R&D for REBCO High Temperature Superconductor Tapes for Next-generation Accelerators

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High Luminosity Large Hadron Collider (HL-LHC) for high energy physics is transitioning from Nb-Ti dipoles to Nb_3Sn for higher operating magnetic fields [1]. Even higher gains in beam energy and luminosity for the proposed High Energy Large Hadron Collider (HE-LHC) can be obtained by using High Temperature Superconductors (HTS) which are the only option for fields in the vicinity of 20 T [1, 2].

RE-Ba-Cu-O (REBCO, RE=rare earth) tapes are a leading candidate for HTS dipoles. The high yield strength (> 700 MPa) of REBCO tapes is especially beneficial to withstand the intense forces in high magnetic fields. Additionally, the use of REBCO does not limit materials that can be used for construction of accelerator magnets as is the case with wind-and-react methods needed for Nb_3Sn and Bi-2212 superconductors. Additionally, very high engineering current densities beyond 5000 A/mm^2 at 4.2 K, 15 T are feasible with REBCO tapes [3].

Over a dozen companies world-wide manufacture REBCO tapes and are ramping up their operations to meet the growing demand for high magnetic field applications. Still, many challenges exist for REBCO to be used in next-generation accelerators, including

- High cost
- Non-uniformity of critical current in lengths over 300 meters
- Flat profile rather than a round, multifilamentary architecture of other superconductor wires
- Quench detection and protection

R&D opportunities:

Lower-cost REBCO tapes:

Many designs of high-field accelerator magnets would require bundled REBCO tape strands [4]. A block-design dipole magnet recently demonstrated 3.1 T dipole field [CERN] and a CCT coil dipole made recently showed a peak dipole magnetic field of only 1.2 T [5]. High-field compact REBCO accelerator inserts need to provide at least 5 T dipole field within 90 – 110 mm aperture of the outsert magnets. Many more REBCO tape strands would be required to achieve higher dipole fields which 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.

Long tapes with uniform critical current:

While REBCO tapes have been fabricated in continuous lengths of more than 1300 meters over 10 years ago [6], routine availability of REBCO tapes is limited to less than 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 [7-11] 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 to for real-time control of the film composition and nanoscale defect structure in a narrow window over kilometer lengths 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 accelerator 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 [12]. 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 [13] indicate that in-field critical current testing at 65 K or 77 K over 100% tape length could be sufficient.

<u>REBCO tapes for multi-strand wire architecture</u>:

A challenge with REBCO tapes as compared to Nb-Ti, Nb_3Sn and Bi-2212 wires is their flat rather than round geometry and a wide (~ 12 mm) profile rather than a multifilamentary architecture. A round wire is mechanically isotropic in bending which can benefit multiple conductor and magnet designs. It has been shown that the flat REBCO tape geometry can be converted to round cable by helical winding of flat tapes on a round core [14]. However, neither this nor any previous HTS wire/cable methods have been able to meet the stringent bend radius requirement that is required for REBCO dipole insert magnets that will operate in a limited aperture of LTS magnets. For instance, an engineering current density (J_e) of 540 A/mm^2 at 4.2 K, 21 T at a bend radius of 15 mm is a key requirement of CCT coils [5]. If the minimum bend radius of the round wire can be reduced to 15 mm, the tilt angle can be lowered to 30^o and the dipole transfer function can be nearly doubled to 0.48 T/kA with a four-layer design and to 0.73T/kA with a six-layer design [5]. 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 [15, 16]. Custom-made, symmetric REBCO tapes hold the promise of achieving such round wires, 1 – 2 mm in diameter with excellent bend tolerance [17]. 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. Delamination of REBCO tapes has been discovered only after thermal cycling of coils which is a costly problem [18]. Methods to non-destructively predict potential delamination issues, prior to coil fabrication have to be established.

<u>Quench detection and protection</u>:

The normal zone propagation velocity of REBCO tapes is too small to facilitate early quench detection [19]. Techniques such as Rayleigh scattering and acoustic emission have been developed for quench detection in coils made with REBCO tapes [20, 21]. Robust methods for rapid quench detection and protection that can be reliability used amidst background noise and spurious signals have to be established.

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