ADVANCES IN HTS MATERIALS

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Abstract

HTS (High Temperature Superconductor) offer great opportunities to reach higher magnetic flux densities when compared with LTS (Low Temperature Superconductor). The upper generally accepted limit of 23 T using Nb3Sn can be overstep with HTS.

HTS Bi-2212 round wires have shown critical current densities as higher than 1000 MA/m^2 under 45 T at 4.2 K. The road for very high fields is open. The round shape suits rather well for magnets, especially with high current specifications since the “classical” high current cables (Rutherford, CIC) require elementary round conductor. The absence of current anisotropy in round conductor is another advantage.

The YBaCuO coated conductors (HTS second generation conductors) show large opportunities for high fields. Their higher mechanical performances (IBAD process) compared to Bi conductor bring advantages for high field magnets.

The protection of HTS magnet is an identified issue since degradations have been observed in several magnets after a quench. A state of the art of HTS materials, especially in Europe, will be presented.

INTRODUCTION

The demand for very high field superconducting magnets increases in several fields such as high energy physics or NMR [1]. Fig. 1 shows the critical characteristics, the basic superconducting property for magnets. From this figure, it is clear that LTS have a limit at about 23 T whereas HTS show no limitation in terms of transport properties up to 45 T at least.

In order to design a superconducting (SC) magnet, one should take into account other parameters than the critical characteristic. Stability and protection are two other relevant parameters [2]. The MQZ (Minimum Propagation Zone) and the propagation velocity of the normal zone are two quantitative quantities for stability and protection respectively. The specific heat plays a predominant part but with opposite sense. A large specific heat improves the stability (higher MQZ) but makes the protection more difficult (lower propagation velocity). The specific heats of materials increase rapidly with temperature (Fig. 2). So the operation at higher temperatures enhances the stability but the protection will be delicate.

Mechanics is fundamental for high field magnets where the electromagnetic Lorentz forces are huge. The stress level is higher than about 150 MPa. The SC wires and conductors should withstand very high stresses/deformations without transport property degradation. HTS are brittle ceramics and the wire and conductor architectures must manage the force.

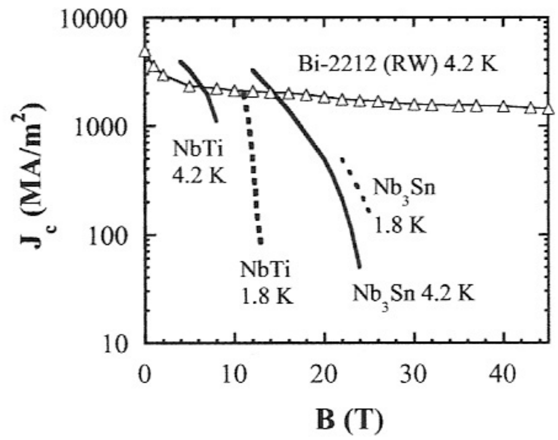

Figure 1: Critical characteristics for NbTi and Nb$_3$Sn (LTS) and Bi-2212 (HTS).

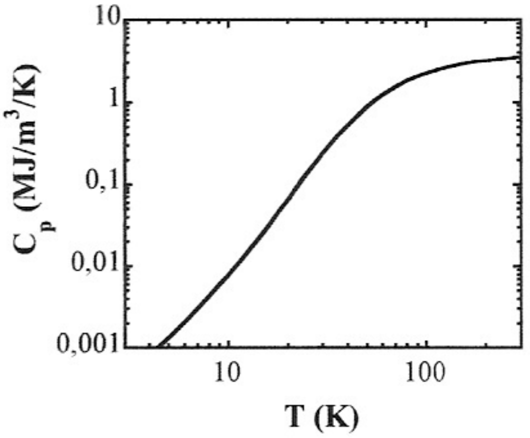

Figure 2: Specific heat per unit volume for copper versus temperature

HTS MATERIALS AND WIRES

After the early years devoted to new superconductor discovery, researches have focused mainly on the development of wires with the two compounds without noxious elements: BiSrCaCuO (BSCCO) and YBaCuO (YBCO). This task has been particularly difficult due to the complexity of these materials. Moreover, the wire should remain inexpensive to be used in other applications than niches.

Fig. 3 shows the irreversibility lines for BSCCO and YBCO. Above the irreversibility field (H*) the superconductor dissipates energy and shows then little interest for magnets. The irreversibility line of YBCO is better than the BSCCO one (Fig. 3) despite a lower critical temperature (92 K compared to 110 K (Bi-2223)). But the conditions for YBCO to carry a high transport are much more severe than for BSCCO. That is why the first generation (1G) of high Tc wires uses BSCCO. 1G is produced in kilometer lengths since some years [3, 4]. YBCO wires are the 2nd generation (2G) and the first hectometre lengths are produced [5, 6, 7, 8].

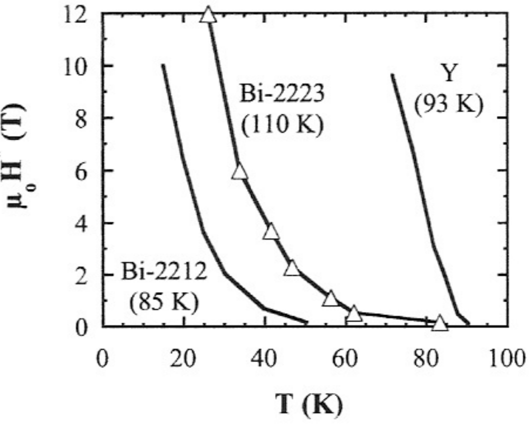

Figure 3: Irreversibility lines for Y, Bi-2212 and Bi-2223 (critical temperatures).

1G BI PIT WIRES

1G uses the BiSrCaCuO compound in the form of fine powder embeded in silver tubes (PIT (Powder In Tube) technique). The wire undergoes mechanical and heat treatments. The 1G process is basically a metallurgical one (drawing, rolling and annealing). The wire forms a classical multifilament composite (Fig. 4).

Figure 4: Cross section of a PIT Bi tape from Nexans (Nexans picture).

Two stœchiometries are industrially developed: Bi2Sr2CaCu2O (Bi-2212) and Bi2Sr2Ca2Cu3O (Bi-2223). The Bi-2212 shows better transport properties compared to Bi-2223 at temperatures lower than about 15 K even when the field is in the favourable direction for the tape (longitudinal direction, parallel to the ab plans). Fig. 5 shows some critical characteristics for 1G at 4.2 K.

Bi-2212 may be produced as tapes or round wires [9] (Fig. 6). Only Bi-2223 tapes (Fig. 4) can be elaborated. Tapes show anisotropy (Fig. 5) with a higher sensitivity to the transverse field, parallel to the c axis. Round wires are isotropic and better suit for magnet design. Bi-2212 round wires may be used in conventional high current conductor.

Fig. 7 shows a Rutherford cable with 30 Bi-2212 wires [10]. To date the maximum current-carrying capacity of another Bi-2212 Rutherford cable from Showa was 12 kA at 4.2 K in a back-up field of 0.6 T [11].

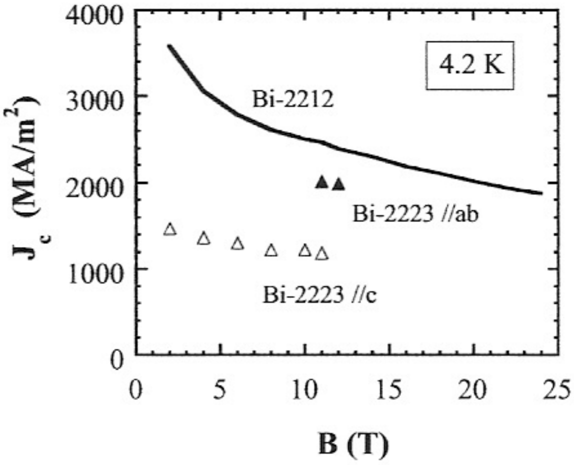

Figure 5: Critical characteristics for Bi-2212 and Bi2223 (longitudinal and transverse directions) at 4.2 K, from D. Larbalestier (Bi-2212: OST round wire, Bi-2223: Sumitomo tape).

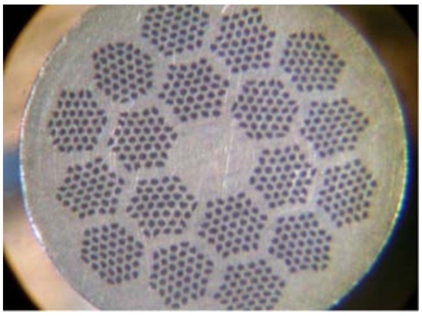

Figure 6: Cross section of a PIT Bi round wire from Nexans (CEA/IRFU picture).

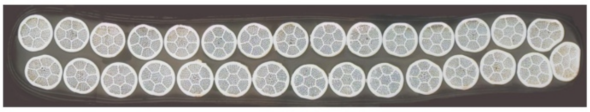

Figure 7: Cross section of a 30 Bi strand Rutherford cable from Nexans (Nexans picture).

Bi-2223 wires must be reacted before winding (R & W technique). For Bi-2212 the reaction may be before or after the winding (W & R or R & W techniques). In general the winding with unreacted wire is preferred since the fragility is then minimum. The bend diameter is also minimum with the W & R process. Dipoles or quadrupoles may experience very short bend diameters in the coil ends. W & R Bi-2212 coils show problems: some conductor leakage can occur. The reaction still has to be optimized.

To improve the mechanical properties of 1G wires an Ag alloy (AgMg) sheath is used but the critical tensile stress remains around 100 MPa. The critical stress is the stress at which the critical current degradation is 5 % and reversible. The tensile critical stress may be increased up to 250 MPa by reinforcement by soldering stainless steel tapes to the 1G wire.

The degradation of Bi PIT magnets after a quench remains an issue [12]. The relevant parameter is not only the hot spot temperature but dT/dx and dT/dt also play important parts [13].

1G wires remain expensive due to the Ag matrix and they have to operate at low temperatures under magnetic fields (Fig. 3). 2G are more interesting from these two points of view and concentrate the main researches and developments about HTS wires.

2G Y COATED CONDUCTORS

The requirements to elaborate a flexible wire with YBCO are much more stringent than for 1G. To fulfil these severe conditions, YBCO is deposited under the form of a very thin epitaxial layer (µm) on a flexible metallic substrate (highly biaxially textured Ni alloy (RABiTS route (Rolling Assisted Bi-axially Textured Substrate)) or stainless steel with a highly biaxially textured layer (YSZ, MGO) (IBAD route (Ion-Beam-Assisted Deposition)) through buffer layers so their name: coated conductors (Fig. 8). A shunt layer (Ag, Au) ends the stack and the coated conductor generally is encapsuled by a normal metal (Cu or stainless steel). The architecture (number and nature of layers) may be complex (up to a dozen layers) and still is under researches and investigations.

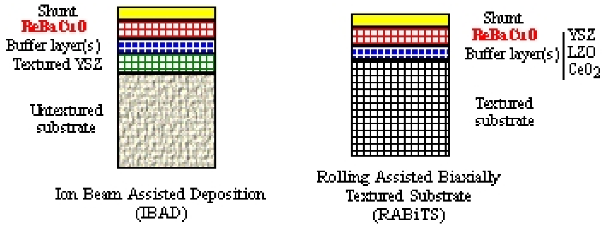

Figure 8: The two main routes of 2G Y coated conductors.

The 2G process associates metallurgical process for the substrate and thin film technology for all the layers deposited on the substrate.YBCO coated conductor are always reacted before winding.YBCO is only a very small fraction of the wire (1% or less), but due to the huge critical current densities (typically higher than 10 000 MA/m^2, 77 K, 0 T) the wire transport current remains high. It is usually expressed in Ampere per unit width of the wire (A/cm-w) to get rid of the superconducting fraction.

Company (Country)	Conductor architecture	Short sample		Long lengths		
		I_c (A/cm)	J_c (MA/m^2)	I_c (A/cm)	Length (m)	I_c*L (A/m)
SuperPower-inc (USA)	$YBCO_{MOCVD}/LMO_{PLD}/MgO_{PLD}/MgO_{IBAD}$	721	22 000	190	790	150 100
SuperPower-inc (USA)	$YBCO_{MOCVD}/LMO_{PLD}/MgO_{PLD}/MgO_{IBAD}$	721	22 000	362	103	37 284
Fujikura (Japan)	$GdBCO_{PLD}/CeO_{2PLD}/GZO_{IBAD}$	540	22 000	305	368	112 166
SRL-ISTEC (Japan)	$YBCO_{MOCVD}/CeO_{2PLD}/GZO_{IBAD}$	480	12 000	213	245	52 185
SRL-ISTEC (Japan)	$YBCO_{MOD}/CeO_{2PLD}/GZO_{IBAD}$	735	24 000	250	56	14 000
AMSC (USA)	$YBCO_{MOD}/CeO_{2PLD}/YSZ_{PLD}/Y_2O_{3\,PLD}/NiW_{RABiTS}$	560	40 000	400	94	32 900
EHTS (Germany)	$YBCO_{PLD}/CeO_{2PLD}/YSZ_{IBAD}$	574	36 000	253	100	25 300

Table 1: some best performances of coated conductors throughout the world (spring 2008).

Table 1 gives the state of the art of the coated conductor at the beginning of 2008. It specifies the deposition techniques.2G cost is potentially low with a possible operation under magnetic field at 50 – 60 K (Fig. 3). The researches are extremely active throughout the word about 2G whose prospective applications are much broader compared to 1G. Chemical deposition methods (MOD, i.e., Metal-Organic Deposition), (MOCVD, i.e., Metal-Organic Chemical Vapor Deposition) [14] are particularly suit for low cost processes when compared to physical deposition methods (PLD, i.e., Pulsed Laser Deposition), (TE, i.e., Thermal Evaporation), …, which are very effective but more expensive.

The mechanical behaviour of 2G is mainly defined by the substrate. The IBAD route with a stainless steel substrate shows higher performances compared to the

RABiTS route with a Ni alloy substrate. IBAD tapes show a critical tensile stress higher than 600 MPa but RABiTS tapes show already tensile values higher than 300 MPa.

For instance 2G are only produced under the form of an anisotropic tape. This geometry is not ideal for a SC magnet. Round or lightly aspected shape with no critical current anisotropy is preferred. High current conductors are not easy to design, even if Roebel bars have been realized [15, 16].

As in any superconductors, the vortex pinning determines the critical current density in coated conductors [17]. Due to the very low coherence length in YBaCuO nanoscale vortex pinning centers are required. BZO (BaZrO3) nanodots meet these requirements and improve a lot the transport current capacity under field. Enhancement of a factor 20 at 1 T and 77 K has been measured [18], increasing the irreversibility field up to 10.7 T at 77 K. These results show that the current capacities of coated conductors are still not reached and that substantial improvements are in progress.

CONCLUSIONS

HTS show excellent abilities for very high field magnets (higher than about 23 T) when LTS can no more be used. Bi2Sr2CaCu2O round wires have a critical current density larger than 1000 MA/m2 below 45 T at 4.2 K. The stability of HTS magnets operating at temperatures above 20 K is improved compared to LTS ones. But quench detecting and magnet protection pose some problems and are an issue today.

The Bi-2212 round wire is an excellent candidate for high field magnets. In addition to its excellent transport isotropic properties, its round form suits well for magnet design and high current conductors (Rutherford cable, CICC). Several Rutherford cables have been already realized. Indeed, Bi-2212 round wires are for a niche market and pose then a problem for industrial production.

YBaCuO coated conductors concentrate the main effort about HTS conductor researches and developments due to a potential lower cost compared to Bi and a more favourable irreversibility line. The huge challenges for these materials to carry currents have been overstepped and hectometer lengths are now available with high performances. The excellent mechanical properties especially for the IBAD route are an advantage for high field magnets. The present flat tape form of the coated conductors with anisotropic properties is not ideal for magnets.

HTS are always not well understood and large improvements are still possible. They are clearly already excellent candidates for high field magnets.

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