Hyperconducting joints using HTS powders

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Abstract

Low resistance joints are of interest in cryogenic applications. Although some applications, such as MRI or NMR rather have superconducting joints, superconducting joints with High Temperature Superconductors have proven difficult. A method is presented for the reduction of resistivity associated with conventional joining materials, using HTS powder in an electrically conducting matrix. Calculations of the joint resistance are performed, and means of implementation are described.   An experiment setup to test the concept is under construction.

Introduction

Highly conducting joining materials at cryogenic temperatures are of interest to magnet designers. The resistive joints usually result in large Joule heat dissipation, especially for applications at 4 K, and represent substantial sources of heat at higher temperatures, especially for applications with high currents, as in transmission/distribution [Haught].

Methods have been developed to obtaining superconducting joints with low temperature superconductors. These methods basically consist of placing the joint in regions with low field, using metals or alloys as the joining material.

In the case that superconducting joints cannot be presently manufactured, as is the case of second generation high temperature superconductors, means of reducing the contact resistance are required. Conventional solders employ alloys of Sn, Pb or In, with resistances in the order of 20-200 nΩ m. [Iwasa] It would be useful to make reduce the resistance of these solders, to decrease the heating at the cryogenic temperature.

For applications where the joint is not metallurgical, as in the case of remakable (demountable) joints, it is useful to have compliant materials that can serve to transfer the current over relatively large areas that are closely, but not exactly, conforming. This is the case when it is desired to make a joint between multi-tape cables, with substantial areas and possibly multiple surfaces. The use of a compliant material that can deform under relatively low pressure can provide good current transfer between cables that are not soldered together.

A simple method is described in the next section to substantially decrease the resistance of solders or compliant layers. Section 3 shows calculations to illustrate the performance of the concept, but not to optimize it, which is outside the scope of the present work. Section 4 describes a technique to prevent or minimize scaling/flaking of the compliant layers. Section 5 describes simple experiments that are being set up for evaluating the

concept. Finally, Section 6 describes means of implementing the technology for demountable and fixed joint magnets and summarizes the work.

Hyperconducting materials

Many superconducting materials are know to be substantially brittle, especially the high temperature superconductors, which are ceramic based. The basic idea behind the hyperconducting materials is to load a soft, electrically conducting matrix with superconducting powders.

Presently, both 2212 and YBCO are commercially available as monoliths. Although 2212 is more developed and is available commercial for applications as current leads [Yamada], and more recently, as components for fault current limiters. [Klaus] Bulk 2212 is available from Nexans [Nexans], either as rods, cylinders or as plates. While its properties are lackluster at 77 K, they are very good at 20-30 K.

YBCO is being developed mainly as materials to be used in bearings, in the US (Boeing), Europe [Nexans, ATZ] and Japan (ISTEC), among others. The characteristics of this material are nothing less than spectacular [Tomita, Tomita1], at temperatures up to 60-65 K. YBCO has limited current density capabilities at 77 K, good enough for tapes, but not for high field magnet applications. YBCO magnets need to be subcooled. The material continues to be improved continuously, and their properties when replacing Y with Gd have been well documents [Cardwell].
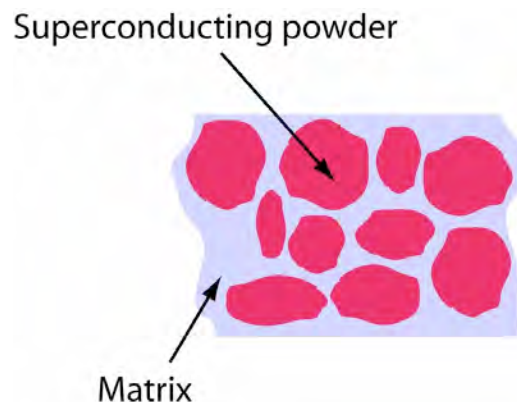
Figure 1. Schematic diagram of hyperconducting material

The most impressive performance of YBCO pucks has been a 17 T magnet at 29 K without a background field [Tomita, Tomita1]. The material recently developed by Cambridge University [Cardwell] where Gd is used instead of Y, results in best performing monoliths, although presently they are available only in ~ 25 mm sizes. For 2212, the MIT group has built a 3 T magnet at 4 K, and a 1 T insert in a 19 T background [Bromberg].

Bulk HTS material has been shown to have almost as good properties as those from epitaxial methods.

The hyperconducting concept is illustrated in Figure 1. A soft matrix is used to serve as electrical shunts for the superconducting powders. The soft matrix could be a conventional solder, or it could be a soft material that can easily deform. Several options exist, such as indium, annealed silver, and even high purity aluminum. As indicated in the figure, it is best to have high fill fraction of the superconducting powder, in order to decrease the length between superconducting elements and to increase the area of near contact between the different elements, both effects decreasing the average resistance of the material.

The random close packing (RCP) for monodispersive elements is about 2/3 [Song] In order to achieve high fill fraction, it is best to have powders of different sizes (polydispersive). It is expected that by using a polydispresive powder, it would be possible to have fill fractions of ~80%

An analogy with permeability of beds with different porosity and sphere diameters (monodispersive) can be made to try to guide the design of experiments. The permeability of a bed with a porosity of ε and a sphere diameter of d is given by [Rump and Gupte]:

$$K = \varepsilon^{5.5} d^2 / 5.6$$

Using the permeability as resistivity (since in this case the open space is resistive), it can be seen that very low porosity and small diameter results in low resistivity in the composite.

Calculation of performance of hyperconducting materials

In this section, an illustrative calculation of the performance of the concept is performed. The case analyzed assumes low temperature solder as the matrix, with the HTS power having a dimension (cylindrical) of about 2/3 of the thickness of the hyperconducting element. This is for illustration purposes, as this leaves substantial thicknesses between the superconducting element and the surface of the element (and thus, high resistance).

The overall dimension of the hyperconducting element is 30 μm. For simplicity (to avoid large difference in spatial scales), it is assumed that the thickness of the HTS is 10 μm. The model assumes that the hyperconducting element shunts between two HTS 2nd generation tapes with 20 μm of electrolytically deposited copper.

The electrical conductivity of the solder and the copper are 4 10^6 /Ohm m and 2 10^8 /Ohm m, respectively. FEMLAB finite element code was used in solving the static problem [COMSOL].
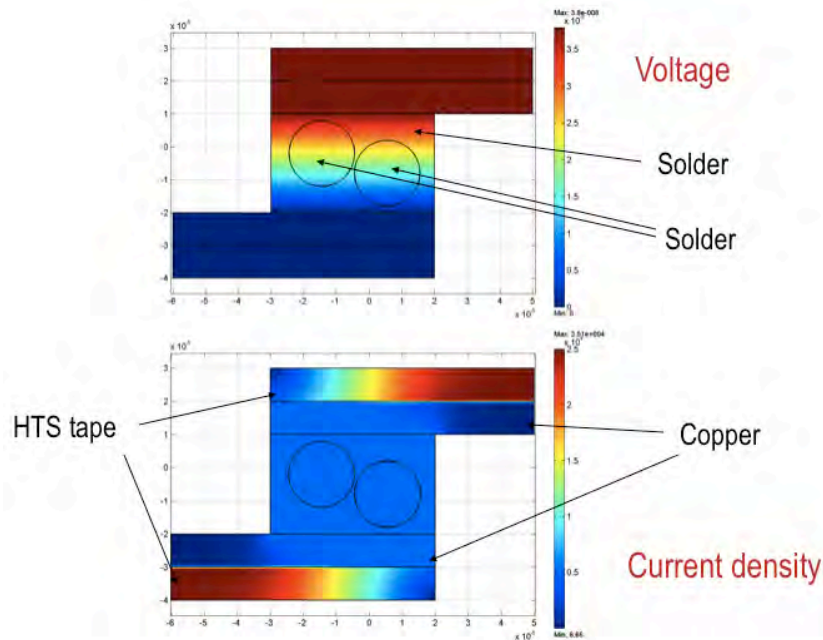
Figure 2. Results for the case without superconducting powder

The model is a 2-D calculation (i. e., infinitely long in the direction normal to the paper). It is assumed that the current flowing in the system is 25 kA/m^2.

The results are shown in Figures 2 and 3. The voltage and the current density are shown in Figure 2 for the case where the powder has the same properties as the matrix, that is, there is no powder. The contours of constant equipotential are parallel to the interface surface. The resistance is dominated by the solder, not by the copper on the tape (between the superconductor and the hyperconducting layer). Also, as expected, the current density is uniformly spread across the solder. The voltage drop is on the order of 3.8 10^{-8} Volts.
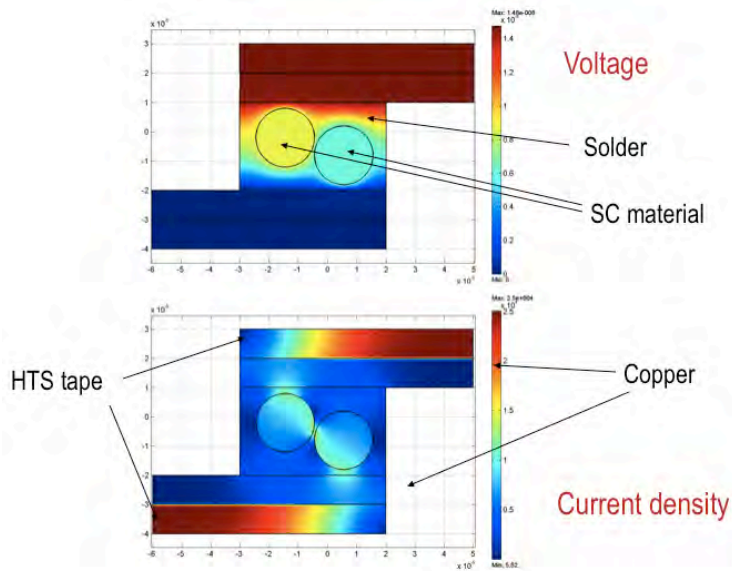
Figure 3. Results in the case of superconducting cylinder in the layer between tapes

Figure 3 shows the results for the case of the superconducting powder. The superconducting region is an equipotential, as would be expected. The current distribution in this case flows very differently than in the case in Figure 2. The current density preferentially moves to the region where the superconducting powder is located. In the bottom region, it flows to the right-hand side of the hyperconducting layer, since the SC is closer to the bottom surface. In the top, it flows through the other SC grain, at the left, as this grain is closer to the top surface. The current flows preferentially across one superconducting grain to the other. The voltage is again mostly across the hyperconducting region. The voltage drop in this case is 1.48 10^{-8} Volts, about a factor of 2.5 lower than in Figure 2.

It is clear from the simple analysis that high fill-fraction (packing fraction) of the superconductor is desired. Also, small diameter of the grain decreases the clearly notable maldistribution of the current density at the interface, as shown in Figure 3.

Non-stick concept

In the case of non-soldered joints, the use of a soft material, such as indium, can result in "scaling/flaking" of the material (during disassembly. This section presents a means to prevent the scaling of these intermediate layers.
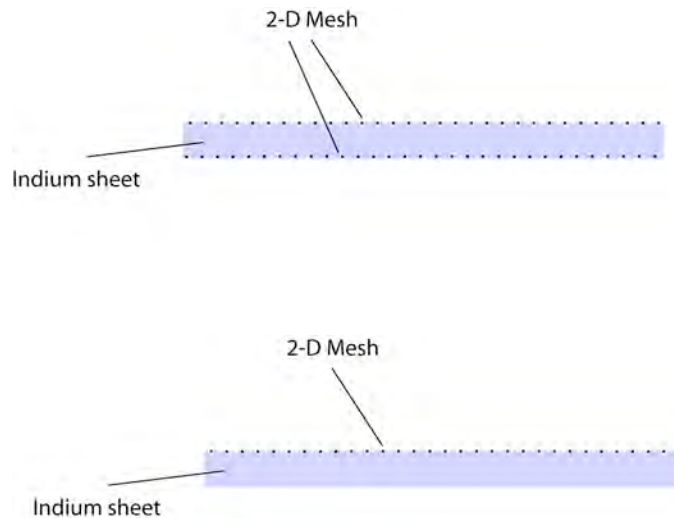

Figure 4. Schematic diagram of the "non-stick" concept.

If the material can be held back through the use of a mesh on the surface, and the mesh density is high, it is possible to increase the yield stress of the composite. In this case, the composite consists of a fine, highly transparent mesh, on the surface of the soft matrix. Because of the high mesh density, there is tight coupling between the soft matrix and the mesh, preventing scaling during removal. Figure 4 shows a schematic of the concept.

The process can be easily modeled using FEM, but we have opted for a quick demonstration of the concept. A fine mesh from Industrial Netting [Industrial Netting] was used in the experiment. The nickel electroformed mesh used was 89% transparent, with 117 wires per in (product BM 0117-01, from Industrial Netting). A 2 mil thick layer of pure indium was placed in between two of these meshes. For comparison, a 2 mil thick layer of the same material was used without the meshes. The two samples were placed in between two fresh copper pieces (with surface oxides removed by fine sanding). A large

pressure was applied across the test unit after which the unit was disassembled. Figure 5 shows a photograph of the copper pieces before testing and after disassembly after test.
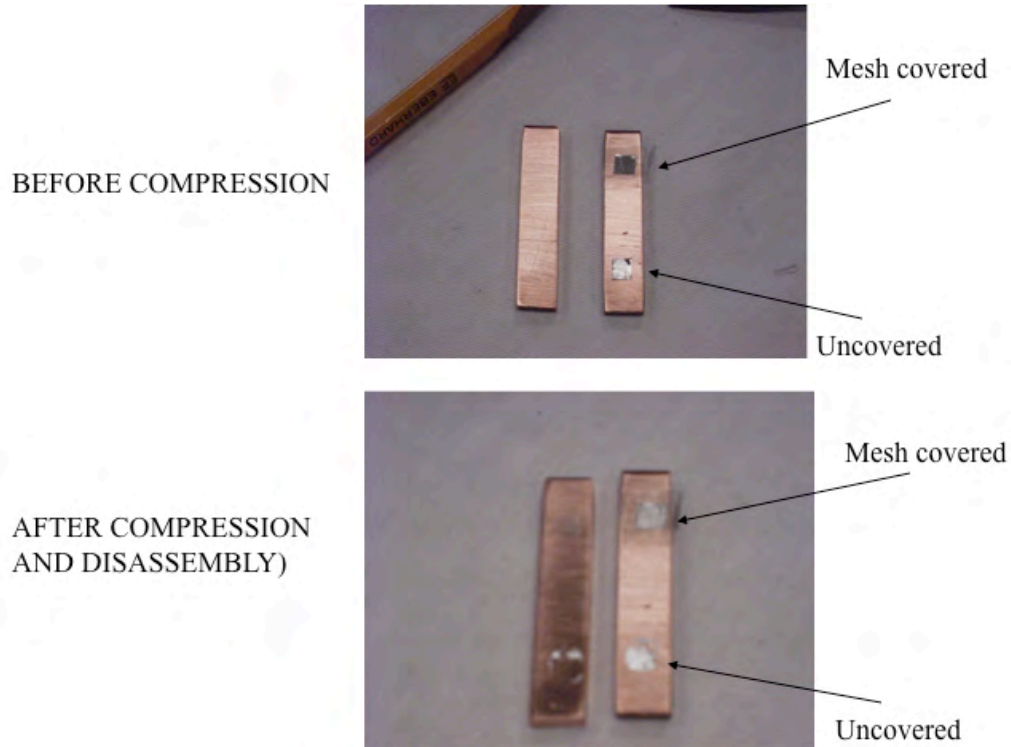

Figure 5. Indium with non-stick process and without, before and after compression test.

It is clear that in the case of non-stick with the mesh there is no or very little scaling/flaking, while in the case without the mesh, substantial fraction of the indium remained stuck to the copper. This is an extreme case, with very high compression and with surfaces that are oxide free, but the example does illustrate the potential of the technique.

Testing of the concept.

We have obtained monolithic samples of GdBCO from Cambridge University [Cardwell]. We intend to grind them and then incorporating them into a matrix through a rolling and folding. The likely material for the matrix is either high purity silver or indium. In the case of silver, repeated heat treatments will take place in order to prevent hardening of the matrix.

In the near term, we will use 1st generation HTS tapes as the compliant material. In particular, the BSSCO 2223 "high current density" tapes from American Superconductor Company, are very attractive for testing the concept. Figure 7 shows the cross section of the tapes. There is no copper, brass or steel that surrounds the silver/superconductor, resulting in a high fill fraction of superconductor and minimizing the distance from the superconductor to the surface.

Figure 6. Cross section of "high current density" tape (BSSCO 2223) from American Superconductor Company.

The first generation material is more appropriate to these tests than 2nd generation materials because the second generation materials have an insulating layer between the superconductor and the substrate that would prevent effective current transfer from one side of the tape to the opposite side.

The anisotropy of the materials could be used by aligning the superconductor powder so that it is along the best orientation for current transfer.

The goal is to modify the silver substrate in Figure 6 or matrix in the general case, in order to minimize the distance between the superconducting elements, between the superconducting elements and the surface, thus minimizing the resistive shunt. It is possible to have large enough deformations that the superconductor is shuttered. However, for the present applications, where the current flows across the superconductor, rather than parallel to it, the effect of filament break up should be small.

It should be pointed out that the material strength should improve because of the presence of the hard powder grains.

We intend to investigate the impact of the tape orientation on the performance of the concept. Figure 7 shows a schematic of the setup that will be used in the experiments. Pressure is applied in the region of the joint by turning the screws, which are provided with Belleville washers.
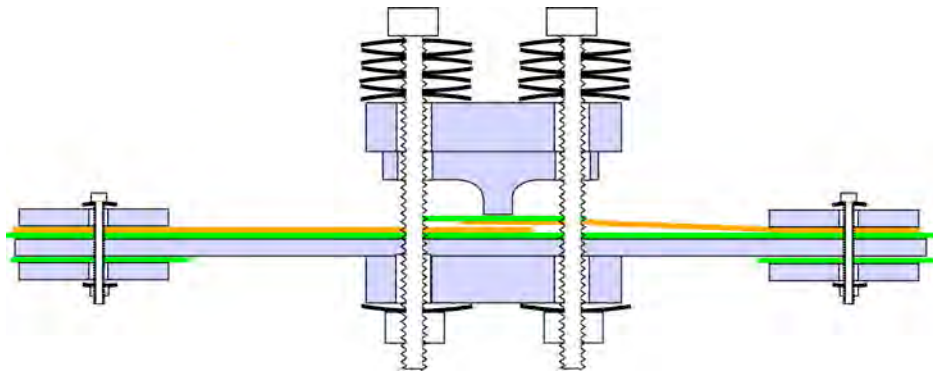

Figure 7. Schematic of the setup for testing the hyperconducting joints, when the joints are demountable.

Conclusions

A concept for decreasing the resistivity of conventional joining materials has been described, and analyzed. Although it is not possible to predict the ultimate capabilities of the concept, it is likely that resistances can be decreased by factors of 3-5, depending on the fill fraction and grain size. Polydispersive grains with higher fill fractions should perform better.

A simple set of experiments is planned to test the concept, using presently available 1st generation 2223 tapes that have high fill fractions.

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