Develop high-temperature superconducting REBCO magnet technology for future circular colliders

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Potential impact

Higher magnetic field strengths enable a stronger potential for particle physics discovery. Since the Tevtron, superconducting accelerator magnets have enabled all major accelerator complexes. Based on Nb-Ti conductors, the LHC uses 1232 superconducting dipole magnets capable of generating 8.3 T at 1.9 K. Dipole magnets using today's Nb_3Sn conductors can generate around a dipole field of 16 T. While active material research continues increasing the potential of Nb_3Sn conductors towards generating a dipole field of 20 T at 4.2 K [Xu14, Ba19, Sa15], high-temperature superconductors (HTS) [Ma12] are required to generate dipole fields beyond 20 T. Two main candidate HTS conductors are Bi-2212 round wires [La14] and REBCO coated conductors [Se12]. Here we will focus on REBCO conductors with the following potentials for future particle colliders.

- Generate high fields (> 20 T) over a wide temperature range. Thanks to the high irreversibility field of REBCO [La01], one can operate high-field REBCO accelerator magnets above 4.2 K.
- Reach operating fields without magnet training. Due to the large stability margin compared to its low-temperature superconducting (LTS) counterparts, REBCO conductors can tolerate a broad spectrum of perturbation that is the sources of magnet training in LTS accelerator magnets. Eliminating magnet training can significantly affect the cost scale of future circular colliders.
- Allow more material options for magnet development. REBCO magnets do not require heat treatment, which allows more material options for magnet mandrel and conductor insulation.

Challenges and required technology development

Although REBCO conductors have a strong potential as a new paradigm of accelerator magnets, significant technical challenges need to be addressed. We summarize these challenges into the following driving questions for the required technology development [Wa19].

1. *How to make high-field accelerator magnets using multi-tape REBCO conductor?* REBCO conductors are brittle and strain-sensitive, which can require specific magnet design and fabrication to minimize the strain-induced degradation. Magnet design and fabrication will help guide the conductor development: architecture, transport performance, bending radius, inter-tape contact and etc. Impregnation and joint fabrication will also be addressed.
2. *What is the maximum field a REBCO dipole magnet can achieve? What is the long-term performance of REBCO magnets under Lorentz loads?* The mechanical limit of REBCO conductors will determine the maximum dipole field a REBCO magnet [Al16]. What is this limit and how can we address it? Will the performance under strong Lorentz forces degrade the conductor and magnet performance?
3. *How do REBCO magnets transition from superconducting to normal state and how can we detect the transition?* The normal zone in REBCO magnets, once initiated, does not grow as fast as in an

LTS magnet, challenging the quench detection and magnet protection against catastrophic damages. Innovative quench detection schemes will be required [Sc16, Ma17].

4. *What is the field quality of REBCO accelerator magnets?* Field quality is what matters for particles. In addition to large magnetization in the conductors, its decay and impact on the accelerator operation needs to be understood and addressed [My19].
5. *What is the required performance for REBCO Conductors to achieve the desired magnet performance?* The conductor and magnet development are strongly coupled. We need to engage the allied material R&D program and conductor manufacturers and help optimize the conductors by and for the magnet performance [Ma18, Ka19, We20].
6. *How to determine the performance of a long multi-tape REBCO conductor for predictable magnet performance?* Accelerator magnets will require conductors with a unit piece length on the order of 100 m. The properties of REBCO conductors can vary along a long length. How do we characterize and improve its uniformity will be important for accelerator magnets [Hu17].

Current status and a path towards a dipole field of 20 T

Several programs are developing REBCO accelerator magnets. The EuCARD series programs, an European collaboration led by CERN, have been pioneering the development for REBCO accelerator magnets [Ro19]. The collaboration successfully demonstrated a record dipole field of 4.2 T at 4.5 K with an aligned-block dipole magnet using a multi-tape Roebel cable [Nu18]. Designs of hybrid dipole magnets with HTS inserts [To14] and stand-alone REBCO dipole magnets were also developed [Nu18b]. The U.S. Magnet Development Program (USMDP) [Go16], supported by the Office of High Energy Physics at the U.S. Department of Energy, has a dedicated component to develop HTS accelerator magnet technology with an initial goal to demonstrate a 5 T dipole field and to measure its field quality.

A significant amount of resources and a strong collaboration between different programs will be required to develop and demonstrate the REBCO accelerator magnet technology. Figure 1 shows a list of to achieve a dipole field of 20 T within a decade with two parallel approaches: one with the LTS/HTS hybrid dipole configuration and the other with the stand-alone REBCO dipole magnet.

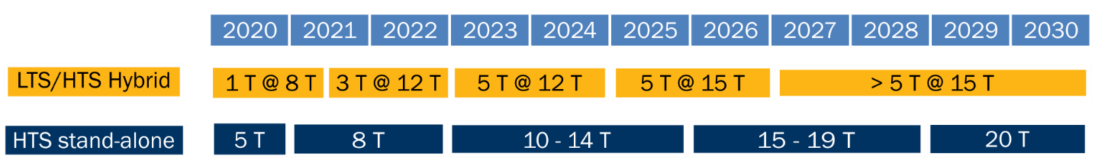

Figure 1 A list of milestones towards a dipole field of 20 T using REBCO conductors.

Conductor cost reduction and synergy with fusion applications

Although there are around a dozen REBCO tape manufacturers worldwide competing for the REBCO market, the conductor cost is prohibitively high. A strategic investment from public and other stakeholders should be planned to support the conductor development and procurement to enable effective and fast development of REBCO magnet and conductor technology, which will in turn enable future particle-physics discovery. A significant market pull will reduce the conductor cost [Ma12b]. Future circular colliders can be such a market. Another candidate can be the fusion energy generation. Recently, the compact tokamak facility concept based on the high-field REBCO magnets attracts significant attention [Ma19] and several private companies are developing the REBCO fusion magnet and conductor technology. The strong synergy in magnet and conductor technology between HEP and fusion applications should be leveraged.

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