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High Temperature Superconductor Cables for DEMO TF-Magnets

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Abstract: Actual progress of High Temperature Superconductor (HTS) *RE*BCO tapes show an enormous increase of critical current density especially at highest field. These results offer new possibilities for the application of *RE*BCO for large fusion magnets with a magnetic field well above 13 Tesla at the conductor and a large temperature margin > 10 K. In parallel promising new proposals for the formation of high current HTS fusion conductors from these *RE*BCO tapes are emerging, promising the applicability for fusion magnets, e.g. for a TF magnet of DEMO.

The actual progress of *RE*BCO tapes and several promising HTS fusion cable proposals will be highlighted which open the path to future high field HTS magnets for fusion. Using such *RE*BCO tape data, calculations and modeling of a TF coil for DEMO based on the PROCESS code will be presented, showing that with today's HTS performance a DEMO TF conductor is feasible, which can be operated at 4.5 K with a maximum field at the conductor of approx. 13.3 T (magnetic field at the plasma center approx. 6.8 T) with a temperature margin of approx. 12 K.

Special attention will be given to a new stacked HTS conductor fabrication technique proposed by KIT which is optimized for long length production of HTS strands with high engineering current density. Due to the cross shape of the soldered superconductor stacked, this type of strand is called HTS CrossConductor or HTS CroCo. The implementation of the simple, reliable and easily scalable fabrication routine will be outlined. Measurement results of first samples show the expected critical current calculated from the individual tape opening the way to a compact kA-class HTS strands. These HTS strands can be used as a basis to build a fusion cable for a TF-coil for DEMO.

Keywords – DEMO TF Magnet, High Temperature Superconductor, high current HTS cable, REBCO

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1 Introduction

The use of High Temperature Superconductor (HTS) materials for fusion machines has been already suggested in 2005 [1]. At that time industry could only deliver the HTS material BSCCO in long length, and this material was used to demonstrate a 68 kA HTS current lead as a proposal for ITER, which was even operated at 80 kA [2, 3]. Consequently, HTS current leads are nowadays foreseen in big fusion machines like ITER or JT-60SA and in the case of W7-X they are already in operation [4, 5].

The use of the HTS material *RE*$Ba_2Cu_3O_{7-\delta}$ (*RE*BCO) with *RE*=Y, Nd, Er or other Rare Earth atoms as a standard material was not possible around 2005 because this material was not mature to be fabricated in good standard quality in long length by industry. However, the superior properties of this superconductor under high magnetic field have been impressive even considering the data available in the early years after 2000 [6].

With increasing knowledge the material *RE*BCO was known to be the "2nd generation" HTS superconductor due to the superior properties, which could be implemented increasingly in long length tapes fabricated by industry [7]. However, the fabrication route of this 2nd generation HTS material *RE*BCO is handicapped because the production is confined by massive boundary conditions. The main restrictions are the two-dimensionality of *RE*BCO with the CuO_2 planes that host the superconductivity

and the extremely short coherence length, due to the crystal structure. As a consequence adjacent *RE*BCO grains have to be oriented almost perfect within only a few degrees to match crystallographic a-, b- and c-axis orientation to allow transport current passing the grain boundary. Due to this problem, the growth of high quality long length *RE*BCO samples is limited to thin layer deposition on substrates with clear crystal orientation that match the lattice constants of *RE*BCO to support the growth in the correct orientation or to methods that directly support the growth of the correct crystal orientation.

Two main solutions have been identified so far to allow long length of *RE*BCO tape production, which is the use of Rolling Assisted Biaxially Textured substrates (RABITs) and Ion Beam Assisted Deposition (IBAD) [6].

RABITs uses mainly Ni based tapes with a controlled rolling process and subsequent annealing, to produce the correct lattice spacing and orientation to match *RE*BCO crystal structure. IBAD uses an ion bombardment under a suitable angle to promote the growth in the correct crystal orientation. However, both methods are only applicable on thin tapes and need a very controlled vacuum process for layer deposition. In addition, the deposition of several buffer layer are necessary e.g. to adjust lattice parameters and to prevent chemical reaction of *RE*BCO and buffer material. As a consequence the methods to produce high quality *RE*BCO tapes result in thin tapes with an unfavorable thickness to length ratio to form a cable. A schematic sketch of a *RE*BCO tape and a view of a typical aspect ratio is shown in Figure 1a) and 1b).

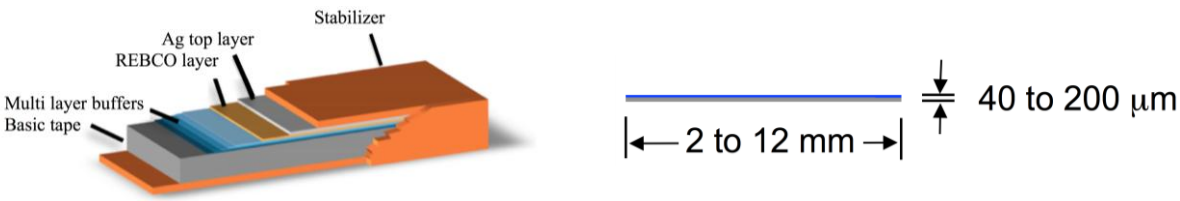

Figure 1: Principle layout of *RE*BCO tapes (left). Typical aspect ratio of *RE*BCO tapes (right).

With the availability of high quality and long length *RE*BCO tapes, the question of how to form high current cables arises e.g. for the application in a fusion magnet. High current cables are essential for big fusion magnets to limit the high voltages during fast discharge because with lower currents more turns would be necessary to reach the same magnetic field. More turns lead to a higher induction with the consequence of much higher voltages during fast discharge e.g. in case of a quench. As an example, ITER uses for the toroidal field coils a current of 68 kA, which results during fast discharge in voltages around 3.5 kV that have to be handled by the insulation system. In failure cases these voltages can be much higher [8]. Another requirement for the ITER TF conductor is to minimize ac losses because the cable is operated at approx. 4.5 K and uses the classical low temperature superconductor Nb_3Sn. At the high magnetic field at the conductor and the high current, the remaining temperature margin for safe operation is only 0.7 K [9, 10]. Therefore additional heating, e.g. by ac-losses, has to be avoided. As a consequence the ITER 68 kA TF conductor is composed of multiple-twisted strands of 0.81 mm diameter with a cabling pattern 3 x 3 x 5 x 4 x 6. It is obvious that such a cable layout cannot be realized using the thin *RE*BCO tapes with the given aspect ratio. Nevertheless, numerous proposals for a high current HTS cable formation have been made, which will be discussed below.

Due to the low temperature margin of 0.7 K the cable is strongly effected by external losses, too, e.g. by nuclear heat deposition. Recent investigations resulted in much higher nuclear heat load than used in the whole design phase which has significant consequences on the operation performance of the TF coils which could require a lower operation temperature of the He cooling. For more details see [10].

In the following first the use of HTS *RE*BCO material for future fusion coils will be investigated to clarify if HTS superconductors can principally be used to build a DEMO TF coil. For this purpose a

DEMO TF coil layout given by PROCESS code [11] will be used and the HTS cable is simplified using average values of the *RE*BCO tape constituents. Subsequently we will show the impressive progress manufacturer have made and are still realizing in fabrication of high quality *RE*BCO tapes. In a next step we will briefly discuss the numerous high current HTS cable layouts, including the new HTS CroCo proposal made by KIT. In the end we will show a proposal, replacing the generic cable layout in our HTS DEMO TF coil analysis from the beginning by a Rutherford cable made from *RE*BCO HTS tapes and the consequences of the rapid performance increase of the *RE*BCO tape properties offered by industry.

2 Analysis of the usability of HTS material *RE*BCO for a DEMO TF coil

To analyze the usability of *RE*BCO for a DEMO TF coil, the coil layout given by the PROCESS code [11] has been used as described in detail in [12]. However, because the available cross-section within process code was changed in July 2012, the work was repeated with this new coil layout [13]. To avoid multiple restart of the work, the starting point was frozen to this July 2012 design of PROCESS, which was used for all further work. The conductor layout was represented only in a generic way by using average values of the tape constituents like *RE*BCO superconductor content, Cu content or void fraction for He cooling. Conductor current, conductor geometry and number of turns fitting to the winding pack geometry were simulated using EFFI [14] to match the required magnetic field at the plasma axis. In a next step the resulting solution was cross checked to match the hotspot criterion of a maximum temperature at the conductor of 150 K after a fast discharge. This iterative approach led to a solution with an operating current of 50 kA and max. field at the conductor of approx. 13.5 T. In Figure 2 the critical current as a function of temperature is shown with a temperature margin of 11.9 K when operated at 50 kA. The temperature of the superconductor cable after a discharge with a time constant of 30.5 s was calculated and is below 150 K to avoid quick temperature changes that affect the thermal expansion in and around the conductor (ITER hot spot criterium). These calculations were performed with *RE*BCO superconductor tapes available in 2012 and shows that a HTS DEMO TF coil magnet is feasible. In the next paragraph the progress of *RE*BCO tape properties available from industry is discussed to highlight the new possibilities using this HTS superconductor with a much better performance with today material. Additional details of HTS high current cables and a conceptional design of a toroidal field coil for DEMO with such HTS conductors can be found in [15].

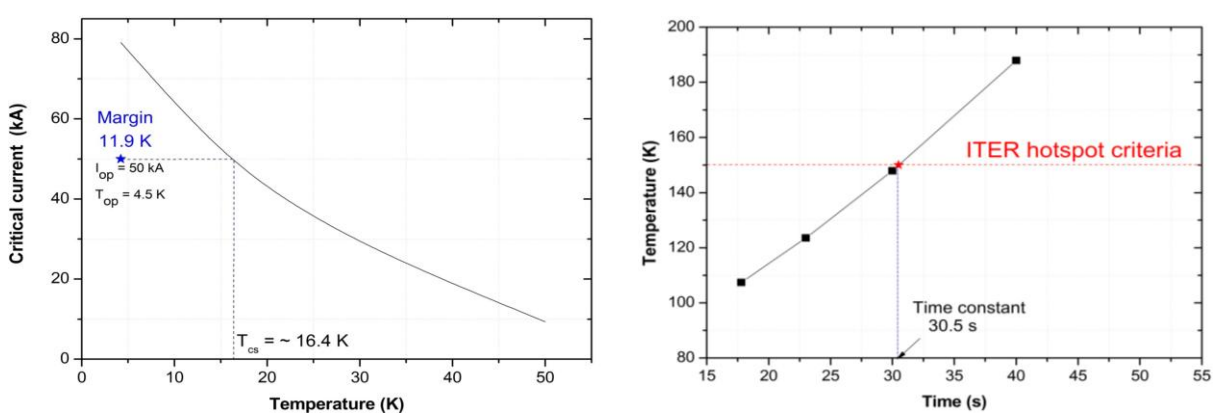

Figure 2: Critical current as a function of temperature shows a temperature margin of 11.9 K when operated at 50 kA (left). Temperature of the superconductor cable after a discharge with a time constant of 30.5 s (right).

3 Highlighting progress of *RE*BCO tape properties available by industry

*RE*BCO suppliers optimized in the last years the pinning behavior of their *RE*BCO tapes to achieve high critical currents even under high magnetic fields [16]. New results demonstrate the industrial availability of doubled disordered *RE*BCO tapes with excellent high critical current densities at 4 K [17]. Figure 3 gives the industrial available tape critical current for a 4 mm wide tape at 4.2 K. The data for the plot in figure 3 have been taken for 2008/09 from [18, 19], for 2013/14 from [18, 19, 20, 21], for 2016/17 from [21] and for 2018/19 from [22]. It is visible that for 20 T the critical current has been increased from 2008/09 to the estimated value in 2018/19 by approx. a factor 5, for 10 Tesla by a factor 6 and for 5 Tesla by a factor 7. This incredible increase is due to an optimization of pinning properties and in addition by increasing the REBCO layer thickness. Up to now it was reported that an increase of *RE*BCO layer thickness in not really beneficial because the *RE*BCO grain orientation is lost and the transport current consequently is not increased with additional *RE*CO layer thickness above approx. 1.5 µm [7]. However, in [23, 24, 25] it is reported that thicker *RE*BCO layers could be produced that gave an essential increase in transport current capability. In addition it was reported that the basic tape thickness of *RE*BCO tapes could be reduced from 50 µm to 30 µm [26] which gives a clear increase of the engineering critical current density. This progress may be complemented by the message that highest critical currents were measured even at 2.5 T and elevated temperatures around 30 K [25]. With such tapes even a temperature margin in the range of 20 K may be possible. Future fusion cables using these optimized *RE*BCO materials can be built either with less superconductor tapes, saving considerable amount of investment, or an operation at higher temperature is possible.

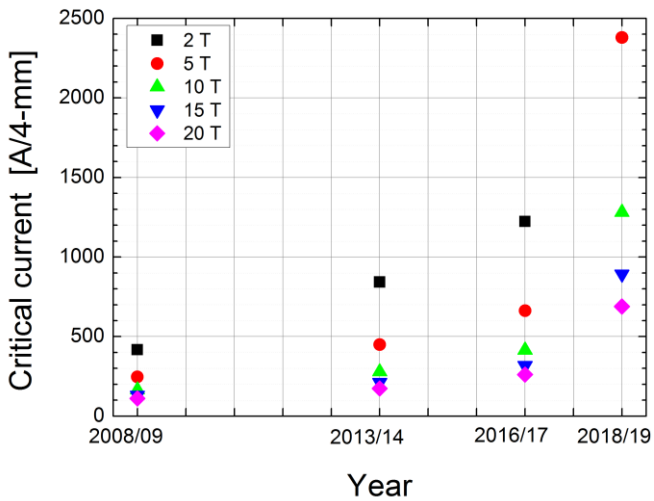

Figure 3(left): Progress of *RE*BCO tape suppliers at 4.2 K and different magnetic fields over the years including properties demonstrated in lab scale that will be industrial available around 2018/19.
The shown data points should be read to give the tape properties around the given years because change of tape properties in sold tapes cannot be clearly located in time.

4 Proposals for High Current HTS cables

Numerous proposals for high current HTS cables have been made during the past years. Most promising is the "twisted stacked tape cables" solution which stacks tapes e.g. in a twisted former [27, 28, 29, 30]. Another promising solution is winding *RE*BCO tapes around a round former to achieve flexible thin cables with high transport current capability [31]. If an optimization to ac losses is mandatory, the Roebel cable approach is most promising [32]. For Heliotron fusion machines simple stacked tapes have been proposed without twisting because for a Heliotron ac loss optimization is not a major concern. 100 kA have been demonstrated with that proposal [33]. SPC (former CRPP) proposed a twisted stacked tape in a round shape and demonstrated recently a current of 60 kA with a Rutherford type cable [29]. Recently a new proposal is presented which optimizes high engineering critical current density in parallel to twistability and an easy long length production method. Two different *RE*BCO tape widths are arranged and soldered to form a cross structure, and are fabricated in long length including twist in a single step [30, 34]. In a second step an enclosing Cu-tube is compacted around with solder filling the space in between. This ensemble is called HTS CrossConductor (HTS CroCo). The HTS CroCo principle is visible in Figure 4 (for visibility the single *RE*BCO tapes are shown in the sketches with enhanced thickness) together with a top view of a HTS CroCo sample, a HTS CroCo core before application of the outer Cu tube and a sketch of a Rutherford cable made from 11 HTS CroCos.

A single HTS CroCo with a diameter of approx. 9 mm, fully equipped with twenty 6 mm wide and ten 4 mm wide *RE*BCO tapes, has at 4.2 K a critical current I_c of approx. 30 kA in self field. At the maximum field of 13.5 T at the conductor calculated for the layout of a future DEMO TF coil, a HTS CroCo has a I_c = 7.6 kA with *RE*BCO tapes available today. The Rutherford cable shown in Fig 4 with 11 HTS CroCos will have at 13.5 T and 4.2 K a I_c = 84 kA. Therefore such a cable can be used for the layout of the HTS DEMO TF coil discussed in chapter 2.

Changing to the improved *RE*BCO tapes expected for 2016/17 (see Fig. 2) results in a cable critical current in the range of 154 kA. And the next development step assumed to enter the market in 2018/19 is still not included. As a consequence such a cable design with 11 fully equipped HTS CroCos would be overdesigned, as it aims for an operation current in the range of 50 or 60 kA. This clearly shows that with such an HTS solution even higher magnetic fields could be possible, or the operation temperature could be increased - or less tapes should be used to save investment.

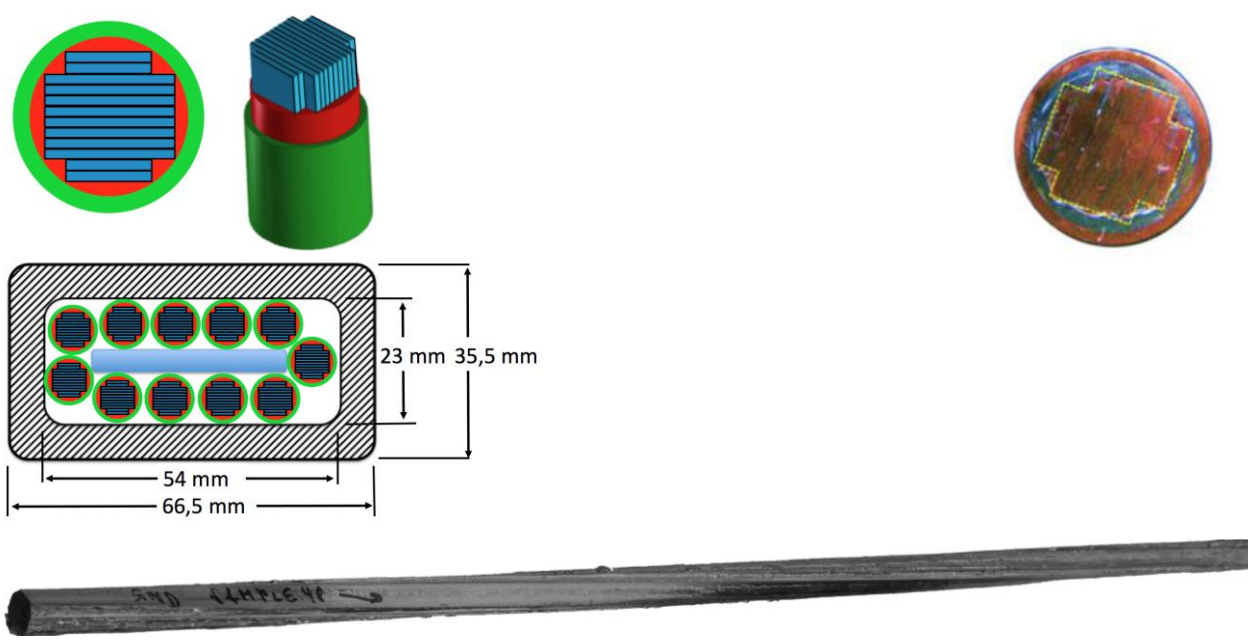

Figure 4 Two sketches of HTS CroCo (left), a HTS CroCo sample with this outer Cu shell, a Rutherford cable with 11 HTS CroCos in a steel conduit as a proposal for a HTS DEMO TF coil conductor (right) and a HTS CroCo core without outer Cu-tube to show the tape twist.

5 Summary

A generic conductor layout has been investigated using high temperature superconductor *RE*BCO for a TF DEMO coil following the PROCESS coil layout. It was demonstrated that with this solution a temperature margin of 11.9 K is obtained using the *RE*BCO tapes actually on the market. New impressive improvements of such *RE*BCO tapes have been discussed, which will allow to increase the temperature margin or the operating temperature or which will give the possibility to reduce the number of necessary tapes to save investment. Several proposals of high current cable layout have been briefly discussed, focussing in the end on the new HTS CroCo layout. A Rutherford cable with 11 HTS CroCo was proposed that can be used as a conductor for the DEMO TF coil layout already with today available *RE*BCO tapes. With the future *RE*BCO development this cable layout can be optimized to higher operating temperature, lower cost by using less *RE*BCO tapes - or even to achieve higher magnetic fields at the plasma center for future fusion machines.

6 Acknowledgment

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