is the most critical element in the magnet that can limit the performance significantly. This paper summarizes the test results of YBCO tape and double-pancake coils in liquid nitrogen and liquid helium, and then focuses on the study of YBCO splices, including the soldering temperatures and pressures, and splice bending test.

KEYWORDS: Superconducting magnets, Helical solenoid, YBCO tape, Splice.

INTRODUCTION

A muon collider is a new type of particle accelerator speeding up muons that are much heavier than electrons, so the accelerator bends very high energy muon beams in beam lines,
recirculates them in the accelerator and makes them collide to discover new subatomic forces and particles. However the challenge is to reduce the muon beam size in a very short time before muons decay away. For this purpose, the concept for the six-dimensional muon beam cooling was suggested in [1]. It is based on a continuous liquid hydrogen absorber and RF cavities imbedded into superconducting magnets which superimpose solenoid, helical dipole and helical gradient field components. A helical solenoid (HS) is one of the designs that satisfy those field requirements [2]-[3]. To achieve the optimal muon cooling rate, generally the HCC for muon collider is divided into several sections, each section with progressively stronger fields, smaller aperture and shorter helix [4]. The field level in the coil for the last section of the HCC exceeds the limit of Nb$_3$Sn. Besides, the small aperture size restricts the proper thermal insulation in between cavity system at ~33 K and magnet system at ~4.2 K, so to operate both systems at same temperature (liquid H$_2$) is one of the solutions.

Due to these concerns, high temperature superconductor HS has been designed and investigated [5]. YBCO tape was selected as the conductor, with the advantages described in [5]. The nominal $I_c$ at 77 K of SCS12050 YBCO tape from Superpower Inc. is 330 A. Due to the configuration of the HS, bridge joints were introduced into the model fabrication as the coil-coil connections and the power leads. 30%Sn70%Pb with melting point ~183 °C was used as the solder. Three HS double-pancake unit models were fabricated and tested at Fermilab. As a demonstration, a HS short model, including three double-pancake units and two dummy cavity insertions, was assembled and tested at 77K. The test results were summarized [6]. $I_c$ degradation was found in all three units, mainly on the account of the bad performance of the splices. Splice soldering technique is very important to the HS and the splice performance dominants the magnet performance.

In Superpower 2G HTS wire specifications, it is described that the maximum soldering temperature is 250°C, joint resistance is 40~50 nΩ-cm$^2$ and the minimum bend diameter at joint is 25 mm [7]. Joint methods of the 4 mm and 6 mm wide YBCO conductor have been studied recently [8]-[11]. Due to the lamination structure of the YBCO tape, soldering YBCO side to YBCO side will get the lowest joint resistance. There is little temperature dependence, magnetic field and field angular dependence of the joint resistance at 77 K in self-field and at 4.2 K in background field. Bending effects on transport property in lap- and butt- joint methods have been investigated [12]-[13]. Besides the bending radius, bending strain was introduced as the parameter to study the degradation due to bending of the splice. Another interesting research is soldering splices inside the fixtures with different bending diameters [14].

SPLICE PERFORMANCE IN HTS HS MODELS

The HS double-pancake unit model was designed at Fermilab. Such design allows providing a gap between two units to insert cavities and absorber feed throughs [15]. The bridge joints are required as the connection between two coils in one unit model namely inner splice, and between adjacent unit models namely outer splice. The outer splices in the top and the bottom of the magnet serve as the power leads. Splice locations are shown in FIGURE 1. Three unit models were fabricated and tested in liquid nitrogen, and two of them were tested in liquid helium. Three models were assembled with two dummy cavities and tested in liquid nitrogen.
The splices were soldered manually in unit 1. It was tested at 4.2 K and found very large degradation in the inner splices. Therefore, a soldering fixture was utilized to make new splices for unit 1 and all splices for unit 2 and unit 3. The coils for unit 1 were rewound. The splices performance can be monitored separately from the coils, shown in FIGURE 2. The short sample limit (SSL) at 77 K of the double-pancake unit model is calculated as 103 A. Three out of nine splices limited the model performance, and the two outer splices degraded more. The resistance of the splices in the models is shown in FIGURE 3. The resistance in one of the outer splices of unit 1 is much higher than the specifications.

To obtain more reliable splice performance, some fundamental study on splice soldering is required, and the reduction of the bending strain in the outer splices is suggested. In the model, the outer splice is bent around the coil. The coil was wrapped with 5-layer 0.025 mm thick kapton insulation and 15-layer 0.1 mm thick stainless steel bandage, and outside the bandage the coil structure was tightened by some stainless steel wires, so high bending strain may damage the outer splice.

FIGURE 1, Bridge Joints in the Model: Inner and Outer Splices.

FIGURE 2, Splice Performance shown in V-I Curves
BRIDGE JOINT EXPERIMENTAL STUDY

Sample Preparation

The joint samples were made by the soldering fixture that was also used in the fabrication of the HS models, shown in FIGURE 4. Three precise grooves were cut in the bottom aluminum plate, so that the bridge joints were made to fit in the inner splice slot of the HS model. Two grooves (G1-G2 or G1-G3) were used for the outer splice.

In this study, joint method for inner splice was adopted. A piece of YBCO tape is placed inside G1 with YBCO side facing up, serving as the bridge. Another two pieces of YBCO tape are placed inside G2 and G3 with YBCO side facing down. Each joint area is 12 mm by 12 mm. Two pieces of 125 µm thick “ribbon” solder (30%Sn70%Pb) are put in between the joint areas, with both surfaces fluxed. An aluminum press bar with a thermal coupler inserted in a drilled hole is put on top of the joints to monitor the soldering temperature. The pressure is applied via four spring loaded bolts, and the pressure uniformity is adjusted by using Fuji film. The heater is inserted into the top aluminum plate. Once reaching the designated soldering temperature, unplug the heater and cool the fixture by using watered cloth.

Two parameters were controlled to make the joints, listed in TABLE1. Three different temperatures and two different pressure ranges give totally six cases, and for each case at least three joint samples were made and measured.

TABLE 1. Soldering Parameters

<table>
<thead>
<tr>
<th>Variation Number</th>
<th>Temperature (°C)</th>
<th>Pressure Range (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>45–65</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>65–92</td>
</tr>
<tr>
<td>3</td>
<td>275</td>
<td>-</td>
</tr>
</tbody>
</table>
The samples were mounted to the testing probe shown in FIGURE 5. Two copper blocks were pressed to the ends of the sample, and a piece of thin indium sheet was put in between the copper and the tape to reduce the contact resistance. Two pairs of voltage taps
were soldered to measure V-I curve of the two joint areas. The samples were tested in liquid nitrogen bath.

Critical current of each joint was obtained from the V-I curve. The joint resistance $R_J$ is equivalent to the slope of the curve. During the analysis, the V-I curve was modified by subtracting the resistance portion $R_JI$ from the total voltage $V$. The critical current was then determined by extrapolating the transition curve section to the axis of the current $I$, an example shown in FIGURE 6.

Results and Discussion

The $I_C$ measurements of the joint samples are shown in FIGURE 7. The critical currents of four out of sixteen samples soldered under pressure 1 at different soldering temperature (in diamond symbol) are below the nominal $I_C$ line, while the critical currents for all the splices under higher pressure range (in cross symbol) are on or above the nominal $I_C$ line. The critical current decreases a little as the soldering temperature increases from 200°C to 275°C under both pressure ranges. To find the reason for the current drop of the joints soldered under low pressure range, more investigation is needed. The joint resistance is dependent on the soldering temperature, shown in FIGURE 8. The joint soldered at 200°C get the resistance inside or below the specification band. From the result comparisons, the high pressure range and 200°C soldering temperature are the best soldering condition.

The sketch of the joint transverse cross-section is shown in Figure 9. To better understand the factors that may change the joint resistance, the joint resistance is calculated based on each component’s resistance in the joint transverse direction, with the formula shown as follows,

$$R_J = R_{Cu} + R_{Ag} + R_J + R_{c1} + R_{c2} \quad (1)$$

$$R = \rho \frac{t}{A} \quad (2)$$

Where $R_J$ is the joint resistance, $R_{Cu}$ is the resistance of 40 µm copper in between two layers of YBCO, $R_{Ag}$ is the resistance of 4 µm silver in between two layers of YBCO, $R_s$ is the resistance of solder, $R_{c1}$ is the contact resistance inside the conductor including silver to YBCO and silver to copper, and $R_{c2}$ is the contact resistance outside the conductor between copper and solder in (1). $R_{Cu}$, $R_{Ag}$ and $R_s$ can be calculated by (2), where $\rho$ is resistivity, $t$ is thickness and $A$ is joint area.

In the joint samples, $R_{Cu}$ and $R_{Ag}$ are constant and $R_{c1}$ is assumed constant (actually dependent on the quality of the conductor). The joint resistance is now dependent on $R_s$ and $R_{c2}$ that are related to the solder thickness and soldering quality. Solder thickness can be controlled by choosing thinner “ribbon” solder and keep high soldering pressure. Good soldering quality usually relies on the soldering temperature, flux selection, no bulb of trapped air or flux, etc.
FIGURE 7, Joint Critical Current Vs. Temperature and Pressure

FIGURE 8, Joint Resistance Vs. Temperature and Pressure

FIGURE 9, Joint Cross-Section Sketch
CONCLUSION

HS models based on YBCO tape have been demonstrated. The bridge joints in the model limited the model performance. The joint soldering conditions, soldering temperature and soldering pressure, were studied and analyzed. 200˚C soldering temperature and the high pressure range 65–92 MPa were found as the proper condition. The joint resistance decreases as the soldering temperature reduces.

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