Use of High Temperature Superconductors for Future Fusion Magnet Systems

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Abstract. With the construction of ITER the feasibility of a fusion machine will be demonstrated. To commercialize fusion it is essential to keep losses as small as possible in future fusion power plants. One major component where losses can be strongly reduced is the cooling system. For example in ITER where efficiency is not a major goal, a cooling power of 64 kW at 4.4 K is foreseen taking more than 20 MW electric power. Considering the size of future commercial fusion machines this consumption of electric power for cooling will even be higher.

With a magnet system working at 20 K a fusion machine would work more efficient by a factor of 5-10 with respect to electric power consumption for cryogenics. Even better than that, would be a machine with a magnet system operating at 65 K to 77 K. In this case liquid nitrogen could be used as coolant saving money for investment and operation costs.

Such an increase in the operating temperature of the magnet system can be achieved by the use of High-Temperature Superconductors (HTS). In addition the use of HTS would allow much smaller efforts for thermal shielding and alternative thermal insulation concepts may be possible, e.g. for an HTS bus bar system.

This contribution will give an overview about status, promises and challenges of HTS conductors on the way to an HTS fusion magnet system beyond ITER.

1. Status of development towards industrial HTS conductors

There are several families of HTS available. Hg- or Tl- compounds offer the highest T_c values of 134 K and 125 K, respectively, but for reason of environmental aspects BSCCO and YBCO superconductors with T_c values of approx. 110 K and 92 K, respectively, are in the focus of actual development. An overview about High-T_c superconducting materials with a focus on power application is given in [1].

The common feature of all HTS materials is the occurrence of CuO_2 layers that host the superconductivity. Perpendicular to these planes it is very difficult to achieve a good conductivity which causes a strong anisotropy. Thus the critical current is anisotropic as well as its dependence on the magnetic field. For the field anisotropy calculated from $H_{c2,//}$ over $H_{c2,\perp}$ (parallel and perpendicular to the superconducting CuO_2 planes) a factor of 5–7 for YBCO, and 50–200 for Bi-2223 has been found [2]. Therefore a strong texture in the HTS material is necessary to achieve good transport properties. Grain boundaries in the grown materials can cause additional problems for transport currents [1 ,3]. Only when neighboring grains have almost the same orientation e.g. only small angle grain boundaries are present, a high critical current is achieved. These properties demand for an almost perfect texture of the HTS materials.

For YBCO conductors these problems are solved for short samples and the transfer to long lengths in an industrial process is the challenge now. This is discussed in detail below. However, BSCCO HTS-tapes are commercially available nowadays and can be used in low and high field applications depending on the cooling temperature. As an example FIG. 1

shows a reel with 1200 m BSCCO tape from the manufacturer EAS (other HTS supplier offer similar conductors). BSCCO is nowadays ready for technical application but the operating temperature has to be adjusted to the applied magnetic field. At temperatures of 77 K, external fields are very detrimental to the critical current j_c which is the maximum current that can be carried by the conductor without losses. In the case of low magnetic fields e.g. in self-field like in power transfer lines or current leads, such a conductor consisting of BSCCO-2223 in a stabilizing silver matrix is capable to carry a typical current of 80 A for a 4 mm wide and 0.2 mm thick tape. At temperatures of approx. 20 K and below these BSCCO tapes can be used even in much higher external fields (e.g. at 12 Tesla which is the field of the ITER TF coils).

FIG. 1: Reel with 1200m BSCCO tape from EAS (European Advanced Superconductor, Hanau, Germany)

2. Demonstration of BSCCO use for fusion

As a demonstration for the use of BSCCO in fusion technique, FZK has developed in collaboration with CRPP in the frame of an EFDA task a high temperature superconductor current lead (HTS-CL, see FIG. 2) for ITER-TF coils. The HTS-CL consists of two main parts, the HTS module using BSCCO tapes embedded in stainless steel and the copper heat exchanger. The HTS module covers the temperature range between 4.5 K and 65 K and is cooled by heat conduction from the 4.5 K end. The heat exchanger covers the temperature range from 65 K to room temperature and is actively cooled by 50 K He gas. At the 4.5 K end, a clamp contact provides the connection to the superconducting bus bar.

The maximum steady state current of the HTS-CL was 80 kA which exceeds the value of 68 kA needed for the ITER TF coils. In addition it was shown that even when the He-cooling has been blocked, a current of 68 kA could be carried for more then 6 minutes which shows the stability of this CL. Last but not least it could be shown that the He-refrigerator power consumption was reduced by a factor of 5 compared to conventional copper current leads. Details of the development and test results can be found in [4, 5, 6].

This development shows that industrial available BSCCO-2223 HTS conductors can be used today for fusion in the case of current leads and bus bar systems. The idea to use HTS materials for the coil system of a fusion machine itself brings us to the open challenges. To explain this in more detail we will first give the status of the HTS material YBCO which is most promising for the use in high fields at 65 K and then we will discuss the open issues that have to be solved on the road to a HTS fusion conductor.

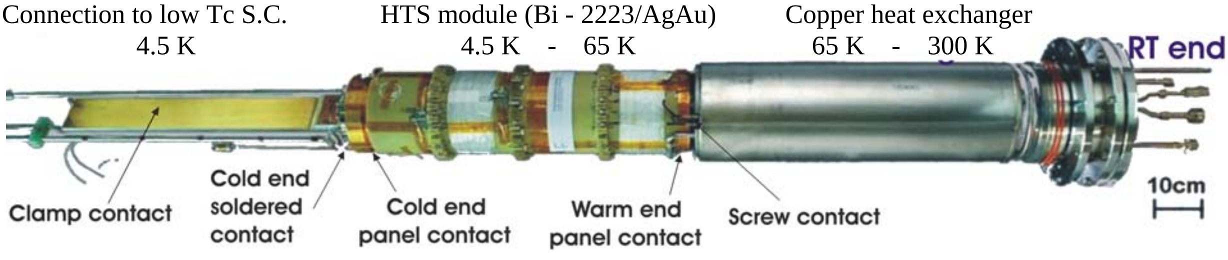


FIG. 2. HTS current lead developed at Forschungszentrum Karlsruhe using Bi-2223/AgAu tape

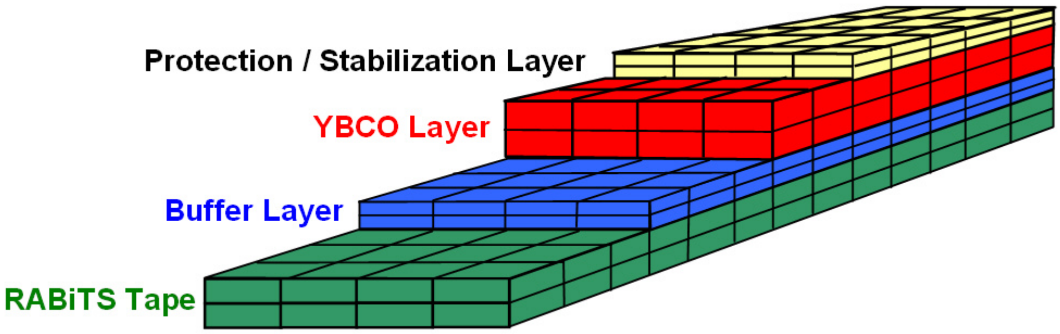
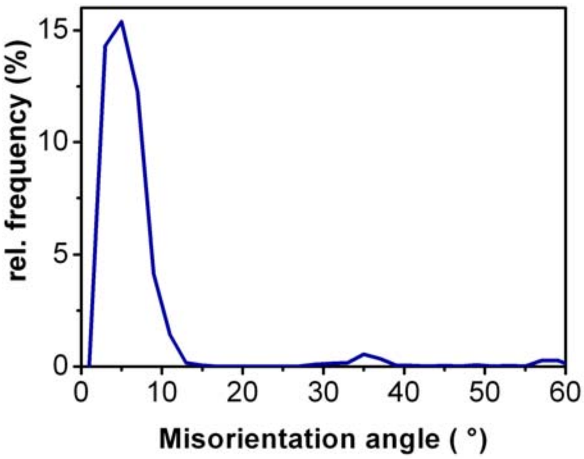


FIG 3. Principle of YBCO Coated Conductor where a RABiTS tape is used to define a well defined texture for buffer and YBCO layers.

3. Status of HTS material YBCO

YBCO is the most promising material material candidate for a use at 65 K or even higher because of its high current capability at high magnetic fields. However, the main problem is the need of oriented grains in the material because high angle grain boundaries are very detrimental for the critical current. The most promising route to fabricate wires is the concept of YBCO Coated Conductors (see FIG. 3) where cube-textured Ni-alloy tapes are used for the growth of ideally oriented YBCO films. To achieve this texture, the Ni-substrate material is thermomechanically processed in a well defined manner to achieve such a Rolling Assisted Biaxially Textured Substrate (RABiTS) tape [7]. A buffer layer is then deposited to prevent chemical reaction of the Ni substrate with the subsequent deposited YBCO layer while preserving the texture. On top a layer for protection and thermal stabilization is grown.
The buffer and the YBCO layers adopt the texture from the substrate which leads to well defined orientation of the YBCO grains with small angle grain boundaries, only. At the moment, the encouraging results from this technique causes industry to built up production capacity. However, the use of the well working but slow vacuum deposition techniques (e.g. Ion Beam Assisted Deposition or Pulsed Laser Deposition [8]) for the YBCO layer is the snag of these production methods for the production of long length HTS conductors because they are too slow for the production of long length conductors in the kilometer range.
Therefore, the development of alternative production methods for buffer and YBCO layers



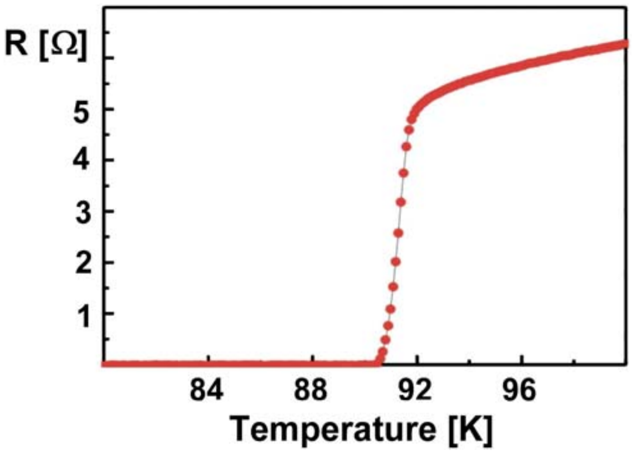


FIG. 4a (left). Rel. frequency of grains as a function of misorientation angle for a chemically deposited CeO_2 buffer on a RABiTS tape
FIG. 4b (right). Resistivity of a chemically deposited YBCO film on $SrTiO_3$

are essential. A difficult but very promising solution is the use of chemical deposition techniques which are under development. As an example figure 4a shows the grain misorientation of a CeO_2 buffer layer film that was chemically deposited on a RABiTS tape at Forschungszentrum Karlsruhe. Almost all CeO_2 grain boundaries have an alignment better than 8%. In the same group the chemical deposition of superconducting YBCO has been demonstrated on a $SrTiO_3$ substrate (see figure 4b). To push the development of chemical coating of buffer and YBCO a virtual Helmholtz Institute has been created with Forschungszentrum Karlsruhe, the IFW Dresden and the Universities of Braunschweig, Tübingen and Wuppertal as partners. Beside this activity, many other groups and industries are engaged in the development of YBCO coated conductor produced by chemical deposition.

4. On the way to HTS fusion cables

Principally BSCCO and YBCO could be used both for fusion coils. In the case of BSCCO, tapes are available but the operation temperature is limited to approximately 20 K if high magnetic fields are required. As discussed above the YBCO coated conductor is underway to be available in long lengths and will allow an operation temperature in the range of 65 K or even higher.

However, both HTS materials will be available in the form of small tapes with high aspect ratio which makes an optimization of ac-loss properties difficult. On the other hand this optimization is essential because for fusion coils higher ac-losses can not be tolerated because this would lead to an increase of needed cooling power. The effort that has been spent to optimize classical fusion conductors with respect to ac-losses can be illustrated by showing the conductor of the TF model coil (TFMC) of ITER (see FIG. 5). The base of this conductor is an internal tin Nb_3Sn strand with a diameter of 0.81 mm (FIG. 5b) where Nb_3Sn filaments are embedded in a bronze matrix (FIG. 5a) surrounded by a Ta barrier from the Cu rim. To reduce the ac-losses each strand is twisted within the strand with a 10mm twist pitch. 720 of these strands and additionally 360 Cu strands for thermal stabilization are cabled with a specific twist in each of the five cabling stages. A detailed description of the TFMC conductor design and the fabrication methods can be found in [9, 10]

In the last stage 6 bundles are enclosed in a stainless steel tube, arranged around a central spiral that allows an easy cooling with supercritical Helium with a moderate pressure drop along the conductor (fig. 5c and 5d). The complexity of this cable illustrates the need for an optimization of a fusion cable with respect to ac-losses and cryogenic performance. Whatever will be developed as a future HTS cable it has to be compared with such a sophisticated

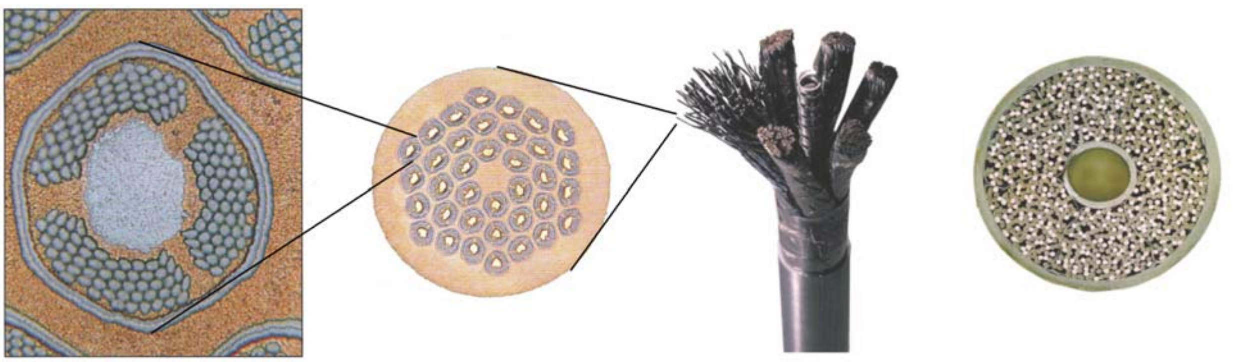


FIG. 5a (left). Nb filaments embedded in bronze surrounded by a Ta barrier with internal tin depot before heat treatment.

FIG. 5b. Nb_3Sn strand ($\varnothing$ = 0.81mm) manufactured by Europa Metalli - LMI used for the TFMC

FIG. 5c. Explosion view of the ITER TF model coil conductor

FIG. 5d (right). Cross section of the conductor of ITER TF model coil "classical" fusion cable. The gain due to a higher operating temperature with a HTS fusion cable should not be balanced by much higher ac-losses. On the other hand it should be clearly said that the development of the Nb_3Sn cable shown above took more than 15 years from the first idea to the final cable layout. For a HTS fusion conductor we are in the start position now and it will naturally take the adequate time to do the optimization. First ideas to use HTS tapes by forming a Roebel bar type conductor are presented. Adequate cabling and bundling techniques have to be developed first in the laboratory scale and must then be transferred to industry.

The development, construction and demonstration of a High Temperature Superconductor coil system for Fusion is a scientific and technologic long term challenge which has to be tackled already now for becoming ready in time. This work should be done in close collaboration of European associations and industry. The benefit from a HTS coil system will help Fusion to be a commercial success and to secure world's power generation during the next decades.

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