High temperature superconductivity: challenges and perspectives for electric power applications

Applications of High Temperature Superconductors (HTS) in large-scale electric devices strongly depends on the capability of making them in form of high-current wires or tapes. The advantage of using HTS materials relies on the possibility of increasing the operating temperatures above the liquid helium required for low-temperature superconductors, with relevant benefits in terms of costs, cryogenic and technological simplifications. This would bring superconductor technology closer to the ultimate desire of moving beyond the medical and scientific applications and coming into the power grid. Despite many physical and material conflicting requirements that deeply complicate the manufacturing of HTS materials as a practical conductor, technologies for the production of wires and tapes have been developed and successfully tested in demonstrations of transmission cables, motors and other electric devices. Now the challenge is the contraction of costs through both material science and manufacturing process tasks

Giuseppe Celentano, Andrea Augieri

Superconduttività ad alta temperatura: sfide e prospettive per le applicazioni elettriche

Le applicazioni dei materiali superconduttori ad alta temperatura critica (HTS) in dispositivi elettrotecnici di potenza dipendono dalla capacità di ottenere fili o nastri superconduttori per il trasporto di elevate correnti elettriche. Il vantaggio dei materiali HTS risiede nella possibilità di aumentare la temperatura di esercizio al di sopra di quella dell'elio liquido, necessaria per i superconduttori a bassa temperatura, con notevoli vantaggi in termini di costi e di semplificazioni tecnologiche. Questo porterebbe la tecnologia dei superconduttori più vicina all'obiettivo finale di ampliare le proprie possibilità di applicazione, oggi limitate ai settori medicale e scientifico, e di inserirsi in quello della rete energetica. A dispetto dei vincoli che complicano la realizzazione di fili e nastri HTS, le tecnologie di produzione sviluppate stanno dando dimostrazione di successo in prototipi come cavi di trasmissione, motori ed altri dispositivi. Adesso, la sfida è la contrazione dei costi che si può ottenere affrontando sia aspetti legati alla scienza dei materiali sia al processo di produzione

As soon as Prof. Heike Kamerlingh Onnes discovered superconductivity he realized the revolutionary implications of such materials. Cooling a superconductor below a specific temperature called critical temperature, T_c, the electrical resistance suddenly jumps to a value immeasurably low. Since the electric resistance R is responsible of the heat generated when a current, I, flows in a metal ($E = RI^2$), this implies that, unlike normal metals, a superconductor

Giuseppe Celentano, Andrea Augieri
ENEA, Technical Unit for Nuclear Fusion

can sustain electric current without any associated losses. The potentiality of this phenomenon for electric applications was promptly evident to him. The discovery of superconductivity is dated 8th April 1911 and occurred while measuring the sharp drop in the resistivity of a Mercury wire to *"...practically zero..."* upon cooling below 4.2 K (the T_c of mercury)[1]. Two years later, Kamerlingh Onnes envisioned the design of very powerful magnets exceeding by far the maximum intensity achievable with the conventional technology, based on normal metal iron or copper. Persistent electric current was indeed measured in a superconducting closed loop – in that case Lead (T_c = 7.2 K) wire was used – indicating the absence of resistance, but large magnetic fields were never achieved. He attributed this lack to technical problems to be easily solved. The actual nature of this problem rather than technical was physical and was "solved" in 1961, when it was demonstrated that superconductors can sustain high current in high magnetic fields.

Along this 50-year period, more insight on the physics and the magnetic properties of superconductivity was achieved. It became clearer that superconductivity was not simply a state of perfect electric conduction, but a new thermodynamic state with peculiar electric and magnetic properties. Upon cooling below T_c under an external magnetic field condition, the magnetic flux is expulsed from the superconductor just as that within the bulk $B = 0$, *i.e.*, a state of perfect diamagnetism is established. This is called *Meissner-Ochsenfeld effect* from the name of Walter Meissner and Robert Ochsenfeld, who firstly observed this phenomenon in 1932. As for temperature, the normal state is restored for field strength higher than a critical value, H_c. The values of Hc, characteristics of each superconductor, are strictly dependent on the temperature being maximum at $T = 0$ K and zero at $T = T_c$. The current flowing without losses in a superconductor presents also a critical value, J_c (it is preferred to refer to the current density), and its value is strictly related to the magnetic field strength and temperature. These three critical parameters define a critical surface in the (T, H, J)-space delimiting the region in which the superconducting state exists. An example of a typical critical surface is shown in Figure 1a.

Considering the different magnetic behavior, superconductors can be classified in Type I or Type II. In the first case, a full diamagnetic state is established, consequently currents can flow only on the surface and superconductivity is destroyed by weak fields (H_c is about tens of mT). On the other hand, Type II superconductors exhibit a more complex behavior, their main features being the existence of two critical fields defined as lower, H_{c1}, and upper, H_{c2}, whose values are typically tens of Tesla. Full diamagnetic state is established only for $H < Hc_1$, while for $H_{c1} < H < H_{c2}$ a partial diamagnetic state emerges, called *mixed* state, characterized by the formation of quantized magnetic vortices, or *fluxons*. In this state, a superconductor is capable of carrying bulk currents. For $H > H_{c2}$ the normal state is restored. Simple elements such as Mercury, Tin, Indium or Lead (the highest T_c = 7.2 K) belong to Type I superconductors, while Nb, alloys and binary or more complex compounds to Type II (highest T_c = 23 K for Ga_3V). In 1961, Kunzler, et al.[2], measured $J_c > 10^5$ A/cm^2 at 8.8 T in a Nb_3Sn wire (Type II superconductor with T_c = 18 K), showing for the first time that superconductors were really suitable for high field applications. Since then, superconductors have found wide application in magnet manufacturing. Today superconductor-based technologies find applications in the high-energy physics sector for relevant experiments and new generation of particle accelerators (Large Hadron Collider at CERN) or in plasma physics for the development of experimental controlled thermonuclear fusion machine (ITER). However, the most relevant commercial business of superconductors is the manufacturing of magnets for magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR). After a century, the prediction of Kamerlingh Onnes for high field magnets has been largely met.

All these applications are based on two superconductors that can be routinely produced into form of wires with very viable and consolidated technologies: Nb-Ti (T_c = 9 K) and the already mentioned Nb_3Sn (T_c = 18 K). It is also worth mentioning MgB_2 (T_c = 39 K), discovered only ten years ago but a mature conductor technology has been developed and is now ready for magnet applications. The main drawback in their use is related to the refrigeration issue. Several applications were proposed for different electrotechnical devices, but the advantages related to the introduction of superconductors were always compensated by the additional technological complication related to the use of liquid helium (LHe) as coolant, and by the additional costs. For these reasons Nb-based technology has been relegated to the high energy physics and medical sectors, where no competition with copper based technology existed. This poses severe limits in the perspectives of superconductor technology diffusion at market level.

With the discovery of superconductivity in the family of cuprates by J. Bednorz and A. Muller, occurred in 1986, a new era begun. These materials are called High critical Temperature Superconductors (HTS), as opposed to Low Temperature Superconductors (LTS) [3]. Soon after, superconductivity was discovered in $YBa_2Cu_3O_{7-x}$ and its rare earths variant (ReBCO, Re = Y and rare earths), having T_c in the range 90-95 K above the boiling point of nitrogen (77 K under normal pressure conditions, reduced to 65 K in vacuum). This means that liquid nitrogen (LN2), instead of helium could be used as coolant implying dramatic advantages in terms of cryogenic complexity and costs (0.1 € per litre of LN2 instead of about 10 € for LHe). To date, even though hundreds of HTS with progressively higher T_c have been discovered (world record > 180 K), ReBCO represents the best candidate for the development of superconductor technology operating at LN2 temperature ranges and that could compete with the conventional copper technology. This review is focused on REBCO superconductors and on the technology for the realization into tape conductor form, i.e. *coated conductors* or 2G HTS tapes. The margin of improvement and perspectives for applications will be also discussed. The role and contribution of the ENEA Superconductivity Laboratory in this field will also be reported.

HTS materials and wire processing

Even before the discovery of HTS materials, it was clear that the manufacturing of conductors capable of su-

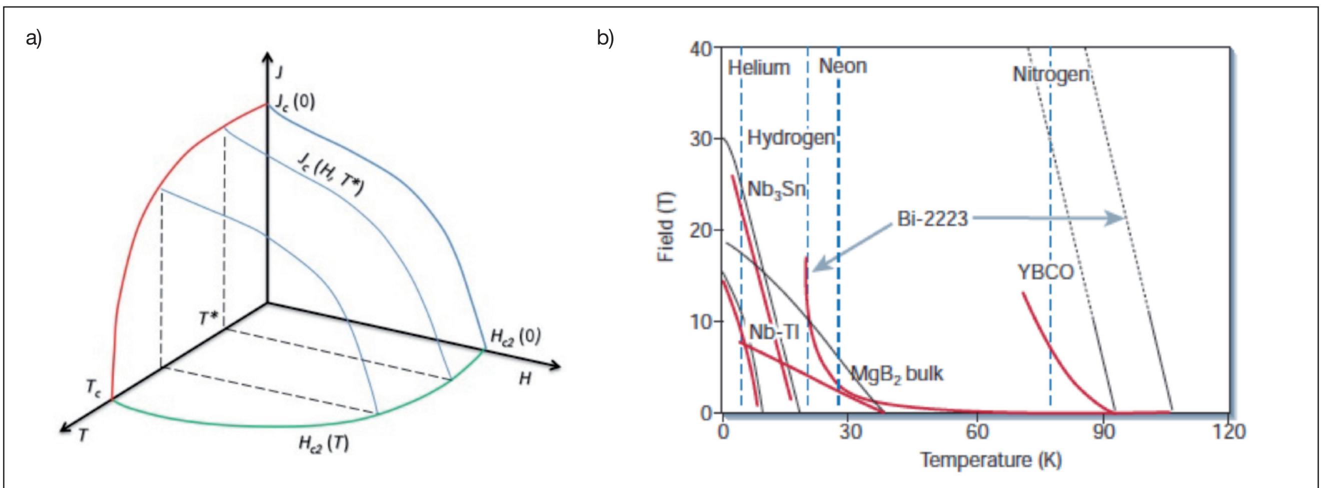

FIGURE 1 a) Sketch of a typical Type II (see text) superconductor phase diagram. The blue, green and red curves represent the critical parameter $J_c(H, T = 0)$, $H_{c2}(T)$ and $Jc(H = 0, T)$ dependences. The boundary of the region in which superconductivity is established is called critical surface. As far as superconductors are used in motors, magnets or power transmission lines the most relevant parameter is J_c and its dependence on H and T. $J_c(H, T)$ is a decreasing function of both H and T. The $J_c(H)$ dependences at given temperatures $T \neq 0$ K are also shown as light blue curves lying on the critical surface. b) Phase diagram in the H-T plane for some of the most relevant "practical" superconductors. For each of them both the $H_{c2}(T)$ and irreversibility line $H^*(T)$ are reported: black and red curves, respectively. For HTS BiSCCO and YBCO the critical fields along c-axis are only shown for clarity (see text for more details)

staining high electric current implies much more than just superconductor. However the strategy of making a superconductor useful, *i.e.*, in form of wire, was well assessed and defined: taking a material, developing a reliable technology for the production in form of filaments and embedding them in a copper matrix, in order to obtain a composite with proper thermal and electrical stability and mechanical properties as well. With HTS materials the situation is more complicated due to the peculiarities of cuprates: anisotropy and grain boundary.

In Figure 2, the crystalline unit cell of Nb_3Sn as representative of LTS is shown together with the one of ReBCO. In addition, the structure of $Bi_2Sr_2Ca_2Cu_2O_{10-x}$ (BiSCCO) HTS compound, having T_c = 110 K, is also reported. As it can be seen while Nb_3Sn exhibits the cubic A15 crystal structure, cuprates have a more complex layered perovskite structures. This structural nature has dramatic effects on superconducting properties. Lossless currents, or *supercurrents*, flow more easily along the CuO_2 layers so that the J_c in this plane (denoted as *a-b*, being *a and b* the corresponding crystallographic axes) exceeds the J_c in the direction perpendicular to the CuO_2 planes (*c*-axis). Similar anisotropic nature is also observed in the magnetic behavior characterized by the presence of two critical fields ($H_{c2}^{a\text{-}b}$ and H_{c2}^{c}, along *a-b* plane and *c*-axis, respectively). The ratio $y = H_{c2}^{a\text{-}b}/H_{c2}^{c}$, taken as the measure of the material anisotropy, is 5-8 for ReBCO and 50-200 for BiSCCO. By contrast y = 1 for Nb_3Sn. Even though H_{c2} are very large (values exceeding 100 T at T=0 K are predicted for both ReBCO and BiSCCO), for HTS materials J_c does not vanish at H_{c2}, as it happens in LTS (see $J_c(H)$ curves reported in Figure 1a), but for a much lower field H^*, called irreversibility field. As a results cuprates can carry currents without dissipation in a smaller part of the H-T plane limited by $H^*(T)$ instead of $H_{c2}(T)$.

In Figure 1b the phase diagram in the *H-T* plane for several application relevant superconductors are reported. As can be seen, even though BiSCCO has higher T_c, the H^* line is well below the one of ReBCO. This is strictly related to the larger anisotropy of BiSCCO. At 77 K $H^* \approx 0.3$ T prevents from employing BiSCCO in any significant magnetic field condition. Conversely

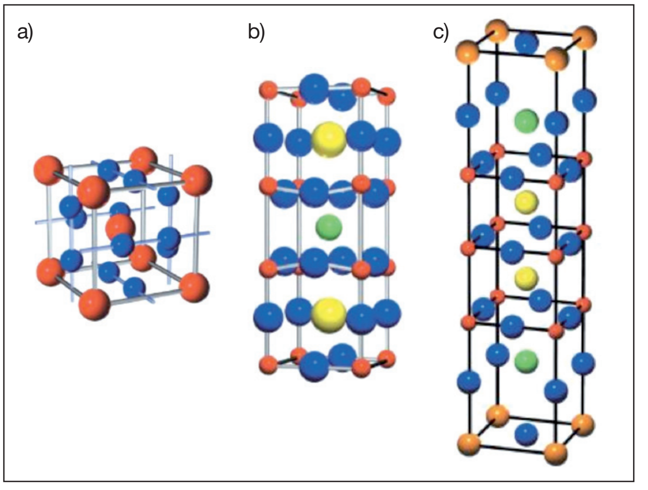

FIGURE 2 Comparison among the crystal unit cells of different superconductors (not in scale): a) Nb_3Sn, cubic A15 structure; b) $YBa_2Cu_3O_{7-x}$ orthorhombic perovskite; c) $Bi_2Sr_2Ca_2Cu_2O_{10-x}$ tetragonal perovskite

for ReBCO, due to the moderate anisotropic nature, the irreversibility line remains closer to H_{c2} so that, even at the LN2 temperature range, it can sustain supercurrents at relatively high fields $H^*(77\ K) \approx 7$ T. That is why ReBCO represents the only candidate for the development of superconductor technology operating in magnetic field at LN2 temperature. However, both ReBCO and BiSCCO make the region of very high fields accessible as temperature is reduced, exceeding by far the limit of LTS at 4.2 K.

One of the most disappointing feature of cuprates is the strong depression of J_c across a grain boundary between two misoriented crystallites. The supercurrent exponentially drops with the misorientation angle (no matter if crystal axes are twisted or tilted with each other) being reduced to one tenth of the original J_c as soon as angles are about 10° and two or three orders of magnitude at 45°[4]. This represents a big complication for the development of conductors, considering that conductors are polycrystalline. If typical grain size of 10 μm is assumed, 1 km long wires with 1 mm diameter consist of about 10^{10} grain boundaries. Since some of them partially reduce J_c while others act as a full block, the net current carried by the wires is completely suppressed due to the meandering through the network of

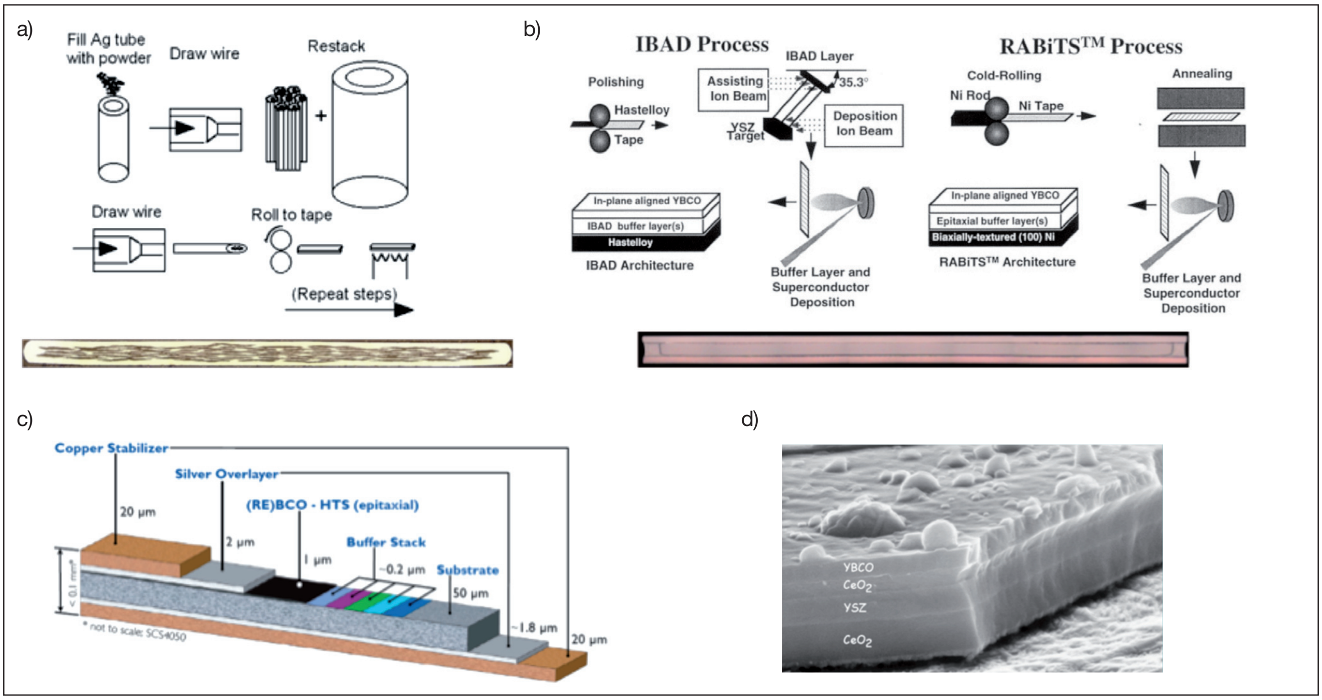

FIGURE 3 Production process for BiSCCO (a) and ReBCO (b, c, and d) tapes. **a)** Oxide Powder-in-Tube (O-PIT): precursor powders are put in a Ag tube and drawn, the obtained filaments are stacked and put in a larger Ag tube and drawn once again. The tape is ultimately obtained after rolling and thermal treatment for the conversion of precursors in the superconducting phase; a-*bottom*) cross section of the multifilamentary tape. Embedded in the Ag matrix, the deformed BiSCCO filaments are distinguishable (gray spots). Typical sizes are: width 4.4 mm and thickness 0.2-0.3 mm. **b)** Sketch of coated conductor manufacturing methods. In case of polycrystalline randomly oriented tape such as Hastelloy, Inconell or stainless steel, the texture is forced on buffer layer by a Ion Beam Assisted Deposition (IBAD) process. Oxides such as MgO, Y_2O_3 – stabilized ZrO_2 (YSZ) and $Gd_2Zr_2O_7$ can develop by IBAD process a suitable texture for successive epitaxial growth. In general more than one layer is required before YBCO deposition. In **3c**, the structure of a typical IBAD coated conductor tape is reported (from Super Power Inc.). In the second approach, only metals such as Ni, Cu and their alloy are used because they can be biaxially textured after a thermomechanical process consisting of rolling an annealing at a proper temperature (RABiTS, Rolling Assisted Biaxially Textured Substrate). In this case the substrate texture is transferred to YBCO film through the buffer layer architecture by epitaxial growth. A typical multilayered structure (developed at ENEA) including buffer layer and YBCO is reported in **3d**. *b-bottom*) cross section of a typical coated conductor tape (344-amperium from American Superconductors Co.). Typical sizes are: width 4.4 mm and thickness 0.1-0.2 mm. The ReBCO film on the substrate surface is not appreciable (1 μm)

grain boundaries. As a result, the extreme sensitivity to grain misorientation coupled with anisotropy determines a precise requirement: texture must be controlled (texture, in material science, means the distribution of the crystallographic orientation of a sample).
The challenge for textured HTS conductors has been addressed and solved for both BiSCCO and ReBCO. In the former case a suitable technology for the production of multifilamentary tapes was successfully developed. These tapes, consisting in BiSCCO filaments embedded in Ag sheath, are manufactured by the powder-in-tube metallurgical process which is essentially the same technology already used for Nb_3Sn and MgB_2.
Following this process, whose main steps are reported in Figure 3a, BiSCCO grains result uniaxially textured with the *c*-axis parallel to the tape surface. Commercial tapes in km piece lengths by several manufacturers are currently available[5]. The tape, 4.4 mm wide and 0.2-0.3 mm thick, can sustain at 77 K in zero applied magnetic field critical currents in the range 100-200 A depending on the wire type. The resulting overall critical current density (engineering critical current density, J_e), calcu-

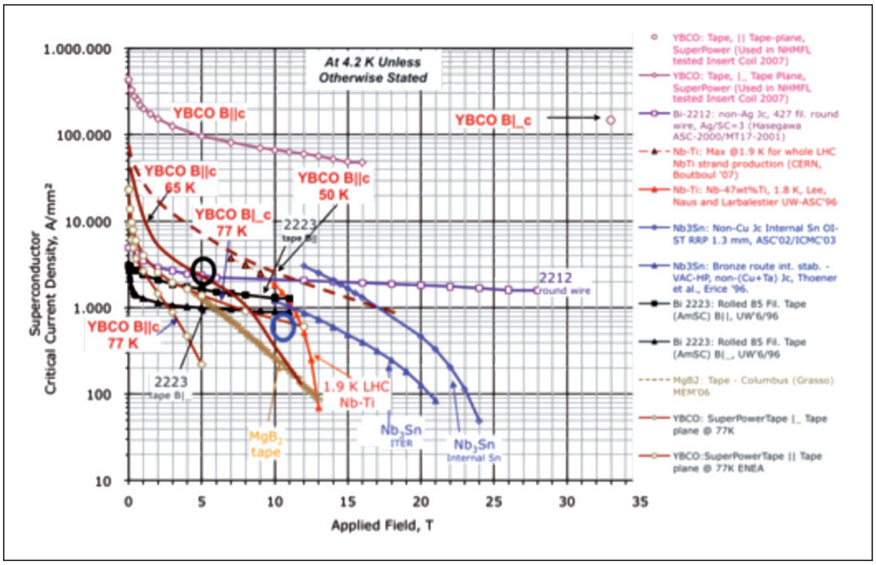

FIGURE 4 $J_c(H)$ curves measured on commercial superconductor wires and tapes. Black and blue circles represent the ITER Poloidal and Toroidal magnets operation conditions

lated on the whole tape cross section including both superconductor and normal materials, is 100-250 A/mm^2, that means even 100 times as much as the copper typical current carrying capability (2-4 A/mm^2). Apart from the intrinsic limit for application in magnetic field at 77 K, the main drawback of the BiSCCO-based technology (usually mentioned as first generation HTS tape technology (1G)) is the cost. In fact the cost per unit length normalized to performances of BiSCCO tape ranges within 60-100 €/kA·m depending on the wire type and operation conditions are still five times as much as copper cable (10-20 €/kA·m). This gap cannot be further reduced considering that is mainly due to the material cost related to the extensive use of Ag, representing about 70-80% of the whole tape.

On the contrary, on ReBCO are placed expectations for HTS tapes competitive with copper prices. The more recent ReBCO tape technology, called *second generation* (2G) or *coated conductor*, is based on a completely different process, in which Ag is replaced by much cheaper Ni. These tapes consist of a flexible metallic tape, typically Ni or Ni based-alloys, coated by ReBCO film by means of thin film deposition methods[6]. Employing thin-film deposition techniques for ReBCO conductor manufacturing may, at a first glance, appear as a complication factor in view of the development of an industrial scalable manufacturing process. However, this is justified by considering that film texture can be reliably controlled through epitaxial process and that best ReBCO J_c can be achieved in the epitaxial films. By thin-film deposition, biaxial alignment is achieved, *i.e.*, ReBCO film grains result aligned not only with the c-axis perpendicular to the tape surface but also *a*-axes are aligned to each other on the tape surface. Between metallic tape and ReBCO film a multilayer oxide film structure (buffer layer) is required because of chemical and structural optimization reasons. The tape architecture is completed by outer stabilization copper layer. Tape manufacturing processes are based on two different approaches depending on the different crystalline nature of the metallic tape used as substrate for the stack of buffer layers and YBCO (see Figure 3b, c and d for details).

The main advantages of 2G over 1G technology are its better mechanical properties and better critical current performances. The use of Ni tape, instead of softer Ag sheath employed in 1G tapes, guarantees higher tensile stress and bending strain behaviors more suitable for applications. In Figure 4 the electrical performances of coated conductors are reported and compared with the other superconductor wires. The high J_c achieved in coated conductors are ascri-

Mixed state and critical currents

The *mixed state* of Type-II superconductors is the region of the *H-T* phase diagram which is delimited by lower, $H_{c1}(T)$, and upper, $H_{c2}(T)$, critical field values. In this region the field partially penetrates inside the material as *fluxons*. Fluxons, or vortices, are composed by a normal core region of diameter 2ξ (ξ is called the coherence length, ~ 1 nm in YBCO) surrounded by annular screening currents decaying over λ (λ is the magnetic field penetration depth, ~ 100 nm in YBCO). Within the vortex core the magnetic field penetrates in the form of a quantum of magnetic flux $\Phi_0 = 2.07\ 10^{-11}$ T·cm^2.
The imperfect diamagnetism of the mixed state can be detrimental for any application of Type-II superconductors. Any electrical current applied to the superconductors, in fact, exerts a driving force on fluxons through the Lorentz force, F_L, which causes vortices to move with a viscosity limited velocity. The vortex movement generates an electric field whose component parallel to the electric current gives rise to ohmic dissipation. Hence, flux flow gives rise to dissipation even though the superconductive state is still present.
The only way to avoid dissipation in the *mixed state* is to prevent vortices from moving. From energetic considerations, it can been shown that any nanometer-sized defect acts as sites where fluxons penetrate and remain pinned, with a force called *pinning force, Fp.*
As long as the Lorentz force exerted on fluxons by the bias current is lower than the pinning force, the vortex movement is prevented and the dissipation-free state is restored. When the Lorentz force exceeds the pinning force, the flux flow starts and dissipation occurs. The value of the current corresponding to the depinning of vortices is called ***critical current*** or *depinning current* J_c.
In the mixed state, two regions can be identified: the first one, at lower temperature and magnetic field values, where vortices are pinned and current can flow without dissipation up to the critical value $J_c(T, H)$; the second one, for higher *T* and *H* values, where fluxons are depinned by just the thermal energy and the current flow is always associated to dissipation. The curve in the *H-T* phase diagram which identifies these two regions is called the ***irreversibility line***, *H**.
Critical current and *irreversibility line* are the most important parameters for type-II superconductors applications. It is worth noting that they are not characteristic of the superconductive material but rather they depend on flux pinning, which is strongly related to the number, density and nature of defects created inside the superconductive matrix. Hence, a shift of the irreversibility line towards higher magnetic field values and the achievement of higher critical current values can be obtained by improving the pinning efficiency. It is for this reason that many efforts are done in order to understand the *vortex matter*, that is the study of vortex-vortex and vortex-defect interactions which give rise to a very complex and fascinating phenomenology.

bed to the very accurate degree of grains alignment and texture control along the tape. The misorientation angles among the crystalline directions of the grains are kept well below the safe limit of 4-8° in both perpendicular and plane directions so that ReBCO films reach similar performances of epitaxial films on single crystal substrates. Despite of the very reduced fill factor (fraction of the superconductor on the overall cross section) typically 1-2%, coated conductors achieve very high J_e assuming similar value of Nb-Ti at 4.2 K. These performances are the result of a very impressive material science “tour de force” operated in the last 10-15 years by many academics, institutes (among which ENEA) and industries for the control and the accommodation of the severe requirements derived from the complex nature of this composite conductor and set by applications. Several topics have been addressed as the mitigation of grain boundary effects, the development of proper metallic substrates, the investigation of epitaxial growth in highly oxidizing condition on metallic surface and their potentiality for long length production, the study on HTS films for J_c optimization.

Application perspectives of HTS tapes

In the last few years, coated conductors are being commercially available from several manufacturers from Europe, Asia and USA (Table 1). Nevertheless, today performances do not completely meet the application needs. In Table 2 requirements emerged by utilities and industries consensus are summarized for some of the most relevant applications in the energy sector [7]. The J_c performances and mechanical properties of commercial tapes in general meet, or are very close to, the application requirements. However, as demonstrated by the maximum, today available tape piece length (200-300 m) and costs (about 400 €/kA·m at 77

Company	Sumitomo Electric Industry-SEI	American SUperconductor Co.-AMSC	Superpower Inc. – SPI	Fujikura Electric Industry	SuNAM	Bruker
Process	RABiTS	RABiTS	IBAD	IBAD	RABiTS	IBAD
Buffer layer deposition	Physical	Physical	Physical	Physical	Physical	Physical
ReBCO deposition technique	Physical: PLD	Chemical: liquid solution of MOD precursors	Chemical: MOCVD	Physical: PLD	Physical: RCE	Physical: PLD
Record piece length (km)		0.5	1.4	1	0.1 (1*)	0.1 (1*)
Production capability (km/year)		> 1000	> 300		2000*	

TABLE 1 List of the main 2G tape suppliers and main tape production features.
PLD = Pulsed Laser Deposition; MOD = Metal Organic Decomposition; RCE = Reactive Co-Evaporation; * planned value

Application	J_c (Acm^{-2})	H (Tesla)	T (K)	I_c (A)	Wire length (m)	Strain (%)	Bending radius (m)	Cost ($/kA·m)
Transmission power cable	10^5	0.15	67-77	200	> 500	0.4	2 (cable)	10-50
Synchronous condenser	10^5	2-3	30-77	100-500	> 1000	0.2	0.1	30-70
Fault current limiter	10^4-10^5	0.1-3	70-77	300	> 1000	0.2	0.1	30-70
Industrial motor	10^5	4-5	30-77	100-500	> 1000	0.2-0.3	0.1	10-25
Generator	>10^4	2-3	50-65	125 @ T_{op}, 3 T	> 1000	0.4-0.5	0.1	5-10
Transformer	>10^6	0.15	70-77	100 @ 0.15 T	> 1000	0.3	0.05	10-25

TABLE 2 Industry consensus wire performance requirements for various utility device applications (source: Navigant Consulting, [7])

K in zero field representing the highest price among superconductor wires), there are still several technological and manufacturing issues to be addressed. The key factors determining the costs/performances ratio for coated conductors are raw materials (among which substrate is the most relevant), production process (in particular coating process and production yield-meters of continuous tape per unit time within specifications) and the current carrying capability, *i.e.*, I_c. The latter can be addressed by the increase in the ReBCO thickness and/or improving the $J_c(H)$ dependences. Many efforts are currently focused on the development of 2-5 μm films by suitable deposition techniques. Better $J_c(H)$ curves are going to be obtained through nano-engineerization of ReBCO films[8]. As far as costs are considered, materials represent only a little percentage of the whole tape costs, so the main concerns are related to production process. The level for market penetration has been set to 100 €/kA·m (at 77 K) while larger commercial diffusion is expected as copper price is approached. SuperPower Inc. – one of the 2G tape leading companies – expects to reduce the price to commercial levels in 5-10 years by intensive R&D on manufacturing process and on performances[9]. In addition, it is general belief that year tape production capability must be greatly increased in order to support application demand (the current production capability – around 10^3 km – would be sufficient for a few MW wind turbine generators[10]). For the time being, production processes are very expensive because they are based on complex buffer layer architecture deposited by vacuum techniques. The simplification of the buffer layer architecture (*i.e.*, reduction of the number of layers) and the development of a fully-chemical coating process should have a strong impact on tape costs. In fact, chemical non-vacuum methods are intrinsically more economic than physical techniques (vacuum equipment costs are saved), more versati-

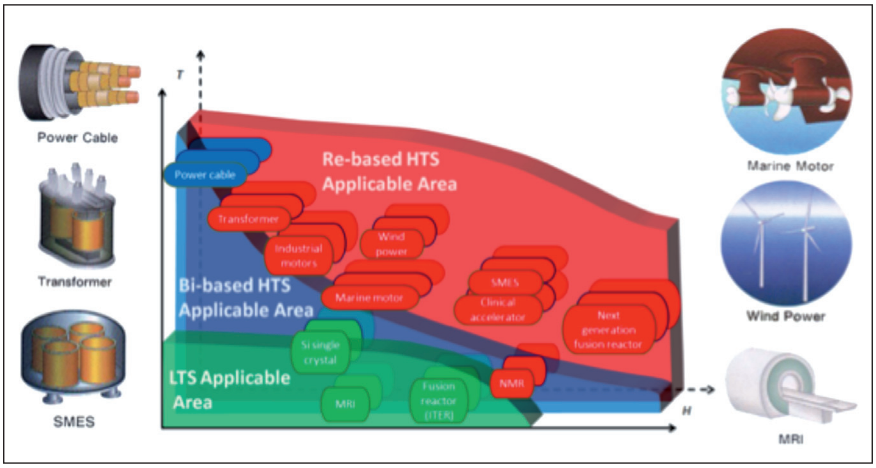

FIGURE 5 Area of applications for LTS and HTS technologies with expected *T-H* operation conditions

le and more easily scalable to industrial production. These methods are expected to a have a decisive role for the development of a copper-competitive HTS wire technology and are currently the subject of several industrial and academic R&D projects.

Due to the limits imposed by costs, it is expected that HTS technology will be firstly applied in performance-driven sectors in which competition is weak (science, research and technological development (RTD), and in military applications). The use of BiSCCO-based current leads for the ITER magnets feeding system is a first demonstration that HTS technology is already finding a market share in this field. In fact, most of the largest magnet systems today already use HTS current leads to reduce the heat load on the cryogenic part so HTS current leads are today commercially available and are expected to extend their applicability in the next future even to smaller systems such as MRI/NMR systems.

Longer-term projects are the development of 2G tape-based high current cable for the feeding system of LHC magnetic system[11] and the realization at Fermi Labs of a muon collider by using extremely high intense magnetic field (about 40 T) with an HTS coil. It has to be noticed that 2G tape coils generating 9.81 T at 4.2 K and the 26.6 T in a background field of 19 T have been successfully tested[12], indicating that a proper winding technology can be developed and 2G tapes exhibit suitable mechanical and stability properties for high field magnets. In addition, first studies for the development of high current cable suitable for fusion magnets are recently started. HTS technology has the potentiality for either increasing the maximum achievable magnetic field strength well above the limit fixed by LTS or alternatively simplifying the reactor design if operation at higher temperature than LHe is considered. Even though this is a very long-term objective, preliminary results on kA-range 2G HTS cable concepts are encouraging.

As for NMR and MRI systems the new trend towards higher magnetic fields is possible because of HTS insert coils. This market is by far the biggest one for superconductor technology, reaching more than €4 billion in 2011, and it is expected to increase steadily in the next 5 years with the contribution of HTS technology[13].

However, the most exciting perspective for HTS technology is the possibility to gain some market share in the highly cost-competitive commercial market of energy. In this field HTS superconductors can play a key role in the generation, transmission and improvement of the electric grid quality. In the latter case Fault Current Limiter (FCL) and synchronous condensers can be included. They are considered the applications in which the HTS attributes are most valued. FCL is a self-switching and self-recovering device that offers a new functionality of network operation for controlling short-circuits in electric grids, so it acts as surge protection of power grid. The FCL effectiveness and

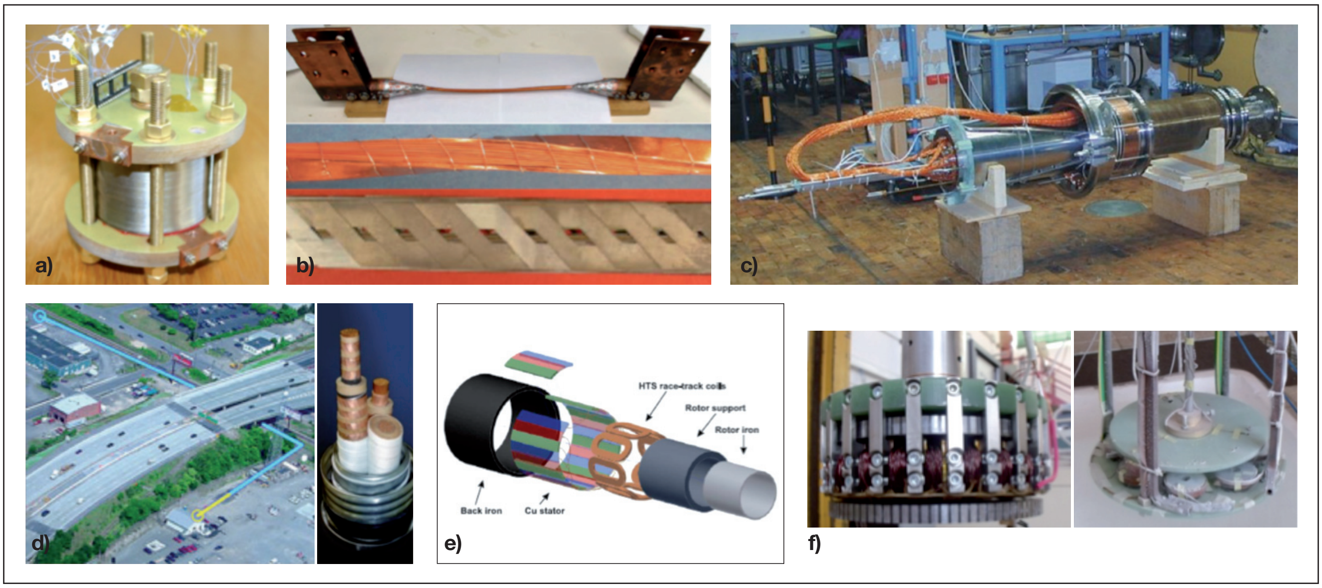

FIGURE 6 **a)** First solenoid magnet made of 2G superconductor with 82 mm winding diameter and 52 mm winding height operating at the field 26.8 T (in a background field of 19 T) at 4.2 K world record at the time it was tested in 2007 by NHMFL (USA). Operation at 35.5 T has been more recently demonstrated due to the improvements of the tape performances; **b)** Basic concepts for kA-range @ 77 K HTS cable made with 2G tapes: upper panel) 2.8 kA coaxial cable, middle panel) 1.54 kA twisted stacked tapes, lower panel) 2.6 kA Roeble cable; **c)** the 70 kA HTS current lead for ITER magnets, produced at the Karlsruhe Institute of Technology (source: http://www.iter.org/newsline/169/652); **d)** Site of the Albany Cable Project on the National Grid electrical network in Albany, NY (Blue = 350 m long 1G HTS Cable, Yellow = 30 m 2G HTS Cable), right panel: Sumitomo *3-in-1* 2G HTS power cable configuration; **e)** typical layout of a HTS generator for multi- MW wind turbines [25] **f)** prototype of superconducting rotating machines developed by ENEA: (upper image) MgB_2 based radial machine operating at LHe (activity carried out in the framework of ENEA-EDISON-Ansaldo CRIS contract) and (lower image) prototype of axial machine operating in LN2 made with field excitation armature consisting of 8 YBCO coils arranged in a circular path with radius 12 cm (activity carried out in the framework of SURE:ARTYST)

viability have been widely demonstrated and successful installation of commercial devices in real grid has been shown last year[14]. Synchronous condensers are special rotating machines that can provide dynamic power factor control and regulation on transmission and distribution networks. The introduction of HTS rotor coils renders the machine more efficient and it produces many times more reactive power than a similarly-sized commercial machine. Both applications are the most mature technologies in the energy sector ready for commercialization[15].

A field that has recently found new increased interest is the Superconducting Magnetic Energy Storage (SMES), *e.g.*, for uninterruptable power sources at customer sites (local application) or to stabilize fluctuations of the electric grid (large scale application). SMES systems use superconducting magnets to store energy in a magnetic field very efficiently (greater than 95%), offering the advantages of instantaneous energy discharge and a theoretically infinite number of recharge cycles. As example of large scale commercial level prototype SMES, it is worth mentioning the collaboration (funded by DOE with $4.2 M) among engineering company ABB and superconducting 2G wire manufacturer SuperPower, Brookhaven National Laboratory, and the University of Houston for the development of a 1-2 MWh commercial-scale device that is cost-competitive with lead-acid batteries[16]. Other national projects for MJ class HTS wire SMES are active in Korea and Japan. A detailed overview on recent SMES projects and perspectives can be found in [17].

Superconducting cables and transformers offer not only reductions of losses, size and weight, but also oil-free operation. These aspects are very significant, *e.g.*,

in densely populated cities when the electric grid has to be upgraded, or in mobile applications like trains. In Albany (NY, USA), the longest underground HTS power cable connecting 2 grid substations has been installed since 2005, and is still operating. The project, funded by DOE with $ 13.5 M, has been carried out by 2G wire manufacturer Superpower, Sumitomo Electric Industries as cable maker, Linde for cooling technology and NY National Grid company[18]. Even though there are many world-wide active projects in power transmission cable, this application is not considered fully ready to enter the market[19]. Further improvements in ancillary technologies such as cryogenic efficiency and cryostat reliability will be decisive for commercialization.
Employing superconductors in electrical motors and generators reduces the excitation losses, increases the magnetic flux density, allows to eliminate ferromagnetic cores and reduces weight[21]. Low speed HTS machine are expected to find applications in the next few years as generators, rated up to 10 MW for multi-MW wind turbines, and as ship propulsion motors, rated up to 40 MW. In 2007, the world's highest torque motor at 36.6 MW for US Navy was built with HTS field windings[21]. The trend toward larger multi-MW wind turbine and the need to reduce operations, maintenance and installation costs, particularly for offshore plants, can be satisfied by the application of superconductivity to direct-drive wind-turbine generators[10]. The expected potential of superconducting technology for wind turbine is confirmed by some important research projects launched around the world[22].

Conclusions

In this review, the perspectives of the HTS materials for applications in large scale electrical devices have been reported. Reliable technologies for manufacturing high current tapes based on BiSCCO and ReBCO materials are presented and discussed emphasizing the main relevant features in view of applications. The BiSCCO 1G technology is mainly limited by material costs while on the more recent ReBCO 2G tapes, despite the complex manufacturing process, perspectives are placed in the highly cost-competitive energy sector. In fact, unlike 1G, 2G tapes present large margins for cost reduction by the development of an industrial process more adequate for the mass production and there is still room for improvements in the tape performances. As a consequence, in 5-10 years, the conductor costs/performances ratio is expected to reach a level adequate for market diffusion of HTS technology.

HTS activity in ENEA

The ENEA Superconductivity Laboratory is the largest Italian group working on applied superconductivity and stems from the first Italian team working on superconductivity born in Frascati in 1961.
Research activities related to HTS materials are mainly focused on ReBCO materials and on the development of YBCO based coated conductors and cover several aspects ranging from the fundamental physics to the material science and applications (motors, generators, magnets). The Superconductivity Laboratory developed one of the earliest non magnetic textured substrates (ENEA patent). It was one of the first group studying ternary Ni-, and more recently, Cu- based alloys as substrates for coated conductors. In view of process simplification chemical techniques with liquid solution precursors were studied and successfully transferred to coated conductor production process. Nano-structured YBCO by introduction of $BaZrO_3$ secondary phase was deposited and studied for optimization of the pinning strength.
Recently, the Superconductivity Laboratory has joined two important HTS projects: SURE: ARTYST (coordinated by ENEA) funded by Ministry of University and Research in the framework of FIRB "Futuro in Ricerca", program for the study of solution based chemical deposition techniques and pinning mechanisms, and EUROTAPES, funded by European Union in the framework of the FP7 program in which ENEA is partner of the most important European institutions, academies and private companies operating in the HTS field.
The Superconductivity Laboratory has solid expertise on textured substrate development, deposition of heterostructures on metallic substrates for YBCO coated conductors and flux pinning properties. It hosts a comprehensive Laboratory for textured metallic substrate preparations, for bulk synthesis and for thin film depositions and characterizations by means of micro-structural investigations by AFM/STM, SEM and XRD and superconducting properties by both dc transport and magnetic measurements.

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