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Overview of Superconductivity and Challenges in Applications

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Considerable progress has been achieved during the last few decades in the various fields of applied superconductivity, while the related low temperature technology has reached a high level. Magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) are so far the most successful applications, with tens of thousands of units worldwide, but high potential can also be recognized in the energy sector, with high energy cables, transformers, motors, generators for wind turbines, fault current limiters and devices for magnetic energy storage. A large number of magnet and cable prototypes have been constructed, showing in all cases high reliability. Large projects involving the construction of magnets, solenoids as well as dipoles and quadrupoles are described in the present book. A very large project, the LHC, is currently in operation, demonstrating that superconductivity is a reliable technology, even in a device of unprecedented high complexity. A project of similar complexity is ITER, a fusion device that is presently under construction. This article starts with a brief historical introduction to superconductivity as a phenomenon, and some fundamental properties necessary for the understanding of the technical behavior of superconductors are described. The introduction of superconductivity in the industrial cycle faces many challenges, first for the properties of the base elements, e.g. the wires, tapes and thin films, then for the various applied devices, where a number of new difficulties had to be resolved. A variety of industrial applications in energy, medicine and communications are briefly presented, showing how superconductivity is now entering the market.

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Considerable progress has been achieved during the last few decades in the various fields of applied superconductivity, while the related low temperature technology has reached a high level. Magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) are so far the most successful applications, with tens of thousands of units worldwide, but high potential can also be recognized in the energy sector, with high energy cables, transformers, motors, generators for wind turbines, fault current limiters and devices for magnetic energy storage. A large number of magnet and cable prototypes have been constructed, showing in all cases high reliability. Large projects involving the construction of magnets, solenoids as well as dipoles and quadrupoles are described in the present book. A very large project, the LHC, is currently in operation, demonstrating that superconductivity is a reliable technology, even in a device of unprecedented high complexity. A project of similar complexity is ITER, a fusion device that is presently under construction. This article starts with a brief historical introduction to superconductivity as a phenomenon, and some fundamental properties necessary for the understanding of the technical behavior of superconductors are described. The introduction of superconductivity in the industrial cycle faces many challenges, first for the properties of the base elements, e.g. the wires, tapes and thin films, then for the various applied devices, where a number of new difficulties had to be resolved. A variety of industrial applications in energy, medicine and communications are briefly presented, showing how superconductivity is now entering the market.

Keywords: Superconductivity; Meissner effect; high temperature superconductors; magnetic resonance imaging; nuclear magnetic resonance; thermal stability of superconducting wires; magnetic energy storage; Large Hadron Collider; ITER; effect of high energy irradiation on superconducting properties.

1. Overview of Superconducting Properties

1.1. Introduction

Since the discovery of superconductivity by Kamerlingh Onnes in 1911, this phenomenon has exerted an unbroken fascination, and the search for new materials with higher transition temperatures goes on. Today, it is widely accepted that the discovery of new materials with considerably higher transition temperatures or improved fabricability with respect to the presently known ones is still possible, leading to unexpected applications.

The ability to carry large currents in the superconducting state under operating conditions, even in the presence of high magnetic fields, is a stringent requirement for an industrial wire. Soon after the discovery of the sudden transition of the electrical resistivity of Hg to zero, however, Onnes observed that superconductivity in the materials known at that time (defined today as type I superconductors)

was destroyed by applying rather small currents or magnetic fields. This observation limited the interest in applied superconductivity for a few decades, but this changed dramatically after the discovery of type II superconductors, which are the basis of all present developments.

At present, an increasing variety of devices are based on the effects of superconductivity. Several important industrial achievements could not have been made without the effect of vanishing electrical resistivity. This holds for magnets, where the possibility of *persistent currents* in NbTi and Nb₃Sn wires has revolutionized the field of spectroscopic analysis. The two main examples are represented by magnets for magnetic resonance imaging (MRI) for medical analysis and high field nuclear magnetic resonance (NMR) for industrial research in pharmacy, and molecular biology. Worldwide, the total number of magnets for resonance analysis has reached several tens of thousands and is still increasing.

Superconductivity represents the only viable alternative for large applications in accelerators and energy: the LHC collider reaches fields of up to 8.8 T and is already in operation. At present, the upgrade with fields reaching 15 T in the quadrupole magnets is under study, while ITER, the experimental fusion magnet designed for 12 T, is already under construction. In all these cases, the electrical resistance in Cu cables would have led to prohibitively high levels of heating.

A large number of applications in the energy sector requiring only low or intermediate magnetic fields have already been successfully tested on an industrial scale, e.g. fault current limiters, high current cables, transformers and generators. Considerable market penetration could be expected within the next few years. The list of superconducting applications would not be complete without mentioning the transportation issues: the construction of a levitated high speed train between Tokyo and Osaka has been decided and will be operational within a few decades. Finally, first studies undertaken regarding wind generators show that superconductivity would constitute a real alternative at power levels exceeding 10 MW.

The history of superconductivity is marked by the sudden discovery of new material classes with new or improved properties. On the way from the discovery of a new material class to its application, considerable experimental and metallurgical difficulties had to be overcome, depending on the individual nature of the superconductor. The search for solutions to these high technology requirements has also led to substantial progress in various research fields: new methods had to be developed for fabricating complex wires of kilometer lengths based on Nb_3Sn , a very brittle superconductor, and to use them as a basis for high field magnets. Another example is given by the coated conductor tapes based on the superconductor $\text{YBa}_2\text{Cu}_3\text{O}_7$ or $\text{R.E.Ba}_2\text{Cu}_3\text{O}_7$, called Y-123, in the following: the need for industrial lengths of high quality tapes with high critical currents has not only led to intensive development of complex thin film deposition techniques, but also to progress of analysis methods in the nanometric range.

In the first part of this article, a brief introduction to superconductivity as a phenomenon is given. It would lead too far to give a detailed description of all aspects of superconductivity: the present

discussion will thus be limited to those fundamental properties necessary for understanding the technical behavior of superconductors. More detailed information about fundamental properties can be obtained from the series of books [2–6] which were used for preparing the present overview. The second part will treat selected material problems and their challenges, while the last part will be devoted to the main applications, in view of present and future developments. The challenges in a variety of industrial devices are discussed.

1.2. Historical

Since 1911, a series of steps have led to the present understanding of superconductivity. A very complete overview can be found in the book *100 Years of Superconductivity* [1]. The following steps mark the progress in superconductivity over the last decades:

- 1933: Expulsion of the magnetic field by Meissner and Ochsenfeld: perfect diamagnetism.
- 1934: London two-fluid model; prediction of penetration depth.
- 1937: Observation of a new behavior in superconductors in the presence of magnetic fields (later called type II), by Shubnikov.
- 1950: Phenomenological theory by Landau and Ginzburg, based on Landau's theory of second order transitions.
- 1957: Theoretical prediction of a triangular flux line lattice by Abrikosov.
- 1957: Microscopic theory of superconductivity by Bardeen, Cooper and Schrieffer (BCS theory).
- 1954: Discovery of Nb_3Sn .
- 1962: First commercial superconducting NbTi wires and first superconducting magnet.
- 1962: Discovery of the Josephson effect.
- 1987: High T_c superconductors, by A. Müller and G. Bednorz (T_c up to 130 K).
- 2001: Discovery of MgB_2 ($T_c = 39$ K).
- 2008: First superconducting Fe-based pnictides, with T_c values up to 56 K.

1.3. Meissner effect and penetration length

In 1933, Meissner and Ochsenfeld found that the magnetic flux of a superconducting sample cooled below the critical temperature, T_c , is completely

expelled from the interior of the sample: the magnetic induction $\mathbf{B}$ inside the material was found to be zero. This behavior characterizes the superconductors of type I, which were the first ones to be discovered. With a few exceptions (Nb, Ta, V, etc.), metallic elements are all type I superconductors. After finding a different behavior in new compounds, and based on theoretical arguments, Abrikosov in 1957 proposed classifying them as type II superconductors.

The expulsion of the magnetic field (see definition in footnote a) from the interior is due to the critical currents at the vicinity of the surface, which cause a magnetic flux being opposed to the applied external field: $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, with $\mu_0 = 4\pi \times 10^{-7}$. Thus, the Meissner effect with $\mathbf{B} = 0$ corresponds to $\mathbf{M} = -\mathbf{H}$, i.e. the sample becomes a perfect diamagnet. For a superconducting wire with a given diameter d , a critical current I_c can be defined. For simple superconductors this current, which generates the critical field at the surface, is given by Silsbee's rule: $I_c = d/\mu_0 B_c$. There is a critical magnetic flux B_c , the thermodynamical critical field, above which the surface supercurrents can no longer exclude flux from the inside. The variation of B_c with temperature for type I superconductors is well described by the empirical formula

$$B_c = B_0 \left[1 - \left(\frac{T}{T_c} \right)^2 \right]. \quad (1)$$

This parabolic behavior is strictly observed in type I superconductors (Fig. 1), but represents also a good approximation for type II superconductors. The first description of superconductivity has been given by the two-fluid model of Gorter and Casimir, who assumed a superconductor to be containing electrons of two different types: normal electrons and superelectrons. The normal electrons have the same properties as in normal metals, while the superelectrons present the new, unusual properties. For their explanation of the Meissner effect, F. and H. London proposed replacing in superconductors Ohm's law $\mathbf{J} = \sigma \mathbf{E}$ by Newton's law of motion

$$\frac{\partial \mathbf{J}}{\partial t} = (1/\Lambda) \mathbf{E}, \quad (2)$$

^aIn vacuum, the quantities H (magnetic field) and B (magnetic induction) differ only by a multiplicative constant: $B = \mu_0 H$. Inside a superconductor, $B = \mu \mu_0 H$, where μ is the permeability. Informally, though, and formally for some recent textbooks, the term "magnetic field" is used to describe B as well as or in place of H . In the present overview, the symbol B will be used, but where necessary it will be distinguished between applied magnetic field strength and magnetic flux.

Fig. 1. Thermodynamical critical fields B_c vs. T for the type I superconductors Hg, Sn, In and Tl.

where $\Lambda = m_e/n_s e^2$ is the London parameter and n_s the density of superconducting electrons. Using Maxwell's equation, and taking into account that in the bulk of the superconductor, $\mathbf{J} = 0$ and $\mathbf{B} = 0$, they found that

$$\nabla(\Lambda \mathbf{J}_s) = -\mathbf{B}, \quad (3)$$

the second London equation. Introducing Ampère's rule and after several transformations, it is

$$\nabla^2 \mathbf{B} = \mathbf{B}/\lambda_L^2. \quad (4)$$

This result implies that the external magnetic field (and current) can penetrate only a thin surface layer of a superconductor, the London penetration depth, defined as $\lambda_L = (m_e/\mu_0 n_s e^2)^{1/2}$. The solution to this equation is represented by $B_a(x) = B(0)e^{-x/\lambda}$ and reflects the screening effect: near a plane surface, the magnetic flux and the supercurrent density both decay exponentially with depth x (Fig. 2). The treatment of the Meissner effect leading to a penetration depth λ_L became the basis of the electrodynamics of superconductors. The situation in a wire is drawn in Fig. 3. The value of λ_L varies between 40 and >100 nm, as illustrated for several superconductors in Table 1.

The shielding of the magnetic field and current due to the Meissner effect in type II superconductors is the basis of magnetic levitation. Today, known applications of magnetic levitation are ultrarapid

Fig. 2. Exponential decrease of the magnetic flux B with distance x into a bulk superconductor, with the characteristic decay length λ_L (London penetration depth).

Fig. 3. The current in a type I superconductor flows only in a surface layer. For currents $I \geq I_c = B_c \cdot 2\pi R / \mu_0$, the thickness of this layer is zero and the wire becomes normal.

Table 1. Some values of the penetration depth at 0 K.

	$T_c(K)$	$\lambda_L(nm)$
Al	1.1	50
Nb	9.2	40
NbTi	9.5	60
Nb ₃ Sn	18.3	80
YBa ₂ Cu ₃ O ₇	92	400

centrifuges, while prototypes of levitating trains and flywheels have been tested successfully. Particularly noteworthy is the 18-km-long test track for levitating trains in Japan: a series of successful tests in

the last 20 years were the main argument for the already-mentioned construction of the first levitating train between Tokyo and Osaka.

There is another useful application of the Meissner effect: it is still the ultimate practical test when one is determining whether a newly discovered material is really superconducting or not.

1.4. Heat capacity of superconductors

The free enthalpy of a superconductor with the volume V in the presence of an external field strength H and the magnetic flux $B = \mu_0 H$ can be formulated:

$$dG = -S dT + V dp - V \cdot M \cdot dB. \quad (5)$$

The difference between the free enthalpies $G_n(T, B)$ for the normal state and $G_s(T, B)$ for the superconducting state can be calculated taking into account the Meissner effect with $M = -B/\mu_0$:

$$G_s(T, B) = G_s(T, 0) + B^2. \quad (6)$$

Since at the thermodynamical critical field B_c there is $G_s(T, B_c) = G_n(T, B_c)$ and $G_n(T, B_c) = G_n(T, 0)$, it follows that

$$G_n(T, 0) - G_s(T, 0) = B_c^2, \quad (7)$$

and $G_n > G_s$, the difference reflecting the stability of the superconducting state. Using $S = -(\frac{\partial G}{\partial T})_B$, one can calculate the difference between the entropies:

$$S_n - S_s = -V. \quad (8)$$

Since $\frac{\partial B_c}{\partial T} < 0$, there is $S_n - S_s > 0$; thus, the superconducting state has always a higher order. Since $B_c(T) = 0$ for $T \rightarrow T_c$; it follows that $S_n - S_s = 0$ at $T = T_c$; thus, in the absence of a latent heat, the superconducting transition is a phase transition of the second order. This is in contrast to the case where the normal state at $T = \text{const}$ is caused by a magnetic field $B > B_c$; in this case, the thermal energy $(S_n - S_s)T$ has to be added, and the transition is of the first order.

These considerations can be used to calculate the change of specific heat at the superconducting transition. With $C = -T(\frac{\partial^2 G}{\partial T^2})_{p,B}$, the difference at $T = T_c$ can be written as

$$C_s - C_n = (\partial/\partial T)^2. \quad (9)$$

Fig. 4. Discontinuity at $T = T_c$ of the specific heat C_v of a superconductor.

This is the Rutgers formula, which implies that there must be a discontinuous jump at $T = T_c$ in the specific heat as a function of temperature. This jump of C_v , reflecting the second order transition, is schematically represented in Fig. 4.

1.5. The mixed state

The difference between type I and II superconductors can be illustrated on the basis of Fig. 5, which shows the variation of magnetization as a function of the applied field $B_a = H_a/\mu_0$. In type II superconductors, the flux is completely expelled up to the applied field B_{c1} (the lower magnetic field), as in type I superconductors. However, with an increasing applied magnetic field, the flux partially penetrates until B_{c2} , the upper critical magnetic field, is reached. The correlation between B_{c1} , B_{c2} and B_c is illustrated by the equality of the two hatched surfaces in the regions $B_{c1} < B_a < B_c$ and $B_c < B_a < B_{c2}$.

Figure 6 shows schematically the variation of the critical fields B_{c1} and B_{c2} as a function of temperature. The upper critical field B_{c2} can reach values >100 T in HTS materials (see Table 2, where some type II superconductors are listed). On the basis of the Ginzburg–Landau theory, Abrikosov found in 1957 that superconductors of type I and type II can be characterized on the basis of the energy at the normal/superconducting boundary. This boundary is characterized by two energies: the energy for the expulsion of the magnetic field, ΔE_B , and the energy decrease due to the condensation of the Cooper pairs,

Fig. 5. (a) Magnetization as a function of the applied field $B_a = H_a/\mu_0$ for a type II superconductor. A “Meissner” behavior is only observed for $B_a < B_{c1}$, (b) Partial penetration of magnetic flux as a function of B_a .

Fig. 6. Variation of the critical field flux B_{c1} and B_{c2} as a function of temperature for type I and type II superconductors.

ΔE_C . For the total energy, it follows that

$$\begin{aligned} \Delta E_{\text{tot}} &= \Delta E_C - \Delta E_B \\ &= (\xi - \lambda) A \cdot B_c^2 / 2\mu_0, \end{aligned} \quad (10)$$

where A is the boundary surface while the volume for the energies corresponding to ΔE_C and ΔE_B is simplified by $\xi \cdot A$ and $\lambda \cdot A$, respectively.

For $\xi > \lambda$, $\Delta E_{\text{tot}} > 0$: when building up the boundary, the energy loss due to condensation is

Table 2. Upper critical fields and coherence lengths for several type II superconductors. The asterisk indicates a wide range of B_{c2} and ξ_0 values in HTS and FeAs superconductors.

Compound	$T_c(K)$	$B_{c2}(T)$	$\xi_0(nm)$
NbTi	9.5	14	6
Nb ₃ Sn	18.3	28	4
Nb ₃ Al	19	33	4
MgB ₂ (bulk)	39	39	5
PbMo ₆ S ₈	15	60	2.2
Rb ₃ C ₆₀	29.3	50	~2
La _{1-x} Sr _x CuO ₄	38	65*	~1.5*
YBa ₂ Cu ₃ O ₇ (123)	92	120*	~1*
FeAsO _{1-x} F _x (1111)	55	>50*	~2.5*
(Ba _{0.6} K _{0.4})Fe ₂ As ₂ (122)	38	70–135*	~2*

larger than the expulsion energy. The most favorable energy configuration is thus the expulsion of the magnetic field flux, which is the condition for a type I superconductor.

For $\xi < \lambda$, $\Delta E_{\text{tot}} < 0$: the energy associated with the boundary between superconducting and normal regions is negative; and this will favor the formation of as many boundaries between normal and superconducting regions as possible. This is the behavior of type II superconductors. Since the magnetic flux in the normal region is not B_c but generally B , the boundary energy is

$$\Delta E_{\text{tot}} = \Delta E_C - \Delta E_B = \xi \cdot B_c^2 < \lambda \cdot B^2. \quad (11)$$

For $\Delta E_{\text{tot}} < 0$, there is $\xi \cdot B_c^2 < \lambda \cdot B^2$. With the definition $\kappa = \lambda/\xi$, the so-called Ginzburg–Landau parameter, one gets $B^2 > B_c^2/\kappa$. It follows that superconductors of type I and type II can clearly

be defined:

$\kappa > \frac{1}{\sqrt{2}}$: type II superconductors;

$\kappa < \frac{1}{\sqrt{2}}$: type I superconductors.

In the mixed state range between B_{c1} and B_{c2} , the Meissner effect is only partial. As mentioned above, for $B_{c1} < B < B_{c2}$, the magnetic flux penetrates the superconductor in the form of *flux lines*, consisting of fine flux threads along which the superconductor has a normal core. Each vortex carries a quantized magnetic flux:

$$\Phi_0 = \frac{h}{2e} = 2.067 \times 10^{-15} \text{ Wb(Tm}^2\text{)}, \quad (12)$$

where h is the Planck constant and e is the charge of the electron. The magnetic flux B is directly related to n , the number of vortices per m^2 , by the relation $B = n\Phi_0$.

In the mixed state the superconductor can withstand strong applied magnetic fields, up to B_{c2} , without returning to the normal state. A schematical representation of the flux penetration in the mixed state is shown in Fig. 7. Abrikosov found in 1937 that the vortex lattice in a pure type II superconductor is triangular (Abrikosov lattice), which was experimentally confirmed in 1957 by Essmann and Träuble by means of a decoration technique.

The distribution of vortices in a superconductor is schematically shown in Fig. 8. At the center of each penetrating flux line, the value of n_s is zero and rises over ξ , the coherence length (see Fig. 9).

The magnetic field flux associated with each normal core is spread over a region with a diameter of λ , each normal core being surrounded by a vortex of circulating current. The coherence lengths for a

Fig. 7. Magnetic flux penetration in the mixed state.

Fig. 8. Flux lines in a type II superconductor in the mixed state. The Lorentz force $f_L = j \cdot \Phi_0$ acts on each flux line.

series of type I and type II superconductors are listed in Tables 1 and 2, respectively.

Based on the above remarks, one can analyze the behavior of a type II wire carrying a current I . Only the fields in the mixed state region, where $B_{c1} < B < B_{c2}$, are of interest. The current transport in a pure type II superconductor is represented in Fig. 8. A Lorentz force f_L acts on each flux line carrying a current $f_L = j \cdot \Phi_0$, which will lead to a flux flow perpendicular to B and I , thus causing a dissipation of energy. It follows that it is not possible to carry a supercurrent without losses in a *pure* type II superconductor!

In order to avoid this dissipative process, it is necessary to hinder the flux line movement. This is

achieved by the introduction of a homogeneous distribution of normal conducting defects (or inclusions) in the superconductor, with the size being comparable to the coherence length. This can be understood by comparing the formation energy e_F per unit length between two flux lines, one of which (2 in Fig. 10) passes through a normal inclusion. Comparing the formation energy per unit length, it is seen that the energy loss of flux line 2 is smaller than that of 1, the normal core (the normal inclusion) being already there. In order to move the flux line from 2 to 1, a force $F = e_F \cdot l/x$ is necessary. As long as this force is smaller than the Lorentz force, there will be no movement: these inclusions are acting as *pinning centers*. Regardless of the nature of the superconducting material, the optimization of J_c will always depend on the distribution and density of nanosized defects or inclusions, as will be shown in the following.

The magnetization curve of a superconductor of type II exhibits a hysteresis (Fig. 11), as a direct consequence of the presence of pinning centers. The hysteresis is due to the shielding current at the surface of the superconductor. Flux does not penetrate up to B_{c1} , but remains pinned to the pinning centers at the surface, and there is almost perfect diamagnetism. Above B_{c1} , the flux lines will start to penetrate up to a disappearance of magnetization at

Fig. 9. Schematical representation of an isolated vortex and of a triangular vortex array. Distribution of the magnetic field flux B , of the order parameter (superelectron density). J is the current circulating around the normal cores.

Fig. 10. Pinning force F of a flux line through a normal conducting inclusion.

Fig. 11. Magnetization loop of an industrial (hard) type II superconductor, indicating the initial curve from zero induction (a, b), and a pair of magnetization values (c, d) used to extract $J_c(B)$.

B_{c2} . If the field is now lowered, the flux lines will still remain trapped in the superconductor, even at $B = 0$.

1.6. The Bean critical state model

In order to interpret the irreversibility of the magnetization curves, Bean has developed a simple

empirical model for deducing the critical current of the sample. The main hypothesis of his *critical state* model is that the magnetic field penetration in the sample is linear and not exponential as in the London equation. In addition, the slope $\frac{dH}{dx}$ does not depend on the applied field. In contrast to the London model, where the field penetrates in an entirely superconducting sample, the penetration occurs now through the vortices. An important advance of the Bean model over the London equations is that it allows one to explain the hysteresis effects and thus energy loss per cycle.

As already mentioned, the force on the vortex is given by $\mathbf{f} = \mathbf{j} \times \Phi_0$, which can be rewritten as the force per unit volume for the one-dimensional case, e.g. in one direction x , as $F = \frac{dH}{dx} B$. If F_p is the pinning force per unit volume, there will be vortex motion as long as $F > F_p$. This motion will stop once $F = F_p$ is reached at all points: this physical regime is called the *critical state*. The variation of the field inside the sample is directly linked to the current J_c , which can pass through the sample without vortex motion:

$$F_p = J_c B = \frac{dH}{dx} B. \quad (13)$$

For a superconducting slab of thickness d with an applied longitudinal field B , its penetration above B_{c1} will reach a depth $\Delta = \frac{dH}{dx}$. Figure 12 represents the situation for increasing values of a longitudinal applied magnetic field B up to the values B^* for full field penetration, followed by a decrease of B .

The applied field at which the magnetic flux is fully penetrated in the rod is $B^* = \frac{1}{2}\mu_0 J_c d$. If the

Fig. 12. Schematic critical state flux profile: field penetration of a longitudinal field B in a superconducting rod. B first increases (1–3), then decreases (4–6). B^* is the field for full field penetration.

applied field is again decreased to zero, a considerable quantity of flux remains trapped in the sample. During the whole cycle, there is dissipation of energy, necessary for the movement of the vortices. These losses due to hysteresis limit the potential efficiency of type II superconductors in ac applications. From a hysteresis cycle, one can deduce the critical current density, $J_c(B)$. The difference $\Delta M(B)$ between the magnetization measured in increasing and decreasing fields can be calculated from Fig. 11. Applying the Bean model, one gets

$$J_c[\text{Am}^{-2}] = 2 \frac{\Delta M}{d}. \quad (14)$$

Although this formula does not account for uniformity differences in real conductors, it is often used for the determination of J_c , as indicated in Fig. 11, as an alternative to the measurements by transport. However, particular care has to be given to the definition of the boundary conditions which may affect the result of the inductive J_c measurement. The critical state Bean model can also be used for describing the field penetration in a cylindrical wire where a current I is flowing, as shown in Fig. 13.

For the following consideration, j_c is assumed to be constant and $x \ll R$. For a current $I \ll I_c$, the flux penetrates up to the depth x_1 , given by $I = j_c \pi (2Rx_1 - x_1^2)$, and $x_1 = I/2\pi R j_c$. For a current $2I$, the penetration depth is x_2 , which can be determined

to $x_2 = 2x_1$. The full penetration $x_n = R$ will be reached for the current $I_n = \pi R^2 j_c$. If the current is decreased from $2I$ to I , the penetrated flux must again be expelled from the wire. Following the Bean model, this happens by inverting the direction of the current in the outermost region x_4 of the wire. The thickness x_4 can be found from $x_4 = x_2 - x_4$:

$$x_4 = \frac{x_2}{2} - \frac{I}{4\pi R j_c}. \quad (15)$$

1.7. Stabilization criteria for superconducting wires

A superconducting wire in a magnet must be able to recover its equilibrium even after a perturbation which leads locally to zones where the temperature can exceed T_c . A simple presentation of the effects of a thermal perturbation on a wire of radius R in a bath of temperature T_b is shown in Fig. 14 and will be discussed in the following. Many reasons can lead to a perturbation causing a local enhancement of temperature in a superconducting wire. In the following it will be simply supposed that the perturbation has already taken place, regardless of the causes.

After linearization, the temperature gradient in the perturbed zone is $T' = dT/dx = 2/a(T_p - T_b)$. The equilibrium conditions leading to a normal zone can be determined by the balance of the power terms

Fig. 13. Penetrating magnetic flux in a cylindrical wire under a current I . The regions through which the current flows are calculated with the Bean model. (a) Current $I \ll I_c$; (b) increased current, $I = 2I_c$; (c) decreasing current from $2I$ to I . (After P. Komarek [5].)

Fig. 14. Cryogenic stabilization of a technical superconducting wire.

in the system:

- (1) Joule heat in the normal zone. With $j = I/\pi R^2$ and ρ_n , the normal resistivity at T_c , there is

$$P_{\text{Joule}} = R_n I^2 = \rho_n a j^2 \pi R^2. \quad (16)$$

- (2) Transmitted power from the normal zone to the neighboring superconductor, by thermal conductivity. With the thermal conductivity λ ,

$$P_{\text{thermal}} = 2\pi R^2 \lambda \frac{dT}{dx} = 2\pi R^2 \lambda T'. \quad (17)$$

- (3) Power transmitted to the cryogenic bath over a line dx of the normal zone, introducing the heat transition coefficient h :

$$P_{\text{bath}} = 2\pi a h [(T_c - T_b) + a T']. \quad (18)$$

The stability condition can thus be formulated as

$$P_{\text{Joule}} = P_{\text{thermal}} + P_{\text{bath}}, \quad (19)$$

$$\begin{aligned} \rho_n J^2 &= 2\lambda T' \frac{1}{a} + \frac{h T^*}{2R} a + 2h \frac{T_c - T_b}{R} \\ &\equiv f(a). \end{aligned} \quad (20)$$

The minimum of this equation can be found to be

$$f_{\min} = 2T'(\lambda h/R)^{1/2} + 2h \frac{T_c - T_b}{R}. \quad (21)$$

The stability condition $\rho_n J^2 < f_{\min}$ is now

$$\alpha_{\text{st}} = \frac{\rho_n^2}{f_{\min}} < 1, \quad (22)$$

where α_{st} is the *Stekly* parameter [7].

After some improvements, the Stekly criterion is currently used for determining the stability of magnets. In order to improve the conditions of stability, various parameters in the equation of α_{st} can be optimized, which leads to some general

principles:

- The difference $(T_c - T_b)$ in Fig. 14 should be as large as possible.
- The radius of the wire R should be as small as possible. More generally, it is thermally more favorable to subdivide the wire in order to get a multifilamentary structure.
- Heat transfer: the filaments should be enclosed in a highly conductive matrix, e.g. Cu or Al, to ensure a high thermal transmission to the cooling medium.

1.8. Relation between J_c , B_{c2} and T_c

The ability to carry large currents in the superconducting state even in the presence of high magnetic fields is the most important requirement for an industrial superconductor. The superconducting state in a wire carrying a current I is defined by the three quantities J_c , the critical current density, B_{c2} , the upper critical magnetic field (the magnetic flux) and T_c , the critical temperature. These three quantities are correlated, as schematically shown in Fig. 15. If only one of these three critical quantities is exceeded, the wire becomes normal: only working points below the envelope are possible.

For $B_{c2}(T)$, the experimental results can be approximated by $B_{c2}(T) = B_{c2}(0)[1 - (T/T_c)^2]$. The critical current density depends on the density of pinning centers, which in turn is field-dependent, as described by E. Kramer in 1973 [8]. In order to understand the effect of pinning, one can consider an ideal flux line lattice and a random distribution of defects as pinning centers. For very small pinning forces, i.e.

Fig. 15. Correlation between critical current density J_c , upper critical magnetic induction B_{c2} and transition temperature T_c in industrial superconducting wires.

at low magnetic fields, the lattice will respond elastically: the regular flux line lattice will essentially subsist, and the pinning effect by defects or inclusions will still be small. The total pinning force F_p is smaller than would be possible taking into account all built-in defects. With an increasing field, the positional long-range order of the flux line lattice is lost. More and more flux lines will be trapped by defects, thus leading to an enhancement of F_p . With further increase of the magnetic field, the number of flux lines will increase. The global pinning force per volume, F_p , frequently exhibits scaling behavior with a reduced field $b = B/B_{c2}$ and κ : with magnetic field will in general have the following behavior:

$$F_p = BJ_c = S \cdot B_{c2}^n / \kappa^m b^p (1 - b)^q, \quad (23)$$

where the constant S is a geometrical function of the microstructure [8]. For normal particle pinning, this approximation is better than a few percent for $b > 0.4$. As an example, the variation of F_p vs. B for a multifilamentary wire as measured by J. Ekin [9] is shown in Fig. 16. It shows that this representation is still valid after applying uniaxial tensile stress on the wire: $F_{p\max}$ does not change for various strain values ε . This simple formulation fails at low flux densities and at phase lines where there is a change in the basic pinning mechanism due, for instance, to dimensional crossover or to the onset of thermally activated processes.

Fig. 16. Pinning force as a function of the applied magnetic field for a binary multifilamentary Nb_3Sn wire at 4.2 K for various strain values ε . The upper critical field B_{c2}^* as determined from Kramer extrapolation is 20.8 T and the fitting parameters are $p = 0.56$ and $q = 2.0$. (From Ref. 9.)

2. Challenges for Superconducting Materials and Conductors

2.1. Time between discovery and application

The list of envisageable applications involving superconductivity is very long, and an impressive number of prototype devices for a large variety of purposes have already been constructed and successfully tested. When one is studying the impact of superconductivity in the near future, a question arises about the R&D and the necessary time for reaching the step of industrialization. It is interesting to compare superconductivity to other high technology areas, e.g. semiconductors or fiber optics. In these areas, the time gap between ideas and preliminary experimental work on prototypes and market penetration and commercial success was of the order of 3–4 decades. For example, the initial development of transistors at AT&T Bell Laboratories started in 1947, but the first integrated circuit was built in 1958. More than 30 additional years were necessary to reach the present highly sophisticated industrial level. A second case is fiber optics communication: the concept of channeling light was produced in 1858 by J. Tyndall, while communication by light was realized in 1880 by Alexander Graham Bell. The first optical fibers were only developed in 1971 by Corning.

In the case of superconductivity, it took more than 50 years between its discovery in 1911 and the first NbTi magnet. Nb_3Sn was discovered in 1954 by B.T. Matthias, and was rapidly followed by small prototype magnets. However, the first industrial Nb_3Sn magnet producing a field of 15 T was not available before the 1980s. In a similar way, the HTS materials were discovered in 1987 and the market penetration is starting only now, 25 years later, after a strong worldwide effort expended on a multitude of prototypes. These prototypes were developed for very different purposes, the most important ones being e.g. high current cables, fault current limiters, transformers, energy storage, generators and microelectronics. It is very important for the future developments that all prototypes involving superconductors were successful: it can be said that superconducting systems have demonstrated their reliability under industrial conditions.

Fig. 17. Highest T_c values in various superconducting material classes discovered since 1911. (The pnictides, discovered after 2008, were added to the original graph established by DOE.)

2.2. Superconducting materials with higher T_c values

The superconducting material classes found since 1911 are shown in Fig. 17. The highest T_c value reached so far was produced by applying 30 GPa to the compound HgBaCaCuO , leading to an increase from 131 to 164 K [10]. The question arises whether new materials with even higher T_c values can still be found. However, it must be said that, up to the present day, all superconductors shown in Fig. 17 were found unexpectedly. No valid principle is known to predict new superconducting materials with higher T_c values.

2.2.1. The search for new superconductors

In spite of the failure of the known strategies for the search for new superconductors with higher T_c , there is no reason to exclude the possibility that one of the known strategies, possibly after slight changes or in combination with other ideas, may lead to success in the future. The search for new superconductors being an important challenge, it may be of interest to briefly mention the strategies which have been applied so far.

In the 1970s, B.T. Matthias started his search with a purely *empirical principle*: the number of electrons per atom in a given lattice. This guideline, which was not supported by any theory, led to interesting results, but was limited to the class

of binary superconductors based on transition metals, with a maximum T_c of 23 K for Nb_3Ge [11]. A new era started in 1987 with the discovery of HTS oxides by Müller and Bednorz [12]. This discovery had the merit of stimulating the synthesis of a large variety of compounds where superconductivity was not expected. In the meantime, many new classes of superconductors were discovered, the latest one being the family of Fe-based pnictides (see Fig. 17). Now, the search was extended to crystal structures with four elements (quaternaries) and even to those with five elements and more. It is easily seen that the number of possible new combinations for a purely empirical search exceeds 10^7 . This unrealistic number can be reduced only if new restricting criteria are found. However, after the failure of the BCS theory for most compounds found after 1987, no new model is presently able to describe satisfactorily all aspects of HTS superconductivity.

We are still far away from finding superconductors by design. The field to be investigated is extremely wide, as illustrated by the complexity of the various theoretical problems to be solved:

- Electronic structure calculations by density functional theory;
- Large scale phonon calculations in the nonlinear, anharmonic limit;
- Formulation of “very strong” electron–phonon coupling (beyond Eliashberg theory);

- Determination of quantitative pairing mechanisms for high temperature superconductors.

In spite of all these difficulties, the search for new superconductors goes on, as illustrated by the recent progress achieved in organic superconductors, where the highest T_c value for the alkali-metal-doped hydrocarbon with the formula 1,2:8,9-dibenzopentacene is now 33 K [13].

2.3. Superconducting wires and tapes for applications

At the present time, there is still no ideal superconducting material with the potential for all temperatures up to T_c values in the presence of high magnetic fields. The choice of industrial superconductors is quite limited and does not even include the compounds with the highest T_c values shown in Fig. 17. Indeed, mainly due to metallurgical difficulties in preparing high quality wires and tapes based on the compounds HgBaCaCuO and TlBaCaCuO, the choice of industrial superconductors is limited to compounds with T_c values below 110 K (see Table 3). Within these limits, the choice of the superconducting material for industrial applications will essentially depend on the operation conditions, e.g. operation temperature, operation magnetic field, critical current density, ac losses, mechanical and thermal stability, sensitivity to high energy irradiation and, last but not least, production costs. One cannot establish general rules, since each application requires a different solution. Particular aspects of superconducting wires are briefly treated here.

Table 3. Transition temperature (T_c), upper critical fields (B_{c2}), anisotropy (γ) and coherence lengths (ξ) of various superconducting high field compounds for industrial applications. Exception: FeAs-122, which is still not industrial.

Material	T_c (K)	$B_{c2}(0)$ (B)	γ	ξ (nm)	ξ_{ab} (nm)	ξ_c (nm)
NbTi	9.6	14	1	6		
Nb ₃ Sn+Ti	18.3	28	1	4		
MgB ₂	39	40	~5		5	~2
YBCO	93	>100(//)	≤14		1.5	0.8
Bi-2212	92	>100(//)				
Bi-2223	110	>100(//)	>100			
FeAs-122	38	>70(//)	>70		2–3	1–1.5

The last material in Table 3, FeAs-122, has not reached the industrial level, but deserves a particular mention. It belongs to the large family of Fe pnictides, discovered in 2008 by Hosono *et al.* [14]. This material class exhibits lower T_c values than HTS compounds (up to 38 K), But has very high B_{c2} values too, exceeding 70 T. Pnictides crystallizing in the 122 structure have a considerably reduced anisotropy of B_{c2} , reflecting a smaller anisotropy of coherence length ξ . In contrast to HTS compounds, which require highly textured tapes, pnictides have the potential to be prepared as round wires. At present, the highest reported critical current density of the first round AsFe-122 wires is 2×10^4 A/cm² at 10 T and 4.2 K [15]. Considering the high value of B_{c2} , the decrease of J_c vs. B is very slow, showing that this material not only has potential for the fabrication of round wires, but may be promising for very high fields.

2.4. Wires for high field magnets

A real challenge in the long term development of applied superconductivity consists in the production of very high fields in various magnet types, e.g. solenoids, dipoles and quadrupoles. For the present LHC collider at CERN, the dipoles were constructed for reaching 8.3 T at 1.8 K, but for the next generation, the high luminosity LHC upgrade, magnetic fields above 15 T are envisaged. A possible future development could be the muon collider with fields exceeding 30 T. The presently known superconducting materials are listed in Table 3, together with the transition temperatures and the upper critical fields. However, these data are not sufficient for deciding about the applicability of a given material for a very high field application. A choice can only be made taking into account the fabricability of wires or tapes on an industrial scale. In addition, it must be considered that in contrast to cubic Nb₃Sn and NbTi, the achievable magnetic field in the anisotropic compounds MgB₂ and the HTS depends on the irreversibility field B_{irr} , which is considerably lower than B_{c2} , in particular for fields applied perpendicular to the axis.

2.4.1. Field ranges and challenges

The superconducting material used for a wide range of industrial applications is ordinarily taken

depending on the magnetic field range and the operation temperature. Some examples are given in the following, but this list is certainly not complete. The definition of the various field ranges is somewhat arbitrary, but is introduced here for better clarity.

Low and middle field ranges:

- Superconducting fault current limiters (SFCLs) and high current HTS cables usually operate at 77 K, at the self-field. Only the 13,000 A cables for the LHC upgrade (LINK project) [17] based on MgB₂ wires are designed for operation at 10 K.
- MRI magnets operating at 4.2 K consist of NbTi wires. Their magnetic field for medical applications presently reaches 3 T, but it can follow the future market requirements up to considerably higher magnetic fields.
- The operation range for HTS motors or wind generators at 77 K and fields up to 3 T is envisaged, but still constitutes a challenge.
- Due to the considerably lower costs of MgB₂ wires with respect to HTS-coated conductors, such a conductor may be envisaged for motors and wind generators up to 25 K at fields up to 3 T and more.
- Due to the low relaxation rate of MgB₂ [18], this conductor wire is presently also used for MRI magnets at 20 K, the present operation field being of the order of 1 T. The challenge consists here in a substantial field increase, maybe to 3 T, in the next few years.
- NbTi is used up to fields around 9 T at 4.2 K and is the only ductile high field superconductor. It can be produced in large quantities and is the most economical one among all known superconductors. It is used for the background field of all laboratory and NMR magnets producing fields above 10 T.
- NbTi is also used for the poloidal field coils of ITER.

High field range:

- All laboratory magnets as well as the NMR magnets consist of Nb₃Sn magnets in a background field produced by external, concentric NbTi magnets. At 1.8 K, these magnets can produce magnetic fields close to 11 T.
- The highest field achieved in the Nb₃Sn solenoid was realized by an industrial NMR magnet, which produced 23.5 T at 1.8 K [19]. However, it can be seen from the behavior of B_{c2} vs. T in Fig. 18 that

Fig. 18. Irreversibility fields for wires of Nb₃Sn, MgB₂, Bi-2212 and tapes of YBCO for applied fields B parallel to the axis. For the cubic Nb₃Sn, $B_{c2}(T)$ and $B_{irr}(T)$ are almost identical. (From Ref. 16.)

this field is very close to the high field limit of Nb₃Sn.

- The central coil as well as the Tokamak coils for ITER are based on Nb₃Sn wires and are designed for fields of the order of 12 T at 4.2 K.
- The magnetic field in the quadrupoles for the future high luminosity LHC upgrade collider is designed for 15 T. The strong requirement for the noncopper J_c value, which should exceed 1,500 A/mm² at 15 T and 4.2 K, has recently been fulfilled [20]. A substantial improvement of this value in Nb₃Sn wires would constitute a real challenge.

Very high field range (above 23.5 T):

- There is a need for considerably higher fields than the 23.5 T achieved by the Nb₃Sn magnet. This goal can be achieved using HTS superconductors: recently, a prototype laboratory magnet based on Y-123-coated conductors has reached a magnetic field of 33.8 T at 4.2 K in a background field of 31 T [21]. Magnetic fields well above 20 T have also been produced in prototype magnets based on Bi-2212 and Bi-2223.
- Very high fields would also be needed for other hypothetical future projects, such as the muon collider or the LHC Tripler.

It follows from Fig. 18 that the known HTS conductors cannot produce high fields at 77 K. Thus,

high field magnets based on both Bi-based compounds must be operated at 4.2 K, while high fields at 30 K seem possible for YBCO. Several manufacturing companies are presently working on the project to build industrial HTS high field magnets. It is only a matter of time before the first industrial HTS magnet yielding, say, 30 T is produced. The main difficulties to be resolved for HTS magnets are related to thermal and mechanical stability. In the following, the challenges to various magnet types are mentioned.

2.5. Wires for magnets operating in the persistent mode

An NMR magnet consisting of alloyed Nb₃Sn wires has reached the record field value of 23.5 T [19], thus corresponding to a resonance frequency of 1 GHz. However, so far it has not been possible to get satisfactory operation in the persistent mode with HTS conductors, which is inherently due to the particular situation at the HTS grain boundaries; the published value is of the order of $10^{-9}\Omega$, with the insulating outermost layer leading to a high contact resistance. The lowest contact resistance, as low as $10^{-12}\Omega$ at the joints of an NMR magnet, is required for performing a high quality NMR operation. Such low contact resistances have so far only been obtained for NbTi or Nb₃Sn wires. It should be mentioned that joints between MgB₂ wires, but also between MgB₂ and NbTi, have been operated in the persistent mode too.

In order to use HTS conductors for NMR applications at higher magnetic fields, the challenge consists in finding new ways for a considerable reduction of the contact resistance. Another possibility consists in replacing the persistent mode by a driven mode. However, for NMR this would require the development of a power supply with unprecedented stability characteristics, which also constitutes a real challenge.

For spectrometers beyond 1 GHz, another possibility exists: long term NMR measurements. Indeed, waiting a sufficiently long time after coil excitation (of the order of ~ 1000 h), the field drift rate approaches the field decay rate of the persistent current (10^{-8} h^{-1}). This technique is envisaged in a 1 GHz currently under work in Japan, based on Bi-2223 tapes.

2.6. Wires for accelerator magnets

Engineering physics and construction requirements for accelerator magnets require Rutherford cables made by round wires. The situation is simplest below 9 T, where NbTi wires constitute a technically and economically satisfactory solution. For higher fields, e.g. 15 T as envisaged for the quadrupoles in the high luminosity LHC upgrade, the only available round wire material is Nb₃Sn, which has fulfilled the condition of noncopper J_c values of 1500 A/mm² at 15 T [20].

Another hypothetical candidate material for round wires is Bi-2212. At present, the *overall* critical current density of Bi-2212 round wires is still lower than required, but may be improved in the light of recent progress at NHMFL [21]. Due to the difficulties in bending tape conductors around the normal to the flat surface, the fabrication of dipoles and quadrupoles based on tape conductors would constitute a real challenge.

2.7. Wires for fusion magnets

The ITER fusion project comprises an assembly of various coil types, NbTi poloidal field coils and two types of Nb₃Sn coils: the D-shaped Tokamak coils and the central magnet. The magnetic field of both coils is of the order of 12 T at 4.2 K, and Nb₃Sn was chosen as the only industrial alternative. For future fusion devices requiring higher fields, e.g. DEMO, the possibility of using HTS-coated conductors is presently being discussed. The challenge will consist in finding a practical cable configuration.

2.8. The critical current density

Regardless of the differences between low T_c (or LTS) superconductors and high T_c (or HTS) superconductors from the point of view of crystallographic, metallurgical or physical properties, the main challenge for a given wire or tape is to maximize its critical current at the operation temperature and field. This involves the following two conditions:

- The pinning strength should be enhanced to its highest possible value;
- The irreversibility field should be raised as high as possible (this holds for all superconductors with the exception of the cubic NbTi and Nb₃Sn, where B_{c2} is very close to B_{irr}).

It is well known that the value of B_{c2} in Nb_3Sn wires can be enhanced by up to 3 T by Ta or Ti additions. It was found that Ta substitutes the Nb sites, while Ti goes on the Sn sites [23]. In MgB_2 wires, the values of B_{c2} and B_{irr} can even be enhanced by 5 T by the addition of SiC, resulting in a substitution of carbon on the B sites [24].

For the considerations about pinning, the notion of coherence length and penetration depth remains valid in all studied compounds. It turns out that the transport current behavior in a general compound is mainly controlled by two factors: the size of the *coherence length*, and the *anisotropy* of the physical properties. These two factors have to be taken into account when optimizing wire or tape conductors.

2.8.1. Pinning strength in LTS compounds

In LTS compounds, the pinning strength is strongly connected with the conditions at the grain boundaries. This was first demonstrated on Nb_3Sn by Schauer and Schelb [25], who showed that the pinning force increases inversely to the grain size. This result has in the following been extended to other compounds, as Nb_3Sn , and even to MgB_2 . In both cases, reaction at higher temperatures leads to larger grains and thus to a reduced pinning force. It follows that the maximum J_c value in these systems is always obtained after the lowest temperature where a reaction of the A15 phase is possible.

At the grain boundaries, the periodicity of the lattice is broken, which causes the formation of dislocations and a local shift of the boundary atoms from the equilibrium positions. These defects create the condition for a greater number of vortices in the boundary region, thus explaining why the smallest grains lead to the highest pinning force, which is synonymous with enhanced J_c values. The precise width of this “damaged” region cannot be measured by diffraction measurements, due to the absence of periodicity. The thickness of the damaged zone at each grain boundary must of course be considerably smaller than the coherence length, but is not well known. From a comparison between LTS and HTS compounds, it follows that this thickness changes from compound to compound and that it also depends on the orientation of the grain surface relative to the crystal orientation.

So far, no way has been found to influence the thickness of this damaged zone at the grain boundaries: the challenge, at least for LTS compounds, for MgB_2 and probably for FeAs-122, consists in reducing the grain size as much as possible.

2.8.2. Pinning strength in HTS compounds

In contrast to LTS compounds, the behavior at the grain boundaries is not the dominant effect for the pinning behavior in HTS compounds. Here, the vortex dynamics inside the grains is decisive, in its static and dynamic configurations. The pinning behavior in HTS compounds can be influenced by including nanoparticles. As an example, we mention here the case of BaZrO_3 nanoparticle addition to Y-123 by J. L. MacManus-Driscoll *et al.* [26]. The effect of these additives is to enhance the pinning force, an additional beneficial effect being the reduction of anisotropy. Several manufacturers have accomplished strong enhancements on J_c of R.E.-123-coated conductor tapes using nanoparticles. As an example, the enhancement of J_c , in the tape surface in the course of the last few years by SuperPower, is illustrated in Fig. 19 [27] with the applied field parallel to the tape surface (J_c is here defined as the critical current density of a 10-mm-wide tape, and has the unit A/cm-w). This figure also shows that the enhancement of J_c is partly due to an increased thickness of the superconductor layer, provided that the orientation remains constant during the growth process. It is expected that both nanoparticle additives and improved deposition techniques will lead to further enhancements of J_c . The highest reported values for

Fig. 19. Enhancement of critical current density at 77 K, zero field in R.E.-123-coated conductor tapes with various nanosize additives. (From Ref. 27.)

a 4-mm-wide tape are close to $I_c = 320$ A, corresponding to 830 A/cm-w. However, it must be mentioned that this value has so far only been measured on samples several meters long. The J_c values of standard coated conductor tapes with lengths of several hundreds of meters are somewhat lower, of the order of 100–200 A for a 4-mm-width. These results illustrate that there is still a challenge to reach higher values.

A reduction of anisotropy has also been obtained by the addition of R.E.₂O₃ nanoparticles [28]. A convincing example for the considerable lowering of anisotropy achieved by American Superconductors is shown in Fig. 20 [29]. With further progress it is expected that, in future, R.E.-123-coated conductor tapes J_c may behave “isotropically.” These examples show that the development of improved coated conductor tapes still constitutes a valuable challenge. For more information, see article 2 of the present book.

2.8.3. High energy irradiation of superconductors

The energy level in the high luminosity LHC as well as ITER involves high energy irradiation that will have an impact on the material properties of the superconducting magnets. The situation is, however, very different for the two cases, and the effects on the superconducting material (Nb₃Sn) as well as on the Cu stabilizer are expected to be different.

(a) High energy neutron irradiation

The radiation in ITER consists of 1 MeV neutrons and by photons. The effect of photons at this energy level on the superconducting properties of Nb₃Sn is assumed to be negligible, while the effect of neutrons

Fig. 20. Anisotropy of J_c in HTS-coated conductor tapes at 77 K/1 T. (From Ref. 29.)

is well documented. The overwhelming amount of neutron irradiation data on LTS superconductors (in the bulk as well as in the filamentary state) has been performed prior to 1987 and has recently been reviewed [30]. The effect of neutron irradiation on J_c of Nb₃Sn wires is shown by the bronze route technique, while the present wires are fabricated using either the internal Sn diffusion or the powder-in-tube (PIT) technique. It is expected that these wire types may behave differently, based on recent specific heat measurements, represented in Fig. 22 [33]. These measurements reveal a difference of the average Sn content between PIT and bronze route wires of the order of ~ 1 at. % Sn, thus suggesting atomic ordering effects. This question is presently being studied at CERN, in collaboration with the Atominstut in Vienna.

In the last few years, the effect of high energy irradiation has been concentrated on HTS-coated conductor tapes [34] (Fig. 23) and in MgB₂ wires [35]. For all measured materials, e.g. Nb₃Sn, MgB₂ and R.E.-123, the variation of J_c/J_{co} vs. fluence ϕt shows an increase at higher magnetic fields, which is attributed to the enhancement of the normal state electrical resistivity with neutron irradiation.

(b) The high energy irradiation spectrum of the LHC

The irradiation spectrum at the high luminosity LHC upgrade is shown in Fig. 21 [31]. The maximum

Fig. 21. Variation of the ratio J_c/J_{co} between irradiated and unirradiated Nb₃Sn bronze route wires. The maximum J_c/J_{co} is markedly higher for binary Nb₃Sn wires than for Ti-alloyed wires. (From Ref. 31.)

Fig. 22. T_c distribution in the filaments of Nb_3Sn wires prepared by the bronze route (GAP #24), internal Sn diffusion (OST) and PIT (SMI), and in Nb_3Al wires prepared at NIMS. (From Ref. 33.)

Fig. 23. Variation of J_c/J_{co} for an industrial HTS-coated conductor tape of AMSC, showing an increase of J_c at higher applied magnetic fields [34].

Table 4. Composition of the radiation spectrum reaching the quadrupole Q2a of the LHC [30, 36].

High energy source	Composition (%)	Energy maximum
Photons	88	1 MeV
Neutrons	7	1 MeV (100 MeV)
Electrons	4	10 MeV
Positrons	2.5	10 MeV
Pions (+/-)	0.45	1 GeV
Protons	0.15	200 MeV

Fig. 24. Energy spectrum of neutrons in the LHC, showing a main peak at ~ 1 MeV and a shoulder at around 100 MeV [30, 36].

Fig. 25. Energy spectrum of protons in the LHC, with a flat maximum at 200 MeV [36].

of J_c/J_{co} for the binary Nb_3Sn wires is observed at much higher fluences than for Ti-alloyed wires, which was confirmed by independent neutron irradiation measurements [32]. The measurements in Fig. 21 were performed on Nb_3Sn wires and were produced by collider calculated by F. Cerutti at CERN [36] is very complex. More details are contained in a recent publication [30] treating the problems of superconductivity in the quadrupoles of the LHC. The composition of the various high energy sources is listed in Table 4, showing that the main contribution is due to the photons. The highest fluence will be reached at the inner winding of the quadrupole Q2a, at a distance of 33 m from the LHC collision point. The neutron spectrum is centered at 1 MeV (similar to the situation in ITER), but with a shoulder at 100 MeV (Fig. 24). The expected maximum radiation fluence was calculated to 2×10^{21} n/cm² per

year, assuming an operation of 200 days a year [30]. The effect of these fluences on T_c and J_c of Nb_3Sn wires can be estimated using the neutron irradiation data reported on binary and ternary alloyed superconducting wires at neutron energies between 1 and 14 MeV [37, 31, 38, 32]. It is particularly interesting to analyze the effect of the other high energy sources in the LHC upgrade. The various energy spectra have all been calculated [36] and they show in all cases flat maxima. The energies corresponding to these maxima are listed in Table 4; they reach from 1 MeV for photons to 10 MeV for electrons and finally to 1 GeV for pions. The impact of photon and electron irradiation on the superconducting properties of Nb_3Sn wires is in general assumed to be small and will be neglected here. The proton spectrum is of particular interest and is shown in Fig. 25, as an example for charged high energy particles. From Table 4, it is seen that the ratio between the charged high energy particles (proton and pions) and neutrons in the LHC is around 8%. From the results of proton irradiation at 3 MeV [39, 40] and neutron irradiation at 1 MeV [31], a direct comparison of the respective damage can be performed. It is found that the maximum of $J_c^{\text{un}}/J_c^{\text{irr}}$ for proton irradiation of binary Nb_3Sn is obtained at a fluence of $7 \times 10^{20} \text{ p/m}^2$ [39, 40], which is around 30 times lower than the corresponding value for neutron irradiation, $2 \times 10^{22} \text{ n/m}^2$ [31]. This shows that charged protons (but in general charged particles) have a considerably higher potential of damage than neutrons.

The published proton irradiation data were obtained on Nb_3Sn samples which were thin enough to avoid a Bragg peak inside the sample. However, a realistic damage estimation for charged high energy particles has to be taken into account for the enhanced local damage in the region of the Bragg peak. This condition has to be studied, since in LHC quadrupoles almost all regions where the Bragg peaks occur will be situated in the magnet windings. From these remarks, it follows that the total effect produced by the 8% charged particles on the superconducting properties of Nb_3Sn wires will be considerably higher than that of the 92% neutrons.

After this brief discussion, it follows that we do not yet have all elements for estimating the behavior of the critical current densities in Nb_3Sn quadrupoles of the high luminescence LHC upgrade

collider during operation. In conclusion, it can be said that the effect of high energy irradiation on the Nb_3Sn quadrupoles is somewhat higher than expected, but that the operational safety margin for the quadrupoles is still sufficient. A series of experiments are presently underway or meeting the challenge of a precise calculation of the irradiation effects in the LHC upgrade.

3. Challenges in Superconducting Applications

3.1. Applications in energy

In the preceding sections, the application of superconductors for resonance purposes (MRI and NMR) as well as for accelerators and fusion devices has been briefly discussed. In the following, several emerging energy applications will be mentioned.

3.1.1. Superconducting magnetic energy storage

Reliable power delivery will require effective electric storage solutions. Presently, renewable energy sources, such as wind and solar energy, are important sources of power, and it can be foreseen that their importance will increase in future. However, these energy sources have inherently a variable and somewhat uncertain output. The variability of these sources has led to challenges regarding the reliability of the electrical grid. Superconducting magnetic energy storage (SMES) is expected to offer improved performance and efficiency compared with other utility devices.

For example, high capacity superconducting cables, with their inherent high efficiencies, will enable a new generation of transmission and distribution electrical grids that can meet the steady increase in demand for electrical power. The performance and efficiency of SMES (98%–99%) are higher than for fuel cells. The energy is stored in the magnetic field of a dc current that flows in a superconducting wire or tape. The consequence of the dc current is low energy losses. A high reliability is expected, the major part of SMES being static. The advantages of SMES are:

- Higher power quality, reliability across the transmission and distribution networks;

- Flexibility and fast response in energy storage and delivery;
- Continuous electricity supply by storing excess capacity from intermittent renewable energy generation sources.

3.1.2. Power cables

Superconducting cables carry considerably higher current than Cu wires having the same cross section. This is of particular interest in crowded urban areas, where they can replace already existing Cu cables, thus avoiding expensive underground constructions. This procedure, called “retrofit,” leads to strongly enhanced capacity. The last few years saw the implantation of several superconducting cables, mainly using first generation Bi-2223 tapes, with lengths varying by up to 600 m. At present, a cable 1000 m long is under construction in Essen (Germany). First attempts have been made to replace short lengths of Bi-2223 cables by cables based on second generation Y-123-coated conductors (Long Island Port Authority, LIPA, New York, 215 MVA, 138 kV). New cables based on Y-123-coated conductors are planned in Korea (1000 MVA, 154 kV) and in Japan (275 kV@3 kA).

However, in spite of these promising projects, the adoption of HTS by the electrical utility industry may possibly be restricted to a small number of cables for very special purposes. In the USA, severe reductions have recently been made in funding for superconducting cables. A high obstacle to introducing superconducting cables is the fact that the cable market is a very conservative one, the average lifetime of a conventional high power Cu cable ranging between 40 and 60 years. In addition, it must be mentioned that, today, overhead transmission and distribution is less expensive than underground transmission. Under these conditions, a reduction in the production costs of HTS-coated conductor tapes in the next few years appears to be essential. In spite of the present situation, it is worthwhile to mention the advantages of superconducting cables in cases where the retrofit solution is envisageable:

- Enhancement of transmitted current through existing rights of way;
- Enhancement of current over conventional lines by a factor between 5 and 8;

- Transmission of higher currents at lower voltages;
- Reduced stray fields.

3.1.3. Fault current limiters

Superconducting fault current limiters (SFCLs) limit the current in a crucial branch of the circuit so that no component in the system becomes overloaded. SFCLs work by inserting impedance in a conductor when there is an excess of current on utility distribution and transmission networks. They are invisible to the system, having nearly zero resistance to the steady-state current. At the occurrence of an excess of electricity (otherwise known as a fault current), the SFCL enters into action dissipating it, thus protecting the transmission equipment on the line. It is obvious that the SFCL has the potential to contribute in reducing wide-area blackouts, thus making the modern grid more efficient by protecting high voltage power lines and the electrical grid equipment from damage. The advantages over conventional FCLs are:

- Enhanced safety, reliability and efficiency of power delivery systems; reduced blackouts;
- Unlike conventional FCLs, SFCLs work in a reproducible way, i.e. there are no circuit breakers to be replaced after a limiting operation;
- SFCLs have a reduced recovery time after the occurrence of a disruption;
- Possibility of building a fault-current-limiting transformer.

3.1.4. Motors and generators

The possibility of carrying higher currents than by Cu cables leads to smaller and more efficient motors and generators. The successful operation of motors up to 36 MW by several manufacturers has demonstrated their reliability. The strong reduction in the volume and total mass of superconducting motors compared to conventional motors leads to enhanced performance. There is a wide field of applications for motors, including magnetically levitated trains, ship propulsion systems, electric cars and even aeroplanes. The advantage of mass reduction appears clearly when one is considering wind generators with power levels of 10 MW and more, where the total mass would be reduced from 800 tons to 400 tons, with strong consequences for the mechanical

stability of the whole, >100-m-high system. Superconducting rotating machines have the following advantages:

- The higher efficiency will lead to energy conservation;
- Reduction by $\sim 50\%$ in total mass and volume leads to higher flexibility;
- Enablement of new transport technologies;
- Increased environmental protection through decreased emissions (no CO_2 emissions).

3.2. Applications in medicine

As mentioned before, there is already a large market for MRI magnets at fields of up to 3 T operating at 1.8 K. The first MRI systems with the MgB_2 magnets at higher operation temperatures, around 20 K, have already been built, following the principle of the “open sky magnet.” Here the patient is not enclosed in a narrow tube, but is located in an open space which even allows a direct medical treatment during the analysis. It can be projected that future developments will also include MRI magnets operating at fields well above 3 T. Since for MRI the requirement for the contact resistance is considerably less stringent than for NMR, this will open the choice to HTS materials. Finally, the use of noninvasive diagnosis of human organs like the heart and brain by means of magnetic source imaging and magnetocardiography systems is envisaged.

3.3. Applications in communications

Superconductivity has also opened the door to thin film technologies: it has allowed the construction of digital circuits based on rapid single flux quantum technology as well as rf and microwave filters for mobile-phone base stations. Superconductors are used to build Josephson junctions, which are the building blocks of SQUIDs (superconducting quantum interference devices), the most sensitive magnetometers known at present. As a major result, the SI volt unit has been calibrated by a series of Josephson junctions allowing a very precise voltage-to-frequency conversion, combined with the cesium-133 time reference. Finally, SQUIDs are also used in scanning SQUID microscopes and in medical applications, e.g. magnetoencephalography.

3.4. Energy storage

Persistent current makes possible two different storage devices: superconducting magnet energy storage (SMES) and flywheel electrical energy storage (FEES).

- SMES stores energy in the magnetic field of a coil. The energy is stored because the current persists without substantial power input power, i.e. negligible energy is dissipated in the coil — there is no resistance and no loss.
- FEES stores energy in a rotating mass in which rotation persists because magnetic bearings are used. Unlike conventional magnetic bearings, which are unstable without energy-consuming power electronics that provide feedback, superconducting bearings provide stability as well as levitation.

4. Conclusions

Storage also provides a necessary (but not sufficient) condition for the widespread use of *wind and solar generation*. It is often said that the fluctuating, unpredictable availability of wind will limit its use to roughly 10%–20% of generation. Economical energy storage would permit one to considerably increase this number.

It is noteworthy that superconductivity presents possibilities for both electrical and electronic applications. There is no doubt that superconducting materials will have a significant role and will contribute to the progress of selected industrial and scientific applications. The main problem of superconducting applications is of course connected with the cooling costs, which may in many cases influence the choice in favor of conventional systems. Major benefits are expected in various sectors, including energy, environment and healthcare.

The greatest opportunity for HTS to reduce the threats to the environment, safety and health is the role it may play in contributing to technology for storing shaft power or electrical power, thereby reducing the use of fossil and nuclear fuels.

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