High Temperature Superconductors for Future Fusion Magnet Systems – Status, Prospects and Challenges

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1. Introduction

The application of High Temperature Superconductors (HTS) in fusion research has, until now, been limited to the use in current leads. Studies for a use in bus bar systems show a technological potential, too. The applicability of HTS in fusion magnets is presently not feasible but would be desirable for use in future fusion reactors, e.g., DEMO and beyond. The main driver to use HTS materials for fusion coils is to operate the magnets either at high magnetic fields, e.g. 20 T, or at medium or high operation temperatures (50 – 65 K). As the low temperature superconductor (LTS) layouts for a Tokamak or a Stellarator has been optimized by balancing the requirements for current distribution, AC losses and cooling capability, the situation is different in case of HTS, especially for YBCO coated conductors. While transient cooling is not important due to the much higher heat capacity of the materials, AC losses, thermal stability, hot spot temperature and current distribution will play a challenging role due to the structure of the coated conductor tape.
This contribution will give an overview about status, promises and challenges of HTS conductors on the way to an HTS fusion magnet system for DEMO and beyond.

2. Prospects and options for HTS use in future fusion machines

The main driver for the selection of HTS is the possibility to use the material either at high magnetic fields, e.g., 20 T, or at high operation temperatures, e.g., 50 – 65 K. While the first option would be applicable to high density low-β Tokamak designs, the second option could be realized in high-β designs and would drastically reduce the cooling power requirements. Examples for such reactor designs (tokamak and stellerator) are DEMO [1], ARIES [2], VECTOR [3] and ARIES-CS [4], ASRA-6C [5].
At present, four HTS options for the magnet system of a fusion reactor like DEMO are discussed. They combine various magnetic fields and operation temperatures, depending on the available HTS material:

1. High field & low temperature (18 - 20 T, 4.5 K)
2. Conservative field & medium temperature (12 T, 20 K)
3. Medium field & high temperature (15 T, 50 K)
4. Conservative field & very high temperature (12 T, 65 K)

The two different HTS materials that are available on an industrial level are BSCCO (Bi-2212, Bi-2223) and YBCO (Y-123). Industrial production of Bi-2212 conductors is possible but not settled because of the rather small application area. Bi-2223 tapes are industrially available in large quantities but practically mainly used in power applications at LN2 or LNe cooling temperatures. YBCO tapes are presently industrially available only in medium lengths (up to 300 meters) but YBCO is on the way to enter the market. The present record for a 12 mm wide and 322 m long YBCO tape is 263 A at 77 K in self field [6]. Because of the strong field dependence of the current carrying capability of Bi-2223 at temperatures above 20 K a high operation temperature is possible with YBCO, only.

3. Current Results for YBCO Coated Conductors (CC)

Industry is presently able to manufacture CC in lengths of a few 100 meters using different deposition techniques for the superconductor layer (e.g. AMSC, SuperPower, THEVA). Stabilized tapes are also available, e.g. copper-clad CC by AMSC and SuperPower and Ag-clad by THEVA. Today the main reasons for limitation of the critical current are inhomogeneity of the YBCO layer and insufficient optimization of flux pinning behaviour.
There is a general agreement to produce YBCO CC with reduced width of 4 mm to be compatible with the Bi-2223 tape production. To speed up production wider tapes (typically 4-10 cm) are produced and then cut in 4 mm wide tapes. This is to ease the designer’s life in power application although this is not necessarily important for the development of a fusion conductor.

4. Main Challenges for a HTS Fusion Conductor

Following the requirements taken from the reactor studies, the suitable HTS material and a suitable cable design has to be selected according to:

1. High engineering current density in the conductor at the specific temperature and field.
2. Sufficient mechanical strength (stress-strain characteristics) or option for reinforcement.
3. Tolerable hotspot and quench behaviour of the HTS conductor (stabilisation).
4. Optimized current distribution, i.e. feasibility of good joints and optimized inter-strand resistance and inductance.
5. Possibilities to limit the AC losses.
6. Compatibility of coolant choice, e.g., Nitrogen, Helium, Neon or Hydrogen.
7. Tolerable activation of materials due to neutron flux.

4.1 High engineering current density in the conductor at the specific temperature and field.

The engineering current density has to be high enough to generate the desired field with a tolerable number of windings because otherwise the inductance of the magnet would be too high and as a consequence the high voltage in case of a fast discharge would be critical. The engineering current density is strongly influenced by the amount of electrical stabilizer and mechanical reinforcement material.

As an example, the TF coil parameters of ITER, i.e. a coil current of N*I = 9.1 MA and a self inductance of L = 0.349 H, were used to calculate discharge voltage and time constant for different conductor currents. Low currents result in either enormously high voltages of about 160 kV or in unrealistic large discharge time constants of about 190 s. Table I summarizes the results of the parametric analysis. As a result, 30 kA seems to be the minimum acceptable conductor current which is a compromise to limit both the discharge voltage and the discharge time constant.

TABLE I: RESULTS OF THE PARAMETRIC ANALYSIS FOR VARIOUS CONDUCTOR CURRENTS

Number of turns	Conductor current	Inductance ratio L/L_{ITER}	Discharge voltage (with τ_D = 12 s)	Discharge time constant (with U_D = 10 kV)
134	68 kA	1	3.5 kV	4 s
304	30 kA	5	17.5 kV	21 s
910	10 kA	45	158 kV	190 s

4.2 Sufficient mechanical strength (stress-strain characteristics) or option for reinforcement.

The superconductor performance decreases in case of high strain. This is especially critical in the case of a high field operation where the enormous Lorentz forces will cause massive problems that can be hardly handled with today's available materials. For Bi-2223 and YBCO such forces can cause cracks due to the related strain that will drastically limit the available current density.

4.3 Tolerable hotspot and quench behaviour of the HTS conductor (stabilisation).

In case of a quench where superconductivity is lost locally the coil current will deposit a large amount of power due to ohmic heating in this area. Although a fast discharge of the coil is triggered in such a case, the conductor has to be stabilized to withstand the energy deposition until the coil is discharged.

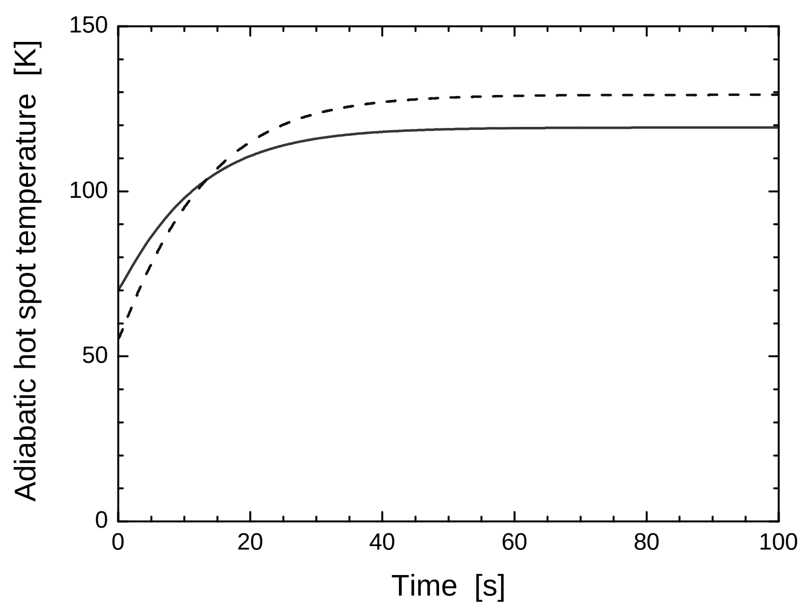

FIG. 1. Temperature rise during a safety discharge for the two sample conductors. Here an YBCO layer thickness of 1 μm, and a Cu stabilizer thickness of 50 μm (solid line) and 300 μm (dashed line) have been used.

As an example: if using a 4 mm wide YBCO-CC, a critical current density in the 1 μm thick YBCO layer of 2000 A/mm^2, and a thickness of the copper stabilizer of 50 μm, the resultant hot spot temperature during a discharge (τ = 21 s) will be about 120 K. For a critical current density of 10000 A/mm^2, the copper thickness of 300 μm would be required to limit the hot spot temperature to 130 K. So if the additional copper stabilizer is taken into account the increase of the critical current density in the YBCO by a factor of five results in an increase of the overall engineering current density of only a factor of two. *FIG. 1* shows the temperature rise during a safety discharge for the two sample conductors.

4.4 Optimized current distribution, i.e. feasibility of good joints and optimized inter strand resistance and inductance.

To load the superconducting cable uniformly with current and to minimize losses on superconductor-superconductor connections good joints have to be feasible with a resistance of only a few nOhms or less. An optimized inter-strand resistance helps to allow a current redistribution in case of non conformity.

4.5 Possibilities to limit the AC losses.

Induced currents caused by field changes will cause massive losses when the superconducting cable is not optimized with respect to AC losses. This is especially critical for the classical Tokamak design that uses the field ramping of the central solenoid to drive the plasma current. Goal should be to limit the coupling and eddy current losses to the level of the hysteresis losses.

4.6 Compatibility of coolant choice, e.g., Nitrogen, Helium, Neon or Hydrogen

The choice of HTS material and the conductor layout depend of course on the choice of coolant.

4.7 Tolerable activation of materials due to neutron flux.

Due to the high Neutron flux in future fusion machines, HTS and structure material should be chosen to minimize Neutron activation as far as possible. Therefore e.g. the presently used Ni tapes for the YBCO conductor should be replaced by a low activation material.

5. Example for a HTS Conductor Layout

For low T_c superconductors (LTS) the conductor requirements discussed above have lead to sophisticated designed Nb_3Sn or NbTi strands and numerous varieties of optimized cable layouts depending on the application. The conductor layouts were optimized for Tokamak or Stellarator designs e.g. by balancing current distribution, AC losses and cooling capability (transient as well as steady state).
In case of HTS a similar optimization strategy is desirable. The minimization of AC losses surely is challenging because of the large inductive loops present in non twisted superconductors. The coated conductor tapes cannot be twisted easily and technologies like multi-staged multi-filamentary twists are obviously impossible. Other critical properties like current distribution and thermal stability are also an issue because of the structure of the conductor tape.

Existing coated conductor layouts for fusion reactor designs (ARIES-AT [7], VECTOR [8]) use non twisted high aspect ratio CCs which are not optimized with respect to AC losses and current distribution.

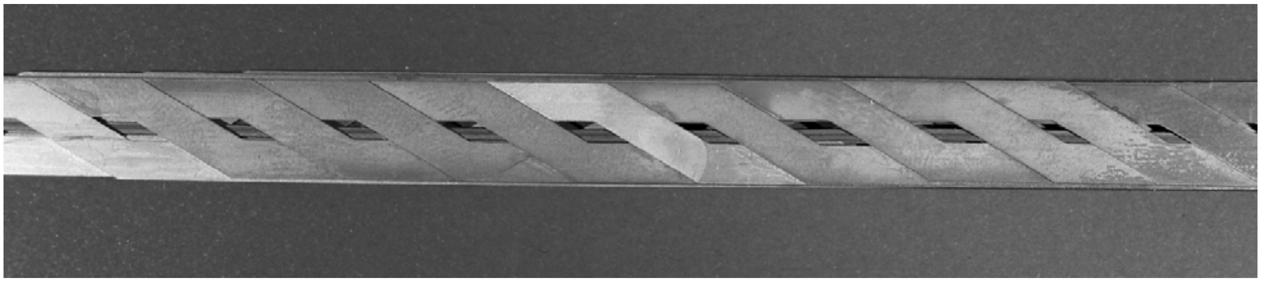

FIG. 2. View of the 16 strand ROEBEL assembled coated conductor (RACC) made from DyBCO-CC (THEVA), Cable dimensions 10 mm width, 1 mm thickness and 180 mm strand transposition length

A promising new layout of a low AC loss cable for CC tapes with high aspect ratio is based on a classical ROEBEL cable concept. The CC tapes are pre-shaped by cutting out trapezoidal pieces which results in tapes with a meander form. These meander tapes are put together to form a ROEBEL bar by the cable assembly (RACC-technique) which turns out to be compatible with the tolerable bending load of the CC material. A sufficient thermal stabilization of the strands can be achieved by enclosing the CC tape in a copper cover. Current redistribution problems in such a RACC cable will be diminished by an improved current homogeneity in the coated conductor. *FIG. 2* shows a picture of a 16 tape RACC type conductor where the capability to realize transport currents of >1 kA at 77 K was demonstrated [9]. The new RACC cable design for coated conductors opens up the possibility for low AC loss CC cables and an easy scale up of the current carrying capacity towards several kA.

Quite recently a second 0.45 m long RACC-cable made from MOCVD-CC (SuperPower) was presented with a critical transport current of 1020 A at 77 K and s.f. [10]. At this temperature the self field effect caused a 30% loss of the transport current compared to the value calculated as sum of j_c values of the single YBCO strands. The modelling of the self field effect applying a Biot-Savart-Law approach gave 1040 A and could explain quantitatively the observed current reduction if an average field was used, which is illustrated in *FIG. 3*. This result indicates a perfect current redistribution and an excellent homogeneity of the used Coated Conductor.
As this cable showed already an excellent performance and reached an engineering current density of 11.3 kA/cm^2, an extrapolation to a lower temperature of 50 K leads to an expected transport current including self field effects of 4-5 kA when based on measured single tape properties.

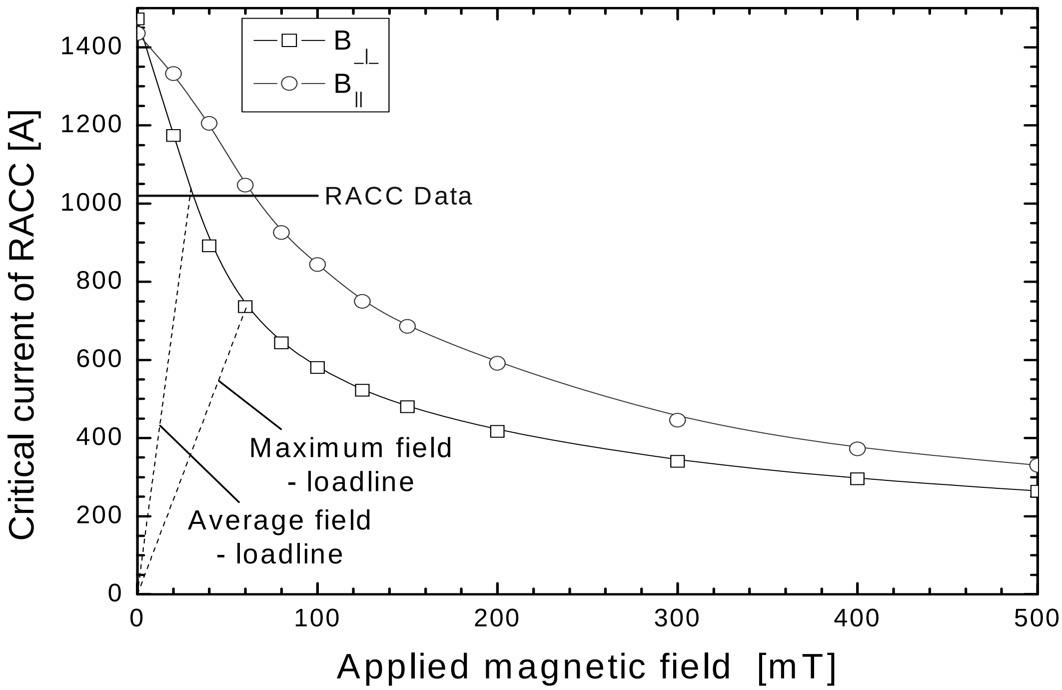

FIG. 3. Critical current characteristic of MOCVD-CC (Superpower) with field orientation parallel and perpendicular, scaled up to the RACC-cable design current of 1467 A. The load lines from self field effect calculations (see text) intersect the worst $I_c(B)$ curve at 1040 A and 736 A for the different approaches. The very good agreement using the average field approach indicates a very well working current redistribution.

6. Conclusions and Outlook

Today a high current HTS conductor of ITER size (or even for 30 kA) is a real challenge.
For a conductor made of YBCO CC the operation current is limited by the number of tapes which can be used for cabling. In order to limit the hot spot temperature the copper stabilizer needs to be large and good contact to the superconductor is required. Possibly segregated copper could be used but for this a good current transfer and a rather homogeneous current distribution are required.
The AC losses which might be large have to be removed from the conductor which leads to the question which coolant could be used and if indirect cooling is possible.
One of the manufacturing issues will be the structural reinforcement which will lead to a further reduction of the overall current density. Because of the high heat treatment temperature during the YBCO layer formation process a react&wind technology has to be reconsidered.
Further investigations are needed to extend the CC technology to a high current capacity conductor. The enormous progress for short samples with respect to improved irreversibility fields, tailored flux pinning and reduced magnetic field anisotropy of transport currents, give very good prospects to reach in a midterm horizon RACC cable currents well above 10 kA at 50 K. Actually Coated Conductors became a commercial product, being available from 3 suppliers in reliable quality with the option to come to longer length of several hundred meter, soon. Promising efforts in several laboratories to develop a filamentary structure in the strands gives in addition space for further reduced AC losses in future cable designs.

At the end of a long term development program (~ 15 to 20 years), the construction of a HTS model coil is feasible and will be mandatory in order to demonstrate the ablicability of such a new technology to DEMO and beyond.

7. Acknowledgement

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8. References

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