



High temperature superconductor cables for EU-DEMO TF-magnets

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ARTICLE INFO

Keywords:

DEMO TF magnet
High temperature superconductor
High current HTS cable
REBCO

ABSTRACT

Actual progress of High Temperature Superconductor (HTS) REBCO tapes show an enormous increase of critical current density especially at highest field. These results offer new possibilities for the application of REBCO for large fusion magnets with a magnetic field well above 13 T 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 REBCO tapes are emerging, promising the applicability for fusion magnets, e.g. for a TF magnet of an European DEMO.

The actual progress of REBCO 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 REBCO tape data, calculations and modeling of a TF coil for an EU-DEMO based on the PROCESS code will be presented, showing that with today's HTS performance an EU-DEMO TF conductor is feasible, which can be operated at 4.5 K with a maximum field at the conductor of approximately 13.3 T (magnetic field at the plasma center approximately 6.8 T) with a temperature margin of approximately 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 an EU-DEMO.

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 $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (REBCO) with $\text{RE} = \text{Y}$, 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 REBCO 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 REBCO is handicapped because the simple mass production is hindered by basic physics of this type of superconductor. The main restriction is the two-dimensionality of REBCO with the CuO_2 planes that host the superconductivity and the extremely short coherence length, due to the crystal structure. As a consequence adjacent REBCO 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 REBCO samples is limited to thin layer deposition on substrates with clear crystal orientation that match the lattice constants of REBCO 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 REBCO tape production, which is the use of Rolling Assisted Biaxially

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<http://dx.doi.org/10.1016/j.fusengdes.2017.07.025>

Received 26 February 2016; Received in revised form 26 July 2017; Accepted 26 July 2017
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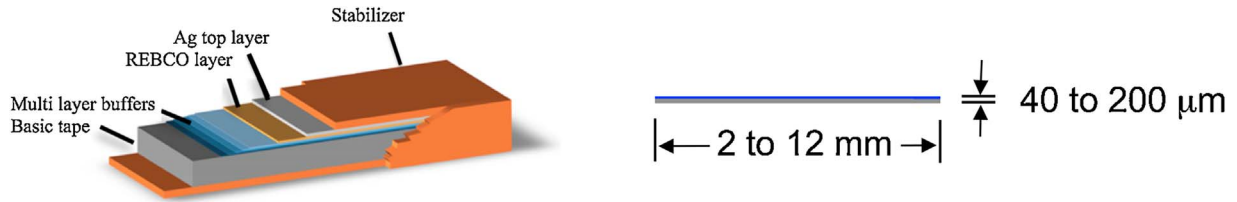


Fig. 1. Principle layout of REBCO tapes (left). Typical aspect ratio of REBCO tapes (right).

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 REBCO 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 REBCO and buffer material. As a consequence the methods to produce high quality REBCO tapes result in thin tapes with an unfavorable thickness to length ratio to form a cable. A schematic sketch of a REBCO tape and a view of a typical aspect ratio is shown in Fig. 1.

With the availability of high quality and long length REBCO 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 ≈ 4.5 K and uses the classical low temperature superconductor Nb₃Sn. 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 $3 \times 3 \times 5 \times 4 \times 6$. It is obvious that such a cable layout cannot be realized using the thin REBCO 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 REBCO material for future fusion coils will be investigated to clarify if HTS superconductors can principally be used to build an EU-DEMO TF coil. For this purpose an EU-DEMO TF coil layout given by PROCESS code [11] is used, that just defines the available space and the necessary Ampere*winding number without giving a detailed layout. For simplicity, the HTS cable is simplified using average values of the REBCO tape constituents. Subsequently we will show the impressive progress manufacturer have made and are still realizing in fabrication of high quality REBCO 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 REBCO HTS tapes and the consequences of the rapid performance increase of the REBCO tape properties offered by industry.

2. Analysis of the usability of HTS material REBCO for a DEMO TF coil

To analyze the usability of REBCO for a EU-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 REBCO 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

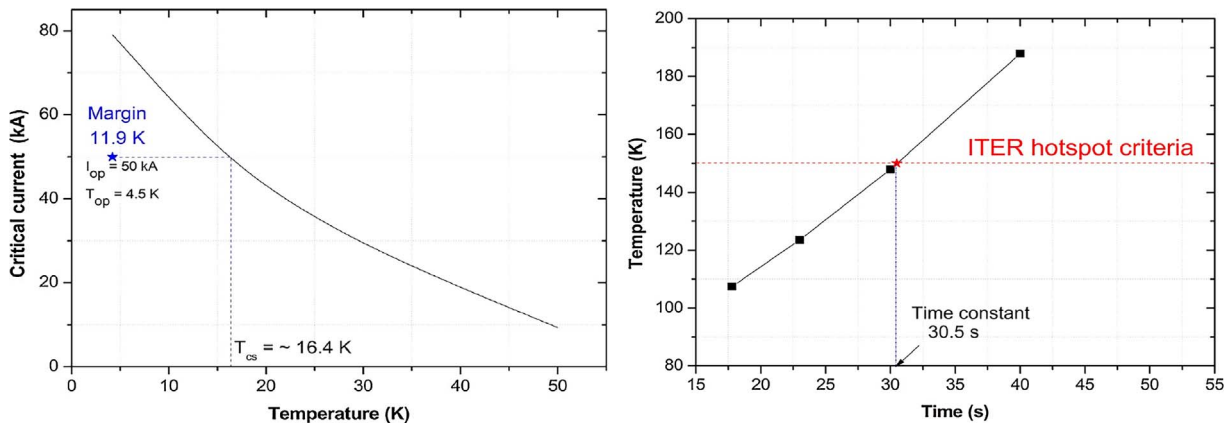


Fig. 2. Critical current as a function of temperature shows a temperature margin of 11.9 K when operated at 50 kA (left). Temperature of the superconductor cable after a discharge with a time constant of 30.5 s (right).

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