BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division
Magnet Note

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Title: Intercoil Connections for HTS Magnets

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Intercoil Connections for HTS Magnets

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Abstract

Measurements are presented on joints between sections of stainless steel clad BSCCO HTS ribbon conductor. The resistance of such connections calculated from the properties of the stainless foil agree with the measured values within 10%.

Introduction

Due to conductor length limitations HTS magnets are usually made up from a number of spiral wound "pancake" coils. These coils are connected together in pairs on the inner turn to form "double pancakes" and the magnet itself is built up of an array of such double pancakes by connecting neighbouring coils together on the outer turn. This procedure has the advantage of allowing the preliminary testing of individual sub-units but results in a large number of joints in the finished magnet so that the technique used for interconnecting coils must be simple, reliable and produce low resistance joints. The conductor used in the RIA prototype quadrupole is laminated on both sides with a thin layer of stainless steel which significantly improves the mechanical properties of the HTS ribbon. American Superconductor Corporation (ASC), the manufacturer of this tape does not recommend removing the stainless cladding at the joints because of deterioration of the superconducting characteristics of the conductor. ASC further recommends the use of a low temperature solder such as indium and a special flux for making joints in this material.

Joint Testing Procedure

The method used to test joints is shown schematically in Fig. 1a. Two lengths of conductor representing the two coils in a double pancake are positioned on the test fixture so that the spacing between them approximates the separation between coils and a short length of conductor or "jumper" is soldered between them. Additional jumpers, indicated by the dotted lines in Fig. 1a are added in parallel to further reduce the resistance of the connection. The critical current of the conductors is determined from the V-I characteristics of the sections labeled A-B and E-F in the diagram. B-C and D-E are used to check the properties of the portions of the tape that are actually involved in the joint and C-D gives the voltage drop across the splice. Fig. 1b shows the details of the soldered connection. The upper portion of the "jumper" is a short length (~ 1 cm.) of silver matrix ribbon that has been coated with indium. The lower section of Fig. 1b represents the stainless clad tape that forms the coil. To get from one half of a double pancake to the other half the current must pass from the superconducting filaments through the silver layer on the outside of the conductor, then through the stainless steel layer and the silver on the jumper into the filaments of the jumper and repeat the process in reverse into the filaments of the other half coil.

ASC provided BNL with sample lengths of both stainless clad (high strength) and bare (high current density) ribbons for joint testing and evaluation. For the clad material the resistance from coil to coil is dominated by the resistivity of the stainless steel and can be readily calculated from the dimensions and measured properties of the cladding. In the case of bare ribbons the effect of filament surface conditions makes it difficult to calculate the coil to coil resistance. In Table I below, the first two columns give the measured resistance in μohm for joints made up using from one to four jumpers in parallel, for both clad and bare conductor, measured at 77 K and up to 100 amps.

Table I

Number of Jumpers	Stainless Clad Resistance, μohm	Non-Clad Resistance, μohm	Calculated SS Resistance, μohm	Ratio SS_{meas}/SS_{calc}
1	3.34	0.30	2.85	1.07
2	1.70	0.15	1.42	1.09
3	1.10	0.09	0.95	1.06
4	0.86	0.07	0.71	1.11

The third column is the calculated resistance due to the stainless foil. Measurements on samples of this foil give a room temperature resistivity of 78 μohm-cm and a resistance ratio of 1.41 at 77K. The fourth column was formed by subtracting the bare conductor resistance from the clad resistance to get the stainless contribution to the resistance and then dividing by the calculated value. This column indicates that the measured values are approximately 10% higher than the calculated values, possibly due to the solder used in cladding the high strength conductor. Fig. 2 is a plot of the joint resistance against the reciprocal of the number of jumpers. As expected this graph is linear and extrapolates to zero for an infinite number of cross jumpers. A voltage-current plot for a joint is shown in Fig. 3 illustrating the constant resistance nature of such connections.

While the joint resistance can be made arbitrarily small by increasing the number of cross jumpers, each additional one has a progressively smaller effect on the total resistance so that practical considerations indicate that four to five jumpers is sufficient. This means that the effective resistance for stainless clad material will be about 0.8 μohm per inter-coil connection. This value is of course only true for zero field, 77 Kelvin operation, but since it is almost entirely due to the stainless foil only small changes are expected with magnetic field and temperature.

Joint resistance values as high as this would be unacceptable in a magnet that was intended for persistent mode operation but are permissible in a magnet driven by a power supply. The total voltage across all the joints in the prototype magnet will only be about 1mV at the proposed operating current of 100 amps. Typical V-I characteristics of the HTS ribbon are illustrated in Fig. 4. The voltage is seen to rise rapidly with current near the "critical current" which is usually specified at an electrical field gradient of one microvolt per centimeter (1 μV/cm). In this region the voltage is increasing as the seventeenth power of the current and a practical operating level is equivalent to 0.1 μV/cm or 87% of the nominal critical current. Even at this lower current the voltage drop across one of the pancake coils equals approximately 2mV, twice the voltage across all the joints in the whole magnet, so reducing the joint resistance would have a negligible effect on magnet operation.

Conclusions

Suitable connections between pancake coils made from stainless clad HTS tape can be made relatively easily with pure indium solder. The resistance of these joints can be reliably predicted and are expected to be almost independent of magnetic field or operating temperature.

References

American Superconductor, 2 Technology Drive, Westborough, MA 01581

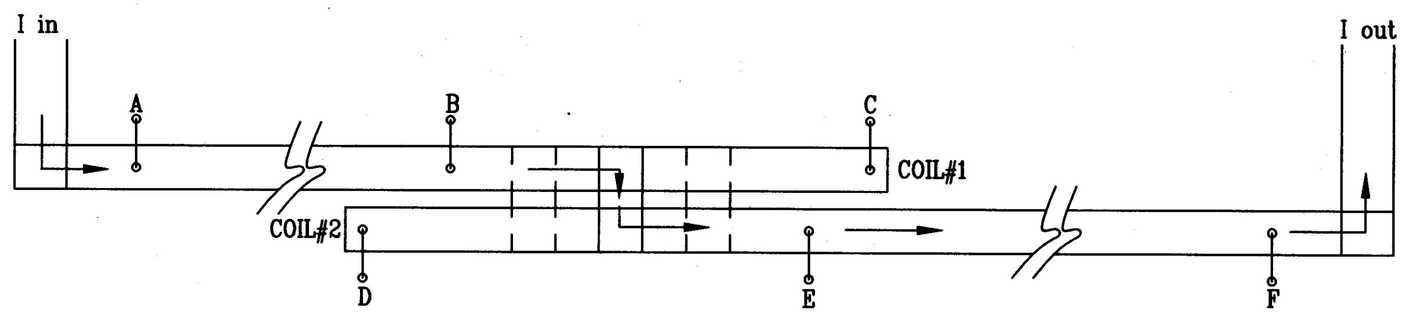

I in
A
B
C
COIL#1
COIL#2
D
E
F
I out

FIG. 1A

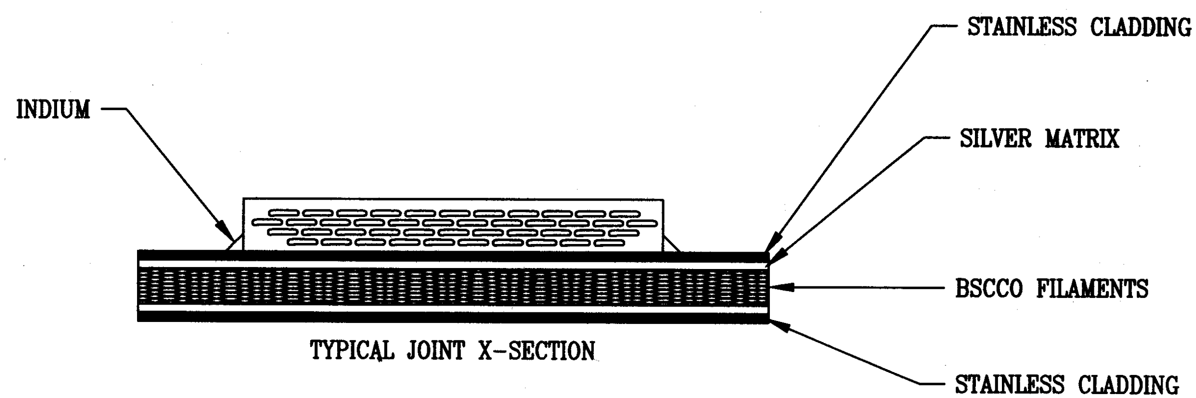
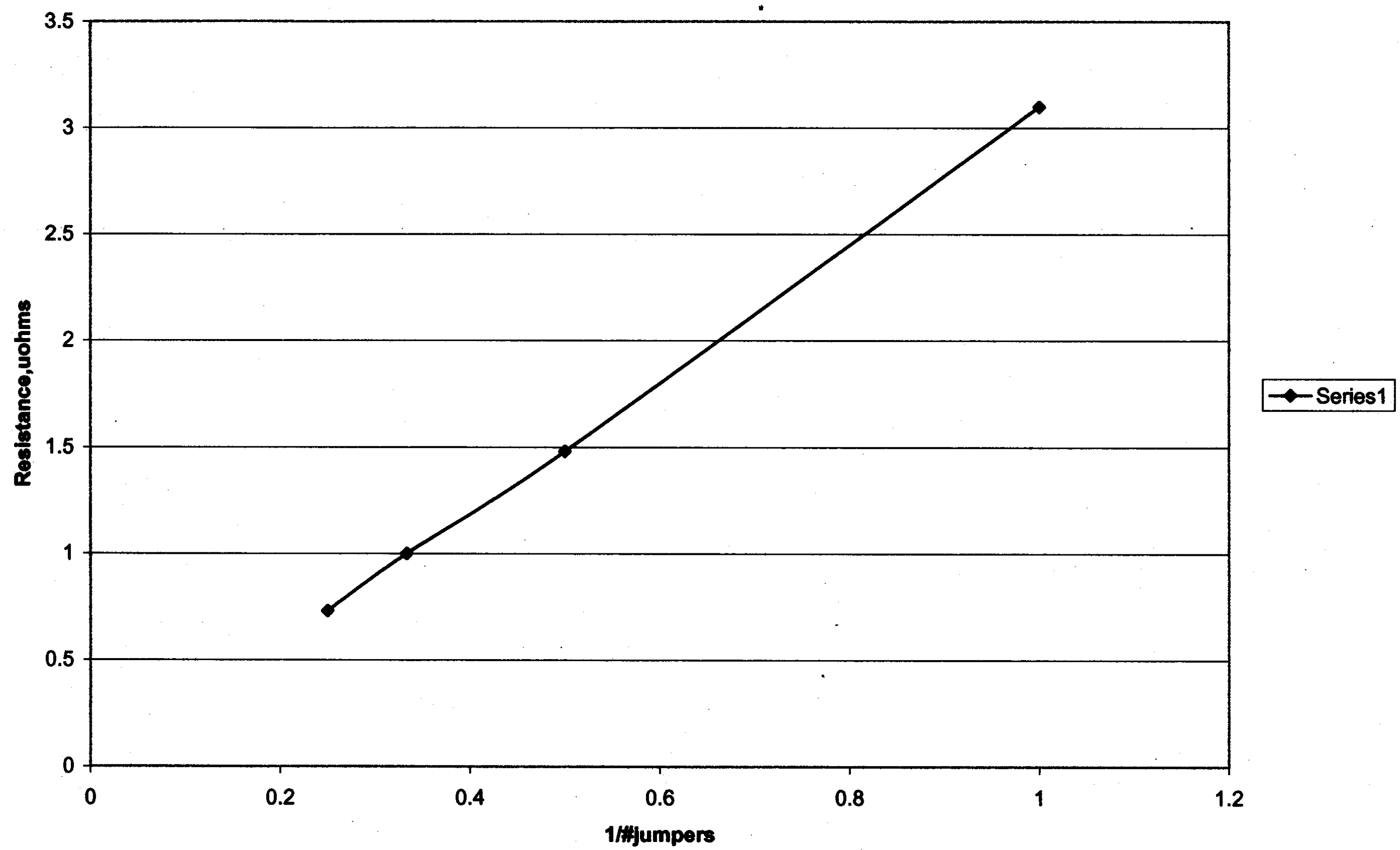

INDIUM
STAINLESS CLADDING
SILVER MATRIX
BSCCO FILAMENTS
STAINLESS CLADDING
TYPICAL JOINT X-SECTION

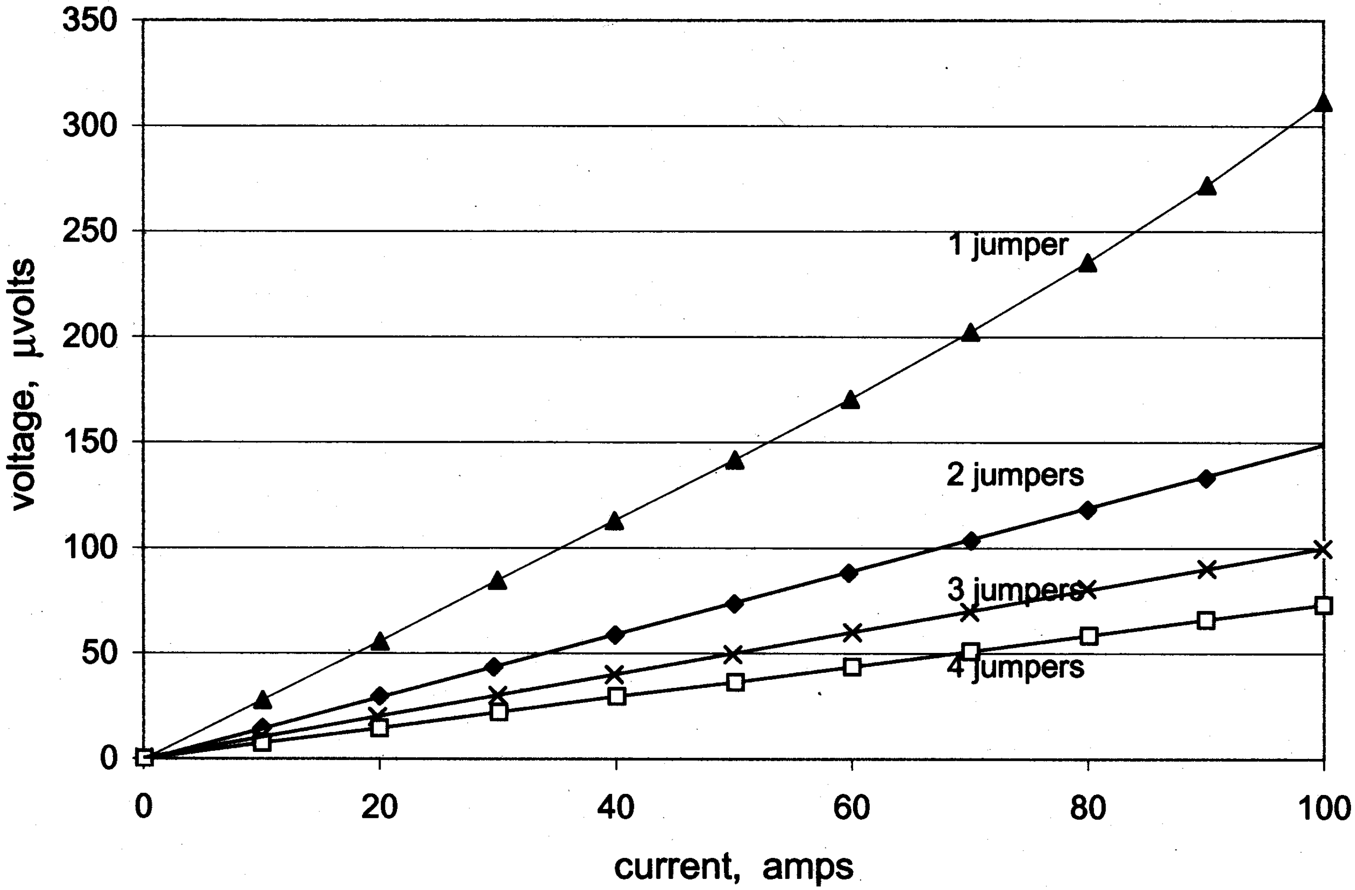
FIG. 1B

Fig.2



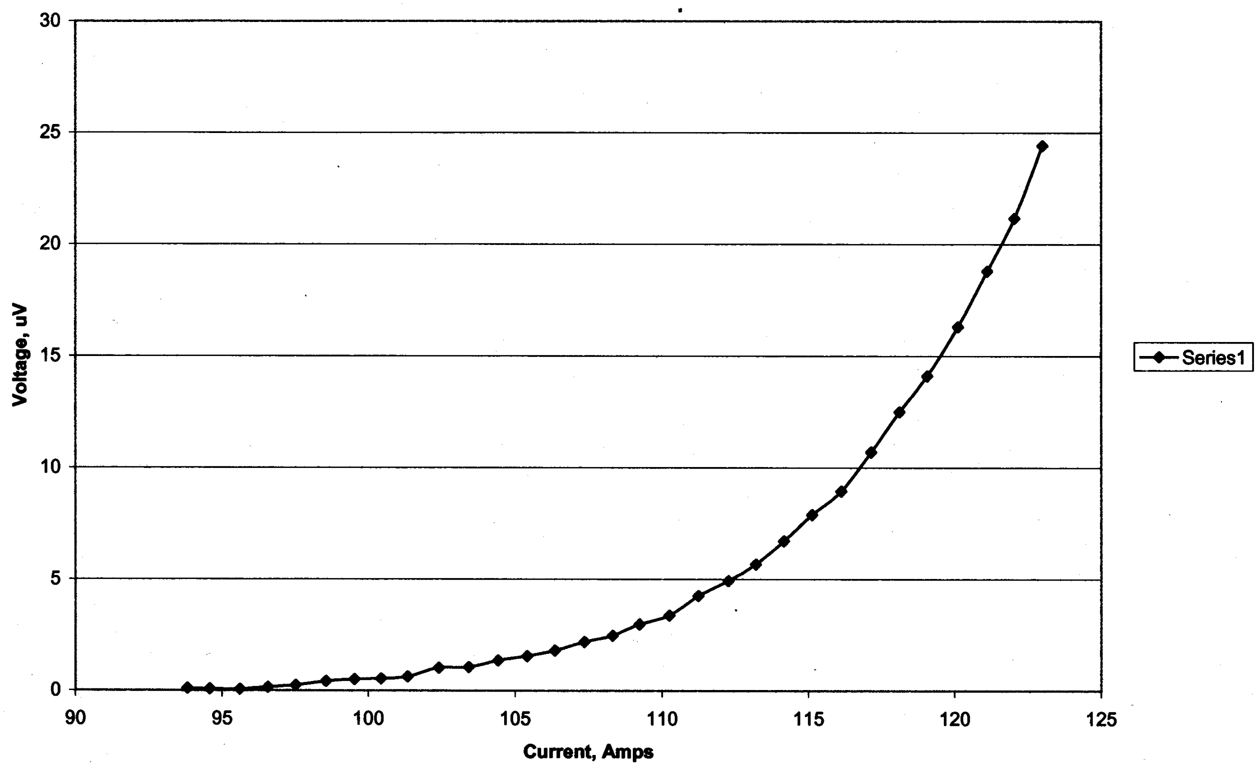
3.5
3
2.5
2
1.5
1
0.5
0
Resistance,uohms
0
0.2
0.4
0.6
0.8
1
1.2
1/#jumpers
Series1

Figure 3



350
300
250
200
150
100
50
0
voltage, µvolts
0
20
40
60
80
100
current, amps
1 jumper
2 jumpers
3 jumpers
4 jumpers

Fig.4


30
25
20
15
10
5
0
Voltage, uV
90
95
100
105
110
115
120
125
Current, Amps
Series1