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PRACTICAL APPLICATIONS OF SUPERCONDUCTIVITY

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[3] TILLEY David R., TILLEY John., Superfluidity and Superconductivity, third edition, IOP Publishing, Philadephia 1990, ISBN 0-7503-0032-9 (hbk), 0-7503-0033-7 (pbk)

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Abstract

This bachelor’s thesis is focused on the elaboration of a summary overview of the use of superconductivity in technical solutions and applications, which means not experimental use, but use in a real technical solution. This work deals with the description of basic superconductivity attributes in the first part (without which the principle of superconductivity cannot be fully understood and therefore description of superconductivity is a necessary part of thesis), in the second part the division of superconductors and superconducting categories according to specific criteria is described, and the last part of this thesis states examples of applications of superconductivity as we can encounter them in everyday life.

Key words

BCS Theory, critical parameters, high-temperature superconductor, low-temperature superconductor, Maglev, Meissner phenomenon, perovskite, SMES, superconductivity, superconductor, superconductor Type I and II, superconducting magnets, SQUID.

Anotace

Předložená bakalářská práce je zaměřena na zpracování souhrnného přehledu využití supravodivosti v technických řešeních a aplikacích, čímž se rozumí nikoliv experimentální využití, nýbrž využití v reálném technickém řešení. Tato práce se věnuje zejména popisu, v první části základním atributům supravodivosti, bez nichž není možné princip supravodivosti pochopit a jsou tudíž nezbytnou součástí práce, ve druhé části rozdělení do kategorií supravodičů podle určitých kritérií, a v poslední části popisuje příklady aplikací supravodivosti tak, jak se s nimi můžeme setkat v každodenním životě.

Klíčová slova

BCS Teorie, kritické parametry, nízkoteplotní supravodič, vysokoteplotní supravodič, Maglev, Meissnerův jev, perovskit, SMES, Supravodivost, supravodič, supravodiče I. a II. typu, supravodivé magnety, SQUID.

Prohlášení

Tímto prohlašuji, že jsem bakalářskou práci vypracovala sama s pomocí mého konzultanta prof. Ing. Pavla Fialy, Ph.D., vedoucí práce PaedDr. Alenou Baumgartnerovou a s pomocí zdrojů a pramenů, jež jsou uvedeny na konci této práce.

Jako autor uvedené bakalářské práce dále prohlašuji, že v souvislosti s vytvořením této bakalářské práce jsem neporušila autorská práva třetích osob, zejména jsem nezasáhla nedovoleným způsobem do cizích autorských práv osobnostních a/nebo majetkových a jsem si plně vědoma následků porušení ustanovení § 11 a následujících zákona č. 121/2000 Sb., o právu autorském, o právech souvisejících s právem autorským a o změně některých zákonů (autorský zákon), ve znění pozdějších předpisů, včetně hmotných trestněprávních důsledků vyplývajících z ustanovení části druhé, hlavy VI. díl 4 Trestního zákoníku č. 40/2009 Sb.

V Brně dne ....

Tereza Mádrová

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Poděkování

Tímto chci poděkovat za spolupráci vedoucí této mé práce paní PaedDr. Aleně Baumgartnerové za celoroční svědomité vedení, trpělivost, vstřícnost, cenné rady a také za čas strávený se mnou na konzultacích věnované této práci.

Můj dík také patří mému odbornému konzultantovi, vedoucímu Ústavu teoretické a experimentální elektrotechniky FEKT VUT, prof. Ing. Pavlu Fialovi, Ph.D., který se mi intenzivně věnoval po celý rok a dělil se se mnou o cenné rady, které jsem využila při tvorbě této práce.

Dále pak můj velký dík patří také mým nejbližším a mé rodině, kteří mi byli velikou podporou po celou dobu studia, v neposlední řadě pak děkuji také Filipovi.

V Brně dne ....

Tereza Mádrová

CONTENTS

1 INTRODUCTION

One of the most promising areas of physics of current world are, unquestionably, superconductivity and nanotechnologies [1].

This relatively new phenomenon hides a huge amount of usage in modern devices since it would be very useful for an electrical charge to flow with no losses [2]. Superconductivity is important part of Physics (also a part of engineering) and should not be neglected because it is possible to pick it up to other future research. For instance, to demonstrate a relation between a superconductivity and a magnetic field, if we make a bowl of lead and immerse it in a liquid helium, the bowl will be superconducting. Subsequently, the permanent magnet will be triggered into the bowl. When approaching the bowl, it will start to float when it hangs loosely over the bowl. Magnet creates shielding currents by its magnetic field in the superconducting bowl and the opposite magnetic field, which effects against the weight of the magnet [3].

The thesis is divided into few parts (chapters). The first chapter is introduction (where the reader is now). Second chapter is focused on the history of superconductivity (briefly mentioned history), the next chapter is focused on the physical background of superconductivity, which means mentioning of elementary particles (physics of elementary particles), BCS Theory, critical parameters (parameters defining superconductivity), equations necessary for confirmation and support of superconductivity as physical phenomenon, Meissner and Josephson phenomena. The fourth chapter focuses on dividing of superconductors according to certain criteria and the fifth chapter, the main chapter of the thesis, is focused on the usage of superconductors and superconductivity itself. At the end of the thesis (see Chapter Appendix), future usage of superconductivity is mentioned, especially the combination of nanotechnology and superconductors, other theories of superconductivity, List of Figures, Tables, Abbreviations, Units and a List of superconductors are mentioned too.

As written above, superconductivity itself could be (and is) applied in many branches of technology. This thesis is only the literature research work focused on usage of superconductivity in an industry or other applications in practical level; there is not included any advanced my own research. Superconductivity is used for instance in magnetic resonance, in electromagnetic levitation (trains), superconductive transformers and engines. More about using superconductivity is written in Chapter 5.

2 HISTORY OF SUPERCONDUCTIVITY

In 1908, Dutch scientist H. Kamerlingh-Onnes liquefied Helium to 4.2 K (its boiling point). Later in 1911, he made an experiment with using liquid He and distilled Hg. Onnes noticed that liquefied He causes the resistance of Hg to descend suddenly to unmeasurable value at critical point (T_c = 4.153 K), thus Hg is an ideal electric conductor in this state (at the T_c). He called this phenomenon as “Superconductivity” (super conductivity). For its discovery he obtained the Nobel Prize in 1913. Onnes also noticed that superconducting state is lifted when values of electrical current and magnetic field are too high. (see Figure 2.1) [1,2,3].

The diagram mentioned below shows transition to superconducting state after reaching critical temperature T_c.

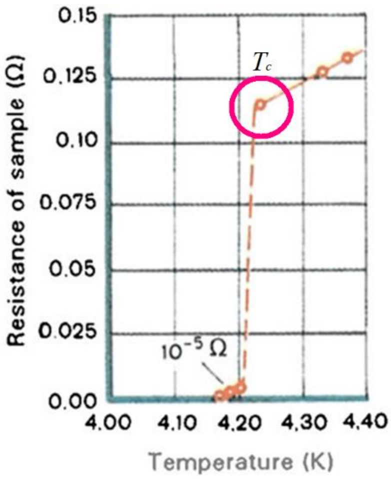


Figure 2.1: The characteristic of superconductivity (printed later). Graph shows the resistance *R* as a function of temperature *T*. T_c notes the critical temperature (for more information about Critical Parameters see Chapter 3.3) [4].

In 1933, Walther Meissner and Robert Ochsenfeld found out that magnetic field lines are parallel to the surface of the superconductor, although the sample was cooled below the critical temperature in the magnetic field. This fact means that the superconductor is not only the ideal conductor but also the ideal diamagnetics (for more about Diamagnetics see Chapter 4.3). To explain this phenomenon, quantum mechanics is needed [1].

In 1935, brothers Fritz and Heinz London made a breakthrough with the description of the ideal diamagnetism of superconductors and introduced a new term in field of superconductivity called the "depth of magnetic field penetration" (see Relation 13 in Chapter 3.4). The point of this theory is that magnetic induction towards the superconductor (to superconducting half-space) exponentially decreases over distance given by this characteristic length – which is in the order of 10 to 100 nm. The density of the shielding superconducting current drops similarly. The London brothers upheld that conductivity electrons in the superconductor behave as in macroscopic atom and therefore superconductivity is a macroscopic quantum phenomenon. Therefore, in a superconducting ring (normal area closed by a superconducting loop), the magnetic flux will only be discrete values that are an integer multiple of some magnitude of magnetic flux [1]. For more see Chapter 3.4.

In 1957, John Bardeen, Leon Cooper and John Schrieffer created first successful microscopic theory known as the BCS theory. This theory explains superconductivity as a macroscopic quantum phenomenon, which is the result of a small attractive interaction between electrons at Fermi's surface and that is mediated by phonons (crystal lattice vibrations). The superconducting state consists of pairs of electrons with opposite momentum and spin. These pairs, known as Cooper's pairs, have an integer (zero) spin. About the BSC theory is written more in Chapter 3.2., more about Elementary particles is written more in Chapter 3.1 [1].

At these days, many theories about future applications of superconductivity could be found. One of these theories is SU (2) theory which is the theory about recent findings about the SU (2) scenario for the underdoped phase of the cuprate superconductors. Of course, research of high-temperature superconductors continues and is bringing new discoveries in field of superconductivity. About high-temperature superconductors is written more in Chapter 4.1 [56, 62].

3 PHYSICAL BACKGROUND OF SUPERCONDUCTIVITY

Firstly, it is necessary to define what superconductivity is: "Superconductivity is a phenomenon in which the electrical resistance of solid matter drops to almost zero. This phenomenon occurs at very low temperatures and at electric current density smaller than the critical density of superconductor current I_c, which is the one of the characteristics of a superconducting substance" [6].

3.1. Elementary particles, criteria of superconductivity

Criteria of Superconductivity

In order to understand the basic nub of superconductivity, it is important to mention the substance of elementary particles. In the periodic system of elements, superconducting elements are found in two main groups (see Table 4.4 and Chapter 4.3), but it is turning out that superconductivity depends on the electron structure of the crystal lattice and not on the nature of the atoms. A practical demonstration of this claim is tin - white tin is superconducting at temperatures less than 3.69 K, whereas superconductivity was not detected for grey tin even at 1.2 K. For alloys and compounds, ratios (proportions) between are even much more complicated, because superconductivity is influenced not only by the composition of the substance, but also by the relative ratio of components. Superconductivity was found in both, alloys and compounds, whose at least one component is superconducting, as well as some substances without any superconducting factor/coefficient. However, for a given substance, the critical temperature can be influenced in either direction: the increase is achieved by mechanical stress or the addition of a suitable additive, whereas the reduction of the critical temperature is caused by the magnetic field [7].

Magnetic Field in Superconductor

Soon after the discovery of superconductivity, Kamerlingh-Onnes found out that superconductivity in stronger magnetic fields, or larger electrical currents flowing through the sample, disappear (as well as the resistance disappear), in the conductor. This transition occurs in pure samples in the longitudinal (axial) magnetic field at temperatures lower than T_c [7].

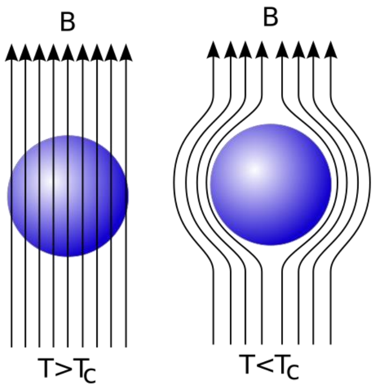


Figure 3.1: Behaviour of superconductor in magnetic field [8].

Fermions

Fermions are particles with half-integer spin. Two fermions with the same quantum numbers cannot exist in the same closed system (core or electron shell) – briefly defined Pauli's exclusivity principle; there is no more information about this principle in this thesis. Fermions can be created and destroyed only in conjunction with antiparticles of the same class.

Thus, for instance, if the electron degrades with beta decay, the decay must be accompanied by the formation of an anti-neutrino. Conversely, if positron beta is emitted by decay, neutrinos must occur. When two fermions interact, the bosons are bled and absorbed. They always have the same spin - Pauli's exclusivity principle does not apply to them, and there is no anti-particle formation at the same time. A typical representative one of fermions is an electron. It is electron thanks to its intolerance that different atoms have different behaviours. Fermions are named after Enrico Fermi, a prominent Italian quantum physicist, well-known for launching the first nuclear reactor in the world in 1942 under the Chicago University Stadium, thus launching the mankind into the nuclear era. All low-temperature fermions occupy the energy states one by one. The last occupied state is called Fermi Level. At higher temperatures, some states may remain unoccupied. It never happens that one quantum state would be occupied by two fermions at the same time (Pauli’s exclusivity principle) [9, 10].

Bosons

Bosons are elementary particles with integer spin. They are typical of the Pauli Exclusion Principle, thus there can be bosons with the same value of spins. These are particles that mediate interactions between fermions. Among the bosons, are included also photons and gluons. Each type of boson mediates a different type of interaction of varying scope and application (see Table 3.1). At low temperatures, all bosons occupy one single so-called “basic quantum state” and create an interesting state of substance called “Bose-Einstein ‘s condensate”. All condensate particles behave as a single unit, they may exhibit superconducting or super-liquid properties – this state is called “Superfluidity” and it is highly related to Superconductivity [9, 10].

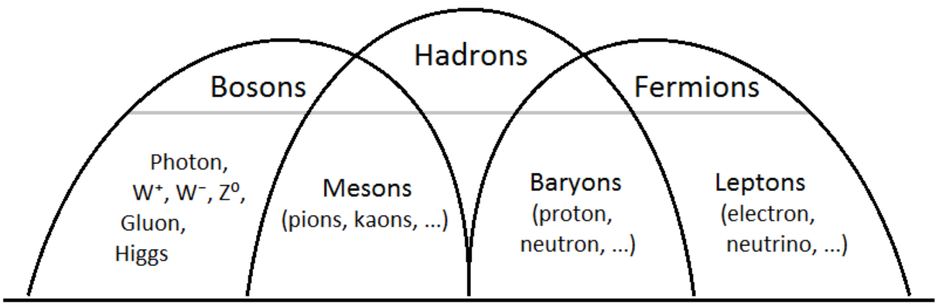


Figure 3.2: Bosons, hadrons, fermions [13].

Division of bosons shows Table 3.1 on the following page.

Basic division of bosons			
Force	**Relative force magnitude at distance 10^{-15} m**	**Usage (example)**	**Field quality**
Strong	1	Core Structure	Gluons
Electromagnetic	10^{-3}	Structure of atoms	Fotons
Weak	10^{-15}	In radioactive decay β	Bosons and Z_0
Gravitational	10^{-40}	In astronomy	Hypothetical gravitons

Table 3.1: Basic division of bosons and their characteristics features [9].

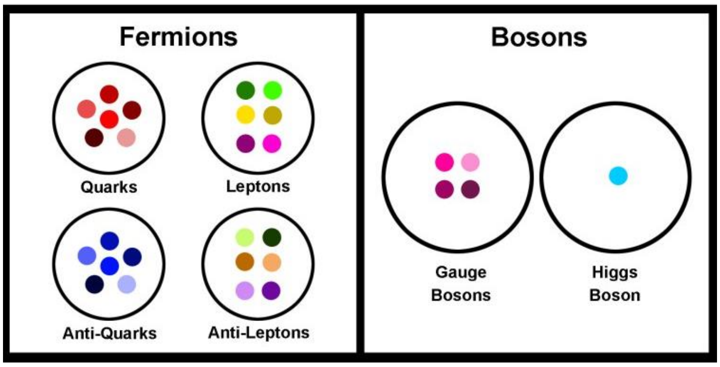


Figure 3.3: Fermions and bosons division [10].

Fermi 's Energy

Fermi's energy is one of the characteristics of solids, it is the highest occupied level at $T = 0$ K and it has the meaning of chemical potential [11].

Spin

Spin is the intrinsic property of elementary particles, whereby the particles can be divided into two main groups - bosons (which have an integer spin) and fermions (which have a half-integer spin). For more, see previous Chapters and Figure 3.4.

Spin informs about how particles look from different directions. For similitude to classical physics we can imagine it as a rotation of a ball around its axis. However, according to the rules of quantum physics, the particles do not have a well-defined axis of rotation [9].

- Zero spin particles appear to be the same from all sides
- Particles with spin 1 appear different in rotation, and to reach the initial appearance again, they must rotate about 360 ° about the axis
- Particles with spin 2 will reach original appearance even after turning 180 °

For instance, particles having a spin ½ (eg, electron) form a substance of the universe - stars, planets, and us. One characteristic of semi-spin particles is that their behaviour is given by the Pauli's exclusion principle [9]. For more see Table 3.2. and Figures 3.2 + 3.4.

Particle	**Neutron**	**Proton**	**Electron**	**Positron**	**Photon**
Type	hadron	hadron	lepton	lepton	photon
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1

Table 3.2: Particles and their spins [9].

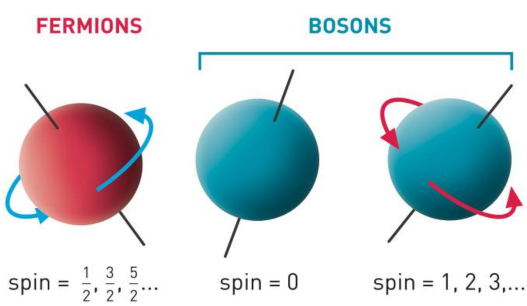


Figure 3.4: Spin of fermions and bosons [12].

Cooper Pairs

In 1956, firstly described by American physicist Leon Cooper, these pairs are an important concept in the field of superconductivity theory. Cooper pair is an initial element for BCS theory (see Chapter 3.2). At low temperatures, the pairing of electrons occurs with the counter-spinning electrons pairing. There is an interaction that holds them together despite the repulsive Coulomb forces, but the bond itself is not very strong. This pair (consisted of two fermions) behaves outwardly as a boson. If there is a pair of electrons in the material, the material is superconducting. At 0 K, one pair of 10^6 electrons is generated. If the temperature increases, the number of pairs is decreasing, with none at the critical temperature T_c [14].

Electron pairing is determined by the properties of the crystal lattice - the electrons interact together through the lattice. The flying electron affects the vibration of the grid atoms in its surroundings. The other electrons respond to this change, the most responsive electron reaches the nearest electron to the opposite spin. Thus, the bonding of Cooper's electron pairs mediates the dynamics of the lattice [14].

Spin electron is related to its magnetic moment. By inserting the superconductor into the outer magnetic field, the spin of the electron is pulled into the direction of the magnetic induction lines of the outer magnetic field. Thus, Cooper's pairs are gradually disintegrated, and the material ceases to exhibit superconducting properties [14].

This theory has been very well confirmed in the first kinds of superconductors. High-temperature superconductivity, which is structurally complicated, cannot be explained in this way. Verification of different hypotheses and final interpretation will take some time [14].

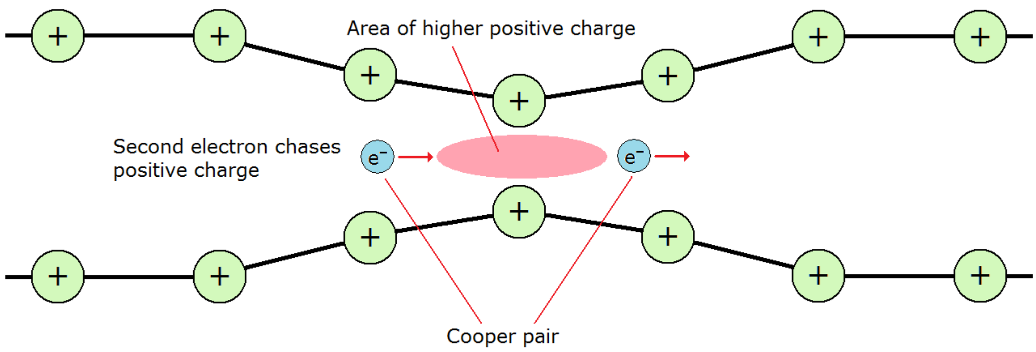


Figure 3.5: Cooper pair principle [15].

3.2. BCS Theory

In 1957 John Bardeen, Leon Cooper and John Robert Schrieffer created the theory of superconductivity based on the idea of pairing electrons with the opposite spin and the direction of motion. These pairs of electrons (known as "Cooper pairs") behave like bosons and can share exactly the same deformation in the crystalline lattice at low temperatures - simply electrons create pairs that behave like bosons. Due to this, they behave like a coherent macroscopic liquid. For energies higher than threshold energy, this coherent state is disturbed by thermal excitations of kT. They received the Nobel Prize for Physics in 1972. It is the first theory to describe superconductivity. At the same year, superfluidity was discovered [16].

According to the BCS theory, the interaction between electron spins with opposite spin is responsible for the transition to the superconducting state. Under T_c, these vapours form a condensate, occupying only one quantum state which moves without a resistance and deflects an external magnetic field, which makes the substance behave like an ideal diamagnetic, meaning it represents itself as a Meissner effect (more about this phenomenon in Chapter 3.5). At low temperatures, the final amount of energy is enough to create an electron condensate. This power hole (called "energetic hole") was predicted by London brothers. For more understanding, see Figure 3.6 on the following page [17].

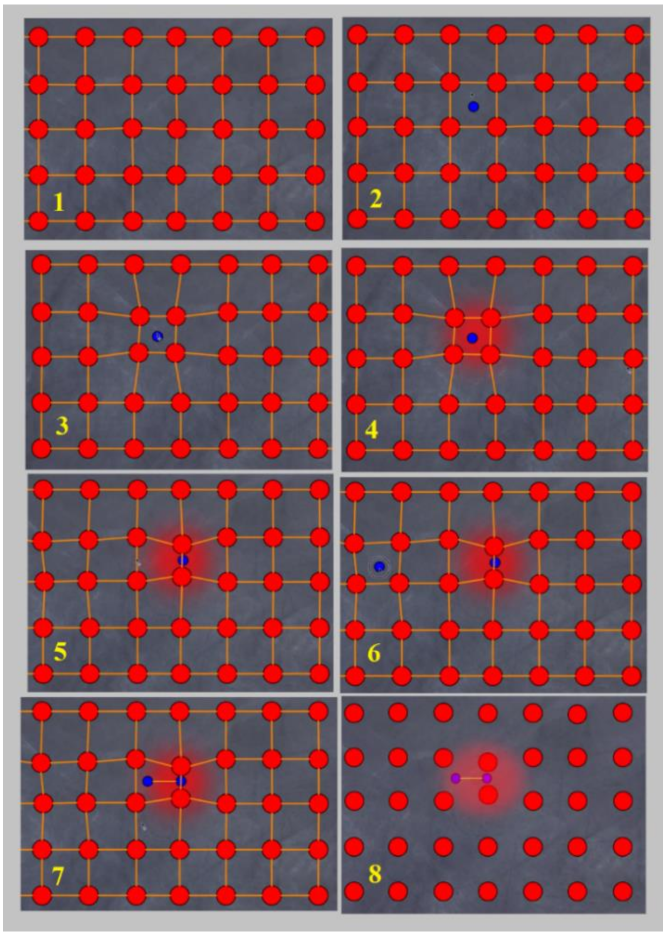


Figure 3.6: BSC Theory shown in the collage. Imagine, lattice is vibrating much slower below T_c (see *section 1*). In section 2, the electron is below T_c placed to some area and atoms surrounding the electron are attracted to this because the electron (*blue one*) is negatively charged, and the rest (*red ones*) is positively charged. This phenomenon is called the distortion of the lattice (see *section 3*). That means an increase of positiveness and phonon electron interaction. Moving electron means distortion of another part of lattice (the rest gets back to previous state). Moving electron means distortion of lattice (see *section 4*) and the rest of lattice return to its initial form (see *section 5*). What happens after is that another electron is attracted to distortion, 2nd electron is attracted to these distortions as it moves through the field (note that the electron is not attracted to 1st electron) – see *section 6*. Weak bonds are developing between two electrons. This is called a Cooper pair – see *section 7*. As the electron moves through the lattice, it takes together also 2nd electron and "goes" with it (see *section 8*). That explains two things: 1) why the material becomes superconducting, 2) BCS Theory – electron passing through the lattice unhanded, is vibrating at all and is causing distortion to allow to take place (for more, deeper, understanding of this phenomenon, the quantum mechanics should be known) [18].

3.3. Equations Needed for Superconductivity (Mathematical Models)

The physical model is based on the solution of the reduced Maxwell equations describes the external conditions of the electromagnetic field on the elemental elements of the mass [19]. The quasistationary magnetic/electric field can be described as

$$rot\,\boldsymbol{H} = \boldsymbol{J} \quad , \quad rot\,\boldsymbol{E} = 0 \quad , \quad div\,\boldsymbol{B} = 0 \quad , \quad div\,\boldsymbol{J} = 0 \quad , \quad div\,\boldsymbol{D} = 0 \qquad (1)$$

where ***H, J, E, D, B*** are the vectors of magnetic field intensity, current density, electric field intensity, electric flux density, magnetic flux density, respectively. The material relations are represented by the expressions

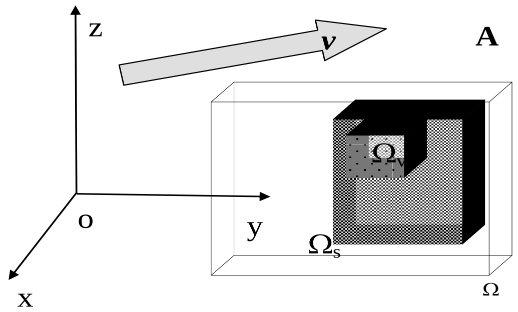


Figure 3.7: Basic model of the A system in the Cartesian coordinate system, motion of the area part at velocity ***v***.

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H} \quad , \quad \boldsymbol{J_v} = \gamma \boldsymbol{E} \quad , \quad \boldsymbol{D} = \varepsilon_0 \varepsilon_r \boldsymbol{E} \qquad (2)$$

where ε, μ, γ are the permittivity, permeability, conductivity of the environment. Vector functions of the electric and the magnetic fields ***E, B*** are expressed by the help of the scalar electric potential ϕ_e and the vector magnetic potential ***A***; for the stationary, quasi-static, quasi-statitionary, non-stationary task, Figure 3.7**,** in the relation for the electric field intensity, the time derivation of the vector magnetic potential is zero

$$\boldsymbol{E} = -grad\,\phi_e - \frac{\partial \boldsymbol{A}}{\partial t} ,$$

$$\boldsymbol{B} = rot\,\boldsymbol{A} \qquad (3)$$

The resulting current density ***J*** from relation (2) is formed by the exciting current density $\boldsymbol{J}_s = \rho \boldsymbol{v}$ with the specific density of electric charge ρ and the current density caused by eddy currents.

$$\boldsymbol{J}_v = \frac{\partial \rho}{\partial t} \mathrm{d}\boldsymbol{l} \tag{4}$$

where d$\boldsymbol{l}$ is the element of length of the trajectory on which the eddy currents close. Motion effect for the instantaneous velocity vector $\boldsymbol{v}$ is respected in the model by current density

$$\boldsymbol{J}_{\mathrm{m}} = \gamma \left(\boldsymbol{v} \times \boldsymbol{B} \right) \tag{5}$$

Then, in respecting currents (4) $\boldsymbol{J} = \boldsymbol{J}_{\mathrm{v}} + \boldsymbol{J}_{\mathrm{s}} + \boldsymbol{J}_{\mathrm{m}}$. The electromagnetic field distribution is formulated using expressions (1) to (5). $rot\,\boldsymbol{H} = \boldsymbol{J}$ in the entire region of model Ω,

$$rot\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{6}$$

In the non-dynamic system, the model is shown in relations (1) and (2). In order to eliminate possible errors, it is suitable to include in relation (7) the term which respects Faraday´s law of induction

$$rot\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} + rot \left(\boldsymbol{v} \times \boldsymbol{B} \right),$$

$$rot\,\boldsymbol{H} = \boldsymbol{J}_s + \boldsymbol{J}_m + \frac{\partial \boldsymbol{D}}{\partial t} + rot \left(\boldsymbol{v} \times \boldsymbol{D} \right) \tag{7}$$

Equations of London Brothers (brief version)

London equations come from Maxwell equations.

When expressed in terms of measurable fields, two London equations exist.

$$\frac{\partial \boldsymbol{J}_s}{\partial t} = \frac{n_s e^2}{m} \boldsymbol{E}, \tag{8}$$

$$\nabla \times \boldsymbol{J}_s = \frac{n_s e^2}{m} \boldsymbol{B} \tag{9}$$

where $\boldsymbol{J}_{\mathrm{s}}$ is the superconducting current density, $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric intensity and magnetic flux density respectively within the superconductor, e is the charge of an electron & proton, m is electron mass, and n_s is a phenomenological constant loosely associated with a number density of superconducting carriers.

$$\boldsymbol{J}_s = -\frac{n_s e^2}{m}\boldsymbol{A} \quad , \tag{10}$$

If the second London equation is manipulated by aplying Ampere's law

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}_s \quad , \tag{11}$$

then

$$\nabla^2 \boldsymbol{B} = \frac{1}{\lambda^2}\boldsymbol{B} \quad , \tag{12}$$

$$\text{For } \lambda \equiv \sqrt{\frac{m}{\mu_0 n_s e^2}} \quad , \tag{13}$$

where λ is characteristic length scale, over which external magnetic fields are exponentially suppressed. This value is the London penetration depth (characterizes the distance to which a magnetic field penetrates into a superconductor and becomes equal to e^{-1} times that of the magnetic field at the surface of the superconductor) [20].

3.4. Critical Parameters

In the case of pure metals of cylindrical shape and in solid models, superconductivity is disturbed by critical current I_c, which induces a critical value of the magnetic induction $\boldsymbol{B}_c$ on the surface. To determine the critical current, Silsbee's formula is applied (see Relation 14). F. Silsbee first expressed the hypothesis about a critical flow of cylindrical superconductors in 1916. Basically, this formula is a classical expression for calculating the field inductance value $\boldsymbol{B}$ at a distance of R_0 from an infinitely long conductor [3].

$$I_c = 2\pi R_0 \frac{B_c}{\mu_0} \quad , \tag{14}$$

Silsbee's formula. R_0 [m] is the radius of the cylindrical conductor, μ_0 permeability of vacuum ($4\pi*10^{-7}$ [Hm^{-1}]).

Critical Temperature T_c [K] – When a material is cooled down, its specific resistance gradually decreases and at a critical temperature it suddenly drops to zero. It is a state when the material becomes superconducting (this temperature is characteristic and typical of the given conducting material). This is the temperature which exists for every conducting material and element and differs in different materials. Under the critical temperature, the material is superconducting and there is no resistance to the flow current. Therefore, a current can be drop to the coil from such a material, then the current source can be disconnected and the induced current flows unchanged through the coil for a very long period of time (even several years). The critical temperature T_c is in the range of $\sim 10^{-5}$ K for Ag, Au or Cu. The critical temperature is not the only criterion for defining electrical resistance ρ. The next important criterion is the **Critical Magnetic Induction** $\boldsymbol{B}_c$ [T]. If a superconductor is located in the magnetic field with intensity H, it is able to conduct magnetic flux to any defined value. That value is called the critical magnetic flux density $\boldsymbol{B}_c$. Superconductivity is disrupted in cases of $\boldsymbol{B} > \boldsymbol{B}_c$ and $T < T_c$. [21]. The dependency of $\boldsymbol{B}_c$ is shown in following equation:

$$\boldsymbol{B_c}(T) \;=\; \boldsymbol{B_c}(0)\left(\frac{T}{T_c}\right)^2 \tag{15}$$

Note: $\boldsymbol{B_c}(0)$ is magnetic flux density extrapolated for temperature 0 K [21].

3.5. Meissner Phenomenon

Also known as Meissner effect (or Meissner–Ochsenfeld effect), this phenomenon was discovered and described in 1933 (as was mentioned in Chapter 2). This effect is based on the fact that magnetic induction $\boldsymbol{B}$ is equal to zero inside a superconducting material. It means that magnetic flux lines get around the surface of superconductor. The magnetic flux density vector is represented by following formula:

$$\boldsymbol{B} = \mu_0 \mu_r \left(\boldsymbol{H} + \boldsymbol{M}\right), \tag{16}$$

where μ_0 is the permeability of vacuum ($4\pi * 10^{-7}$ [Hm^{-1}]), μ_r ($\mu_r * \mu_0^{-1}$) is a relative permeability, $\boldsymbol{M}$ is a vector of magnetization. Magnetization also deals with the structure of material and its relative permeability μ_r. For Meissner phenomenon, it can be written as $\boldsymbol{B} = \boldsymbol{0}$. From this formula ensues $\boldsymbol{M} = -\boldsymbol{H}$. Superconductor behaves as a diamagnetic material. For more about diamagnetics see Chapter 4.2.

Magnetic flux density magnitude does not drop to zero hike, but there is a certain depth of magnetic field penetration into material volume. Briefly defined, Meissner effect occurs when a critical part of used material makes the transition from normal to superconducting state and actively excludes magnetic fields from its region. Meissner effect principle is shown in Figure 3.8 [21, 22].

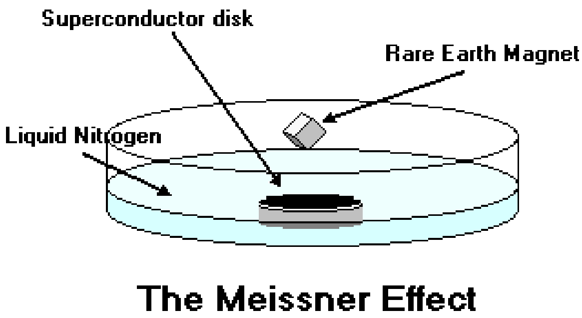


Figure 3.8: Meissner effect shown in detail [23].

3.6. Josephson Phenomenon

The Josephson phenomenon is also known as Josephson Effect. This effect enables to define a initial value of the voltage which is used for calibration of the measuring devices (in order to ensure that one volt has the same value in Portugal as well as in New Zealand). Josephson effect is very sensitive when measuring the value of the magnetic field (for more about Magnets see Chapter 5.3), because the phase variation of a superconductor can be linked to the magnetic flux. After that becomes possible to use this for building very accurate magnetic field measuring devices, SQUIDs – these devices are the most precise means to measure a magnetic field (see Chapter 5.5). This effect arises when two pieces of superconductor are separated by a physically small area where the superconductivity is weakened. Such a weakly superconducting field – called “Josephson junction” – can be produced in many ways [24].

In other words, when a material is able to be superconducting, the electrons in superconductor create form Cooper pairs and “condensate” in the shape of a unique collective quantum wave. If the electric insulator, separating two superconductors, is extremely thin, then the wave can spill out of the superconductor – see Figure 3.9 [25, 26].

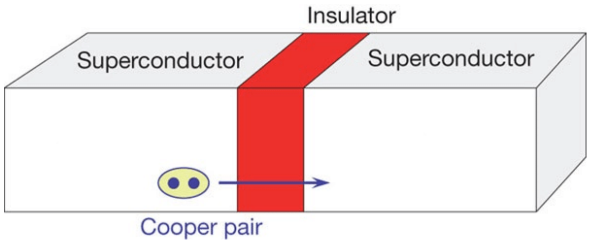


Figure 3.9: An image of two superconductors and insolent between them (S-I-S) junction [25].

Direct Current Josephson Phenomenon – DC flows through Josephson junction with no voltage at barrier [27].

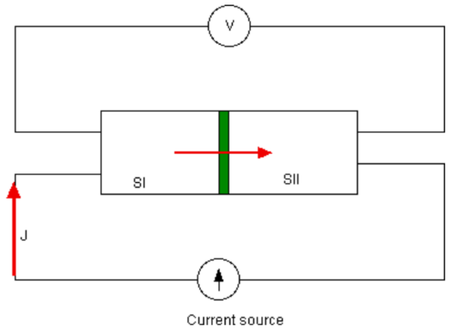


Figure 3.10: Schematic diagram DC Josephson effect. Two superconductors S_I and S_{II} (the same metals) separated by a thin insulating layer (noted as green one). DC Josephson current flows without leakage through the insulating layer (see red arrows) [28].

Alternating Josephson Phenomenon - by bringing DC voltage to the Josephson junction, current oscillations are created. This kind of Josephson junction works as a perfect *voltage-to-frequency* converter [27, 28].

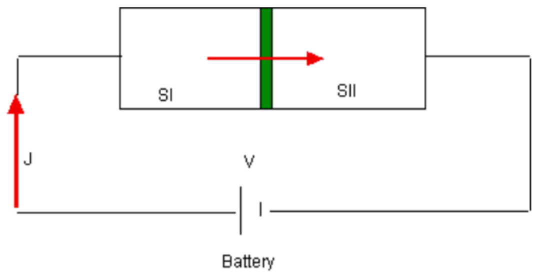


Figure 3.11: Schematic diagram of AC Josephson effect. A finite DC voltage is applied across both the ends [28].

Inverse Alternating Josephson Phenomenon - by bringing AC (with help of external electromagnetic field) to the Josephson junction, DC voltage is created on the barrier between the superconductors. This transition works as a perfect *frequency-to-voltage* converter (because of it inverse – see paragraph above). This effect is used in quantum voltage standards; thus, the standards serve as transmitters of the time unit per unit of voltage. For more understanding, see Figure 3.12 below [27, 28].

Josephson Junction

The point of this junction is that two superconductors are separated by a very thin dielectric (so-called "short-circuit"). Josephson derived this equation for inverse alternating effect written as

$$U = n f \frac{h}{2e}, \tag{17}$$

where U is voltage produced at Josephson junction, n is quantum state (integer $n = \pm$ 1,2,3,4 ..., f is the frequency of the external electromagnetic field, h is Planck constant (6.626 * 10^{-34} Js), e is the elementary charge. Josephson's junctions are a basic element of the standard of voltage, SQUIDs, detectors, and THz radiation generator [27].

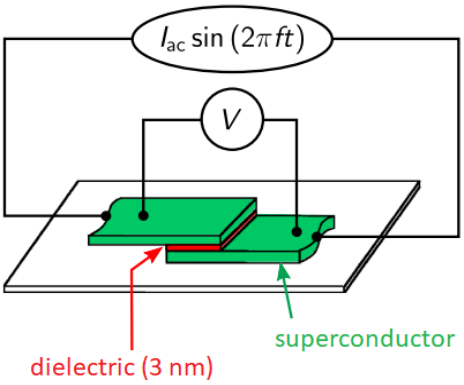


Figure 3.12: Scheme of Josephson junction and inverse Josephson phenomenon (bringing AC to structure, DC is produced at the barrier) [29]. The formula shows that the voltage at Josephson's junction does not depend on the amplitude of the alternating current but only on its frequency. Josephson constant is K_J = 483597,9 [GHz*V^{-1}]. The formula for calculation of Josephson constant is

$$K_J = \frac{h}{2e} , \quad (18)$$

Figure 3.13: Schematic sign of Josephson junction used in electrical engineering [30].

4 SORTING OF SUPERCONDUCTORS AND SUPERCONDUCTING MATERIALS

What is superconductivity and how does it manifest itself? Today, almost everyone knows that metallic materials are mostly good (or perfect) electrical conductors, unlike insulators. It is also generally known that when current passes through the conductor, the heat is generated. This heat is the greater the higher the passing current and the higher the so-called "specific resistance" of the conductor. Some metal alloys (as Ka, NiCr, etc.) have high resistivity and therefore are suitable for various heating devices; other conductors (as Cu, Au, Ag, Al etc.) have low resistivity and therefore are used for electricity distribution. Although their resistivity is low, it is enough to lose up to one third of the electrical energy in the form of heat and that is very unpleasant. It would be advantageous to find a material which would have small or zero resistivity. A superconductor is such material [1].

At the beginning of the 20th century, superconductors existed only in form of simple metals (or elements) such as Hg, Pb, Bi, etc. These elements have become superconducting only at the very low temperatures thanks to liquid He (T_{He} = 4.2 K). During the period of 75 years from the describing of superconductivity, great advances have been made in understanding of how superconductors work. Many alloys were found that were superconducting at some "higher" temperatures. Unfortunately, none of these alloy superconductors were able to work at higher temperatures than 23 K. That is why liquid He remained as the only refrigerant that could be used when working with these superconductors. In 1986, researchers at an IBM laboratory in Switzerland discovered fact that few kinds of ceramics were able to conduct at a temperature of about 35 K. A year later in 1987, these Swiss scientists obtained a Nobel Prize because it was a revolutionary discovery. In the superconductivity, during this year, it was discovered that perskovite (a type of ceramics) is able to (super)conduct at temperatures around 90 K. This was very important because now it becomes possible to use liquid N as the refrigerant. These materials are able to conduct at a significantly higher temperature, that is why they are called "High-Temperature Superconductors" [31]. For more see Chapter 4.1.

Superconductors are divided according few aspects into three groups. Firstly, distinguishing between superconductors of low-temperatures (LTS) and of high-temperatures (HTS) – Chapter 4.1, secondly, distinguishing between Type I superconductors and Type II superconductors – this division depends upon their behaviour in magnetic field (Chapter 4.2) and thirdly, distinguishing superconductors by used material – see Chapter 4.3 [32].

4.1. Sorting by the temperature

Low-temperature Superconductors (LTS)

This group of superconductors refers to the niobium-based alloy (as Nb_3Sn and Nb_3Al ones). These alloys were used for the first time in 1986 when discovering of "high temperature" superconductivity. The critical temperature of these materials refers to the defined temperature to which the superconductor has to be cooled (for more see Chapter 3.4). For LTS the temperature is usually well below 25 K (-253 °C). NbTi alloy has become the main commercial superconductor thanks to one reason – it can be manufactured in economical way in a ductile form (with the prerequisite nano-structure needed for high critical current). Likewise, Nb_3Sn based fibres, can be manufactured into strong composites in degrees of kilometres (as well as microstructures that promote high critical current densities). These superconductors are mostly known as “technical superconductors” because they are applied mostly in engineering tasks. All these conductors need to be cooled down to $T = 4$ K, thus He is the most used coolant [3].

LTS are preferred at applications as MRI and NMR devices. For more see Chapter 5.4.

High-temperature Superconductors

High-temperature superconductor is material that behaves as superconductor at unusually “high temperature” [2].

Whereas “ordinary” or metallic LTS superconductors usually have transition temperatures (temperatures below which they conduct) below $T = 25$ K (-243.2 °C), HTS have been observed with transition temperatures as high as $T = 138$ K (-135 °C). Until 2008, only given compounds of Cu and O (so-called “cuprates”) were known and believed to have HTS properties. The term high-temperature superconductor was used with cuprate superconductor for compounds such as BSCCO and YBCO. Mostly, high-temperature superconductors are brittle ceramic materials, and the technology of superconductor production is very demanding [32].

Today, two ways of keep from the brittleness of these materials are being pursued: 1) rolling a polycrystalline material in a silver matrix (capillary), 2) steam deposition, 3) chemical deposition of thin monocrystalline layer of superconductor on flexible support in the form of a long strip. Today's technology allows superconducting tapes to be produced up to a maximum length – which is about 1.5 km. Although the first coils made from such wires are already tested in the laboratory, the path to economic usage in common use is still long [33].

Figure 4.1: This superconducting tape is able to conduct the same current as a 100 times larger Cu cable [33].

Obstacles in Common Usage of High Temperature Superconductors

- **Process temperature** - components made of high-temperature superconductors must be cooled with liquid N to 77 K (-197 °C).
- **Mechanical properties -** high temperature superconductors are generally fragile ceramic materials, and the technology of conductor production is very demanding. At present, two ways are being followed: 1) combined rolling and annealing of polycrystalline material in a copper or silver tube, 2) steam or chemical deposition of thin layers of superconductors on flexible supports in the form of a long strip [33].

4.2. Sorting by Behaviour in Magnetic Field

Depending on the behaviour in the magnetic field, it is possible to divide materials into 4 groups:

- ferromagnetic
- antiferromagnetic
- paramagnetic
- diamagnetic

All materials with filled electron orbit are diamagnetic but atomic diamagnetism is weak. Magnetic susceptibility of these materials is only $\chi = -10^{-5}$ and therefore they levitate only in a strong magnetic field greater than 10 T. The susceptibility of the superconductor, the ideal diamagnetics, is $\chi = -1$ and therefore the superconductor is able to levitate in a much weaker magnetic field. Superconductors are perfect diamagnets, they push the magnetic field out of its entire volume [1, 33].

Features of Diamagnetic Materials (diamagnetics)

The property of all substances is to be repulsed (expelled) out from the magnetic field and weaken the outer field. However, this property is overlaid for ferromagnetic and paramagnetic materials. The magnetic field aroused by flowing induced current has a direction opposite to that of the induction current and therefore influences against change that has been induced. In case of a superconductor, it is matter of a DC magnetic field [3].

The formula for calculating the magnetic induction in the material is

$$\boldsymbol{B}_J = \mu_0 \boldsymbol{H} + \boldsymbol{B}_v \,, \tag{19}$$

$$\boldsymbol{B}_J = \mu_0 \left(\boldsymbol{H} + \boldsymbol{M} \right), \tag{20}$$

$$\boldsymbol{B}_J = \mu_0 \left(1 + \chi \right) \boldsymbol{H} \,, \tag{21}$$

where χ is susceptibility. Relative permeability of environment is $\mu_r = (1 + \chi)$. For diamagnetic environment is $\chi < 0$ a $\mu_r < 1$. For paramagnetic environment is $\chi > 0$ and $\mu_r < 1$. Since inside the massive superconductor $\boldsymbol{B} \equiv 0$, it is possible to declare that $\mu_r = 0$ and $\chi = -1$. A superconductor is not an ideal conductor, but ideal diamagnetics [1, 21].

Superconductors Type I

Today, these superconductors are known as the "**soft superconductors**". They were described as first and require the coldest temperatures to become superconductive. They show a very sharp transition to a superconducting state (see Figure 4.2) and to a "perfect" diamagnetism. Superconductors of Type I are those superconductors which lose their ability of superconductivity very easily when they are placed in the external magnetic field [34, 35].

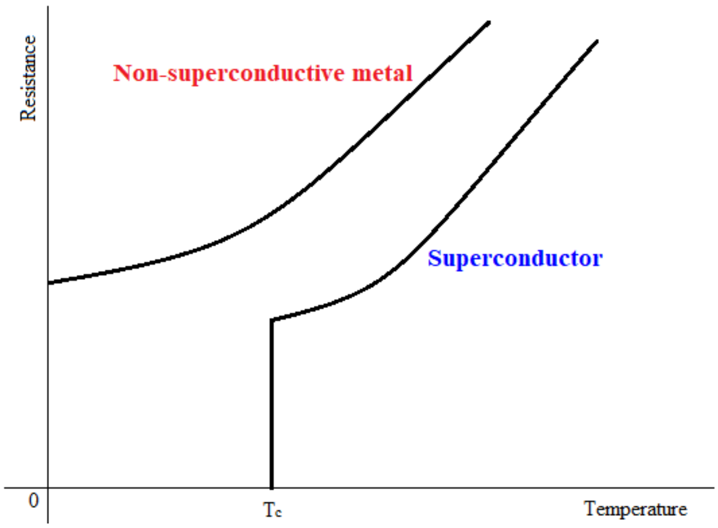


Figure 4.2: Dependence of resistance and temperature in context of non-superconductive metal and a superconductor [34].

In the Table 4.1 below, there are some elements with its critical temperatures.

MATERIAL	T_c [K]	$\mu_0 H_{c0}$* [T]
Ti	0.40	0.0056
Zn	0.85	0.0054
Al	1.18	0.0105
In	3.41	0.0281
Sn	3.72	0.0305
Hg	4.15	0.0411
V	5.40	0.1403
Pg	7.19	0.0803
* 0 K		

Table 4.1: Type I Superconductors (some of many, selected ones only) [36].

<u>Superconductors Type II</u>

The superconductors of Type I are superconductors which lose their superconductivity gradually but not easily when placed in the external magnetic field. Type II superconductors start to lose their superconductivity at lower critical magnetic field and completely lose their superconductivity at upper critical magnetic field. Type II superconductors are also known as "**hard superconductors**" due to this reason. These superconductors partially obey Meissner effect but not completely. Type II superconductors are used for strong field superconducting magnets [37, 38].

In the Table 4.2 are shown some selected materials (Type II superconductors) and their critical temperatures.

MATERIAL (type)	T_c [K]	$\mu_0 H_{c0}$* [T]
Nb	9.5	0.2*
NbTi	9.8	10.5 †
NbN (metalloid)	16.8	15.5 †
Nb_3Sn (intermetalic compound)	18.3	24.5 †
Nb_3Al	18.7	31.0 †
Nb_3Ge	23.2	35.0 †
MgB_2	39	~15*
* 0 K †4.2 K		

Table 4.2: Type II Superconductors (some of many, selected ones only) [36].

Conventional Superconductors

Conventional superconductors are materials that show superconductivity as BCS theory describes. Ni and V are Type II superconductors, whereas most conventional superconductors are Type I materials. Most of compound and alloy superconductors are Type II materials. The most commonly applied conventional superconductor in applications is a NiTi alloy – this is a Type II superconductor with a T_c of about 11 K. In the meantime, the highest critical temperature so far achieved in a conventional superconductor was 39 K (-234 °C in MgB_2). The most common conventional superconductors are mentioned in Table 4.3 [39].

Covalent Superconductors

Covalent superconductors are materials in which the atoms are linked by so-called "covalent bonds". The first such material was boron-doped synthetic diamond grown by the HPHT method. The discovery had no practical importance, but many scientific meaning – as superconductivity had not been observed in covalent semiconductors, which also include diamond and silicon [40].

MATERIAL	T_c [K]
Aluminum (Al)	1.20
Mercury (Hg)	4.15
Molybdenum (Mo)	0.92
Niobium (Nb)	9.26
Lead (Pb)	7.19
Tantalum (Ta)	4.48
Titanium (Ti)	0.39
Vanadium (V)	5.30
Zinc (Zn)	0.88

Table 4.3: The most common conventional superconductors with critical temperature [40].

4.3. Sorting by Used Material

To start with materials, have a look on the periodic table (Table 4.4) and focus on elements. This is very important for future knowledge. Table 4.4 is placed on the following page. Under STC, these elements show superconducting properties: Li, Be, Ti, V, Cr, Zr, Nb, Mo, Tc, Ru, Rh, Pb, La, Hf, Ta, W, Re, Os, Ir, pt, Hg, Ti, Pd, Cd, In, Sn, Zn, Ga, Th, Pa, U Am. These are elements whose superconductivity exists only at high pressure: Ca, Sc, Sr, Y, Cs, Ba, Fe, B, O, Si, P, S, Ge, As, Se, Br, Sb, Te, I, Bi, Ce, Eu, Lu. In case of C (carbon), applying superconductivity is possible only at some of its special structures (alloys). Other elements from periodic table which are not mentioned, are non-superconducting [41].

Applications of superconducting materials include strong superconducting magnets without any iron cores. These superconducting magnets are needed in particle accelerators, NMR and MRI (medicine), Maglev, magnetic circular dichroism instruments, magnetic energy storage, magnetic refrigerators and SQUIDs for very sensitive magnetic field measurements. Many applications of superconducting materials were discovered and developed still use, older, low-temperature superconductors [35].

As mentioned in previous chapters, moreover, from economical point of view, cooling down with liquid N rather than liquid He, is much more efficient. The difficulty is that moulding the high-temperature superconductors into strong forms which must be, moreover, flexible (wires) and the greater T_c lowering that accompanies greater magnetic field strength have limited their use up to the present time. Few companies have developed methods improving the transfer of charge among superconducting particles; and it appears that the best superconductors may be impure ones that allow (the more disordered) ceramic glass formation rather than ceramic crystallite formation [35].

In the Figure 4.3, the timeline of superconducting materials and the history of some of the discovered superconducting compounds is displayed. Note the cuprates (blue *diamonds*), the iron-based superconductors (yellow *squares*) and a particular the BCS superconductors (green *circles*). In the time axis, notice also a change around year 1980 and (T_c = 50 K) [37].

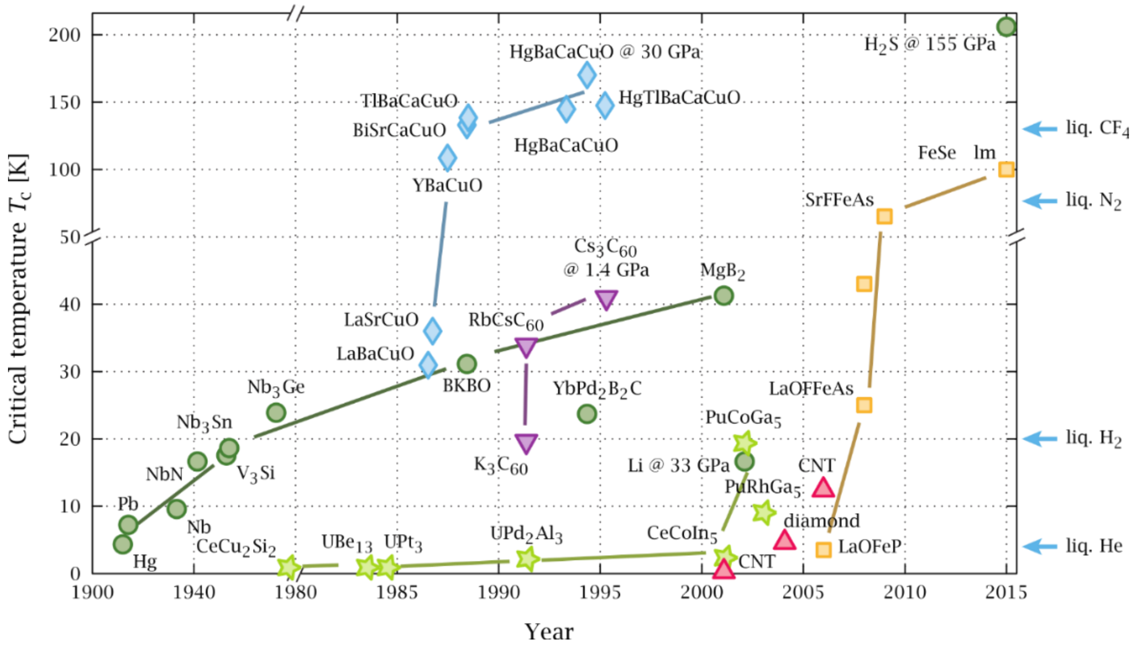


Figure 4.3: The timeline of superconducting materials. At the time line it is displayed the development of superconducting materials [37].

Superconducting Magnets

Superconducting magnets are electromagnets made of superconducting materials (see Table 4.3). Compared to other (traditional) electromagnets, they have advantages. Firstly, they do not allocate electrical resistance, so it is possible to charge them once. They are also able to create a more intense magnetic field than permanent magnets and normal temperature electromagnets [42].

As everything made by Nature, superconducting magnets also have some disadvantages, the main disadvantage is the need to control the magnet below the T_c of the superconducting material. Today, superconducting magnets mostly work at $T \sim 4$ K, or less (requiring cooling with He). If the magnet gets a temperature growth or other magnitude (local magnetic field strength) above its critical value, the magnet material goes into a normal (non-equilibrium) state, and all the energy stored in the magnet, is released at a very short period of time [42].

This process is called “quench” and is caused by a heating of the magnet and its surroundings, which causes gasification of cryogenic fluid and a rise in pressure inside the cryostat. This can also damage the solenoid. Small magnets usually survive without quenching. For large magnets (e.g., in fusion reactors) that work close to their stability limits, the consequences of unplanned quenches can be very unpleasant, thus, different magnet detection and protection systems are used [42].

Materials Used for Production of Superconducting Magnets

At present, metal alloys are used for construction of superconducting magnets. They are NbTi (up to 9 T) or Nb_3Sn (over 9 T) often, which can produce very long (hundreds of meters) and fibres, which are homogenous, even for ultra-strong magnets. Pure copper or CuNi alloy is used only as a pure fiber. Under normal circumstances, Cu would act as a conductor. But if the solenoid (coil which is wounded into highly packet helix) is cooled below the T_c, the R of the superconducting fibre decreases to zero, and the current will flow through this fibre, and the copper will behave as a non-conductor (its resistance will be sometimes higher than that of the superconducting fibre). Even though the fibres flow at a very high current flow - hundreds of amperes - their diameter may be rather small (due to the absence of Ohmic resistance) [42].

Nowadays, there is a large group of high-temperature superconductors that have a T_c in liquid N temperature in range about 77.15 K (-196 °C) but have not yet been able to produce long fibres, cannot generate a sufficiently intense magnetic field. About magnets and calbes is written more in Chapters 5.3 and 5.2 [42].

Metallic Materials

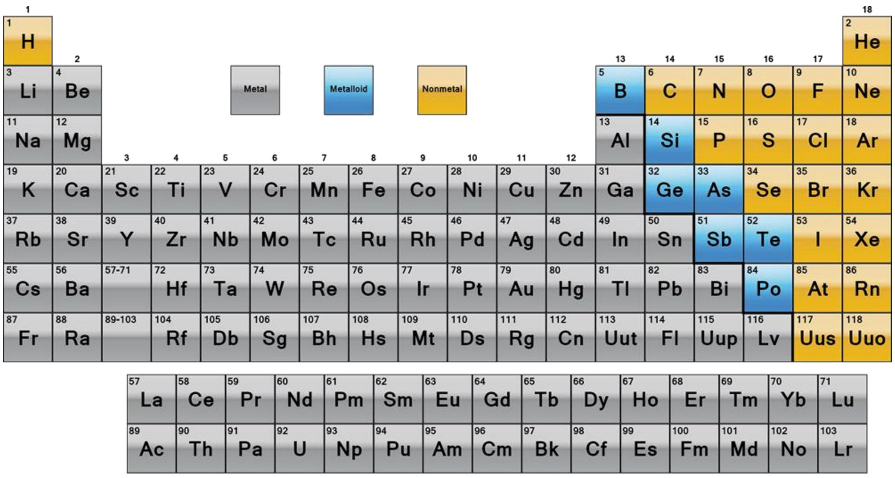


Table 4.4: In the periodic table above, metals are noted as grey, metalloids as blue ones, nonmetals as yellow ones [43].

Focusing on the elements shown in the periodic table (Table 4.4), only 31 of them have certain superconducting properties after cooling at STC. Critical temperatures of pure elements move close to absolute zero, from a few hundred K to a maximum of 9 K (for Ni). This requires cooling with liquid He. Interestingly, for the elements from the centre of the periodic table with the highest classical conductivity, such as Cu, Ag and Au, there were no conditions under which the current could be superconducting [44].

Ceramic Materials

Ceramic materials, which are used for production of superconductors too, are a class of materials called “perovskites”. Superconductors that are currently researched are compositions based on Y, Ba and Cu. More about is written in subchapter below [45].

Conductive Ceramics

Thanks to modifications in their structure, conductive ceramics, so-called “advanced industrial materials”, are widely used as electrical conductors. These are modern materials and their properties are modified with precise control over when they are fabricated – compressive strength, hardness and brittleness. Moreover, to the well-known physical properties of ceramic materials (as brittleness or hardness) they have also the property of electric resistivity. Ceramic materials, such as porcelain, have traditionally been processed into electric insulators – thanks to fact that most ceramics resist the flow of *I.* Some ceramics are excellent conductors of electricity. As in most materials, electric conductivity in ceramics is of two types: 1st ionic and 2nd electronic. **Ionic conduction** compared to electronic conduction differs in consisting of the transit of ions (atoms are consisted of positive or negative charge) from one side to another – via point defects called vacancies in the crystal lattice [46].

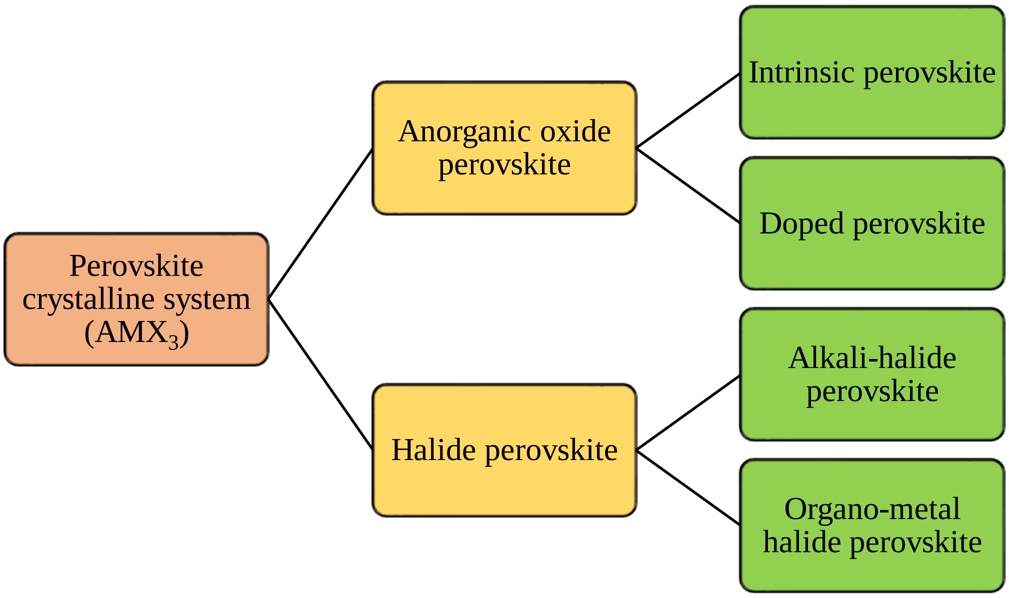
The next type of conductivity in ceramics is **Electronic conduction** is the passage of free electrons through a material. In ceramics, the ionic bonds holding the atoms together do not allow free electrons. Electronically conductive ceramics are used in for instance as resistors, electrodes, or heating elements [46].

Superconductive Ceramics

The best ceramic conductors are called “high T_c superconductors”, materials that lose their resistance at much higher critical temperatures. Most high T_c ceramics are structures, with two-dimensional CuO sheets along which superconductivity takes place. At the beginning, the 1st from claiming these might have been uncovered in 1986 by Swiss scientists J. Georg Bednorz and Karl Alex Müller. Inside an $YBa_2Cu_3O_7$ required along to bring a T_c higher over 77 K which is the boiling point of N (77.4 K). This, revolutionary, finding raised the likelihood for practical superconductors being cooled by liquid nitrogen – conventional superconducting materials must be cooled down by liquid He. Despite the fact that still higher transition temperatures have since been achieved, ceramic superconductors are very difficult to manufacture plus they are more brittle (compared to metal alloy superconductors) [46].

Perovskite Ceramic Material

Classification of perovskite system [47]:



Perovskite is consisted of CaTiO or $CaTiO_3$. The Perovskite was discovered by Gustav Rose in 1839 and is named after Russian mineralogist Lev Alekseevich Perovski. These materials have extremely stable structure, many practical applications and large number of compounds. Figure 4.4 shows a structure of an ideal cubic perovskite (ABO_3) [47].

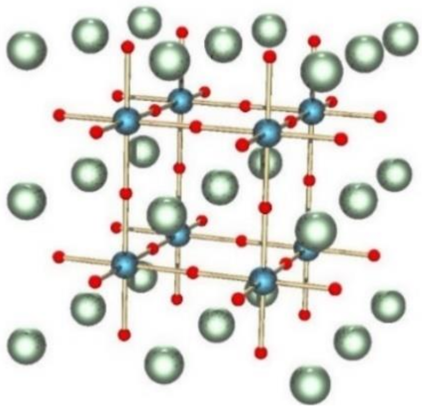


Figure 4.4: A general perovskite structure with a chemical formula ABX_3. The *red* spheres sign the X atoms (oxygens), the *blue* spheres are atoms B (a smaller metal cation), and the *green* spheres are atoms A (a larger metal cation). Pictured is the undistorted cubic structure [48].

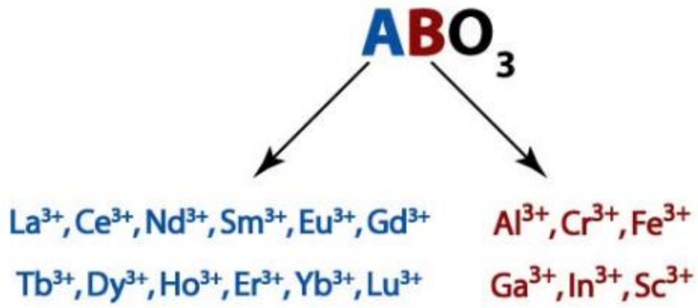


Figure 4.5: The structure of ABO_3 perovskite composition displayed schematically and generally [49].

The perovskite structure has the general stoichiometry (calculation of relative amounts of reactants and products in chemical reactions) ABX_3, where "X" is an anion "B" and "A" are cations. The "B" and "A" cations can have a variation of charges and in the original Perovskite mineral ($CaTiO_3$) the "A" cation is divalent, and the "B" cation is tetravalent. Lattice sites which are occupied by ions "A" and "B" are shown in Figure 4.6 [50].

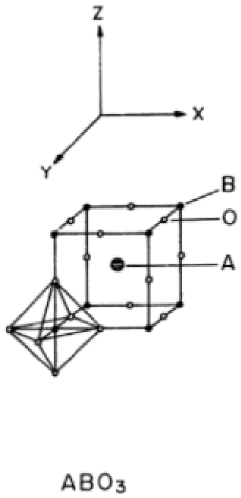


Figure 4.6: Structure of ABO_3 (general stoichiometry). See position of O, B and A at the lattice [50].

Traditionally, perovskite lattice is that it is consisted of small "B" cations within O octahedron, and larger "A" cations which are coordinated by O. This structural family is named after the mineral $CaTiO_3$ (original perovskite). The structure of an ideal cubic perovskite is shown in Figure 4.7 [49].

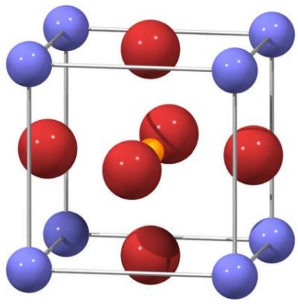


Figure 4.7: Ideal cubic perovskite unit cell. Blue spheres represent the "A" cations, yellow one represents the "B" cation, and red spheres represent O anions (moulding octahedra). The "A" cations are shown at the corners of the cube, and the "B" cation in the centre with O ions in the face-centred positions. [49]

Structure of LaBaCuO

The LaBaCuO structure contains one CuO_2 layer. The CuO_2 layer is denoted as the conductivity layer due to its presence which is determinant for the occurrence of superconductivity. Conductivity layer from above and below bounds the LaO layer. High-temperature superconductivity was first observed right on this structure. The picture shows the $La_{2-x}Ba_xCuO_4$ crystal [50].

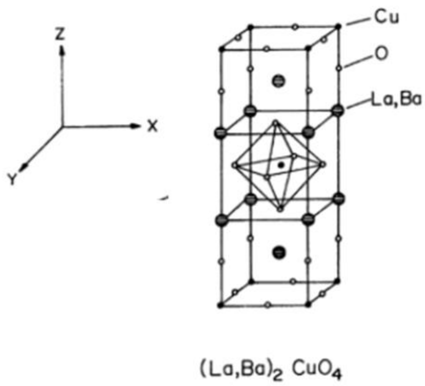


Figure 4.8: The $La_{2-x}Ba_xCuO_4$ crystal [50].

Structure of YBaCuO

The diamond crystallographic system consists of three perovskite cells. It contains two layers of CuO_2 separated by Y. 1) Adding of Y by Ba causes the modification of structure, 2) as well as reduction of Cu_{3+} to Cu_{2+} state and thus resulting in the reduction in the number of required O ions and hence creates O vacancies in the structure. This enables a transition temperature of ~92 K below which the compound has zero electrical resistance and therefore is superconducting. This structure is shown in the Figure 4.10 [50].

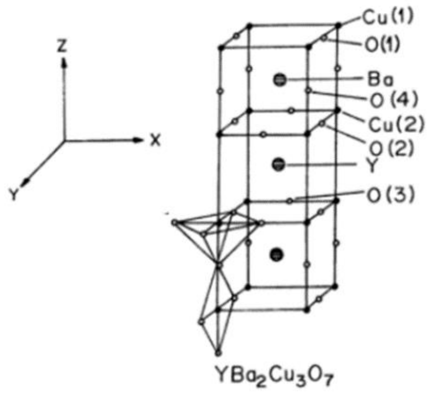


Figure 4.9: Structure of YBaCuO [50].

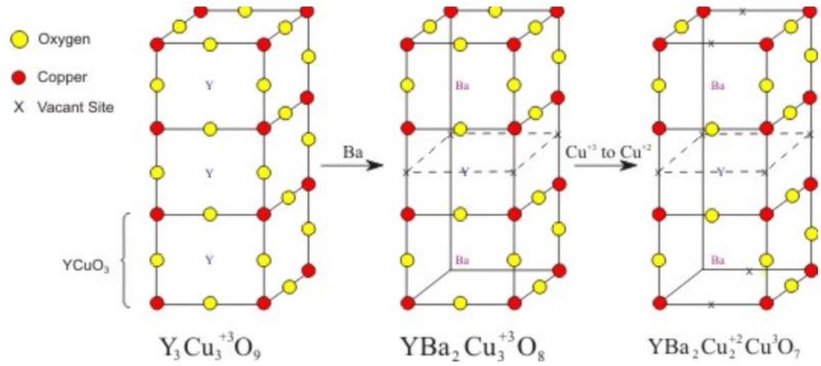


Figure 4.10: Triple perskovite unit; change of formula [51].

Structure of $La_{2-x}Sr_xCuO_4$

Mother compound La_2CuO_4 is a mixture of one NaCl structured compound, LaO and one perovskite structured compound, $LaCuO_3$ chemical pattern and can also be written as $LaOLaCuO_3$. The structure shows a layered structure with layers stacked as A_4O-AO_4-A_4O, as is shown in the Figure 4.11, where "A" is La element. Substitution of La by Sr is resulted in the compound La_{2-x} Sr_x CuO_4 turning into a superconductor with a T_c ~35K [50, 51].

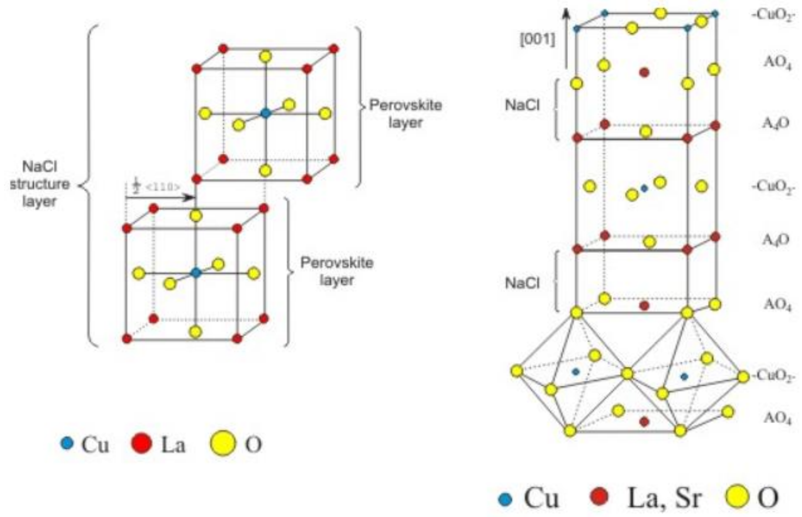


Figure 4.11: Two perkovite cells [51].

Organic Materials

"Organic superconductivity refers to the regular phenomenon of superconductivity as it is observed in some metals and metallic inorganic compounds. However, what makes organic superconductivity so distinctive is that conduction in organic molecular conductors is linked to the transport of free charges (electrons or holes) between π-like molecular orbitals of neighbouring open shell molecules. In addition, these new materials reveal quasi one-dimensional features of their electronic transport properties due to their peculiar crystal structure." [52].

By way of explanation, organic (super)conductors are materials which are consisted of relatively large organic molecules – an amount is around 20 atoms in each molecule. Majority of materials composed of organic molecules usually are not metals (because of hybridization which is causes leaving their conduction and valence bands filled). This property was firstly covered by combining planar organic molecules with inorganic anions (as ClO_4, PF_6 and other ones) which serve as acceptors or donors thus resulting in the appearance of partially filled conduction and/or valence bands. Such materials are called charge transfer salts. In 1981, Klaus Bechgaard synthesized (TMTSF) $2ClO_4$, the first organic material that was superconducting under pressure (according him are named Bechgaard salts). This salt has low superconducting temperature (~1.2 K). Interesting fact is that organic conductors are very complex (convoluted) organic salts [53].

5 APPLICATIONS OF SUPERCONDUCTIVITY IN PRACTICAL LEVEL

Supported by previous knowledge about superconductivity in Chapter 4, moreover, obtained from physical background of this phenomenon mentioned in Chapter 3, final, and main, part of this thesis is focused on practical applications of superconductivity. The unmeasurable small resistance offers a number of possibilities for applications of superconductivity.

5.1. Application of Superconductivity – General List

A. APPLICATIONS OF WEAK SUPERCONDUCTIVITY

The effect of weak superconductivity has its origin in the quantum environment of superconducting state (all electron pairs in the superconducting state occupy the same quantum level common to all of them and their behaviour is mutually conditioned). Weak superconductivity is mainly used in quantum electronics. In these applications, the dependence of critical current, weak magnetic field, temperature and quantization of magnetic flux in SQUID is, used. The applications of weak superconductivity are divided into three groups [3]:

1. *Low Frequency Applications*

- biomagnetism (contactless measurement of spontaneous activity of human heart, brain, eye(s), brain responses etc.)
- geomagnetism and geophysical applications (measurement of Earth magnetic field variations, earthquake prediction, measurement of properties of minerals etc.)
- nuclear and electron magnetic resonance in weak fields
- detection of gravitational waves in gravity antennas with skits
- measurement of magnetic susceptibility of substances, measurement of superconducting properties of materials
- *the most sensitive* measurement of magnetic field and magnetic flux [3]

2. *High Frequency Applications*

- implementation of voltage standard
- wideband microwave and infrared radiation detectors
- usage in field of radio astronomy (used as radiation detectors) [3]

3. ***Digital Applications***

- realization of memory elements, analogue-to-digital converters
- realization of a superconducting pulse counter, transistor or superconducting computer
- development of a digital sampling oscilloscope [3]

B. APPLICATIONS OF STRONG SUPERCONDUCTIVITY

In this overview, the most important applications are mentioned, especially applications of the second type of superconductors (where the values of the critical parameters for realization of large magnetic fields are used) [3].

- superconducting magnets for physical, chemical and biological laboratories
- tomography with nuclear and magnetic resonance
- superconducting accelerators
- polarized targets for nuclear experiments
- superconducting magnetic giants for controlled thermonuclear fusion
- trains (Maglev)
- Magnetic energy storage batteries

5.2. Wires and Cables

Superconducting wires and cables are used in superconductive power transmission and scientific research in ultra-high intensity magnetic fields [54].

Compared to conventional copper cables, the transmission capacity of HTS cables may be up to five times higher at significantly lower losses. Switching to superconducting cables would allow the transition from a voltage level of 440 kV to 110 kV, since at this voltage it is possible to transmit power up to 1000 MV. These cables will generally increase the flexibility of network traffic and, thanks to very low losses, its overall efficiency. Cables for both, DC and AC transmission are being developed. DC cables are economically more advantageous because they do not generate any losses and their construction is more compact. In the cables, the Type I. superconductors are cooled by liquid N. It is cooled to 80 K or less. Thus, the temperature of the cooling agent limits the length of the cable or its individual parts. As a thermal insulation, a cryostat, two concentric tubes, is used. It can be supplemented with a reflective layer limiting heat loss. The thermal leakage of HTS cables is around 1 $W*m^{-1}$, this loss of heat must be carried out by the cooling system. The cooling channel, cryostat and electrical insulation occupy the largest amount of space in the cable, the own superconductor has a thickness of several mm. The cable dimensions are therefore almost independent of the size of the rated current of the cable [58]. Comparison of a 1,000 mile, 5 GW line shows Table 5.1.

HTS cables are developed in the USA by Pirelli and Southwire Corporation, Pirelli, NKT Cable and BICC in Europe, Sumitomo Electric Corporation, Furukawa and Fujikura, Mexico and Condumex in Mexico [55].

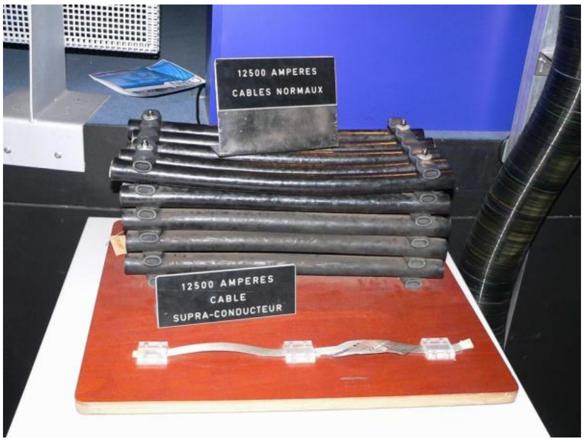


Figure 5.1: Normal cables compared with superconducing one [56].

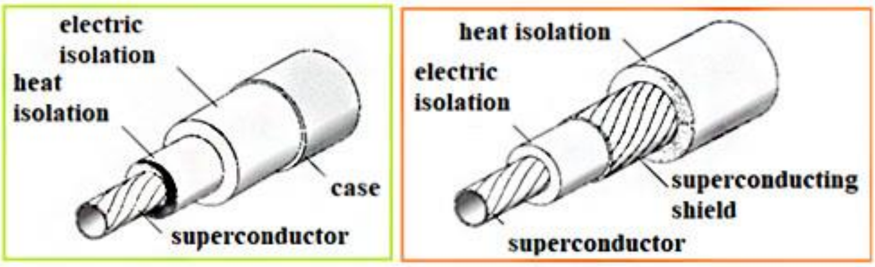


Figure 5.2: Conception of both types of cables (warm one, cold one) [55].

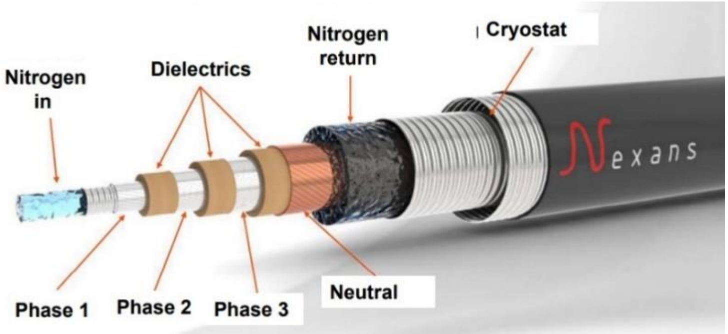


Figure 5.3: Cold dielectric dielectric design cuperconducting cables – 3 concentric phases in one cryostat cryostat [92].

	Metric	200 kV DC Superconductor cable	765 kV AC Transmission Lines
Performance	Power Loss	3 %	9 %
	Storm/Security risk	Low	high
	Precise Control for Efficient Markets	Yes	No
	Cost Allocation Method	Simple	Complicated
	Reuires Rebuild of Underlying Grid	No	Yes
	Black Start Capability	Yes	No
Siting	Required Right on way	7.5 m	180 m
	Aesthetics	Good	Bad
	Elecromagnetic Field	None	High
	New Land Required	No	Yes
Cost	Efficiency Savings Per Year	$170 million	n/a
	CO_2 Emission Savings Per Year	2.5 million tons	n/a
	Cost Per Mile	$8 million for 5 GW pipe, $13 million fuly redundant	$7-10 million minimum

Table 5.1: Comparison of a 1,000-mile, 5 GW Run [57].

Figure 5.4: Long-distance superconducting transmission line in Long Island [91].

5.3. Superconducting Magnets

The most outstanding feature of a superconducting magnet is its ability to support a high current density with an almost infinitely small resistance. This characteristic permits magnet to be constructed that is able to generate intense magnetic fields. This feature also permits steep magnetic field gradients to be generated at fields so intense that the usage of ferromagnetic materials for field shaping is limited by effectiveness [59].

Small superconducting magnets are used in hospitals in MRI, Josephson junctions, formed at contacts between two superconductors, can convert a direct voltage into an alternating current whose frequency rises with applied voltage (see Chapter 3) [46].

Applications of Superconducting Magnets

As was written (and paraphrased) before, these magnets are used in applications requiring a strong magnetic field (for more about Application of Strong Superconductivity see Chapter 5.1B).

- NMR (Nuclear Magnetic Resonance)
- MRI (Magnetic Resonance Imaging) - a medical technique designed to display tissues
- accelerators - in order to accelerate electrically charged particles, it is necessary to use a very intense magnetic field
- ITER reactors (International Thermonuclear Experimental Reactor) - a thermonuclear fusion reactor, the magnetic field keeps hot plasma inside the reactor not to touch the walls
- Tokamak (Toroidal Chamber in Magnetic Coils)
- research of magnetic properties of substances [42, 60]

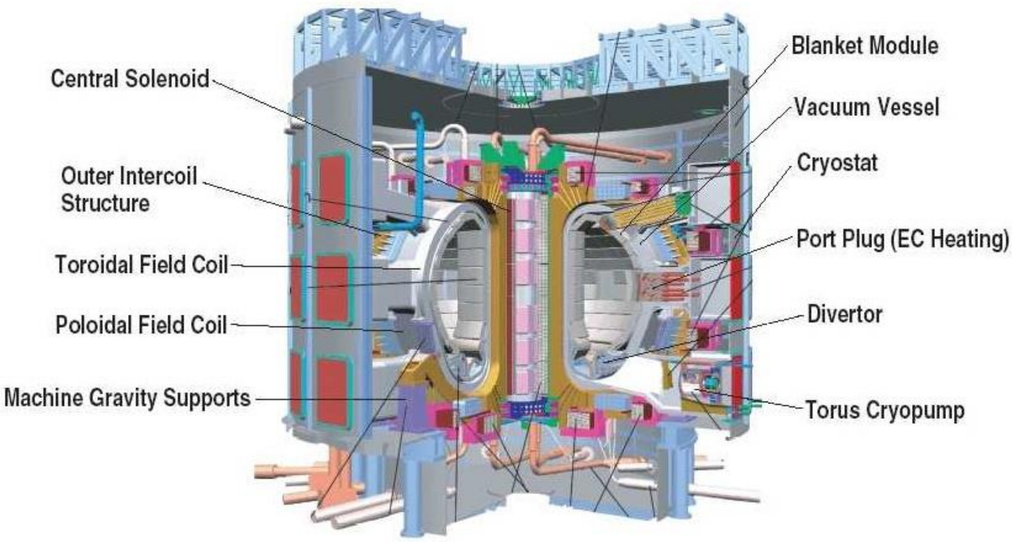


Figure 5.5: The description of ITER [61].

Superconducting Magnet Principle

As mentioned above (before), the temperature at which the substance becomes superconducting is called a critical temperature (see Chapter 3 - Critical parameters). The current flows through the conductor, and because the current creates the magnetic field around the conductor, the superconducting coil is the source of the magnetic field. This is the principle of a superconducting magnet, which is used everywhere where a high magnetic field is needed (and a cooling medium is necessary). The fundamental advantage of superconducting magnets is that due to the zero resistivity of the superconducting material, it is possible to use a much thinner conductor for the safe flow of a relatively high current than would be the case with a conventional coil. Therefore, a large number of threads can be cramped into a relatively small cross-section of the coil [1].

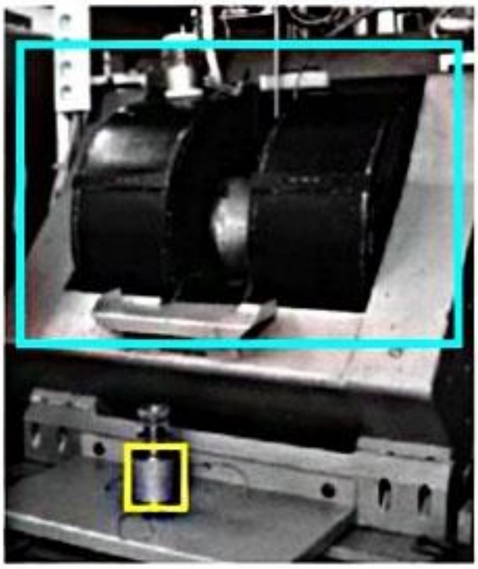


Figure 5.6: Comparison of a conventional electromagnet (black large coil in turquoise frame) with a superconducting magnet (in a yellow frame). At the same current of 100 A, the electromagnet inducts the field 2 T, while the superconducting magnet inducts, in a comparable, field volume 5 T [1].

The magnet field of the coil is proportional to the number of At – multiple of current and number of coil threads. The huge amount of superconducting threads makes it possible to substantially reduce required current compared to conventional magnets. Thus, it is possible to create, with several currents of tens of amperes, the magnetic field of order of few T, which would require, using classical procedures, a small power plant. Figure 5.5 shows the difference between proportions of the conventional and superconducting coils, which produce a comparable magnetic field at the same current 100 A. The small superconducting magnet, even, produces fields more than twice large, whereas the experimental environment is similar in both cases – few tens of cubic centimetres [62, 1].

Nowadays, superconducting magnets are used in particle accelerators, magnetic resonance imaging laboratories, as well as in medicine (magnetic resonance tomography, one of the most demanding investigational devices). They are used in the industry, for example for magnetic water treatment [62, 1].

However, mentioned the advantages of zero resistivity for power distribution is unquestionable, but due to the cost of the necessary superconducting cable cooling, its usage is not economical yet. In this direction, great hopes are being put into high-temperature superconductors (see Chapter 4.1).

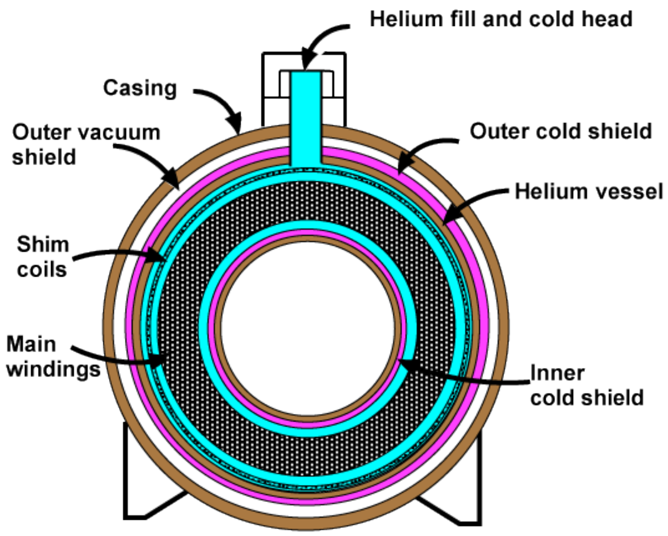


Figure 5.7a: Cross-section of (general) superconducting magnet. Liquid He chambers are notes as blue one. Active shielding coils (not shown) are near the shim coils at the two scanner ends [63].

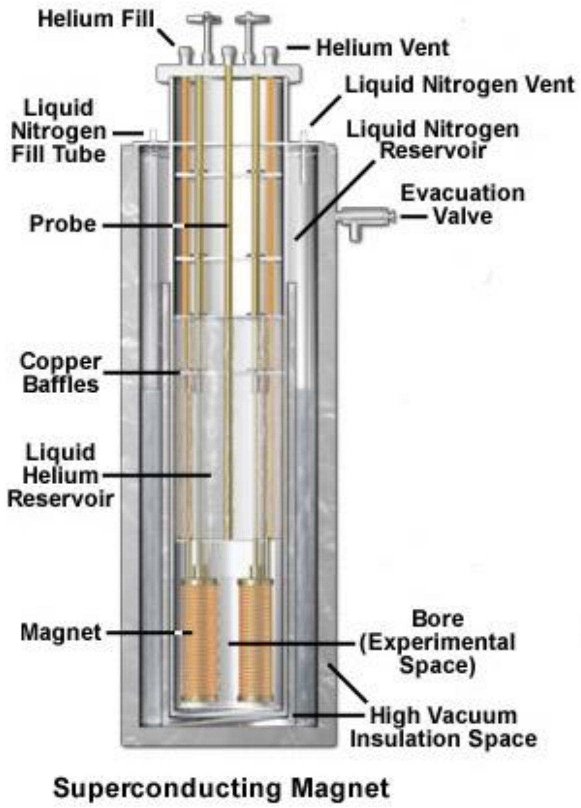


Figure 5.7b: Longitudinal cross-section of superconducting magnet [64].

Magnetization of Superconductor

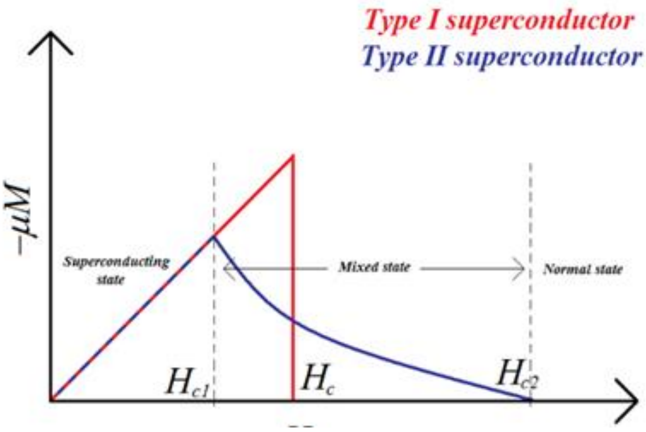


Figure 5.8: The graph of magnetization of Type I and Type II superconductor [65].

When the superconductor is a Type I, the transition between the superconducting and normal states is of first order (that is, when observing a discontinuity between both states for a magnetic field $\boldsymbol{H_c}$). If it is a Type II superconductor, the phase transition between both states is of second order (which means it does not have a discontinuity at a given $\boldsymbol{H_c}$, instead, the superconductor enters a mixed state between $\boldsymbol{H_{c1}}$ and $\boldsymbol{H_{c2}}$) [65].

5.4. Electric Machines, Superconducting Devices

Superconducting Devices

Generally, superconducting devices perform functions in the superconducting state that would be difficult or impossible to implement at room temperature, or that contain components which perform such functions. Superconducting devices may be divided into two categories: 1) small-scale thin-film devices (small-scale devices), and 2) large-scale devices which operate with zero-resistance superconducting windings made of Type-II superconducting materials [66].

a) **small-scale devices**

Many conventional devices offer higher performance compared to their nonsuperconducting counterparts. Ni-based devices, patterned on silicon wafers using photolithographic techniques taken over from the semiconductor industry, have reached a high level of development, and an amount of such devices are available. These devices operate below 4.2 K [66].

b) large-scale devices

Compared to previous ones, large-scale devices applying superconductivity covers quietly different applications - especially medical, energy, transportation and other applications. When strong magnetic fields are needed, superconducting magnets offer several advantages. One of them is lower cost of electric power - that is because of the system is energized only once and the only refrigeration requires power input, which is generally only 5 % - 10 % of an equivalent-field resistive magnet. Most suppliers of superconductors and superconducting materials offer products in many different forms [66, 67].

Electric Generators

These generators are built with superconductive wire have achieved 99% efficiency ratings in experimental tests but have yet to be built commercially [66, 67].

Electric Power Generation

Electric power generation using superconducting cables and transformers has been experimentally tested and demonstrated [66, 67].

Tokamak

Name of this machine is derived from Russian word *“*Токамак*“* as an abbreviation consisted of initial syllables (or letters) of words „**то**роидальная **ка**мера с **ма**гнитными **к**атушками“ [68].

Essentially, Tokamak is a machine which is, a transformer whose secondary coil has one toroidal tube shape. The deuterium and tritium plasma are located inside the toroidal hollow vacuum ring. The electrical current of the primary circuit of the transformer induces electromotive voltage in the secondary circuit. The gas (which is ionized) generates a discharge in the toroidal tube, and the induced current heats it to a high temperature. The magnetic field of this current will keep the plasma generated in the toroid axis, thus, it does not touch the wall of the chamber. Due to the magnetic field, the thermal load on the walls is reduced to a technologically manageable value, thus, walls are expected to cool to temperatures <373.15; 1573.15> K. The dimensions of the reactor and its performance depend on the properties of the materials that form the reactor surface, not on the properties of the plasma. The electric power of these reactors will be in the range of about (2, 3) GW. Working principle of Tokamak is upon warming to the above certain temperature, a thermonuclear fusion occurs and energy which is released. It carries the neutrons (coming from the nuclear reaction) and heats the refrigerant, which is mostly water. This primary water circuit flows into a heat exchanger where the water of the secondary circuit and the steam generated to the steam turbine are heated. It is powered by an AC generator. (the overall scheme of the power plant is the same as for a nuclear power plant using fission reactions). The nuclear reaction products in the plasma and the surrounding environment are purified in the cryodestation apparatus. From there, tritium returns to the toroid with plasma, while the helium formed is discharged off the toroid. At the same time, deuterium is added to the toroid [68].

The ratio of fuel to Tokamak dimensions: If we imagine the Tokamak container of diameter of 4-meter-wide and a 3-meter-high tire, then the fuel has the volume as a broken piece of a mechanical pencil [68].

The largest of Tokamak, referred to as JET, in Culham, is a joint facility of Western European countries. It has a ring diameter of 6 m and flows through a $5 * 10^6$ A current and has reached a temperature of $200 * 10^6$ K for about one second. In Tokamak, the magnetic field is induced by a current pulse and the plasma ring generates a secondary thread of a huge transformer [68].

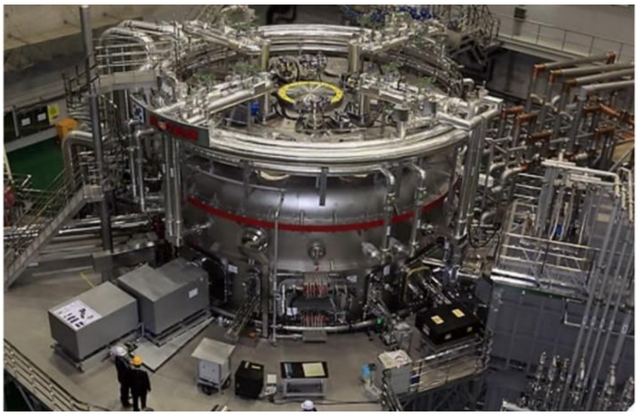


Figure 5.9a: Tokamak machine in real scale [69].

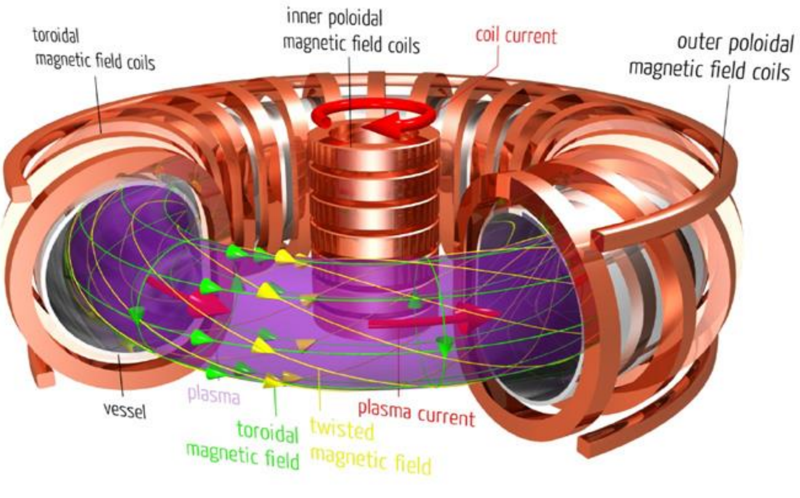


Figure 5.9b: The Tokamak shown in more detail [70].

MagLev Trains

Maglev trains are based on magnetic forces – as magnetic poles repel each other, opposite magnetic poles attract each other – to lift, propel, and move a vehicle over a trajectory (or guideway). Maglev train propulsion and levitation may involve rare-earth magnets, diamagnets, electromagnets and the usage of superconducting materials. Maglev explodes superconducting magnets in order to eliminate friction between the train and the tracks practically [71].

The working principle of magnetic levitation is that a train (vehicle) can be suspended and propelled on a guidance track made with magnets. The vehicle on top of the track may not be propelled with the help of a linear induction motor. Although, Maglev does not use steel wheels on a steel rail, they are still referred as trains as by definition a long chain of vehicles which travel in the same direction. The train will be floating about 10 mm above the magnetic track. The train is propelled to move by the guide way itself. Thus, there is no need of any engine inside the train. The train is propelled when changing in magnetic fields. As soon as the train starts moving, the magnetic field changes sections by switching method and thus the train is again pulled forward. The whole guide way is run by electromagnets to provide the magnetic effect [71]. There are different Maglevs operational in China and in Japan – for more see Figures 5.10a + 5.10b.

MagLev Compared to Traditional (Conventional) Train

Maglev trains have several advantages and, understandably, differences when comparing with traditional trains known today. The main difference between both the trains is that conventional trains need steel wheels and a steel track for their movement, whereas Maglev does not need wheels. Another difference lies in the used engine - Maglev does not need engine(s) as conventional trains do. The engine used for conventional train provides power to pull a chain of compartments along steel tracks. In case of Maglev train, the power propelling the train is provided by the magnetic fields created by the electric coils keeping in the guidance tracks which are added together to provide huge power [72].

An advantage of Maglev is that they are less expensive for operation and, also thanks to one fact, that the absence of rolling friction means that parts do not wear out quickly (as the wheels conventional rail ones do). This fact means, fewer materials are consumed by the train’s operation (because parts do not constantly have to be replaced). Another advantage is that when levitating (operating), Maglev trains produce almost no air pollution because no fuel is being needed and burned, and the absence of friction makes the trains quiet (both within and outside the cars) and provides a very smooth and enjoyable ride for passengers [71].

Side note: The Maglev train reached speed of 603 km/h on April 21, 2015 [72].

Figure 5.10a: Maglev train in China [73].

Figure 5.10b: Maglev train in Japan [74].

Magnetic Resonance Imaging (MRI)

MRI is an imaging technology that produces 3D detailed images of anatomy without any usage of life-threating radiation. This technique is often used for detection of diseases, diagnoses, as well as for monitoring of treatment. MRI works at very sophisticated technology that excites and detects the change in the direction of the rotational axis of protons found in the water (they create living tissues) [75].

MRI uses magnetic fields generated by superconductor for interaction with fat molecules within the (human) body and H atoms. Then these atoms and molecules release energy that is detected and transferred into a graphic image. MRI is a widely used radiographic method for medical diagnosis or staging of diseases such as cancer [67].

For operation of MRI, powerful magnets, which produce a strong magnetic field which forces protons in the body to balance out with that field, are need. When a radiofrequency current is then pulsed through the body of patient, the protons are stimulated, and spin out of equilibrium, straining against the pull of the magnetic field., The MRI sensors are able to detect the energy released as the protons realign with the magnetic field when the radiofrequency field is turned off. The time it takes for the protons to re-align with the magnetic field, as well as the amount of energy released, changes depending on the environment and the chemical nature of the molecules. Physicians are able to specify the difference between many types of tissues based on these magnetic properties [76].

MRI devices are used as MRI scanners which are particularly well suited to image the non-bony parts or soft tissues of the body. They differ from CT, because they do not use the life-threating ionizing radiation of x-rays. The ligaments, spinal cord and nerves, as well as muscles, brain, and tendons are seen much more clearly with MRI than with CT and regular x-rays; due to this reason MRI is often used to image shoulder injuries and knee [76].

In the brain, MRI can differentiate between white matter and grey matter and can also be used to diagnose aneurysms and tumours. When frequent imaging is required for diagnosis or therapy, especially in the brain, MRI does not use x-rays or other radiation, it is the imaging modality of choice However, MRI is more expensive device than CT scanning or x-ray imaging [76].

One kind of specialized MRI is fMR. This type is used to observe brain structures and determine which areas of the brain are “active” (consuming more oxygen) during various cognitive tasks. It is used to advance the understanding of brain function and organization and offers a potential new standard for assessing neurological status and neurosurgical risk [76]. For more understanding see Figures 5.11 and 5.12 on the following page.

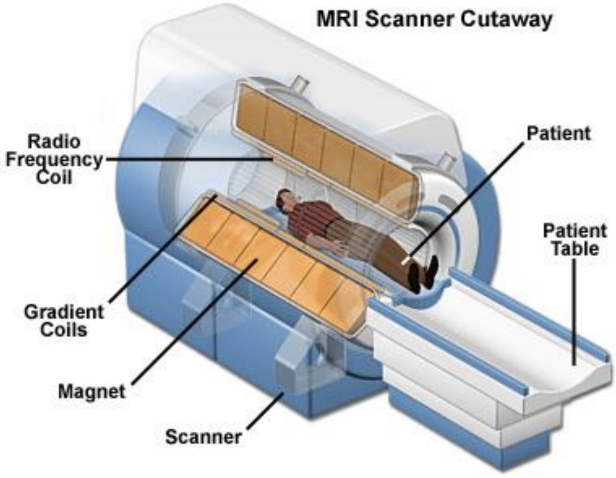


Figure 5.11: The description of MRI scanner [77].

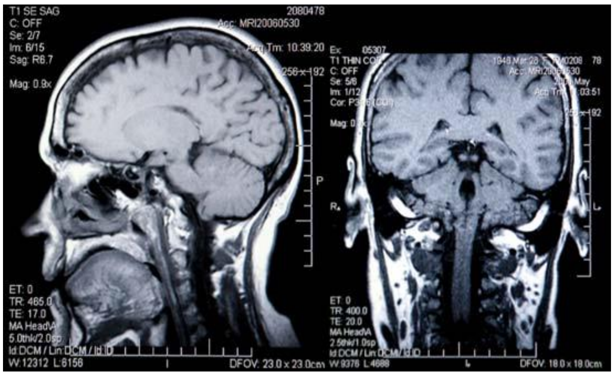


Figure 5.12: A shot of human's brain made by MRI [78].

<u>Superconducting Magnetic Energy Storage (SMES)</u>

This technology originates in three concepts that do not apply to other energy storage technologies. 1) some materials lead current with no losses caused by resistance, 2) electric current produces magnetic field, 3) magnetic field is stored in form of pure energy. Combination of these provides the potential for the remarkably efficient storage of electrical energy in a superconducting coil. Nevertheless, the SMES is different from other storage technologies in the way – the fact that a permanently circulating current within the superconducting coil produces the stored energy. Cryogenically cooled superconducting coil and power conditioning system (which are motionless and result in higher reliability than many other power storage devices). Moreover, the only conversion process in the SMES system is in both foms AC and DC. As result of this process, no inherent thermodynamic losses which are associated with conversion of one type of energy to another exist. Ideally, once the superconducting coil is charged, the current will not decay, and the magnetic energy could be indefinitely stored. The principle of SMES is shown in the Figure 5.13 on the next page [79, 80].

Technical Attributes of SMES

a) rating* of *the energy storage - energy stored in the SMES plant depends on requirements of the application. This is the product two aspects: 1) the power capacity and 2) the length of time the installation delivering this power [80].

b) capacity - the power capacity for a SMES system is dictated by the application, e.g., power quality, power system stability. The capacities of existing individual micro-SMES installations range from 1 MW to about 3 MW [80].

c) efficiency of the system - the overall efficiency of a SMES depends on many factors. Generally, it can be as high as 95 % in very large systems. On the other hand, for low-quality power systems, the overall system efficiency is lower. Fortunately, in applications as these, efficiency is usually not the most significant economic driver. There are also some losses associated with changing current when charging and discharging, and the resulting change in magnetic field. In general view, these losses, which are referring as eddy current and hysteresis losses, are small [80].

d) physical dimensions - the physical size of a SMES system is combination of sizes of the coil, the refrigerator and the PCS (power conditioning system) [80].

Potential of SMES

The SMES has the potential to provide electrical storage to a majority of applications. However, this technology is still emerging, and more R&D will be needed to make SMES competitive in a wide range of utility storage markets [81].

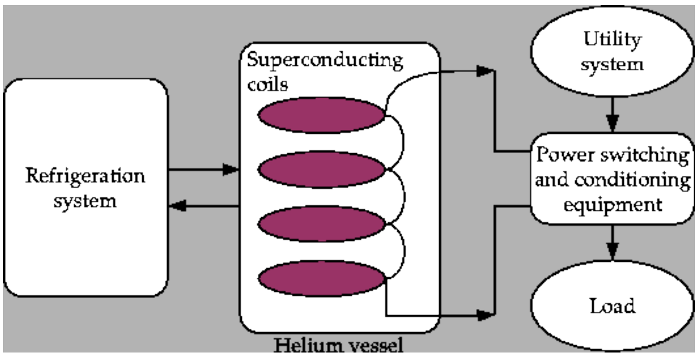


Figure 5.13: Diagram of working of SMES [82].

5.5. SQUID

SQUID (superconducting quantum interference device) is based on Josephson phenomenon (see Chapter 3.6). SQUIDs are highly sensitive sensors (measuring weak magnetic field) which are based on a superconducting ring with a weak link, a point where the material comes back to to its normal nonsuperconducting state at a small current related to the rest of the ring. SQUIDs are widely used in geophysics for measuring magnetic field oscillations of the Earth. The device can be configured as a magnetometer to detect incredibly small magnetic fields - small enough to measure the magnetic fields in living organisms. They are also used for recording magnetograms of organs in the human body (magnetometers are used to measure the magnetic field of the brain; experiments proved that threshold for SQUID is 10^{-14} T, magnetic field of human heart is 10^{-10} T, magnetic field of human brain is 10^{-13} T.). The non-linear characteristics of the superconductor-insulator-superconductor transitions make it possible to mix signals up to THz frequencies and are used as microwave radiation detectors, mainly radio astronomy. Generators of electromagnetic radiation based on the alternate Josephson effect (phenomenon) also work up to THz frequencies [83].

The SQUID consists of two superconductors which are separated by thin insulating layers forming two parallel Josephson junctions (that means two Josephson transitions within the superconducting ring). Interesting fact is, that SQUIDs have been used for measuring the magnetic fields in mouse brain to test whether there might be enough magnetism to attribute their navigational ability to an internal compass [83, 84].

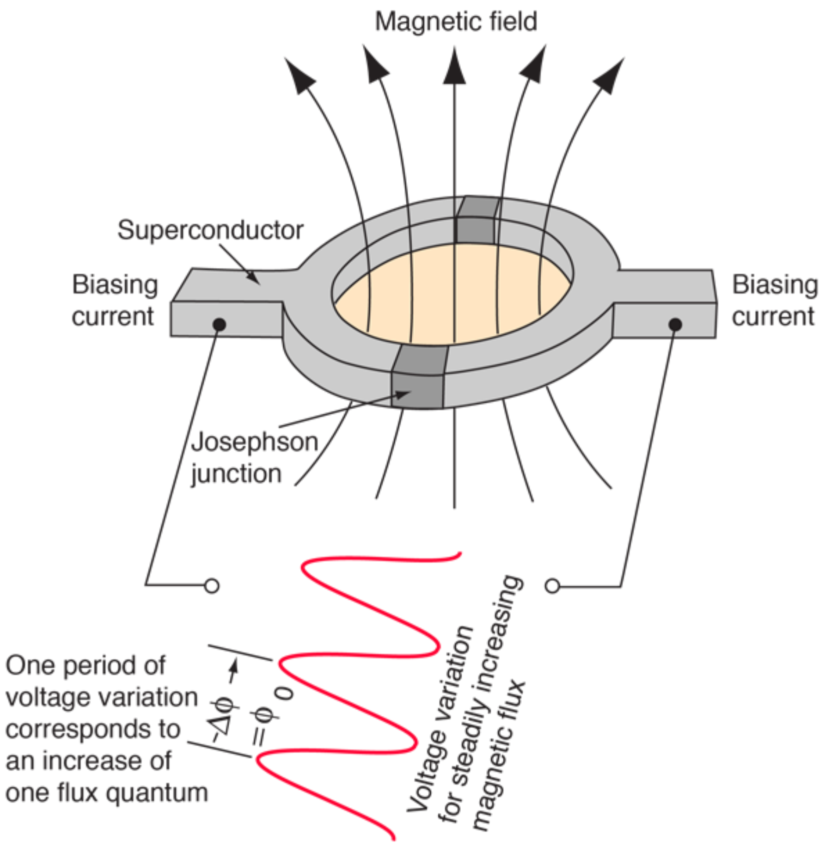


Figure 5.14: SQUID shown and described in the picture [85].

5.6. Cryotron

Cryotron is a very simple device based on the superconductivity disturbance by the magnetic field of the flowing current. Its basic design shows Figure 5.14. The core consists of a 3 cm long straight Ta wire of about 0.2 mm in diameter around which a layer of insulated wire of Ni is wound around (density is approximately 100 turns per 1 cm). The whole device is immersed in liquid helium under normal pressure. Cryotrons can replace electron tubes (or semiconductors) in a series of connections, with the basic circuit of the cryotron being analogous. In this case, minor modifications of the basic design of the cryotron are used, for instance the basic circuit is common to several cryotrons, the advantage of the cryotron is the independence of its operation on the direction of current in the storage and control circuit and small losses [7].

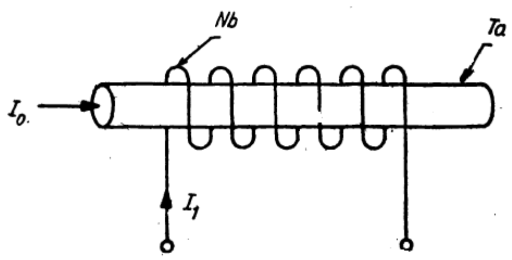


Figure 5.15a: Basic design of cryotron (Nb, Ta wire) [7].

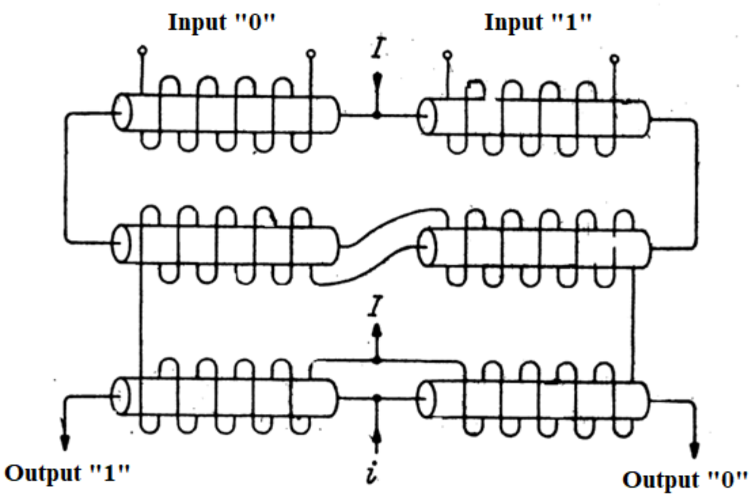


Figure 5.15b: Cryotronic memory circuit with write and read write [7].

6 CONCLUSION

It is necessary to find cheap technological processes of production for the mass use of superconductivity in our life or try to discover new materials with even more advantageous electrical and above all mechanical properties than those present have. In addition, in advanced technology of current world, it is exremelly necessary to understand principles which are supporting superconductivity in new materials. This is the task of future years, and it is possible that it is waiting for some of you.

The aim and purpose of this thesis was to map out the usage of superconductivity in technical solutions and applications. This thesis is focused on pure description of superconductivity from physical and practical points of view (in which situations of everyday life superconductivity could be used).

Notionally, this thesis is divided into four chapters – Introduction, Theory, Practice, and Conclusion. Nevertheless, it would be too complicated to divide this topic according division mentioned in previous sentence, thus whole thesis is divided into better arranged 8 chapters, and subsequently chapters are divided into subchapters. A brief history of superconductivity and the basic attributes (physical background of it) as critical parameters, Meissner phenomenon and Josephson phenomenon are mentioned in the first part of this work. Dividing superconductors by temperature, magnetic field behaviour and sorting by material is mentioned in the following part. The fifth chapter is the core of work, namely the application of superconductivity in everyday life and it includes the technical solutions (Maglev train, MRI, etc.). The last chapter presents the list of superconductors.

This thesis was written in order to help reader to understand the superconductivity itself, without any previous knowledge. Thus, the content of this thesis was selected according to few of John Amos Comenius's principles - principle of continuity as well as principle of illustration (figures).

As final thought, a few facts would be mentioned. Firstly, it took many years before the superconductivity could be used in technological applications. Since the day of describing of superconductivity, many researchers have published a lot of breakthrough phenomena in the physics of low temperature and material sciences. Materials used in applications are called low-temperature superconductors (generally) and their operation is very expensive (as was mentioned above in Chapter 3). On the other side and in many ways of usage, high-temperature superconductors, whose research has just begun, are more favourable. Secondly, today, tens of thousands of tons of superconducting materials are produced every year, but the real "D-day" for superconductivity is to come. Thirdly, superconductivity is very interesting physical phenomenon. It took a long time to physics until they found a microscopic explanation of this occurrence. Superconductivity is very important phenomenon in physics of elementary particles, astrophysics, as well as in nuclear physics and in other physical branches (for more see Chapter 8.3). Lastly, this thesis might establish a starting point for further research and analyses in field of superconductivity not only for reader.

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8 APPENDIX

8.1. List of Elemental Superconductors*

In this Table 8.1 placed below, some of the parameters which are superconductors of simple structure are shown. Letters X: Y signs material X doped with element Y, T_c is the highest achieved temperature in K and $\boldsymbol{H_c}$ signs a critical magnetic field in T. The term “BCS” signs whether, or not, the superconductivity is explained in reach the BCS theory in this material/element.

Element	T_C (K)	H_C (T)	Type	BCS
Al	I.20	0.01	I	yes
Cd	0.52	0.0028	I	yes
C:B	11.IV	4	II	yes
Ga	1.083	0.0058	I	yes
Hf	0.165		I	yes
α-Hg	IV.15	0.04	I	yes
β-Hg	III.95	0.04	I	yes
In	3.IV	0.03	I	yes
Ir	0.14	0.0016	I	yes
α-La	4.IX		I	yes
β-La	6.III		I	yes
Mo	0.92	0.0096	I	yes
Nb	IX.26	0.82	II	yes
Os	0.65	0.007	I	yes
Pa	1.IV		I	yes
Pb	VII.19	0.08	I	yes
Re	2.IV	0.03	I	yes
Ru	0.49	0.005	I	yes
Si:B	0.4	0.4	II	yes
Sn	III.72	0.03	I	yes
Ta	IV.48	0.09	I	yes

Element	T_C (K)	H_C (T)	Type	BCS
Tc	7.46–11.2	0.04	II	yes
α-Th	I.37	0.013	I	yes
Ti	0.39	0.01	I	yes
Tl	II.39	0.02	I	yes
α-U	0.68		I	yes
β-U	1.VIII		I	yes
V	5.III	1	II	yes
α-W	0.015	0.00012	I	yes
β-W	1–4			
Zn	0.855	0.005	I	yes
Zr	0.55	0.014	I	yes
COMPOUNDS				
Ba_8Si_{46}	8.VII	0.008	II	yes
C_6Ca	11.V	0.95	II	
C_6Li3Ca_2	XI.15		II	
C_8K	0.14		II	
C_8KHg	1.IV		II	
C_6K	1.V		II	
C_3K	3.0		II	
C_3Li	<0.35		II	
C_2Li	1.IX		II	

Element	T_C (K)	H_C (T)	Type	BCS
C_3Na	2.3–3.8		II	
C_2Na	5.0		II	
C_8Rb	0.025		II	
C_6Sr	I.65		II	
C_6Yb	6.V		II	
C_60Cs_2Rb	33		II	yes
C60K3	19.VIII	0.013	II	yes
C_60RbX	28		II	yes
FeB_4	2.IX		I	
InN	3		II	yes
In_2O_3	3.III	~ 3	II	yes
LaB_6	0.45			yes
MgB_2	39	74	II	yes

Element	T_C (K)	H_C (T)	Type	BCS
Nb_3A_l	18		II	yes
Nb_3Ge	23.II	37	II	yes
NbO	I.38		II	yes
NbN	16		II	yes
Nb_3Sn	18.III	30	II	yes
NbTi	10	15	II	yes
SiC:B	1.IV	0.008	I	yes
SiC:Al	1.V	0.04	II	yes
TiN	5.VI			yes
YB_6	8.IV		II	yes
ZrN	10			yes
ZrB_{12}	6.0		I	yes

Table 8.1: List of superconductors [86].

8.2. Failed and Other Theories of Superconductivity

"Every failure of a person will teach something if he wants to learn."

Charles Dickens

When thinking about failed attempts in way of understanding superconductivity, one fact has to be kept in mind – that attempts are a natural and healthy part of our lives as well as the scientific discourse. They are important part well of the process as well as finding correct answers. This subchapter gives information based on interesting facts during discovering of superconductivity – this phenomenon had been predicted by few scientists – they worked on the same fact independently to each other almost at the same time period [86].

In light of the topic of this ("yellow journalism") subchapter, it is kind of ironical that the original discovery by Kamerlingh Onnes seems to have been motivated by an incorrect theory itself, which had been proposed by another highly acclaimed scientist during that period of time (superconductivity has T_c unit expressed according his name). Lord Kelvin had argued kind of theory very near to theory of superconductivity, using the law of corresponding states, that the resistivity of all substances diverges at low temperatures. Kamerlingh Onnes was a bit aware of Kelvin's work, and whereas he might have been sceptical about this statement, the proposal underscored the importance to investigate $T \to 0$, diverges to the limit of the electric resistivity [87].

In 1950, the isotope effect had been predicted and researched (in the group composed of Bernard Serin and Emanuel Maxwell, the National Bureau of Standards in Washington, D. C.). These researchers led experiments and found changes in the transition temperature upon changing the ion mass via isotope substitution (they demonstrated that vibrations of the crystalline lattice). Bardeen and, independently to each other, Fröhlich (prediction of this phenomenon) worked on the same problem and concluded that vibrations of the crystalline lattice lead to a net attraction between electrons thus they “cause” of superconductivity. Starting in 1950 one should not refer to Bardeen's ideas as more likely failed, rather than incomplete. The link between the established attraction made between excitations of electrons and superconductivity have not been solved yet. This research helped when discovering BCS Theory later [87].

Other of few “failures” in way of explaining superconductivity, two theories are involved noteworthy for their elegance and the distinguished participants. Those are the spontaneous current approach independently proposed by Felix Bloch and Lev Landau and their theory of coherent electron–lattice motion predicted by Niels Bohr and, at the same period of time, by Ralph de Laer Kronig. It could be said that authors of these ideas worked on wrong theories, but actually not that they proposed “uninteresting” ideas. Both concepts had some kind of lasting impact or minimal relevance [87].

It is interesting that for a wartime purposes (in WW II), superconducting bolometers have been constructed – they are very sensitive especially in the infrared spectrum (they have a small heat capacity and their sensitivity can be greatly increased since a small temperature difference will cause a great change in resistance). Other device which has been constructed for wartime purposes has been a radio receiver with superconductors. [7]

8.3. Future View of Superconductivity, New Theories

"I am never afraid of the future. It will come soon."

Albert Einstein

When thinking about future, many factors should be considered (factors as environment, price, power, population, science etc). One of few possible future applications of superconductivity lies in field of SU (2) theory (cuprate superconductors - this phenomenon remains one of the most enduring mysteries of material science) or lies in field of nano-technologies (an interplay between ferromagnetism and superconductivity in Ni nanowires) [88, 89].

The next "hope" for future applications, comparing power vs. price, are HTS. Electric power systems application of HTS is the main orientation of the HTS Technology Collaboration Programme of the International Energy Agency whereas technical ideas, challenges and needs are introduced and discussed in field of wires, cryogenics, cables or generators. The point lies, for instance, in electric power grids – it is not such a long time till now, HTS has made significant technical progress in a relatively short period of time since its discovery (the exploration is still continuing). Wire and electric grid applications development progressed along the technology commercialization pathway and also there are large testimonies of projects for several applications [58, 90].

From my point of view, when focusing on facts written above, new thesis focused only to new theories could be written as well as any chapter could be extended to other stand-alone thesis.

8.4. Lists of Figures, Abbreviations, Tables and Units

List of Figures

List of Tables

List of Abbreviations

AC .... alternating current
BCS .... Bardeen–Cooper–Schrieffer theory
CT .... computed tomography
DC .... direct current
fMRI .... functional Magnetic Resonance Imaging
HPHT .... High Pressure High Temperature
HTS .... high-temperature superconductors
IBM .... International Business Machines
JET .... Joint Europien Torus
LTS .... low-temperature superconductors
MRI .... magnetic resonance imagining
NMR .... nuclear magnetic resonance
R&D .... research and development
S-I-S .... superconductor – insulator – superconductor
SMES .... Superconducting Magnetic Energy Storage
SQUID .... superconducting quantum interference device
STC .... Standart Test Conditions
SU (2) .... special unitary (2)

List of Quantities and Units

Quantity .... **Name of quantity** .... **[Unit]**
A .... vector magnetic potential .... [$V*s*m^{-1}$]
At .... ampere-turns .... [At]
B .... magnetic flux intensity .... [T]
$\boldsymbol{B}_c$ .... critical magnetic induction .... [T]
D .... electric flux intensity .... [Vm]

Quantity	Name of quantity	[Unit]
$\boldsymbol{E}$	electric field intensity	$[N*C^{-1}]$
e	elementary charge	[C]
f	frequency	[Hz]
h	Planck constant	[J*s]
$\boldsymbol{H}$	magnetic field intensity	$[A*m^{-1}]$
$\boldsymbol{H_c}$	critical magnetic field	[T]
I	electrical current	[A]
I_c	critical current	[A]
$\boldsymbol{J}$	current density	$[A*m^{-2}]$
$\boldsymbol{J_s}$	superconducting current density	$[A*m^{-2}]$
$\boldsymbol{J_v}$	current density (caused by eddy currents)	$[A*m^{-2}]$
K_J	Josephson constant	$[GHz*V^{-1}]$
m	mass	[g]
n	quantum state	[-]
n_s	number density of superconducting carriers	[-]
P	power	[W]
ΔP_t	thermal leakage	W/m
T	thermodynamic temperature	[K]
t	temperature	[°C]
T_c	critical temperature	[K]
U	voltage	[V]
v	velocity	$[ms^{-1}]$
γ	conductivity	[S]
ε	permittivity	$[F*m^{-1}]$
λ	characteristic length scale	[m]
μ_0	permeability of vacuum	$[N*A^{-2}]$
μ_r	relative permeability	[-]
ρ	density	$[kg*m^3]$
ϕ_e	specific density of electric charge	$[C*m^{-3}]$
χ	susceptibility	[-]