REBCO Soldered Lap Joint Resistance Versus Length and Tape Manufacturer

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***Abstract*—REBCO high-temperature superconductor tapes are made in piece lengths too short for many complete devices such as high-field solenoid magnets, cables, fault limiters, etc. In-line splices are required, and soldering is the preferred method of fabrication. The resistance and contact resistivity of such lap joints is a topic of ongoing investigation. To date it is well understood that the resistance of a soldered REBCO lap joint depends inversely upon the length of the joint in the range practical for devices. It is also well understood that the dominant contributor to the resistance of a lap joint is the interface resistance between the REBCO conductor and its applied silver coating. This property could differ by manufacturer. In this study, a direct comparison is made by fabricating lap joints with REBCO tape from several manufacturers in a range of lengths and measuring the resistance.**

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

I. Introduction

THE resistance and resistivity of soldered REBCO lap joints has been studied extensively since REBCO tape has been commercially available. [1], [3], [4], [5], [6], [7], [8], [9], [10], [12], [13] Notably, [3] presents a detailed investigation of the contribution of each of the materials and interfaces in the current path of a soldered REBCO lap joint. In all the cited studies, small batches or single samples were tested, usually to compare different manufacturers, solder materials and process parameters. The range of resistivity values reported is 25–730 $n\Omega\cdot cm^2$.

In [1], 211 lap joint resistance measurements were made with tape from SuperPower for the 32 T project at the National High Magnetic Field Laboratory (MagLab) and 38 measurements were made during the first year of the MagLab 40 T project.

In this paper, findings from three studies are presented. The first study compares lap joint resistances for tapes from four manufacturers. For each manufacturer lap joints were made in four different lengths from a single piece of tape. The second study presents lap joint resistance data from the 2nd and 3rd years of the MagLab 40 T project. The third study presents lap joint resistance data from small batches of tapes made by Faraday Factory and Fujikura.

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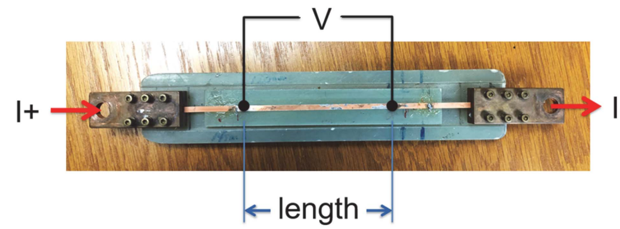

Fig. 1. REBCO lap joint mounted in test fixture, with schematic indication of current connections, voltage tap and lap joint length.

II. Splice Fabrication Method

A standard method for soldering lap joints for REBCO high-temperature superconducting (HTS) coils has been adopted for the 32 T and 40 T projects at the MagLab. The process is described in detail in [1]. 4 mm width REBCO tapes were cut to length from each spool received from the manufacturer and soldered together with REBCO layers facing one another. For the 32 T project and for the initial phase of the 40 T project, quality control (QC) specimens of each conductor procured for the projects were made in this manner. For the 32 T project, the length of the lap joints was 80 mm. For the first two years of the 40 T project, the lap joint length was 120 mm.

The present practice for the 40 T project is to make the QC specimens with a handheld, temperature-controlled soldering iron without fixturing or compression and to use a 25 mm lap joint length. This method was adopted after a comparative study using previously measured conductors showed very similar results.

III. Measurements

For a typical lap joint resistance measurement, a specimen is mounted to a test fixture, as shown in Fig. 1 with current connections and voltage taps and cooled in liquid nitrogen. The current is ramped up and down at 3 rates: 2, 5 and 10 A/sec. The voltage and current are recorded.

A typical voltage and current trace is shown in Fig. 2.

IV. Analysis

Voltage and current data collected for each lap joint specimen are fitted to the function $V\ (t) = V_{offset}\ + L\frac{di}{dt} + R\cdot I + V_c\cdot(\frac{I}{I_c})^n$ to estimate inductive, resistive and offset voltage

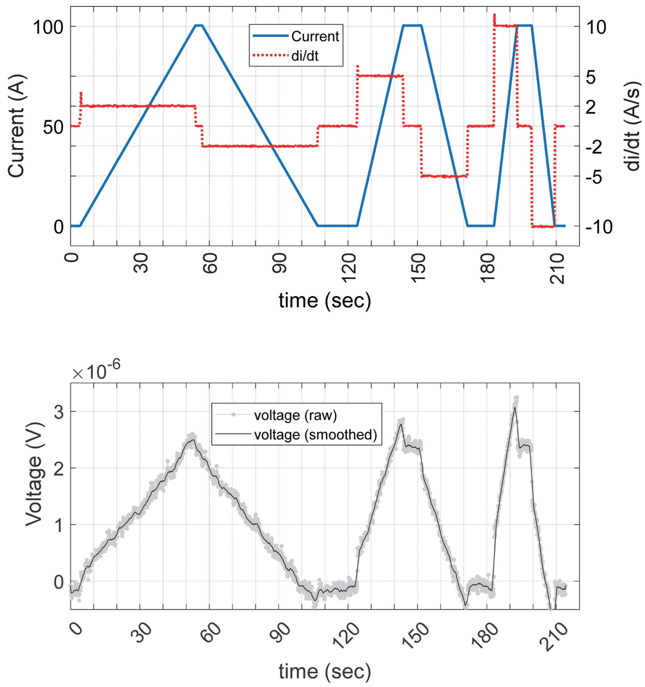

Fig. 2. Current, voltage and calculated di/dt from a typical lap joint resistance test.

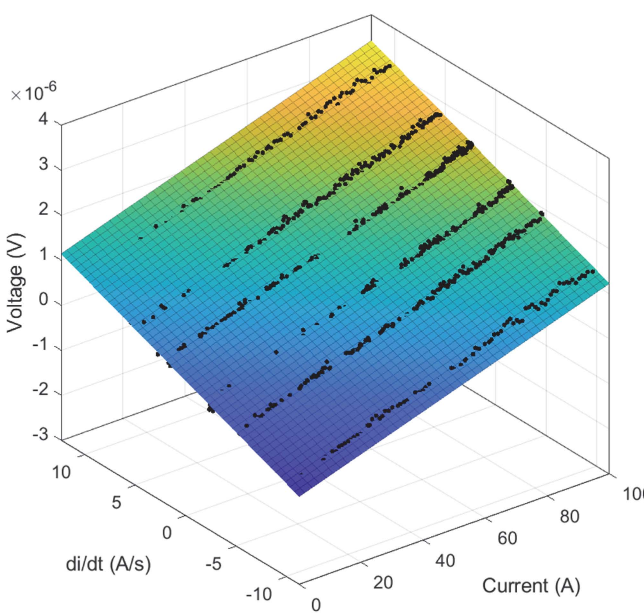

Fig. 3. Graph of voltage data and fit surface for joint resistance test.

contributions. For resistance measurements, ramping current to the transition is not strictly required, but if done, the curve fit may include additional terms to estimate critical current and n-value. A graph of a typical curve-fit is shown in Fig. 3.

V. Findings

Findings from three studies are reported. For the first two studies, the resistivity is found by fitting data to the function

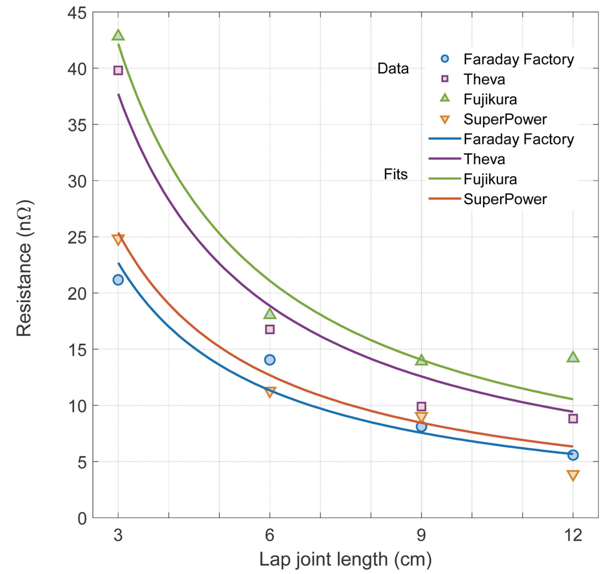

Fig. 4. Resistance data and fits vs. lap joint length for 4 manufacturers.

$R = \frac{\rho}{A}$, where ρ is the resistivity of the lap joint in $\Omega \cdot m^2$, and A is the surface area of the lap joint.

For the 3rd study, all the lap joints were 2.5 cm length, so resistivity was calculated for each measurement by multiplying the measured resistance by the contact area.

1st study – 4 vendors, 4 joints from one tape

For the first study, one lap joint in each of four lengths (3, 6, 9 and 12 cm) was made from a single tape supplied by four manufacturers (Theva, SuperPower, Faraday Factory and Fujikura). Data and fits from these measurements are graphed in Fig. 4.

2nd study – SuperPower tape, sample batches for characterization and quality control

For the second study, samples were made from each SuperPower tape spool procured for the conductor characterization and QC efforts for the 40 T project. The number of samples, mean, median and standard deviation of the resistance for each data set are given in Table I along with results from [1]. Histograms and distribution fits for results not previously reported are shown in Fig. 5.

The resistivity of the SuperPower tapes are estimated using the median value from each data set using the same fitting method applied in the 1st study. Fig. 6 is a graph of the median values from Table I vs. lap joint length and of the fit to the function $R = \frac{\rho}{A}$ applied in the same manner as in Fig. 4.

3rd study – Other vendors

For the third study, as part of an effort to evaluate alternative tape suppliers for the 40 T project, samples of lap joints made with Faraday Factory and Fujikura tapes were made. The number of samples, mean, median and standard deviation of the resistance for those tests are given in Table I. Histograms and distribution fits are shown in Fig. 5.

In Table II, the resistivity values found in each study are given.

TABLE I
DESCRIPTIVE STATISTICS FOR RESISTANCE MEASUREMENTS IN 2ND AND 3RD STUDIES

Data set	Joint length (cm)	# samples	Mean (nΩ)	Median (nΩ)	Std dev (nΩ)
32 T (SuperPower)	8	211	24.7	17.1	19.5
40 T Year 1 (SuperPower)	12	38	10.4	10	3.1
40 T Year 2 (SuperPower)	12	76	12.6	9.4	18.4
40 T Year 3 (SuperPower)	2.5	44	49.6	48.3	13.4
Faraday Factory	2.5	10	23.4	22.2	8.2
Fujikura	2.5	13	106.6	66.2	69.8

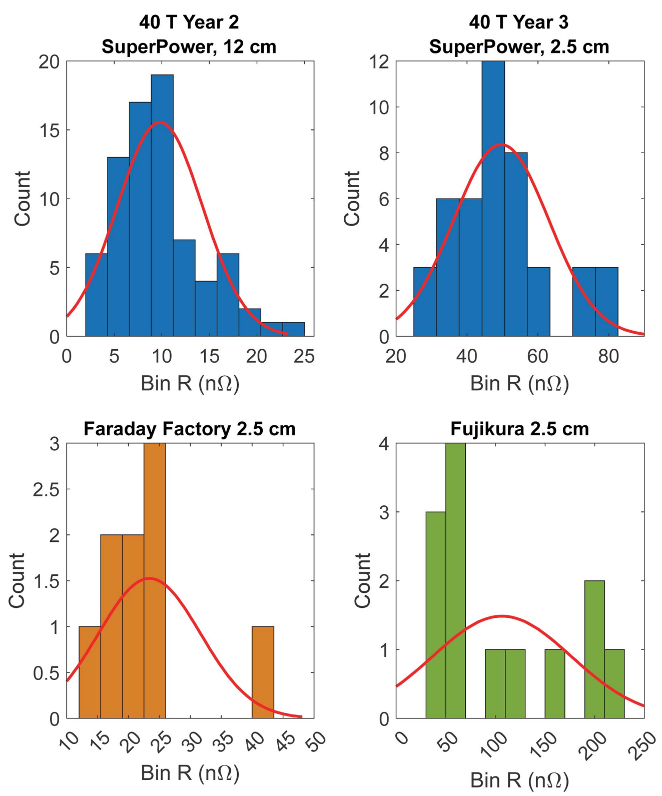

Fig. 5. Histograms of lap joint resistance data by manufacturer with superimposed normal distribution plot.

TABLE II
SUMMARY OF FINDINGS –RESISTIVITY FROM FIT OR MEDIAN (nΩ·cm^2)

Study	Faraday Factory	Theva	Fujikura	Super-Power
1st	27.2	45.3	50.6	30.4
2nd, 3rd	22.2	n/a	66.2	48.7

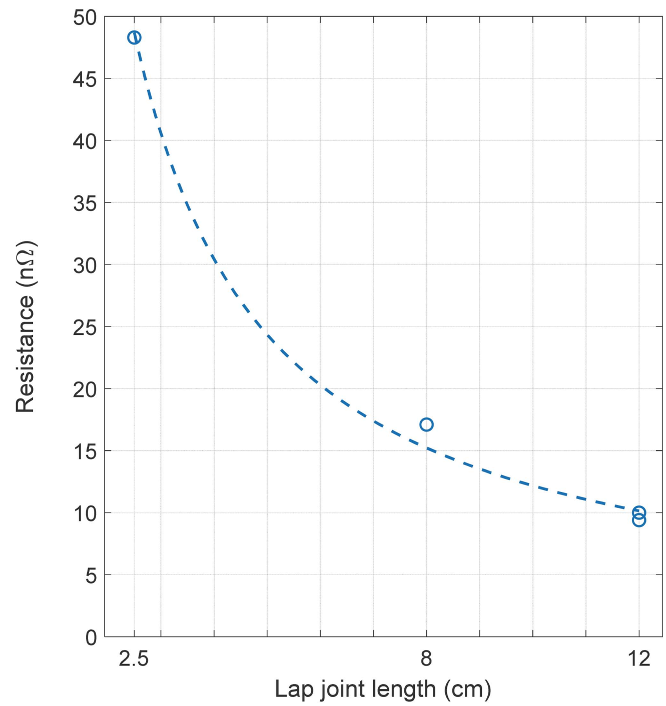

Fig. 6. Median resistance vs. lap joint length and fit for SuperPower data in Table I.

VI. DISCUSSION

The largest set of lap joint resistance data is for SuperPower tape, having been measured for both the MagLab 32 T and 40 T projects. The resistivity and variance have changed little from values published previously [1]. Faraday Factory tapes show the lowest resistivity of those sampled and the smallest variance. Fujikura tapes had several samples with higher resistivity than the others.

Given the variance observed, and the difference in the population size between manufacturers it is premature to conclude that the observed difference in resistivity between manufacturers is significant.

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