PROSPECTS FOR THE USE OF HTS IN HIGH FIELD MAGNETS FOR FUTURE ACCELERATOR FACILITIES

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Abstract

The enthusiasm that followed the discovery of High Temperature Superconductors (HTS) and the hope that they could replace Low Temperature Superconductors (LTS) was damped by low current-carrying capacity, short piece lengths, and fragility of the brittle oxide materials. Development of applications was mainly on devices less demanding of conductor performance. However, with continuing development, progress was made with the cuprate superconductors, and long lengths of BSCCO 2223 and REBCO tape conductors are now commercially available. Progress has also been made in the development of BSSCO 2212 round wire, where implementation of a new production process has led to a breakthrough in performance.

Though still at the research level, attainments in material synthesis and theoretical understanding of iron-based materials may lead to their development into practical superconductors, featuring high upper critical field and low anisotropy.

A review of the potential of HTS as applied to accelerators is presented, with a focus on using the presently available materials and on the perceived needs for further development.

INTRODUCTION

Accelerators to date have relied on high field magnets made with high current density (~ 3000 A/mm^2 at 5 T) Nb-Ti superconductor operated at liquid and superfluid helium temperatures. This conductor meets performance parameters for high-field accelerator dipoles, which include current density, piece length, effective filament size, mechanical strength and cost. The Large Hadron Collider (LHC) contains about 1200 tons of high performance Nb47Ti conductor, and it represents the largest application of superconductivity for High Energy Physics (HEP) after the Tevatron, HERA and RHIC. The upper critical field of Nb-Ti ($\mu_0 H_{c2}$~14.4 T) limits its application to magnets operated at fields of up to about 10 T.

Nb_3Sn conductor ($\mu_0 H_{c2}$ up to 28 T-30 T) can cover operation over a wider range of field. As Nb-Ti, it is a multi-filamentary wire in a metallic matrix, and its state of development is such that accelerator quality magnets are being developed for integration in the LHC machine for the Hi-Luminosity upgrade [1]. The ITER fusion program has pushed development of Nb_3Sn wire toward large scale production (~ 600 t) of high quality conductor with homogenous and controlled properties [2]. It should be noted that technical requirements for accelerator magnets are more demanding than for fusion technology, and critical current densities (J_c) of Nb_3Sn wires required for the LHC Hi-Luminosity upgrade (~ 2450 A/mm^2 at 12 T) are more than double of those specified for the ITER project (~ 985 A/mm^2 at 12 T) [2]. Intrinsic characteristics of Nb_3Sn and effective magnet designs indicate magnet fields of about 16 T as the saturation limit of the Nb_3Sn accelerator dipoles [3].

High Temperature Superconducting materials open the door to magnets producing fields beyond the reach of Nb-Ti and Nb_3Sn. The high critical temperature (T_c) and magnetic field of the cuprate superconductors are not enough to enable high field applications at higher temperatures: current-carrying capacity deteriorates rapidly with increasing temperature and field. Differently from LTS, the irreversibility field ($\mu_0 H_{irr}$) of cuprate materials, which is the field above which flux pinning becomes ineffective and moving of flux lines causes dissipation, is much lower than their upper critical field. Mainly because of the large anisotropy, the value of $\mu_0 H_{irr}$ at 77 K, at which J_c vanishes, is as low as 0.3 T for BSCCO 2223 and about 7 T for REBCO (a more general acronym for YBCO, where RE = Rare Earth).

High field magnets benefit from the unique properties of HTS conductors at low temperature, and the design of accelerator magnets, which includes cost analysis aspects, must be based today on operation with liquid helium cryogenics and on graded coils concepts [3]: Nb-Ti and Nb_3Sn are used in their respective maximum range of field operation, and a HTS insert produces the boost in field required to exceed the 16 T limit.

Properties of superconductors define the achievable performance target of magnets and impact to a great extent on field quality. The performance of HTS materials has now reached a level where realistic coils providing enhancement of field can be designed, and activity focusing on the understanding of technological issues associated with magnet assembly and test can be pursued. However, it should be borne in mind that continuous improvement in performance of available materials and progress on new superconductors in the next decade are essential for the future of the high field and eventually higher temperature applications, and yet-to-come achievements may replace the choices that can be made today on the basis of available state-of-the-art conductors.

HTS CONDUCTORS

BSCCO 2223, BSCCO 2212 and REBCO cuprate superconductors are manufactured in long lengths. They have as a common feature a complex layered crystal

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structure with CuO_2 sheets, which define the a-b planes with the c-axis perpendicular to the sheets, intercalated by rare earth elements and insulating metal oxide layers. This layered structure is responsible for a large anisotropy in physical properties. Superconductivity takes place in the CuO_2 planes. Perpendicular to these planes, i.e. parallel to the c-axis, it is very difficult to achieve a good conductivity, and critical current is anisotropic in its dependence on magnetic field. This anisotropy must be taken into account in the design and optimization of HTS magnets and devices, and it introduces challenges and boundary conditions that are new with respect to conventional LTS. The physics of HTS materials at 4.2 K is different from that at higher temperatures and properties such as critical current and its field dependence at 4.2 K cannot be extrapolated reliably from measurements at 77 K. From this point of view, the HTS community working on high field magnets has specification and test requirements that differ from those of most of the other HTS users – and companies producing HTS conductor have until now invested mainly in material development and characterization at liquid nitrogen temperature.

Another common feature of HTS cuprates is their nature of being brittle ceramics. This characteristic adds complexity in developing flexible conductors with mechanical properties that can make them suitable for assembly into cables and for winding into magnet coils.

BSCCO 2223 and REBCO conductors with good electro-mechanical properties are only available, today, in the form of tape. BSCCO 2223 requires uniaxial texturing to limit current blocking effects due to randomly oriented grain boundaries. The tape, which is produced via Powder In Tube (PIT) technology, is 4 to 4.3 mm wide and 0.2 to 0.23 mm thick; it has a silver alloy matrix that contains the superconducting filaments, and metallic laminations for reinforcement of mechanical properties and/or addition of metallic stabilizer can be incorporated. A great advantage of BSCCO 2223 conductor is its commercial availability in kilometre lengths with guaranteed quality control of properties [4]. Electrical joining techniques are well developed, and experience from long term operation of this material is based on its use in electrical devices such as long distance power transmission lines and low-loss HTS currents leads. In the LHC machine about 200 kg of multi-filamentary BSCCO 2223 Ag-Au tape are incorporated in the current leads that feed magnets operating at currents ranging from 550 A to 11800 A [5]. Today BSCCO 2223 has not yet achieved its full potential in performance, and critical current of BSCCO 2223 tape is lower than that of REBCO and BSCCO 2212 conductors (see Fig. 1).

REBCO is produced via a complex coated conductor technology, which enables deposition of a bi-axially aligned, presently 1 to 3 μm thick, superconducting film onto a ~ 50 μm thick high strength metallic substrate [6]. The REBCO film is protected by a silver layer, and metal stabilizer is added by either electro-deposition of copper, some tens of microns thick, around the tape or by the soldering of copper strips. Intermediate layers between the substrate and the superconductor provide the chemical barrier and a textured surface necessary for the deposition of the superconductor. The strong bi-axial texture obtained in the REBCO film with the coated conductor technology helps to overcome limitations due to grain boundaries, and high values of J_c are obtained in commercial tapes: REBCO is to date the superconductor with the highest critical current density (see Fig. 1) and is commercially available in lengths of some hundreds of metres. Artificial pinning centres such as nano-precipitates, nano-clusters and nano-rods have been introduced into REBCO films, and significant enhancement of in-field performance has been measured. The inclusion of $BaZrO_3$ (BZO, barium zirconate) nanoparticles has emerged as being one of the most effective techniques for improving the performance of REBCO tape both in terms of I_c in-field performance and angular I_c anisotropy [6]. Possible routes for reaching higher J_c in high fields are increase of thickness of the superconducting film and improvement of pinning composition. REBCO tape is usually produced in widths of 12 mm, which can be then split in smaller widths of typically 4 mm. The thickness of the tape is about 0.1 mm, the superconductor occupying about 1% of the total cross section. The strong anisotropy in the tape cross section, which has the thin superconducting layer deposited onto a much thicker resistive metallic (Ni-W, Hastelloy C or stainless steel) substrate, imposes constraints on the conductor disposition in multi-tape assemblies and on the optimization of electrical joints, current transfer through the substrate meeting with a non-negligible resistance.

BSCCO-2212 is the only cuprate that exists in the form of multi-filamentary round wire. It is produced with the PIT technology in diameters of 1 mm or less. The superconducting filaments, which are contained in a silver alloy matrix, consist of BSCCO 2212 powder that is melted during an optimized heat treatment performed at high temperature (~ 900 °C) in an oxygen atmosphere. A significant recent breakthrough [7] [8] has been the identification of a current limiting mechanism – in the previous generation of wires – due to formation of bubbles during melting of the BSCCO 2212 powder, and the adoption of an over-pressure heat treatment (up to 100 bar) to prevent bubble formation and de-densification driven by internal gas pressure [7]. This progress has led to the achievement of record in-field critical currents for BSCCO 2212 at 4.2 K.

The newer MgB_2 conductor is now produced in bulk, thin film, tape, and wire geometry. The conductor is very interesting because of its simple structure, low anisotropy, transparency of grain boundaries to current flow, and simple PIT manufacturing process that enables production of long (kilometres) lengths of tape and wire at potentially low cost. Great progress was recently made with the development of round wires, having electrical and mechanical properties – after reaction – suitable for assembling into high - current cables, and with the

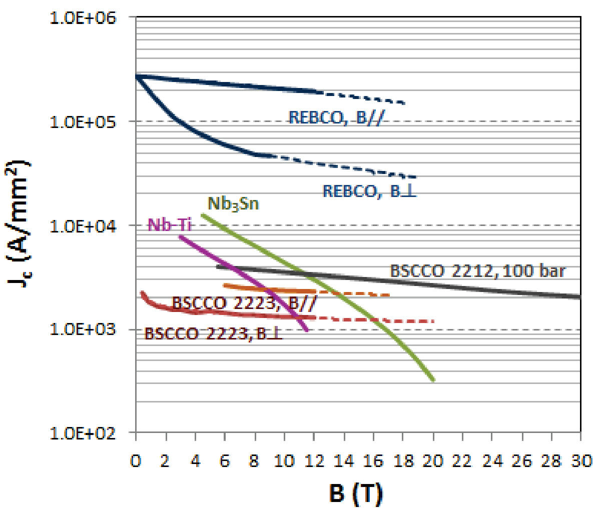

Figure 1: Critical current density (Jc) of superconductors in parallel (B//) and perpendicular (B⊥) magnetic field (B). Values for BSCCO 2212 are from [7], BSCCO 2223, REBCO and Nb_3Sn curves are from measurements at 4.2 K performed at CERN on commercial materials. The LHC Nb-Ti curve is at 1.9 K.

measurement of a record current in a 40 m long MgB_2 superconducting line operated at 20 kA and at 24 K [9] [10]. While this project demonstrated the feasibility of reaching high-currents in MgB_2 cables operated in low-fields (≤ 1T) and higher temperatures that do not require liquid helium cooling, operation in high fields is still limited by low μ_0H_{irr} - at 4.2 K it is about 7 T, lower than Nb-Ti. Increasing μ_0H_{irr} in MgB_2 wire (μ_0H_{c2} of 29 T and 49 T have been measured respectively in un-textured bulk poly-crystals and in thin films [11]) could lead to the development of a competitive and low-cost conductor for high-field magnet applications.

Since the discovery of iron-based superconductors (FBSs), studies on development of these families of materials were undertaken because of their very high μ_0H_{c2} (varying from 60 T up to about 300 T depending on the superconducting family and on the field orientation [12]), and their relatively high T_c (~ 55 K). Short lengths of tape and wire have been produced for the purpose of studying and understanding the physical properties of the materials. The work is presently being done by laboratories and institutes at the research level, and industry is not yet involved in production.

The discovery of MgB_2 came in 2001 and that of FBSs in 2008. The cuprate materials required more than fifteen years to become the industrial products available today, and their performance is still improving significantly year-by-year, twenty-eight years after the discovery of high temperature superconductivity. Focused development of superconducting tapes and wires from these more recent materials can gradually increase possibilities for their practical use. The intrinsic characteristics of MgB_2 and FBSs superconductors give hope for their potential suitability for future high field magnet applications.

HTS CONDUCTOR FOR HIGH-FIELD MAGNETS

High-field dipole magnets require high current density across the total superconductor cross section (J_e). To limit stored energy and voltage generated during magnet discharge, cables operating at high (~ 10 kA) currents are needed. Rutherford cables with high compaction factor were developed for Nb-Ti magnets and used in all superconducting accelerators constructed until today. A great deal of study and experimental work together with extensive experience accumulated over the years have defined the main ingredients that are the input for producing cables for HEP high field magnets: high compactness, full transposition, dimensional accuracy, controlled inter-strand resistance to limit coupling between strands, and small (~6 µm) twisted superconducting filaments inside the wire to reduce magnetization and field errors in the low-field region. In addition, the mechanical strength of cables, which is given by both strand and cable characteristics, must be such as to withstand the high stresses (~ 150 MPa for $\cos\vartheta$ magnets) applied during magnet assembly and operation, and assure controlled and precise position of the cable and of the strands in the coil during winding.

Conductor for production of prototype HTS high field coils must be available in unit lengths of at least 100 m - large magnet production would require about 1 km - and with an engineering current density (J_e) of at least 400 A/mm^2 at 4.2 K. This is now the case for both REBCO and BSCCO 2212 conductor at about 20 T. BSCCO 2212 multi-filamentary round wire can be assembled into Rutherford cables [13] and it can profit from know-how developed for conventional LTS. However, it requires a Wind-and-React (W&R) technology that, on the basis of the present development work done on wires, necessitates high-pressure heat treatment of the coils in oxygen atmosphere [7]. REBCO conductor exists only in the form of tape. Today it has better mechanical properties than BSCCO 2212 thanks to its strong metallic substrate, but it has a very large bending radius in the plane of the tape. The only cable geometry identified today as meeting compaction and transposition requirements for application to HEP high field magnets is the Roebel cable. This geometry was first developed in 1912 for use in resistive generators, it has been adopted since 1940 in conventional transformers, and proposed in recent years for REBCO cables [14] [15]. The idea is to cut a meander-type conductor from a 12 mm wide REBCO tape, and assemble several meander tapes to obtain a transposed cable with typical transposition pitches of 100 mm - 300 mm. A few cables have been measured at 4.2 K, and the in-field current capability demonstrated [16] [17]. Development work is on-going to verify suitability for winding.

REBCO tape is like a “wide mono-filament” wire, where the filament is the superconducting film above the substrate. With that geometry, and in view of the large J_c of the superconductor, persistent currents at low fields are important. This consideration has to be taken into account in the design of the magnet as well as the anisotropy of the tape and the effect of current distribution across the tape width.

THE CHALLENGE OF USING HTS IN MAGNET WINDINGS

HTS conductors with sufficient current carrying capacity in strong magnetic fields are now available, but their geometric, electrical and mechanical characteristics call for new approaches in their application to magnets. So far, experience with HTS magnets is limited.

REBCO and BSCCO 2223 windings have been made with single tapes. High field HTS solenoid inserts are in an advanced stage of development. For example, construction of a 32 T solenoid consisting of a 15 T LTS outer magnet and a 17 T insert REBCO coil is underway at the NHMFL [18], where also coils made from BSCCO 2212 round wire have been tested in the background field of resistive magnets [19]. About 100 rectangular windings, using BSCCO 2223 and REBCO tape material, have been produced for the low-field magnets designed for the Facility for Rare Isotope Beams (FRIB) [20]. These magnets are operated in helium gas at up to 50 K and at currents below 500 A, and for this application HTS offers the possibility of accommodating high heat loads.

Solenoids are by far the easiest type of coil to wind, and it is with solenoids that there is the best experience in making high field magnets using superconductor of any type. For accelerator technology, by combining HTS insert windings with Nb_3Sn and Nb-Ti outserts, it is reasonable to envisage 25 T to 30 T magnets [21], thus extending the range for which solenoid focusing can be used. The constraints on field quality and alignment for solenoids are lighter than for quadrupoles [22]. Unfortunately the focusing power of a solenoid is proportional to (field / beam momentum)^2, so while the higher field allows effective focusing for higher energy beams, very high energy machines must use quadrupoles.

REBCO conductor enables the adoption of the React-and-Wind (R&W) technology. The strong anisotropy of the tape has to be dealt with in the magnet design. Magnet coils wound from high-current REBCO cables have not yet been made.

Work on insert coils for HEP accelerators is presently concentrated on dipoles. The FP7-Eucard 2 high field magnet program aims at developing 10 kA range REBCO cables to be used in a 40 mm bore, accelerator quality, dipole insert. This insert is designed to generate 5 T in a background field of 15 T. Roebel cables with 5 kA to 10 kA current-carrying capacity in high field are being optimized for this purpose, and an innovative “aligned block coil” design has been proposed for the insert [23]. The design deals with the high anisotropy of the REBCO conductor by aligning the background field generated by the LTS dipole in the favourable direction for the conductor, i.e. parallel to the tape plane, in the straight section of the coil, with the ends of the coils flared at an angle of a few degrees [23]. In the framework of the FP7-Eucard 1 high field magnet program, a REBCO insert to be tested at CERN inside the FRESCA 2, 13 T and 100 mm bore Nb_3Sn dipole magnet [24] – in phase of construction within the same framework collaboration – is being assembled at CEA-Saclay [25]. The insert uses a cable made from stacked wide tapes, transposed at the ends of the magnet during the winding operation.

BSCCO 2212 round wires have been assembled in Rutherford cables, and small pancake coils have been wound using the W&R technology and tested [13].Possibility of applying high pressure on cables in coils during heat treatment, as done on high Jc wires [7], still has to be verified.

From the point of view of magnetic optimization, the isotropic nature of the BSCCO 2212 does permit the adoption of the cosϑ magnet geometry. But for high field HTS coils, stress management is crucial to the design. While combining coils of rectangular cross-section in the so-called block designs are less efficient in their use of superconductor, they provide an easier route to stress management, and for this reason they are probably more appropriate for high field HTS windings.

An alternative way of producing a dipole or quadrupole field in a circular aperture with access through the ends is by using a concentric combination of canted solenoids where the solenoidal component of the field is cancelled. This approach is currently being studied at LBL [26]. The conductor is inserted into grooves that are machined onto a stainless steel cylinder. Besides locating the conductor, the walls of the grooves provide good mechanical support, limiting stress in the windings. A proposal for such a type of magnet with a LTS outsert and a BSCCO 2212 insert is being studied at LBL [26].

Electrical insulation techniques for REBCO and BSCCO 2212 windings must be different. W&R technology can use conventional insulation methods developed for Nb-Ti superconductor, why R&W technology calls for new materials able to withstand high temperatures during the heat treatment in oxygen atmosphere.

Quench protection of HTS coils has to deal with slow quench propagation in HTS conductor. This brings in new challenges for the protection of HTS magnets related to both timely detection of the transition and fast propagation of the resistive zone. It could be possible to use quench heaters for the latter, but other methods of heating the winding may be more effective for fast discharge and limiting overheating in the HTS coils. In past studies for a superconducting switch using REBCO tape [27], methods based on pulsed overcurrent and high frequency excitation of eddy currents were proposed and tested [28]. The application of a similar approach to rapid distribution of quench in LTS magnets has been studied in detail and validated [29]. The high frequency excitation is provided by the oscillation of the LC circuit formed by the discharging capacitor and the inductance of the magnet winding.

Besides the high field dipole and quadrupole magnets required for future HEP accelerator facilities, there are several other applications that would benefit from the use of HTS. These include HTS current leads (BSCCO 2223 or REBCO), superconducting links connecting the power converters to the magnet circuits [10] and, in regions with high energy deposition, HTS windings, possibly with stainless steel insulation, operated with a generous temperature margin.

CONCLUSIONS

Significant progress has been made in the past years on the development of both BSCCO and REBCO conductors, and electrical performance of these materials has now reached the level required for application to high field magnets.

Experience with coil winding is still limited. It is based on the use of single REBCO or BSCCO 2223 tape, and only a few pancake coils made from BSCCO 2212 Rutherford cables have been assembled and tested.

REBCO and BSCCO conductors have different electrical and mechanical properties, and this implies that different cable types, magnet concepts and magnet technologies must be adopted for best use of material characteristics. REBCO is a tape with high mechanical strength and high J_c, and it can be wound after reaction, BSCCO 2212 is a round wire that can be used in Rutherford cables, but it requires reaction after winding.

The tape conductor is well-adapted for use in solenoids, and fields above 30 T have already been achieved. Roebel REBCO cable with high J_e is considered today a viable option for assembly of short prototype coils, but cost considerations call for further development and new cable concepts that can limit the amount of material wasted during tape shaping into the required geometry.

The use of HTS requires that a significant and focused effort is made on the understanding and characterization of strands and cables in operating condition, as was done for the Nb-Ti Rutherford cables for HEP.

At present, windings based on Rutherford cable made from multi-filamentary BSCCO 2212 wire and Roebel cable made from REBCO tape, in respectively Wind-and-React and React-and-Wind technologies, are being developed, and experience from this work will be an important learning phase. Technologically challenging issues related to management of forces, quench protection and field quality have to be addressed specifically for each type of HTS material and coil configuration.

For high fields, due to the cost of present conductors the effort is concentrated on producing HTS coil inserts to enhance the field produced by external windings of low temperature superconductors (Nb-Ti and Nb_3Sn). The long slender geometry with tight bending radii at the ends imposes formidable constraints on the use of presently available HTS material in high field accelerator magnets.

For some low-field superferric magnets, MgB_2 can already today be a competitor of standard Nb-Ti. The potential of MgB_2 and iron-based superconductors for use in high field applications is such as to deserve a dedicated and vigorous R&D effort.

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