HTS APPLICATIONS

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Abstract

Superconductivity has found many attractive applications in medicine, science, power systems, engineering, transport and electronics. One of the most prominent applications of superconductivity are superconducting magnets e.g. MRI magnets, NMR magnets, accelerator magnets, and magnets for fusion; most applications still use low temperature superconductors.

Since the discovery of high temperature superconductivity (HTS) in 1986 there has been a tremendous progress in R&D of HTS material, wires and applications. Especially for power system applications, HTS offers considerable economic benefits. Many HTS demonstrator or prototype applications have been built and successfully tested, and some HTS applications like cables and superconducting fault current limiters seem very close to commercialisation. This paper gives an overview about the present and future HTS applications in power applications, high field magnets and current leads. In addition results of the Forschungszentrum Karlsruhe program to develop HTS technology for magnet applications are presented. A special focus is set on the development of HTS magnets for fusion application.

INTRODUCTION TO HTS APPLICATIONS

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 presence 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.

BSCCO HTS-tapes are commercially available nowadays and can be used in low and high field applications depending on the temperature. BSCCO is nowadays ready for technical applications 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, i.e., the maximum current that can be carried by the conductor. 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).

For YBCO conductors the basic problems are solved for short samples and the transfer to long lengths in an industrial process is the challenge now. Due to the fast progress of coated conductor development in recent years and the promising cost perspectives, special interest is focused on this material which is a good candidate for present and future HTS applications.

POWER APPLICATIONS

The applications in which superconductivity has the potential to be effective in an electric power system can be separated into two general classes [4]. The first class includes cables, motors, generators, and transformers where superconductors replace resistive conductors. The second class includes technologies that will be enabled by superconductivity and that have little or at most limited capability if conventional materials are used. Examples are superconducting magnetic energy storage (SMES) and fault-current limiters (FCLs).

Many demonstrator and prototype tests showed the technical feasibility of HTS in power system applications; examples are rotating machines, cables, transformers, current limiters, SMES. Superconducting cables and superconducting fault current limiters seem very close to commercialisation. Power system applications may open a continuous demand for HTS and therefore accelerate the R&D for HTS material and tapes. At a cost level of less than 10 k€ per kA a broad application of HTS devices seems very likely. Compared to conventional solutions the HTS devices should be comparable in cost but the reliability and the problem-free integration has to be demonstrated.

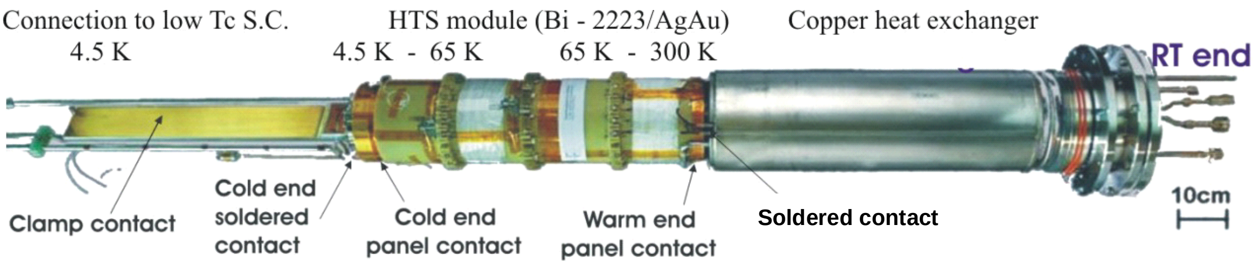

Figure 1: 68 kA HTS current lead developed at the Forschungszentrum Karlsruhe using Bi-2223/AgAu tape.

HTS FOR CURRENT LEADS

Current leads are the component of a sc magnet system where commercialized HTS material can be used because the external field is usually well below 0.5 T. A large scale application for an HTS current lead (up to 13 kA) was developed for LHC [9]. A second example is the ITER HTS current lead demonstrator (HTS-CL, 68 kA) which has been developed and built by the Forschungszentrum Karlsruhe in collaboration with the Centre Recherches en Physique des Plasmas, Switzerland in the frame of an EU Fusion Technology task. This HTS-CL consists of two main parts, the HTS module that uses BSCOO-2223/AgAu tapes embedded in stainless steel and the copper heat exchanger. The HTS module is cooled by heat conduction from the 4.5 K end and covers the temperature range between 4.5 K and 65 K. The conventional 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. A picture of the HTS-CL is shown in Fig. 1.

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 current lead. Last but not least it could be shown that the He-refrigerator power consumption was reduced by a factor of 5 compared to conventional current leads. Details of the development and test results can be found in [10-13]. This development has brought ITER to the decision to use HTS-CL for the ITER magnet system which can save about 22 kW refrigerator power. In the meantime, other fusion devices under operation or construction like EAST (China), W7-X (Germany) and JT60-SA (Japan) plan to use HTS current leads [14-16].

HTS FOR HIGH FIELD MAGNETS

One key application for HTS is high field magnets. Here the main emphasis is not the operation at higher temperature but to reach high magnetic field levels which are beyond the limit of low temperature superconductors. Possible areas are:

- high field magnet test facilities for scientific research;
- high field magnets for NMR;
- high field wide bore magnets for MRI;
- high field magnets for accelerators.

The Forschungszentrum Karlsruhe has a long term experience in the development of superconducting high field magnets. A series of high field solenoidal magnet systems up to 20 T (JUMBO, HOMER-I, HOMER-II) are available in the laboratory. Within successful long term collaboration with Bruker BioSpin high field NMR magnets (750 MHz, 800 MHz, 900 MHz) were developed and now the target is 1 GHz. Presently the main focus is on the development of HTS insert coils for the test facility HOMER-II.

Most magnet systems in operation so far consist of low temperature superconductors, the main effort worldwide is now focused on HTS insert coils. First test coils for magnetic field of 5 – 8 T in background fields up to 20 T have been achieved so far [5-8]. Although the test coils reached their expected field levels, they suffered from degradation and destruction, e.g. ballooning of the conductor during He-II operation [6, 7]. Obviously there is necessity for further R&D.

HTS FOR FUSION MAGNETS

The cooling power of a fusion power plant like ITER is determined by the 4.5 K cooling of the LTS magnet system, the cryo-pumps, the neutral beam pellet injection and by the 80 K cooling of the radiation shield. In total a room temperature electric power of about 33 MW is required [17]. Using HTS magnets, the cooling power can be reduced by about 20 - 30%, depending on the temperature level. For example for LN2 cooling the complex radiation shield can be avoided which allows a more compact and simpler machine with additional savings of investment and operation costs.

Principally both, BSCCO and YBCO coated conductor could be used for fusion coils [18]. In the case of BSCCO, tapes are available but the operation temperature is limited to approximately 20 K if high magnetic fields are required. This limits the attractiveness to use BSCCO drastically. However, as discussed above the YBCO coated conductor is underway to be available in long lengths and will allow

Figure 2: Nb_3Sn conductor of the TF model coil of ITER made of about 1000 superconducting and Cu strands embedded in a stainless steel conduit.

an operation temperature in the range of 65 K or even higher.

Both HTS materials are available in the form of small tapes with high aspect ratio only which makes an optimization of ac-loss properties difficult. On the other hand this optimization is essential because for fusion coils high ac-losses can not be tolerated because this would increase the 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 (Fig. 2). This conductor contains about 1000 Nb_3Sn strands in a multiple twisted cable layout embedded in a stainless steel conduit [19]. The complexity of this cable illustrates the need for an optimization of a fusion cable with respect to ac-losses and cryogenic performance. A future HTS cable has to be compared with such a sophisticated "classical" fusion cable i.e. the gain due to a higher operating temperature with a HTS fusion cable can 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 take an adequate time to find optimized solutions.

Following the requirements taken from various studies, the suitable HTS material and a suitable cable design has to be developed to achieve [20]:

- high engineering current 10 – 30 kA in the conductor at a specific temperature 50 – 70 K and magnetic field 10 – 15 T;
- sufficient mechanical strength (stress-strain characteristics) or option for reinforcement;
- tolerable hot spot and quench behaviour of the HTS conductor (stabilisation);
- optimized current distribution, i.e., feasibility of good joints and optimized interstrand resistance and inductance;
- possibilities to limit AC losses;
- good cooling possibilities, e.g., Nitrogen, Helium, Neon or Hydrogen;
- tolerable activation of materials due to neutron flux.

Figure 3: View of the 16 strand ROEBEL assembled coated conductor (RACC).

First ideas to use HTS tapes by forming a Roebel bar type conductor have been developed at the Forschungszentrum Karlsruhe [21]. Fig. 3 shows an example of a 16 strand ROEBEL assembled coated conductor (RACC) made from YBCO coated conductor (Superpower), which carried a current of 1 kA at 77 K and self field [22]. A 45 tape cable is under preparation. 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 Forschungszentrum has started a long term program HTS4Fusion to develop HTS conductors for fusion magnets:

1. Conductor development:
    a. HTS material development;
    b. development of cabling/bundling techniques for both wires and tapes;
    c. develop HTS cable concept for 20 kA class 12 T, >50 K;
    d. characterisation of HTS strands and sub-size cables in upgraded FBI (warm bore);
    e. conductor development.
2. Structural material in the cryogenic lab:
    a. prepare material database for structural materials beyond ITER;
    b. tests of advanced structural materials.
3. Demo-Solenoid:
    a. Demo-Solenoid design & construction;
    b. Demo-Solenoid test in TOSKA;
4. HTS TF-Demonstration Coil.

This program shall be linked to other associations coordinated by the European Fusion R&D program.

SUMMARY

The actual status of LTS/HTS application is summarized in Table 1. It is shown that high temperature superconductors have many attractive applications in medicine, science and power systems engineering. Until now, HTS have reached a commercial stage in induction heater magnets and in current leads. Regarding magnets, R&D is underway in high field applications for research and NMR/MRI and has started in accelerator applications and fusion. Although it is challenging to reach with HTS applications the LTS level, large progress is expected within the next decade.

Table 1: Outlook HTS Applications

	LTS now	HTS now
MRI Magnets	☑	-
NMR Magnets	☑	-
Accelerator Magnets	☑	-
Fusion Magnets	☑	-
SMES Magnets	☑	-
Induction Heater Magnets	-	☑
Current Leads	-	☑

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