Developing HTS Magnets for Fusion Applications

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1 Description of HTS Magnet Technology

All design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of the magnetic fields. High Temperature Superconductors (HTS) represent a *new game changing opportunity* that could significantly advance the economic and technical status of magnetic confinement physics experiments and fusion reactors. It could revolutionize the design of magnetic fusion devices leading to very high performance in compact devices with simpler maintenance methods and enhanced reliability. This could lead to significant acceleration of fusion energy development [1].

The advantages of HTS are that they can operate at very high magnetic field, high cryogenic temperature, high current densities, and larger mechanical stresses and strains compared to existing low-temperature superconductors (LTS). Each of these parameters is extremely important and constraining to a fusion reactor design. The expanded volume of operating space in these critical parameters opens a large space for enhanced magnet design. The most revolutionary aspect of HTS, particularly Rare-Earth Barium Copper Oxide (REBCO) superconductors, is their ability to maintain high current-carrying capability at very high magnetic fields. Historically, the maximum field on coil (limited by achievable current density in the superconductor) has been a primary driver for designing magnetic fusion devices. Consider a tokamak: HTS allows an increase in B_T over LTS technology from ~5.5 T to 10-12 T. (The field at the coil increases from ~12 T to 20 T).

2 Benefits to Fusion Program

High-field, high-temperature superconductors would enable a new generation of compact fusion experiments and power plants, dramatically speeding the development path and improving the overall attractiveness of fusion energy. Since magnet systems are the ultimate enabling technology, HTS could significantly enhance the performance and feasibility of almost any type of magnetic confinement or plasma physics device including, Spherical Tokamaks, Field Reverse Concepts, gas dynamic trap, magnetic mirrors levitating dipoles, etc. HTS can be used with any magnetic field configuration including 3-D shaped devices such stellarators and helical devices.

1. *Smaller burning plasma experiments:* High magnetic field at small size formed the basis of the US magnetic fusion program for 20 years prior to entering ITER. The science was successfully demonstrated on the Alcator devices and the US planned for flagship devices such as CIT, BPX, and FIRE. Community consensus was reached that a small high-field burning plasma could be successful with copper magnets [2,3,4]. HTS enables even smaller devices at higher field without the issues associated with copper magnets, accelerating fusion development.
2. *Performance vs. Cost*: The B^3 - B^4 dependence of well-known fusion parameters (power density, Lawson criterion) allows both high energy gain and power density in much smaller devices and may be crucial for fusion's eventual commercial realization.

3. *Operational Robustness*: High-field compact devices operate far from all intrinsic disruptive kink, pressure, density, and shaping limits, and use normalized plasma regimes (βN, H, q) already integrally demonstrated in present devices.
4. *Steady-State Physics*: Analysis shows that high-gain, robust steady-state operation, with significant external control of the current, will arise from the combination of small size, high field, high safety factor, and associated improvements in current drive at high magnetic field.
5. *Demountable Magnets*: The higher critical temperature and higher heat capacities of materials at higher temperatures enables fusion magnets that incorporate demountable resistive joints that lead to vastly improved access for construction and maintenance, important for experiments and reactors.

3 Current status of R&D and Readiness

All practical superconductors can be characterized by a critical surface below which the material is a superconductor, and outside of which it is a normal conducting material. The three primary variables that define the critical surface are the critical temperature T_c (K), the upper critical magnetic field, B_{c2} (T), and the critical current density, J_c (A/mm^2). The critical surface of the HTS conductor gives an order of magnitude advantage in operating space over LTS conductors.

The thin-film type of superconductor is purchased from suppliers who produce it in thin strips instead of wires in automated thin-film processes which build up the constituent layers. Characteristics already achieved and well documented include:

1. **High field.** REBCO superconductor carries sufficient current density for magnet applications at fields up to 100 T [5]. It has recently been incorporated into solenoid magnets at fields of 35 T [6] and very recently over 40 T [7]. This surpasses the requirement of ~20 T on coil for very compact high-field tokamaks.
2. **High temperature operation.** REBCO, with critical temperature at 90 K can operate near 77K but performs much better when subcooled and thus high-field fusion and accelerator magnets often target 20-30 K or lower. The significance of the high temperature operation goes well beyond the thermodynamic advantages in the cryogenic system. Operation at temperatures well above those limited by liquid helium and the relative insensitivity of the critical current to temperature results in magnets with much higher operating stability, a critical consideration for the long-life operation required in a dynamic fusion environment. Further, these properties have enabled some REBCO magnets to forgo incorporating electrical insulation [8] eliminate cyrogens for low heat load devices [9] and allows the incorporation of resistive joints [10]. The high critical temperature and stability margin could also allow operating in a nuclear heating environment significantly higher than allowed in LTS magnets.
3. **High engineering current density.** REBCO has been incorporated into magnets at over 40 T at engineering current densities exceeding 1000 A/mm^2 [7]. This is an order of magnitude higher current densities compared to LTS equivalent magnets. This leads to much smaller magnets for the same magnetic field, taken to distinct advantage in compact all REBCO user magnets at fields of 32 T just being commissioned [11]. In fusion applications this leads to more room for structure in the magnet and nuclear radiation shielding.

4. **High strength and high modulus.** REBCO's primary constituent material (~50-90% by volume) is high strength nickel alloys or steels. The superconductor remains reversibly superconducting at tensile stresses over 600 MPa, which is comparable to the supporting steel structure, and strains up to 0.45% [12], factors of two improvement over LTS, thus enabling smaller magnets and more compact designs.
5. **No reaction process as part of winding.** Unlike LTS materials like Nb_3Sn where additional processing optimization and controls including high temperature, long duration heat treatments are required, REBCO conductor is ready for operation directly from the manufacturer and can be wound into final position in a single operation. This feature has the potential to simplify the manufacturing process and widen candidate magnet materials for electrical insulation and structural purposes.

4 National and International Programmatic Context

The U.S. has the opportunity to develop a world leading HTS superconducting magnet development program that will attract the best researchers from the U.S. scientific community, along with a strong industrial component. The U.S. took the initiative with development of the Cable-In-Conduit-Conductor (CICC) concept when the rest of the world was straggling along with outdated pool-cooled magnet technologies. The CICC concept was revolutionary and now dominates the international fusion magnet technology. The same will be true if the U.S. fusion program in collaboration with other US government scientific programs investments in and leads in development of HTS conductor and magnet technology. The U.S. community is also developing high-field solenoid and accelerator magnets using REBCO conductors and cables for other, non-fusion applications, which can be leveraged for the fusion magnet program. In fact, an excellent opportunity exists now to coordinate HTS technology development across multiple DOE-SC programs.

The time frame for HTS technology to be made ready for use in a next step device depends primarily on the funding rate. If it is desired to be used in an FNSF device then the technology development should be accelerated. It is most likely to be in time for any type of DEMO device, but the engineering and operation feasibility, as well as the economic value should be demonstrated on a much smaller device if one is needed in support of a DEMO reactor.

5 Possible 15-year U.S. Research Agenda

Operation of HTS materials has already been demonstrated for small-bore superconducting magnets at fields, current densities, stresses and JxB forces larger than required for fusion magnets [7]. Commercially available HTS conductor based on REBCO must be packaged into cable, suitable for large volume, high-field fusion magnet system. It then has to be incorporated into large bore magnets along with the engineering systems required to safely operate the magnet with significant stored energy. The challenges in this area are primarily electro-mechanical in nature involving integrated mechanical engineering of high strength structures and manufacturing and assembly processes. Many of these engineering decisions share strong similarity to the experience gained from LTS development [13][1]. It must be noted that existing tokamaks (e.g. C-Mod) and burning plasma designs (BPX, FIRE) have successfully

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[1] "Taking advantage of a large experience gained in the course of a ten-year activity of supervision of CICC manufacture in industrial environment. [it] can be envisioned for further CICC development employing HTS material… opening completely new routes in the design of large-size, larger-current superconducting systems" [13]

dealt with similar mechanical stresses and doing so requires engineering discipline but not advances in materials or physics [14].

Recent studies indicate that HTS magnets could be made demountable [10] which would have large impact on fusion reactor operation due to improved ability to maintain the machine, increasing reliability and availability. Demountable coils require relatively short lengths of REBCO, effectively increasing conductor production yield, and lowering conductor cost. A strong synergy exists between the high-B, smaller size, and demountable coils, allowing for simplified and improved fusion engineering choices: e.g. immersion liquid blankets, and a modular vacuum vessel, which then becomes the only replacement item in the reactor.

6 Research Directions Beyond 15 Years

Once HTS conductor and magnet technology is developed through a phased and well-funded R&D program, the technology should be transferred to industry through one or more large-scale magnet prototypes, followed by series fabrication for a burning plasma physics experiment. At that point the industrial scale will be demonstrated, as has been the case for ITER magnet construction.

7 Critics' Objections and Advocates' Responses

REBCO materials are sufficiently advanced for next-step fusion applications. The technology has progressed out of the laboratory and into industrial production. Present performance of commercially produced REBCO tape is already sufficient for use in practical fusion experimental devices now. These conductors have been operated in conditions they would encounter in a fusion magnet in solenoids.

1. **Very high operating stresses at high magnetic field.** Since the critical field of the REBCO superconductor is so high, the ultimate magnet, and thus fusion device performance is primarily limited by the mechanical strength of structure around it. Existing high strength stainless steel and superalloy materials are adequate for projected fusion requirements. REBCO does not require heat treatment and allows more flexible choice of structural materials. If exotic new, nano-strengthened materials or composites can be developed with increased tensile strength, elastic modulus, and fracture toughness, further performance improvement in the form of reduced magnet build and higher field operation is possible.
2. **Thin, flat tape geometry is not convenient for multi-strand, high current conductors**. In the present configuration of the superconductor as a flat tape, AC losses and current distribution, are non-ideal for fast transient or ac or pulsed operation. These can be improved with further R&D investment, e.g., the demonstrated striation process. However, current performance is sufficient for the TF coils of a tokamak where field is most important and operation can accommodate the increased loss.
3. **Quench detection is difficult in HTS magnets.** Although extremely stable in operation, quench detection is a significant issue due to very slow propagation of a normal zone. The present standard use of inductively balanced voltage taps could be a limitation on safe performance. Therefore, further R&D of innovative methods for quench detection is warranted. For example, normal zone sensing by the use of optical fibers is presently being studied at laboratory scale [15].
4. **Insufficient production piece length**. For a fusion magnet the typical cable lengths are 200-700 m. (ITER TF conductors are 700 m). REBCO with uniform critical current along the

length is regularly available in lengths of 100-300 m with continuous lengths approaching 1000 m. Lengths longer than this can easily be achieved with small resistance joints. This has no relevant performance penalty in a multi-tape cable, which easily share current, and the loss is insignificant compared with nuclear heat loads.

5. **Sufficient production volume.** Although REBCO conductors are in commercial production by at least 11 companies around the world, production rates are relatively low and product costs are high. Production rates need to be significantly increased and defect rates in the conductor reduced to increase yield and lower costs. This can be done with increased investment in capital equipment for production and improved conductor process control and quality insurance. A capital expenditure of order \$10M is sufficient for most companies to make a factor of 2 or 4 increase in production and a factor of 2 decrease in cost per kA-m [16]. A fusion reactor requires ~5,000,000 kA-m of tape. Current single manufacturer annual production is approximately 1/50th of this but is scaling fast with doubling rates of a few years [16]. Needs from other magnet applications (e.g., HEP and medical) can help increase the production volume and reduce the conductor cost.
6. **Radiation resistance.** Numerous studies have been performed verifying REBCO has similar resistance to neutron damage as the leading LTS candidate [17, 18]. Until now, the radiation damage to organic insulators has been the life limiting component for the superconducting confinement magnets. If radiation damage to HTS materials is proven to be no worse than to Nb_3Sn, then this could actually be considered a positive attribute.
7. **High cost.** Current prices for REBCO are ~\$100/kA-m which is a factor of 5-10 higher than price parity for Nb3Sn. Price by this figure of merit has decreased significantly year over year due to increased current carrying capability and process improvements. At production levels anticipated in market adoption or for a fusion device, REBCO manufacturer's and market researchers predict costs to reduce to price parity [16, 19]. Further, the superconductor itself represents a small fraction of the cost of the device, so spending here to shrink the device size is prudent.

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