Fe-based high field superconductors for cost-effective future accelerator magnets

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The 2014 Particle Physics Project Prioritization Panel (P5) strongly supported a future high-energy proton-proton collider, noting that a primary enabler would be transformational high field magnet R&D with substantial performance increase and simultaneous cost reduction [1]. In response, the US Magnet Development Program (MDP) accepted the ambitious challenge of 16 T accelerator dipoles with significant cost reduction [2]. These are great challenges for P5 and MDP, because all present high field superconductors allowing such a performance increase (Nb_3Sn, $REBa_2Cu_3O_x$ (REBCO) or $Bi_2Sr_2CaCu_2O_x$ (Bi-2212)) are expensive. We need to explore all possibilities to satisfy both performance and cost goals of P5. The new class of high-field Fe-based superconductors (FBS), in particular Na- or K-doped $AEFe_2As_2$ (AE122, where AE = Ba, Sr, Ca) with 90 T H_{c2} and 38 K T_c, has the potential to perfectly fulfill such P5 ambitious goals if high critical current density (J_c), round, twisted multifilament, Rutherford-cable-ready conductors are realized. Indeed, Chinese high energy physicists are eagerly investigating the 122 FBS conductors for their dipole magnets in their CEPC (12T) and SPPC (20-24 T) circular collider designs [3, 4].

The clear advantage of 122 FBS over the other high field superconductors is its low raw material cost. Table 1 tabulates the cost per unit volume and superconducting properties of Co-/K-doped 122 FBS (Co-122 and K-122, respectively) and other state-of-art LTS and HTS magnet-ready superconductors. Very striking is the high cost of all high field superconductors beyond Nb-Ti. Partly this is due to the cost of the raw materials, like high purity Nb for Nb_3Sn and Ag for Bi-2212, and partly to large capital equipment costs and low yields for REBCO coated conductors. On the other hand, the conductor cost of FBS can be close to Nb-Ti, well below the cost of Nb_3Sn. The 122 Fe-based superconductors (FBS) use cheap Fe, Ba (or Sr/Ca) and As (and K, Na, Co or P as dopant) raw materials. Round wires can be made by the powder-in-tube (PIT) method within a cheap metal matrix such as Cu or Fe. Even with a Production Cost factor (P) of 10 (the ratio of the final product cost to the raw material cost), a value characteristic of present Bi-2212 PIT wires produced on the 10 liter scale by Bruker-OST, 122 FBS conductor would cost just $4,000/liter, about one quarter that of Nb_3Sn. Besides the cost advantages, 122

Table 1: Cost and property comparison of candidate superconductors for accelerator magnets

Material	P factor	Conductor cost per liter	T_c	H_{c2} (4.2 K)	Intragrain J_c (20 T, 4.2 K)	Intergrain J_c (20 T, 4.2 K)	Conductor J_E (20 T, 4.2 K)
Nb-Ti	3	~$2,000	9.2	11 T	n/a	0 A/mm^2	0 A/mm^2
Nb_3Sn*	6~7	~$15,000	18	26 T	n/a	~400 A/mm^2	~280 A/mm^2
Bi-2212*	~10	~$100,000	85	~100 T	n/a	~6,000 A/mm^2	~1,200 A/mm^2
REBCO*	>10	~$100,000	92	>120 T	~20,000 A/mm^2	~20,000 A/mm^2	~420 A/mm^2
Co-122	**~10 ****	**< $4,000**	**22**	**~70 T**	**~4,000 A/mm^2**	**~2 A/mm^2**	**n/a**
K-122	**~10 ****	**< $4,000**	**39**	**~90 T**	**~6,000 A/mm^2**	**~100-1000 A/mm^2**	**n/a**

* Property values are quoted for production grade tapes and wires
** Production factor (the ratio of final product cost to raw material cost) is assumed to be the same as Bi-2212
Small high field magnets being made at the NHMFL typically use about one liter of conductor.

FBS has the following key features as a high field superconductor; (a) Twice higher T_c (~38 K) and 3 times higher H_{c2} (~90 T) than Nb_3Sn, (b) High J_c and strong pinning in single crystals, (c) Unlike Bi-2212, the sheath material of wires can be the same inexpensive Cu matrix as Nb-Ti and Nb_3Sn, (d) High J_c can be developed by reaction at ~600 °C, a temperature lower than that for Nb_3Sn.

What is not yet fully realized is a high J_c magnet-ready 122 FBS conductor, although there is no concern about its inherent strong vortex pinning in single crystals. But polycrystalline 122 FBS is making steady progress toward the FCC target [5]. Recently a Chinese and Japanese group reported a J_c (15 T) of 900-1,000 A/mm^2 in a polycrystalline flat tape [6, 7]. Tamegai *et al*. recently reported a J_c (5 T) of 600 A/mm^2 in the round wire [8]. Underlying challenge of 122 FBS toward the magnet-ready conductor is: **Can we make grain boundaries (GBs) in 122 FBS much better connected so as to realize the wire J_c to >1500 A/mm^2 at 4.2 K, 16-20 T?** In order to accelerate the development of 122 FBS, we need to fully understand the materials science and chemistry, in particular what constrains current flow from grain to grain so that the intergrain J_c (J_c across the grain boundaries (J_c^{GB})) can be driven much closer to the single crystal J_c values of ~6 kA/mm^2. Recently we developed an effective synthesis route for making K-Ba122 polycrystal bulks with minimal amounts of current-blocking impurities at the GBs. Our clean synthesis method significantly suppressed the formation of current-blocking FeAs and oxide GB by-products, allowing deeper exploration of the role of extrinsic and intrinsic GB blocking effects in controlling the J_c of polycrystalline 122 FBS [9]. This clean synthesis method provides the great opportunity to fully evaluate how the powder properties and the wire fabrication parameters affect J_c in 122 FBS conductors.

In next 5-10 years, we propose to address the following key issues so that FBS can be transformed into a magnet-ready conductor with J_c >1,500 A/mm^2 at 4.2 K and 16-20 T:

1. *Define the most effective synthesis for high quality 122 FBS powder with strong intergrain connectivity*: Our clean synthesis method reveals that our understanding of 122 FBS synthesis reaction from the earlier studies is incomplete. Indeed our recent electron microscope studies indicated that poor reproducibility of J_c in some of 122 FBS tapes results from the uncontrolled reaction with oxide impurities due to dirty precursors or preparation environment. The 122 FBS synthesis consists of multiple high energy milling and heat treatments under elevated pressure. The effects on J_c of those entangled synthesis parameters have to be fully understood following very clean synthesis protocols to excluded extrinsic effects. We need to determine the most effective synthesis and the best starting composition in a clean and controlled reaction pathway.
2. *Comprehensive evaluation of the true nature of GB superconductivity*: The claim that rolling textures the tape, allowing stronger intergrain connectivity has not yet been verified. Our recent magnetization studies suggest that the average GB in our clean 122 FBS is NOT a weak link, but that nanoscopic GB voids reduce the effective cross section for current flow. We need to address the intrinsic properties of GBs in nearly 100% dense, clean 122 FBS in order to find the best wire design and fabrication route for the realization of high J_c conductors.
3. *Define the most effective wire design and fabrication route*: Unlike the HTS cuprates, 122 FBS does not require expensive sheath materials like Ag. However, a proper material has to be selected for the innermost sheath to avoid poisoning of 122 FBS. Foreseeing a multi-filamentary architecture, the size and separation of filaments need to be investigated. Interestingly, Tamegai *et al.* recently obtained high J_c by self-alignment of the 122 grains in small-diameter filaments as seen in Bi-2212 round wires [8]. For the realization of high J_c 122 conductor, it is clearly fundamental to address the correlations among J_c, heat treatment, wire design and processing.

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