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Article

# Experimental investigation of low resistance joints for high field HTS magnets

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**Abstract:** High-temperature superconducting (HTS) tapes are now commercially available for various magnet applications. Their higher tensile strength enhances strain tolerance, allowing for the winding of smaller diameter coils. The most crucial component in a double pancake winding of a coil is the fabrication of inter-double pancake joints with minimal electrical resistance. This is due to the structural design of REBCO (RE—rare earth) tape, which consists of very thin layers of materials prone to deterioration when exposed to temperatures exceeding the recommended value, optimal joint overlap length, and the selection of solder materials. In this study, we investigated the effects of tape overlap lengths, solder materials, and soldering temperatures on joint resistance. The lowest joint resistance recorded was 18 nΩ, achieved with an overlap length of 150 mm at 4.2 K in a self-field, as reported in this paper for a 3.5 T REBCO coil winding pack.

**Keywords:** double pancake winding; HTS REBCO tape; overlap length; joint resistance; solder material

## 1. Introduction

To utilize high-temperature superconducting (HTS) tapes for magnets with double pancake or layer winding configurations, it is necessary to develop the joining techniques for these tapes to optimize the electrical resistance at the joints. HTS tape-based high-field magnets consist of several spiral-wound pancake coils that are electrically continuous on the inner turns, forming a double pancake with two open outer terminals. The outer HTS tape terminal of the first double pancake (DP) is joined to the adjacent double pancake tape terminal using intermediate HTS tapes, with low-resistance solder applied in between to ensure electrical continuity throughout the winding pack. The joining technique for HTS tapes requires a precise joint fabrication process. The foremost requirement before fabricating the joint is the thorough cleaning of the surfaces of the HTS tapes, followed by uniform tinning with low-melting-point solder. Uneven tinning can create voids between the tape surfaces, resulting in increased resistance. Proper cleaning, tinning, and uniform solder wetting on the meeting surfaces of HTS tapes are essential to ensure uniform current transfer and to minimize the electrical joint resistance of the magnet winding pack. Elevated resistance at inter-pancake and inter-layer joints can cause local hotspots within the winding pack, potentially causing thermal quenching of the magnet. Several research groups have investigated both superconducting and resistive joining techniques using silver-sheathed BSCCO (Bismuth Strontium Calcium Copper Oxide) tapes with various joining configurations. We previously reported on experimental studies of different joint configurations for BSCCO tapes

[1,2]. Kim and colleagues [3–5] reported the performance of overlap joints for both superconducting and resistive joining between multi-filamentary BSCCO tapes. Sohn et al. [6,7] and Kar et al. [8] studied the joint resistance between two parallel silver-sheathed BSCCO tapes with different joining configurations. Techniques for joining REBCO tapes were developed by the authors [9–14]. However, there has been limited research on bridge overlap joints between two parallel REBCO tapes. This paper briefly describes various joint configurations in Section 2, material selection and fabrication processes in Sections 3 and 4, experimental details for the joint test setup in Section 5, experimental results in Section 6, advancement & achievement in Section 7, and a summary & conclusion of the test results in Section 8.

## 2. Joint sample description

Two types of joints, namely a) Bridge Overlap Joint and b) Overlap Joint, have been realized using REBCO and Di-BSCCO tapes. The joints were fabricated with overlap lengths of 100 mm and 150 mm. The REBCO tapes were available in two different widths: 4.1 mm and 8 mm, while the Di-BSCCO tapes had a width of 4.4 mm. For the Bridge Overlap Joint configuration, we used two parent HTS tapes, each measuring 220 mm in length. The joining sections consist of additional tapes, measuring 100 mm and 150 mm, placed parallel to the parent tapes to form the bridge joint.

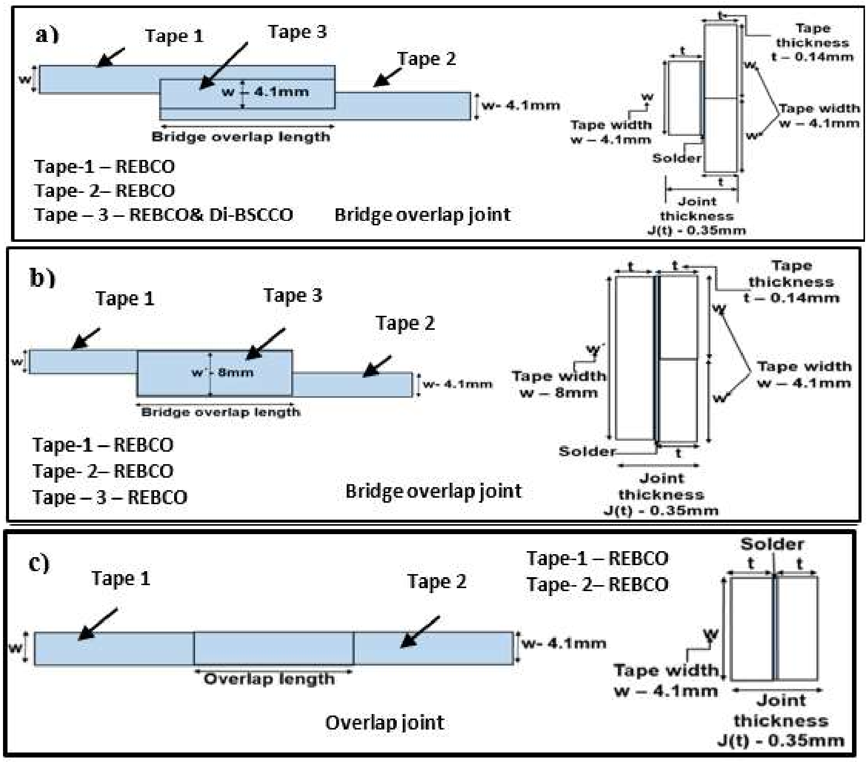


**Figure 1.** Schematic cross-section view of joints **(a)** bridge overlap 4.1 mm REBCO & 4.4 mm Di-BSCCO width of HTS tape; **(b)** bridge overlap 8 mm width of REBCO HTS tape; **(c)** overlap joint 4.1 mm width of HTS REBCO tape.

In the overlap-type joint configuration, the setup involved two parent HTS

REBCO tapes, each measuring 220 mm in length and 4.1 mm in width. However, the joining method differs, focusing on the direct overlap joining of these tapes. The schematic and cross-sectional views of the joints are shown in **Figure 1a–c**. **Figure 1a** illustrates the bridge overlap joint using a 4.1 mm wide REBCO tape and a 4.4 mm wide Di-BSCCO tape. **Figure 1b** represents the bridge overlap joint with an 8 mm wide REBCO tape only. **Figure 1c** presents the overlap joint with a 4.1 mm wide HTS REBCO tape. All types of joints were fabricated and characterized for the purpose of developing 1T and 3.5T HTS REBCO-based double pancake winding solenoid magnets.

## 3. Material selection for joint fabrication

The joint fabrication process includes a) HTS tapes, b) solder materials, and c) soldering flux. To optimize joint resistance to below 100 nΩ for high-field magnets, various joint trials were conducted using different HTS and solder materials. The technical parameters of the HTS tapes and solder materials used in the joint fabrication trials are explained in the following sections.

### 3.1. REBCO tape

The technical parameters of the REBCO superconducting tape of transition temperature ($T_c$) 90 K were procured from SuNAM, South Korea. **Table 1** & **Figure 2** show the technical specifications and the cross-section micrograph of this tape.

**Table 1.** Technical specification of REBCO tape.

| Sr.# | Parameter | Value |
|---|---|---|
| 1 | ThicknessofREBCO tape ($t$) | 0.14 mm |
| 2 | Width ($w$&$w'$) ofREBCO tape | 4.1 & 8 mm |
| 3 | Silver layer thickness | 2.40 µm |
| 4 | Substrate layer thickness | 104 ± 4 µm |
| 5 | Copper stabilizer layer thickness | 20 µm |
| 6 | Critical current | >200 A @ 77 K,self-field |

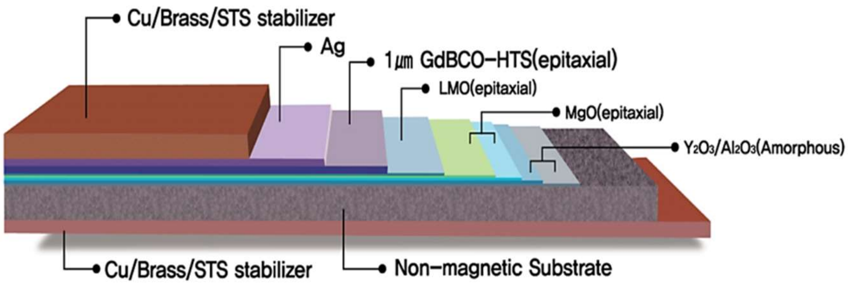


**Figure 2.** Cross-sectional view of REBCO tape.

### 3.2. Di-BSCCO tape

Di-BSCCO superconducting tape with a critical temperature of 110 K was procured from Sumitomo Electric Industries and fabricated using the standard powder-in-tube (PIT) method. The tape contains 61 filaments and has a silver-to-superconductor ratio of 1.5:1. The dimensional details of this tape are presented in

**Table 2**, while the cross-sectional view and optical image are shown in **Figure 3**.

**Table 2.** Technical specification of HTS Di-BSCCO tape.

| Sr.# | Parameter | Value |
|---|---|---|
| 1 | Thicknessof Di-BSCCO tape (*t*) | 0.340 mm |
| 2 | Width of Di-BSCCO tape (*w*) | 4.4 mm |
| 3 | Average thickness ofDi-BSCCO substrate filament | 17 μm |
| 4 | Thicknessofsolder | 23 μm |
| 5 | Thicknessofcopper alloy | 56 μm |
| 6 | Critical current | 160 A @ 77 K,self-field |

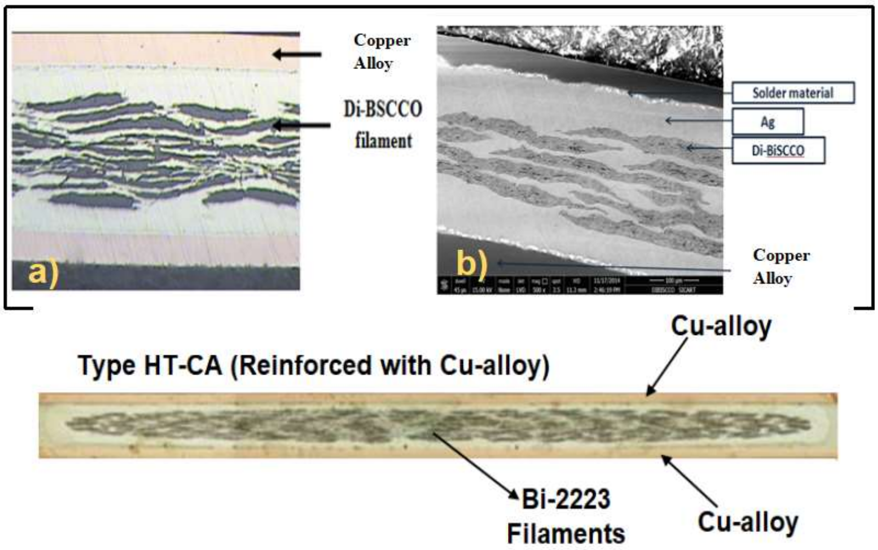


**Figure 3. (a)** Optical image; **(b)** SEM image of HTS Di-BSCCO tape.

### 3.3. Solder material

Two different types of solder materials were used for joint fabrication trials: 1) Pb-Sn (60:40) and 2) indium foil with different flux materials [15]. The melting point of Pb-Sn solder is 188 °C, while that of indium foil is 156 °C. During the joint fabrication process, the temperature was maintained below 200 °C to prevent degradation of the HTS tape. The technical parameters of the solder materials are shown in **Table 3**.

**Table 3.** Technical parameter of used solder material.

| Solder material | Pb-Sn (60:40) solder foil | Indium foil |
|---|---|---|
| Melting point | 183–190 °C | 156.6 °C |
| Thermal conductivity | ~50 W/m·K | 86 W/m·K |
| Electrical resistivity @ RT | $16 \times 10^{-8}$ Ω.m | $10\times 10^{-8}$ Ω.m |
| Electrical resistivity @ 77K | $3.7 \times 10^{-8}$ Ω.m | $1.8\times 10^{-8}$ Ω.m |
| Electrical resistivity @ 4.2K | $0.2 \times 10^{-8}$ Ω.m | - |
| Flux compatibility | Rosin based flux | TIX flux (Zinc chloride and ammonium chloride based) |

## 4. Joint fabrication process

Bridge overlap and overlap joints have been fabricated using Di-BSCCO and REBCO tapes. The bridge overlap type joints were created with various overlap lengths of 110 mm and 150 mm, while the overlap type joints were made with an overlap length of 150 mm to maximize the contact area between the interconnecting tapes. To fabricate the joints, Pb-Sn solder (60% lead and 40% tin) with a melting point of 188ºC and indium foil with a melting point of 156 ºC were utilized in the joining process of the tapes. Joints were prepared both with and without copper alloy sheath material, which was removed through mechanical etching from the surface of the HTS Di-BSCCO tape. The step-by-step fabrication processes for both types of joints are mentioned below.

### 4.1. Bridge overlap joint

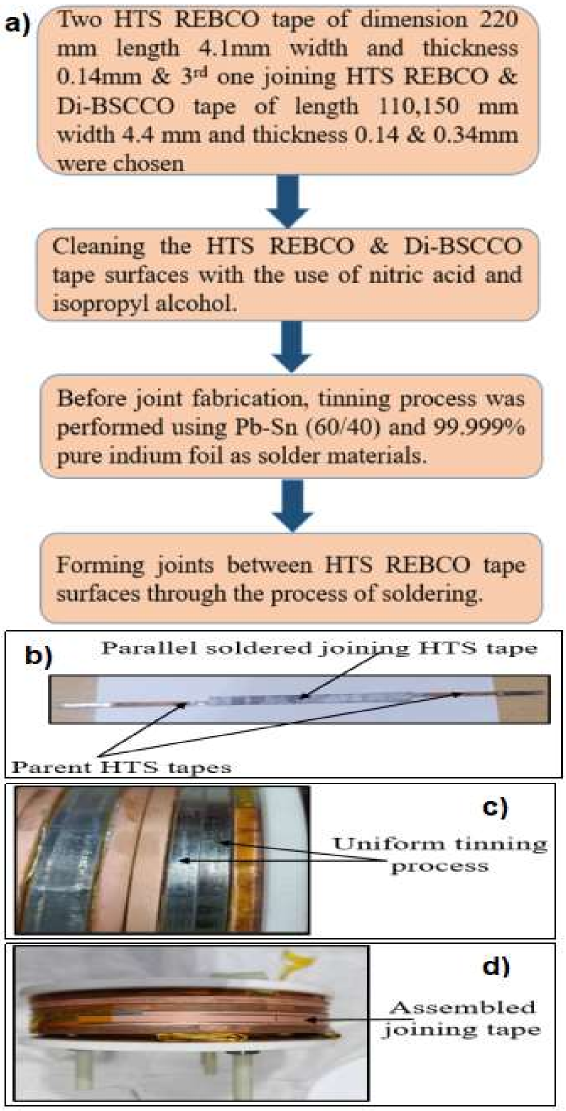


**Figure 4. (a)** Work flow chart for bridge overlap joint fabrication process; **(b)** lab-scale trial of bridge overlap joint; **(c)** uniform solder tinning on HTS tapes and **(d)** implementation of joints on magnet winding packs.

The bridge overlap joints have been fabricated using Di-BSCCO and REBCO tapes. Before the fabrication of the joints, the surfaces of the high-temperature superconducting (HTS) tapes were cleaned with nitric acid and isopropyl alcohol. Nitric acid is used to remove the copper oxide layer from the surfaces of the REBCO tape. The presence of this oxide layer can result in non-uniform tinning of the HTS tape surfaces, and uneven tinning may create voids between the tape surfaces, leading to increased resistance. Several trials of this kind of joint, with varying overlap lengths and solder materials, were performed for the feasibility of DP-type magnet winding. The workflow chart for joint fabrication and photographs of these joints are shown in **Figure 4a–d**.

## 4.2. Overlap joint

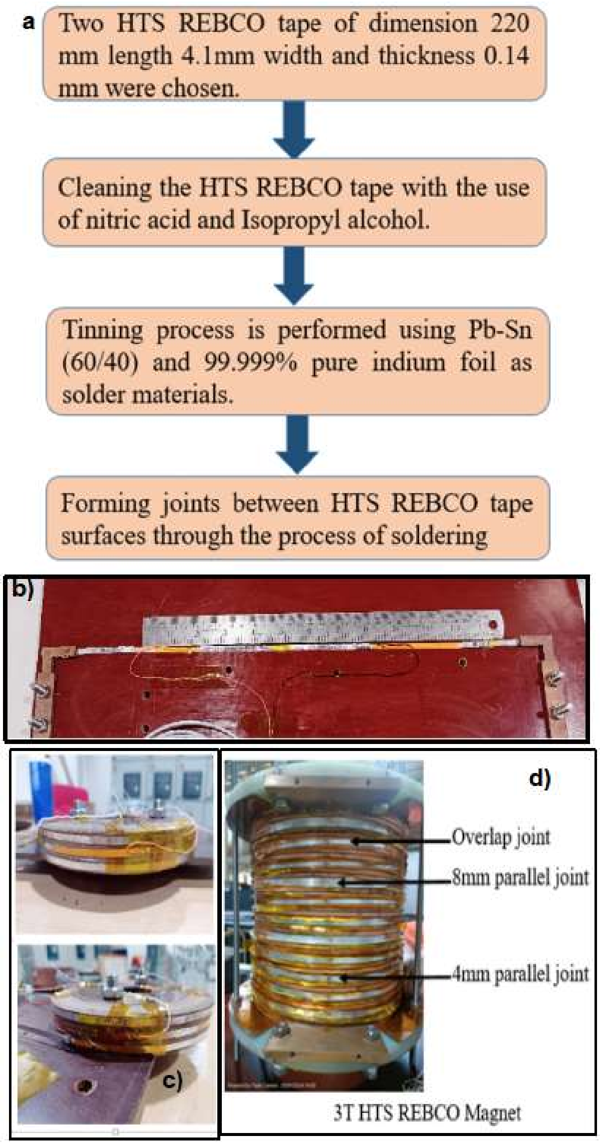


**Figure 5. (a)** Work flow chart for overlap joint fabrication process; **(b)** lab-scale trial of joint; **(c)** bending test of lab-scale fabricated joints; **(d)** implementation of joints on magnet.

The overlap joints have been fabricated using REBCO tapes. These types of joints were also prepared by Huang et al. [16] with varying overlap lengths. In REBCO conductors, one side is superconducting while the other is non-superconducting. During the fabrication of double pancakes (DPs) for a 3.5 T magnet, we observed that the upper side of some DPs is superconducting, while others have a non-superconducting upper side. During the stacking of DPs for this winding pack, inter-DP joints were prepared on the superconducting side of the REBCO tapes. This approach resulted in lower joint resistances, which are essential for the reliable operation of superconducting magnets. The schematic diagram and photographs of this type of joint are shown in **Figure 5a–d**.

## 5. Description of joint test setup

To measure the joint resistances of different configurations at various temperatures, current-voltage (I–V) characteristic curves were obtained at 77 K, 64 K, 55 K, & 4.2 K. Lower temperatures of 64 K and 55 K were obtained using sub-cooling of liquid nitrogen at reduced pressure, which is not the subject of this paper, but it is discussed in reference [17]. I–V characteristics of joints were obtained at 4.2 K using liquid helium. The standard four-probe method was used to measure I–V characteristics of joints. American Magnetics Inc. (AMI) current source and Keithley Nano Voltmeter were used for voltage measurement for this experiment. The block diagrams for the experimental setup are shown in **Figure 6**. The joint resistances of joints have been estimated from the slope of the I–V characteristic curves.

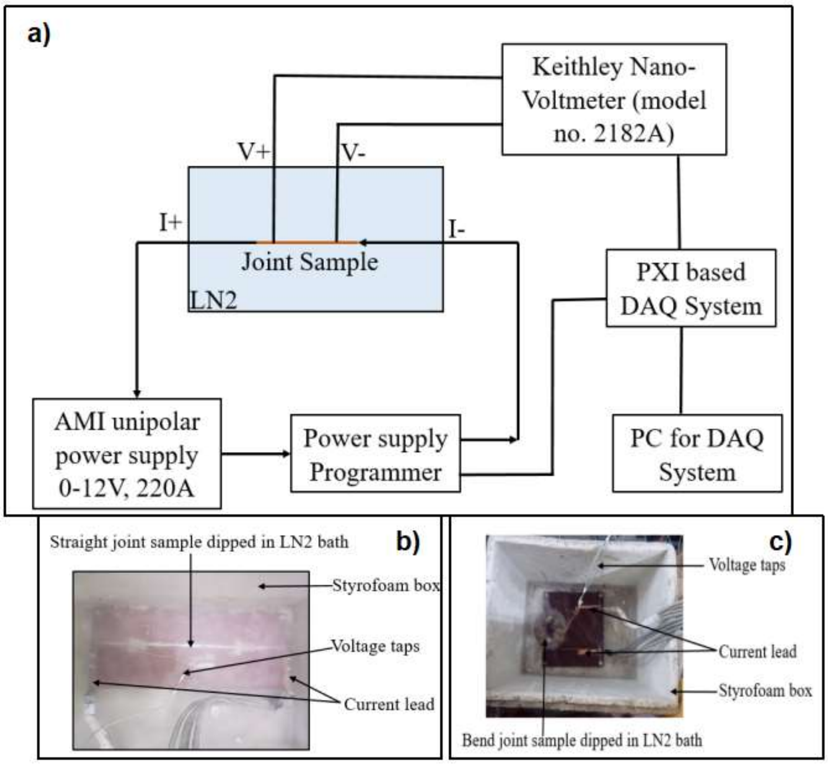


**Figure 6. (a)** Block diagram of experimental set-up; **(b)** testing of straight sample; **(c)** testing of bend sample.

## 6. Experimental result

The experimental results of bridge overlap and overlap joints are described in subsequent sections.

### 6.1. Bridge overlap joint

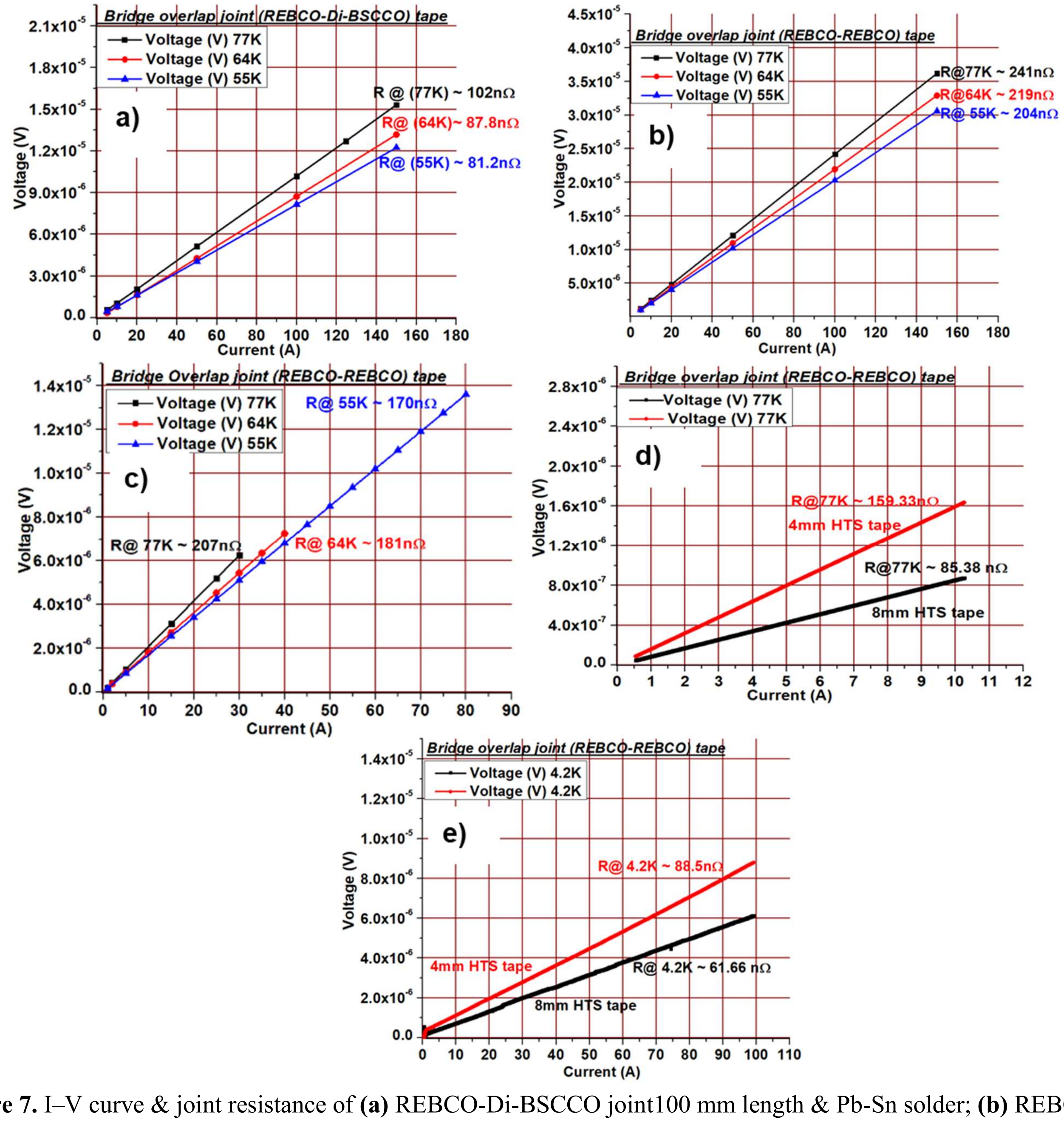


**Figure 7.** I–V curve & joint resistance of **(a)** REBCO-Di-BSCCO joint100 mm length & Pb-Sn solder; **(b)** REBCO-REBCO joint with 100 mm length & Pb-Sn solder; **(c)** REBCO-REBCO joint with 150 mm length & Pb-Sn solder; **(d)** REBCO-REBCO joint with 150 mm length & indium foil at 77K; **(e)** REBCO-REBCO joint with 150 mm length & indium foil solder at 4.2K.

**Figure 7a–d** illustrates the I–V curves for the bridge overlap joint. I–V characteristics exhibit linear behavior with transport currents below the critical current of the HTS tape. Initially, we attempted to fabricate a joint between REBCO and Di-BSCCO tapes with an overlap length of 110 mm, achieving a joint resistance of approximately 102 nΩ at 77 K. However, due to the magnetic field limitations of the HTS Di-BSCCO tape, we decided to conduct further trials using REBCO-REBCO HTS tapes, exploring different overlap lengths of 110 mm and 150 mm to reduce the joint resistance to below 100 nΩ. To achieve this, we explored the use of indium solder, which was chosen for its superior electrical properties. Indium solder has a lower electrical resistivity compared to conventional Pb-Sn (lead-tin) solder, making it a more effective material for minimizing joint resistance. **Figure 7a**,**b** indicate the REBCO-Di-BSCCO and REBCO-REBCO joints with Pb-Sn solder of length 110 mm. **Figure 7c** indicates the REBCO-REBCO joint with an overlap length of 150 mm and Pb-Sn solder, and **Figure 7d**,**e** REBCO-REBCO joint with an overlap length of 150 mm and indium solder. In **Figure 7c**, the joint resistances were measured at different current levels, taking into account the limitations of the magnet operating current at varying operating temperatures. As the magnet's operating temperature increased, the allowable operating current decreased. This type of joint has also been fabricated with 1T and 3.5 T magnet winding packs and DPs and successfully tested without any kind of degradation.

### 6.2. Overlap joint

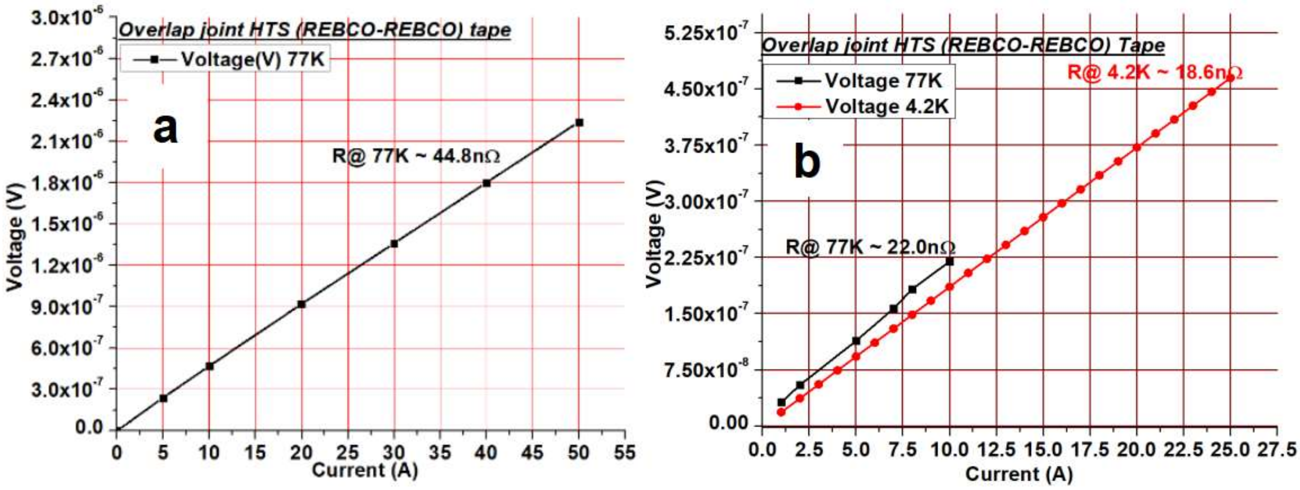


**Figure 8. (a)** I–V curve and joint resistance of overlap joint with indium foil solder; **(b)** I–V curve and joint resistance of Overlap joint with Pb-Sn foil solder.

**Figure 8** illustrates the current-voltage (I–V) curves of the overlap type joint resistance in joint configuration 2. I–V characteristics exhibit a linear behavior with transport current below the critical current of the tape. In this joint configuration, we conducted a trial with a 150 mm overlap length for REBCO-REBCO joints using different solder materials. **Figure 8a** indicates the joint between REBCO-REBCO with an overlap configuration, and the overlap length is 150 mm with Pb-Sn solder material at a 77 K temperature. The trials were initially performed on a lab scale, achieving a joint resistance of about 45 nΩ. Subsequently, the same joint configuration was tested using a different indium foil solder material, which reduced the joint resistance to around 22 nΩ at 77 K. Both trials were also tested under bending conditions (with a bending diameter of 160 mm) before implementing this type of joint on a high-field superconducting magnet. There was no degradation in joint resistance when tested with a bend condition. **Figure 8b** indicates the I–V curve for the REBCO-REBCO overlap joint configuration at 77 K and 4.2 K. In **Figure 8b**, the joint resistance was measured at different current levels, taking into account the limitations of the magnet's operating current at varying temperatures. The different results with different HTS and different joining materials are shown in these figures. This kind of joint has also been made in 1 T and 3.5 T magnet DPs and successfully tested without any kind of degradation in the performance.

## 7. Advancement and achievement

The joints in a superconducting magnet play a crucial role in its desired operational performance. Higher inter-pancake joint resistance may lead to quenching during current ramp-up/ramp-down and even at the flat-top while attempting the steady-state operation of a superconducting magnet. The nano-Ohm range joint resistance within the winding pack at the operating temperature ensures the cryostable operation of a superconducting magnet. In the present work, an attempt has been made to achieve nano-Ohm joint resistance per joint with 1 T and 3.5 T REBCO HTS coils. The overlap REBCO tape joint parameters optimization, right from sample to functional tests, is reported in this manuscript. The design, fabrication, and testing of these joints were driven by several factors, such as soldering material selection, soldering temperature, overlap length, tape orientation, and in-situ fabrication with the HTS coil winding packs. The meticulous joint fabrication process optimization, HTS tape surface modifications, joint length optimization for magnet winding pack, material selection, and soldering temperature to achieve an optimal joint resistance of ~18 nΩ are the major achievements highlighted in this manuscript.

## 8. Summary and conclusion

In this study, various trials of resistive joints were conducted with the aim of optimizing the joint resistances of inter-DP joints of 1 T and 3.5 T winding packs. A summary of test results is presented in **Table 4**.

**Table 4.** Summary of result for different trialsjoints.

| Sr. No. | Used HTS tape | Joint configuration | Joint length (mm) | Joining material | Temperature (K) | Joint resistance (nΩ) |
|---|---|---|---|---|---|---|
| 1 | REBCO-Di-BSCCO | Bridge overlap joint | 110 | Pb-Sn solder foil | 77K<br>64 K<br>55K | 102<br>87<br>81 |
| 2 | REBCO-REBCO | Bridge overlap joint | 110 | Pb-Sn solder foil | 77K<br>64 K<br>55K | 241<br>219<br>204 |
| 3 | REBCO-REBCO | Bridge overlap joint | 150 | Pb-Sn solder foil | 77 K<br>64 K<br>55 K | 208<br>182<br>170 |
| 4 | REBCO-REBCO | Bridge overlap joint (4.1mm tape) | 150 | Indium solder foil | 77K<br>4.2 K | 158.3<br>88.5 |
| 5 | REBCO-REBCO | Bridge overlap joint (8 mm tape) | 150 | Indium solder foil | 77 K<br>4.2 K | 85.8<br>61.66 |
| 6 | REBCO-REBCO | Overlap joint | 150 | Pb-Sn solder foil | 77 K | 44.8 |
| 7 | REBCO-REBCO | Overlap joint | 150 | Indium solder foil | 77 K | 22 |
| 8 | REBCO-REBCO | Overlap joint | 150 | Indium solder foil | 4.2 K | 18.6 |

In the present study, we investigated overlap & overlap bridge joint configurations and fabrication processes using different joining materials. Mechanical etching was employed to remove the oxidized layer from the copper sheath of the HTS tape, resulting in a reduction of joint resistance. The reductions in joint resistances were further enhanced by increasing the joint overlap lengths, pre-tinning of tape terminations, and indium solder for final joining at optimal temperature. The optimal joint parameters reported in this manuscript may be valuable inputs to researchers and the scientific community working on the development of HTS magnets for various applications.

**Author contributions:** Conceptualization, AB, PR and UP; methodology, AB and PR; software, AB; validation, AB, UP and PR; formal analysis, AB and PR; investigation, AB, UP, PR, NK and AP; resources, AB, PR, NK, AP, BP, PV and UP; data curation, AB; writing—original draft preparation, AB; writing—review and editing, AB, PR and UP; visualization, AB and PR; supervision, UP; project administration, UP, PR and AB. All authors have read and agreed to the published version of the manuscript.

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**Conflict of interest:** The authors declare no conflict of interest.

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