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MEASUREMENT OF AN INTERNAL JOINT AND A LAYER-TO-LAYER JOINT AS A FUNCTION OF THE MAGNETIC FIELD

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Abstract

We have measured the resistance of an internal (repair) joint, 510 mm long, as a function of an applied magnetic field from 0 to 4 T. In the same experimental set-up we have also measured: i) the matrix aluminium RRR; ii) the contact resistance between the Rutherford cable and the matrix and iii) the resistance of a layer-to-layer joint, 105 mm long.

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CONTENTS

1 INTRODUCTION

We have already presented [1,3] our facility to measure the joint resistance. In this instrumentation the sample is made out of two pieces of conductor, in which an equal and opposite current flows (see Fig. 1). This arrangement was chosen with the aim of cancelling -at a first order- the forces exerted by the external magnetic field. In the present experiment the lower conductor contains an internal (repair) joint, while the upper one acts –in principle- only as a return line.

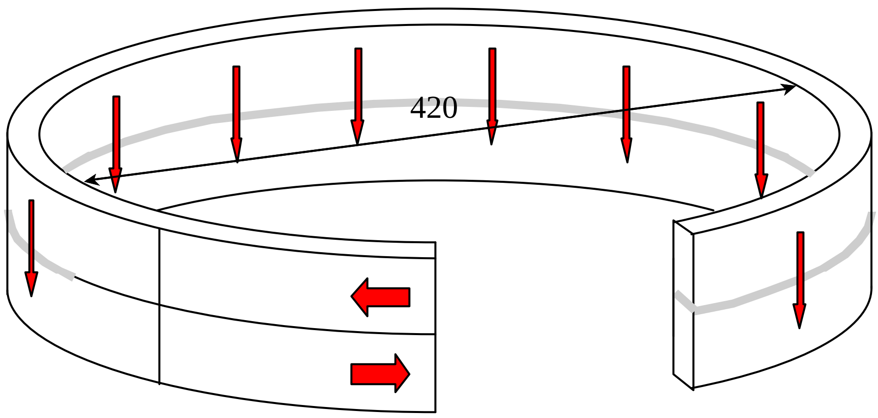

FIG. 1: Sample layout composed of two conductors welded along their narrow faces. The arrows describe the current flow. This sample was used for specific resistance measurements, already presented [2,3,4].

The two conductors are insulated from each other but at their extremities, where the current contact is provided by a connection 105 mm long with exactly the same characteristics of a layer-to-layer joint. Since our facility allows measuring up to eight voltage drops with high accuracy, we decided to make good use of the upper conductor also. We machined a slot about 50 mm long close to the centre of the conductor to remove the Rutherford cable. In this way the current is forced out from the superconductor and then back inside. The total voltage drop far from the slot is then the sum of the contributions of twice the superconductor-Al matrix interface resistance plus the aluminium resistance. The voltage drop along the slot is also measured; in this way the contribution of the aluminium resistance may be evaluated and then subtracted, leaving only the contact resistance.

2 SAMPLE PARAMETERS

The multipurpose sample used in these measurements is shown in Fig. 2, along with the position of the voltage taps 1-6. The last two channels (7-8) were short circuited and kept close to the sample, in order to act as 'noise monitors'.

The repair joint is 510 mm long, performed according to the procedure [5,6,7] depicted in Fig. 8: it was made with two sections of the 27/Nov/98 test conductor, while the upper conductor came from the February 98 extrusion test (this last one was done with a 38 strand Rutherford). The central part is nearly 400 mm long and the two tapered extremities are about 50 mm each. The two parts were welded all along their narrow sides, but not on the broad side of the conductor, in order not to get too close to the Rutherford insert. We assume an uncertainty on the length of +/- 20 mm, due to the fact that the welding is not homogeneous at the ends. The inhomogeneities along the joint and the end effects were not estimated explicitly, but they are likely to introduce a relative error similar to the one found in layer-to-layer joint. The temperature during the welding process was monitored with a thermocouple, and it never exceeded the peak value of 350 °C, reached for few seconds. The chamfer was at 45° and 5 mm deep. As filler material we used a pure aluminium wire, made by drawing the aluminium coming from the matrix of a similar conductor. We also measured the filler RRR, which was 980±50.

The joint between lower and upper cables was again obtained by TIG-welding the terminals of the two conductors along their narrow side on a length of about 105 mm, by means of a similar chamfer. It is therefore similar to that used in the BT/B0 magnets to connect the two pancakes composing a coil. The slot on the upper cable was 50 x 27 mm^2 and the voltage taps inside were about 20 mm apart. The end sections of the conductors were etched with NaOH, to remove completely the Al matrix; then the bare Rutherfords were used as current connections.

3 EXPERIMENTAL PROCEDURE

Although our power supply is capable of 30 kA, we found very difficult to make measurements with it due to the extremely high level of noise, typically in the range 10µV-1mV, much greater than the signals we were looking for. We therefore adopted a lead-acid battery-based power supply, used for the single strand Ic measurement. The highest current is much lower (with the configuration used we could go only up to 1.5 kA) but the noise level was sufficiently low to observe clear signals. The current was changed in a stepwise fashion, making measurements according to the following general scheme: 0 A, 0.5-0.8 Imax, Imax, 0.5-0.8 Imax,

0. In this way we could determine the presence of non-linearities and hysteretic behaviours, which nonetheless never appeared. The typical measurement length was about 1000-2000 s. Measurements in magnetic fields (0, 0.5, 1, 2, 3 and 4 tesla) were performed by means of our SOLEMI facility.

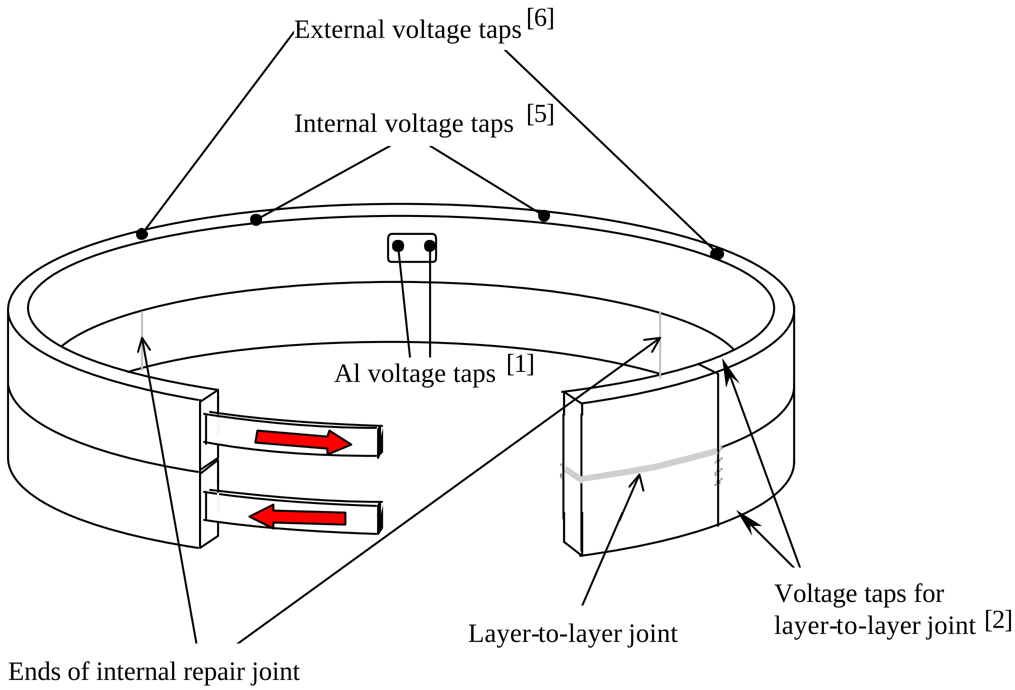

FIG. 2: The new sample is similar to the previous one (Fig. 1) except for a reduced layer-to-layer joint length and the presence of an internal joint in the lower conductor. Voltage taps 3 and 4 are not visible but positioned in a symmetrical way as 5 and 6 across the repair joint.

4 DATA ANALYSIS

Two examples of measurements are shown in Fig. 3 (B = 0 T) and Fig. 4 (B = 2 T); each voltage step contains typically 50-150 points. Voltage measurements taken at the same current were averaged, after discarding the first ones that could be affected by transient behaviour. The graph with the (averaged) voltage signals vs. current for the first measurement is shown in Fig. 5. The error of the single point in figure was determined as the r.m.s. of the mean. A weighted least squares straight fit was used to estimate the resistances, along with their errors. The resistance values of the joints are multiplied by the joint lengths themselves, giving a specific resistance in $\Omega\cdot$m. Now let us analyse the different quantities under investigation.

4.1 Aluminium RRR

As explained, the aluminium resistance was measured by interrupting the Rutherford cable and forcing the current to flow in the Al matrix. Typical values at 4K were of the order of 1-3 nΩ, with an accuracy of 1-3%, while the value at room temperature (T = 23 °C), was 1.17μΩ, with an error less than 1%.

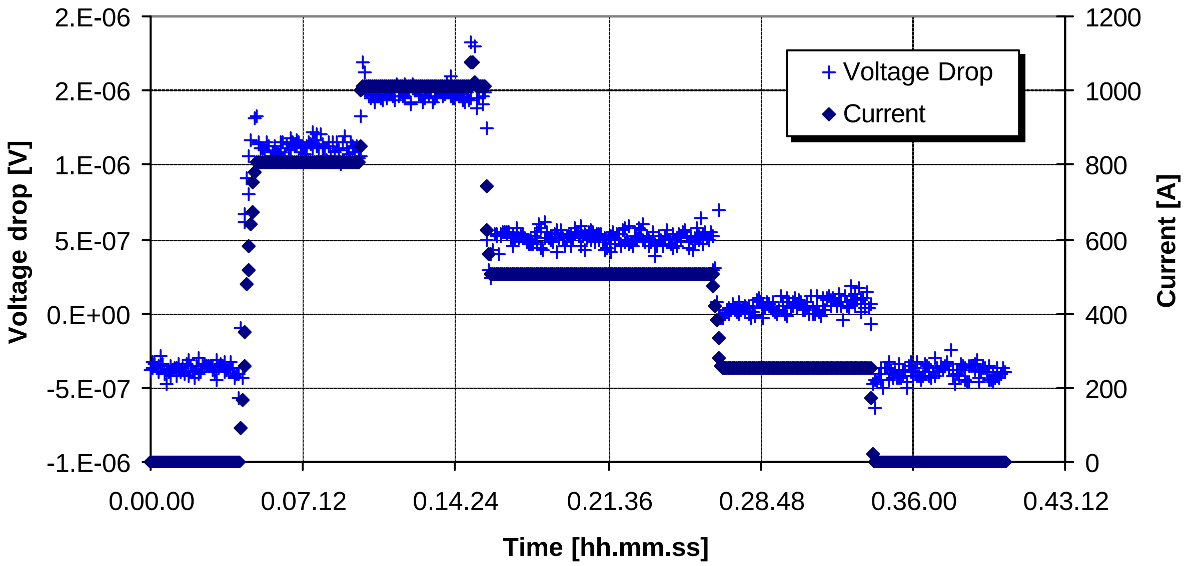

FIG. 3: An example of our measurements with no applied external magnetic field: the layer-to-layer voltage drop and current vs. time. Inductive transient signals are clearly visible, with a decay time constant of few seconds.

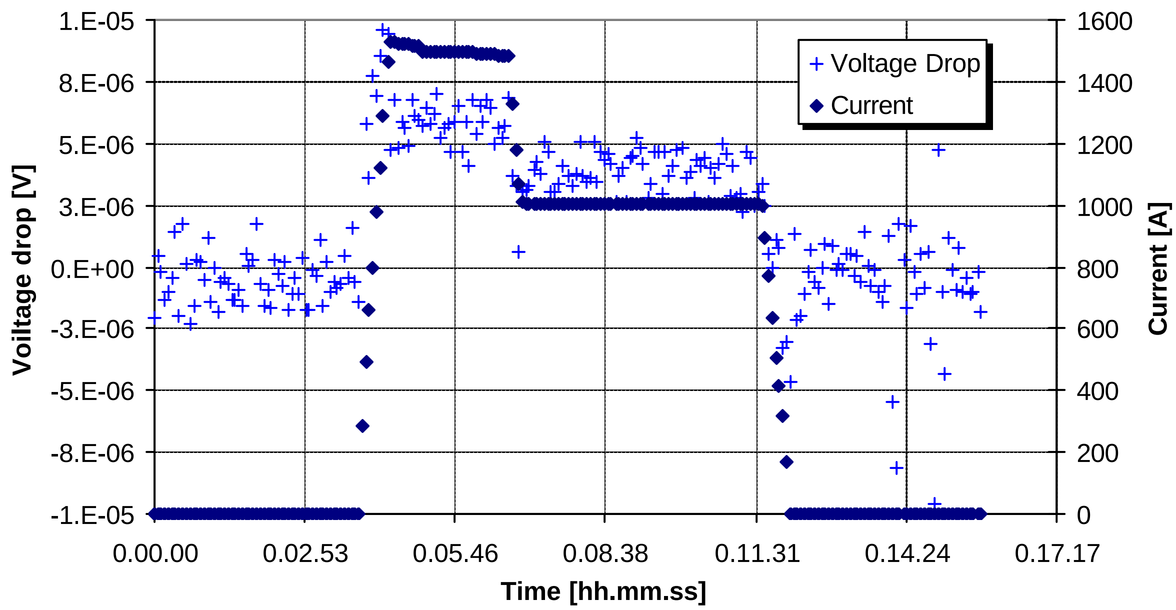

FIG. 4: Applying an external magnetic field the noise level grows. Here a 2 T magnetic field was present, leading to a disturb still acceptable.

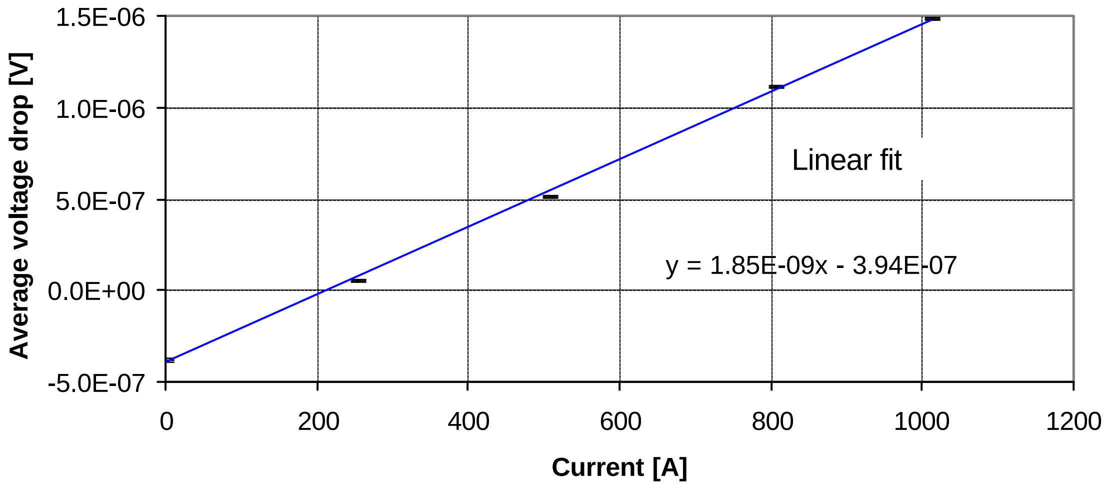

FIG. 5: Average voltage drop values are plotted as a function of the current fed; the resulting resistance is derived by means of a weighted least squares straight fit. Notice the absence of hysteresis.

This last uncertainty is mostly due to the fact that the voltage drop depends on the precise position of the voltage taps, which were dismounted and then mounted again between the measurements in liquid Helium and at room temperature.

The RRR is defined as R(273K)/R(4K). To scale the room temperature value at 273K we have assumed [8] $dR/(RdT) = 0.0039\ K^{-1}$, giving 1.07 μΩ @273K. The RRR as a function of magnetic field is shown in Fig. 6, and the numerical values are reported in Table 1. From measured values of the Al matrix resistance it is also possible to obtain its magnetoresistance, also shown in Fig. 6.

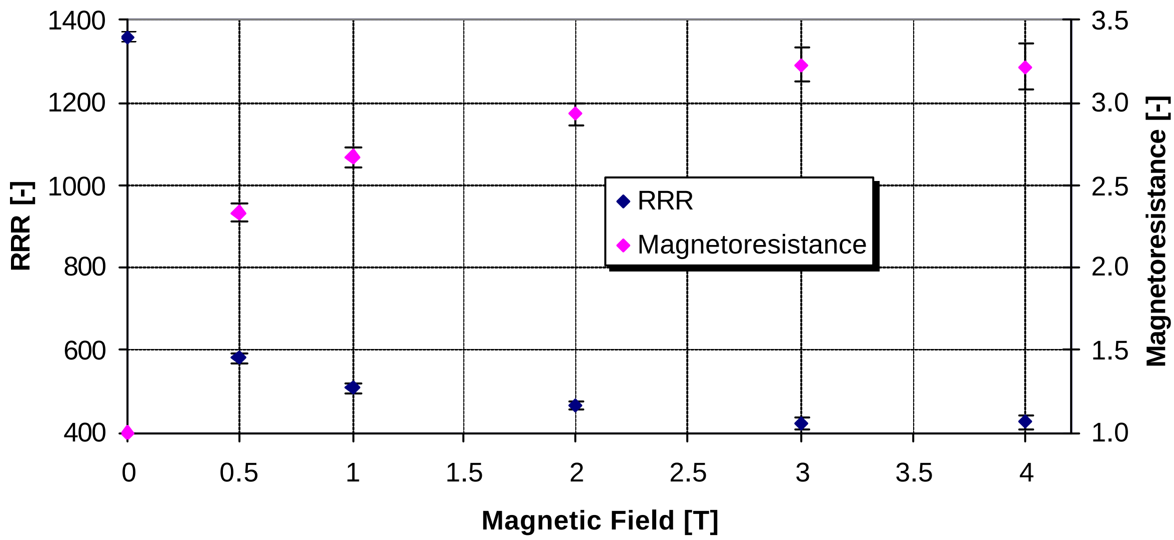

FIG. 6: Aluminium RRR as a function of B and its "reciprocal", the magnetoresistance.

B[T]	RRR	R_l-to-l joint [W ·m] (x10^{-10})	R_int. joint [W ·m] (x10^{-10})	R_{cont} [W ·m] (x10^{-10})	tr. length [mm]
0	1362 ± 14	1.93 ± 0.18	1.24 ± 0.12	0.15 ± 0.007	22 ± 6
0.5	581 ± 12	2.85 ± 0.28	2.08 ± 0.30	0.22 ± 0.03	17 ± 6
1	509 ± 12	3.53 ± 0.36	3.08 ± 0.57	0.32 ± 0.05	20 ± 6
2	463 ± 10	4.56 ± 0.46	3.2 ± 1.2	0.67 ± 0.09	27 ± 6
3	420 ± 14	5.40 ± 0.56	4.6 ± 1.9	1.07 ± 0.21	33 ± 6
4	423 ± 18	6.12 ± 0.64	4.1 ± 2.0	1.99 ± 0.50	45 ± 7

Table 1. Measured quantities as a function of the applied magnetic field.

4.2 Layer-to-layer joint.

The upper and lower conductors were welded along their narrow side for a length of 105 mm. This joint was similar, but for its length, to the layer-to-layer joint to be used between the BT pancakes. The results are reported in Table 1 and their graph is shown

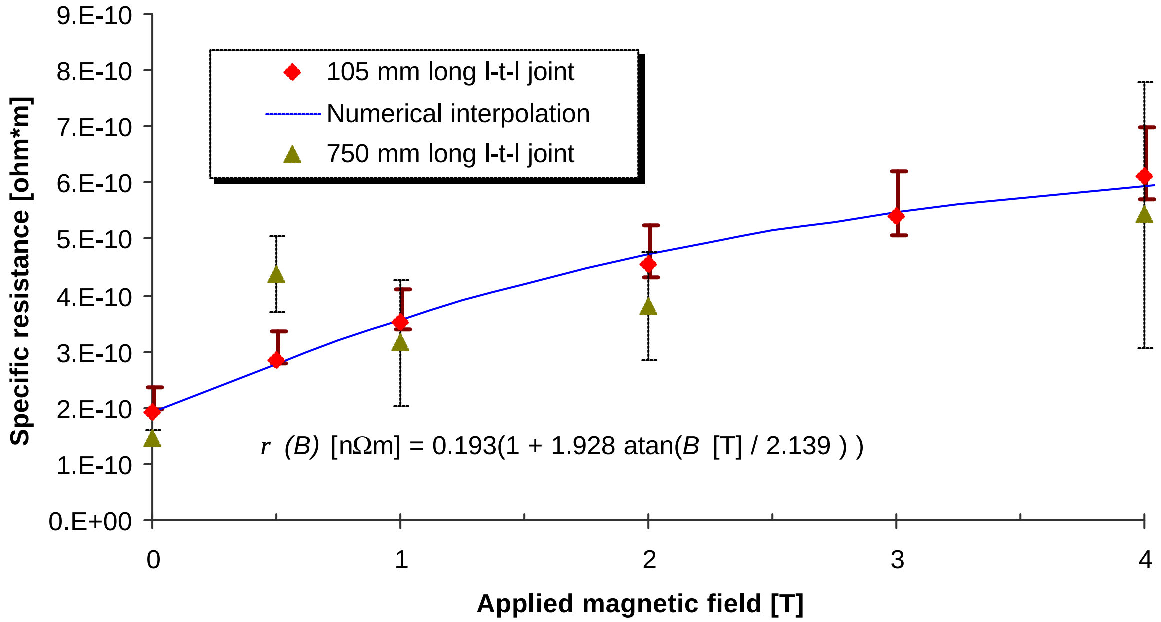

FIG. 7: Comparison between layer-to-layer joint measurements.

in Fig. 7, along with the results from the previously measured layer-to-layer joint sample, 721 mm long, already published [2,3,4]. The agreement is satisfactory at fields of 1 T or larger; the measurements at 0.5 T do not agree each other. We have re-analysed the previous measurement at 0.5 T finding no obvious error. Nonetheless we are prone to discard this point since it is manifestly out of the trend well established by the other points. Also the points at 0 T do not agree each other, but in this case this is easily explainable, since the *precise value* of specific resistance depends on geometrical factors, which are not well controlled from one joint to the other; at higher fields, this discordance is overwhelmed by the experimental errors. The difference between the two values at 0 T is $4.80 \cdot 10^{-11}\ \Omega \cdot m$, to be compared with $2.37 \cdot 10^{-11}\ \Omega \cdot m$, the squared sum of their errors. The effect of magnetoresistance is instead, so to speak, an absolute effect, since it should be independent from form factors. The conclusion of [3], according to which the specific resistance is basically that coming from the aluminium resistance, is therefore not correct. As last remark we should not forget that the 105 mm joint is shorter than the Rutherford transposition pitch, and this could introduce some non-uniformity.

4.3 Internal joint.

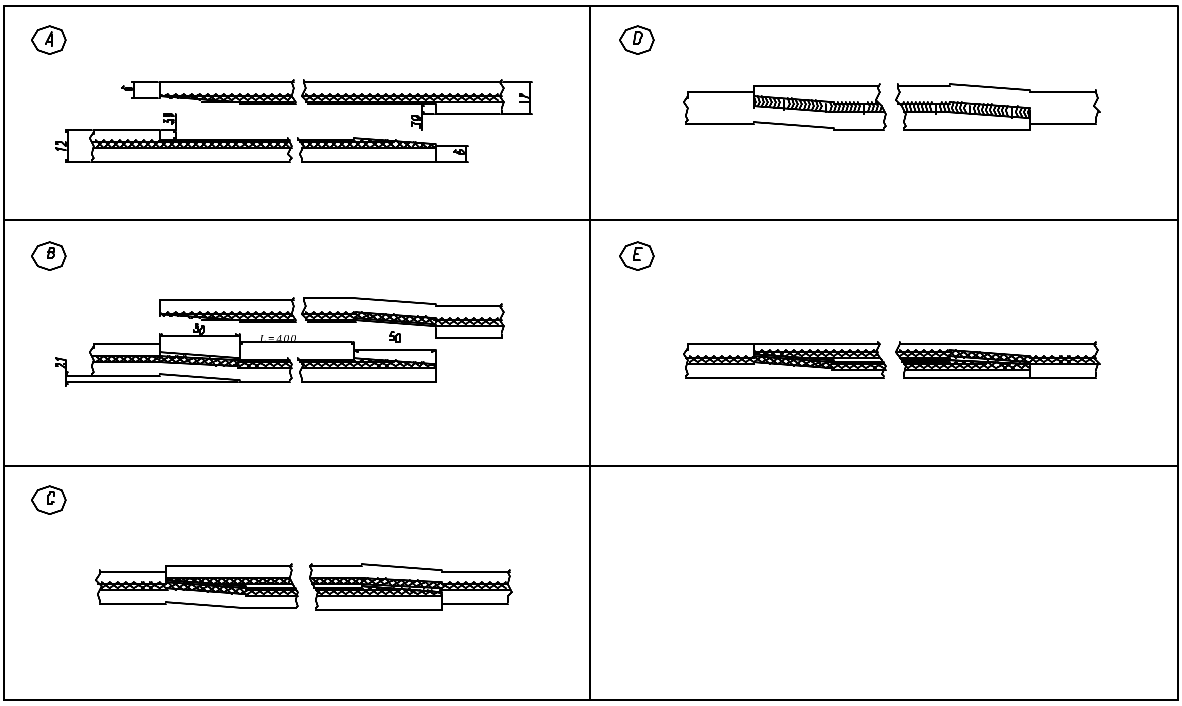

FIG. 8: Sequence of the operations to perform a TIG-welded repair joint along ATLAS cables [4].

The internal joint scheme is as in Fig. 8. As with the layer-to-layer joint we report the specific resistance. The results are shown in Fig. 9. The high noise level, due to the strong coupling with the applied magnetic field, lowers significantly the accuracy of the measurements.

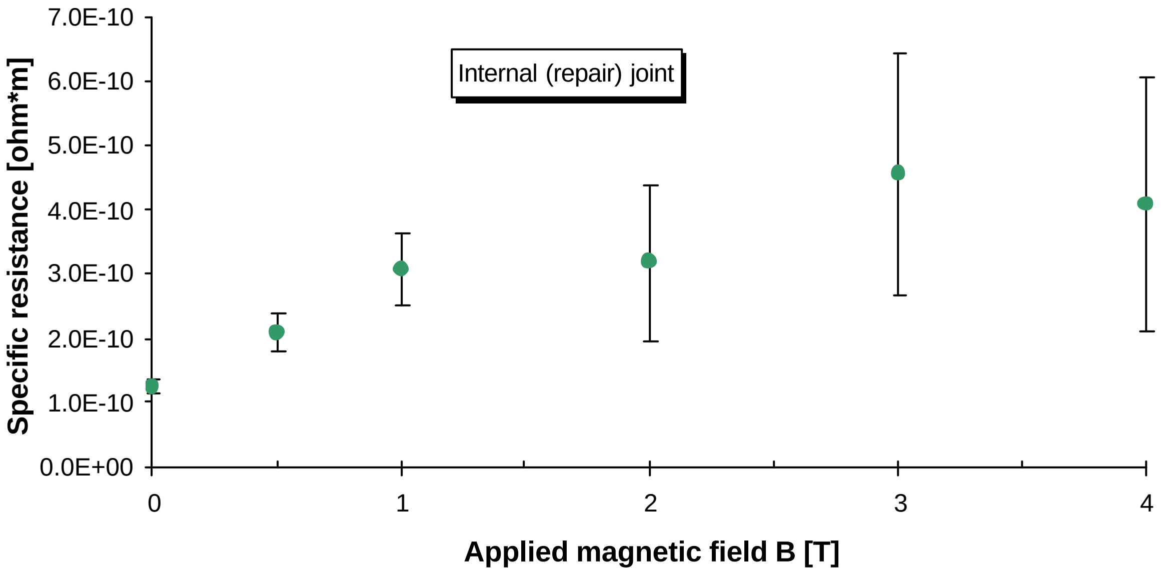

FIG. 9: Internal (repair) joint specific resistance vs. external field

4.4 Contact resistance and transfer length.

As shown elsewhere [3,9,10)], the specific resistance is explainable as the effect (though not simply addictive) of bulk's aluminium resistance, interface resistance and welding degradation. Aluminium degradation due to the welding technique is not easy to determine and can be partially controlled by standardizing the welding procedure.

The interface resistance is instead an index of the quality of the contact between the superconducting cable and the aluminium stabilizer and can be deduced by interrupting the superconducting cable and forcing the current to transfer in the matrix and then in the cable again, thus measuring the voltage drop far from this point. The resulting value of contact resistance, R_{cont} is equal to:

$$R_{cont} = \frac{(R_j - c \cdot R_1)^2}{4 \cdot R_{Al}} \quad , \qquad (1)$$

where R_j is the resistance corresponding to the upper conductor, far from the machined slot, R_1 is the resistance of aluminium between voltage taps 1, which can be scaled to the total Al resistance between the interrupted section of the Rutherford by multiplying it for a proper form factor χ (we assumed an error of 20%) and R_{Al} is the aluminium resistivity at 4.2 K times the magnetoresistance divided the matrix area. R_{cont} is therefore expressed in $\Omega \cdot$m.

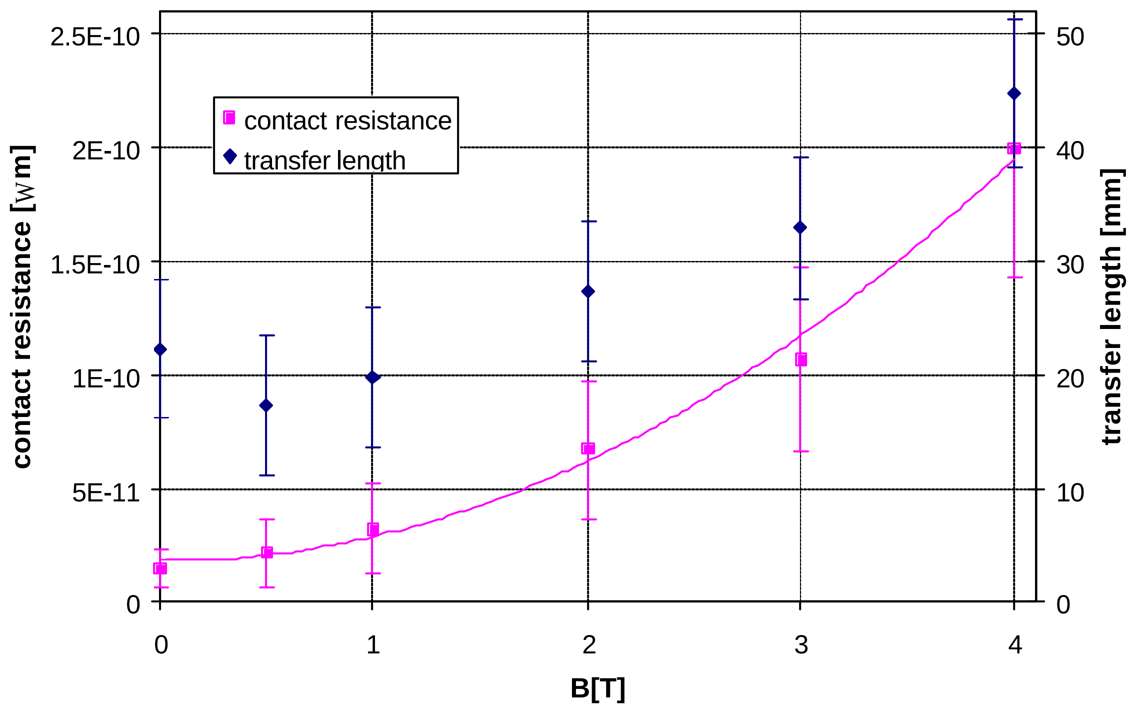

FIG. 10: Contact resistance and transfer length as a function of magnetic field; contact resistance can be fitted by a parabolic curve.

Connected to the contact resistance is the transfer length λ, that is the distance within which the current is almost completely transferred into the superconductor. The two quantities are related in the following way [11)]:

$$l = \sqrt{\frac{R_{cont}}{R_{Al}}} \quad . \tag{2}$$

It is important to observe the apparently anomalous behaviour of the transfer length as shown in the above figure, where λ initially decreases and then grows; this is explainable considering that magnetoresistance saturates almost immediately while the resistance in the upper conductor grows approximately linearly becoming predominant at high fields.

The voltage taps distance for total voltage drop inside the upper conductor should be at least twice the double transfer length (plus the slot dimension); as can be seen in Fig. 10 and in Table 1, this is achieved with a length exceeding about 250 mm, condition which was well satisfied in our sample, both by taps 5 and 6.

5 CONCLUSIONS

The multipurpose sample measured allowed us to deduce important informations about the two kinds of junction that could be used in the ATLAS Barrel Toroid: layer-to-layer and internal junctions. They confirmed the results already obtained on the first joint-test sample, apart from minor discrepancies.

We could measure the matrix aluminium bulk resistance as well as the contact resistance between the Rutherford cable and the matrix itself.

6 ACKNOWLEDGEMENTS

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