

# Splice Testing for LHC Quadrupole Magnets

E. Barzi, R. Bossert, S. Feher, J. Kerby, V. V. Kashikhin, M. J. Lamm, D. Orris, G. Ray, M. Tartaglia, and A. V. Zlobin

**Abstract**—Electrical splices between NbTi Rutherford type cables need to be made for the LHC IR inner triplet quadrupoles. Splices between magnets as well as internal to the magnets are necessary. Various splice configurations, solders, and fluxes have been considered. Testing of these splices at cryogenic temperatures and at various currents has been completed. The results were satisfactory; Fermilab is capable of making excellent low resistance ( $<1 \text{ n}\Omega$ ) solder joints for the LHC project.

**Index Terms**—Solder joints, splice, superconducting magnets.

## I. INTRODUCTION

THE FINAL focus triplets in the interaction regions at the Large Hadron Collider (LHC) require high gradient quadrupoles. Each triplet consists of four quadrupoles with 70 mm bore and peak operating field gradients of 215 T/m. Fermilab is providing half of the Interaction Region inner triplet quadrupoles and KEK the other half. Fermilab will do the final assembly and cryostating of all magnets.

Fabrication of the quadrupoles and installing them into the LHC tunnel requires splicing together superconducting cables. To develop the design and fabrication procedures for reproducible manufacturing of superconducting magnets, a 2 m model-magnet program was started in 1997 and successfully completed in 2000 [1]. As part of this program several splice tests were performed to validate the splice design and the splicing technique originally developed for the Tevatron.

This paper summarizes the test results of these splice measurements.

## II. SPLICE DESIGN AND RESISTANCE CALCULATION

Under high DC and AC current operation, soldered cable joints will generate heat due to their finite resistance and eddy current losses at the spliced area. The larger the spliced area, the lower is the resistance of the splice. On the other hand AC losses are inversely proportional to the splice area.

It has been shown that a 120 mm long splice area is short enough to keep eddy current losses within an acceptable limit even if the splices are located in a relatively high magnetic field region. It was also shown that when the magnet joint resistances are kept around 1 n $\Omega$ , the magnet would not suffer any performance degradation [2].

In order to estimate the splice resistance from the conductivity of the solder and the copper matrix of the strands several splices

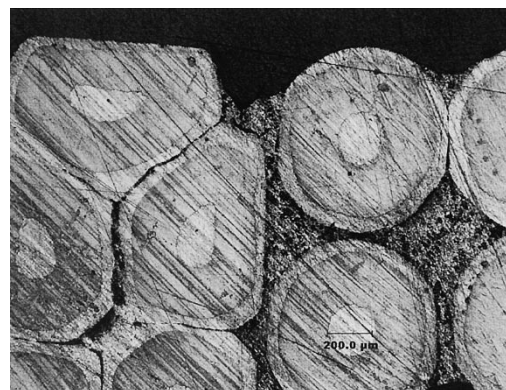


Fig. 1. LHC inner cable to LHC inner cable splice cross section.

were sliced and polished. Using a microscope we were able to distinguish between the solder and the boundary of the strand (see Fig. 1). Since the solder resistivity in general is several orders of magnitude larger than that of the copper, the strands can be treated as equipotentials. A further reasonable approximation is to assume that the crossing current flows in straight lines perpendicular to the lap joint. With these assumptions, we may calculate the joint resistance as the summation of parallel current paths. The splice resistance dominated by the solder layer between the two cables can be estimated as:

$$\frac{1}{R_{\text{splice}}^{\text{layer}}} = \frac{L}{\rho} \sum_i \frac{\Delta a_i}{d_i}$$

where  $L$  is the length of the splice,  $\rho$  is the resistivity of the solder,  $\Delta a$  is a distance segment (used for the computation) along the width of the cable and  $d$  is the distance across the solder between the strands. Obviously  $\Delta a$  should be chosen to be small enough that  $d$  is approximately constant along  $\Delta a$ . In order to estimate the total resistance of the splice the resistance of the second layer should be added in parallel with the first one. Since from the second layer the current has to pass three times as much solder as the first layer, plus it has to go through the copper matrix of the strands of the first layer, the total resistance of the splice will be reduced by 10% relative to the first layer resistance.

The resistances were calculated for two types of splices: i), the splice between FNAL/LHC inner to FNAL/LHC inner cable; and ii), the splice between FNAL/LHC inner to FNAL/LHC outer cable. Using  $\rho = 7.4 \times 10^{-9} \text{ }\Omega\text{m}$  for 70/30 Pb/Sn solder [3] and  $\rho = 1.69 \times 10^{-10} \text{ }\Omega\text{m}$  for the copper matrix resistivity (at 4.5 K) within the strand, we obtained i), 0.22 n $\Omega$ ; and ii), 0.18 n $\Omega$  values. Due to the low resistivity value of the copper matrix its contribution to the total resistance is  $\sim 5\%$ .

Manuscript received August 6, 2002. This work was supported by the U.S. Department of Energy.

The majority of the authors are with Fermi National Accelerator Laboratory. G. Ray was summer student at Fermilab at the time the splice measurements were taken.

Digital Object Identifier 10.1109/TASC.2003.812654

TABLE I  
CABLE PARAMETERS

Cable Type	Strand diameter	Cable width/ mid thickness	Number of strands	Twist pitch
FNAL Inner	0.808 mm	15.4/1.45 mm	37	114 mm
FNAL Outer	0.648 mm	15.4/1.15 mm	46	102 mm
KEK Inner	1.065 mm	15.0/1.89 mm	28	110 mm

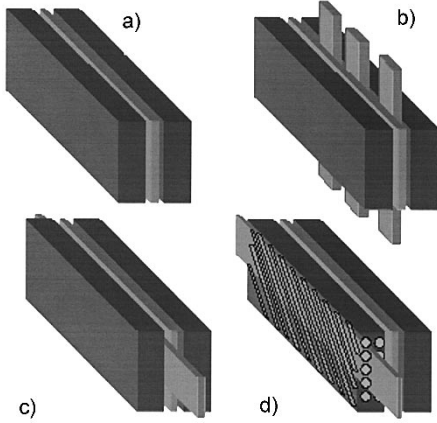


Fig. 2. Schematics of the different type of solder joints are shown. The standard solder joint is made by placing solder strip between the cables (a). Kapton film was placed vertically (b) and horizontally (c) between the cables to reduce the area of the splice. Kapton film was placed in between the cable itself to check the effect of the solder penetration inside the cable (d).

### III. SPLICE MEASUREMENTS

#### A. Sample Preparation

The superconducting cables used in this study are described in Table I. After the cable was cleaned with Scotchbrite and alcohol the spliced area was pre-tinned or filled with solder before the splice took place. During pre-tinning, solder was applied with a soldering iron using solder wire anywhere from 0.75 mm to 3 mm in diameter.

Most of the splices were made by placing a strip of solder between the cable pairs that were soldered. The strip was manufactured specifically for this application, and was either 0.12 mm or 0.25 mm thick by 15 mm wide. The spliced area was placed into a fixture, which had a cavity machined to the size of the splice cross section. The fixture was bolted together using shoulder screws with die springs to provide a uniform clamping force. The applied pressure was approximately 3.5 MPa (500 PSI). Electric cartridge heaters inserted into holes in the fixture provided heat. When the heaters were turned on the temperature of the soldered area was monitored with a thermocouple. The heater cartridge was turned off when the solder melted, which was visually observable. After cooling, the splice was removed from the fixture and the exterior was cleaned with Scotchbrite.

Four batches (16 splices per batch) of splices were made and tested. The primary goal for the first batch was to check the splice quality as a function of the amount of the spliced area. Samples with Kapton films inside or between the cables were used to model the effect of the solder penetration inside the cable or to reduce the splice area by a controlled amount. The schematics of these different types of solder joints are shown in Fig. 2.

TABLE II  
SPLICE SAMPLES

Joint Type	1st Cable	2nd Cable	Solder Type	Kapton Coverage	Solder Strip	No of Samples
J1	C1	C3	S1	-	0.12 mm	6
J2	C1	C3	S1	KH	0.12 mm	2
J3	C1	C3	S1	KV	0.12 mm	2
J4	C2	C3	S1	-	0.12 mm	9
J5	C1	C3	S1	K1	0.12 mm	2
J6	C1	C3	S1	K3	0.12 mm	2
J7	C1	C3	S1	K1,K3	0.12 mm	2
J8	C1	C3	S1	-	-	2
J9	C3	C3	S1	-	0.12 mm	2
J10	C1	C1	S1	-	0.12 mm	2
J11	C2	C2	S2	-	0.25 mm	4
J12	C2	C3	S2	-	0.25 mm	8
J13	C3	C3	S2	-	0.25 mm	5
J14	C2	C4	S3	-	0.25 mm	10
J15 <sup>a</sup>	C2	C2	S3	-	0.25 mm	4

C1 – FNA/LHC Inner left lay cable

C2 – FNAL/LHC Inner right lay cable

C3 – FNAL/LHC Outer left lay cable

C4 – KEK/LHC Inner right lay cable

S1 – Lead tin solder Pb(70%)Sn(30%) using Kester 1544 Flux

S2 – Tin Silver solder Sn(95%)Ag(5%) using Kester 135 Flux

S3 – Tin Silver solder Sn(96%)Ag(4%) using Kester 135 Flux

KH(V) – Kapton was placed horizontally (vertically) between the two cable covering 50% of the spliced area

K1 – Kapton was placed inside C1 providing 50% coverage

K3 – Kapton was placed inside C3 providing 50% coverage

<sup>a</sup>Additional pure copper cable was placed in between the superconducting cables

Since the outer and inner cable is different we also checked the affect of the different cable combinations used to make the splices. The reason for the second batch was to obtain more data on the standard LHC quadrupole splices. For the first two batches we used 70/30 Pb/Sn solder and Kester 1544 flux which was the solder type used in the High Gradient Quadrupole R&D program.

Early in the long magnet production process, discussions with CERN revealed that the solder to be used in the interconnect area at the LHC was 96/4 Sn/Ag. In addition, the small amount of chloride (0.44%) contained in the Kester 1544 flux was undesirable, due to the possible corrosive effect on stainless steel. As a result, Fermilab switched to the 96/4 Sn/Ag solder with Kester 135 flux for the production program to avoid contamination of CERN joints with the FNAL material and to eliminate the chloride. The third batch of splices was done primarily to validate the soldering techniques described above using the Sn/Ag with Kester 135 combination. Both 95/5 Sn/Ag and 96/4 Sn/Ag are used and treated identically for these tests due to their similarity.

The size of the cable used by KEK to build quadrupoles for the LHC is different from the one Fermilab is using. The fourth batch of splices was made by using KEK and Fermilab type of cable joints. Table II contains the description of all the different types of splices that were tested and Fig. 3. shows the cross section of three different types of splice samples.

#### B. Test Setup

In order to test sixteen splices at once a special fixture was developed shown in Fig. 4. The splices were kept rigidly supported between G10 plates. Grooves were also introduced to provide cooling channels for the splices.

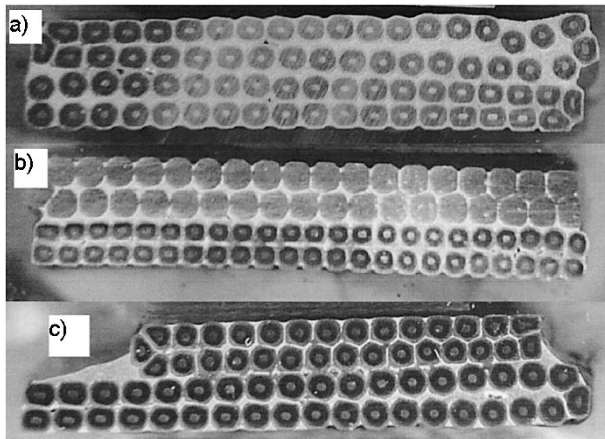


Fig. 3. Splice cross sections: (a) Fermilab inner cable to Fermilab inner cable splice; (b) Fermilab inner cable to Fermilab outer cable; (c) Fermilab inner cable to KEK inner cable.

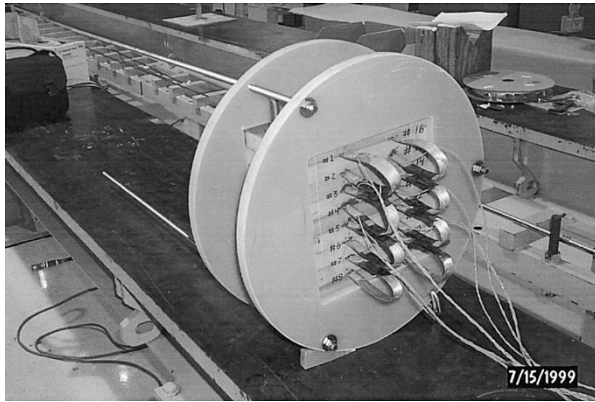


Fig. 4. Typical splice measurement using two different type of solder.

The test was performed at the Fermilab Magnet Test Facility using test Stand 3 [4], which was primarily developed for testing HTS power leads. This stand was capable of conducting current up to 5000 A and cooling the samples down to 4.3 K. The voltages across the splices were measured with an HP3158A DMM. The current was increased in stair steps of 500 A up to 5000 A and back down to 0 A. Each reading was taken by applying a 40 line-cycle integration time to reduce noise.

### C. Test Results

Typical measurements of splice measurements vs. current are plotted in Fig. 5. The 70/30 Pb/Sn solder is a weak type II superconductor. We performed magnetization measurements and obtained  $B_{c1}$  (4.2 K) = 88 mT and for  $B_{c2}$  (4.2 K) = 132 mT values. Since the peak self field at the splice area is  $\sim 50$  mT/kA the splice resistance up to few kA will be dominated by the copper resistance of the strands, which, as we have seen earlier, is very low  $\sim 0.01$  n $\Omega$ . In order to predict the splice resistance change as a function of current we need to know the value of  $J_c$  of the solder as a function of the magnetic field. On the other hand, the splice resistance is not changing rapidly around 5000 A indicating that the solder at this current (and higher) becomes normal. Splice resistance values reported in this paper for lead-tin solder joints were measured at 5000 A.

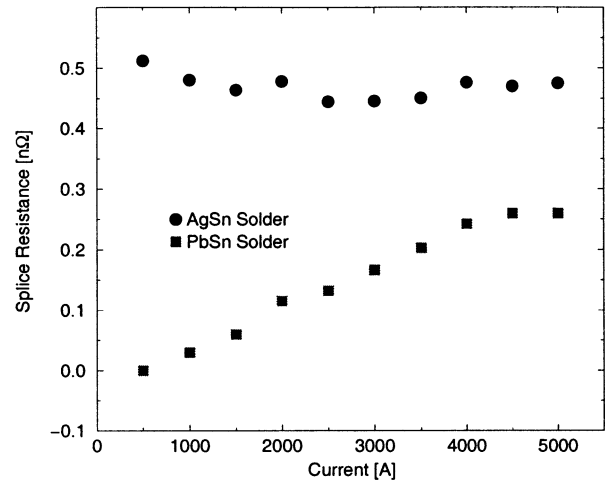
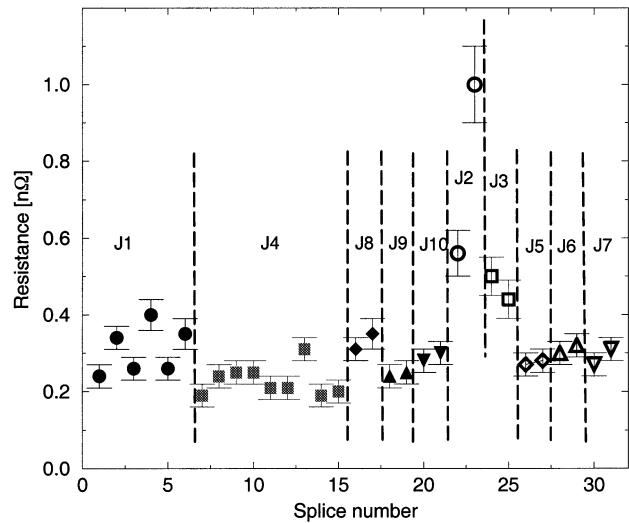


Fig. 5. Typical splice measurement using two different type of solder.



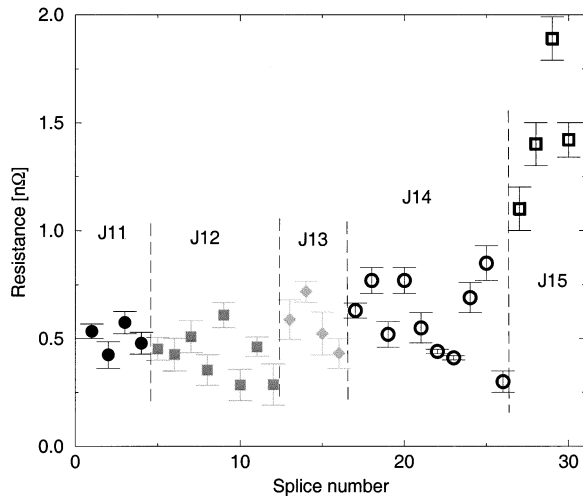


Fig. 7. Splice resistance measurements for splices made with tin-silver solder. J11, . . . , J15 are the notations of the different type of solder joints described in Table I.

TABLE III  
SPlice MEASUREMENTS

J1	J2	J3	J4	J5	J6	J7	J8
0.24	0.56	0.50	0.19	0.27	0.30	0.27	0.31
0.34	1.00	0.44	0.24	0.28	0.32	0.31	0.35
0.26			0.25				
0.40			0.25				
0.26			0.21				
0.35			0.21				
			0.31				
			0.19				
			0.20				
J9	J10	J11	J12	J13	J14	J15	
0.24	0.28	0.53	0.45	0.59	0.63	1.10	
0.25	0.30	0.42	0.43	0.72	0.77	1.40	
		0.57	0.51	0.52	0.52	1.89	
		0.48	0.35	0.43	0.77	1.42	
			0.61		0.55		
			0.46		0.44		
			0.28		0.41		
			0.29		0.65		
					0.30		
					0.69		

The splice resistance values are in nΩ

The error of the measurements was  $\sim \pm 10\%$

the second layer to the total resistance is small so we can conclude that solder penetration inside each cable doesn't have a significant effect on the quality of the solder joint.

The average measured resistance value for the lead tin solder was  $0.27 \text{ n}\Omega$ , which is about 25% higher than the predicted resistance ( $\sim 0.2 \text{ n}\Omega$ ). It is also noticeable that there is a wide spread of the resistances. This might be related to the splicing technique, which can produce irregular solder coverage or change of the solder resistivity.

In Fig. 7 it is also noticeable that the cable type doesn't have a strong effect on the splice resistance. However, the average resistance value of the J14 sample is about 30% higher than that of the J11, J12 and J13 samples. The KEK cable is narrower than the Fermilab cable by the same amount, by  $\sim 30\%$ , which explains the difference.

#### IV. CONCLUSION

A variety of splices were tested at Fermilab to validate the splice design and manufacturing technique. Using the soldering procedure developed, we can systematically produce splices with less than  $1 \text{ n}\Omega$  resistance values. The average splice resistance value is in good agreement with prediction. We have also demonstrated that the CERN recommended AgSn solder can be used for the USLHC magnet program.

#### ACKNOWLEDGMENT

The authors thank the staff of Fermilab's Technical Division who have worked so hard on the effort of producing excellent superconducting magnets over the course of the past few years.

#### REFERENCES

- [1] N. Andreev *et al.*, "Status of the LHC inner triplet quadrupole program at Fermilab," *IEEE Transactions on Applied Superconductivity*, vol. 11, no. 1, p. 1558, March 2001.
- [2] A. Zlobin, "Unpublished note," 1997.
- [3] J. R. W. Fast, "Electrical and mechanical properties of lead/tin solders and splices for superconducting cables," *Cryogenics*, vol. 28, pp. 7-9, Jan. 1988.
- [4] G. Citver *et al.*, "HTS power lead test results," in *Proc. Of the 1999 Particle Accelerator Conf.*, New York, 1999, pp. 1420-1422.