VIEWPOINT

Progress in superconducting joints between Bi-2223 tapes

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Viewpoint

Progress in superconducting joints between Bi-2223 tapes

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This is a viewpoint on the letter by Takeda *et al* (2022 *Supercond. Sci. Technol.* **35** 02LT02).

$Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) are currently the only commercially available multi-filament high-temperature superconductors (HTSs) that can be used for high field generation in LHe at 4.2 K. These properties and the fact that they are also readily available in very long continuous lengths—typically 1–1.5 km and currently ~500 m for high strength alloy laminated Bi-2223NX—make them strong candidates for applications where low magnetization-losses and low screening current effects are desired. This is the case in magnets where long-term field stability and high field homogeneity are required, like nuclear magnetic resonance (NMR) magnet systems.

The fact that Bi-2223 retains useful transport properties also at elevated temperatures of LN_2 (77 K) makes this conductor also an ideal candidate for efficient power transport. The JST-MIRAI program (the funding source of this superconducting joint effort) combines these two perspectives, HTS high field magnet technology and HTS power transport in an ideal way, bringing together the needs of Japanese Rail for efficient power distribution in its urban rail network with the needs of the RIKEN labs to develop the next generation of highest field NMR and magnetic resonance imaging (MRI) magnet technology [1]. Along with other areas of HTS R&D, power transport technology using HTS has substantially advanced in the recent years as can be seen in several examples of successful, mature power cable installations like the AmpaCity project that consists of a 3 km urban power distribution system also using Bi-2223 conductor. This system has been running continuously since 2014 [2]. An important aspect of a successful HTS system technology is the availability of electrical joints with low resistance, be it for the minimization of cryogenic losses in power systems applications or the need to operate magnet systems in persistent mode as is the case for NMR and MRI magnets.

While there has been substantial R&D carried out on superconducting joints in the recent past, HTS joints in general are still awaiting practical solutions that are as easily implemented as is the case for joining low temperature superconductors (LTS) [3]. Superconducting joints are technologically demanding since they must be considered a multi-functional entity that ought to combine a set of very different requirements e.g. retention of most of the transport properties of the original conductor in self-field as well as in-field, high performance under various mechanical conditions ranging from mechanical loads under operating conditions, including fatigue loads to mechanical loads caused by thermo-cycling [4–11]. On top of that, the joint making procedure must be compatible with the conductor and coil making procedures, which are particularly complex with all cuprate-based HTS in one way or the other. Finally, these joints need to present a compact entity that does not severely affect the winding-pack density of the coil where the joint is to be implemented [12–14]. The development of better probes and highly stabilized power supplies on the other hand may alleviate the issue to some degree by allowing some of the magnet systems run in driven mode thus not requiring true persistence.

The paper by Takeda *et al* [6] presents an important step towards a procedure to determine how electrical joints can be made with Bi-2223 tape conductor. The authors made a set of native joint samples with unreinforced conductors as well as a jointed spiral of several turns applying two different manufacturing routes and tested these samples in self-field and in a small external field of 1 T. They report that better than target joint resistances on the order of 10^{-15} Ω were reached with actual joint lengths of 15 mm. Their intent is to apply these joints to their 1.3 GHz NMR magnet project. A magnet of that size, however, will require a significant amount of mechanical reinforcement and the prime manufacturer of Bi-2223 conductor, Sumitomo SEI, offers a high strength alloy laminated variant (Sumitomo HT-NX) that would be ideal for this purpose. Unfortunately, the lamination procedure makes it a fairly complex composite and as other groups have also shown, the lamination process leaves the conductor under residual stress that is reduced when removing the laminate and the stress differential between conductor and joint makes the joint area particularly vulnerable [12, 15]. Beyond that, the high strength alloy lamination is carried out using a PbSn solder, that is likely to interfere in the joint making procedure, particularly during the heat treatment where it is likely to alloy with the silver matrix of the conductor. The choice of the reinforced Bi-2223 conductor may thus be a tough one. Considering the 1.3 GHz project goal at Riken labs, testing the joints at 1 T appears too low as a placement of a joint in the actual magnet within that field range would require particularly tall joints. The heat treatment process appears to be delicate. The paper, however, states that the samples appear to survive the temperature differential between the winding at RT and the joint at 810 °C sintering temperature quite well. However, a deeper discussion of the effects of a temperature differential on the conductor properties would be a valuable addition. The paper also lacks a detailed description of the actual heat treatment used, presumably because the details are commercially sensitive. The microstructures of the joint area clearly show the presence of significant void space, which besides the mentioned degradation caused by the uniaxial pressing of the joint during heat treatment, may have contributed to the observed 40% loss of performance comparing sample with and without electrical joint. It would surely be interesting to narrow down the loss mechanisms further by looking in detail at the crystallographic phase assembly as well as signs of mechanical damage in the joint area to get a better idea about the transport current limitations, something this paper by Takeda *et al* [6] does not explore further. Coil joints of the type shown in figure 5 of this paper and several other papers too [8–11], are not very compact extending radially from the winding pack and do not represent any practical engineering form factor. Some additional effort will have to be undertaken to improve the joint layout particularly when nesting such a coil inside another coil shell as it will be the case of the authors' 1 GHz magnet project. Also, while the authors describe their joints as mechanically robust, definitive guidelines for an ultimate joint form factor are lacking as more systematic electro-mechanical testing in various background fields will be necessary. As the transport properties of the joints improve, they will experience increased mechanical loads, making the mechanical tolerance even more important.

The authors succeeded in making superconducting joints mastering a complex manufacturing process. While there is still work ahead developing a robust manufacturing process to achieve high joint performance, electrically as well as mechanically, the steps presented in this paper point to the right direction. It appears that it is only a question of time and effort until this hurdle is overcome. I am positive that the HTS R&D community is eagerly looking forward to more magnet technology enabling results on persistent joints.

Data availability statement

No new data were created or analyzed in this study.

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