conducting order parameter and the three components of the antiferromagnetic order parameter. The breaking of SO(5) symmetry corresponds to phase transitions into the superconducting, antiferromagnetic, and mixed states. What is new here is the introduction of a dynamic degree of freedom associated with a collective triplet mode (the π-mode) that mixes the superconducting and antiferromagnetic components. The resonance in the inelastic scattering of neutrons observed in a number of hole cuprates is explained in Ref. [30] through the softening of this π-mode.

The above model with large total momentum of the pair in the singlet state corresponds to softening to zero at momentum K of the singlet π-mode at point T_c. It is assumed that the frequency of the triplet π-mode remains finite. The existence of the superconducting order parameter discussed earlier and not included in the SO(5) group is allowed for in the more general SU(4) group [31].

Yang [32] has pointed out that solutions with large total momentum of the pair may exist in the Hubbard model. Japaridze et al. [33] have studied numerically the possibility of realizing such a state as the ground state for the one-dimensional case with allowance for hopping between the centers of a pair of carriers.

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State of the art in applied high-current superconductivity

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1. Introduction

The name ‘applied high-current superconductivity’ (AHCS) covers the practical applications of unique current-carrying capabilities of what is known as hard (type II) superconductors at temperatures and magnetic fields below their critical values. In superconducting devices, compared to those commonly manufactured of Cu and Al, the current density in the winding is 10 to 100 times higher than in that of traditional devices, there are no Joule heat losses in the DC mode, while in the AC mode at commercial frequencies the losses become as small as 10^{-4} of those in resistive windings. Moreover, the use of AHCS makes it possible to develop devices that are cannot be manufactured by the conventional electrical engineering technologies, e.g. magnetic systems with almost ideally persistent (frozen) current, etc. With the cost of modern industrial low-temperature superconducting (LTSC) wires and cables being about US\$1 to US\$15 for 1 kA m and that of copper wire about US\$15 for 1 kA m, the question of expedience of using a superconducting device is determined by the acceptability of the costs of constructing a cryostatting system for the device and of the operation costs [1].

As is known, AHCS research began 50 years after the discovery of superconductivity phenomenon. Today it has a 40-year history and two areas of superconducting applications have developed. The first area deals with applications impossible without superconducting devices, such as modern accelerators and detectors for high-energy physics, facilities for thermonuclear research with magnetic confinement of hot plasma, magnets of unique precision, stability, and uniformity for magnetic resonance tomography, maximum-field magnets for NMR spectroscopy, and magnets used in research in physics, chemistry, and biology. The other area deals with the use of superconducting devices in ordinary industries, primarily electrical power engineering, transportation systems, mining, and other energy-intensive industries. The brave attempts of the 1970s (especially in the USSR and the US) to incorporate AHCS into ordinary industries after successful R&D of prototypes of various superconducting electrical devices proved to be unsuccessful due to the high costs involved and the low reliability of the superconducting devices of those times in comparison with traditional electrical devices. The main reason here was the high cost and low reliability of the cryogenic equipment operating at liquid-helium temperatures, and in the USSR especially the high cost of the coolant, helium.

Since then (the 1970s) much has improved in the LTSC technologies (the quality of superconducting materials, the possibilities of liquid-helium technology, and the very technology of magnetic systems). At the same time, after the discovery in 1986 of what are now known as high-temperature superconductors (HTSC), there appeared and then developed HTSC technology, or the superconducting technology of liquid-nitrogen temperatures [2]. After the first successes of this new technology it became an integral part of modern AHCS.

2. AHCS operating at liquid-helium temperatures

This is the oldest and most developed part of modern AHCS. Two superconductors represent its basis from the viewpoint of superconductivity proper. One of them is the disordered deformable alloy Nb – Ti with a bcc structure and an approximately equal weight ratio of the components. In Russia this alloy is marked NT-50 (50 wt.% Nb and 50 wt.% Ti), while in the US the alloy contains 47 wt.% Nb and 53 wt.% Ti; the two alloys are close to each other in properties. Their critical parameters are as follows: the critical temperature $T_c = 9.6$ K in a zero magnetic field and with a zero current, the upper critical field $B_{c2} = 12$ T at 4.2 K and with zero current; accordingly, the coherence length $\xi(0) = 4$ nm and the penetration depth $\lambda(0) = 240$ nm. As a result of a prolonged and thorough study of the thermomechanical and electrodynamical properties of this alloy it was established that laminated precipitates of α-Ti with a thickness of about 2 nm oriented along the wire axis are effective pinning centers for the Abrikosov vortices. This study also determined the set of processes of thermomechanical treatment needed to create a structure of pinning centers close to optimal in the final product (wire) and also stably attain a critical current density $J_c = 3 \times 10^9$ A m^{-2} at 4.2 K in a 5-T field. Introduction of artificial pinning centers makes it possible to raise J_c to 5×10^9 A m^{-2}. As noted earlier, the cost of Nb – Ti wire depends on the purpose for which the wire will be used, but usually does not exceed US$10 for 1 kA m.

The second 'workhorse' of low-temperature AHCS is the brittle intermetallic compound Nb_3Sn with the A15 structure which belongs to the class of cubic structures. The critical parameters of this compound substantially broaden the range of operating temperatures and magnetic fields for superconducting magnetic systems (SMS) in comparison with the temperatures and magnetic fields in SMS based on the Nb – Ti alloy. The critical temperature of Nb_3Sn at zero magnetic field and current is 18.3 K, and the second critical field is 24 T at 4.2 K and a zero (measuring) current; accordingly, the coherence length $\xi(0) = 3$ nm and the penetration depth $\lambda(0) = 65$ nm. As Nb – Ti, the Nb_3Sn compound is an almost perfectly isotropic superconductor, and the grain boundaries in it are transparent for the superconducting current. At the same time, it is interesting that the grain boundaries are effective pinning centers, and obtaining a 'strong' pinning structure in Nb_3Sn needed for high critical currents means obtaining an optimal finely crystalline structure. The critical current densities attainable with Nb_3Sn-based materials are higher than those attainable with Nb – Ti-based materials. For instance, in industrial samples of wire the attainable critical current density in the superconductor may be higher than 10^9 A m^{-2} at 4.2 K in a 10-T field. Here one must bear in mind that the wire (Fig. 1) has a complex composite structure (stabilizing and barrier metals and insulators) with a multitude of ultrathin (fractions of one micrometer) filaments of the superconductor proper arranged in the form of a helix with a certain pitch within the bulk of the stabilizing metal. The constancy of the properties and dimensions of such wires must be guaranteed over kilometer lengths, and the operating currents may vary from several amperes to several hundred thousand amperes. Wires that are currently manufactured may contain internal channels or be in the form of cables placed inside solid sheaths with a circulating coolant. Such current-carrying products are especially needed in building large SMS in which the mechanical stresses developing due to the interaction between the windings are exceptionally high and in which heavy demands are placed on the electric insulation. Figure 2 depicts the critical current density J_c as a function of the magnetic induction at $T = 4.2$ K. Because of the high brittleness of Nb_3Sn and, consequently, the strong dependence of the current-carrying capacity on conductor strains, the birth of the Nb_3Sn wire technology and the industrial development of this technology lagged 10 to 15 year behind the development of Nb – Ti superconductors. At present the production of Nb_3Sn wires is done commercially, with their cost varying from US$10 to US$15 for 1 kA m.

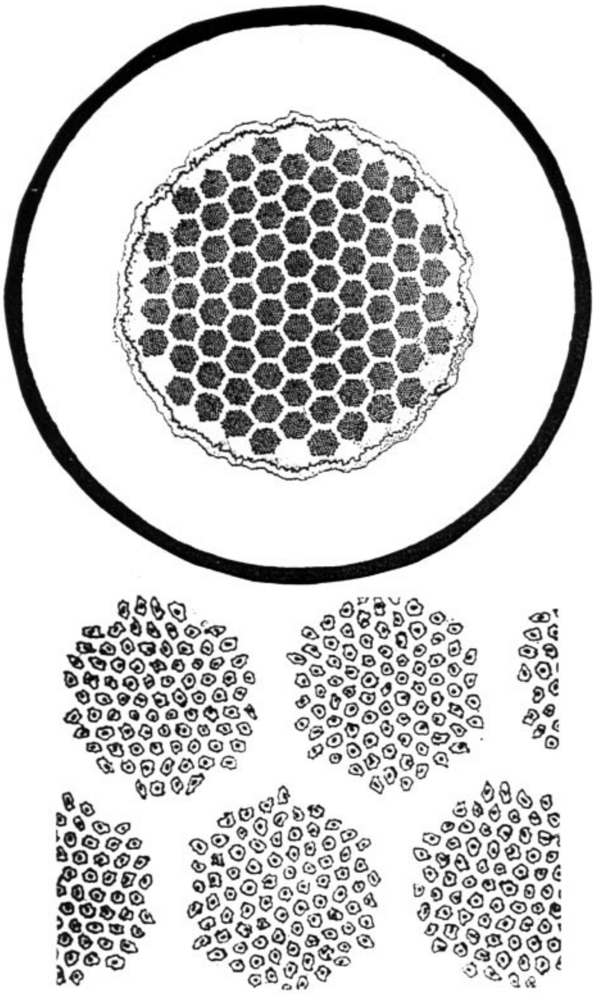

Figure 1. Cross-sectional view of a stabilized multiple-conductor Nb_3Sn-based cable used in the International Thermonuclear Experimental Reactor (ITER). The lower part of the figure depicts an enlarged view of a fragment of the cross section.

The values of attainable current densities and magnetic fields guaranteed by the application of Nb – Ti- and Nb_3Sn-based materials (see Fig. 2) encompass practically all existing and predicted demands imposed of electrophysical and electrotechnical equipment. Of the several thousand SMS in operation over the world, the majority are manufactured of

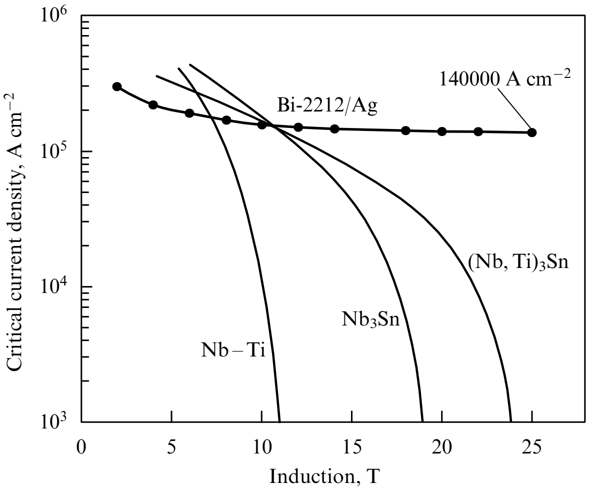

Figure 2. Critical current density as a function of the magnetic induction for industrial superconductors at $T = 4.2$ K.

Nb – Ti-based materials. One of the niches occupied by Nb_3Sn-based materials is high-field magnets, e.g. the SMS of NMR spectroscopy, which require, due to the need of high resolution, magnetic fields close to critical values. Or, to be more accurate, at the operating temperature we need a field that is high enough and yet lower than the irreversibility field H^* above which there can be no fluxoid pinning lattice in the material and the term 'critical current' loses all meaning — the material becomes resistive. In LTSC materials, H^* is close to the second critical field: the difference amounts to about 10%, therefore, the above more accurate definition is basically of academic interest.

The second area in which Nb_3Sn-based materials are used deals with SMS in which the winding is in a compound-strained state and is exposed to high-power electromagnetic pulses, as in the case of toroidal magnets generating the main field of tokamaks at the plasma current breakup. For a reasonable choice of operating parameters of such magnets, the temperature and field margin of Nb_3Sn-based materials guarantee the stability of SMS. This was demonstrated for the first time with the SMS of the Russian tokamaks T-7 and T-15.

It must be acknowledged that the main part of the technology of superconducting magnet creation, namely, the methods of retaining the superconducting state of the magnets and, when necessary, extracting the energy stored in these magnets, may be considered developed and mastered as a result of the large experience gained in the process of constructing SMS of different design and the doing the necessary computational and theoretical analyses. This broad area of research merits a separate discussion. Here, however, we limit ourselves to the general remark that in the AHCS area qualified staff build effective SMS with predictable parameters.

The development of AHCS operating at liquid-helium temperatures is largely affected by the accompanying development of liquid-helium technology. Three factors should be mentioned here. First, today large and medium sized systems (equivalent in refrigeration output to more than 100 l of liquid helium per hour) spend 300 W at room temperature to produce 1 W of helium refrigeration cold and have an increased capacity for prolonged nonstop operation. Second, large-scale systems of cryostatting SMS by employing superfluid helium, primarily at 1.9 K, have been developed and are in operation. This has made it possible, when using Nb – Ti-based materials, to raise the critical current density in the winding and to operate more reliably in fields close to the critical ones. Finally, the third factor essential for AHCS is the development of microcoolers with refrigeration output at liquid-helium temperatures up to 10 W and with a reliability of 10 thousand hours or more of continuous operation. And although the efficiency of these cryogenic devices is almost five times lower than that of more powerful stationary installations, they give SMS a new quality, self-containedness. This quality is used in the many thousands SMS MR-tomographs where microcoolers serve as compensators for the heat influx into the liquid-helium zone (several watts) or are used to build liquid-helium-free SMS. Perfecting cryogenic techniques has recently opened the path by which LTSC technology is penetrating conventional industries, e.g. superfine kaolin separation and kaolin cleaning from Fe and Ti oxides, or is used to build devices based on superconducting inductive energy storage systems with a stored energy of the order of 10 MJ and an output power of up to several hundred kilowatts for UPS systems of important customers, including remote customers.

Summarizing our brief discussion of the state of the art in applied high-current superconducting devices operating at liquid-helium temperatures, a discussion that stressed the outstanding results achieved in the development of unique electrophysical devices, in creating a commercial breakthrough in the field of medical diagnostics, and in making the first steps in conventional industries, we can say that AHCS is practically a modern industry with an annual turnover of more than two billion US$. The possibilities of perfecting LTSC materials and the respective techniques have largely been exhausted. Progress in the field of AHCS devices can be expected from the transition to new superconductors, which will broaden the temperature and field limits of the SMS working capacity [3].

3. AHCS operating at liquid-nitrogen temperatures

One of the outstanding discoveries of physics of the end of the 20th century, the discovery of HTSC, made possible a radical change in the status of AHCS. In 1986, J Bednorz and A Müller discovered superconductivity in the layered cuprate $LaBa_2CuO_4$ with a T_c significantly higher than the T_c of all superconductors known at that time and in the two years that followed new cuprate superconductors were synthesized. Their T_c overstepped the 77.3-K mark, the boiling point for liquid nitrogen under normal pressure, and then the 100-K mark, which opened a new way of changing the two basic components of any superconducting device, the superconductor itself and the cryogenic system. From the viewpoint of practical applications of AHCS, the most important factors are the raising of the operating temperatures and the possibility of replacing liquid helium, a costly and unrenewable coolant, by a new coolant, liquid nitrogen, which as a whole leads to substantial simplification in cryostatting the superconducting device. As a result the maintenance costs of cryostatting drop by a factor of one thousand compared to the costs of cryostatting at liquid-helium temperatures. The reason is that the cost of 1 l of liquid N_2 on average is 70 times smaller than the cost of 1 l of liquid helium, and the latent heat of evaporation of liquid nitrogen is 60 times greater. More than that, when liquid-nitrogen temperatures are involved, superconducting devices become, due to fundamental reasons related to the fact that the operating temperature is higher than liquid-helium temperatures, much more stable against various mechano-magneto-thermal perturbations. In the case when a region in the winding goes from the superconducting state into the normal state (what is known as normal-phase appearance), the rate of growth of the volume occupied by the normal state is several hundred times lower than in LTSC. Hence the protection methods developed for SMS operating at liquid-helium temperatures are quite sufficient for HTSC devices. An important positive factor that enables simplification of the construction of insulation, especially high-voltage insulation, is the high dielectric strength of liquid nitrogen, which is close to that of transformer oil.

The obvious beauty, misleading simplicity, and mystique of the very phenomenon of high-temperature superconductivity, in addition to the above-noted possibilities of applications, have served as a basis for a prolonged euphoria in the scientific community and mass media concerning the pace of development in this area of R&D. Notwithstanding the unprecedented amount of research on HTSCs done in the last 16 years from the time of the discovery of such superconductivity, we still have no accurate and universally recognized theory of this phenomenon. And only the first steps are being taken in the practical applications of high-temperature superconductivity [3].

Out of the more than a hundred HTSC compounds synthesized so far, only two compounds can serve, according to their set of properties and the extent to which they have been studied by physicochemical and technological means, as components of high-current HTSCs: $YBa_2Cu_3O_{7-x}$, with the structure of orthorhombic layered perovskite with $T_c = 94$ K, $H_{c2}(0) > 100$ T, $\xi(0) = 1.5$ nm, and $\lambda(0) = 150$ nm, and $Bi_2Sr_2Ca_2Cu_3O_{10}$ with the structure of tetragonal layered perovskite with $T_c = 110$ K, $H_{c2}(0) > 100$ T, $\xi(0) \approx 1.5$ nm, and $\lambda(0) \approx 150$ nm (for both compounds, the magnitudes of the upper critical field, the coherence length, and penetration depth are given for the basal plane *ab*). These compounds are denoted YBCO-123 and Bi-2223, respectively. They are characterized by an extremely high degree of structural anisotropy, with the result that their physical properties are highly anisotropic. Suffice it to say that the ratio of the values of $H_{c2}(T)$ with the field directed perpendicular to and parallel to the *c* axis, $H_{c2}^{\perp}/H_{c2}^{\parallel}$, amounts to 7 for YBCO and about 100 for Bi-2223. The irreversibility field, which determines the admissible range of operating magnetic fields, is also highly anisotropic. What is more important, however, is that in these materials the values of the irreversibility fields at liquid-nitrogen temperatures, $H^*(77)$, for fields parallel to the *c* axis are discouragingly small: for Bi-2223 this field is of the order of 0.3 T at $H_{c2}(77) \sim 50$ T, while for YBCO it is noticeably higher (~ 7 T) at $H_{c2}(77) \sim 30$ T. Because of the strong anisotropy of the HTSCs which are actually stacks of weakly bound superconducting and normal layers of thicknesses comparable to $\xi(0)$, the conventional ideas about the vortex lattice and the possible estimates of pinning forces proved to be unacceptable [4]. There are still no universally acceptable views on the nature of the (important) pinning centers, whereby optimization of the current-carrying capacity of industrial HTSCs is done, primarily by empirical means.

It seemed, judging by the set of properties and, primarily, because of the smaller anisotropy and higher irreversibility field at 77 K, that the first technology of industrial high-current HTSCs would be based on YBCO. And that actually happened at the beginning. However, the fabrication of ceramic winding materials proved to be much more complicated than the fabrication of materials operating at liquid-helium temperatures. This resulted in an unexpected situation, the technology of the first generation of high-current HTSCs was established for the Bi-2223 compound and its analog with lower parameters at 77 K, the Bi-2212 compound. At first glance the technology used in this case is very simple. It is called powder-in-tube (PIT) technology and consists of a sequence of pressing, broaching, and reduction processes at different temperatures and in the course of different time intervals applied to a blank in the form of a tube fabricated from a silver-based alloy and filled with a powder of what is known as a precursor, a substance or substances that as a result of processing become(s) the superconducting compound Bi-2223. Here, to achieve the highest possible current-carrying capacity of the product, the researchers had to combine many mutually exclusive technologies. The tube is made out of silver or silver-based alloys, which are inert with respect to ceramics, ensure diffusion of oxygen to support the necessary stoichiometry, and promote directional growth of the superconducting phase. The microcrystals proper of the superconductor must be texturized as much as possible: the angle between the grain boundaries must not exceed 3 – 5°, since otherwise the current-carrying capacity will diminish exponentially with increasing grain-boundary angle; also, the cross-sectional area of the product (a single wire) must be filled by the texturized superconductor as densely as possible. However, under mechanical strain, cracks and voids appear in the brittle material of the superconductor, and this drastically diminishes the current-carrying capacity. Hence the technological process must include submelting of the superconductor to heal the cracks. There are also other fine features of the process, namely, the grain composition of the powder, the exclusion of some impurities, and others. The round single-conductor wires are collected into a twisted cable assembly which is packed into a silver tube. The tube is then subjected to thermomechanical treatment, and in the final stage it is flattened and compacted. The result is a current-carrying element (multiple-conductor twisted wire) in the form of a tape with characteristic dimensions of 3 – 4 mm by 0.2 – 0.3 mm with 20 – 40% of the bulk filled by the superconductor and an operating current per tape of 20 to 100 A in the magnetic field of its own current at 77.3 K. The current-carrying elements with a higher operating current are made from single tapes collected into cable products. At present a single length of tape approaches 1000 to 1500 m. A big advantage of the PIT technology is the possibility of industrial scaling. Pilot production of the industrial high-current material Bi-2223 has been organized in several countries, including Russia. Figure 3 depicts the dependence of the critical current density on the field and the field's orientation with respect to the tape plane, and Table 1 lists the state-of-the-art and expected properties of this material according to estimates made by a group of European experts [5]. It must be especially noted that to guarantee unconditional competitiveness of HTSC products manufactured for industrial use the cost of the wire must not exceed US$20 for 1 kA m. In the United States it is hoped to solve this problem by building a big specialized installation with an annual production of 10000 km of tape. With such capacity, the plan is by 2004 not only to reduce the cost of 1 kA m of Bi-2223 but also to substantially improve the performance of this

Table 1. Current state and future prospects of tape superconductors Bi-2223/Ag (according to the data of a European group of experts).

Parameters	2000	2003
Width, mm	2.5–4.5	1–10
Thickness, mm	0.15–0.3	0.15–1
Length, km	1–1.5	2
Superconductor filling factor, %	23–35	40–50
Spread of critical parameters from batch to batch, %	6	2
Typical values of J_c at 77 K in the field of the intrinsic current, kA cm^{-2}	25	50
Design current density J_c (77 K, self-field), kA cm^{-2}	7	25
Typical current I_c (77 K, self-field), A	50	150
Cost of 1 kA m of conductor at 77 K in self-field, EURO	300	< 100
Critical strain, %	0.4–0,5	0.4–0.5
Critical stress, MPa	120	250
Critical temperature, K	110	110
Thermal conductivity of wire in silver at 50 K, W m^{-1} K^{-1}	500	500
Thermal conductivity of wire in silver alloy, W m^{-1} K^{-1}	50	50
AC losses at 77 K, 50 Hz, and magnetic induction 0.1 T (parallel), mW A^{-1} m^{-1}	0.3–0.4	0.1–0.25
Junction resistivity, Ω cm^2	2×10^{-7}	2×10^{-7}
Turn insulation breakdown voltage (insulation thickness 10 μm), V	300	500

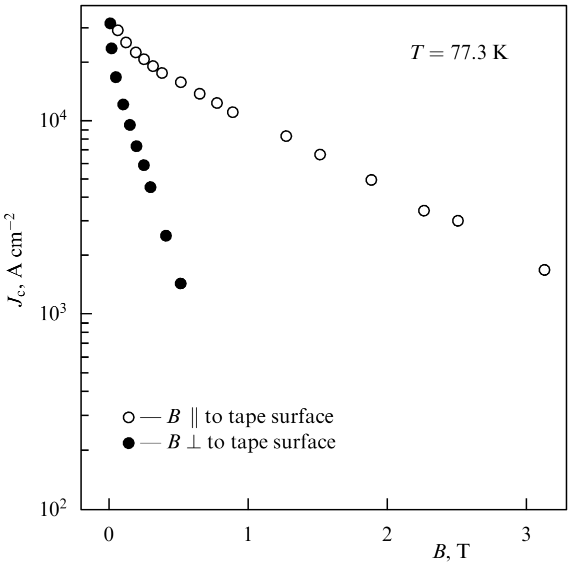

Figure 3. Anisotropy of the dependence of J_c on the magnetic induction for Bi-2223/Ag tapes at 77 K.

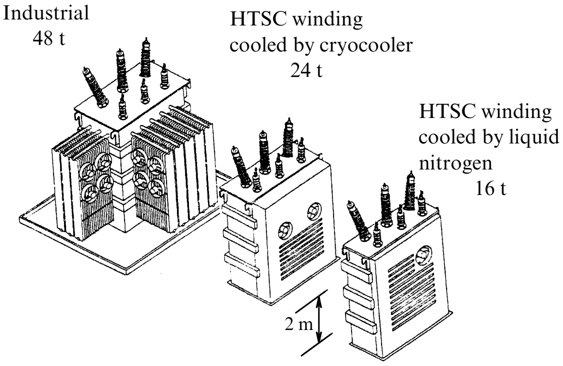

Figure 4. Comparison of overall dimensions of 30 MV A transformers.

superconductor product. So far the annual output of various companies manufacturing such tape has not exceeded several hundred kilometers of superconducting tape.

However, despite the fairly modest output of Bi-2223 superconductors and the more than modest performance at 77.3 K — the operating field perpendicular to the tape plane is no stronger than 0.3 T and the critical current density is about $(2-4) \times 10^8$ A m^{-2}, this first generation of industrial high-current HTSCs produced a breakthrough in the use of SMS in general industry, primarily in the electric-power industry [6, 7]. After the pilot variants of superconducting cables had been developed, full-scale sections of superconducting electric power lines (SEPL) were designed and became operational in real power supply systems (Table 2). HTSC transformers with an output power of about 1 MV A were built and tested in real power supply systems (Table 3 and Fig. 4). It is interesting to note that in such a classical and perfect electrotechnical device as a transformer, the use of superconductors not only increases the efficiency and reduces the mass-overall-dimension factors two to three times but also makes them fire-safe and environmentally sound.

Examples of one of the first electrotechnical devices incorporating HTSCs were superconducting fault current limiters (SFCL) with a nonlinear current–voltage characteristic. Such limiters guarantee almost instant operation and hence a rise in reliability and quality of supply of electric

Table 2. Characteristics of operational three-phase SEPL (superconducting material Bi-2223/Ag).

Parameter	Carrollton (Georgia), USA†	Copenhagen, Denmark	Detroit, USA
Became operational	1998	May 2001	June 2001
Length, m	33	30	120
Voltage, kV	12.5	30	24
Current, kA	1.25	3	2.4
Operating temperature, K	77	77	77
Insulation	'Cold dielectric'	'Warm dielectric'	'Warm dielectric'
Diameter, cm	10	10	10
Type of cable	Rigid	Flexible	Flexible
Losses‡ at operating temperature, W m^{-1}	~ 1	~ 1	~ 1
Number of customers	Equivalent of supplying 18 000 customers	150 000 customers	30 000 customers

† Intracorporate power supply system Southwire Co.

‡ Losses in SEPL reduced to room temperature are 10 to 15 times smaller than in ordinary cable.

Table 3. Parameters of tested and designed transformers.

Parameter	Single-phase model	Three-phase design model
Output power, MV A	0.8	20
Voltage ratio, kV	6.6/3.3	66/6.9
Current ratio, A	121/242	175/969
Working temperature, K	66	66
Frequency, Hz	60	60
Magnetic induction (room temperature), T	1.6	1.6
Impedance, %	0.67	7.5
Superconductor	Bi-2223/Ag	Bi-2223/Ag (alloy)
Coolant	Supercooled liquid nitrogen	Supercooled liquid nitrogen
Test voltage, kV	—	140/350
Losses in copper†, kW	3.54	10.8
Losses in steel†, kW	5.83	12.3
Efficiency, %	99.4	99.9

† Reduced to room temperature.

energy in the existing systems of transmission and distribution. The properties of existing HTSC wires predetermine the inevitability of the operation of such wires at 77 K in the biasing mode. Nevertheless, many types of SFCL with an iron yoke (Fig. 5) have been built, and they are also beginning to be used in electric power systems. Here it must be noted that one iron-free SFCL contains an HTSC coil 1-m in diameter and 0.75-m high in which at $T = 40$ K a magnetic field of 1.4 T is generated at the moment of operation. The list of the various electrotechnical devices that successfully employ HTSC wires can be continued. What is interesting is that such wires also play an important role in the operation of LTSC devices, where the use of HTSC current leads substantially facilitates the conditions of operation of liquid-helium cryogenic systems due to the drop in heat flux along the current leads by a factor of ten. The use of additional windings manufactured from industrial HTSC materials based on the Bi-2212 compound and operating at liquid-helium temperatures, where this material has a higher current density and a higher critical field than Nb_3Sn, makes it possible to raise the attainable field values of purely superconducting magnets needed, for instance, for NMR spectrometry.

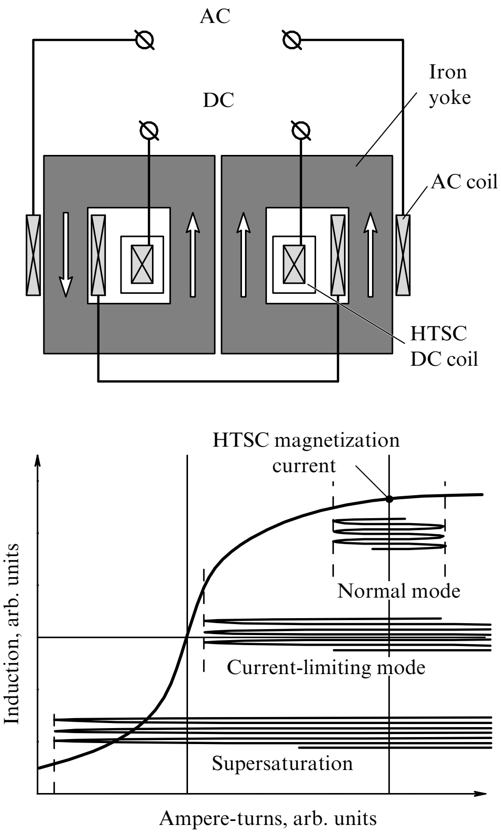

Figure 5. Design and operation principle of a superconducting current limiter (SFCL) with a saturated yoke.

It is quite obvious that increasing the output of Bi-2223 materials, broadening the range of their application, and further improving the technology makes it possible to improve the performance and cost effectiveness of this representative of the first generation of industrial HTSC wires. This, however, brings us no closer to the realization of our dream, namely, building an HTSC-based AHCS, which at liquid-nitrogen temperatures, according to the values of the critical current density ($10^{10}-10^{11}$) A m^{-2} and the range of operating fields 0.2 – 10 T, would open a broad avenue for a really true technical 'rearmament' of all electric-power generating and consuming branches of industry and technology through the use of superconducting equipment as being the most effective, both economically and environmentally.

Solving this problem requires manufacturing a new generation of industrial HTSC materials with higher operating parameters and a production cost that does not exceed that of ordinary superconductors (about US$10 for 1 kA m). Here the first candidate was the YBCO compound because in the earliest stages of HTSC research epitaxial layers of this compound several micrometers thick were obtained on structurally similar substrates by laser ablation, and the critical current density was found to be as high as 10^{11} A m^{-2} at 77.3 K in the magnetic field of the current flowing through the layer. Since the value of the irreversibility field at liquid-nitrogen temperature is high (7 T), this made it possible to solve the problems of AHCS operating at liquid-nitrogen temperatures. However, the situation is complicated by the properties of YBCO, such as the proximity to the metal – insulator transition, the d-wave nature of pairing, the small coherence length, as well as the chemical inhomogeneity, and this imposes severe restrictions on the methods used in fabricating current-carrying elements (the most important requirement is that the texture of superconductor layers must be close to ideal). Hence all modern approaches to fabricating YBCO wires must ensure the epitaxial nature of the super-

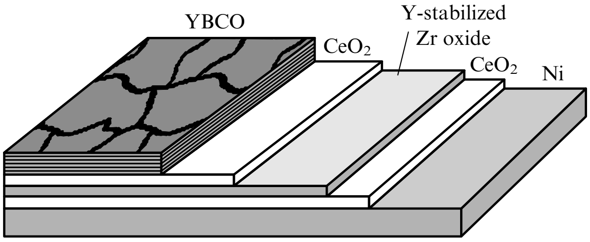

Figure 6. Second-generation HTSC.

conductor layers. Despite the fact that the critical current density attained in the epitaxial layers is high, the average current density proves to be fairly low because the superconducting wire consists of many components and its structure is complex.

One of the most promising technologies is the rolling assisted biaxially textured substrate (RABITS). In this technology, on top of a tape of Ni or its alloy textured by rolling a buffer layer of oxides is deposited consisting of CeO_2, yttrium-stabilized Zr oxide, and again CeO_2. Then comes a YBCO layer about one micrometer thick, a layer of silver or an alloy of it, and, finally, a layer of insulation. Various variants of this method have been suggested. But all this has been done on the laboratory scale, far from a pilot project and, the more so, from an industrial technology of second-generation HTSC devices (Fig. 6). Other HTSC compounds, e.g. mercury cuprates, with high values of irreversibility fields and high critical current densities are also possible candidates. However, compared to $YBa_2Cu_3O_{7-x}$, the research on these compounds is only in the early stages [8].

The metallic superconductor MgB_2 which was discovered at the beginning of 2001, has a hexagonal structure consisting of alternating layers of graphitelike planes of boron and closely packed hexagonal planes of Mg. It has a critical temperature of about 39 K, an upper critical field of about 39 T in the direction perpendicular to the c axis, an irreversibility field at $T = 0$ of about 35 T, and a critical current density of the order of 10^{10} A m^{-2} at $T = 4.2$ K and a 4-T field. Of course, there is still no technology for fabricating MgB_2-wires. However, its properties suggest that technologically MgB_2 will not be as erratic as the cuprate superconductors. The maturity of this technology will not solve all the problems of HTSC materials, but will certainly broaden the temperature and field ranges of operation of metallic superconductors. It is believed that this will take at least five years [9]. Such is the rough scenario of the development of the situation with second-generation HTSCs, provided that there will be no unexpected discovery, and the recent history of superconductivity gives ample proof of the opposite.

And yet, on the whole, the current state of high-current superconducting technology proves without doubt that the progress achieved in the last few years has transformed AHCS from a technology of single electrophysical devices to a technology of a fairly broad industrial nature, even at this early stage. In the 21st century superconductivity will play no less a role than semiconducting materials did in the second half of the 20th century.

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