High Temperature Superconducting Wires with much Enhanced Current Carrying Capability for Fusion Magnets

Quanxi Jia and Leonardo Civale

1Department of Materials Design and Innovation
University at Buffalo – the State University of New York, Buffalo, NY 14260
Email: qxjia@buffalo.edu

2Materials Physics and Applications
Los Alamos National Laboratory, Los Alamos, NM 87545

Background: Superconductors have been considered as the materials of choice for fusion magnets due to their high efficiency and reliability. For fusion magnets, the superconducting wires need to carry extremely high current in the kA range at interested temperature. More importantly, the superconductor has to exhibit high irreversibility field at which the critical current density goes to zero. Figure 1 shows the magnetic field (irreversibility) vs. temperature characteristic of different superconductors. A magnetic field higher than 10 T is generally considered as the minimum requirement for any superconductors to be useful for fusion devices. In other words, superconducting wires used to build fusion magnets must have the ability to carry extremely high current at desired magnetic field and temperature that are application specific. As can be seen from Figure 1, high temperature superconductor (HTS) such as YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) not only offers a wide temperature range for operation but also shows a much higher irreversibility field in comparison with the low temperature superconductor materials such as NbTi and Nb$_3$Sn. The YBCO or more generally denoted as REBCO (RE = Y, Nd, Sm, Eu, Gd, Dy, Ho, Yb,…) for HTS materials has been considered as the best option if superconductors shall be considered for fusion magnets at high magnetic fields and elevated temperatures.

Description of the technology and expected performance: To bring the technology readiness of superconductor fusion magnets to level 6 (TRL6) and/or above, this white paper is focused on our innovation to fabricate HTS coated conductors with much enhanced current carrying capabilities (3x the current carrying capability of the premium tapes currently offered by industry). The design and implementation of superconducting fusion magnets involve both engineering design of the magnets and materials sciences of superconducting wires. Being a viable technology for fusion devices, the superconducting wires must not only perform exceptionally well at interested magnetic field and temperature but also be manufactured at low cost to maximize the performance/cost ratio. Our approaches target to significantly enhance the super-current carrying capability of the superconducting wires with minimal involvement of extra processing steps and use of additional source materials (the whole assembly of the superconducting wires).
The state-of-the-art technology to fabricate HTS wires that are of great interest in motors, fault current limiters, transformers, and power transmission cables is based on coated- or second-generation (2G) conductors schematically illustrated in Figure 2. Considering the close connection and similarity between the power cables and fusion coils, we could effectively tackle the technological challenges of fusion magnets and achieve our objectives by using an integrated approach to address both the architecture and the materials issues related to 2G wires. As can be seen from Figure 2, the templates, either biaxially oriented MgO grown by ion-beam assisted deposition (IBAD) on polycrystalline metal substrates or rolling-assisted biaxially textured substrates (RABiTS), are flexible and mechanically strong enough for fusion magnets. The buffer layer materials (such as LaMnO₃ or LMO) for HTS wires should remain the same since they are simply used to prevent the inter-diffusion between the template and the superconductor coatings and to promote the subsequent epitaxial growth of superconducting films. To make HTS wires a viable technology for fusion magnets, the HTS REBCO coatings should be able to carry a much higher super-current at given field and temperature in comparison with that of the state-of-the-art of HTS wires. It is noted that the standard and premium 4 mm wide HTS tapes commercially available could deliver a critical current around 100 A and 110 – 120 A (77 K, self-field), respectively.

We have used defect [2] and interface engineering [3-5] to enhance the super-current carrying capability. As schematically illustrated in Figure 3, we have discovered that the super-current in the field could be significantly improved by engineering the defect landscape of the superconductor coatings. For instance, we have used BaZrO₃ and other second phase materials in nanoparticle form as the flux-pinning centers to enhance the super-current carrying capability in the field [2]. It is should be noted that the relationship between material defects and super-current is complex. The pinning force depends on not only the defect size and shape but also its composition and structural interaction with the superconductor matrix. It is crucial that we have to acquire the knowledge and skills to control the defect landscape so that the super-current of the superconductor in the field could be maximized. Furthermore, we have also demonstrated that the total super-current of the wire could be multiplied by using a multilayer structure as shown in Figure 4. We have achieved superconductor coatings on metal substrates with a critical current density of up to 4.0 MA/cm².
(75 K, self-field) in films as thick as 3.5 μm, for an extrapolated super-current of 1400 A/cm width. This value represents a critical current around 560 A (75 K, self-field) for a 4 mm tape (4x of the super-current delivered by the premium 4 mm tape currently available). By fully implementing our strategy to control both the defect landscape in the superconductor and the heterointerfaces of the layered architectures, we are ready to fabricate HTS coated conductors with much enhanced current carrying capabilities (3x the current carrying capability of the premium tapes currently available).

**Application of the technology for fusion magnets:** The technology we are targeting to develop will deliver not only high performance HTS wires but also have the potential to build fusion magnets with reduced cost. As illustrated in Figure 3, the control of defect landscape can effectively enhance the flux pinning properties of the superconductor that leads to the improved super-current carrying capability in the field. On the other hand, the use of layered structure shown in Figure 4 can successfully address the main problems of decreased critical current density with the increase of the coating thickness [4]. It is also noted that our approach to use a layered structure to significantly enhance the super-current carrying capability of the superconducting wires marginally involve additional processing steps and use of extra source materials such as template and buffer materials.

**Critical variable(s), current maturity of the technology, and required development:** The achievement of the highest performance of superconducting coatings and without involving extra steps to prepare the template and buffer layers could lead to the further reduction of the production cost. The technology we are proposing is based on our issued US patent (TRL 4-5) [3], and we have demonstrated a total current of 560 A (75 K, self-field) that is already 4x of the premium 4 mm tape currently available from industry. Considering the controllability of different processing techniques (MOCVD, MOD, and pulsed laser deposition) to grow layered HTS films shown in Figure 4, we anticipate that HTS wires with a total current of 360 – 400 A (3x of the premium tapes offered by industry, 77 K, self-field, and 4 mm width) could be fabricated by industry if our innovation is fully implemented.

It is noted that industry has already implemented the strategy to enhance the flux pinning strength of HTS coatings by introducing BaZrO$_3$ nanoparticles or nanorods into the matrix of the REBCO thick films. The only critical variable and required development to implement our technology is to incorporate CeO$_2$ deposition and to optimize the processing parameters to work on layered structures. Integrating REBCO with CeO$_2$ to form a layered structure of (REBCO+BaZrO$_3$)/[CeO$_2$/(REBCO-BaZrO$_3$)]$_n$ (n = 2, 3, 4, 5) should not face big technological
challenges since CeO$_2$ and REBCO are both structurally and chemically compatible. To fully take the advantage of the much higher critical current density of thinner REBCO film and to minimize multiple deposition steps, the thickness of REBCO will be controlled in the range of 0.5 – 0.75 µm so that the critical current density better than 4 MA/cm$^2$ (77 K, self-field) for the individual layer could be achieved.

References


