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Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T

D. C. Larbalestier[1*], J. Jiang[1], U. P. Trociewitz[1], F. Kametani[1], C. Scheuerlein[2], M. Dalban-Canassy[1], M. Matras[1], P. Chen[1], N. C. Craig[1], P. J. Lee[1] and E. E. Hellstrom[1]

Magnets are the principal market for superconductors, but making attractive conductors out of the high-temperature cuprate superconductors (HTSs) has proved difficult because of the presence of high-angle grain boundaries that are generally believed to lower the critical current density, J_c. To minimize such grain boundary obstacles, HTS conductors such as $REBa_2Cu_3O_{7-x}$ and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ are both made as tapes with a high aspect ratio and a large superconducting anisotropy. Here we report that $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) can be made in the much more desirable isotropic, round-wire, multifilament form that can be wound or cabled into arbitrary geometries and will be especially valuable for high-field NMR magnets beyond the present 1 GHz proton resonance limit of Nb_3Sn technology. An appealing attribute of this Bi-2212 conductor is that, being without macroscopic texture, it contains many high-angle grain boundaries but nevertheless attains a very high J_c of 2,500 A mm^{-2} at 20 T and 4.2 K. The large potential of the conductor has been demonstrated by building a small coil that generated almost 2.6 T in a 31 T background field. This demonstration that grain boundary limits to high J_c can be practically overcome underlines the value of a renewed focus on grain boundary properties in non-ideal geometries.

Any conductor for superconducting applications must develop a high critical current density, J_c, in its long-length form. The difficulties in achieving the huge potential for applications envisaged in the early 1990s for the cuprate HTSs has largely revolved around the complexity of making high J_c in polycrystalline conductor forms, because of the great current blocking effects of randomly oriented grain boundaries[1,2]. The principal solution pursued up until now has been to try to evade grain boundaries. Early on it was seen that a passage through the melt phase, first of YBCO (ref. 3), later of Bi-2212 (ref. 4), could produce a self-organized, local grain alignment with a much higher J_c than was possible in randomly oriented polycrystals. There was particular interest in Bi-2212 because it could be conveniently melted inside an Ag-alloy sheath and for a time it seemed that Bi-2212 might develop into a viable conductor technology[5]. However, its critical temperature (T_c) of only 90–95 K and its large superconducting anisotropy restricted its J_c at 77 K and it was soon superseded by its sibling $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223), which, with a T_c of ~110 K, did allow operation at 77 K (ref. 6). High J_c in Bi-2223 requires a complex reaction and deformation-induced texture process, many details of which still remain proprietary, whose goal is to minimize the density of high-angle grain boundaries[7] (HAGBs). After 10–15 years of development and the addition of a hydrostatic pressure step to close voids left behind during the Bi-2223 formation reaction (Bi-2212 + mixed oxides = Bi-2223), a uniaxial texture of ~15° full-width at half-maximum (FWHM) has been achieved that allows a J_c of order 500 A mm^{-2} at 77 K and self-field[8,9].

Although many aspects of a superconducting electrotechnology have been demonstrated successfully with Bi-2223, the real threshold for compelling, cost-effective applications typically occurs when J_c exceeds 1,000 A mm^{-2} in strong fields, which explains why attention has increasingly turned to so-called coated conductors based on $YBa_2Cu_3O_{7-x}$ (YBCO or more generally REBCO, RE = rare earth) in which a much better biaxial texture of 2°–5° FWHM and a much higher J_c (77 K, sf) ~3×10^4 A mm^{-2} can be obtained[10]. The complexity of the coated-conductor fabrication processes, however, is expensive and Bi-2223 still finds a market. A complication for both conductors is that their high costs, restricted lengths and large superconducting and shape anisotropies are all less than ideal for a versatile conductor, which should more ideally be isotropic, round and multifilamentary, as is the case for the low-temperature superconducting (LTS) wires Nb–Ti and Nb_3Sn. In this respect, therefore, it is not surprising that HTS conductors have had great difficulty in displacing LTS conductors from applications such as magnetic resonance imaging and NMR magnets, particle accelerators such as the Tevatron and the Large Hadron Collider (LHC), or fusion devices such as ITER. This may seem surprising because these applications all occur at liquid helium temperatures where the 5 or even 10 times higher T_c values of HTS materials should allow their 4.2 K J_c values to greatly exceed those of LTS conductors. Figure 1 compares the superconducting layer critical current densities J_c of available, long-length HTS and LTS conductors used for magnets at standard operating temperatures of 4.2 or 1.9 K. Indeed, REBCO has the highest J_c by over an order of magnitude and an apparent advantage over both Bi-2212 and Bi-2223. The relatively poor $J_c(H)$ characteristics of Nb–Ti and Nb_3Sn are clear: although their J_c values start off high, they fall below 1,000 A mm^2 at 11 T (at 1.9 K) for Nb–Ti, and Nb_3Sn crosses this threshold at about 17–18 T at 4.2 K or ~20 T at 1.9 K.

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[1] Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, 2031 East Paul Dirac Drive, Tallahassee, Florida 32310, USA, [2] European Organization for Nuclear Research, Geneva CH-1211, Switzerland. *e-mail: larbalestier@asc.magnet.fsu.edu

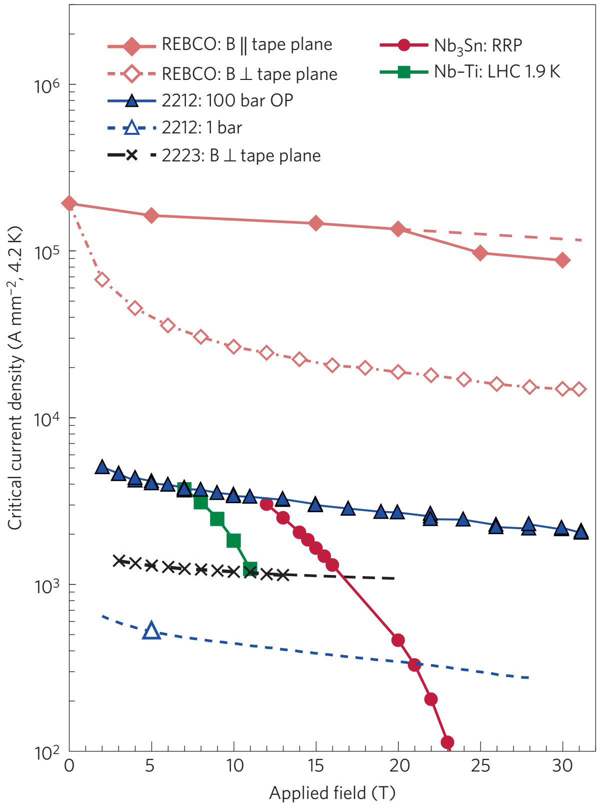

Figure 1 | Critical current densities for representative state-of-the-art conductors used for superconducting magnet construction. Nb$_3$Sn (Rod Restack Process made by Oxford Superconducting Technology), round-wire Bi-2212 (Oxford Superconducting Technology) reacted under total pressure of 1 and 100 bar (OP, overpressure) at a fixed O$_2$ partial pressure of 1 bar, Bi-2223 (Sumitomo DI-BSCCO) and REBCO (SuperPower) coated conductor. All evaluations are at 4.2 K except for the LHC Nb–Ti strand, which is used at 1.9 K, and all were measured at the NHMFL except for the LHC Nb–Ti (courtesy of T. Boutboul, CERN) and the Bi-2223 (courtesy of K. Hayashi, Sumitomo). In virtually all HTS magnet applications the coil performance is limited by the lower J_c values of the anisotropic conductor, thus making the relevant J_c curve that for H normal to the tape plane. Nb$_3$Sn J_c falls off rapidly above 20 T because its zero-temperature upper critical field $H_{c2}(0)$ is only 30 T, compared with over 100 T for Bi- 2212 , Bi-2223 and YBCO. The relevant metric for conductor use must also consider the amount of superconductor that can be inserted into the conductor: this is at present only 1–2% for YBCO coated conductors, whereas it is 25–40% for Bi-2212 and Bi-2223 and up to 50% for Nb–Ti and Nb$_3$Sn. Figure 6 reflects these different superconductor fill factors in presenting the whole-conductor, engineering current densities J_E.

This rapid J_c drop occurs because of their low upper critical fields H_{c2} of 15 and 30 T, respectively. In contrast, the flat $J_c(H)$ characteristics of the HTS conductors are due to their H_{c2} exceeding 100 T (ref. 11). Clearly, high values of $J_c(H)$ do not by themselves make a competitive conductor technology.

Of the conductors of Fig. 1, a very important distinction is that two of the HTS conductors, REBCO and Bi-2223, have a highly aspected rectangular tape geometry, whereas all others are round wires. Figure 2 contrasts the strikingly different architectures of Nb–Ti and REBCO coated conductors. The Nb–Ti LHC conductor contains more than 6,000 filaments, each 6 μm in diameter and in intimate contact with high-purity Cu that provides both electromagnetic stabilization against flux jumps and magnet quench protection[12]. The internal structure of the REBCO coated conductor cannot be clearly seen at this scale: the support is a high-strength, highly resistive Hastelloy substrate on which an oxide template and REBCO is deposited, the whole being surrounded by a 2-μm-thick protective Ag layer on which a 20–50-μm-thick high-purity Cu layer is electroplated[10]. The advantages of this architecture for solenoid winding are considerable[13,14] because the dominant tensile hoop stresses are well supported by the very strong Hastelloy. However, the disadvantages of the geometry are considerable too. Large magnets typically demand operation at many kiloamperes that require cables assembled from multiple strands. Owing to their geometrical anisotropy, rectangular conductors are hard to cable except in special configurations[15–17]. The large superconducting anisotropy of strongly textured tape conductors (the *c* axis is oriented perpendicular to the tape plane and the *a* and *b* axes lie in the plane of the tape) is also a significant complication, as is the fact that the superconducting layer of REBCO coated conductor acts as one filament, which makes it vulnerable to any defect that locally interrupts current flow, especially in a magnet, whose large stored energy can dissipate locally at any defect during quench[12]. For all of these reasons a round-wire, multifilament geometry with multiple independent current paths in which each superconducting filament is directly bonded to high-conductivity normal metal is greatly preferred. Nb–Ti possesses all of these advantages, which is certainly an important reason why it is still by far the most widely produced superconductor, in spite of its T_c being only 9 K and full

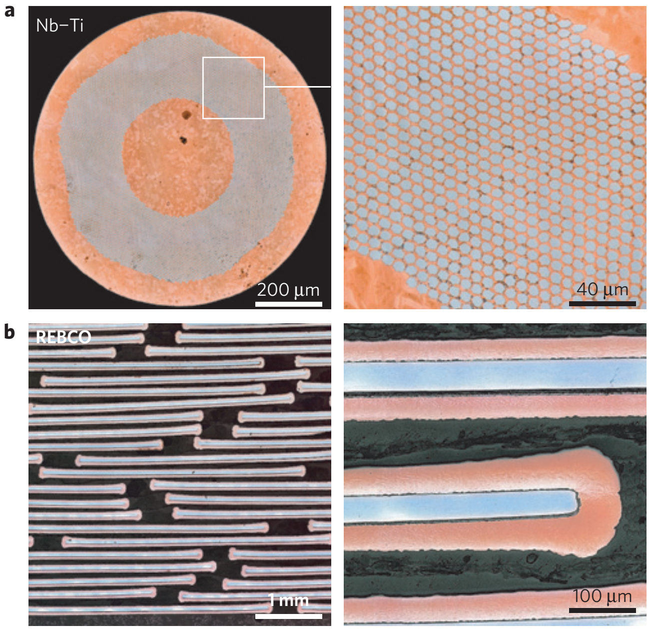

Figure 2 | The extremes of present conductor technology. a, CERN/LHC 0.825-mm-diameter superconducting strand containing 6,426 Nb–Ti filaments each 6 μm in diameter and each surrounded by pure Cu needed to confer electromagnetic stability against flux jumps and magnet quench protection when superconductivity is lost. **b**, State-of-the-art REBCO coated conductor grown on a 50-μm-thick strong Hastelloy substrate on which a 3-layer oxide seed and buffer layer with a strong [001]-oriented biaxial texture (FWHM 2°–3°) is developed by ion-beam-assisted deposition. The ∼1-μm-thick REBCO layer was in this case deposited by metal organic chemical vapour deposition and protected by a 2 μm Ag layer. Finally, Cu is electroplated onto the whole stack in thicknesses of 20–50 μm. A typical conductor is 4 mm wide and 0.1 mm thick, thus having an aspect ratio of 40. The right-hand side of each image shows a magnified view of the conductors shown in full section at left. In this case, the REBCO coated conductor has 50-μm-thick Cu to provide full magnet quench protection rather than the standard 20 μm thickness that is used to calculate J_E in Fig. 6.

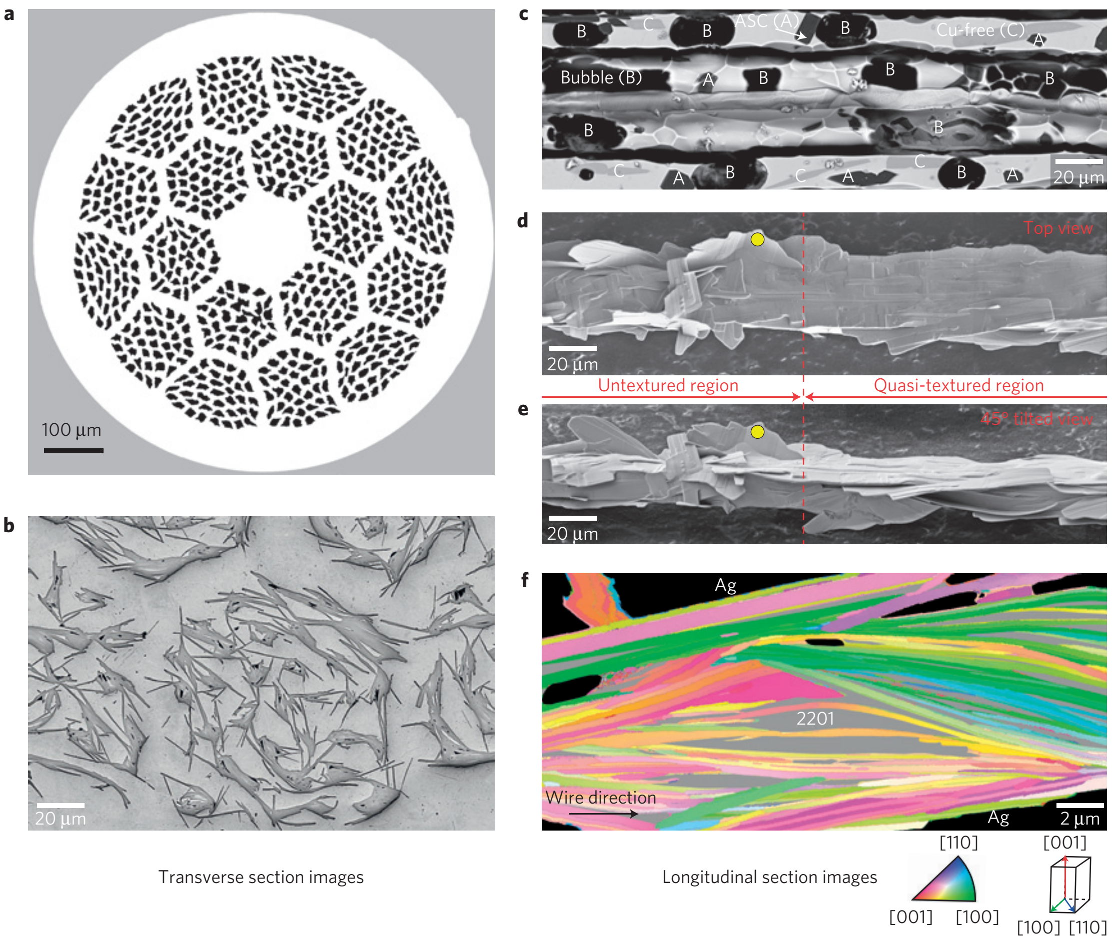

Figure 3 | Macroscopic and microscopic images of the Bi-2212 conductor architecture. a, Transverse section of an as-drawn 0.8-mm-diameter wire composed of 18 × 37 15-μm-diameter Bi-2212 powder filaments embedded in a Ag matrix before the melt process heat treatment needed to establish long-range superconducting connectivity. **b**, Transverse section centred on one 37-filament bundle showing the large aspected grains of 2212 that form after the heat treatment. **c**, Large agglomerated bubbles (B) are present in the filaments when the powder in **a** is melted. **d**,**e**, Longitudinal views (rotated by 45°) of one fully processed filament showing the highly aspected 2212 grains formed during the heat treatment. The yellow dot shows the same point on the filament in the two views. **f**, Electron backscatter diffraction image of a polished dense filament section. The colours correspond to the orientation of the grains (shown below in **f**). The EBSD image confirms both local grain-to-grain texture, and also shows multiple HAGBs and residual liquid that has largely transformed to Bi-2201. These features do not however prevent development of high J_c. The filaments shown in images **c**–**e** were exposed by etching away the surrounding Ag matrix.

use of its capabilities often, as in the LHC, requires operation at 1.9 K, not even 4.2 K (ref. 18). Thus, some of the great challenges that any HTS conductor should address are the need to be round, to be multifilamentary, to possess a high J_c and have high-conductivity normal metal intimately bonded to the superconducting filaments. It is precisely the achievement of all of these goals in Bi-2212 that we describe here.

Bi-2212 round-wire conductors and their challenges

Figure 3a shows a cross-section of the Bi-2212 round-wire conductor in its as-drawn state, here embodied as a 0.8-mm-diameter, with 666, ~15-μm-diameter filaments embedded in a high-purity Ag matrix with a strengthened Ag0.2wt%Mg outer sheath. The filaments are composed of Bi-2212 powder, which must be melted to establish continuous superconducting paths along each filament[19–22]. During this melt and Bi-2212 regrowth heat treatment, large grains of Bi-2212 form on cooling, making the plate-like filament structure shown in Fig. 3b. A key characteristic of any powder-in-tube process is that the powder cannot be 100% dense, because deformation of the conductor by wire drawing requires particle sliding inside the silver tubes. The key to our breakthrough to high J_c was to understand that the crucial current-limiting mechanism is not due to supercurrent blockage at HAGBs, as seemed entirely plausible given the need for high texture in Bi-2223 and REBCO (refs 1,2), but blockage by filament-diameter bubbles grown during the agglomeration of the residual 30–40% uniformly distributed void or gas space that occurs on melting the Bi-2212 powder[19]. These bubbles are seen very clearly in Fig. 3c in samples quenched from the melt step of the heat treatment. After full heat treatment, these bubbles are not generally visible, because 10–40-μm-long Bi-2212 grains grow across the bubbles, providing an essential but strongly compromised connectivity that greatly reduces the long-range J_c. Figure 3d,e shows two 45°-rotated topographic views that clearly expose this highly aspected Bi-2212 growth. Figure 3f provides crystallographic detail of a reacted filament in which some local texture is evident but where the presence of [001]-, [100]- and [110]-oriented grains and many HAGBs is clear. One key point of this paper is that such HAGBs do not prevent high J_c.

The effective solution to the problem of bubbles is to apply sufficient overpressure during heat treatment to prevent their formation, as well as the deleterious creep dedensification[20,21] that

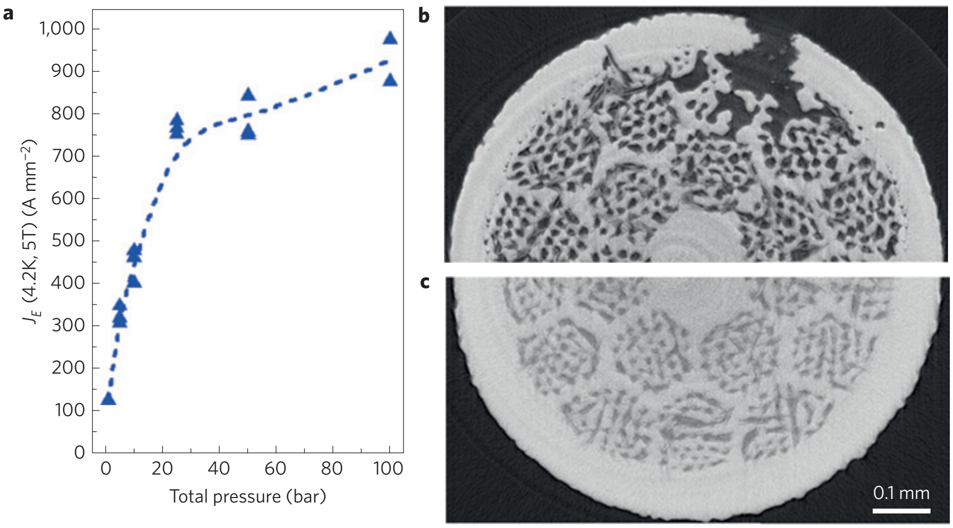

Figure 4 | Reaction pressure dependence of critical current density. a, Overall conductor current density J_E (4.2 K and 5 T) as a function of the overpressure applied during heat treatment to wires shown in Fig. 3. **b**, X-ray tomograms of 1 bar. **c**, 100 bar overpressure processed wires. The extensive porosity of the final wire processed under 1 bar is clear, as is the high density of the 100 bar processed wire. The eightfold increase in J_E is due to the elimination of leakage and suppression of the void porosity seen in **b** by the 100 bar overpressure applied during heat treatment. X-ray tomography was performed at the ID15A beamline in collaboration with M. Di Michiel, European Synchrotron Radiation Facility, Grenoble.

the internal gas pressure drives for heat treatment at 1 bar. Heat treatment under overpressure uses creep of the Ag to fully densify the 2212, greatly increasing its mechanical and superconducting connectivity. Figure 4 shows that reaction under pressures up to 100 bar can raise the whole-conductor (or engineering) current density J_E by up to 8 times. Although these samples were all short (~8 cm), they were reacted with closed ends so that gas generated internally was trapped in the wire, as it would be in long lengths. Wire densities higher than 95% were obtained for >50 bar reactions. The effect of overpressure can be most effectively seen by X-ray tomography as shown in Fig. 4b,c, where the extensive porosity and tendency for a closed-end wire processed at 1 bar to dedensify and leak contrasts (Fig. 4b) strongly with the rather uniform, full density of a wire overpressure processed at 100 bar (Fig. 4c). Figure 4a shows that although the Bi-2212 occupies only 25% of the cross-section of the wire, J_E reaches almost 1,000 A mm^{-2} at 4.2 K and 5 T (Fig. 1 shows that J_c is ~4,000 A mm^{-2}, higher even than the J_c of optimized Nb–Ti at 4.2 K and 5 T).

Proof of capability in a 34 T magnet

Earlier experiments had shown us that high J_c was possible in this system if we took very special care to allow gas to escape from short wire lengths[22], but our solution was not applicable to long-length wires. Developing a short-length model of the long-coil-length wires was essential. Our supposition was that closing the wire ends would make the properties independent of length. To test whether long samples performed as well as short samples, we made a test coil from 30 m of 1.4-mm-diameter Bi-2212 wire, as shown in Fig. 5. Here we were constrained to only 10 bar by our larger diameter overpressure furnace. Nevertheless the coil behaved excellently. In 31.2 T background field it generated 2.6 T, more than twice the 1.1 T field of an earlier similar-sized coil reacted at 1 bar[13]. It was quenched multiple times without any damage and generated a total field of 33.8 T. The wire current density J_E at 34 T was 187 A mm^{-2} which, on the basis of many $J_c(H)$ measurements in other samples, translates to 360 A mm^{-2} at 5 T, 90% of the value predicted from the J_E versus over pressure data in Fig. 4a. The 10% lower J_E is consistent with the shortness of the overpressure furnace relative to the coil length, which pushed the current terminals of the coil into a slightly lower temperature, thus lower J_c zone.

We also tested sections from the 8-cm-long closed-end samples shown in Fig. 4 at fields up to 31 T and multiple samples with properties corresponding to the data in Figs 1 and 6 were obtained. What is now clear is that fully dense Bi-2212 wires, for which dedensification has been prevented by overpressure processing, have a higher J_c than the very best Bi-2223 tape samples[9] with considerable uniaxial texture, although J_c (Bi-2212) is still almost an order of magnitude lower than for REBCO tape with strong biaxial texture. However, this J_c advantage of REBCO disappears when the whole-conductor current density J_E is considered because the REBCO layer is only 1% of the whole-conductor cross-section. Figure 6 shows that now 100 bar processed Bi-2212 (25% superconductor) has a significantly higher J_E than either Bi-2223 (40% superconductor) or REBCO coated conductor (1% superconductor). The J_E values attained by Bi-2212 (J_E 700, 630 and 500 A mm^{-2} at 15 T, 20 T and 30 T) after overpressure heat treatment are all high enough for winding very high-field solenoids for very high-field NMR or for 20 T upgrades for the LHC (ref. 23) or other high-field magnet uses.

There are multiple broad implications of this work. First is that there is now a round-wire multifilament new HTS conductor with at least as high a J_E as the highly aspected REBCO and Bi-2223 tape conductors that until now have defined HTS magnet possibilities. High conductor J_E is essential to magnets because their central field B_0 ($B_0 \sim \mu_0 J_w d$, where J_w is the winding current density and d is the thickness of the solenoid winding) forces their size to be as small as possible so as to minimize the stored energy density ($B^2/2\mu_0$) and the winding hoop stress ($\sigma_{\mathrm{hoop}} \sim J_E B r$, where r is the winding radius). Although the choice of HTS conductor for magnet construction decisively removes the H_{c2} limitations inherent to use of Nb–Ti or Nb_3Sn, it then forces HTS magnets to face the perils of high stress and high energy density and potential inability to protect themselves during quench[12,24]. J_E values of ~500 A mm^{-2} are dangerous[24] because of the slow quench velocities of HTS conductors and the need to restrict current density in the Cu or Ag stabilizer and its associated heating during magnet quench. For example, the 32 T all-superconducting user magnet now being constructed at the National High Magnetic Field Laboratory[25] (NHMFL) uses 100 μm of Cu to protect the 1 μm of REBCO to minimize the integral $\int_0^t J_{\mathrm{Cu}}^2 \cdot \rho_{\mathrm{Cu}}(T)\,\mathrm{d}t$ during its ~1 s quench decay, making its safe J_E

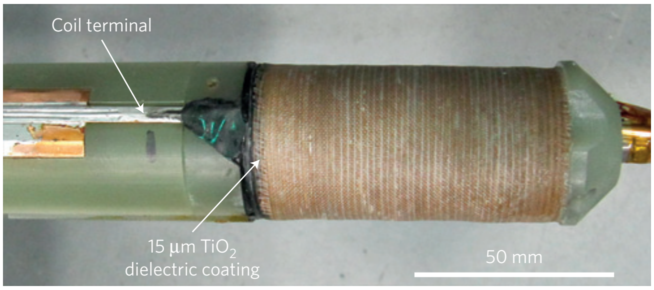

Figure 5 | High-field demonstration coil wound with 30 m of 1.4-mm-diameter Bi-2212 wire. This coil was heat treated at 10 bar in an overpressure furnace. It operated in 31.2 T background field, generating a 2.6 T field increment for a total field of 33.8 T at 6.7 mT A^{-1}. For comparison the previous coil heat treated in 1 bar generated only an additional field of 1.1 T (ref. 13). The coil was quenched multiple times without damage. It achieved a maximum quench current of 388 A (J_E = 252 A mm^{-2} at 33.8 T).

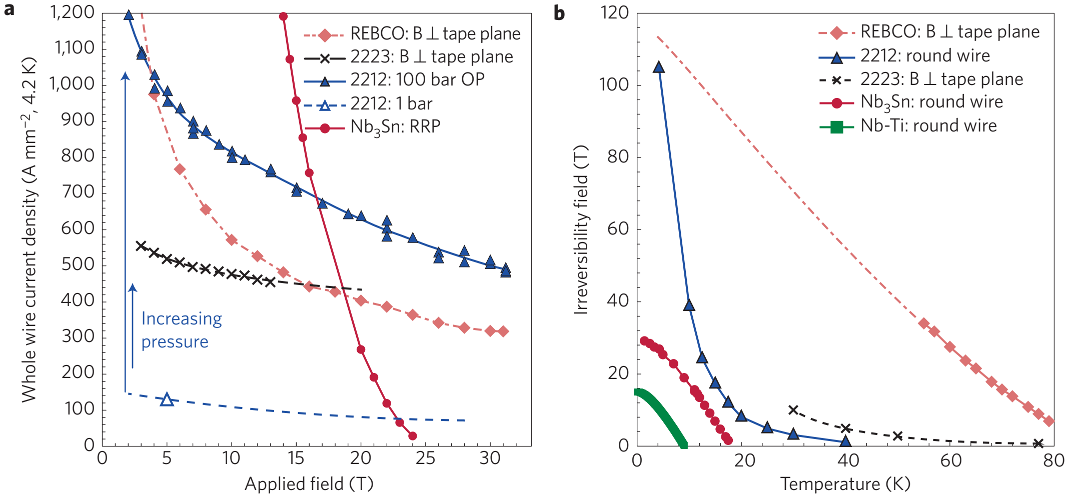

Figure 6 | Critical surfaces of different conductor families. a, Overall conductor current densities J_E possible for conductors made of REBCO, Bi-2223, Bi-2212 and Nb_3Sn used for constructing high-field magnets generating up to 24 T (Nb_3Sn) and up to 35 T (REBCO). It is now seen that overpressure (OP)-processed Bi-2212 has the highest conductor current density J_E of any available conductor above 17 T and moreover that this is achieved in the most desired round-wire, multifilament form. **b**, Upper critical field or irreversibility field data for the conductors. The great opportunities offered by REBCO at temperatures well above 4 K are clear.

well below the values quoted in Fig. 6, where J_E is calculated on the basis of the standard 40 µm Cu thickness normally advertised. This quench and stress problem makes development of much higher J_E values for 4 K use by making thicker REBCO layers[26] or better vortex pinning quite questionable (although they will be very valuable for higher temperature use because of the lower J_c at higher temperatures). Although the data shown for SuperPower coated conductor in Figs 1 and 6 are the best available commercially today, it is certainly reasonable to expect continued development of higher J_E conductors for higher-temperature operation.

An undoubted advantage of ion-beam-textured REBCO conductors for solenoid construction is their ability to texture the template for the REBCO using a very strong Hastelloy substrate that allows safe hoop stresses up to ~600 MPa (ref. 25). To match this capability, Sumitomo have recently announced lamination techniques that permit addition of a similarly strong steel reinforcement to Bi-2223 tape but at the cost of course of reducing J_E (ref. 27). Bi-2212 conductors are not yet as strong. At present we believe the safe $J\,B\,r$ hoop stress to be ~250 MPa (ref. 13), but recent work suggests that Ag0.5wt%Al alloy sheaths can be oxidation strengthened to ~400 MPa (ref. 28), which would be a valuable development. In fact, all high-field HTS magnets must be prepared to rely on separate reinforcement sections to support the electromagnetic loads. For example, a paper design for an all-superconducting 45 T magnet (that at present is supplied only at the NHMFL by a 28 MW Cu magnet giving 33.5 T in the background field of an 11.5 T superconducting magnet) with 32 mm bore might suggest using the J_E = 500 A mm^{-2} value shown in Fig. 6. A coil of 40 mm inner diameter and 100 mm outer diameter would yield ~15 T if designed at J_w = 375 A mm^{-2} (75% conductor packing factor), around which a 30 T outer coil would then be needed. The 30 T portions of these two coils would generate a $J_E\,B\,r$ hoop stress of 750 MPa at J_E = 500 A mm^{-2} and 100 mm winding diameter, a value with no safety margin even for a Hastelloy-strengthened REBCO conductor. The key point is that the J_E values of order 500 A mm^{-2} are quite high enough to generate significant quench and stress challenges. Separate stress management sections will be needed in such coils and quench analysis will almost certainly force operation at lower overall winding current densities. Thus, the current densities of both REBCO and Bi-2212 shown in Fig. 6 are quite large enough for present applications for high-field magnets at 4 K.

The value of flexible round-wire multifilament architectures

Another great value of Bi-2212 is its flexible architecture. REBCO and Bi-2223 conductors are available in essentially only one design. REBCO tapes are single-filament conductors, variable only by being slit to different widths, typically in the range 4–12 mm. Bi-2223 is made only as 4-mm-wide tape. The advantages of such tapes is that they are supplied in the superconducting state and can be wound directly, providing that precautions are taken to avoid winding damage. Their drawback is their one-size-fits-all character. In contrast, Bi-2212 is supplied in the non-superconducting state, allowing the manufacturer great versatility in filament size, number and arrangement[29]. The drawback is clearly that optimization of superconducting properties is now up to the user, but, as for Nb_3Sn (ref. 12), there are many applications for which the user is very happy to accept this added complexity. The isotropic round-wire architecture means that winding high-homogeneity coils such as those needed for NMR is much easier and the magnetization induced in low-field regions of the windings is much less troublesome than is the case for tape conductors[30,31]. Accelerator use is likely to be much more feasible than for tape conductors because the standard form of transposed flat cable, the Rutherford cable, can be made as easily from Bi-2212 round wire as from Nb_3Sn wire[32,33].

In the short run, it would seem that the present world record for magnetic field generated by a superconducting coil (35.4 T in 31.2 T background, made with REBCO coated conductor[14]) should be exceeded using a Bi-2212 coil processed at 100 bar. However, the long-term implications of Fig. 3f are even more powerful. The grain structure visible in this dense filament clearly contains many HAGBs, as well as residual liquid that has transformed largely to Bi-2201. Some of these defects and grain boundaries must be blocking current, reducing the long-range J_c well below that within grains of Bi-2212 and also reducing J_c well below that of biaxially textured REBCO where almost no HAGBs are present (Fig. 1). However, as Fig. 6 emphasizes, Bi-2212 filaments are well enough connected that their 25% cross-section makes their overall current density J_E the best of any available conductor above about 17 T. The really striking opportunity offered by Fig. 3f appears when the irreversibility field characteristics of Fig. 6b are considered.

At present, all of superconducting magnet technology is confined to the small arcs at the lower left corresponding to the $H_{c2}(T)$ phase space of isotropic Nb–Ti and Nb_3Sn. As a result of the huge electronic anisotropy of both Bi compounds, their irreversibility field $H_{irr}(T)$ has a quite different shape (Fig. 6b), making neither conductor particularly valuable for magnets of more than 10 T above 10 K (2212) or 20 K (Bi-2223). However, the much lower anisotropy REBCO shows an irreversibility field of 30 T at ~55 K. As present helium shortages[34] and recent price rises show, there would be great interest in a helium-free, cryocooler-driven superconducting magnet technology capable of 3–15 T operating in the 20–60 K temperature range. To access this range, we need to understand how to engineer the key properties of the Bi-2212 grain boundaries of Fig. 3f into REBCO. Recent studies of *ex situ* $YBa_2Cu_3O_{7-x}$ (ref. 35) and $(Ba_{0.6}K_{0.4})Fe_2As_2$ (ref. 36) show that curved, 'real' grain boundaries can often show much better transparency than more idealized, planar grain boundaries[35,36] and it is precisely these grain structures that seem to enable high J_c with much less texture and the desirable round-wire multifilament architecture presented here. A REBCO equivalent of multifilamentary Bi-2212 round wire would be truly transformational for superconducting magnet technology.

Methods

Wires were fabricated by Oxford Superconducting Technology. Wire ends were sealed by dipping in molten silver followed by either a standard heat treatment at 1 bar or an overpressure heat treatment[20], using pure O_2 for 1 bar heat treatment and O_2-Ar mixtures for overpressure heat treatment. Field emission scanning electron microscope imaging and Orientation Image Analysis were performed in a Carl Zeiss 1540 EsB Crossbeam instrument using a high-speed Hikari camera. X-ray tomograms were acquired using a monochromatic 70.0 keV X-ray beam with a bandwidth of 0.7 keV at the High Energy Scattering Beamline ID15A at the European Synchrotron Radiation Facility, Grenoble using a high-resolution imaging detector with a 15-μm-thick LuAG:Ce^{2+} scintillator that converts the X-ray absorption signal into visible light, which is then magnified and recorded by a high-speed CCD (charge-coupled device) camera with an image pixel area of $1.194 \times 1.194\,\mu m^2$.

Transport critical currents (I_c) were measured on 45-mm-long Bi-2212 wires at 4.2 K and fields up to 31 T applied perpendicular to current flow. I_c was determined at $1\,\mu V\,cm^{-1}$. The coil of Fig. 5 was wound using 30 m of 1.4-mm-diameter Bi-2212 wire with a ~15-μm-thick TiO_2 (nGimat LLC) insulation layer, which is 10 times thinner than earlier ceramic braid insulations[13]. The coil was heat-treated in an overpressure furnace with a slightly too small homogeneous hot zone. The body of the coil was heat treated in a ±0.5 °C temperature zone, but coil performance was slightly degraded because the terminals extended into a lower temperature zone. Reaction of subsequent coils in more homogeneous furnaces with full 100 bar overpressure heat treatment capability should allow generation of a new record high field for a superconducting coil significantly above 35 T.

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Author contributions

J.J. and M.M. reacted the samples, N.C.C., M.D-C and U.P.T. performed the transport critical current measurements, F.K. and J.J. performed the metallography and electron backscatter diffraction, C.S. performed the X-ray tomography, M.D-C, P.C. and U.P.T. constructed and tested the coil and D.C.L., E.E.H. and P.J.L. led the work and took the lead in preparing the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.