Lap Joint Resistivity and Crossover Resistance of REBCO Conductors and Coils

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***Abstract*—During the NHMFL 32 T magnet project, a program to develop a reliable method for making soldered lap joints between REBCO tape conductors was initiated. A standard process was adopted during the program, and then applied during coil fabrication and for quality control (QC) of incoming conductor. For each unique REBCO conductor piece procured for the 32 T project, a lap solder joint was made using the standard process and tested for resistance in liquid nitrogen. A total of 211 lap joints were made and tested. For the NHMFL 40 T magnet project, a similar study was performed using the same standard process on conductors procured for test coils. A total of 38 lap joints were made and tested. Results from both data sets are reported, and compared with findings from the initial study and published findings by others. In the stacked double-pancake construction adopted by the NHMFL for REBCO coils, each double-pancake is connected in series to adjacent modules with a crossover connection, made from an assembly of several REBCO tapes placed in parallel and soldered across the terminal ends of each adjacent module. Resistances of the crossovers in a 32 T test coil and from test articles and test coils made during the 40 T project, are reported here. The resistivity of the crossovers is estimated and compared with the findings from the lap joint measurements.**

***Index Terms*—Resistance, superconducting magnets, solder joint, YBCO coated conductor.**

I. Introduction

METHODS and materials for fabricating soldered lap joints from REBCO coated conductors have been thoroughly studied. The effects of magnetic field magnitude, orientation, applied mechanical stress, operating temperature and process temperature have also been investigated [1]–[9]. Findings from these efforts have informed the lap joint fabrication process standardized by the NHMFL [5]–[7], [9]. For the 32 T and 40 T magnet projects at the NHMFL, this standard process is used for quality control specimens, and for lap joints within coil windings. In Section II, the data and descriptive statistics from quality control (QC) specimens are presented. In Section III, the method adopted by the NHMFL for connecting adjacent REBCO double-pancake modules to form a complete coil assembly is described. These ‘crossover’ connections are made with a process similar to that used for lap joints. Resistance data from several tests are presented.

The 32 T magnet has 54 crossovers. A 40 T magnet could have ∼130 crossovers. The crossovers are likely to be the dominant heat load in a REBCO coil made with stacked double-pancakes. Findings reported here can inform heat load estimates for future REBCO coils.

The conductors used for the 32 T and 40 T projects is made by SuperPower, type SCS4050, with a 50 μm substrate thickness with 20 μm copper electroplate on the outer surfaces. The conductor is described in [10].

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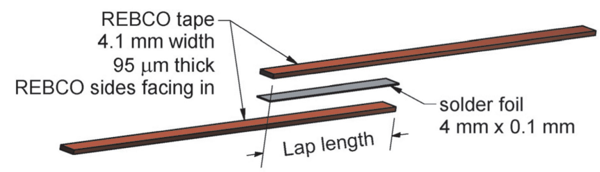

Fig. 1. Schematic lap joint configuration. Tape thickness not to scale.

II. Lap Joint Resistivity

A. Lap Joint Fabrication

To make the lap joint QC test specimen shown schematically in Fig. 1, a pair of REBCO tapes are cut to length, assembled into an aluminum fixture fitted with cartridge heaters and a thermocouple. Rosin solder flux is applied to both REBCO surfaces, and a 0.001” [0.025 mm] thick X 4 mm width foil of Sn63/Pb37 solder is placed between the tapes. The tapes are placed so the REBCO layers face one another. The fixture is mechanically compressed to 35 MPa, and then heated to 195°C for one minute, and then cooled with forced air to room temperature, while under compression. The lap joint is then removed, cleaned with alcohol to remove excess flux, and then set aside for testing.

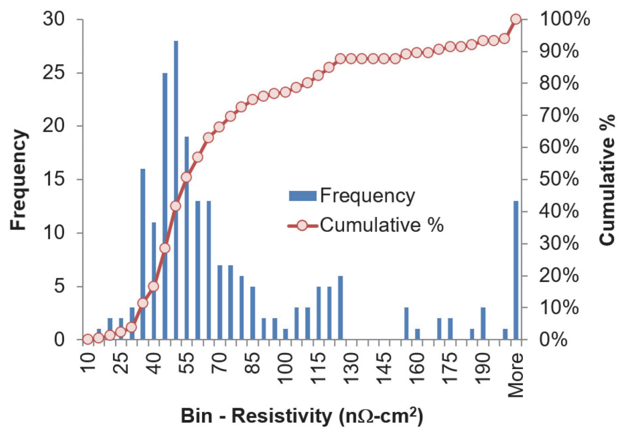

Fig. 2. Histogram of 32 T QC lap joint resistivities.

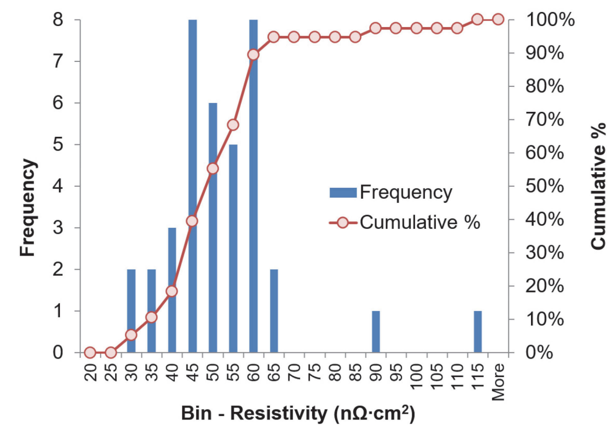

Fig. 3. Histogram of 40 T QC lap joint resistivities.

B. Lap Joint Test

Each lap joint is placed into a fixture fitted with electrical terminals and voltage taps, and then cooled in liquid nitrogen. Current is supplied to the terminals, and ramped from zero to the critical current of the tapes. The voltage across the lap joint taps and the current are recorded. After the test, the voltage and current data are post-processed by fitting the data to the model given in Eq. 1:

$$V(t) = R_{lap\ joint} \cdot I_{op}(t) + V_c \left(\frac{I_{op}(t)}{I_c} \right)^n \quad (1)$$

Where:

$V(t)$ and $I_{op}(t)$ are the measured voltage and current

V_c is the voltage at critical current, equal to $\frac{1\ \mu V}{cm}$ multiplied by the distance between voltage taps

$R_{lap\ joint}$ is the lap joint resistance

I_c is the critical current

n is the resistive transition index, or n-value

The resistance, critical current and n-value are found by least-squares fit.

The resistivity of a lap joint is the product of the resistance and the contact surface area, given in Eq. 2

$$\rho_{lap\ joint} = R_{lap\ joint} A_{lap\ joint} \quad (2)$$

Where:

$A_{lap\ joint}$ is the lap joint area, the product of the conductor width and lap joint length.

C. Findings

For the 32 T project, a total of 211 lap splices, each 80 mm in length, were made for quality control measurements of incoming conductor. For the 40 T project, a total of 38 lap splices, 120 mm in length, have been made at the time of writing. More data will be accumulated over the life of the project. Histograms of both the 32 T and 40 T data are shown in Figs. 2 and 3.

Descriptive statistics, and a comparison with published findings by others are given in Table I.

TABLE I
LAP JOINT RESISTIVITY (nΩ·cm²)

Data ref	Count	Min	Max	Median	Mean	Standard deviation
32 T 2013	211	13.8	345	54.7	78.9	62.5
40 T 2021	38	25.7	110	47.9	50.0	15.0
Lu 2011 [5]	8			98.0	113.4	78.2
Fleiter 2017 [8]	3			40.2	40.7	1.8

Fig. 4. Crossover laminate with 5 REBCO conductors soldered to copper foil.

The histogram of the 32 T data indicates that 80% of the observations were < 110 nΩ·cm². The largest bin was in the range of 45-50 nΩ·cm², with 28 observations. There were a relatively large number of outliers, 26 out of 211 total, that were above 125 nΩ·cm².

For the 40 T findings to date, the histogram indicates that 95% of the observations were < 65 nΩ·cm², with most observations between 45-60 nΩ·cm².

III. Crossover Resistance

A. Configuration

The method for construction of REBCO coils adopted by the NHMFL for the 32 T and 40 T projects is to wind double-pancake modules, and then stack the modules onto a mandrel and join the modules together with a 'crossover' connection at the outer diameter. Each crossover is a laminate of copper foil and REBCO conductor, pre-soldered in a fixture. An example is shown in Fig. 4. The laminate is then soldered to the outermost turns of adjacent double-pancake modules, as shown in Fig. 5.

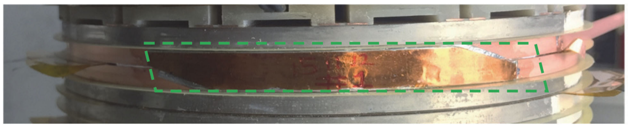

Fig. 5. Crossover connection, after soldering into place to join adjacent double-pancake modules, highlighted by a dashed line.

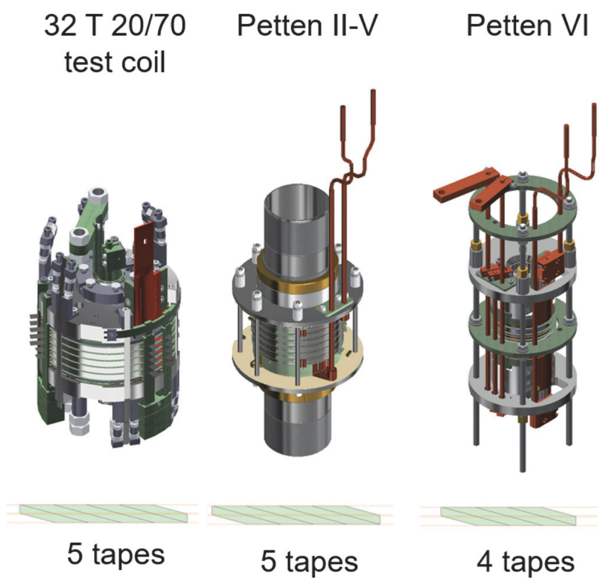

Fig. 6. REBCO test coils, with crossover configurations used represented below each coil.

The process for forming the lamination and soldering the laminate to the coil uses the same solder, flux, solder temperature and duration as for lap joints. Compression of the crossover joint during soldering is not controlled as it is for lap joints.

B. Tests

1) Coil Tests, In-Situ: Crossover resistances were determined from transport current and voltage across each crossover during testing of the 32 T '20/70' test coil [7] and during testing of 5 test coils, designated 'Petten II' through 'Petten VI' during the 40 T project. The test coils were made with 6 REBCO double-pancake modules, and had 5 crossovers each. The 32 T '20/70' coil and the first 540 T test coils had crossovers with 5 tapes. The 6th 40 T test coil had crossovers with 4 tapes. The coil tests were performed at 4.2 K. The 32 T test coil was tested in a 15 T background field. The test coils for the 40 T project were tested in a 7 T background field. Coils and the crossovers used in them are shown in Fig. 6.

2) Test Articles: Two small-scale crossover tests were done at the NHMFL for the 40 T project. The test articles, and the crossover configurations tested are shown in Fig. 7.

The first test was initially conceived to evaluate options for solder, flux, process variables, and to train personnel. For this paper, only the data from crossovers made using the process

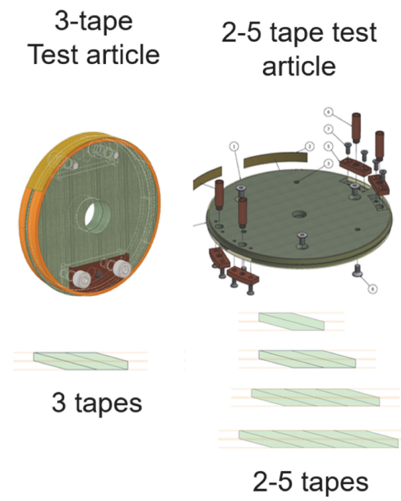

Fig. 7. Crossover test articles, with crossover configurations shown below each.

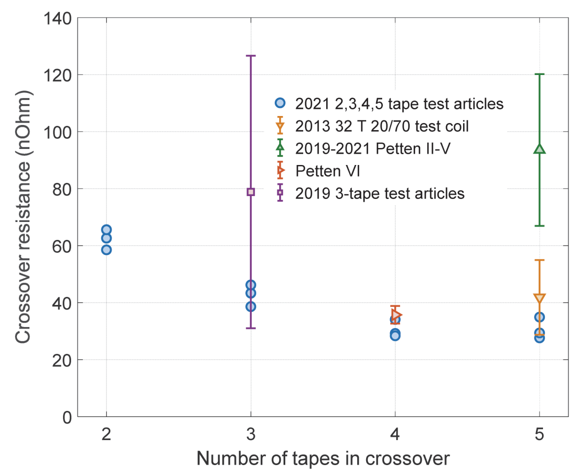

Fig. 8. Comparison of crossover resistances vs. number of tapes for NHMFL REBCO test coils and test articles. The data points with error bars represent the mean and standard deviation of the data from the test.

described in Section III.A are reported, to enable a valid comparison. The test article was a 50 mm dia. former that held 2 tapes and terminals with a crossover mounted between the tapes.

The second test was to assess the impact of the number of REBCO tapes used in a crossover. As with the first test, the process and materials are standardized, and described in the previous sections. A 140 mm dia. former was used. Crossovers were made with 23,4 or 5 tapes, in sets of 3.

Both small-scale tests were performed at 77.4 K at self-field. The same voltage-current fit described in Section II.B was applied to the data to find the resistance.

A direct comparison of the crossover resistances is made in Fig. 8 , with the assumption that the resistivity does not depend strongly on magnetic field and temperature [5].

3) Findings: Results from the coil tests and from first small-scale test with 3-tape crossovers are graphed in Fig. 8 with the mean values and error bars of +/− one standard deviation of

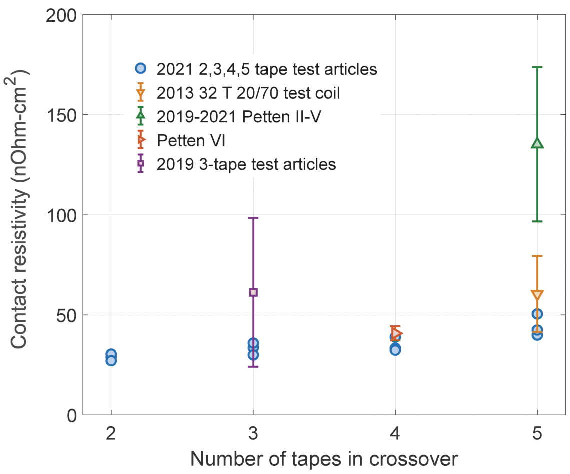

Fig. 9. Comparison of crossover resistivities vs. number of tapes for NHMFL REBCO test coils and test articles. The data points with error bars represent the mean and standard deviation of data from the test.

TABLE II
CROSSOVER CONTACT SURFACE AREA

Number of tapes in crossover	Contact surface area (cm^2)
2	1.88
3	3.11
4	4.35
5	5.58

the resistance. The data for the 2-5 tape test articles are plotted directly. Results for crossovers with 2-4 tapes indicate reasonable agreement, and indicate an inverse relationship between resistance and the number of tapes. When 5 tapes are used in a crossover, however, the resistance does not follow the same trend, and tends to be higher.

An estimate of the resistivity of the crossovers is made using the same definition as for lap joints given in Eq. 2. The resistivity is the product of half of the crossover contact surface area and half of the total resistance. The crossover contact surface areas given in Table II include both contact faces of the crossover.

IV. DISCUSSION

A large data set has been gathered for soldered lap joints made with SuperPower REBCO tapes, both for the NHMFL 32 T and 40 T magnet projects. Data for the 40 T tapes show both lower average resistivity and standard deviation than for the 32 T tapes.

The resistivity of the crossovers compare reasonably well with the resistivity of the lap joints. Crossovers made with 5 tapes tend to be higher resistance than crossovers made with 4 tapes. The resistivity increases with the number of tapes. This is inconsistent with the expected result that the resistivity should be roughly constant. One possible reason for this is that more heat may be required to solder a 5-tape crossover to the coil, resulting in minor degradation of the REBCO. Another possibility is that the current distribution in the crossovers may not be uniform, and screening currents may be induced in the under-utilized REBCO.

V. CONCLUSION

Results from the lap joint quality control tests for the NHMFL 32 T and 40 T magnet projects are reported. Results from several tests of coil crossover connections performed by the NHMFL are reported. The results reported here may be used to estimate the heat load for future REBCO double-pancake coil designs, and to compare against results from future coil tests.

For the 40 T project, more lap joint QC tests are expected, and more test coils are planned. Data from these tests will continue to be accumulated to improve estimates of heating during operation.

Future work with these data include an investigation of the impact of temperature and magnetic field on the predicted resistivity [5], [8], [11].

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