APPLICATION OF HIGH TEMPERATURE SUPERCONDUCTORS TO ACCELERATORS

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Abstract

Since the discovery of high temperature superconductivity, a large effort has been made by the scientific community to investigate this field towards a possible application of the new oxide superconductors to different devices like SMES, magnetic bearings, flywheels energy storage, magnetic shielding, transmission cables, fault current limiters, etc. However, all present day large scale applications using superconductivity in accelerator technology are based on conventional materials operating at liquid helium temperatures. Poor mechanical properties, low critical current density and sensitivity to the magnetic field at high temperature are the key parameters whose improvement is essential for a large scale application of high temperature superconductors to such devices. Current leads, used for transferring currents from the power converters, working at room temperature, into the liquid helium environment, where the magnets are operating, represent an immediate application of the emerging technology of high temperature superconductivity. The LHC, currently under construction at CERN, will transfer more than 3 million ampères of current through leads having high temperature superconducting sections, thus providing a unique opportunity to incorporate these materials into large scale systems. The status of this project and the cost-benefit consequence of its application will be reported.

1 INTRODUCTION

All existing large superconducting accelerator systems have based their magnet technology on the use of NbTi superconductor operating at liquid helium temperature, a well known material which has guaranteed up to now the construction of world's largest machines. The Large Hadron Collider (LHC), presently under construction at CERN, will profit to the full from the NbTi properties by adding the novelty of operating the magnets at superfluid helium temperature, a technology possible thanks to the development and construction of a powerful and complex large scale cryogenic system [1]. Operating at a field of 8.4 T and 1.9 K, the LHC dipole magnets approach the upper limit of practical use of the NbTi conductor. Higher field operation at liquid helium temperature, as requested for future hadron or muon colliders, would require the use of new materials, such as Nb_3Sn or Nb_3Al [2] for fields up to about 13 T, or, at even higher fields, High Temperature Superconductors (HTS).

Since the discovery of high temperature superconductivity, important progress has been made in the development of HTS, with steadily improving electrical and mechanical properties. Long length BSCCO tapes and wire are now commercially available and prototypes have been built to verify the technical viability of the HTS technology in magnets design. However, technical issues like higher critical current density and better mechanical performance still need to be addressed before the HTS could play an important role in the development of superconducting magnets. Due to the fast fall of critical current density at higher temperatures, applications at 77 K, which would present the advantage of greatly simplifying the cryogenic system, are not yet within reach. An important application of HTS in the field of the accelerator technology for which the performance of HTS is already adequate is represented by the current leads. The LHC will need to transport a total current of about 3.4 million ampères into and out the cold mass and will profit of the use of high temperature superconducting current leads, incorporating HTS in the lower section, to reduce the heat input into the already heavy loaded cryogenic system. The LHC current leads represent today the first opportunity to efficiently incorporate these new oxide materials into a large scale accelerator system.

2 HTS MATERIALS FOR LARGE SCALE APPLICATIONS

Long lengths of BSCCO 2212 and BSCCO 2223 PIT conductors are fabricated by a number of companies world-wide (American Superconductor, NST, IGC, Alcatel, Sumitomo, BICC) at a quantity and performance level which has allowed their application to some prototype devices. Average engineering critical current densities of about 14 kA/cm^2 (77 K,self field, 1 μV/cm) can be guaranteed on long length BSCCO 2223 tapes [3]. Tolerable tensile strength at 77 K of about 150 MPa has been achieved on multifilamentary wires in Ag/metal alloy [4] [5], while the addition of a thin reinforcement material to both side of the tape (ASC BSCCO 2223 3-ply wire) [5] has increased the robustness of the superconductor allowing to absorb a maximum stress, at 77 K, of the order of 265 MPa.

However, all present applications of BSCCO rely on operating temperatures lower than 30 K to profit of the higher critical current densities and lower field sensitivity at such temperatures.

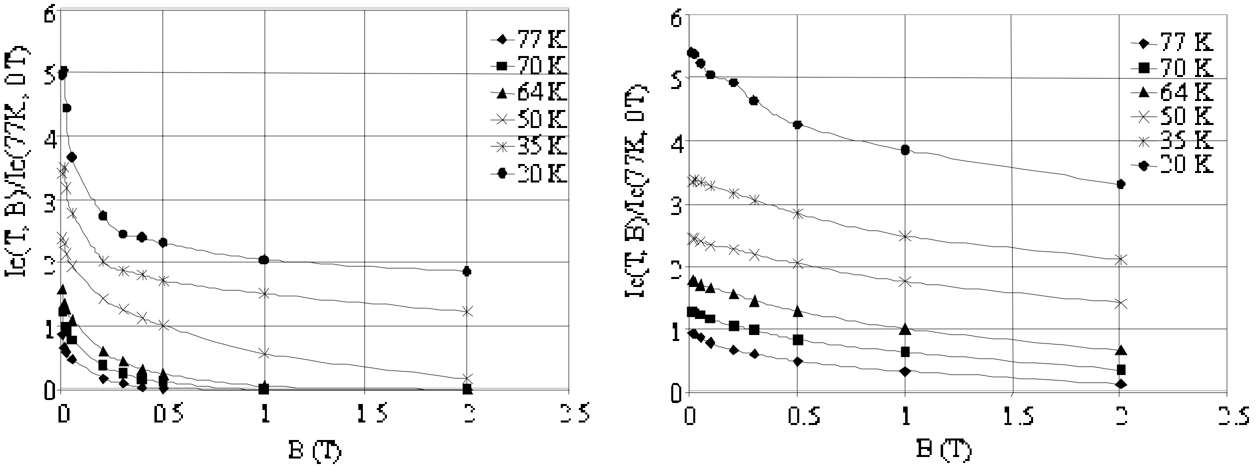

Figure 1: Critical current density as a function of magnetic field for field perpendicular (left side) and parallel (right side) to tape surface (courtesy of ASC)

In Fig. 1 is reported as example the typical magnetic field dependence of the critical current, measured on ASC BSCCO 2223 conductors, at different temperatures. The technology of YBCO coated conductors, in which biaxial texture is created on a substrate and a thick YBCO film is grown epitaxially on the top, is still at an early stage of development. It is promising, thanks to the higher field performances at liquid nitrogen temperature (current densities higher than 600 kA/cm^2 have been routinely achieved at 77 K and self field on short conductors [5]), but it is presently limited to short length samples.

3 HTS FOR MAGNETS APPLICATIONS

In view of the electrical properties of the HTS, an interesting application for accelerator technology is represented by hybrid magnets where insert coils in the bore of a low temperature superconducting magnet can operate in a background field at 4.2 K to allow higher field operation.

An engineering design of a 12 T to 15 T magnet for the VLHC, a proposed new proton collider with energy of 50 TeV per beam or more, envisages, for the high-field option, a new magnet concept (the Common Coil Design) based on the use of Nb_3Sn or HTS coils [6]. With respect to the conventional cosine theta magnets, the Common Coil Design has the advantage of relying on a simple 2-D geometry in which racetrack coils are wound flat and with a large bending radius leading to a much easier design of the ends. For the assembly of coils using HTS material a minimum bending radius in the ends of about 70 mm would enable the use of the react-and-wind technology and thus simplify the issue of choosing electrical insulation compatible with high temperatures as

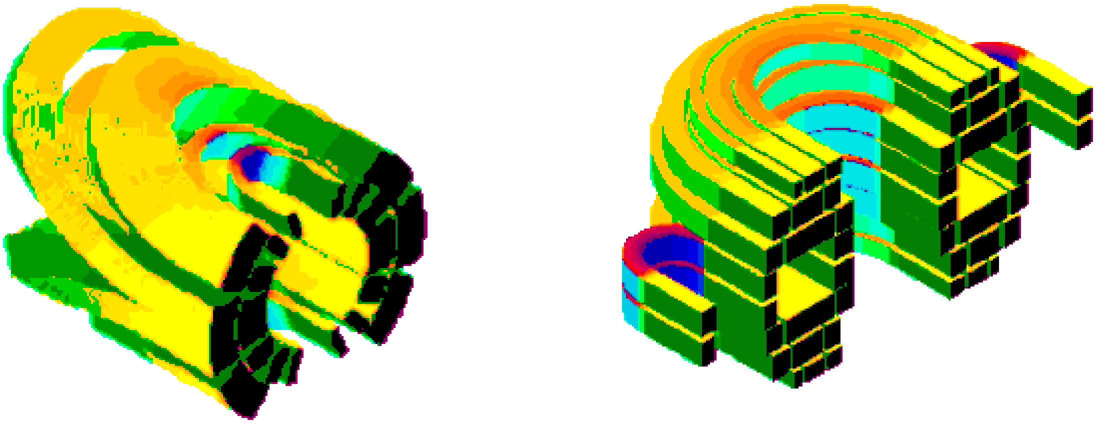

Figure 2: Coil end of LHC main dipole (left side) and common coil design (right side) (ROXIE 8.0)

well as problems due to the presence of oxygen during the heat treatment.

In Fig. 2 are reported for comparison the LHC dipole and the Common Coil Design coil ends. In the first case, a complex 3-D geometry with a minimum bend radius of about 6 mm makes the design prohibitive for present day HTS materials. Calculations of field quality show that good geometric field quality can be obtained in the common coil magnet design [7].

In view of a future application for high field dipole magnets, LBNL in collaboration with IGC, OST and Showa Electric has developed multi-kiloamp BSCCO 2212 Rutherford cables [8]. Cables with metal or ceramic core have recently been produced and tested. Such cables will permit more flexibility in the design of the new generation of magnets.

Prototype magnets operating at higher temperatures have been manufactured and tested by using the cryogenic refrigeration produced by commercially available cryocoolers. An important application is represented by a ion-beam switching magnet installed in March 1997 in the beam line of a carbon-dating van der Graaf accelerator at the Institute for Geological and Nuclear Sciences in Wellington, New Zealand. The magnet, conduction cooled at 30 K by a single stage GM refrigerator, consists of racetrack coils in a iron yoke (Fig. 3), fabricated by ASC from BSCCO 2223 tapes with the wind-and-react technology [9]. Even if the operating field is only about 0.74 T, this magnet, which has been continuously operated for the last there years, represents an important milestone in terms of confirmation of long term reliability of the HTS.

A higher field warm magnet (7.25 T, 20 K), with coils made from ASC BSCCO 2223 tapes, has been designed and successfully tested in the Naval Research Laboratory of Washington.

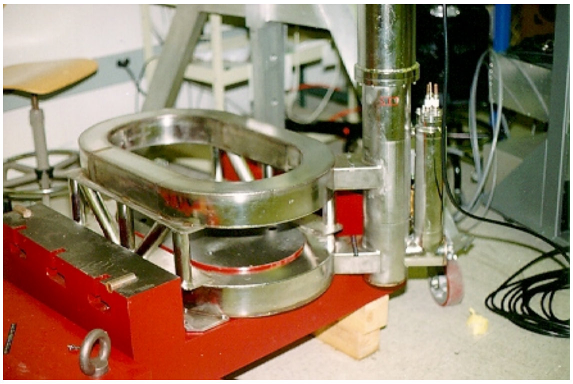

Figure 3: HTS coils (courtesy of ASC)

4 HTS CURRENT LEADS

In all the applications presented above, the HTS is required to have high critical current density and good mechanical properties. Mechanical stress in magnet coils applications comes from winding, pre-load during assembly, Lorenz forces and thermal stresses in operating conditions. In addition, homogeneity of the electrical and mechanical properties has to be guaranteed over long lengths of material as well as electrical insulation of the conductor. For current lead applications the HTS requirements are much less stringent: short lengths of bare conductor are assembled in a simple straight geometrical configuration which takes into account the anisotropy of the material by minimising the field experienced in the direction perpendicular to the plane of the tape. The silver alloy matrix of the BSCCO 2223 tapes is doped with gold to reduce the thermal conductivity of the conductor.

Low-current HTS samples with conduction-cooled resistive upper section also find an immediate application in systems where the refrigeration is provided by cryocoolers offering intermediate stages of heat intercept. For large scale accelerator systems, the design of HTS current leads has to be integrated in the infrastructures of the cryogenic system.

5 HTS CURRENT LEADS FOR THE LHC

The LHC will require the transfer of about 3.4 MA of current for powering the superconducting magnets operating at superfluid helium temperature. A big fraction of this current, 24 %, is represented by leads feeding the main dipole and quadrupole magnets (13000 A), 54 % by leads for the insertion magnets (3500 A-7500 A), 17 % by leads for sextupole correctors (600 A) and the remaining 5 % by leads for dipole correctors (60 A - 120 A). With the exception of the dipole correctors, all the other magnets will be powered with HTS current leads. Prior to starting the design of the LHC leads, a study has been made [10] to evaluate the exergetic costs of different cooling methods offered by the already well defined infrastructure of the LHC machine and the potential saving in liquefaction power. The most convenient solution, now adopted for all the HTS leads, has shown to consist in cooling the resistive heat exchanger with 20 K/0.13 MPa helium gas, recovered from the beam screen cooling line, while the HTS element operates in self-cooling conditions between an intermediate temperature (T_{HTS}), depending from the flow and the design of the resistive part, and the 4.5 K liquid helium bath. The estimated saving in total cooling power with respect to conventional self-cooled leads, now confirmed by tests on 13 kA and 600 A prototypes, corresponds to about 30 %, while the heat load into the liquid helium is reduced by a factor greater than 10. The availability of 20 K helium gas allows to operate the upper end of the HTS section at about 50 K, a temperature at which the electrical performance is such as to permit a compact design - an extremely important feature in view of the large number of leads to be installed in the existing and limited infrastructure of the LEP tunnel. After an initial R&D program devoted to test of high currents HTS elements, technical specifications defining the geometrical limitations and the thermo-electrical performances of 13 kA and 600 A leads were sent out to interested companies world-wide. Prototypes including different types of HTS have been manufactured and delivered to CERN. Intensive tests have been performed at CERN to characterise these prototype leads.

5.1 HTS materials tested

Thanks to the less stringent requirements for leads with respect to magnet applications, different type of materials can be envisaged for current lead design. Materials tested in 13000 A prototypes were BSCCO 2223 Ag/Au tapes (BICC, NST, Sumitomo, ASC), DIP coated BSCCO 2212 (OST), MCP BSCCO 2212 (Alcatel Superconductors), AFM BSCCO 2223 (Cesi) and MT YBCO 123 (Haldor Topsoe). In addition, BSCCO 2212 LFZ fibers (University of Zaragoza) and CCG YBCO 123 (ATZ) rods are proposed for tests in 600 A leads.

5.2 Test results

Tests performed up to now on nine pairs of 13 kA and six assemblies of four 600 A HTS prototype leads have confirmed the specified performances. The heat load measured at 4.5 K is less than 0.11 W/kA with a 20 K cooling flow of the order of 0.055 g/s·kA. The design of the lead is such that the warm end of the HTS operates at about 50 K, which corresponds to an optimum in terms of exergetic consumption [11]. In Fig. 4 are represented the theoretical and measured flows necessary for cooling the resistive heat exchanger and the heat load at 4.5 K for 13 kA leads as a function of the warm end temperature of the HTS. The black line indicates the theoretical minimum flow required for operating a 13 kA lead at a given value of T_{HTS} (optimised conditions). A lead optimised for 50 K operation (m ~ 0.7 g/s) can run with T_{HTS} = 40 K by overcooling the resistive heat exchanger with respect to the optimum flow.

To avoid failure during operation, the design of the HTS leads requires that, in case of resistive transition of the HTS, the element is still able to discharge the magnet or magnets chain at its nominal current decay rate. This condition is particularly severe for the leads powering the main dipoles chain, where an inductance of the circuit of about 15 H gives a time constant of the order of 120 s. Tests on several prototypes have proved that such a requirement can be satisfied without compromising the thermal performance of the leads [12].

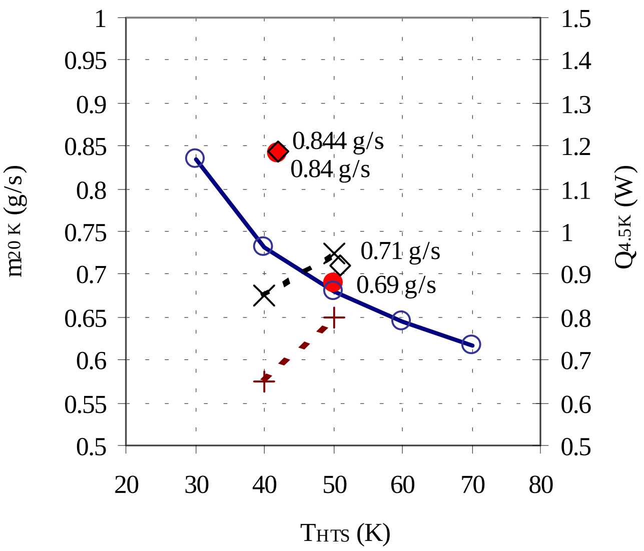

Figure 4: Calculated (-○) and measured (-●, -◇) 20 K helium flow and measured heat load at 4.5 K (-×, -+) on two 13000 A prototype leads, operating at nominal current, as a function of the temperature at the warm end of the HTS

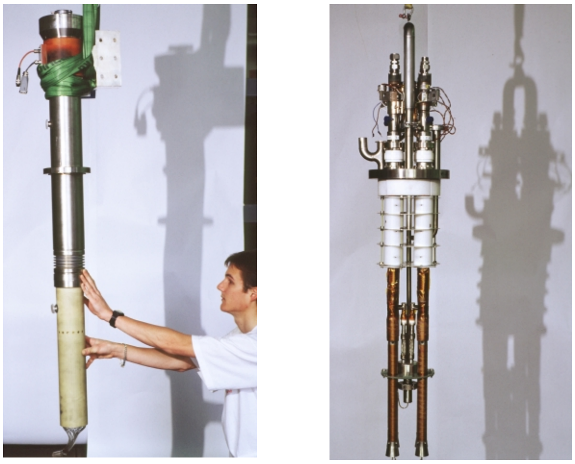

Figure 5: 13000 A prototype and 4×600 A leads assembly

The measurements have confirmed the capability of the commercially available HTS to transport the currents required for the powering of the LHC, the main difficulty coming from the complexity of the engineering design of the complete lead assembly, especially for high current ratings. High efficiency of the conventional resistive heat exchanger, low contact resistance both in the resistive and in the superconducting sections, adequate sealing at the interface between the HTS and the resistive part and high electrical insulation voltage in helium gas atmosphere (3.1 kV for 13000 A and 1.5 kV for 600 A leads) are key parameters for a successful lead design.

5.3 Cost analysis benefit

Savings in operational costs due to the use of HTS current leads can be estimated by considering for the LHC, as for LEP, 200 days (4800 hours) of scheduled operation per year. Taking into account an efficiency of about 60 %, the leads will be powered about 2880 hours per year and will operate in stand-by conditions in the remaining time. The lifetime of the LHC is expected to be about 20 years, but for the purpose of such estimations the operation lifetime is taken to be 10 years. Considering a cost of electricity of 60 CHF/MWh [13] and an efficiency of the LHC refrigerators corresponding to 30 % of the Carnot cycle, the operational costs of conventional self cooled leads would amount to about 11 MCHF. The saving in these costs due to the use of HTSC leads corresponds to about 7.4 MCHF.

In addition, the eight 18 kW @ 4.5 K refrigerators foreseen for the LHC, which already constitutes the largest cryogenic system in the world, would not be sufficient if the powering of the magnets was provided by conventional self-cooled leads. The capital cost of an additional refrigerator having a capacity at 4.5 K for cooling all resistive leads would amount to several MCHF [14].

Thanks to our development programme it has been demonstrated that the use of HTS for the leads is feasible for the LHC, and it is confidently expected that the additional cost with respect to conventional vapour-cooled leads will be modest, and in any case far less than that expected from the long term savings.

5.4 Status of LHC current lead project

The design, specification and ordering of the current leads are progressing to meet the LHC deadline which expects to have the installation completed in the year 2005. Series production of 600 A, 6000 A and 13 kA current leads will be launched in the coming year. Six 13 kA and seven assemblies of four 600 A of the recently tested prototype leads will be installed in the String 2000 magnets test station where they will undergo an important number of electrical and thermal cycles.

A collaboration has been established between CERN and the Nuclear Physics RRC Kurchatov Institute for investigation on radiation resistance of HTS materials, used in current leads, irradiated by fast neutrons at different intermediate temperatures.

6 CONCLUSION

Important progress has been made in the last years in the field of the high temperature superconductivity. Thanks to the continuous improvement of the new oxide material properties, some prototypes for special applications have been built and designs for high field magnets are already being studied. A first application for accelerator technology is represented by the current leads of the LHC, which will give a unique opportunity to demonstrate the value of incorporating HTS materials into a large scale system. An important effort still needs to be made before the performance, cost and commercial availability of these materials will be such as to convince accelerator scientists and engineers to replace the well known low temperature superconducting material. However, taking into account that it may be 10 years before a future large accelerator is approved for construction, and with the expectation that continued progress will occur in the mechanical and electrical performance of the HTS based material, with an attendant reduction in the (presently prohibitive) price of the material, the present R&D effort on magnets using these materials is certainly worthwhile.

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