NEXANS ACTIVITIES AND PLANS ON HTS MATERIALS. HIGH-PERFORMANCE BI2212 TAPE AND BULK CONDUCTORS FOR MAGNET TECHNOLOGY.

J. Bock, F. Breuer, C.-E. Bruzek, N. Lallouet*, M.O. Rikel and H. Walter*
Nexans SuperConductors GmbH (Hürth, Germany), * Nexans (Jeumont, France)

Abstract

Nexans activities on HTS materials are briefly reviewed with the emphasis on materials for magnet technology–Bi2212 bulk conductors for current leads, the first commercial application of HTS materials in electrical engineering; and long-length Ag-sheathed Bi2212 tape conductors for high magnetic field applications at low temperatures, the material that only recently has proven to be technologically competitive to other high-field superconductors. Recent advances of Nexans: fabrication of kilometre lengths of reinforced multifilamentary Bi2212 tapes with excellent engineering critical current densities of Je(4.2 K, sf) = 1200 A/mm2; Je(4.2 K, 20T) = 510 A/mm2 (parallel field) and 380 A/mm2 (perpendicular field) and Je(20 K, 5 T) = 300 A/mm2 (parallel field) and 170 A/mm2 (perpendicular field).

1. INTRODUCTION

Commercialisation of high-temperature superconductors (HTS) is on agenda since end of 1990s [1]. Though the price-to-performance goals formulated at that time are not fully met, the progress in materials development [2], an increased number of running projects on prototype demonstrator devices with continuously growing participation of industry [3] clearly shows that real commercialisation is not a very far future.

As one of the world biggest cable manufacturers, Nexans (former Cable and Components sector of Alcatel separated in 2001) has a clear strategy on utilization of HTS materials in the energy sector. The main focus is on the development of superconducting cables for transmission and distribution. Nexans is the major manufacturer of a 660-m long superconducting cable to be installed at the Long-Island Power Authority in early 2006 (the DOE funded LIPA project headed by AmSC, a supplier of Bi2223 tape conductors [4, 5]). Nexans coordinates an EU-funded project Super3C that aimed at development and fabrication of a 30-m long 1-phase cable completely based on the YBCO coated conductors [6]. These activities are carried out at Nexans cable plant at Hannover in close collaboration with Nexans competence centres in Almaden (Norway) and Kale (France).

Development of conductors for cables is another activity of Nexans. First-generation BSCCO wires are manufactured at Nexans cable plant in Jeumont (France) using precursor materials produced by Nexans SuperConductors (Hürth, Germany) [7, 8]. Assembled Bi2212 tape conductors is Nexans contribution to a 800 kJ SMES project [9] funded by Délégation Générale pour l'Armement. Nexans also develops all-chemical route for second-generation ReBCO coated conductors [10].

Continuing production of raw HTS materials, Nexans SuperConductors more and more focuses on development of components that can be easily integrated in the real systems. Nexans YBCO monodomain bulk materials are widely used in levitation devices [11]. Nexans is currently involved as a supplier of complete superconducting bearing for a 4 MVA superconductor motor project headed by Siemens [12].

this example, is an absorber held at a higher temperature than the coil to minimize the refrigeration cost. Clearly, this will be a very difficult magnet, with regard to achieving field strength as well as field quality. The gap height is a key parameter: the smaller the gap the more straightforward it is to achieve field strength and field quality, but the higher the energy deposition in the coil from the forward-going collision debris. The required height of the gap must take into account the width of the forward cone of collision debris, the divergence of the beam, and alignment and orbit errors. It may be advantageous to include some sort of low-mass "bridge" between the upper and lower coils, which could reduced deflections under the magnetic forces, but not initiate full hadronic showers.

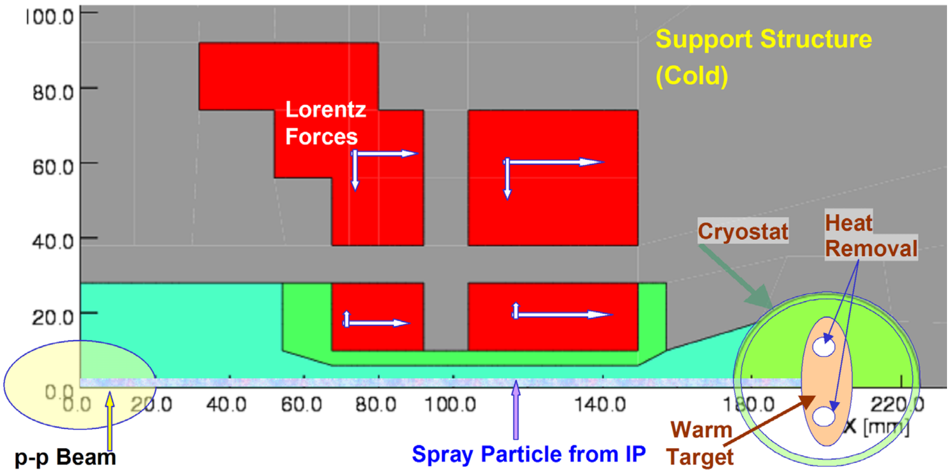

Fig. 6 Design concept for a 15 T dipole with block-type coils and an open mid-plane..

While Nb_3Sn offers a clear and promising path to the magnet parameters required for a luminosity upgrade of the LHC, this is far from a mature technology. Thus technology development will be a crucial aspect of the US LARP magnet R&D program. Among the issues that must be addressed are the superconductor itself, where achieving high J_c with small effective filament size and good strain tolerance remains a challenge, cabling, coil winding and reaction procedures, conductor-friendly coil and support structure designs, and radiation hard materials for coil impregnation and support structures. An important tool for technology development is the so-called "sub-scale" model program[8], which utilizes small racetrack coils, about 15 cm long, assembled in pairs in a "common coil" geometry as shown in Fig. 7. These allow relatively inexpensive and quick tests of various superconductor, fabrication, material, and instrumentation issues.

Over the next one to two years the top priorities of the US LARP magnet R&D program are to do coordinated magnet conceptual design and accelerator physics studies, to determine the most likely IR upgrade options and the boundary conditions on them, to develop the superconducting cable and other technologies for the new magnets, and to build and test a simplified model quadrupoles and, if possible, dipole. The first model will be a quadrupole, which will be made from two layers of an eventual four-layer magnet, which will most likely be assembled using the "bladder and key" method[9], as shown in Fig. 8. When resources permit, a simplified open mid-plane dipole will be constructed possibly using coils from the HD-1 dipole (see below). Figure 8 shows a cross-section of concept for this magnet[10].

3. US BASE PROGRAM IN HIGH FIELD MAGNET R&D

The US LARP magnet R&D builds on a base program at BNL, FNAL and LBNL in the development of high-field accelerator magnets for future hadron colliders. Indeed, the ambitious goal of US LARP, to develop magnet designs to a production ready state using the difficult Nb_3Sn superconductor, have a good chance to success only because the LARP is supported by the base program.

The Nexans melt-cast centrifugal forming process for bulk Bi2212 is widely used for development and production of current leads, bifilar coils for fault-current limiting devices currently successfully integrated in a 10 kV distribution power grid at Siegen (Germany) [13]. Appreciation of the fact that any superconducting cable should be in future protected by an FCL device enhances the Nexans efforts to develop FCL technology for high-voltage transmission lines. As a supplier of melt-cast tubes Nexans participates in a Matrix FCL project for a 138 kV transmission level (the DOE-funded project headed by IGC Superpower [14]).

In this contribution to WAMS workshop, we present current advances at Nexans on HTS materials for magnet technology: Bi2212 bulk conductors for current leads and long-length Ag-sheathed Bi2212 tape conductors.

2. BULK 2212 FOR CURRENT LEADS

Current leads are the first commercial application of HTS materials in electrical engineering. Nexans focuses on development of Bi2212 bulk current leads using Nexans-patented melt-cast process (MCP) [15]. In this process, Bi2212 with admixture of Sr sulphate is molten in Pt crucibles and then cast either in moulds to produce rod-shaped conductors or centrifugally cast in rotating preheated moulds to produce bulk tubes. In both cases Ag contacts are incorporated during casting. Subsequent heat treatment converts the quenched products in Bi2212 phase (see [15] for details). The process is well established and thanks to the bulk nature of conductivity is characterized by high reproducibility.

Various shapes (rods or tubes) and sizes (up to 60 cm length) are available (Fig. 1a) covering current levels from 0.2 to 20 kA. The corresponding (77 to 4 K) heat leak varies from 10 mW to 2.2 W (Fig. 1b). Note that the large heat leak in case of tube conductors of 200 mm outer diameter is mostly due to their short length (≤100 mm); using three longer (300 mm) tube conductors of 70 mm diameter, it is possible to transfer the same current with three time smaller heat leak.

The basic material properties are summarized in Table 1. The critical current density as function of magnetic field and temperature is shown in detail in Fig. 2.

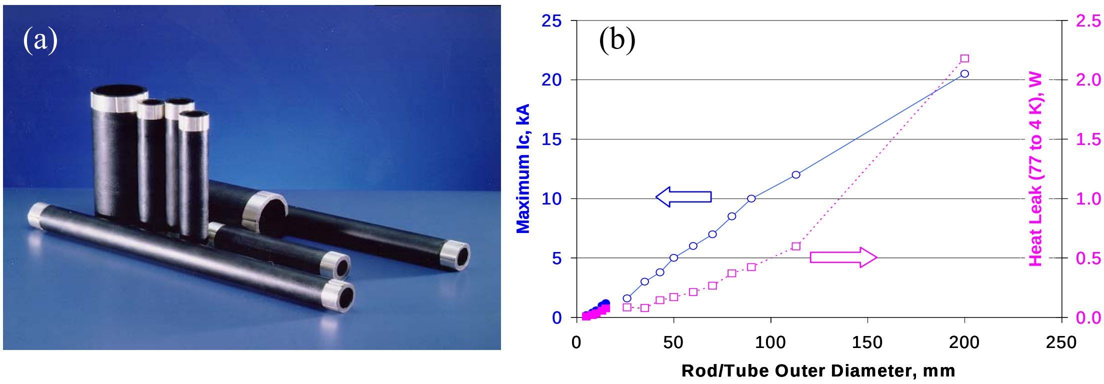

Fig 1. (a) Tubular current leads and (b) maximum I_c (circles) and heat leak (squares) as function of tube (open symbols) or rod (closed symbols) outer diameter. The tube wall thickness can be varied from 3 to 8 mm.

Table 1

Basic properties of MCP Bi2212 current leads

Tc(R=0) K	Jc (sf), kA/cm^2 (a)		Heat conductance @77K	Specific heat @77 K (b)	Contact resistance μΩ·cm²		Thermal expansion K^{-1}	Failure point (c), N	
	77 K	4.2K			77 K	4.2K		5 mm	8 mm
90–92	0.6–2.0	> 10	**< 1 W/m·K**	~120Ws/Kg·K	~2	<0.05	3.5·10^{-6}	~70	~250

(a) mainly limited by self-filed effects; (b) changes with admixture; (c) results of four-point bending tests on rods

Because of almost an order of magnitude higher thermal conductivity at 77K (~70 W/m·K [16]), similar heat leak properties in alloy (AgAu) sheathed Bi2223 tapes are only available in ~100 times longer lengths. This makes Bi2212 bulk current leads much less expensive and at the same time reliable solution for a number of applications. Successful use of Nexans current leads is reported by Oxford Instruments–Research Instruments (Abingdon, UK), ACCEL (Bergisch Gladbach),Intermagnetics (Lathan, NY), Mitsubishi Electric Corp. (Kobe, Japan). Bulk current leads are considered the material of choice for 4.2 K-to-1.8 K current transfer [17].

Note that further optimisation of bulk Bi2212 materials, mainly with respect to their irreversibility field at 77 K is in progress for both current lead and FCL applications.

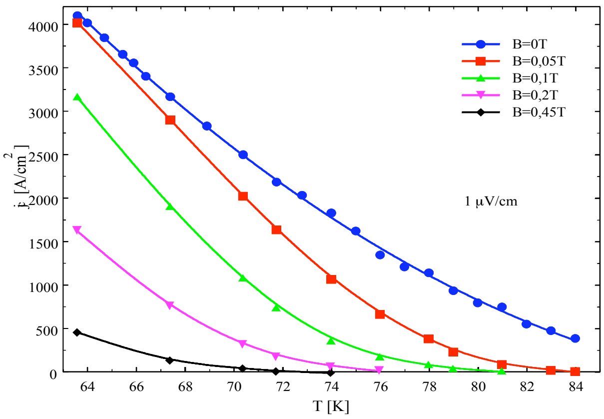

Fig. 2. Temperature dependence of critical current density in 5-mm diameter MCP Bi2212 rods as function of magnetic field.

3. BI2212 TAPE CONDUCTORS

Although BSCCO-based conductors (both 2223 and 2212) did not meet price-to-performance ratio that makes them attractive for a widespread use in transmission cables [2], the low-temperature performance makes them materials of choice for magnet applications at intermediate temperatures and for high magnetic field applications at low temperatures [18]. For magnet applications below 20 K, melt-processed Ag-sheathed Bi2212 tapes and wires appear to be more promising than Bi2223 conductors because of the better performance and the ability to apply Wind & React technology [19-21].

(a)

(b)

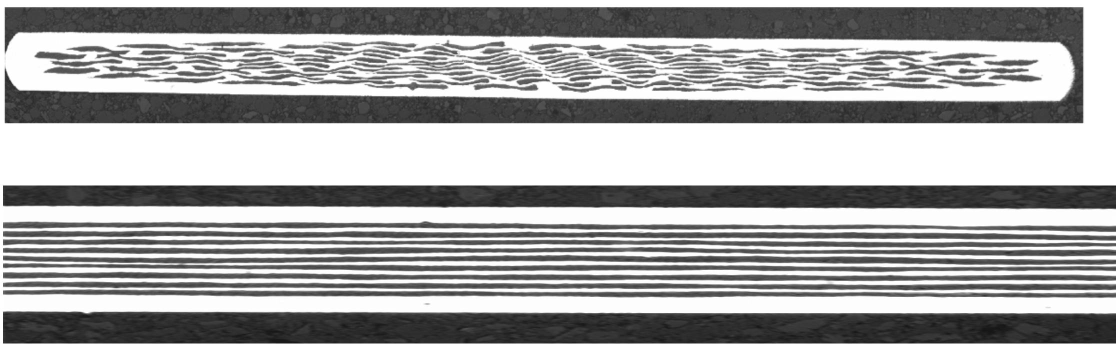

Fig. 3 (a) Transverse and (b) longitudinal cross sections of the as rolled tapes (0.25 x 4.2 mm) with fill factor of 32% AgMg alloy is used as an outer sheath.

Bi2212 conductors at Nexans are developed within a 800kJ SMES demonstrator project. Within this project [9], Nexans has to deliver about 40 km React & Wind multifilamentary tapes with the requirement on the operating current of 100A at 20K in a 5.6 T field parallel and 2.0 T field perpendicular to the tape surface. The first problem addressed was the problem of precursor material. Based on the melt-cast process, we developed precursor specially designed for melt processing OPIT Bi2212 conductors in terms of sharpening melting event and minimizing final phase separation during the melting step. Highly robust and reproducible technology was developed that resulted in conductors with almost twice better performance achieved both at Nexans [7] and Oxford Superconductor Technology (OST) [20]. At OST, Nexans precursor contributed to the successful production of Bi2212 pancake coils for a 5-T insert that reached 25.1 T central field [20].

The 85-filament conductors are prepared via standard OPIT method using pressed Bi2212 precursor rods. Figure 3 shows the geometry of as rolled tape.

In September 2003, we reported our results on optimising tape thickness and heat treatment (maximum processing temperature) in short (10 cm long) and medium (10 m long) samples with the fill factor of 32% [7]. In tapes reinforced with oxidized AgMg alloy that can withstand tensile stresses at 77 K up to 150 MPa and strains up to 0.15% before current degradation, we reproducibly obtained engineering current densities Je (4.2 K, sf) = 940 ± 20 A/mm2, Je (4.2 K, 20 T) = 430 A/mm2 (parallel field), Je (20 K, sf) = 540 A/mm2, Je (20 K, 5T) = 330 and 190 A/mm2 (parallel and perpendicular fields, respectively). We have also shown that 80% short-sample performance can be attained when samples are uniformly distributed over the load of a dummy 1.5-km long tape.

The main advances since then are processing of kilometre tape lengths, further improving conductor performance by increasing the fill factor to 38%, and assembling melt-processed tapes in stranded four-ply conductors reinforced with stainless steel tape to facilitate coil manufacturing.

Using principally the same heat treatment in 100%O2 as reported earlier [7], we melt processed 1.5 km long tape load without any visual bubbling in the piece lengths up to 950 m. Adjusting Tc of the tape to 85–87 K by post annealing, we were able to improve Ic(77 K, sf) of the tape above 10 A and show its 15%.

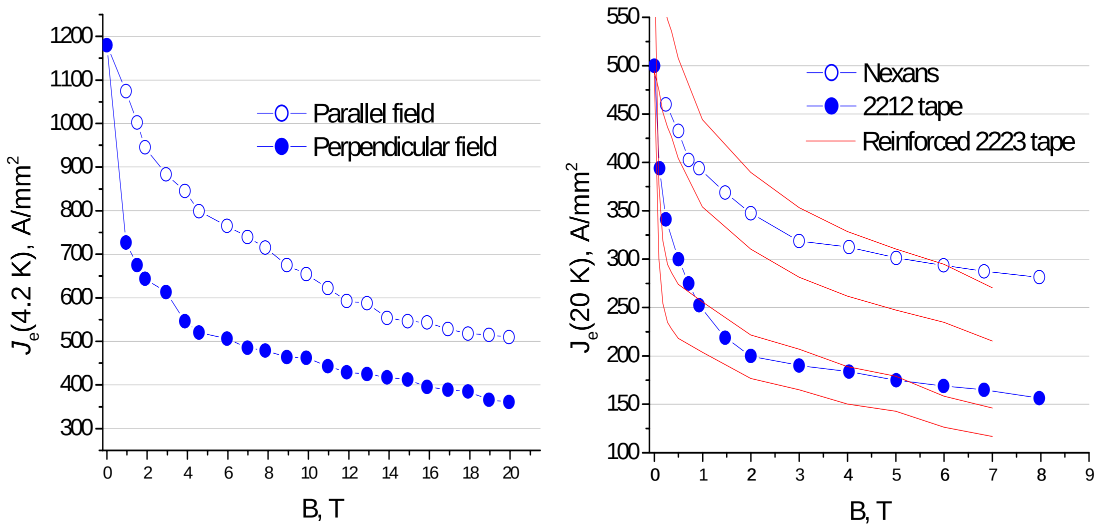

Fig. 4. Field dependence of J_e at (a) 4.2 K and (b) 20 K in magnetic fields parallel and perpendicular to the tape surface. The upper and lower curves for 2223 tape conductors in (b) are calculated from J_e(20K,B)/J_e(77K,sf) data using the J_e(77K,sf) = 113 and 90 A/mm^2 characteristic of reinforced tape made by American Superconductor Corp. [22].

uniformity by continuous Ic measurements. The uniformity of Ic(4.2 K, sf) was found to be better than 3% by measurements on 10 cm-long samples uniformly distributed within the same load.

Increasing the fill factor to 38%, we obtained high-performance tape conductors with average Je (4.2 K, sf) of 1040 A/mm2 (averaging over about 50 samples uniformly distributed over 1.5 km length). The highest Je (4.2 K, sf) = 1230 A/mm2. The self-field performance attained in the kilometre length is about 85% of the world record values [20, 21]. Figure 4 shows the field dependence of Je (4.2 K) for the short (10 cm long) sample. At 20 T, Je (4.2 K) in the perpendicular field is above 77% performance of the one of the best round wire [20]. The n-values are of an order of 15 as in [20].

Performance of Nexans best 2212 tape at 4.2 K is approximately 50% better than that of 2223 conductors available on the market and, as is shown in Fig. 4b, almost coincides with that of the reinforced 2223 tapes at 20 K [22].

4. SUMMARY AND OUTLOOK

In this contribution, we briefly reviewed the Nexans activities on HTS materials and presented in more detail our results on two materials for magnet technology–the melt cast processed Bi2212 bulk current leads that are in our production list since 1995 and melt processed B2212 tapes conductors that are only at the development stage, but already show very high potential to become soon a commercial product.

Production and development of variety of HTS materials requires resources, but gives a real synergy. The advances in 2212 precursor and conductors reported in this paper are a good example of such synergy. Based on the technology of melt cast processing developed for bulk Bi2212 [15] and understanding the difference in requirements on BSCCO precursors for melt processing Bi2212 and Bi2223 conductors [7, 8], we developed a new Bi2212 precursor that has shown excellent performance in OPIT conductors produced at both Nexans and OST. This development has a clear feedback to the melt cast processing of bulk Bi2212 materials. We are currently optimising heat treatment of bulk MCP Bi2212 in order to improve its c-axis conductivity; we anticipate significant improvement in performance of conductors for current leads and components for FCL devices.

Fabrication of high-performance Bi2212 OPIT tape conductors in kilometre lengths reported in this paper clearly shows that they can be considered as real conductors for magnet applications at 4.2–20 K. Note that as in [7], the recent conductors were optimised with respect to their geometry (tape thickness) and maximum processing temperature. It is known that conductor performance strongly depends on solidification conditions; optimisation of these conditions may give further significant improvement [23]. However, even with the achieved performance, 2212 conductors are highly competitive with best 2223 conductors at 4.2–20 K. Note that, in general, Bi2212 OPIT conductors were studied essentially less than their 2223 counterparts. We believe that, having much more transparent than 2223 melt-processing heat treatment, 2212 conductors can be further significantly improved. In addition to optimising the heat treatment parameters discussed above, the most important directions of further studies are :

- choice of proper cation composition in order to improve performance and expand the window for processing temperatures [7, 19];
- introduction of nanoparticles as pinning centres that may improve the irreversibility field [24] and shift the possible working temperature to the 40–50 K range;
- improving homogeneity of final conductors in order to improve n-values.

Correlation of critical current with microstructural properties [25] suggests that 50% better performance of 2212 conductors should be considered as a very realistic anticipation.

For magnetic applications in a persistent mode, it is worth noting that completely superconducting joints between bulk and OPIT 2212 conductors are easily achievable.

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