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# Overview of Possible Applications of High $T_c$ Superconductors

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## 1. Introduction

The history of high- $T_c$  superconductors (HTS) begins in 1986 with the famous discovery of superconductors of the system Ba-La-Cu-O (Bednorz & Müller, 1986). Practical applications of superconductivity are steadily improving every year. However, the actual use of superconducting devices is limited by the fact that they must be cooled to low temperatures to become superconducting. For example, superconducting magnets used in most particle accelerators and in Magnetic Resonance Imaging (MRI) are cooled with liquid helium, that is, it is necessary to use cryostats that should produce and maintain temperatures of the order of 4 K. Helium is a very rare and expensive substance. On the other hand, because helium reserves are not great, the world's supply of helium can be wasted in a near future. Thus, because liquid nitrogen is not expensive and the reserves of nitrogen could not be wasted, it is important to use high- $T_c$  superconductors cooled with liquid nitrogen. Superconductors with critical temperatures greater 77 K may be cooled with liquid nitrogen.

Copper oxide superconductors are the most important high- $T_c$  superconductors (Cava, 2000). Up to the present time, after one hundred years of the first Kamerlingh Onnes discovery, the highest  $T_c$  is approximately equal to 135 K at 1 atm (Schilling & Cantoni, 1993), in superconductors of the Hg-Ba-Ca-Cu-O system. The discovery of a room temperature superconductor should trigger a great technological revolution. Nevertheless, in the meantime, waiting for this revolution, it is necessary to be prepared to apply existing technologies and develop new applications of HTS. The objective of this chapter is to give an overview of the most important applications of HTS. We shall discuss actual applications of HTS as well as possible applications of HTS in a near future.

Depending on the strength of the applied magnetic field, applications of HTS may be divided in two groups: large scale applications (large magnetic fields) and small scale applications (small magnetic fields).

Because HTS materials are brittle, the future of applications of HTS depends on the discovery of new radical solutions for this difficulty.

You will find in this chapter only discussions about practical applications of HTS. If you are interested in theoretical aspects of such applications, you may read a review book (Orlando & Delin, 1991).

The plan of this chapter is as follows:

The fabrication of HTS cables and coils are essential for all types of applications of HTS. Thus, in Section 2, we describe the state-of-the-art of the technology involved in the fabrication of cables, coils, electromagnets and magnets using HTS.

In Section 3 we study the most important projects involving large scale applications of HTS. In Sections 4 and 5 we describe small scale applications of HTS. We claim that the most relevant small scale applications of HTS are applications of superconducting electronics, that is, the use of superconducting HTS devices in all types of electronic applications. Thus, in Section 5 we describe the researches involving applications of HTS in superconducting electronics.

In Section 6 some possible HTS applications in medicine are discussed. Finally, in Section 7 concluding remarks are presented.

## **2. Uses of HTS in cables, coils, electromagnets and magnets**

Because cables and coils are essential for all types of applications of HTS we begin the study of practical applications of HTS by this topic. It is well known that HTS are brittle materials. Thus, there is a technological difficulty to produce cables, tapes and coils using these materials. However the researches and developments in this area indicate that many solutions have been obtained and HTS equipments and devices will become commercially available in a near future.

It is well known that metals are appropriate to electric field screening. However, metals are not appropriate to magnetic field screening. One outstanding property of a superconductor is the capability of magnetic field screening. Thus, only superconductor coaxial cables and tapes can be used for the best electromagnetic screening. In a great number of small scale applications and in large scale applications of superconductivity it is very important to make electromagnetic screening. This is another possibility in HTS applications using cables and tapes with HTS materials. On the other hand, bulk HTS materials may also be used for this purpose.

The use of superconducting cables in high-voltage transmission lines is one of the most important applications of HTS materials. The performance of HTS cable depends on the quality of HTS tapes. HTS tapes for power transmission cables must be produced long enough to fulfill the required length of cable core to be installed. On the other side, it also must have sufficient critical current density and good mechanical characteristics.

Essential for the fabrication of coils, electromagnets and magnets is the development of new processes for the production of wires, cables and tapes using HTS. A study about the progress of researches for the production of wires, cables and tapes is available in chapters of a recent book (Polasek et al., 2009).

## **3. Possible large scale applications of HTS**

Very high magnetic fields are involved in all possible large scale applications of superconductivity. Because HTS materials are type-II superconductors, it is crucial the use of HTS in the fabrication of coils, electromagnets and magnets.

The most important large scale applications of superconductivity are in: power transmission lines, energy storage devices, fault current limiters, fabrication of electric generators and motors, MAGLEV vehicles, in medicine (see Section 6) and applications in particle accelerators.

Now we discuss possible applications of HTS in the fabrication of electric generators and motors. The production of superconducting bearings is the crucial problem involved in the development of generators and motors. It is well known that a HTS material may levitate steadily above a magnet. The inverse position, that is, the levitation of magnets above superconductors is also stable (Davis et al., 1988). The stability of this levitation is due to the property of the magnetic flux quantization (see Section 4.1). Taking advantage of the capability of stable levitation of HTS materials it is possible to fabricate bearings for the development of generators and motors (Hull, 2000; Ma et al., 2003; Sotelo et al., 2009).

The development of an hydroelectric power generator has been successfully obtained (Fair et al., 2009).

In the next two sections we discuss the applications of HTS in energy storage devices, fault current limiters and applications in MAGLEV vehicles.

### 3.1 Fault current limiters and energy storage devices

It is well known that in electrical network, there are various faults produced by lightning, short circuits, etc. When these events occur, the current increases abruptly and there happens unexpected faults in the equipment, producing many damages, like fire and blackout. It is important to control these large currents for power system security. The objective of a Fault Current Limiter (FCL) is to limit very high currents in high speed when faults occur.

It seems that Superconducting Fault Current Limiters (SFCL) may provide the most promising solution of limiting the fault current in power systems. It is known that a superconductor has zero resistance when the current is lower than a certain critical current ( $I_c$ ). If fault current exceeds  $I_c$ , superconductor becomes a normal conductor and this property may be used to design a SFCL.

An overview about the progress of the researches on high temperature superconductor fault current limiters is available in a review paper (Noe & Steurer, 2007).

Certainly energy storage devices are the most important equipments for energy conservation and ecological energy projects. The applications of solar energy, wind energy and other alternative energy sources, is limited by the fact that all these energies sources are intermittent. Thus, it is convenient to develop energy storage devices to storage these intermittent energies. HTS materials may be used in two important energy storage devices: in flywheels or in superconducting coils. The applications of HTS in flywheels is based on the use of HTS in superconducting bearings (see the end of the last section).

Because superconductors have zero resistance and considering the magnetic flux quantization rule, we conclude that the best method to storage energy is to maintain persistent currents in superconducting coils. Superconducting Magnetic Energy Storage (SMES) seems to be the best solution for energy storage projects.

A study about HTS energy storage devices is available in an article (Wolsky, 2002)

### 3.2 Applications of HTS in MAGLEV vehicles

The most relevant techniques for MAGnetic LEVitation (MAGLEV) vehicles are: (1) Electrodynamics Levitation (EDL), (2) Electromagnetic Levitation (EML), and (3) Superconductor Magnetic Levitation (SML).

EDL projects are based on Faraday-Lenz law: when a magnetic flux changes in he neighborhood of a conductor, a current is induced in the conductor. Superconductor

magnets are maintained inside the train. There is an experimental project in Japan with two railway tracks between Osaka and Tokyo and the train based on this technique has reached a record speed of 582 km/h.

EML projects are based on the attractive force between an electromagnet and a ferromagnetic material. In this case it is not necessary to use superconductor magnets. It is well known that the levitation due to the force between an electromagnet and a ferromagnetic material is not stable and so it is necessary to use stabilization systems. There is a commercial train using this technique in China and a railway line with 30 km is used to transport people between Shanghai International Airport and Shanghai Lujiazui.

SML projects are based on the perfect diamagnetism of superconductors. It is well known that a HTS material may levitate steadily above a magnet. Conversely, the levitation of magnets above superconductors is also stable (Davis et al., 1988). Because HTS are type II superconductors, the magnetic flux exclusion (Meissner effect) is partial. Inside a type II superconductor there are Abrikosov vortices. A magnetic field may be maintained inside an Abrikosov vortex. Thus, the stability of this type of levitation is due to the property of the magnetic flux quantization (see Section 4.1). SML projects take advantage of this property. Thus, SML levitation is more stable than EDL and EML levitations.

Considering the above mentioned property, we conclude that a simple SML project for MGLEV vehicles is as follows. Permanent magnets may be used in the tracks and blocks of HTS materials may be used inside the train. The levitation and the motion of the vehicle is due to the magnetic repulsive force between the track and the train. There are some projects of application of HTS materials and permanent magnets in MAGLEV trains using this SML technique (David et al., 2006; Stephan et al., 2008; Sotelo et al., 2010).

#### 4. Possible small scale applications of HTS

The most important small scale superconducting devices fall into two basic classes: (a) SQUID systems, which are designed to measure magnetic flux and other electromagnetic measurements, and (b) Josephson devices which take advantage of the electromagnetic characteristics of Josephson junctions to perform traditional electronic functions. We have divided the study of small scale applications in these two classes, but we emphasize that SQUIDS are fabricated using Josephson junctions as well. A collection of works about SQUIDS, Josephson junctions and other superconducting devices is available in a review book (Ruggiero & Rudman, 1990).

##### 4.1 Magnetometers and other devices based on SQUIDS

It is well known that Superconducting QUantum Interference Devices (SQUIDS) are the most sensitive detectors of magnetic flux available. Basically, a SQUID is a flux-to-voltage transducer, providing an output voltage proportional to the magnetic flux.

SQUIDS combine two physical phenomena: flux quantization and tunneling (Josephson, 1962). Magnetic flux quantization is the most important macroscopic property of the superconducting state. Consider a closed loop in the bulk of a superconductor. It is known that quantum mechanics must be applied for the superconducting state. Applying the Bohr-Sommerfeld quantization rule to this loop we may write:

$$\oint \vec{p} \cdot d\vec{l} = nh \quad (1)$$



where  $p$  is the linear momentum,  $dl$  is a line element,  $n$  is an integer and  $h$  is Planck's constant. The canonical momentum is given by:

$$\mathbf{p} = m\mathbf{v} + q\mathbf{A} \quad (2)$$

where  $m$  is the mass,  $v$  is the velocity,  $q$  is the charge and  $A$  is the magnetic potential vector. Considering  $v = 0$  in the bulk of the material, by equations (1) and (2) we have

$$\oint q\vec{A} \cdot d\vec{l} = nh \quad (3)$$

Using the rotational theorem in equation (3) we find

$$\iint \text{rot } \vec{A} \cdot d\vec{S} = nh / q \quad (4)$$

where  $dS$  is an area element. We know that  $B = \text{rot } A$  and  $q = 2e$  (Cooper pair). Thus, by equation (4) we have

$$\Phi = \iint \vec{B} \cdot d\vec{S} = nh / 2e \quad (5)$$

Equation (5) is the flux quantization rule, that is, the magnetic flux  $\Phi$  must be quantized in a superconducting loop according to the rule:  $\Phi = n \Phi_0$ , where  $\Phi_0$  is a quantum of magnetic flux:

$$\Phi_0 = nh/2e = 2,07 \times 10^{-15} \text{ Wb} \quad (6)$$

A SQUID is, in essence, a superconducting closed loop containing one or two Josephson junctions. Taking advantage of the flux quantization rule, it is possible to measure a very small magnetic flux of the order assigned in equation (6). On the other hand, because a SQUID is a flux-to-voltage transducer, providing an output voltage proportional to the magnetic flux, it is possible to measure quantities smaller than  $10^{-15}$  Wb. By this reason, we conclude that SQUIDS are the most sensitive system for magnetic flux measurements. We conclude also that instruments based on SQUIDS are the most appropriate to be used in very high precision electric and magnetic measurements.

There are two kinds of SQUIDS: (a) dc SQUID and (b) rf SQUID. A dc SQUID consists of two Josephson junctions connected in parallel in a closed loop; it operates with a steady current bias (dc bias). The rf SQUID involves a single Josephson junction interrupting the current flow around the superconducting loop and it is operated with a radiofrequency bias.

Because it required only a Josephson junction, the rf SQUID was simpler to manufacture and became commercially available. However, in the mid of the 1970 decade, it was shown that dc SQUID is more sensitive than rf SQUID. Since then, there has been great developments of dc SQUIDS. By contrast, there has been little developments of rf SQUIDS in the last decades. Only low-Tc superconductors have been used in commercially available SQUIDS until 1988. However, in the last two decades HTS have been used in SQUIDS.

Because the tremendous sensitivity to magnetic flux, low-Tc and HTS SQUIDS remain the most practical ultra-sensitive magnetic field detectors. Thus, SQUID systems may be projected for a number of practical applications: submarine detection and relative motion magnetic field detectors, mineral surveying, medical diagnostics, and so on. On the other hand, with proper circuitry design, SQUID systems may be projected for a great number of

scientific instruments. A number of HTS SQUIDs have been projected in the last two decades. There is also advances in HTS thin-film SQUIDs (Koch et al., 1987).

There are many works about applications of HTS in SQUIDs. We list some of these works (Zimmerman et al., 1987; Golovashkin et al., 1989; Mankiewich et al., 1988).

#### 4.2 Devices based on Josephson junctions

We study now the most important small scale superconducting devices based on Josephson junctions. For practical applications of Josephson effects there are two types of Josephson junctions: (a) Superconductor - Insulator - Superconductor (SIS) junction and (b) Superconductor - Normal - Superconductor (SNS) junction. SIS junctions are also known as tunneling junctions because it occurs tunneling of Cooper pairs from one superconductor to the other through the insulator barrier. The tunneling of Cooper pairs was predicted by Josephson in 1962 (Josephson, 1962).

In the case of SNS junctions there is no insulator barrier, there are only two SN interfaces. Thus, it is easy to conclude that the current - voltage characteristic curve of a SIS junction should be completely different from the current - voltage characteristic curve of a SNS junction.

Interesting studies about Josephson effects and Josephson junctions may be found in review books (Barone & Paternò, 1982; Likharev, 1986).

A theoretical prediction of the current - voltage characteristic curve of a SNS junction has been successfully obtained (Kummel et al., 1990).

It is important to note that the current - voltage characteristic curve of a SNS junction exhibits a negative resistance region (Kummel et al., 1990). Taking advantage of this negative resistance region, two terminal devices based on SNS junctions may be projected for a great number of applications in superconducting electronics (Luiz & Nicolsky, 1991). In the next section we shall study such possible applications.

### 5. Applications of HTS in superconducting electronics

In Section 4 we have stressed that SQUIDs are fabricated using Josephson junctions. On the other hand, Josephson junctions are used directly in a great number of small scale applications of superconductivity. Thus, to study applications of HTS materials in superconducting electronics it is necessary to describe the properties and capabilities of Josephson junctions.

We claim that SNS junctions are more appropriate than SIS junctions for HTS small scale applications of superconductivity. This conclusion is based on the following comparison of 4 characteristics:

1. It is well known that in a SIS junction there is a very thin insulator between the two superconductors of the SIS junction. To occur tunneling, it is necessary that the thickness of the insulator layer should be of the order of the coherence length of the superconductor layer. The coherence length of a HTS is about 1000 times greater than the order of magnitude of the coherence length of a low-Tc metallic superconductor. For example, in a HTS material of the system Bi-Sr-Ca-Cu-O, the coherence length is approximately equal to 1 angstrom ( $10^{-10}$  cm) along the c-axis and approximately equal to 40 angstroms in the transverse direction (Davydov, 1990). Compare this value with the (isotropic) coherence length of a metallic superconductor which is of the order of 1000 to 10000 angstroms. It is known that it is not easy to make a SIS junction because the difficulties of fabrication of very thin layers of insulators. Thus, in the case of a SIS junction made with HTS this drawback is very enhanced.

In the case of a SNS junction there is no insulator barrier, no tunneling occurs in the SN interfaces, thus the above mentioned difficulties are not present in the fabrication of SNS junctions.

2. There is another important reason to use SNS junctions (instead of SIS junctions) in all possible applications of small scale applications of superconductivity using HTS. Generally a SIS junction is very small. To enhance the performance of a SIS junction it should be necessary to use arrays of a great number of SIS junctions. By the above mentioned reasons, to make arrays of SIS junctions is a very difficult task. However, because a SNS junction is a normal metal region between two superconductors, a SNS junction may have macroscopic dimensions. It is sufficient to make a constriction in a bulk superconductor to obtain a SNS junction. On the other hand, the so called microbridge may be actually realized with macroscopic dimensions. Consider a certain great current flowing in a HTS. Consider a constriction in this material. In the constriction, the current density increases. If the current density is greater than the critical current density of the HTS material considered, the constriction becomes normal and the system becomes a SNS junction. An important example of a SNS junction obtained with a HTS material (YBCO) is available (Alvarez et al., 1990).
3. It is well known that the current – voltage characteristic curve of a SIS junction exhibits hysteresis. However, it has been shown that in the current–voltage characteristic curve of a SNS junction there is no hysteresis (Kummel et al., 1990). Because in a great number of applications in superconducting electronics it is necessary to use devices without hysteresis, we conclude that, for those applications, SNS junctions are more appropriate than SIS junctions.
4. At last, we may compare the equivalent circuit of a SIS junction with the equivalent circuit of a SNS junction. Because there is an insulator barrier in a SIS junction, the equivalent capacitance of a SIS junction is greater than the equivalent capacitance of a SNS junction. Because in a great number of applications it is necessary to use low equivalent capacitances, it is obvious that, for those applications, SNS junctions are more appropriate than SIS junctions.

In the past 50 years, the development of *semiconductor electronics* have produced a great technological revolution. With each generation of integrated circuits, the semiconductor devices became smaller, more complex and faster. However, the clock rate of semiconductor devices used in electronics has saturated around 5 GHz. The speed of the processors and all the devices of semiconductor electronics will soon reach a limit of this order of magnitude. One reason for this limit is not the switching speed of the transistors, but is due to power dissipation.

What is *superconducting electronics*? We may say that *superconducting electronics* is a new type of electronics based on superconducting devices.

There are two possible improvements in the traditional semiconductor electronics taking advantage of superconducting devices: (a) hybrid electronic systems, that is, systems containing semiconductors and superconductors, and (b) complete *superconducting electronics*, that is, electronic systems containing only superconducting devices, without semiconductor devices. A study about the state-of-the-art and future developments of superconducting electronics is available in a review article (Anders et al., 2010).

Until now, the most reasonable improvement in the performance of the traditional semiconductor electronics seems to be provided by hybrid electronic systems containing semiconductors and superconductors. We know that traditional semiconductor electronics



has been the most reliable and modern technology in the past 50 years. However, the speed limit mentioned above is a fundamental difficulty in the further development of this technology. The prime reason for that limit is explained by Joule's law:  $Q = RI^2$ , where  $Q$  is the heat loss,  $R$  is the resistance and  $I$  is the current. The heat loss in the metallic interconnections can be avoided if superconducting interconnections could be used. In this case the speed of the processors and other devices should be increased.

In the above mentioned improvement in the traditional semiconductor electronics, we give an example of a solution involving an hybrid semiconductor-superconductor system.

Now we discuss the second possibility: a complete *superconducting electronics*, that is, electronic systems containing superconducting devices, without semiconductor devices. In the following sections we discuss this possibility.

### 5.1 Generators, amplifiers, mixers, detectors switches and thin-film filters using HTS materials

The most important electronic devices are generators, amplifiers, mixers, detectors and switches.

Superconducting devices based on SIS junctions and SNS junctions may be projected to substitute these and other semiconductor devices.

In this section and in the next 3 sections we discuss the possible use of superconducting devices in order to substitute semiconductor devices.

We have pointed out in the previous section that SNS junctions are more appropriate than SIS junctions in the prospective applications of Josephson junctions in superconducting electronics.

Combining a SNS junction with appropriate resonant circuits, it is possible to project many types of generators (Luiz & Nicolsky, 1990; Luiz & Nicolsky, 1991; Nicolsky & Luiz, 1992).

Taking advantage of the negative resistance region of SNS junctions, two-terminal devices based on SNS junctions may also be used to design electronic switches (Luiz, 1993; Luiz & Nicolsky, 1993).

On the other hand, using this same property of SNS junctions, it is possible to design mixers and detectors (Gorelov et al., 1997; Luiz et al., 1997; Luiz et al., 1999).

Signal amplification and harmonic generation may be obtained using SNS junctions with appropriate circuits (Luiz et al., 1998; Luiz et al., 1999).

Terahertz oscillations have also been obtained using HTS Josephson junctions (Güven et al., 2009; Minami et al., 2009; Machida & Tachiki, 2001).

In high frequency ranges up to 100 – 500 GHz the surface resistance of HTS like  $\text{YBa}_2\text{Cu}_3\text{O}_7$  is so low that it becomes commercially interesting to build thin-film filters and resonators with quality factors of the order of  $10^6$ .

Telecommunication applications of HTS are specially useful in the cellular phone market. For example, hundreds of superconducting filters have been installed in the USA in critical base stations for cellular phone communications (Anders et al., 2010).

### 5.2 Digital signal processing and analog signal processing

In the previous section we have pointed out that SNS junctions may be used for switching circuits and other superconducting electronic devices. The very high switching speeds that may be obtained using superconducting switching circuits suggests that wideband signal processing is an interesting possible application of HTS materials. A discussion about the

possibility of applications of superconductor devices in digital signal processing is available in a review article (Van Duzer & Lee, 1990).

On the other hand, the use of other types of superconducting circuits is also possible in analog signal processing and in analog-to-digital converters. A discussion about the possibility of applications of superconductor devices in wideband analog signal processing is available in review articles (Clarke, 1988; Withers, 1990). Other reviews are available in a book (Van Duzer & Turner, 1998).

### 5.3 Three-terminal devices using HTS

In Section 5.1 we have described the possibility of applications of two-terminal superconducting devices based on SNS junctions for a number of applications of HTS in superconducting electronics. However, it is also feasible to use three-terminal superconducting devices in applications of HTS in superconducting electronics.

The most important three-terminal superconducting devices are superconducting transistors. A study about the characteristics and the performance of HTS transistors is available in a review article (Mannhart, 1996).

### 5.4 Digital computer, quantum computer and flux qubit

An exciting application of superconducting electronics should be provided by the possible applications of HTS in digital computers.

The most important components of a digital computer are memory units and arithmetic units.

The metallic interconnections of the traditional semiconductor digital computer should be substituted by superconducting interconnections.

The memory ferromagnetic units of the traditional digital computer should be substituted by superconducting memories containing superconducting loops. In Section 4.1 (equation 5), we have emphasized that in superconductors we must apply the flux quantization rule, that is, the magnetic flux  $\Phi$  must be quantized in a superconducting loop according to the rule:  $\Phi = n \Phi_0$ , where  $\Phi_0$  is a quantum of magnetic flux. Thus, using appropriate circuits, the ferromagnetic memories of the traditional computers may be substituted by superconducting memories containing superconducting loops.

Arithmetic units are based on the action of transistors and other semiconductor devices. These arithmetic units may be substituted by superconducting devices described in Sections 5.1, 5.2 and 5.3. Therefore we conclude that digital superconducting computers will be feasible in a near future. The overall speed of a superconducting computer should be up to 1000 orders of magnitude greater than the speed of a traditional computer (Anders et al., 2010).

Superconducting digital technology is based on the Rapid Single Flux Quantum (RSFQ) logic. Another application of RSFQ is in superconducting **quantum bits (qubits)**. The *quantum computer* is based on qubit operations. Classical **bits** are used in traditional computers. However, in a quantum computer, the quantum bit (qubit) may carry two quantum states at the same time. Quantum mechanical phenomena such as quantum superposition, quantum entanglement and other quantum mechanical properties are the concepts involved in a *quantum computer*. Interesting discussions about flux qubits are found in the literature (Chiorescu et. al., 2003; Clarke & Wilhelm, 2008).

## 6. Possible applications of HTS in medicine

The ultimate objective of science and technology is human welfare. Thus, it is natural to ask how superconductivity may be applied in medicine. Medical applications of HTS involve small scale as well as large scale applications of superconductivity.

The most important large scale applications of superconductivity are Magnetic Resonance Spectroscopy (MRS) and Magnetic Resonance Imaging (MRI).

The most important small scale applications of superconductivity are those applications based on the properties of SQUIDs and Josephson junctions (Sections 4 and 5). We have pointed out that SQUIDs are the most sensitive devices for magnetic field measurements. It is well known that blood contains ions. Therefore, the circulation of blood produces small magnetic fields that can be detected using SQUIDs.

By measurement of the magnetic fields produced by blood circulation in the human body it is possible to make non-invasive diagnosis of diseases. The most important applications of HTS in medicine are (1) magnetoencephalography (MEG) for non-invasive tests of the brain activity and (2) magnetocardiography (MCG) for non-invasive tests of the heart activity. The magnetic activity of other regions of the human body may also be detected using SQUIDs.

A study about the state-of-the-art and future developments of applications of superconductivity in medicine is available in a review article (Anders et al., 2010).

## 7. Concluding remarks

In this chapter we have studied the most relevant questions about the possible applications of HTS. The history of superconductivity has not been smooth. Generally, very slow process was witnessed between breakthroughs. Practical applications of superconductivity follows a breakthrough with a time lag of about 30 years.

Practical applications of HTS are emerging steadily every year. However, as we have stressed in the Introduction, radical technological solutions should depend on the discovery of a HTS material with critical temperature in the neighborhood of room temperature. However, what happens to the basic science of HTS? As it has been noted in a recent book (Luiz, 2010), the microscopic mechanisms in HTS are unclear. However, nearly every year new theories are proposed and new HTS materials are synthesized.

Large scale applications of HTS have a bright future. Electric energy production and energy storage are the most important large scale applications of HTS. On the other hand, small scale applications of HTS have a bright future as well; these applications are more feasible than large scale applications of HTS. Because small scale applications of HTS generally involve small volumes, that is, very small Josephson junctions volumes, it is not necessary to use cryostats with liquid helium (or liquid nitrogen). In some very small systems, it is sufficient to use a thermodynamic cycle to maintain the temperature of the system at a value lower than the critical temperature of the material. On the other hand, experimental evidences show that HTS behave like a stack of superconductor-insulator-superconductor interfaces (SIS junctions) and superconductor-normal-superconductor interfaces (SNS junctions), that is, HTS materials may be considered as a network of intrinsic Josephson junctions (Kleiner & Müller, 1994; Machida & Tachiki M, 2001).

Finally, according to the study in Section 5, we claim that applications of HTS materials and SNS junctions should give new radical solutions for the use of superconducting devices in superconducting electronics.

The future of applications of HTS is very exciting. Because HTS materials are brittle, it is necessary to overcome this difficulty. Nevertheless, this drawback exists only in the fabrication of cables and coils (see Section 2). However, in a great number of HTS applications it is sufficient to use HTS cylindrical blocks. We hope that the researches described in this overview will be helpful for the discovery of new practical applications of HTS.

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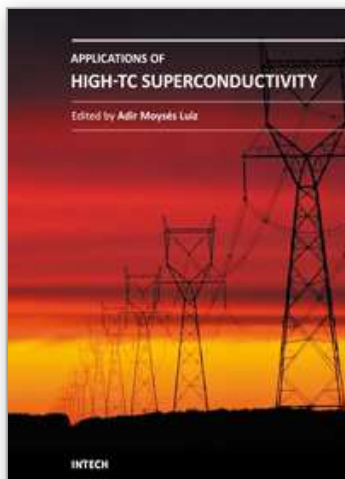


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## **Applications of High-Tc Superconductivity**

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This book is a collection of the chapters intended to study only practical applications of HTS materials. You will find here a great number of research on actual applications of HTS as well as possible future applications of HTS. Depending on the strength of the applied magnetic field, applications of HTS may be divided in two groups: large scale applications (large magnetic fields) and small scale applications (small magnetic fields). 12 chapters in the book are fascinating studies about large scale applications as well as small scale applications of HTS. Some chapters are presenting interesting research on the synthesis of special materials that may be useful in practical applications of HTS. There are also research about properties of high-Tc superconductors and experimental research about HTS materials with potential applications. The future of practical applications of HTS materials is very exciting. I hope that this book will be useful in the research of new radical solutions for practical applications of HTS materials and that it will encourage further experimental research of HTS materials with potential technological applications.

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