R&D in Nb_3Sn and Iron-based Superconductors for High Field Magnets

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The discovery of the Higgs boson at the LHC in 2012 opened a new era of exploration and since then the High Energy Physics (HEP) community has been asking for a strong push towards the energy frontier beyond the HL-LHC. Among several proposals around the globe, the most ambitious and scientifically challenging projects involve circular colliders with a circumference of around 100 km. Unfortunately, large rings are very expensive and with the current state-of-the-art magnet technology the costs are challenges for Nb_3Sn and almost prohibitive for cuprates. Feasibility studies are on-going in Europe (Future Circular Collider, FCC [1, 2]) and in China (Super proton-proton Collider, SppC) while in US future collider options are under discussion and represent one of the topics of this Snowmass process [3, 4]. In particular, the target dipole field has been set for FCC-hh at 16T while for SppC at 12T, to be followed by a 20T. Taking into account that 16T is the limit of Nb_3Sn technology, the only way to push beyond it will be to resort to new materials. Indeed, though the Nb_3Sn performance can still be improved, as demonstrated by recent results obtained at Ohio State University and Fermilab [5] and National High Magnetic Field Laboratory (NHMFL) [6], the critical current density drops as the field grows, requiring an increasing amount of material to carry a given current thus increasing also the cost. Since Nb_3Sn is technically the Low-Temperature Superconductor (LTS) with the highest performance, this will require a move to High-Temperature Superconductors (HTS). A new class of material called Iron-Based Superconductor (IBS) has been proposed as a route to 20T dipoles for China's SppC [7]. The technology study of IBS is interesting from the point of view of the material, but unfortunately the magnet technology based on this HTS is still not mature. Thus, as it was also stressed as high priority in the European strategy document released last June, to achieve high-performance cables at a reduced cost, "*the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors*" [8].

The purpose of this LOI is to address the recent status in the R&D of superconductors for HFM applications focusing on Nb_3Sn wires and the still young but very promising generation of IBS. We expect that thanks to the development of these conductors it will be possible to achieve the ultimate goal of cost reduction.

Nb_3Sn wires

While R&D in fabricating HTS magnets attracts vast attentions, Nb_3Sn – as the only superconductor of which the technical feasibility for producing high-field accelerator magnets beyond NbTi range has been proven so far – is still the most promising superconductor to be relied on if a multi-billion-dollar energy-frontier collider for which failure is not an option is to be built in the next few decades. Indeed, the planned use of dozens of Nb_3Sn dipole and quadrupole magnets for the HL-LHC as well as mass production (~600 tons) of Nb_3Sn conductors for the International Thermonuclear Experimental Reactor (ITER) provides a springboard for its future use in an energy-frontier circular collider. In addition, even assuming the HTS technology becomes viable in the future, it is very likely that a Nb_3Sn/HTS hybrid configuration is to be used to reduce the cost [9]. On the other hand, despite their technical readiness, current state-of-the-art Nb_3Sn conductors still need significant improvement in properties in order to be used to build economic magnets with desirable performance (e.g., 16 T operational field with high field quality, low a.c. loss, minimum magnet training, etc.). The most important property is the critical current density (J_c). Although the J_c level of state-of-the-art Nb_3Sn conductors has been at a plateau for nearly two decades, it is significantly below the desired level for 16 T dipole magnets. In addition to J_c, there are a number of other desirable goals, such as reduction of low-field magnetization (which requires reduction of either low-field J_c or subelement size), improvement of mechanical property to reduce sensitivity to transverse pressure and uniaxial stress, etc.. Although emerging technologies are being developed to improve the above properties (e.g., the new artificial pinning center (APC) technology based on internal oxidation can not only double J_c at 16 T and above, but also dramatically reduce magnetization below 3 T [5]), production of Nb_3Sn conductors with all the above goals achieved and pushing such new-type conductors to practical magnet grade are no doubt a challenging task and require extensive R&D efforts. Since Nb_3Sn conductors are the core building blocks of magnets and ultimately limit the performance of the magnets, such efforts to develop Nb_3Sn conductors of improved performance are critical for future accelerator magnets.

The challenge of Iron-Based Superconductors

Nowadays, there is a strong interest in increasing the nominal dipole field beyond 16T (Nb_3Sn limit) to reduce the machine circumference at fixed beam energy while reducing costs (not achievable just by design optimization) [3]. Considerable efforts are devoted to fabricating high-field magnets with High Temperature Superconductors such as ReBCO and Bi-2212 that have already shown proven performance (high critical current density, J_c). On the other hand, these HTS have one main disadvantage, i.e. very high costs. In addition, the strong anisotropy and the limited piece length of REBCO tapes is inconvenient for large scale production. An emerging technology with a great potential to provide low-cost, small anisotropy conductor for magnetic fields >20 T is based on a new class of HTS: Iron-Based-Superconductors (IBS). IBSs, discovered in 2008, formed the second high-T_c superconductor family after cuprate superconductors and over the past decade have been the subject of extensive research into their physical nature and application potential [10-13]. Many laboratories in the world (China, Japan, Italy, Austria, Switzerland) have already started R&D activities in this emerging field and, as previously said, China is betting on building their high-energy collider with this new technology. Among the main players worldwide, USA is only weakly involved, through efforts at National High Magnetic Field Laboratory (Florida), at Ohio State University and recently at Fermilab. IBSs are characterized by high upper critical fields and, compared to the cuprate superconductors, they show small anisotropy, favorable for the design and operation of high field magnets, as well as less severe weak-link problems. Indeed, high angle Grain Boundaries (GBs) in iron pnictides as high as 9° deteriorate inter-grain currents much less than in cuprates, where the angles are as small as 2-5°. It follows that high transport J_c can be expected in IBS wires and tapes fabrication using the simple and low-cost Powder-in-Tube (PIT) method instead of the complex, expensive coated conductor technique [14]. A recent proof-of-principle demonstration by Y. Ma et al. [14] showed that PIT technique is a feasible method to produce more than 100m-long IBS wires with good values of J_c (up to $1.3x10^4 A/cm^2$ at 4.2/10T) but still below the practical level (>$10^5 A/cm^2$). In addition, the predicted J_c is weakly reduced by magnetic fields and, if the expected values in 2025 will exceed the practical level ($500A/mm^2$ at 4.2K/10T), a considerable potential in large scale applications can be envisaged. The first IBS single pancake coil (SPC) has been already fabricated and tested in China using the 7-filamentary Ba122 tape by wind-and-react method and tested under 24T background field at 4.2K proving that IBS are very good candidates for the development of high-field magnet [15]. This situation provides an opportunity for the application of current IBSs to higher magnetic fields at a reduced cost [16].

Despite the many advantages of IBS, just described, transport properties are still poor and the limits due to the flux pinning defects landscape, granularity and weak link have to be overcome to be of interest for practical application. It follows that R&D on this new promising class of HTS material has to be strongly encouraged and supported; collaborations worldwide have to be established in order to create a common effort to turn IBS in a low-cost cutting-edge technology for High Field Magnets production.

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