Measurement of Resistance and Strength of Conductor Splices in the MICE Coupling Magnets

Author
Xu, Feng Yu

Publication Date
2009-08-21

Peer reviewed

Advances in Cryogenic Engineering **55**, AIP Press (2009) MICE Note 257

MEASUREMENT OF RESISTANCE AND STRENGTH OF CONDUCTOR SPLICES IN THE MICE COUPLING MAGNETS

F. Y. Xu[1], H. Pan[1], H. Wu[1], X. K. Lui[1], E. Li[1], M. A. Green[2], D. Dietderich[2], H. C. Higley[2], D. G Tam[2], F. Trillaud[2], and Li Wang[1]

[1] Institute of Cryogenics and Superconductive Technology (ICST), HIT, Harbin, 150080, P. R. China

[2]Lawrence Berkeley National Laboratory
Berkeley CA 94720, USA

ABSTRACT

The superconducting magnets for the Muon Ionization Cooling Experiment [1] (MICE) use a copper based Nb-Ti conductor with un-insulated dimensions of 0.95 by 1.60 mm. There may be as many as twelve splices in one MICE superconducting coupling coil. These splices are to be wound in the coil. The conductor splices produce Joule heating, which may cause the magnet to quench. A technique of making conductor splices was developed by ICST. Two types of 1-meter long of soldered lap-joints have been tested. Side-by-side splices and up-down one splices were studied theoretically and experimentally using two types of soft solder made of eutectic tin-lead solder and tin-silver solder. The resistances of the splices made by ICST were tested at LBNL at liquid helium temperatures over a range of magnetic fields up to 5 T. The breaking strength of 250 mm long splices was also measured at room temperature and liquid nitrogen temperature.

KEYWORDS: Splice Resistance, Splice Strength

INTRODUCTION

The coupling magnet for the MuCool experiment at Fermilab and the two coupling magnets for the Muon Ionization Cooling Experiment (MICE) [2] at the Rutherford Appleton Lab in the UK require about 80.8 km of conductor. The insulated dimensions of the coupling coil conductor are 1.0 x 1.65 mm. (The un-insulated dimensions of the conductor are 0.95 x 1.60 mm.). The dimensions of the coupling coil are: inner radius 750 mm, coil length 285 mm long, and coil thickness 102.5 mm. The coil has 96 layers with 166 turns per layer. The magnet is designed to have 15936 turns.

Under the best of circumstances, the maximum conductor length that can be wound into the coupling coil is 33.5 km to 35 km (for a single conductor from a full billet of superconductor composite). Since eight billets of conductor are required to wind the three coupling coils a minimum of two splices are required per coupling magnet. However, the conductor as manufactured by the vendor came in about forty pieces. If one picked and chose the conductor going into the coils, the average number of splices per coil is about eleven. Depending on how the conductor is selected for use in the magnet, the number of splices per magnet can be as low as seven and as high as fifteen.

Since there must be a lot splices in the coupling coils, these splices must have a low resistance. The maximum operating current for the coupling magnet is 210 A. Since the magnet is to be cooled using two 1.5 W (at 4.2 K) coolers, the coupling magnet designers set an upper limit of 10 mW of heat produced by all of the splices within the coil. Based on fifteen splices per coil, the maximum allowable resistance for a conductor splice could be about 15 nΩ. The maximum allowable splice resistance was set at 10 nΩ.

The resistance of three types of splices was calculated for the conductor that could be wound into the coupling magnet. The three types of splices are: 1) a cold welded butt splice, 2) a side-by-side soldered lap joint (the conductor is soldered on the short face), and 3) a up-down soldered lap joint (the conductors is soldered on the broad face). The three types of splices are shown in FIGURE 1. Butt splices can be used anywhere in a coil with no loss of turns. Side-by-side splices can be used in the middle of a coil layer provided one is willing to lose a turn. Up-down splices can be used only at the ends of a layer. In this case, no turn is lost, but more conductor will be scrapped because one must make the splice at the end of a layer. Thus up-down splices should only be used in relatively short coils.

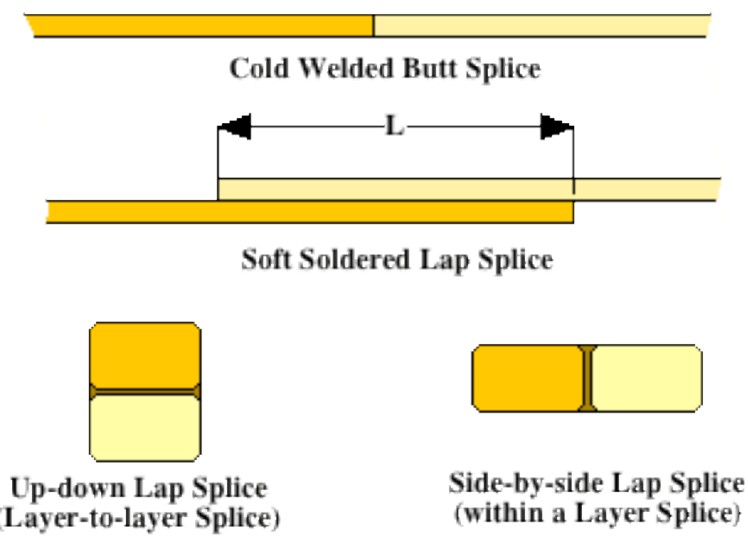

FIGURE 1. A Cold Welded Butt Splice and Soft Soldered Lap Splice of Length L. (The definition of an up-down splice and a side-by-side splice are shown below the butt and lap splices.)

CALCULATION OF SPLICE RESISTANCE AND FAILURE FORCE

This section shows a method of calculating the resistance of butt splices and both types of soft soldered lap splices. This section also shows how one would estimate the breaking strength of splices. Since there are a number of uncertainties that result from the splice fabrication process, the calculated values of the splice resistance and breaking strength must be regarded as estimates.

Calculation of Splice Resistance

Cold welded butts splices are attractive because they can be stronger than the conductor itself and they can be wound into a coil without the loss of a turn. The problem with this type of splice is whether the splice resistance be low enough for use in a MICE magnet. An expression for the resistance of a butt joins is given as follows;

$$R_j = \frac{\rho_j L_j}{A_{cj}} \frac{(r+1)}{r} \quad (1)$$

where R_j is the resistance of the splice; ρ_j is the electrical resistivity of the weld material in the splice; L_j is the length of the fused region within the splice; r is the copper to superconductor ratio for the conductor that is cold welded together; and A_{cj} is the cross-sectional area of the conductor splice. FIGURE 2 below shows the basic dimensions for a typical conductor that is being used to wind the MICE tracker and coupling magnets.

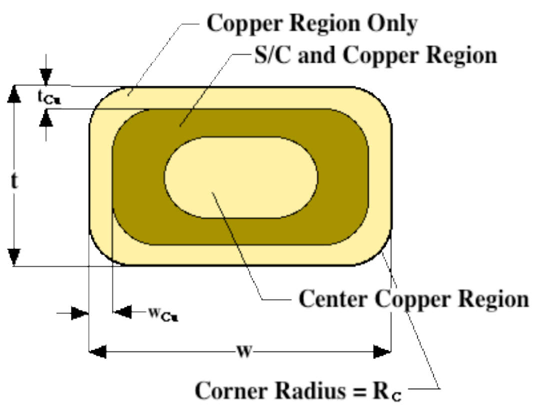

FIGURE 2. The Conductor Dimensions used in the Splice Resistance Calculation Equations for the Splices made with the Coupling Magnet Conductor.

There are two prediction problems with a cold welded butt splice. They are: 1) The resistivity ρ_j in the welded section of the splice is unknown. 2) The fused length L_j of the welded section is also not known. Butt splices can be superconducting at low field. Splices within the coupling coils may be at inductions as high as 6 T. Thus the splices will certainly be normal. One can estimate the resistance of a cold welded butt joint for MICE magnets using a conductor cross-section A_{cj} =1.5 x10^{-6} m^2. If ρ_j = 1.6 x 10^{-9} Ωm (the copper RRR = 10), and the weld zone thickness L_j = 100 μm, the joint resistance will be about 106 nΩ, which is an order of magnitude too high for the MICE coupling magnets. The calculated splice resistance appears to agree reasonably well with measurements made some years ago on a butt splice made by cold welding two conductors with a cross-sectional area of 6 mm^2. The measured butt splice had a resistance of about 25 nΩ [3].

The resistance of a lap splice can be divided into two parts, the copper resistance and the solder resistance. A simplified equation that ignores the rounded corners can be used to estimate the splice resistance [4]. (This assumes that there is no solder in the rounded corners.) The resulting equation should be a worst-case for calculating the lap splice resistance because in reality, there will always be some solder in the corners. The simplified resistance equations take the following form;

$$R_j = \frac{2\rho_{Cu} t_{Cu}}{L(w-2R_c)} + \frac{\rho_{sol} t_{sol}}{L(w-2R_c)}, \text{ for up down joints and} \tag{2}$$

$$R_j = \frac{2\rho_{Cu} w_{Cu}}{L(t-2R_c)} + \frac{\rho_{sol} t_{sol}}{L(t-2R_c)}, \text{ side by side joints.} \tag{3}$$

When two round conductors of radius R_C are soldered together, the estimated splice resistance equation, takes the following form;

$$R_j \approx \frac{2\rho_{Cu} t_{Cu}}{\pi L R_c} + 0.5 \frac{\rho_{sol}(R_c + t_{sol})}{L R_c}. \tag{4}$$

In this case t_{Cu} is the average thickness of the copper between the superconductor and the surface of the conductor.

TABLE 1 presents the resistivity of the copper and a lead-tin (60Pb-40Sn) soft solder at 4.2 K as a function of magnetic induction seen by the copper and the soft solder [5], [6]. From TABLE 1, it is clear that at low RRR, the copper becomes a more important part of the joint resistance. At an RRR = 70 (the MICE coupling coil conductor RRR), the joint resistance is dominated by the solder in the joint. Therefore it is very important that the thickness of the solder between the conductor flats be minimized. The joint resistance is in fact strongly influenced by the quality of the soldering.

TABLE 1. The Resistivity of 60Sn-40Pb Solder and Copper as a Function of RRR and Magnetic Induction

B (T)	ρ_{sol} (Ω-m)	**RRR = 7**	ρ_{Cu} (Ω-m) **RRR = 70**	**RRR = 300**
0	5.40×10^{-9}	2.53×10^{-9}	2.25×10^{-10}	5.18×10^{-11}
2	5.50×10^{-9}	2.62×10^{-9}	3.20×10^{-10}	1.47×10^{-10}
4	5.59×10^{-9}	2.72×10^{-9}	4.15×10^{-10}	2.42×10^{-10}
6	5.69×10^{-9}	2.81×10^{-9}	5.11×10^{-10}	3.37×10^{-10}
8	5.78×10^{-9}	2.88×10^{-9}	5.85×10^{-10}	4.11×10^{-10}
10	5.88×10^{-9}	2.90×10^{-9}	6.06×10^{-10}	4.42×10^{-10}

TABLE 2. The Calculated splice Resistance for a Joint between Two 1.38 mm Round Wires and between Two MICE Conductors (0.95 x 1.60 mm) with Up-down and Side-by-side Spices. (Note: copper RRR = 70, t_{Cu} = 150 μm, w_{Cu} = 200 μm, and t_{sol} = 100 μm. For the round wire t_{Cu} = 190 μm.)

Induction (T)	1-meter Long Joint Resistance (nΩ)				
	Round	**Rectangle (up-down)**		**Rectangle (side-by-side)**	
	R_c = 0.69 mm	**R_c = 0.2 mm**	**R_c = 0**	**R_c = 0.2 mm**	**R_c = 0**
0	2.95	0.518	0.389	1.147	0.662
2	3.01	0.555	0.417	1.234	0.713
4	3.08	0.591	0.444	1.320	0.764
6	3.20	0.628	0.472	1.408	0.816
8	3.30	0.659	0.495	1.480	0.854
10	3.32	0.673	0.505	1.514	0.871

From TABLE 2, it is clear that 1-m long lap joints have a lower resistance when made with rectangular wire than when made with round wire with the same cross-sectional area. The radius of the corner has a strong influence on splice resistance. The uncertainties in the calculation are the actual solder thickness and the length within the splice where the solder bond between the conductors is really good.

Calculation of the Splice Breaking Strength

For short splices, the breaking strength of the splice should be proportional to its length. Short splices fail because the solder in the splice has shear failure. If the splice is longer than its shear length, the conductor will not break in the splice. For typical soft solders, the shear failure stress τ_{sol} is from 20 to 35 MPa depending on the solder and the bond between the solder and the copper. The length below which solder shear failure occurs L_{sf} can be calculated using the following expressions for the two lap splices:

$$L_{sf} \approx \frac{\sigma_{ult}}{\tau_{sol}} t \text{, for up-down splices.} \tag{5}$$

$$L_{sf} \approx \frac{\sigma_{ult}}{\tau_{sol}} w \text{, for side-by-side splices.} \tag{6}$$

The ultimate failure stress in the insulated conductor is from 470 to 550 MPa (at 300 K). Depending on the shear strength of the solder the calculated shear failure length L_{sf} is from 13.4 to 27.5 mm for up-down splice; L_{sf} is from 21.5 to 44.0 mm for side-by-side splices. Since the coupling magnet spices are expected to be long (about 1-m), the conductor will break before the splice fails. The equations above assume there is a good bond between the conductors over the whole length of the splice. This may not be a valid assumption.

MEASURED RESISTANCE OF SOFT SOLDERED LAP SPLICES

LBNL measured the resistance of four splices that were about 1-meter long. These measurements were done at 4.2 K with the splices in a magnetic field up to 5 T. Two of the splices were up-down splices and two were side-by-side splices. One splice of each type used Sn96-Ag3.5-Cu0.5 solder (Sn-Ag solder), which melts at ~220 C. The other splice of each type was soldered using Sn63-Pb37 tin lead eutectic solder (Sn-Pb solder), which melts at ~185 C. For many room temperature applications, Sn-Ag solder is preferred, because it contains no lead. Most superconducting magnet groups use Sn-Pb (50-50, 60-40, or the tin lead eutectic) solder. A solder with lead in it does not become brittle at temperatures below 100 K. The lower melting point of these solders means that the heat treatment in the superconductor is not altered during soldering.

Four voltage taps are put across the splice as shown in FIGURE 3. The inner voltage taps are spaced 250 mm apart within the splice. This allows one to compare the normalized resistance of various regions in the solder lap splice. To calculate the normalized resistance of the splice or part of the splice, multiply the measured voltage drop times the length of the splice between the voltage taps and divide by the current across the splice.

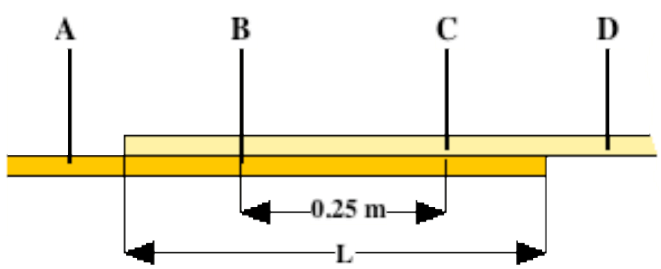

FIGURE 3. The Voltage Tap Arrangement used for measuring the Splice Resistance from A to D, A to C, B to C and B to D. (The voltage drop is measured as a function of the current across the splice.)

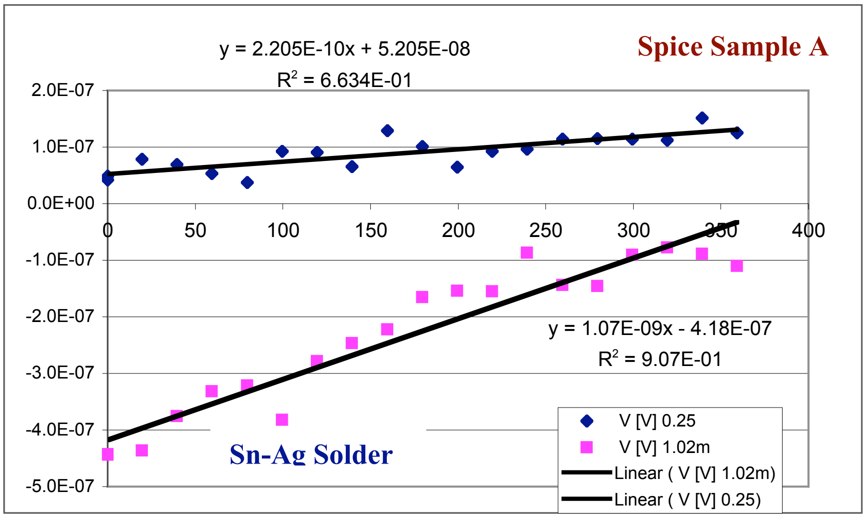

FIGURE 4. Raw Voltage Drop versus Current for the First Up-down ICST Splice measured at LBNL (Type of Solder 96Sn-3.5Ag-0.5Cu; L =1.02m, $L_{B\text{-}C}$ = 0.25 m; and B = 1T.)

FIGURE 4 shows the basic data for the first ICST splice measured at LBNL at 4.2 K in a magnetic induction of 1 T. The squares show the voltage of voltage tap A with respect to voltage tap D as a function of the current in the 1.02-meter long splice. The diamonds show the voltage of tap B with respect to the voltage of tap C (for the 0.25-meter center section of a 1.02-meter long splice) as a function of the current in the splice.

The overall resistance of splice R_J = 1.06 nΩ. The effective resistance of the splice center R_{JC} = 0.212 nΩ. When one looks at the normalized resistance for the whole splice R_{JN} and the normalized resistance of the splice center R_{JNC}, one finds that R_{JN} = 1.081 nΩ, and R_{JNC} = 0.859 nΩ. Since the center section normalized resistance is nearly the same as the total splice normalized resistance, the splice appears to be a well made. The solder thickness within the splice is not known.

It is useful to look at the normalized resistance of the all of the splices tested at LBNL. From these tests, one can determine the effect of the splice overall length and the effect of the solder resistivity. By comparing the normalized resistance of the splice center with respect to the splice as a whole, one can determine whether the quality varies along its length. The properties, resistances R_J and R_{JC} and normalized resistances R_{JN} and R_{JCN} of the ICST splices are shown in TABLE 3.

In splices A, B, and C the normalized resistance of the splice center section appears to be lower than the normalized resistance of the whole splice. This is an indication of a good quality splice from end-to-end. In splice D, the center section normalized resistance is significantly higher the normalized resistance of the whole splice. This indicates that the solder bond in the center section is not as good as at the ends.

TABLE 3. The Measured Splice Resistance R_J Center Section Resistance R_{JC} and the Normalized Splice Resistances R_{JN} and R_{JCN} at B = 1 T (The type of splice, the splice solder and the splice length are given.)

Splice	Splice Type	Splice Solder	Splice L (m)	Splice Resistance (nΩ)			
				R_J	R_{JC}	R_{JN}	R_{CN}
A	Up-down	Sn-Ag	1.02	1.06	0.212	1.08	0.86
B	Side-by-side	Sn-Ag	1.00	1.17	0.285	1.17	1.14
C	Up-down	Sn-Pb	1.04	1.20	0.207	1.25	0.86
D	Side-by-side	Sn-Pb	1.00	1.54	0.835	1.54	3.34

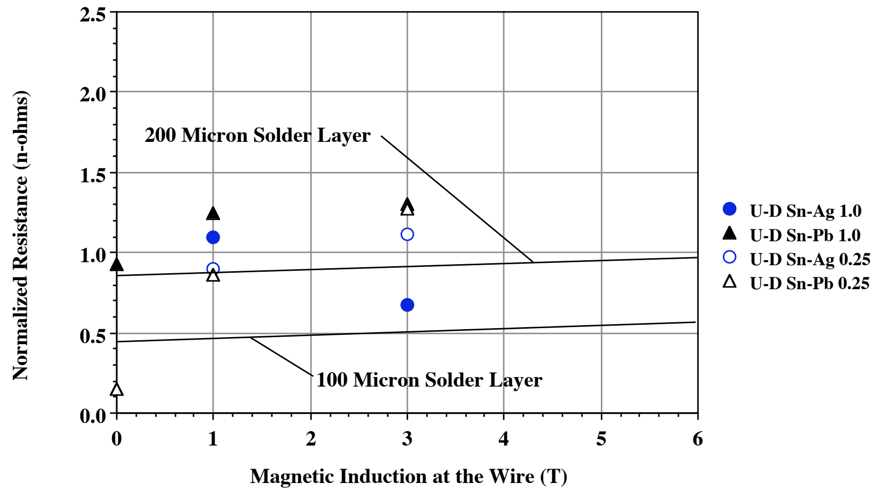

FIGURE 5. Normalized Resistance of Two Up-down Splices as a Function of Magnetic Induction, for both the Full length (~1.0 m) Splice and the Center (0.25 meter) Sections of the Splices.

FIGURE 5 shows the normalized resistance of the two side-by-side splices (one splice with each solder type) is plotted as a function of magnetic induction and section length.

MEASURED SPLICE BREAKING STRENGTH

All of the splice samples that were used for the break test were up-down splices that were about 250 mm long. In all cases, the splice length is greater than eight times the length where the splice itself should fail. The breaking stress for a single conductor is from 470 to 550 MPa. TABLE 4 shows the measured breaking stress for up-down splice samples as a function of temperature and the type of solder used to make the splice.

All of the splice samples broke in the conductor, not in the splice. The 300 K splices broke close to the splice. At 77 K, the samples broke at the 300 K ends of the samples. The 300 K samples exhibited no peel within the splice, after the break. Samples at 77 K using the Sn-Ag solder exhibited peel up to 100 mm within the splice. One 77 K sample that used the Sn-Pb solder exhibited a 7 mm peel, while the other exhibited no peel.

TABLE 4. Splice Type, Solder Type, Splice Length, Splice Temperature, and the Splice Failure Stress for Samples measured at Harbin (HA and HB) and the Lawrence Berkeley Lab (LR and LB)

Sample	Splice Type	Solder Type	Splice Length (mm)	Splice T (K)	Failure Stress (MPa)
HA-1	Up-Down	Sn-Ag	267	300	557
HA-2	Up-Down	Sn-Ag	271	300	536
HA-3	Up-Down	Sn-Ag	270	300	518
HB-1	Up-Down	Sn-Ag	255	77	536
HB-2	Up-Down	Sn-Ag	250	77	538
HB-3	Up-Down	Sn-Ag	251	77	530
LR-1	Up-Down	Sn-Pb	236	300	456
LR-2	Up-Down	Sn-Pb	235	77	516
LR-3	Up-Down	Sn-Pb	230	77	510
LB-1	Up-Down	Sn-Ag	232	300	474
LB-2	Up-Down	Sn-Ag	238	77	522
LB-3	Up-Down	Sn-Ag	233	77	510

CONCLUDING COMMENTS

From the theory it is clear that splice resistance is inversely proportional to the splice length and proportional to the thickness of normal material in the joint just as it is with HTS conductors [7]. We have demonstrated that 1-meter long splices within the MICE coupling coils can have a resistance that is at least five times smaller than the 10 nΩ required splice resistance. The splice resistance is low enough so that the L/R time constant for the coupling coil were it in persistent mode would be larger than 3 x 10^{11} s. The measured resistances are within a factor of two of the calculated resistances. The thickness of the solder layer in the splices is not known. Since the splices were hand made, the quality is somewhat uneven as demonstrated by comparing the normalized resistance of the center section compared to the splice as a whole. The MICE coupling coil will use up-down splices between layers at the ends of the coils. The splice technique within a magnet has been demonstrated on the ICST 1.5-meter inside diameter test coil [8].

The strength of the splices has been demonstrated using splice samples that are about 250-mm long. The length of the splice samples used for the breakage test were about an order of magnitude longer than the splice length where the splices would fail in shear. In all cases, the conductor being spliced broke in a room temperature part of the sample. None of the room temperature splice samples exhibited any peel within the splice, when they were broken. There was peel in many of the 77 K sample that were tested. The peel was significantly worse in the Sn96-Ag3.5-Cu0.5 solder samples as compared to the Sn63-Pb37 samples. The lead tin eutectic solder appears to be less prone to peel at low temperature. We recommend that this solder be used despite the fact that it contains lead. The solder melting point is lower and the solder is more ductile.

ACKNOWLEDGEMENTS

This work was supported by the fund for cryogenics and superconductivity engineering technology innovation, the second phase of the "985 Project" of the Harbin Institute of Technology. This work was also supported by the Office of Science of the US Department of Energy under DOE contract DE-AC-02-05CH11231.

REFERENCES

1. Gregoire, G,, Ryckewaert, G., Chevalier, L., et al, "MICE and International Muon Ionization Experiment Technical Reference Document," http://www.mice.iit.edu, 2001.
2. Wang, L., F. Xu, F. Y., Wu, H., et al, "Magnetic and Cryogenic Design of the MICE Coupling Solenoid Magnet System," *IEEE Transactions on Applied Superconductivity* **19**, No. 3, p 1344 (2009), MICE Note 234, http://www.mice.iit.edu.
3. Gou, X. L., Harbin Institute of Technology, private communication concerning the resistance of 6 mm^2 cross-section area butt splice.
4. Green, M., Dieterich, D. Higley, H. , et al, "The Calculated and Measured Resistance for Splices between Conductors in a MICE Superconducting Coil," MICE Note 238, , http://www.mice.iit.edu.
5. *Handbook of Materials for Superconducting Machinery*, Metal and Ceramics Information Center, MIC-MB-04, National Bureau of Standards, January 1977.
6. Heringhaus, F., and Painter, T. A., "Magnetoresistance of Selected Sn and Pb based solders at 4.2 K," *Materials Letters* **57**, Issue 4, pp 787-793, Elsevier BV (2002).
7. Baldan, C. A., Oliveira, U. R., Shigue, C. Y., and Filho, E. R., "Evaluation of Electrical Properties of Lap Joints for BSCCO and YBCO Tapes," *IEEE Transactions on Applied Superconductivity* **19**, No. 3, p 2831, (2009).
8. Xu, F. Y. Harbin Institute of Technology, private communication concerning splices with the large test coil for the MICE and MuCool coupling coils.