Strong roundceramic superconducting wires for very high field magnets

High magnetic fields have many advanced applications. In medical Magnetic Resonance Imaging they make it possible to scan the soft tissues of the human body, in Nuclear Magnetic Resonance spectroscopy, they enable studies of molecular structure and molecular interactions. Magnetic fields curve the paths of charged particles in circular particle accelerators like the Large Hadron Collider at CERN. They serve to confine the plasma in experimental thermonuclear reactors that produce energy by the same fusion reactions as occur in the sun. These and other applications are making continuing demands for more and more powerful magnets.

Very high magnetic fields can be produced by large electric currents circulating in a copper-wire magnet, but these currents dissipate energy by the Joule effect. The losses can be enormous. For example, at the Grenoble High Magnetic Field Laboratory, 24 MW are dissipated to produce a flux density of 36 Tesla in a 34 mm diameter bore. 24 MW is the average power consumption of a European town of 24 000 inhabitants! The solution for dramatically reducing the power consumption has been to use metallic superconductors, which have zero Joule losses below a critical temperature, T_c, near absolute zero. But the magnetic flux density is limited to a certain value, the "critical field" B_c, that destroys the superconductivity. Even the best metallic superconductors (niobium-titanium and niobium-tin alloys) cannot satisfy future needs for higher fields.

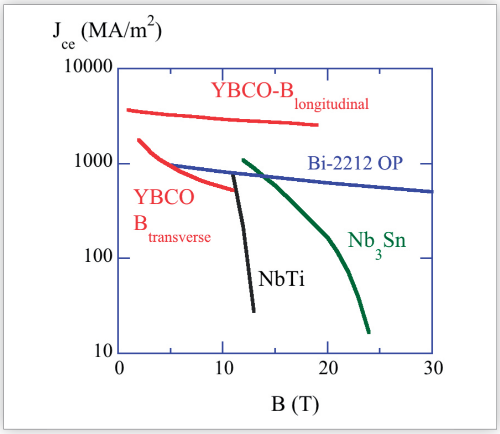

Fig. 1: *Engineering critical current density J_{ce} at liquid helium temperatures for superconducting wires used for winding high field magnets. (The "engineering" critical current density is the maximum sustainable current per unit area of the total cross-section of the wires, i.e. including non-superconducting structural and reinforcing materials.)*

Advances in High Temperature Superconductors are changing the situation. These ceramic materials, with values of T_c up to around 100 K, can outperform metallic superconductors when used at liquid Helium temperature. In particular, "YBCO" (Yttrium Barium Copper Oxide) and "Bismuth-2212" (Bismuth Strontium Calcium Copper Oxide, $Bi_2Sr_2CaCu_2O_x$) can remain superconducting up to very high current densities at 4 K, even under very high fields B, see Fig. 1.

YBCO can sustain very high currents, but has several drawbacks, notably its shape: it is supplied as very thin tapes. The Bi-2212 oxide can be produced as round wires, much better suited to building a magnet. And this compound has another big advantage: its absence of anisotropy. For YBCO, when the magnetic field direction is transverse (out of the plane of YBCO tape), the engineering critical current density J_{ce} decreases very rapidly (Fig. 1).

Recently the current carrying capacity of the Bi compound has been greatly enhanced using a new oxygenation process under high overpressure (D. C. Larbalestier *et al., Nature Materials* 2014). Thus Bi-2212 round wire is now an attractive option for high field magnets. However its mechanical properties are not yet good enough to withstand the extremely high Lorentz forces experienced when it carries a high current under a strong magnetic flux density. An additional problem is that the oxygenation heat-treatment process for Bi-2212 must often be done after winding the wire into its final shape.

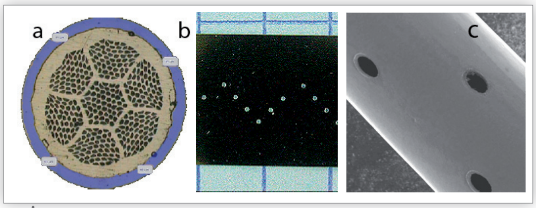

Fig. 2: (a) *Cross-section of a 0.8 mm diameter multi-filament Bi-2212 wire with our 50 µm thickness reinforcing sheath in Inconel (blue).* ***(b)*** *Inconel strip material with zigzag pattern of holes.* ***(c)*** *Tube-like sheath formed by rolling the Inconel strip round the wire and stretching it to fit; the holes (elongated by the stretching) enable oxidising heat treatment of the wire.*

In collaboration with the electrical-cable company Nexans-France, we have studied and implemented an original solution for mechanically reinforcing round Bi-2212 wires. The reinforcement is performed by a metal sheath wrapped around the wire using the Nexans company's shaping and welding process. This intricate and delicate process consists in mechanically shaping a thin strip of metal around the wire, then welding it by laser. Finally, the sheath is stretched to adjust to the wire diameter.

The 0.8 mm diameter Nexans Bi-2212 wire employed has seven sub-elements, each with 85 filaments of superconducting material, see Figure 2a. These filaments are embedded in a matrix of pure silver with a stronger alloy MgAg for the outer part. Several metals for the sheath were studied to determine their resistance to the heat treatment of the Bi-2212 and their mechanical properties after the treatment. We chose the austenitic, nickel-chromium based "superalloy" Inconel 601. It shows a good weldability, an acceptable ductility at room temperature, and it degrades the wire's critical current I_c only very slightly. To enable the oxygenation of the Bi-2212 during the heat-treatment, we developed a process of perforating the metal sheath in a "zig-zag" pattern (Fig. 2b and 2c) that minimizes weakening of the metal. The 50 µm thick external sheath increases the wire's mechanical stress resistance by a factor of 2.1 while reducing J_{ce} measured at 4 K by only 21%.

These results validate our reinforcement method, an essential step in making Bi-2212 wires a feasible solution for building big magnets for fields to 20 T and beyond.

CONTACT

Pascal TIXADOR
pascal.tixador@neel.cnrs.fr

FURTHER READING

"Mechanically reinforced Bi-2212 strand"

P. Tixador, C.E. Bruzek, B. Vincent, A. Malagoli, X. Chaud

IEEE Trans. Appl. Supercond. 25, 6400404 (2015).