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The Electrical Resistance of Rutherford-Type Superconducting Cable Splices

S. Heck, C. Scheuerlein, J. Fleiter, A. Ballarino, and L. Bottura
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Keywords: Cables, inductance, interconnection, resistance, measurement.

Abstract

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I. Introduction

RUTHERFORD-TYPE cables are widely used for building accelerator magnet coils when the inductance of a magnet wound of a single wire would be too high. An advantage of these compact and flat cables, made for instance of Nb–Ti/Cu, Nb_3Sn/Cu strands, is that lap splices with a well-defined resistance can be relatively easily produced by soft soldering. As an example, the resistance of each of the about 10 000 main busbar cable splices of the Large Hadron Collider (LHC) [1] at 1.9 K in self-field (about 0.7 Tesla at maximum current) is 0.30 nΩ [2].

The LHC busbar cables are surrounded by an additional Cu stabilizer [3]. The LHC interconnection splices consist therefore of the Rutherford cable splices and the splices of the stabilizer profiles (see Fig. 1). During the first long LHC shutdown the resistance of all of the about 20 000 LHC Cu stabilizer profile splices has been measured at ambient temperature and the results are reported elsewhere [4].

The goal of this paper is to describe how the resistance of the superconducting Rutherford cable lap splices varies with the intercable contact area and with different cable defects. In addition we compare the resistance of the standard lap splices to that of another splice geometry connecting two side-by-side cables, as it could possibly happen to connect an inner and an outer layer inside a magnet.

Splice resistances have been measured in self-field at 4.3 K with two independent methods, notably by measuring the current decay time in test loops with known inductance, and by four-point resistance measurements with currents up to 27 000 A.

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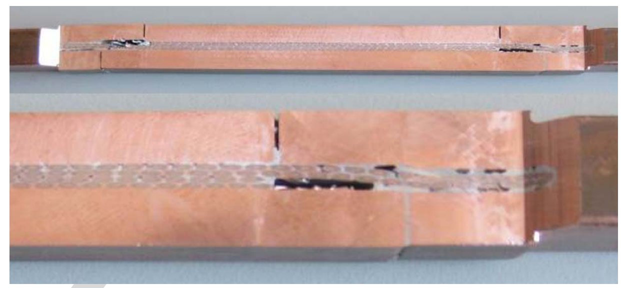

Fig. 1. Longitudinal cross section through an LHC main interconnection splice.

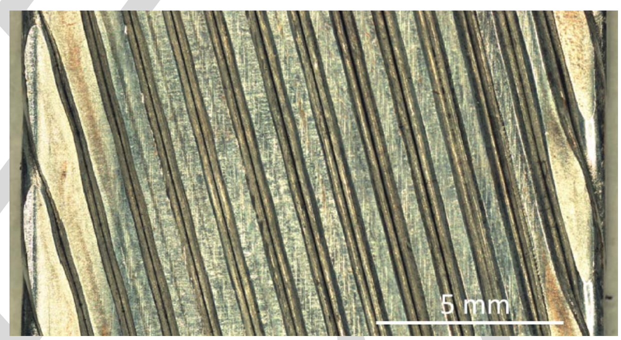

Fig. 2. Outer surface of an LHC-type 01 Rutherford cable.

II. Experimental

A. Rutherford Cable Splices

Splices made out of Nb–Ti/Cu LHC main busbar cable have been assembled by soft soldering, using inductive heaters [5]. The LHC superconducting strands are already coated with a 0.1 to 1 μm thin Sn–Ag layer [6]. In order to prevent the complete transformation into Cu_6Sn_5 and Cu_3Sn intermetallics [7], before connection the cable extremities have been pre-tinned in a resistively heated furnace. Soldering was performed using 0.2 mm thick Sn96Ag4 foil and non-activated rosin liquid flux Kester 135. During the soldering process with a peak temperature of 270 °C the residual resistivity ratio of the Cu matrix of the strands increases to about 200 [8].

The 15.1 mm wide LHC busbar cables consist of 36 strands with a nominal diameter of 0.825 mm. The cable mid-thickness is 1.48 mm and the keystone angle is $0.90 \pm 0.05°$. The cable transposition pitch is 100 ± 5 mm [9].

Fig. 2 shows the outer cable surface of an inner layer LHC dipole conductor. It can be seen that the initially round strands

Fig. 3. Both intercable contact areas after fracturing of an LHC busbar cable splice with 10 mm cable overlap length.

Fig. 4. LHC busbar cable test loops for current decay constant measurements. The cable splices have been prepared with different cable overlap lengths ranging from 3 to 120 mm.

are flattened during the cabling process, and that the cable cross section that is in contact with the opposing cable is significantly smaller than the projected cable area and depends on the strand diameter and the cable compaction.

The resistance of splices with cable overlap lengths varying between 3 and 120 mm has been measured. The overlap lengths have been measured after fracturing the splices during tensile tests at 4.3 K (see Fig. 3). The accuracy of the stated cable overlap lengths is ± 1 mm.

B. Resistance Measurements

Splice resistance measurements have been performed with two different methods, notably by measuring the current decay time in test loops, and by four-point resistance measurements.

Current decay measurements have been performed at the CERN Cryolab. The measurement of the current decay time in test loops with a well defined geometry [10] allows to determine very low splice resistances, which are difficult to determine otherwise. Some of the test loops made of the spliced Rutherford cables produced for this study are shown in Fig. 4.

The resistance R is determined from the loop inductance L and the current decay time constant $\tau(\mathrm{R} = \mathrm{L}/\tau)$. The inductance of 260 nH that has been calculated for a busbar cable loop with ideal dimension [11] is somewhat lower than the average loop inductance of 306 nH determined by comparing splice resistance results obtained by four-point measurements

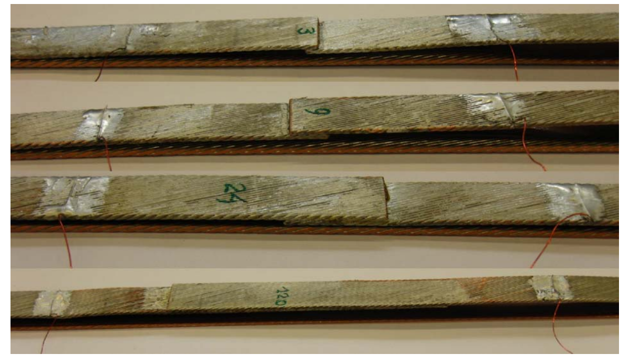

Fig. 5. Cable splices with 3, 9, 24, and 120 mm intercable contact lengths instrumented with voltage taps.

TABLE I
CURRENT DECAY CONSTANT τ OF 13 kA LHC BUSBAR CABLE SPLICES WITH DIFFERENT INTERCABLE CONTACT LENGTHS AT 4.3 K

splice length (mm)	τ (s)	*R (nΩ)
120	970±42	0.31
24	158±3.8	1.93
9.7	64.4±10	4.75
3.6	29.7±2.4	10.3

* The splice resistance R is calculated from τ, assuming a loop inductance of 306 nH.

and the decay constants for the loops made with the same splices. The experimentally determined value of 306 nH is used in the following.

Four-point resistance measurements in self-field at 4.3 K have been performed in the FRESCA test station [12]. Several splices are connected in series. The distance between the different splices is about 120 mm. The voltage taps are placed in a distance of 50 mm from each splice extremity. Photographs of the splices with 3, 9, 24, and 120 mm overlap lengths that were used for the four-point measurements are shown in Fig. 5.

III. RESULTS

A. Splice Resistance as a Function of Cable Overlap Length

Since the resistance in the superconductor along the continuous Nb–Ti filaments is zero, it can be assumed that the cable splice resistance is inversely proportional to the intercable contact area. In order to confirm this assumption resistance measurements have been performed with LHC busbar lap splices for which the overlap length has been varied between 3 mm and the nominal splice length of 120 mm.

The current decay constants determined with loops with lap splices (see Fig. 4) are summarized in Table I. The results shown are average values for three loops that have been produced for each nominal overlap length.

After the current decay constant measurements the loops were cut (see Fig. 5) so that the four-point splice resistance measurements could be performed. The voltages measured across the different splices at 4.3 K as a function of the test current up to 15 kA are presented in Fig. 6. Each data point has been averaged over a measurement time of 300 sec. The current

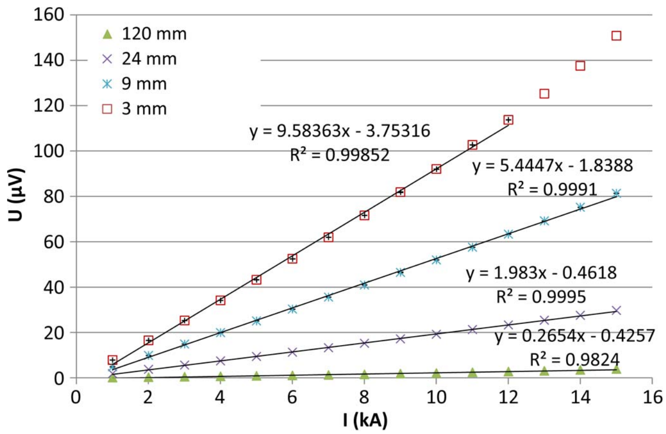

Fig. 6. Electrical potential U as a function of current I at 4.3 K without external field for splices with 3, 9, 24, and 120 mm intercable contact lengths.

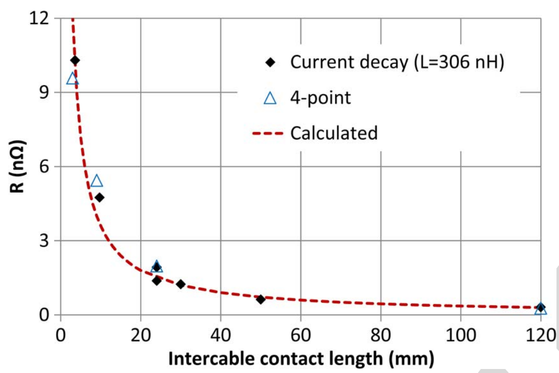

Fig. 7. Comparison of the measured and calculated LHC busbar cable splice resistances as a function of intercable overlap length.

ramp was about 300 A/s. Voltages below 2 μV have not been taken into account for the resistance calculations.

The 4.3 K resistances vary between 0.27 nΩ (1200 mm overlap) and 9.6 nΩ (3 mm overlap). For the 3 mm splice the data points above 12 kA have not been considered because they appear to deviate from the linear voltage–current relationship, possibly because the critical current in some or all strands is approached (the quench current of the 3 mm splice was about 17 kA).

In Fig. 7 the resistances measured for splices with different overlap length are compared with resistances that were calculated assuming that the splice resistance is inversely proportional to the contact length, and that a splice with 120 mm overlap length has a resistance of 0.30 nΩ, which is the average LHC busbar splice resistance measured *in situ* in the LHC [2]. It can be seen that in the contact length range 3–120 mm the splice resistance can be well predicted when the resistance of one splice overlap length is known.

B. Side-by-Side Cable Bridge Splice

The production of lap splices always requires some cable movement and bending, which is acceptable in case of ductile Nb–Ti/Cu cables, but may be a problem for brittle cables, like Nb_3Sn/Cu. A bridge splice can connect two side-by-side cables without any cable bending. In order to verify if the resistance of

Fig. 8. Splice with two side-by-side cables connected with one opposing cable.

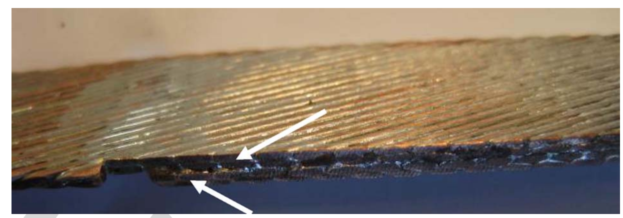

Fig. 9. Rutherford cable splice made with cables in which the strands of both opposing cables were cut on one side along the entire 120 mm overlap length.

such a bridge can be predicted with the simple assumption that the resistance is inversely proportional to the intercable contact area we have produced and tested the bridge splice shown in Fig. 8. The resistance of this splice is 1.31 nΩ.

The bridge splice can be considered as two lap splices that are connected in series. The intercable contact area of each of these is about half of that of a standard LHC lap splice. With this assumption a total resistance of two times $0.6\ \text{n}\Omega = 1.2\ \text{n}\Omega$ can be calculated, which is in reasonable agreement with the measured resistance of 1.31 nΩ.

C. Influence of Mechanical Defects on the Resistance of 120 mm Overlap Lap Splices

In order to determine the influence of different geometrical cable defects on the splice resistance, lap splices with 120 mm overlap length have been prepared using LHC busbar cable on which part of the strands had been cut. Fig. 9 shows a splice made of two cables with all strands cut on one side along the entire 120 mm intercable contact length.

As shown in Fig. 10 this defect increases the splice resistance to 0.45 nΩ, which is about 50% higher than the resistance of a defect free splice. A relatively strong resistance increase to 2.7 nΩ is obtained when all strands are cut along both cables on both sides of the splice.

The 120 mm splice resistances are summarized in Table II.

IV. Discussion and Conclusion

In the following discussion it is assumed that the influence of the solder resistance on the overall splice resistance can be neglected. This assumption is based on the resistivity results obtained for the solder material [13], and on resistance measurements of splices soldered with different solder alloys [14]. The resistance of Nb–Ti/Cu Rutherford-type cables lap

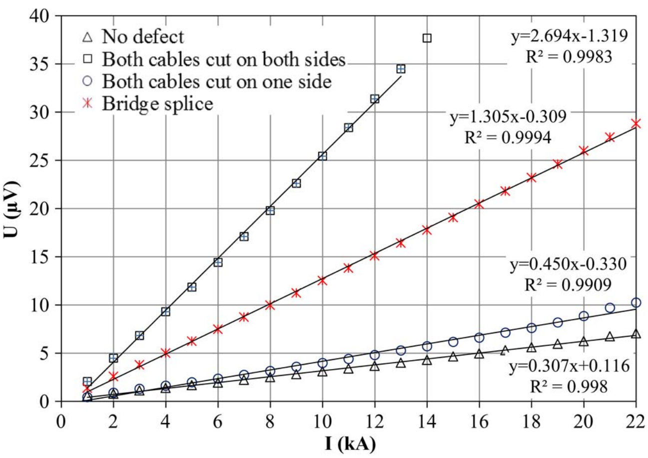

Fig. 10. Electrical potential U as a function of current I at 4.3 K without external field for splices with 120 mm intercable contact length and different defects. The results for the bridge splice of Fig. 8 is shown as well.

TABLE II
RESISTANCE OF 120 mm LONG 13 kA LHC BUSBAR CABLE SPLICES WITH DIFFERENT DEFECTS AT 4.3 K IN SELF-FIELD

Defect	R_{loop} (nΩ)*	$R_{4\text{-point}}$ (nΩ)
None	0.26±0.03	0.31
Bridge splice	n.m.	1.31
All strands of both cables cut on one side	0.48±0.07	0.45
All strands of both cables cut on both sides	n.m.	2.69

* Assumming a loop inductance of 306 nH.

splices can then be predicted from the Cu cross sections and the Cu RRR involved. This is also the case for Rutherford cables made of Nb_3Sn/Cu wires, provided that diffusion barriers do not strongly contribute to the splice resistance [13].

Since the resistance along the superconducting filaments of the continuous cable is zero it can be assumed that in longitudinal cable direction the current is uniformly distributed over the entire splice length, and the splice resistance is inversely proportional to the intercable contact length. This is confirmed by the resistance results obtained for the Rutherford cable lap splices produced with different overlap lengths (see Fig. 7).

The influence of single cut strands on the resistance of the LHC busbar cable splices is negligible. The extreme case where all strands are cut on both sides of the Rutherford cables along the entire splice length causes a resistance of about 2.7 nΩ.

The resistance results presented here have been obtained in self-field with a huge critical current density margin of the Nb–Ti superconductor. The application of external fields influences the resistance of internal magnet splices because of the additional Cu magnetoresistance, and in case the critical current density is exceeded in some strands by a current redistribution.

The resistance of a bridge splice can be estimated from the resistance of a lap splice produced with the same cable, and the intercable contact areas. Unlike lap splices, bridge splices allow to interconnect cables without any cable bending, which is important when brittle superconductors need to be connected. With a bridge splice a layer jump inside a Nb_3Sn magnet maybe possible. Further studies are needed to understand the performance of the different splice layouts in high applied fields.

Because of the strong field dependence of the critical current density of Nb–Ti and Nb_3Sn superconductors, there is always a huge margin in terms of critical current density for splices that are outside the high field region of a magnet. The critical current density of high temperature superconductors like Bi-2212 is only relatively weakly related to the applied field, and if such conductors are exploited at their full potential the I_c margin in self-field will be relatively small, so that the splice production and non-destructive splice tests will require particular attention.

ACKNOWLEDGMENT

We are grateful to M. Pozobon and O. Kalouguine for the production of the splices and to S. Prunet from the CERN Cryolab for the current decay constant measurements.

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AQ1 = Please provide publication update in Ref. [4].
AQ2 = Please provide publication update in Ref. [9].

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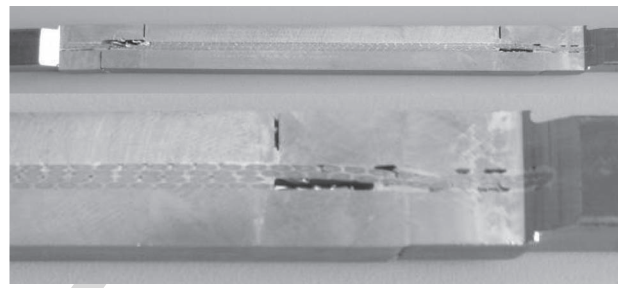

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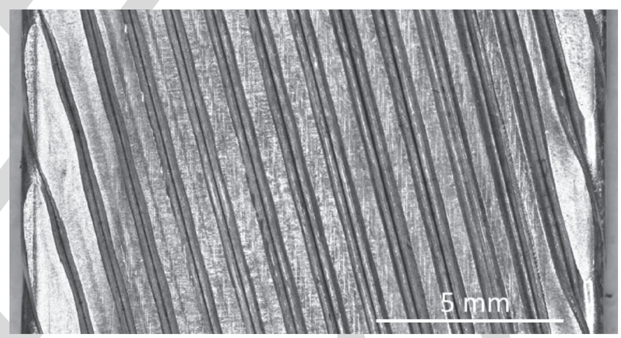

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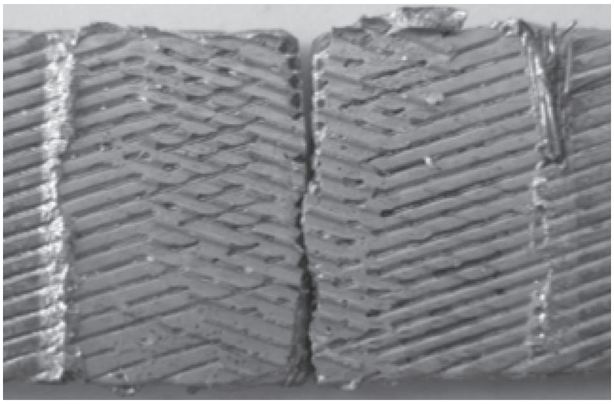

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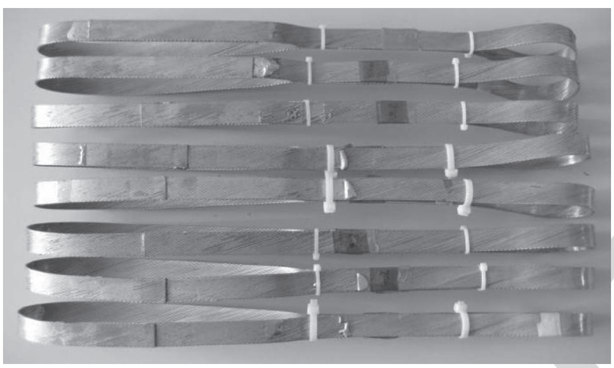

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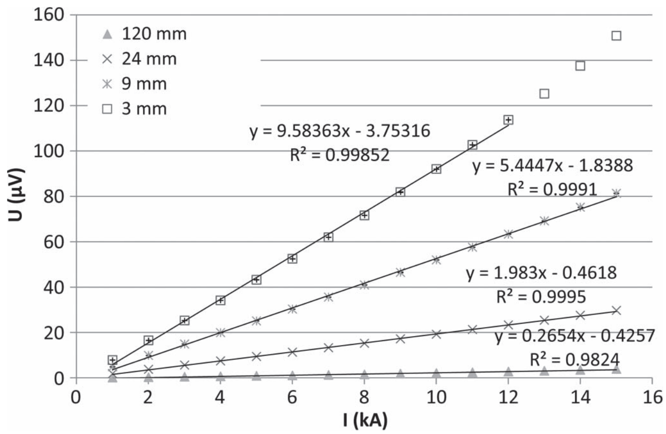

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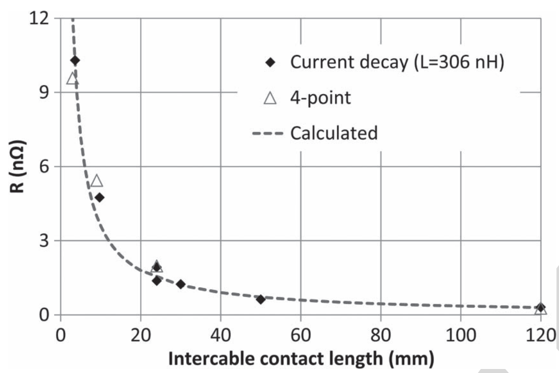

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The 4.3 K resistances vary between 0.27 nΩ (1200 mm overlap) and 9.6 nΩ (3 mm overlap). For the 3 mm splice the data points above 12 kA have not been considered because they appear to deviate from the linear voltage–current relationship, possibly because the critical current in some or all strands is approached (the quench current of the 3 mm splice was about 17 kA).

In Fig. 7 the resistances measured for splices with different overlap length are compared with resistances that were calculated assuming that the splice resistance is inversely proportional to the contact length, and that a splice with 120 mm overlap length has a resistance of 0.30 nΩ, which is the average LHC busbar splice resistance measured *in situ* in the LHC [2]. It can be seen that in the contact length range 3–120 mm the splice resistance can be well predicted when the resistance of one splice overlap length is known.

B. Side-by-Side Cable Bridge Splice

The production of lap splices always requires some cable movement and bending, which is acceptable in case of ductile Nb–Ti/Cu cables, but may be a problem for brittle cables, like Nb_3Sn/Cu. A bridge splice can connect two side-by-side cables without any cable bending. In order to verify if the resistance of such a bridge can be predicted with the simple assumption that the resistance is inversely proportional to the intercable contact area we have produced and tested the bridge splice shown in Fig. 8. The resistance of this splice is 1.31 nΩ.

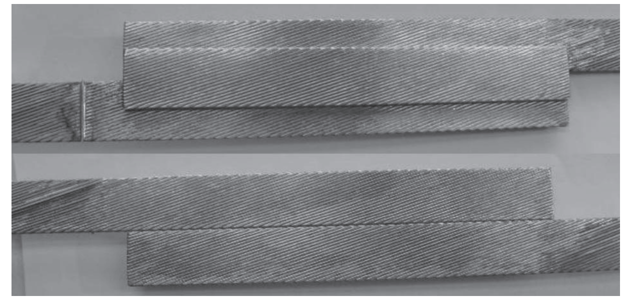

Fig. 8. Splice with two side-by-side cables connected with one opposing cable.

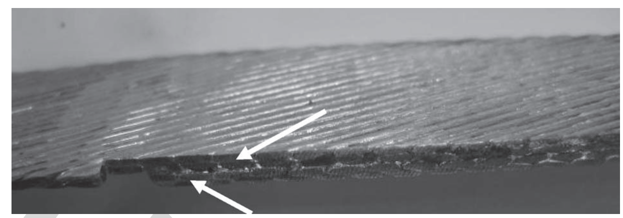

Fig. 9. Rutherford cable splice made with cables in which the strands of both opposing cables were cut on one side along the entire 120 mm overlap length.

The bridge splice can be considered as two lap splices that are connected in series. The intercable contact area of each of these is about half of that of a standard LHC lap splice. With this assumption a total resistance of two times $0.6\ \text{n}\Omega = 1.2\ \text{n}\Omega$ can be calculated, which is in reasonable agreement with the measured resistance of 1.31 nΩ.

C. Influence of Mechanical Defects on the Resistance of 120 mm Overlap Lap Splices

In order to determine the influence of different geometrical cable defects on the splice resistance, lap splices with 120 mm overlap length have been prepared using LHC busbar cable on which part of the strands had been cut. Fig. 9 shows a splice made of two cables with all strands cut on one side along the entire 120 mm intercable contact length.

As shown in Fig. 10 this defect increases the splice resistance to 0.45 nΩ, which is about 50% higher than the resistance of a defect free splice. A relatively strong resistance increase to 2.7 nΩ is obtained when all strands are cut along both cables on both sides of the splice.

The 120 mm splice resistances are summarized in Table II.

IV. Discussion and Conclusion

In the following discussion it is assumed that the influence of the solder resistance on the overall splice resistance can be neglected. This assumption is based on the resistivity results obtained for the solder material [13], and on resistance measurements of splices soldered with different solder alloys [14]. The resistance of Nb–Ti/Cu Rutherford-type cables lap

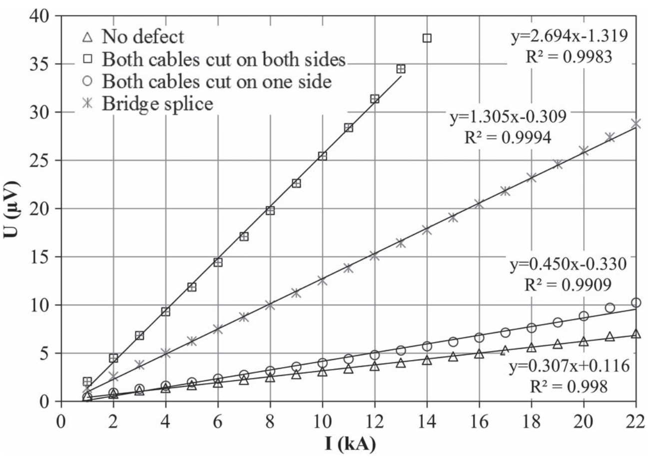

Fig. 10. Electrical potential U as a function of current I at 4.3 K without external field for splices with 120 mm intercable contact length and different defects. The results for the bridge splice of Fig. 8 is shown as well.

TABLE II
RESISTANCE OF 120 mm LONG 13 kA LHC BUSBAR CABLE SPLICES WITH DIFFERENT DEFECTS AT 4.3 K IN SELF-FIELD

Defect	R_{loop} (nΩ)*	$R_{4\text{-}point}$ (nΩ)
None	0.26±0.03	0.31
Bridge splice	n.m.	1.31
All strands of both cables cut on one side	0.48±0.07	0.45
All strands of both cables cut on both sides	n.m.	2.69

* Assumming a loop inductance of 306 nH.

splices can then be predicted from the Cu cross sections and the Cu RRR involved. This is also the case for Rutherford cables made of Nb_3Sn/Cu wires, provided that diffusion barriers do not strongly contribute to the splice resistance [13].

Since the resistance along the superconducting filaments of the continuous cable is zero it can be assumed that in longitudinal cable direction the current is uniformly distributed over the entire splice length, and the splice resistance is inversely proportional to the intercable contact length. This is confirmed by the resistance results obtained for the Rutherford cable lap splices produced with different overlap lengths (see Fig. 7).

The influence of single cut strands on the resistance of the LHC busbar cable splices is negligible. The extreme case where all strands are cut on both sides of the Rutherford cables along the entire splice length causes a resistance of about 2.7 nΩ.

The resistance results presented here have been obtained in self-field with a huge critical current density margin of the Nb–Ti superconductor. The application of external fields influences the resistance of internal magnet splices because of the additional Cu magnetoresistance, and in case the critical current density is exceeded in some strands by a current redistribution.

The resistance of a bridge splice can be estimated from the resistance of a lap splice produced with the same cable, and the intercable contact areas. Unlike lap splices, bridge splices allow to interconnect cables without any cable bending, which is important when brittle superconductors need to be connected. With a bridge splice a layer jump inside a Nb_3Sn magnet maybe possible. Further studies are needed to understand the performance of the different splice layouts in high applied fields.

Because of the strong field dependence of the critical current density of Nb–Ti and Nb_3Sn superconductors, there is always a huge margin in terms of critical current density for splices that are outside the high field region of a magnet. The critical current density of high temperature superconductors like Bi-2212 is only relatively weakly related to the applied field, and if such conductors are exploited at their full potential the I_c margin in self-field will be relatively small, so that the splice production and non-destructive splice tests will require particular attention.

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AQ1 = Please provide publication update in Ref. [4].
AQ2 = Please provide publication update in Ref. [9].

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