Topical Review

Development of RE-Ba-Cu-O superconductors in the U.S. for ultra-high field magnets

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Abstract

High-temperature superconductors (HTSs) make it possible to achieve magnetic fields beyond the 23.5 T limit of low-temperature superconductors. For higher energy density, high-performance HTS with \( J_c > 1000 \, \text{A mm}^{-2} \) enables reduction in coil winding length and a smaller magnet size. Among HTS, REBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (REBCO, RE = rare earth) exhibits excellent mechanical properties and superior performance over a wide range of temperatures and magnetic fields. REBCO tapes can be converted to various formats, including round wires. The state-of-the-art REBCO superconductors for ultra-high field magnets, including cable/wire architectures, are reviewed. R&D needs to address the remaining challenges with REBCO superconductors for ultra-high magnetic field applications is discussed.

Keywords: REBCO, superconductor, critical current, magnetic field, thin film, MOCVD, round wire

(Some figures may appear in colour only in the online journal)

1. Introduction

Since their discovery in 1986, the most appealing feature of high-temperature superconductors (HTS) has been their potential for applications at high temperatures, particularly using liquid nitrogen. Numerous projects on employing HTS in electric power applications, such as cables and fault current limiters were funded in the US, especially by the US. Department of Energy Office of Electricity (DOE-OE) during 1990–2010 [1]. Feasibility of scaling up of REBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (REBCO) superconductors to longer lengths (100–1000 m piece lengths) was achieved by SuperPower and American Superconductor (AMSC) [2, 3], and the implementation of REBCO in the electric power grid was demonstrated [4–7] through these projects. However, the lack of substantial commercial pull for HTS by electric utilities in the US and the halt of the DOE-OE HTS program in 2010 spurred researchers in the US to focus on conventional applications of superconductors, i.e., to generate high magnetic fields. This transition was enabled by several advances in the 2000s: establishment of a pilot manufacturing operation to produce long lengths of REBCO tapes [2], large improvements in the critical current density \( J_c \) of REBCO tapes using artificial pinning centers [8–15] and demonstration of a 27 T superconducting magnet using a REBCO insert coil [16]. These advances in turn have led to a proliferation of projects utilizing HTS in ultra-high magnetic field applications.
magnetic fields. Since the performance of HTS substantially improves at lower temperatures, most of these new applications are designed at 4.2 K and 20 K. Some of these applications of HTS in ultra-high magnetic fields include accelerators, fusion, nuclear magnetic resonance spectroscopy, magnets for research, superconducting magnetic energy storage (SMES), particle beam therapy, and magnetic resonance imaging.

2. Superconductors for ultra-high field magnets

The upper critical field \( H_{c2} \) of Nb$_3$Sn is 23.5 T in subcooled liquid helium which sets the maximum usable magnetic field of low temperature superconductors (LTS). On the other hand, \( H_{c2} \) of HTS exceeds 100 T at 4.2 K [17], which provides a substantial range of opportunities for realizing applications at much higher magnetic fields than LTS. Since the thermally activated flux creep that plagued the deployment of HTS in high magnetic fields at liquid nitrogen temperatures is not much of a factor at lower temperatures, the concern about irreversibility field limits is diminished. The prominent HTS materials that are being implemented in ultra-high magnetic field applications are (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi-2223), Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ (Bi-2212), and REBCO due to their superior performance in high fields at low temperatures [18, 19]. Table 1 compares the features of these three HTS materials.

Due to its round format, Bi-2212 wires can be readily fabricated into cables. Recent developments in converting flat REBCO tape into a round format has been successful as well, as described in section 2.1.4. A challenge with Bi-2212 is that its ductility degrades after heat treatment, hence, a wind and reaction process is used to fabricate magnets that restricts the manufacturing method. Since the \( J_c \) of REBCO films is about two orders of magnitude higher than that of Bi-2223 and Bi-2212, just 1%–2% of superconductor content is sufficient to achieve high critical current (\( I_c \)). Interestingly, the field dependence of \( J_c \) at 4.2 K is similar in all three materials over a range of magnetic fields (10–30 T). A benefit of REBCO is its high irreversibility field at higher temperatures: 30 T at \( \sim 55 \) K, while both Bi-based show irreversibility field of just 10 T at 20 K (Bi-2212) or 30 K (Bi-2223) [20]. So, while Bi-2223 and Bi-2212 are limited to 4.2 K for ultra-high field operation, REBCO has the potential to be used at much higher temperatures.

2.1. REBCO

Unlike Bi-based HTS, REBCO is fabricated by a thin film deposition process. REBCO tape consists of a series of thin films that range in thickness from a few nanometers to a few micrometers, deposited by multiple deposition methods. Unlike Bi-based HTS, REBCO utilizes a high-strength alloy substrate, such as Hastelloy C-276 or stainless steel as the primary metallic component, which provides excellent mechanical properties. Also, the reel-to-reel continuous process used for depositing the various thin films allows less labor-intensive manufacturing. A biaxially-textured template layer is first deposited by ion beam assisted deposition (IBAD)
or rolling assisted biaxially-textured substrate (RABiTS) technology on the metal substrate. REBCO layer is grown on the biaxially-textured stack either by chemical deposition routes including metal-organic chemical vapor deposition (MOCVD) [21], metal-organic deposition (MOD) [22], or by physical vapor deposition routes, including pulsed laser deposition (PLD) [23], reactive co-evaporation (RCE) [24].

MOCVD involves vaporization of precursors that are deposited on a heated substrate. MOD is an ex-situ process that includes precursor coating, calcination and conversion processes. PLD uses laser irradiation of precursor target to deposit thin films on the heated substrate. RCE process is based on evaporation of rare-earth, Ba, and Cu elements to deposit amorphous film and a heat treatment conversion step to form the superconductor layer. The typical thickness of REBCO film deposited in these processes is 1–2 µm, hence the HTS content is only 1%–2% of the whole-conductor cross-section, much less than Bi-2212 (25%), and Bi-2223 (40%).

2.1.1. Low field high-temperature REBCO. Meter-long REBCO tapes with \( I_c > 130 \text{ A/12 mm-width} \) (at 77 K, 0 T) were demonstrated by PLD and MOCVD using IBAD-buffered tapes in 2002 [25]. By 2006, the piece length was scaled up >300 m with a critical current \( >250 \text{ A/12 mm} \) at 77 K, 0 T [26]. About 10 km of REBCO was delivered by SuperPower that year in the world’s first manufacturing demonstration to construct a 30 m long power transmission cable that was installed in the power grid [27]. Piece length of REBCO tape was increased over 1000 m by 2008 [28]. Superpower and AMSC are now capable of routine manufacturing REBCO tape in greater than 300 m lengths with a critical current of \( \sim 450 \text{ A/12 mm} \) at 77 K.

In parallel, new developments in the incorporation of columnar BaMO \(_3\) (M = Zr, Hf) nanoscale defects, originally developed by PLD [9, 10], were demonstrated by MOCVD [12, 13] and then transitioned to industrial manufacturing. Unlike PLD where BaMO \(_3\) is added to the target, Zr or Hf is added to the chemical precursors in MOCVD which then forms BaZrO \(_3\) (BZO) or BaHfO \(_3\) in the superconductor film. It was found that 7.5 mol\% Zr addition yielded the optimum in-field performance in low magnetic fields at 77 K [12, 29]. Earlier REBCO films were typically less than 1 µm in thickness. Deposition of thicker films yielded misoriented and a-axis grains that lowered the \( I_c \) significantly. Multi-pass processing was shown to increase the thickness of the film from 0.7 µm to 2.8 µm with fewer microstructural deficiencies, which increased the \( I_c \) up to 600 A cm\(^{-1}\) width in short lengths [30]. A mixed rare earth (GdY)Ba\(_2\)Cu\(_3\)O\(_{7-\delta}\) composition with Zr-addition was then utilized to increase the in-field \( I_c \) by bi-directionally-aligned defect structures of BZO and (Gd,Y)\(_2\)O\(_3\) [13, 31]. In 2008, \( I_c \) as high as 813 A cm\(^{-1}\) was reported over meter lengths using the modified MOCVD precursor chemistry and 2.8 µm thick film [28].

AMSC uses a RABiTS/MOD process to produce 0.8 µm thick Y(Dy)BCO on 4 cm-wide strips that are slit into multiple narrower tapes. In 2009, the company reported production of 500 m long tapes with an average \( I_c \) over 250 A cm-width [3]. Now, 1.4 µm thick film superconductor tapes are being produced. A solenoid coil of 5 cm inner diameter that generated a 1.5 T field at 64 K has been demonstrated using these tapes [32].

2.1.2. High field low-temperature REBCO. Until 2010, the emphasis of in-field performance improvement for REBCO tapes was nearly exclusively focused on 65 K and 77 K operation in magnetic fields less than 3 T. In 2012, the benefit of heavy doping (15–25 mol\% Zr) was demonstrated by the University of Houston (UH) in REBCO tapes made by MOCVD to double the \( I_c \) in high magnetic fields at lower temperatures [33, 34]. Previously, such a high level of dopant was avoided by researchers since it suppressed the transition temperature and \( I_c \) at 77 K [35]. The UH work showed that the lift factor in \( I_c \) (ratio of the in-field \( I_c \) at low temperature to the \( I_c \) at 77 K, 0 T) can be tripled >6 at 30 K and 3 T to achieve a record high \( J_c \) of 20.3 MA cm\(^{-2}\) at 30 K and 3 T using an optimum composition of \( \text{Ba + Zr}/\text{Cu} \) [36]. Soon after this demonstration, measurements at 4.2 K in magnetic fields up to 31.2 T of UH’s REBCO tape showed record high pinning force \( (F_p) \) levels of 1.7 TN m\(^{-3}\) [37]. While at that time, the improvement was attributed primarily to the higher level of Zr addition, it has now been found that the Ba content plays the primary role in determining the microstructure of the columnar defects, the accompanying strain and in turn, the in-field performance [38]. Thus, a superior performance can now be achieved even with 5 mol.\% Zr addition [38, 39].

While the \( J_c \) and \( F_p \) levels of REBCO in ultra-high magnetic fields at 4.2 K are remarkable, \( I_c \) and \( J_c \) levels were still not noteworthy. One way to improve the \( I_c \) and \( J_c \) of REBCO is to increase the film thickness. However, the problems with decreasing \( I_c \) with increasing thickness was well documented [40, 41]. Realizing that this problem was deposition equipment limited, UH designed an Advanced MOCVD process wherein the precursor flow and temperature are much better controlled to achieve the process conditions required to fabricate high-quality epitaxial thin films as thick as 4–5 µm [42]. In addition to achieving such thick films that yielded \( I_c \) of 1660 A/12 mm-width at 77 K, 0 T [43], the superior process conditions in Advanced MOCVD also enabled a good control of the film composition that resulted in higher lift factor in \( I_c \) at ultra-high magnetic fields. Figure 1 exhibits the tailoring of the microstructure of Zr-added, 4.2 µm thick film REBCO tapes made by Advanced MOCVD by modifying the Ba content in the film. Films with a relatively lower Ba content [(Ba + Zr)/Cu = 0.72] show BZO nanorods along the c-axis interrupted by a high density of RE\(_2\)O\(_3\) (REO) precipitates along the ab plane whereas films with higher Ba content [(Ba + Zr)/Cu = 0.846] show well-aligned BZO nanorods with hardly any REO.

The differences in the BZO nanorod morphology and overall microstructure in films with different Ba content manifests themselves in the flux pinning efficacy in high magnetic fields at 4.2 K. As shown in figure 2, the magnetization \( J_c \) of 4.2 µm thick film REBCO tapes with 15% Zr and 15% Hf addition increases with increasing Ba content up to a certain level [44].
Figure 1. (a) A typical cross section microstructure of Zr-added (Gd,Y)BCO tape at low magnification. Cross section microstructure of 15 mol. % Zr-added (Gd,Y)BCO with (b) low (Ba + Zr)/Cu = 0.72 content and (c) high (Ba + Zr)/Cu = 0.846 content. In figure (b) the in-plane RE$_2$O$_3$ precipitates are indicated by dashed lines. Reproduced from [38]. © IOP Publishing Ltd All rights reserved.

Figure 2. (Left) trend in magnetization $J_c$ of 4 $\mu$m thick 15% Zr- and 15% Hf-added REBCO tapes at magnetic fields of 1.5–13 T and 4.2 K, with increasing Ba content. M refers to Zr or Hf. © 2021, IEEE. Reprinted, with permission, from [44]. (Right) Compositional map of RE, Ba + Zr, and Cu showing the magnetization $J_c$ at 4.2 K, 13 T for different film compositions. It is found that the lift factor in $J_c$ continues to increase with higher Ba content to levels as high as 45 at 4.2 K, 13 T, but because of degradation in REBCO film texture and excessive strain in the film, the $J_c$ itself peaks at an intermediate level of Ba content. Interestingly, the Ba content in both Zr- and Hf-added samples required to achieve the peak $J_c$ at 4.2 K increases for higher magnetic fields as seen in figure 2. It can also be observed from figure 2 (right) that the highest $J_c$ values at 4.2 K, 13 T are obtained in a narrow range of compositions of films made by MOCVD. Consequently, it is vital to control the film composition in stable manner during long deposition processes. Recently, an in-line 2D x-ray Diffraction technique has been developed for real-time monitoring of film texture and compositions necessary to achieve consistently superior performance in high magnetic fields [45]. REBCO tapes produced in Advanced MOCVD stand out over a wide range of magnetic fields and show $I_c \sim 2,100$ A/4 mm-width and $J_c \sim 5,250$ A mm$^{-2}$ (based on 100um thick total tape thickness) at 4.2 K, 15 T [46]. About 15 mol.% Zr-added REBCO tapes displayed $J_c > 10$ MA cm$^{-2}$
of REBCO is that a superior performance is achievable even at higher temperatures. Typically, the in-field $I_c$ of REBCO at 20 K is approximately 50% of its $I_c$ at the same field at 4.2 K. This opens up opportunities for applications, such as compact fusion where a higher operating temperature is desirable. In addition to the superior $I_c$, the high critical tensile stress of about 700 MPa at 100 000 cycles [47], and 0.4%–0.7% longitudinal tensile critical strain and −1.2% compressive strain [48] are attractive properties of REBCO for ultra-high field applications.

### 2.1.3. REBCO magnets

An early demonstration of the potential of REBCO for ultra-high magnetic field applications was that of a solenoid coil made using ∼460 m of 4 mm wide tape and tested in a 19 T axial background field at NHMFL [51]. The coil generated a total central field of 26.8 T (7.8 T insert YBCO coil + 19 T) at a critical current of 221 A. This was followed by many more demonstrations of high-field REBCO magnets, including a 33.8 T solenoid [52].

In 2012, Brookhaven National Laboratory BNL demonstrated a 15 T HTS solenoid using REBCO, the highest field ever recorded with HTS solenoid at that time [53]. The solenoid consisted of 14 pancake coils with a 25 mm aperture. Each coil was wound with 270 turns using 50 m of 4 mm wide REBCO tape co-wound with 4 mm wide, 25 μm thick stainless-steel tape. The operational current of the solenoid was 285 A at 4.2 K, which corresponds to a 16.2 T peak field and 15.8 T central field.

A first attempt to utilize REBCO coils in an application was for an SMES system that was designed to reach 25 T at 4 K in a 100 mm bore [54]. The objective of this project was to demonstrate a 1.7 MJ SMES using several modules in a toroidal geometry. The fully assembled SMES coil consisted of 28 inner pancakes and 16 outer pancakes and used 6 km length of 12 mm wide REBCO tapes. Before testing at full rating, i.e., 720 A (∼26 T) at 4 K, the SMES coil was tested at 350 A (50% of the design current) at 20–30 K, which resulted in a record-high 12.5 T at 27 K. However, a problem during the final testing caused the inner damage to the instrumentation, leading to a few pancakes and a few outer turns. As a result, the completed SMES system could not be tested.

In 2018, NHMFL successfully tested a 32 T/34 mm bore all-superconducting magnet [55]. The coils consist of more than 20 000 turns of an insulated REBCO conductor insert (17 T) and a low-temperature superconducting (15 T) insert in a concentric assembly. The $I_c$ of the 4 mm wide REBCO tapes be greater than 256 A at 4.2 K, 17 T. In addition to producing and qualifying a large volume of tapes, this project advanced other critical technologies, such as high-strength joints operating under high field, winding of tapes with different $I_c$ value to achieve an average current density of 197 A mm$^{-2}$ for the inner coil of the magnet, ultrathin insulation to allow operation at high $J_c$ and stress, and quench protection schemes. Details of magnets demonstrated with REBCO tapes can be found elsewhere in this special issue.

![Figure 3. $I_c$ (H/c) and $F_p$ (H/c) in magnetic field up to 31.2 T at 4.2 K of 0.9 μm thick film MOCVD and 4.6 μm thick film Advanced MOCVD REBCO tapes. Reproduced from [31]. CC BY 3.0. Reproduced from [46]. © IOP Publishing Ltd. All rights reserved.](image-url)

![Figure 4. Engineering current density of R&D-scale REBCO and Bi-2212 superconductors in high magnetic fields at 4.2 K. © 2019, IEEE. Reprinted, with permission, from [49]. Reproduced from [50]. © IOP Publishing Ltd. All rights reserved.](image-url)
Non-insulation (NI) REBCO magnets are considered as an alternative to insulated REBCO magnets for quench protection and higher current densities [56]. No insulation (NI) coils show resistance values of 10–100 micro-ohms cm\(^{-2}\)—this creates field quality and boil off issues, limiting the current ramping rate to as low as \(\approx 0.01\) A s\(^{-1}\) to energize an NI Magnet. The disadvantage of this technique is that the shunting of the inductance and the delay in charging and discharging time affects field control with respect to current and helium boil-off due to Joule heating from radial currents. However, NI coils significantly improve magnet reliability by allowing current to flow into the coil’s adjacent turn, circumventing the quench region and avoid overheating.

2.1.4. REBCO cable and round wire. In contrast to Bi-2212 wires, Bi-2223 and REBCO conductors are produced in tape form with a wide aspect ratio. This makes it difficult to achieve cable geometries with REBCO where isotropic properties are preferred. Cables for superconducting dipole and quadrupole magnets for particle accelerators require 10–20 kA operating current and a \(J_e\) of 600 A mm\(^{-2}\) in a background field of 20 T. Cables for fusion magnets require operating currents of 50–100 kA in a background field 10–20 T. Multi-strand cables result in low magnetic charge inducts that facilitate rapid charging. A fully-transposed cable or wire has similar inductance in all strands and allows uniform current distribution among all the strands during ramping, minimizing AC losses. Another advantage is current-sharing to circumvent possible defective regions in a strand.

In the last decade, several concepts for high-current multi-strand REBCO cable configurations have been developed to address the inherent deficiency of flat tape by converting these flat tapes into cables and round wires, including Roebel cable, twisted stacked tape cable (TSTC), Cable-on-round-core (CORC\(^\circledR\)), and symmetric tape round (STAR) wire. Figure 5 illustrates the formats of these REBCO cables and round wires.

Roebel cables [63] are fabricated by patterning and assembly of REBCO tapes as shown in the figure 5(a). This configuration allows full transposition of the strands and a more homogeneous current distribution between strands. The disadvantages of this design are difficulty in bending in the hard direction of the tapes and stress concentration due to the presence of crossovers in the cable.

In the TSTC approach [64, 65], REBCO tapes are stacked on top of each other and twisted. The twist pitch length should be compatible with the strain limits of the tape to facilitate the bending of the stack. The \(J_e\) of TSTC is high due to the absence of any former material. The bend radius of the TSTC design is high, making it more appropriate for magnet systems like tokomak fusion reactors rather than complex magnets needing significant 3D bend tolerance. Commonwealth Fusion Systems (CFS), in collaboration with the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center (PSFC), uses a TSTC cable geometry in a version dubbed VIPER—vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed [66]. This superconducting VIPER cable is mechanically resilient and robust under extreme thermal conditions and has low resistance joints.

CORC\(^\circledR\) cables and wires are made by spiral winding of REBCO tapes on a round former. While spiral winding of REBCO and other HTS tapes are routinely done for electric power cables, CORC\(^\circledR\) cables build on an early demonstration of the capability of REBCO tapes to be spiral wound to small
Figure 6. Canted cosine theta coil (CCT) fabricated by LBNL with round REBCO wire. Reproduced from [69]. © IOP Publishing Ltd All rights reserved.

Figure 7. (Left) 3D model of an assembled conceptual three-turn CCT coil with two layers. The inset is a close-up of the ‘U’-shaped grooves. (Right) dipole transfer function (TF) and minimum bend radius as a function of the tilt angle for two multi-layer CCT dipole magnets. Each layer has 40 turns of wires. The magnet aperture is 50 mm. Reproduced from [70]. © IOP Publishing Ltd All rights reserved.

twist pitch lengths [67]. CORC® cables of 7.5 cm diameter showed $J_e$ of 344 A mm$^{-2}$ at 4.2 K in 17 T [68]. CORC® cables showed no degradation of $I_c$ until 100 000 cycles at a peak load of 210 kN m$^{-1}$ and critical tensile stress of about 170 MPa [48]. Recently, a canted cosine theta (CCT) magnet made with 70 m of CORC® wire achieved a dipole field of 2.91 T at 6.290 kA, 4.2 K [69]. Figure 6 shows winding of CORC® wire for a CCT coil.

The importance of the minimum bend radius of wire used in CCT coils is evident from the dependency of the dipole transfer function on the tilt angle which in turn depends on the winding radius. As shown in figure 7, in a CCT coil, the wires are tilted at an angle ($\alpha$) with respect to the bore axial direction to cancel the solenoid field components produced by each layer and double the dipole field in the magnet aperture [70]. The dipole transfer function is proportional to $\cos \alpha$ and the minimum bend radius is proportional to $\sin \alpha$ [71]. With CORC® wire’s minimum bend radius of 25 mm, a large tilt angle has to be used. This results in a dipole transfer function of only 0.28 T kA$^{-1}$ in a four-layer CCT design which limits the achievable magnetic field.

As seen in figure 7, if the minimum bend radius of the round wire can be reduced to 15 mm, the tilt angle can be lowered to 30° and the dipole transfer function can be nearly doubled to 0.48 T kA$^{-1}$ with a four-layer design and to 0.73 T kA$^{-1}$ with a six-layer design. Using specially-made symmetric REBCO tapes where the superconductor film is positioned near the neutral plane (figure 5(d)), AMPeers and the UH have demonstrated REBCO round wires as small as 1.3–2 mm in diameter [57]. These STAR wires exhibit excellent tolerance to bend strain and can retain over 95% of their $I_c$ even when wound over a 15 mm bend radius, meeting a key design requirement of CCT. As shown in figure 8, the symmetric REBCO tapes can be bent to even 0.8 mm diameter and retain more than 95% of their $I_c$ whereas standard REBCO tapes begin to fail even at bend diameter of 6 mm. Figure 8 exhibits the performance of a 2.29 mm diameter STAR wire made by winding 11 symmetric tape strands on a 0.81 mm diameter former. This wire shows a $I_c$ of 728 A at 77 K, 0 T in a straight form and retains 95% of this $I_c$ when bent to a radius of 15 mm.

A 1.3 mm diameter REBCO STAR wire reached a $J_e$ of 586 A mm$^{-2}$ at 4.2 K in a background field of 20 T at a bend...
radius of 15 mm [72]. This $J_e$ meets the design requirements of CCT coils. STAR wires have been recently scaled up 23 m with an average $I_c$ of 480 A (1.95 mm diameter) and to 61 m with an average $I_c$ of 370 A (1.84 mm diameter).

Figure 9 summarizes the $J_e$ values of various round REBCO wires and REBCO cables in a magnetic field range of 10–32 T at 4.2 K. Roebel cables showed a $J_e$ of approximately 400 A mm$^{-2}$ at 4.2 K in a 10 T field [73]. TSTCs exhibited a $J_e$ of 482 A mm$^{-2}$ at 4.2 K and 12 T without bending, but after bending to 140 mm radius, showed a lower $J_e$ of 273 A mm$^{-2}$ at 4.2 K, 16 T [74]. Both Roebel cables and TSTC are of rectangular cross-section that is not flexible enough in the hard-bending direction, limiting magnet design and fabrication. CORC® cables have exhibited a $J_e$ of 412 A mm$^{-2}$ at 4.2 K, 10.5 T at a bending diameter of 60 mm [75]. A $J_e$ of 423 A mm$^{-2}$ was reported for a 4.5 mm diameter
CORC® wire at 20 T, 4.2 K [76]. As shown in figure 9, STAR wires stand out with their high $J_c$ even at a very small bend radius of 15 mm.

3. REBCO development needed for ultra-high field magnets

The US. Magnet development program (2020) recently published a roadmap on magnet technology for future collider applications [79]. One of the critical goals was to develop an HTS accelerator magnet with 17–50 mm bore with a 5 T or greater self-field and understand the fundamental aspects of magnet technology. REBCO materials are of particular interest to generate a dipole field of 20 T and above for future circular particle accelerators and fusion reactors because of their high current density over a wide range of temperatures and magnetic fields. DOE Office of High Energy Physics is sponsoring many projects on REBCO superconductors for high field accelerator magnets.

Ultra-high-field superconducting magnets are also enabling compact fusion designs for a Q (net energy gain) of ten as well as a 10x reduction in fusion device size (and thus the cost, time, and complexity). The leading fusion reactor designs are based on tokomaks built using REBCO superconductor. Prototype fusion systems with a net energy gain of two are being constructed for demonstration as early as 2025 by CFS in collaboration with MIT-plasma science and fusion center (PSFC) [80]. An alternative to tokomaks for compact fusion reactors is the stellarator design being developed by companies such as TypeOne Energy in collaboration MIT-PSFC and the University of Wisconsin-Madison. Unlike tokomaks that operate in pulses, stellarators, that confine hot plasma along a twisting circular path, could work continuously, free of disruptions [81]. However, the REBCO superconductor will be subjected to more severe strain due to the contorted shape of the coil in a stellarator. Several fusion projects using superconductors are ongoing in the US, funded by the Advanced Research Projects Agency and the DOE Office of Fusion Energy Sciences.

The following is a description of the development efforts needed for widespread implementation of REBCO in ultra-high field magnets for accelerators, compact fusion and other applications.

3.1. Lower-cost REBCO tapes

Many designs of high-field accelerator magnets would require bundled REBCO tape strands. The large number of tape strands necessary to achieve high dipole fields would greatly increase the cost of the coils. Using tapes with 5–10x higher critical current than the present-day, commercially-available REBCO tapes, the number of strands to achieve the required dipole field can be greatly reduced. So, there is a strong need to scale up higher critical current tapes that have been demonstrated as short samples, to long lengths. Additionally, methods to decrease the unit cost of REBCO tapes ($/m) have to be developed. Processing methods have to be improved to reduce the waste in converting expensive precursor materials to superconductor film. Manufacturing yield needs to be improved with innovative quality control methods.

3.2. Long tapes with uniform critical current

Even though REBCO tapes were fabricated in continuous lengths of more than 1300 meters over ten years ago [28], routine availability of REBCO tapes is limited to about 300 meters. Longer piece lengths require long lead times and are much more expensive. This is because of non-uniformity in critical current over long lengths: drop-outs and fluctuations more than 5% in critical current are common. Unlike other superconductor wires, REBCO tapes are fabricated in a sequential deposition process where the quality of every layer depends on the quality of the previous underlying layer. So, it is essential to develop robust in-line quality control tools for 100% inspection of the quality of every layer so that problems in film quality can be identified and the process remedied in real-time. Even if the critical current at 77 K, 0 T is uniform over long lengths, it is likely that the critical current in high magnetic fields at 4.2 K is not uniform. Tapes with superior high-field performance enabled by as-grown BaMO$_3$ (M = Zr, Hf, Sn) nanoscale defects that exhibit excellent flux pinning [8–14, 33–39] are especially prone to non-uniformity because of the sensitivity of in-field critical current to the film composition and nanoscale defect structure. Innovative methods for real-time control of the film composition and nanoscale defect structure over kilometer lengths in a narrow process window is very important.

While long tapes with uniform critical current are highly desirable, methods to manage local defects in REBCO tapes have to be investigated. Since ultra-high field magnets will likely use REBCO tapes in form of a bundle of multiple strands, techniques that promote current sharing between strands to bypass current around possible local defects need to be developed. Additionally, test techniques need to be developed to qualify the in-field critical current of REBCO tapes over long lengths. At this time, REBCO tapes are qualified 100% over their length only at 77 K, 0 T. Elaborate measurements of REBCO tapes delivered to the 32 T magnet project of the National High Magnetic Field Laboratory showed poor correlation between critical current at 77 K, 0 T and critical current in high magnetic fields at 4.2 K [82]. So, test techniques need to be established for in-field critical current measurement over 100% of the tapes. Good correlations found between in-field critical current at 65 K or 77 K and in-field critical current at lower temperatures [83] indicate that in-field critical current testing at 65 K or 77 K over 100% tape length could be sufficient.

3.3. REBCO tapes for multi-strand wire architecture

The round REBCO wires with bend radius capability of 15 mm have to be tested in CCT and other magnet designs to verify functionality and near doubling of the dipole transfer function as projected in figure 7. If the minimum bend radius could be reduced even further to 10 mm, further increase in the dipole transfer function could be achieved which can reduce the
number of tape strands required. Additionally, round REBCO wires with a bend radius of 10 mm or less can enable new and inexpensive methods such as direct winding of magnets [84, 85]. Low-resistance joints between round wires have to be achieved and the robustness of these joints have to be confirmed. REBCO tapes are subjected to severe tension and torsional strains when they are fabricated into multi-strand wires. Modeling and testing the mechanical properties of these multi-strand wires is important to assure consistent quality and to improve manufacturing yield. Non-destructive methods need to be developed to identify defects in these multi-strand wires before they are used for coil fabrication.

3.4. Non-twisted cables

LTS-based high-field magnets are generally composed of fine, twisted filaments to reduce ac losses and enhance the stability margins. However, HTS materials are more stable due to higher critical temperatures, and higher heat capacities. Therefore, following the design aspects of LTS for HTS cable may not be an efficient strategy to reduce hysteretic loss. The loss in a twisted stack of tapes is only marginally lower (36%) than the saturated loss of a non-twisted stack [86]. The advantage of non-twisted stack designs are higher tolerance to transverse stresses and improvement in critical current density due to the anisotropy of HTS tape. Recently, it was proposed to use a cable made of non-twisted HTS stacks for future tokamak toroidal field coils. The analysis performed on non-twisted HTS stacks-based cable-in-conduit conductors showed wave-like magnetic field distribution along the conductor, which decreased the negative effect of screening currents caused while charging the magnet [87].

3.5. Mechanical robustness

While the mechanical properties of REBCO superconductors are superior to that of Bi-2212 and Bi-2223 superconductors, potential failures in ultra-high field magnets have root causes in the mechanical integrity of REBCO tapes. Delamination of REBCO tapes due to thermal expansion mismatch issues has been discovered only after thermal cycling of coils which is a costly problem [88]. Methods to non-destructively predict potential delamination issues, prior to coil fabrication have to be established. Even though the critical tensile stress of ∼700 MPa of commercial REBCO tapes is sufficient for most applications, a 2x improvement of this metric can open up much higher magnetic field designs, which can be especially useful for compact fusion.

3.6. Quench detection and protection

The normal zone propagation velocity of REBCO tapes is too small to facilitate early quench detection [89]. Techniques such as Rayleigh scattering and acoustic emission have been developed for quench detection in coils made with REBCO tapes [90, 91]. Robust methods for rapid quench detection and protection that can be reliably used amidst background noise and spurious signals have to be established. Ideally, the quench detection scheme should be integrated into the REBCO cable itself to assure fast response of quench events anywhere along the tape/wire length.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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