Design and Evaluation of Joint Resistance in SSC Rutherford-Type Cable Splices for Torus Magnet for the Jefferson Lab 12-GeV Upgrade

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***Abstract*—The Hall B 3.6-T superconducting torus magnet is being designed and built as part of the Jefferson Lab 12-GeV upgrade. The magnet consists of six trapezoidal coils connected in series, with an operating current of 3770 A. The magnet and the joints (or splices) connecting the coils are all conduction cooled by supercritical 4.6-K helium. This paper studies the design and manufacturing process of the splices made between two SSC Rutherford-type cables and discusses the tests performed to evaluate the performance of the splices under varying incident magnetic fields.**

***Index Terms*—Conduction cooled, joints, magnetic field, splices, SSC Cable, superconducting magnet, torus coil, transport current.**

I. Introduction

ONE of the main challenges with the Jefferson Lab 12 GeV upgrade is the size and complexity of the torus magnet system which forms a part of the CLAS12 spectrometer in HALL B [1].

The torus magnet consists of six superconducting coils which are connected and arranged to produce a toroidal magnetic field (Fig. 1). Torus coil parameters are shown in Table I. These double pancake coils have a total of 234 turns which, are vacuum impregnated with epoxy, assembled into an aluminum case and are indirectly cooled by supercritical helium gas, producing what is referred to as the coil cold mass (CCM). Each coil within the aluminum case is conduction cooled via a series of thin copper sheets wrapped around the coil winding pack and soldered to a helium cooling tube. Each CCM is surrounded by a nitrogen cooled thermal shield located between the vacuum vessel walls and the coil case [2]. All six coils are electrically connected in series using soldered joints that are conduction cooled by direct mounting onto liquid helium re-coolers.

The individual coils are wound with surplus outer dipole SSC cable (see parameters in Table II), with 2×18 strands having key-stoned dimensions of 1.05 mm $\times$ 1.26 mm $\times$ 11.7 mm [3]. The cable is further stabilized by soldering into an extruded OFHC copper channel with $Sn_{60}Pb_{40}$ solder—as shown in Fig. 2.

The splice has been designed for low temperature operation at 5 K. Each splice was designed to have a resistance of no higher than 7×10^{-9} Ω thus imposing a joule heating limit of no more than 100 mW, corresponding to operation at 3770 A at 4.6 K and in magnetic fields in the region of 0.3 T. The splice was cooled via copper braids soldered to the helium re-cooler units that are inside the downstream cold beams. The

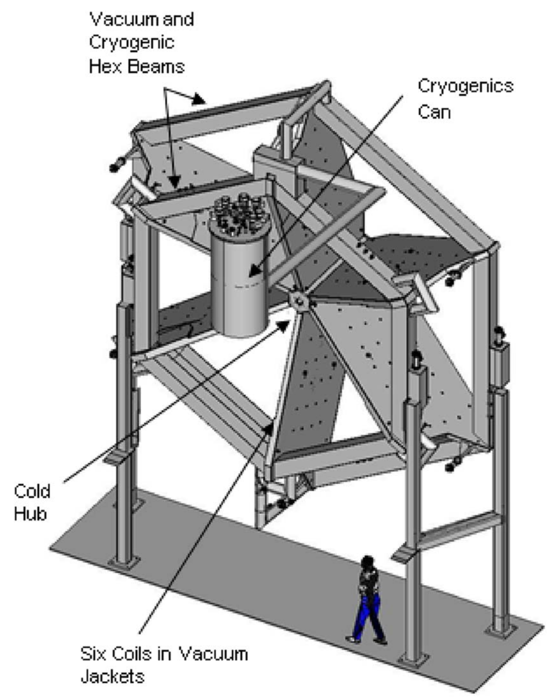

Fig. 1. CLAS12 torus magnet overview.

TABLE I
TORUS COIL PARAMETERS

Parameter	Unit	Value
Peak operating current	A	3770
Coil peak field	T	3.58
Operating temperature (nominal)	K	4.6
Number of coils		6
Total number of turns/coil		2 x 117
Total stored energy	MJ	14.2
Inductance	H	2.0

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TABLE II
TORUS CONDUCTOR SPECIFICATION

Parameter	Unit	Value
Rutherford type of cable (superconductor)		NbTi
Conductor material (NbTi + Cu)		Cu-(NbTi) in Cu Channel
Number of strands in the cable		36
Number of NbTi filaments in each strand		4600
NbTi strand bare diameter	mm	0.648
Cu to non-Copper ratio (strand)		1.8
Twist pitch	mm	15
Conductor size (bare)	mm x mm	2.5 x 20
Conductor size (insulated)	mm x mm	2.7 x 20.2
Short sample current at 4.22 K, 5 T	kA	11
RRR Cu (Cu-NbTi) – Strand		100
RRR Cu Stabilizer (design purpose)		200 (70)

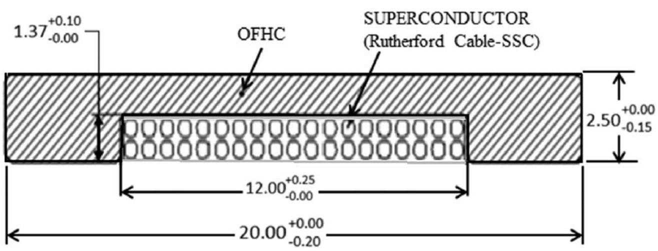

Fig. 2. Torus conductor: SSC outer cable soldered into copper channel (dimensions in millimeters).

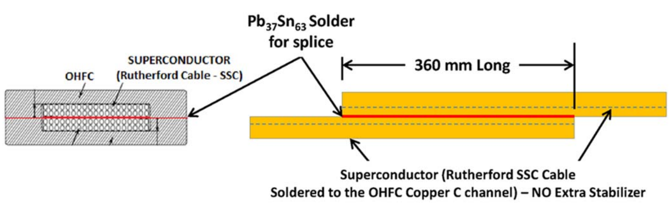

Fig. 3. Typical layout of the test splice for joint resistance evaluation (without any additional copper stabilizer employed in the system).

splice design was also constrained by the available space on the re-cooler units and the requirements for adequate electrical insulation that could stand off 2500 V to ground in a vacuum.

II. DESIGN OF CONDUCTOR SPLICES

Splice Mechanical Design: Reliable low resistance electrical joints [4] are vital to the safe operation of the torus magnet. The structure of the typical single splice been developed primarily to address key requirements-

1) To maximize intimate contact between the spliced superconducting cables to minimize contact resistance (represented in Fig. 3.
2) The second structural feature adds additional stabilizing copper over and above the copper channel in the form of a rectangular section of copper.

a) *Key Risk in Joint/Splice Manufacture*–The key risk to the joint is due to the lack of even solder distribution and the creation of voids within the solder & gaps between the cables. The cables are placed with the SSC cables facing each other and the keystone edges of the mating conductors laying on opposite sides of the joint to ensure a minimum gap between the SSC cables in the splice. Several splice mock-ups were made and destructively tested to qualify the fixture and procedure adopted. This minimized the risk so long as the splices were made using the qualified fixture and process.

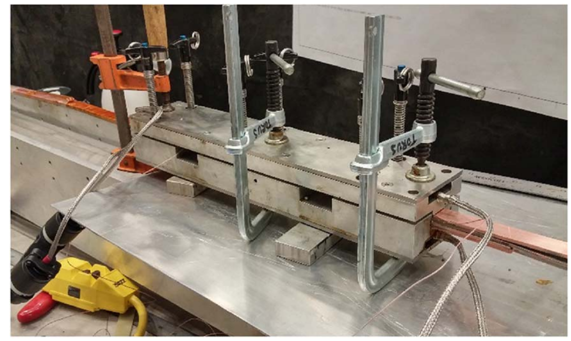

Fig. 4. Aluminum splicing fixture.

b) *Solder Details*–$Sn_{60}Pb_{40}$ solder was used to bond the original Rutherford cable into the copper channel. It has a liquidus of 188 °C to 190 °C (*melts above* 200 °C). The soft solder paste used for the splice is $Sn_{63}Pb_{37}$ (eutectic melting point at 183 °C). By controlling the temperature during soldering, using both thermos-couple monitoring and visual inspection, reflow and delamination of the Rutherford cable and the copper channel can be avoided. This minimizes the chance of voids in the spliced section of cable.

c) *The splice stability balance*–The amount of copper used for conduction and stabilization in a splice for this magnet has to be balanced against the possibility of burning out a conductor if a quench remains un-detected and does not propagate. Analytical calculations, based on MIITs, are used to define additional OHFC copper stabilizer requirements to make the splice quench tolerant [5]. The stabilizer bars, extending over the entire splice length, are soldered to the assembly in the same operation that solders the splice.

Specifically, the total amount of copper through the joint zone is enough to allow recovery from a stick slip induced quench because Joule heating falls within the limited cooling power applied to the splice. Simultaneously, if there is no recovery the copper volume is small enough to develop a telltale voltage that will trip the fast dump interlocks to prevent a conductor burn out [6].

d) *Electrical isolation to Ground (GND) in Vacuum*–The insulation system is designed to accommodate a 2.5 kV standoff to Ground using polyimide film and a minimum tracking length of 1/2 inch. For improved thermal performance, any physical gaps in the assembly are filled with two part epoxy blue Stycast 2850 FT. The assembly is Hi-Pot tested to 1 kV in air to validate electrical isolation and integrity.

III. MANUFACTURING OF THE TEST SPLICES

a) *Design for Manufacturing*–An aluminum fixture (Fig. 4) was designed to act as a heat diffuser as well as an alignment jig to firmly hold the stabilized superconducting conductors and extra copper stabilizer elements in place during the soldering process. It employed electric heating elements controlled using thermocouple sensors for

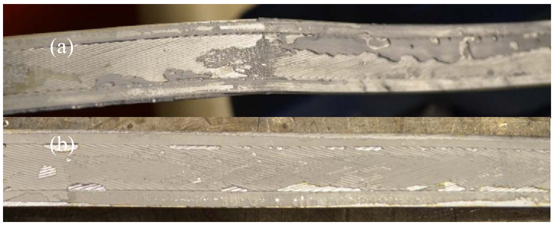

Fig. 5. Conductor after being peeled apart during early splice tests. (a) Large areas that did not adhere uniformly. (b) Change in fixture, flux, and technique resulted in a much more uniform bond between the pieces.

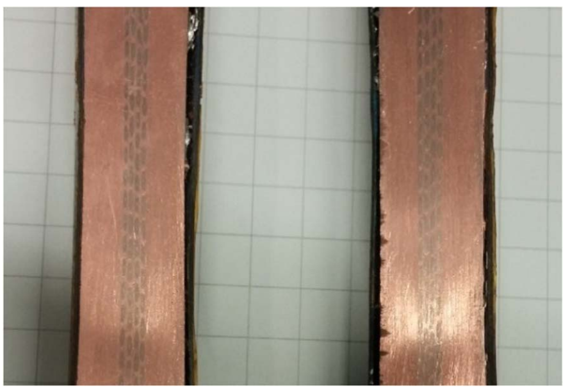

Fig. 6. Splice mock-up end-on view of the sectioned splice cut lengthwise, showing void-free construction. NbTi strands and solder can be seen in the copper matrix. Outer wrap is polyimide film and epoxy.

precise control of the joint temperature. The fixture was designed compactly to fit in the limited space around the Torus' Cold Beams. Openings at the edges of the fixture allow the solder splice to be viewed during the heating cycle and any visible gaps to be backfilled with solder. All the individual pieces are initially cleaned to remove oxidation. Solder paste is then applied to the mating surfaces and the parts assembled in the fixture. A thermocouple monitors the joint temperature during the soldering process. The fixture holds the pieces together loosely while the assembly is heated. Once the assembly reaches 183 °C or the solder is observed to flow, the bar clamps are tightened to force the pieces into intimate contact and to force out excess solder, ensuring a good solder joint.

b) The final version of the fixture was designed to include an aluminum plunger bar on top that pushes the splice parts into the slot in the bottom half of the fixture in order to align the pieces and to control where the excess solder flows. These features yielded a final splice within our tolerance as suggested by Fast *et al.* [7], [8].

Fig. 5(a) shows one of the conductors of a splice where large areas (dark grey in color) have not been completely wetted with solder. Fig. 5(b) on the other hand indicates a conductor with good solder wetting—i.e., uniform distribution of solder.

In-house tests—The first 19 test splices were sectioned or peeled apart to look for voids and thus allowed us to refine the process and tooling as shown in Figs. 5 and 6. In the end, a repeatable method, able to be performed in the field, was successfully developed and the entire process was captured in a written procedure.

TABLE III
CRITICAL CURRENT AND n-VALUE DATA FOR DR4562

Critical Current data			
E field Criteria	10.5 T	10.0 T	9.5 T
100 μV/m	254 A	851 A	1708 A
10 μV/m	165 A	656 A	1415 A
n-Value			
10-100 μV/m	5	9	12

IV. Test Results and Discussion

Samples were prepared for critical current (I_C) and n-value measurements and V-I data measured in different magnetic fields in order to validate the data measured on individual strands. Test splices were manufactured at JLab (two conductors made from bare Rutherford Cable soldered into copper channel) with 360 mm long soldered joints, similar to splices employed between the coils in the torus magnet system. The splice prepared at JLab was tested at the University of Durham, U.K. up to 2000 A in one of two 15 T magnet systems. With the limitation of the measurement set up to accommodate the length of the splice in the magnet, the resistance across the splice was measured at a lower current and an elevated magnetic field at LHe temperature. This measurement is carried out in order to mitigate the splices that will be employed at higher field (4 T) for another magnet system employing similar conductor and splices. The actual splice length is 360 mm and is over 400 mm with the additional stabilizer on the overall joint in order to provide adequate stability for the splice.

A. Critical Current (I_C) Measurement

V-I measurements under an external magnet field generated using a Helmholtz coil pair were carried out on the cable carrying different transport currents at low electric fields. Reliable I_C values and n-values are obtained at higher E-fields (100 μV/m) when the dissipative state ensures the resistance of the superconductor is comparable or higher than the transfer resistances. Standard corrections to magnetic field (self and external magnetic field) and temperature (using scaling laws [9], [10]) were applied to obtain data at 4.2 K and integral and half integral values of magnetic field. Typical critical current and n-values were measured prior to making the joints as shown in Table III for a bare Rutherford cable—sample DR4562. The expected I_C for the SSC Rutherford cable is given in Table II. The cable is characterized with the current limitation in the experimental set, hence evaluated at higher field and lower current. The characterization of the cable was not done at low field due to high current requirement; hence we see low n-values at higher field. Earlier, individual strands were removed from the cable to measure I_C and n-values between 5 and 7 T. The n-values over 25 were measured on single strands with the span of the voltage pair spanning 60 mm [11].

B. Joint Resistance Measurement

Test set up for splice resistance measurement is carried out using a standard V-I technique integrated with an external magnetic field generated using a solenoid and evaluated on sample no. DR4686. The sample was formed to be part of the current leads and no additional conductive materials were used

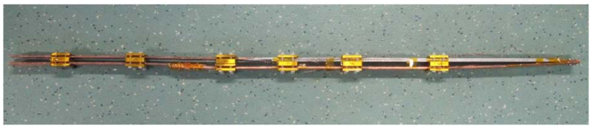

Fig. 7. Sample prepared for joint resistance measurement.

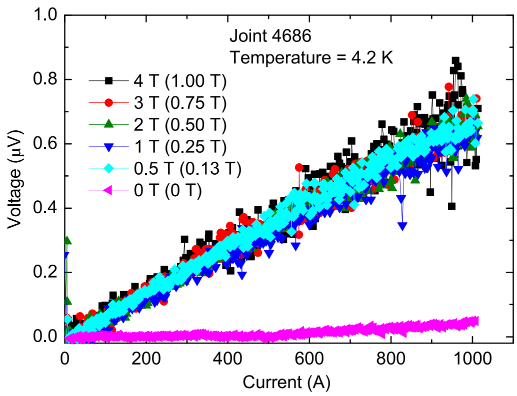

Fig. 8. $V-I$ data at different magnetic fields for the soldered joint of sample DR4686 at 4.2 K. The two magnetic field values shown are those at the field center and at the top of the joint (in brackets), which was about 150 mm away from the field center. A linear fit to the high-field data, where the solder is normal, gives a resistance of 0.7 nΩ.

in order to ensure joint resistance measurement only. Insulated brass spacers were employed to hold the joint fixed (Fig. 7. $In_{52}Sn_{48}$ solder (118°C melting point) was used to solder the voltage taps across the joint of the sample.

V-I measurements on splice samples were made at room temperature and 77 K in zero magnetic field, and at helium temperatures in a 15 T vertical magnet in Durham. At room temperature, the resistance values are predominantly attributable to the resistance of the copper. In preliminary measurements at 3000 A, the cable started visibly bubbling and the solder in the channel started to melt demonstrating the upper limit for current in Ohmic measurements at room temperature.

During the 4.2 K measurements, the top of the joint was just above the top of the vertical magnet while the bottom of the joint was below the field center. The field profile along the vertical direction of the magnet was established using a Hall probe. V-I data were obtained from voltage taps across the entire joint.

The resistance of the joint at 4.2 K saturates at 0.7 nΩ in high fields consistent with the entire joint being in the normal state as shown in Fig. 8. The curve denoted by 3 T (0.75 T) signifies that the measurement has been carried out at a peak magnetic field of 3 T and that the magnetic field was reduced to about 0.75 T near the top of the joint (∼150 mm away). All the solder in the joint was driven into the normal state in high fields as the joint reaches its maximum resistance. Subsequent increases in applied field produced little change in the resistance of the joint. The solder at the top of the joint became completely normal at a field reasonably close to the B_{c2} of Pb-Sn solder. We measured 7 joints. Typically we found that in high magnetic fields, when the joint was entirely normal, all V-I traces were reproducible and independent of the history of the applied field. However, when the joint solder was superconducting along part of the length of the joint, the V-I traces were not reversible and intermediate resistances were observed. Typical resistances measured for DR4686 are given in Table IV.

TABLE IV
RESISTANCE MEASURED FOR DR4686 AT VARYING MAGNETIC FLUX DENSITIES AT 4.2 K

Joint Length (mm)	Field at field Centre (T)	Field at the top of the joint (T)	Joint resistance ($\times 10^{-9}\Omega$)
260	0	0	≤ 0.1
	0.5	0.13	0.70
	1	0.25	0.66
	2	0.50	0.68
	3	0.75	0.68
	4	1	0.7

V. Summary

1. The procedure and the fixtures for manufacturing the splices between the torus coils has been established and exercised successfully.
2. The resistances across the splices are measured with a vertical magnet capable of producing magnetic flux densities up to 15 T. This resistance measurement includes the magnetoresistance of the conductor and the $Sn_{63}Pb_{37}$ solder in the (completely) normal state.
3. The resistance of the splices measured is about 1 nΩ in LHe (4.2 K) at elevated magnetic fields, better than the minimum requirement of 7.0 nΩ (based on 100 mW joule heating at full operating current).

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