Superconductors for Maglev trains

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Contents

1 Introduction

Superconductors, often mistakenly described as perfect conductors, are instead *perfect diamagnets*. Indeed, while their electrical resistance drops to extremely small values in the superconducting state, what truly distinguishes them is their ability to completely expel magnetic flux from their interior. This phenomenon, known as the Meissner effect and discussed in detail in Section 2, reveals that superconductivity is fundamentally a magnetic phenomenon rather than a purely electrical one.

The distinction is crucial: a perfect conductor would merely preserve the magnetic field configuration present at the moment currents begin to flow, whereas a superconductor actively generates surface currents that cancel any internal magnetic field. This behavior can be formally understood through the magnetic susceptibility χ, which characterizes how a material responds to an applied magnetic field. Paramagnetic and ferromagnetic materials possess $\chi > 0$, reinforcing the field, while diamagnets oppose it and exhibit $\chi < 0$. A *perfect diamagnet* has $\chi = -1$, implying complete expulsion of magnetic flux and the absence of any internal magnetization.

Superconductors exhibit this ideal diamagnetic response below their critical temperature T_c and under magnetic fields lower than their critical field H_c. This property is not merely of theoretical interest: it forms the physical basis of magnetic levitation. The ability to sustain stable, frictionless levitation is central to the operation of high-speed transportation systems such as Maglev trains, which rely directly on the perfect diamagnetism and flux exclusion of superconducting materials.

Although perfect diamagnetism defines superconductivity, the nearly vanishing electrical resistance that accompanies it remains technologically invaluable. In the absence of dissipative scattering, electrical currents can circulate indefinitely, eliminating Joule heating and drastically reducing energy losses.

Superconductivity, however, is observed only in specific metals and complex ceramic compounds, and only under stringent thermodynamic conditions, which are not easy to reach.

Among the materials employed for superconducting applications, Nb–Ti is by far the most widely used alloy, owing to its relatively simple fabrication, good mechanical workability, and robust superconducting properties. In particular, Nb–Ti combines a sufficiently high critical magnetic field with excellent ductility, allowing it to be drawn into long, flexible wires suitable for large-scale electromagnetic systems. For these reasons, Nb–Ti has been extensively adopted in practical superconducting devices, especially in applications requiring high current densities under strong magnetic fields.

Magnetig levitation (or maglev) trains, are a promising application for this kind of materials in order to transport people more efficiently. Although no superconductor maglev lines are implemented yet, standad maglev lines exist and a superconducor line is due to be completed in 2034[1]. However they demand superconductors with a high critical temperature or an efficient cooling system, as well as high velocity, in order to work properly.

2 Meissner effect

The fundamental origin of diamagnetism, and by extension of the Meissner effect, in superconductors can be understood in terms of electromagnetic induction as described by Lenz's Law. This principle states that any change in magnetic flux through a closed circuit induces a current whose magnetic field opposes the variation that generated it. At the macroscopic level, this manifests as induced screening currents. At the microscopic scale, a simplified classical picture sees electrons slightly adjusting their orbital motion when subjected to a varying magnetic field, generating microscopic magnetic moments that oppose the applied field. Although a full description requires quantum mechanics, the underlying principle of opposition remains valid. Since this mechanism is universal, all materials are intrinsically diamagnetic; however, this response is usually overshadowed by stronger paramagnetic or ferromagnetic contributions in materials with unpaired electron spins or magnetic ordering.

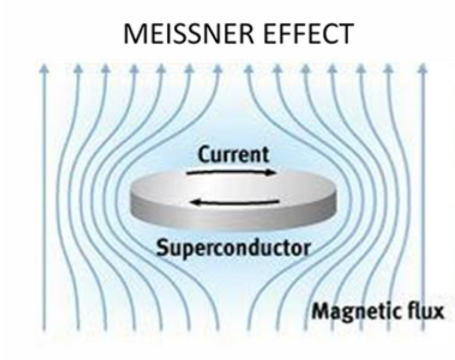

Figure 1: Meissner effect representation

Superconductors represent the limiting case of diamagnetism, displaying perfect magnetic flux expulsion when cooled below the critical temperature. Upon entering the superconducting state in the presence of an external magnetic field, the material generates persistent, resistance-free surface currents, known as Meissner currents that produce an opposing magnetic field able to cancel the applied field inside the sample. This leads to a magnetic susceptibility $\chi = -1$ and manifests as perfect diamagnetism. The magnitude of these screening currents increases with the intensity of the applied field, but only up to the threshold beyond which the superconducting phase can no longer sustain the required current density. This limit is quantified by the critical field H_c, which decreases with temperature and vanishes at the critical temperature T_c, as illustrated in Figure 2 [2].

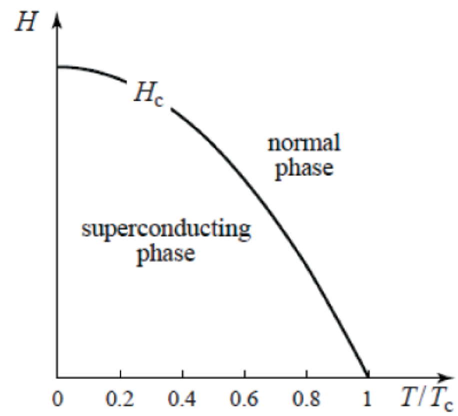

Figure 2: Superconducting phase diagram

The curve shown in Figure 2 describes the behavior of Type I superconductors, which retain a complete Meissner state until superconductivity is abruptly destroyed when the applied field exceeds H_c. This description, while accurate for Type I materials, does not apply to all superconductors. Type II superconductors, which will be discussed in Section 3, possess two critical fields, H_{c1} and H_{c2}. Between these limits they enter a mixed (or vortex) state, where magnetic flux partially penetrates the material through quantized vortices while global superconductivity is maintained. This regime is essential in high-field applications, including magnetic levitation technologies such as Maglev trains, where Type I superconductors with their low critical fields and single-phase transition are unsuitable.

3 Type 1 and type 2 superconductors

As seen in the 2 section, superconductors have a critical field which represents the max intensity the external field can have that can be "shielded". This maximum intensity of external field decreases as temperature increases, to reach 0 at a critical temperature.

As such there are 2 types of superconductors:

- Superconductors type 1, or soft superconductors, that totally shield fields which intensity is inferior to Hc. Their phase diagram is presented at the left curve in figure 3. Most of pure elements are superconductors of type 1 at very low temperatures [3].
- Superconductors type 2, or hard superconductors, which present a perfect diamagnetic behaviour below a critical magnetic field Hc1, a normal diamagnet field above a critical magnetic field Hc2 and a mixed state between the critical magnetic fields Hc1 and Hc2, as presented at the right curve in figure 3. These materials are mainly alloys, like NbTi, Niobium-tin or lead-bismuth alloys, or perovskites, such as YBCO [3].

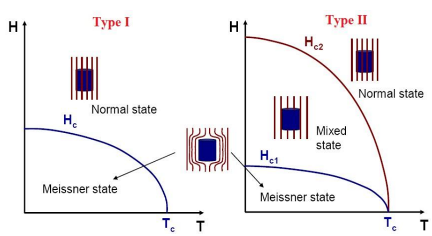

Figure 3: phase diagram for type 1 (left) and type 2 (right) superconductors, taken from the work of Pablo Cayado LLosa [4]

While the superconductor state corresponds to the material being a perfect diamagnet, and the non-superconductor or "quenched" correspond to a material in which the field enters uniformely. In the mixed state between Hc1 and Hc2, the material is still superconductor but experiences partial nonuniform penetration of the magnetic field [5].

This mixed state, as shown in Fig.4, is characterized by the coexistence of regions where the material locally behaves as a normal conductor, allowing magnetic field penetration, and regions that still exhibit superconducting behavior and expel the magnetic field.

In a simplified description, this phenomenon arises from the formation of quantized magnetic flux vortices. Each vortex consists of a normal-conducting core through which the magnetic field penetrates, surrounded by circulating superconducting currents that shield the field in the surrounding regions, thus giving rise to the mixed state.

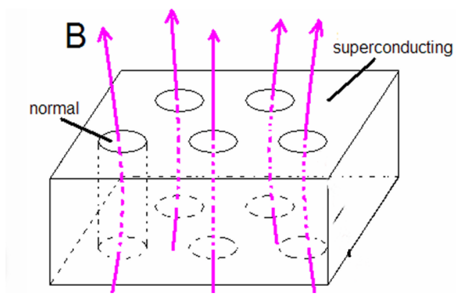

Figure 4: Mixed state representation

The core mechanism of type I and type II superconductivity is the same, and some materials can be converted to type-IT behavior simply by the addition of impurities [5]. However type II superconductors may be preferred for some magnetic application as it allows for superconductivity at higher magnetic fields or higher critical temperatures [3] [5] .

4 Why superconductivity is a low T phenomenon (Cooper pairs)

As explained in section 1, superconductivity only exists below the critical temperature. Below this temperature, the electrical resistance in the materials drops to extremely small values in the superconducting state and the interior of the material has zero magnetic field. The Meissner effect will also be observed [6]. However, why does this phenomenon only exist at low temperatures?

4.1 Quantum mechanics

Quantum mechanics is the basis to the superconductor phenomenon. The wave function are dependent on time and the particles coordinates, and describes the state of a particle. The wavefunction contains all the dynamical information about the system it describes. Further we are going to focus on the information it carries about the location of the particle. If the wave function of a particle has the value Ψ at some point x, then the probability of finding the particle between x and $x + dx$ is proportional to $|\Psi|^2 dx$ [7]. The particle must be somewhere in the infinite space, and therefore the total probability of finding it must be equal to 1.

The Schrodinger equation is an equation that finds the wave equation for a given system. The Schrodinger equation for one particle in one dimension is

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x,t)\right)\Psi(x,t) = i\hbar\frac{\partial}{\partial t}\Psi(x,t). \tag{1}$$

where the wave function is $\Psi(x,t)$.

Particle in a one-dimensional box is a good model to understand the energy levels that the particle can have. The particle is within the interval $x\epsilon = [0, L]$ where $V(x) = 0$, and is not affected by outer forces. $V(x) = \infty$ outside of the interval. $H(x,t)$ is the Hamiltonian operator and describes the total energy of the system. The Schrodinger equation can be simplified if the potential energy is independent on time. Applying the necessary boundary conditions and solving the equation, the solution will be

$$E_n = \frac{n^2\pi^2\hbar^2}{2mL^2}, n = 0, 1, 2, 3, ... \tag{2}$$

which shows that the energy is quantized. [7]

4.2 Free electron model

The free electron model provides an explanation on how electrons behave in metals. The electrons are viewed as gas in a one-dimensional box. At T = 0K, the electrons fill up the energy levels according to Paulis' Exclusion Principle [uni book, 9.4]. The Paulis' Exclusion Principle says that only two electrons can occupy the same orbital, where one electron has spin up and the other has spin down [7]. The energy levels are filled from the lowest until the highest. The Fermi energy is the highest occupied quantum state at T = 0K [8].

To apply this model in a three-dimensional room, the electrons are placed in a metal block instead of a box [8]. For a free particle in three dimensions, for example an electron near a nucleus in an atom, the wave function depends on the point dr with coordinates x, y and z. If the wave function of a particle has the value Ψ at some point r, then the probability of finding the particle in an infinitesimal volume

$$d\tau = dx\, dy\, dz$$

at that point is proportional to $|\Psi|^2 d\tau$ [7].

Applying the same boundary conditions to this model as the one-dimensional one, the energy levels are

$$E = \frac{\pi^2 \hbar^2}{2mL^2} \left(n_1^2 + n_2^2 + n_3^2 \right) \tag{3}$$

[8].

4.3 Electrons in metals

Quantum mechanics and the free electron model can be used to describe the electrons behaviour in metals. The atoms are structured in a periodic lattice. Energy bands are formed when atoms are close enough to each other, and their atomic orbitals overlap. Furthermore, the wave functions of the electrons will also overlap. Because of Paulis' exclusion principle, the atomic orbitals that are equivalent cannot have the same energy level [9].

The valence band is the highest filled energy band. The conduction band is separated from the valence band with a energy gap. What kind of material we have, whether it is a metal, semiconductor, or insulator, depends on how the electrons fill the valence and conduction band.

In an insulator, the valence band is completely full. The conduction band remains empty. There is a large band gap between the bands which prevents the electrons from being excited to the conduction band. As a result, the material does not have electrical conductivity. [9]

The semiconductor have a similar structure to the insulator but with a more narrow band gap. As a result, some electrons can be excited from the valence band into the conduction band at room temperature. [9]

In metals, the conduction band is partially filled or the valence band and the conduction band overlap. Therefore, electrons can easily move to the empty energy states that are nearby. When an electric field is applied, the electrons receive kinetic energy which creates an electrical current [9]

4.4 Superconductivity

In a more simpler model like the free electron model, the electrons are seen as free particles. What this means is that the electrons move through the material without interacting with the positive ions. This is a good model to explain many properties of the materials, but fails to explain superconductivity. In reality, a metal is a crystal arranged structure made of positive ions. The ions are not stuck in one place in the structure, but vibrate around their equilibrium position. The equilibrium position is the position where the ion is stable and the net force on the ion is zero. When an electron moves through the material, it draws the nearest positive ions towards it. This creates a small and temporary displacement in the lattice. Because the ions are connected, when one ion moves, it will pull on its neighbors which will make them move. This movement is causing a displacement, and this will continue in the whole lattice. The spreading of the displacement can be looked as a moving wave, and are called phonons. Phonons will again affect other electrons. This whole interaction is called the electron-phonon interaction [10].

The BCS theory founded by J. Bardeen, L. Cooper and J. Schrieffer explains the electronic behaviour in the superconducting state [6]. Normally, electrons will repel each other because they both have a negative electric charge. However, because of the electron-phonon interaction, this changes. When one electron moves through the lattice and attracts positive ions closer to it, that creates an area where you have more positive charge. When another electron passes this area with a higher positive charge density, it can be attracted to this displacement. If that happens, the two electrons will effectivly be attracted to each other, allowing them to form Cooper pairs. This effective attraction can only exist if certain criterias are fulfilled [11].

A Cooper pair is two electrons that have a weak bond with each other because of the electron-phonon interaction. The two electrons in Cooper pais have a opposite spin and momentum. Therefore, the total spin and momentum of the pair is equal to zero.[12]. This is the lowest energy that the pair can have. Not all electrons can form Cooper pairs. Electrons far below the Fermi level cannot change their quantum states as they are blocked by the Paulis' exclusion principle. Only electrons with energy level close to the Fermi level can participate in Cooper pairs, because they have available quantum states[11].

A Cooper pair is different from electron pairs in atoms or molecules. The electrons are moving around the nucleus in atoms. In Cooper pairs, however, the pair are spread out over a large distance which is much larger than the distance between the electrons and nucleus in atoms. Because the Cooper pairs are spread out over the material, they strongly overlap with one another which causes superconductivity [11]. When several Cooper pairs are existing, they get coupled up together by the Pauli exclusion principle. What that means is that the Cooper pairs act together instead of separately. Many Cooper pairs can have the same quantum state. The total spin for the pair is zero, as mentioned earlier, and therefore the pair will behave as a boson. Electrons are fermions, which means that they do not like to share their quantum state. That means that they do not want to have the same energy, movement and spin as another fermion. Boson on the other hand, do not mind it. This allows Cooper pairs to act together [12].

A minimum energy is needed to break a Cooper pair when a metal turns superconducting. This minimum energy is the energy gap. Because of the energy gap, it becomes more difficult for electrons to gain enough energy and move to a energy level where no Cooper pairs are present. However, if the gap energy is lower than the thermal energy, the Cooper pairs will break. This is why superconductivity is only observed at low temperature, because the thermal energy is not high enough to break the Cooper pairs. [11].

5 Field and zero field cooling

As superconductivity is a low temperature phenomenon, it is necessary to cool it and induce a field to get the most out of a superconductor functional properties. There are two main methods to induce a magnetic response from a superconductor, which are explained as follows in the introduction of the work of Li et al [13]:

1. Field cooling: When the sample is cooled in the presence of a magnetic field until the temperature of the materials drops to Tc. Then the field is removed. According to Li et al [13], the magnetization is lower.
2. Zero-field cooling: When the sample is cooled below Tc before the field is applied. The magnetic properties of the superconductor are measured during the heating phase. According to Li et al [13], Zero field cooling makes the superconductor a more perfect diamagnet and gives it high magnetization (still opposite to the magnetic flux). This method is thus recommended for magnetic levitation.

As such, it is better to use zero-field cooling to make maglev trains.

The figure 5 shows the difference between superconductors and perfect conductors. As such, during field cooling, superconductors behave as a perfect diamagnet and repel the magnetic flux while a perfect conductor will let the magnetic flux flow while the field is applied and then act as a magnetic dipole.

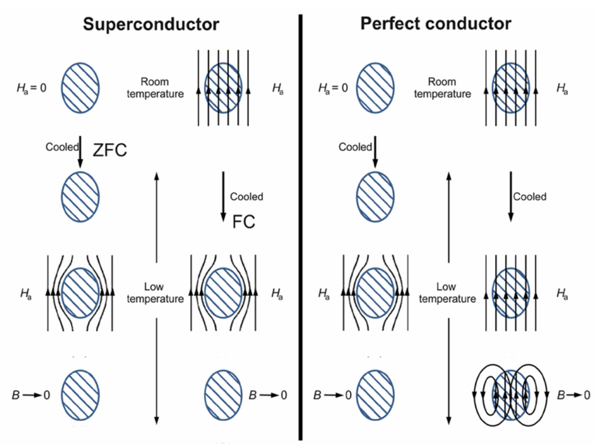

Figure 5: Zero field cooling and field cooling in a Superconductor and a perfect conductor

6 Materials in superconductors

6.1 Low temperature superconductors (LTS)

Once we have established why superconductivity is fundamentally a low-temperature phenomenon, we can introduce that for any commercial application, the differential working property will be the critical working temperature (T_c) of the material. According to this property, we can divide superconducting materials into Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS).

Low Temperature Superconductors (LTS) [14] are materials typically defined by critical temperatures T_c below approximately 20 K, a threshold often associated with the storage temperature of liquid hydrogen (H_2).

LTS materials are predominantly Type II superconductors. This classification is essential because they are primarily used in high-field magnetic applications. Unlike Type I superconductors, Type II systems can withstand significantly higher magnetic fields, up to their upper critical field H_{c2}. Clear examples of the high upper critical fields characteristic of LTS include Nb_3Al ($B_{c2} > 30T$), Nb_3Sn (with $B_{c2} \approx 30$ T) and NbTi, with an optimized B_{c2} of approximately 11.5 T.

Although it has a lower critical field compared to other alloy-based superconductors, NbTi remains the dominant material for industrial applications. This is mainly due to its excellent ductility, which facilitates plastic deformation and fine filament fabrication, as well as its critical temperature ($T_c \approx 9.3$ K), which is not substantially lower than that of other LTS compounds. Among its major applications are medical MRI systems, particle accelerators, and magnetic levitation (Maglev) trains, the latter being the focus of this work.

Beyond its favorable critical parameters and industrial manufacturability, the widespread adoption of NbTi is strongly supported by its well-understood magnetic behavior, particularly in fine-filamentary multi-filament wires. A detailed D.C. magnetization study of NbTi fine-filament superconductors has shown that the magnetic response of these composites is governed not only by their intrinsic superconducting properties but also by proximity coupling between filaments and by the complex pinning structures that arise at sub-micron scales [15].

The study reports that, when the filament diameter is reduced into the 0.5–3.4 μm range, anomalies appear in the temperature-dependent magnetic susceptibility χ(T) and in the initial magnetization curves M(H) under perpendicular magnetic field. These anomalies reveal that neighboring NbTi filaments become coupled through the copper matrix via the proximity effect, effectively causing the strand to behave as a monolithic superconductor under low fields. While such coupling is undesirable, since it reintroduces excess magnetization and increases AC losses, it becomes increasingly prominent as the filament diameter is reduced, highlighting a fundamental trade-off in wire design.

The magnetization analysis also indicates that these coupled filaments form a complex pinning structure within the twisted composites, as evidenced by pronounced hysteresis at low fields. In fact, the lower critical field H_{c1} extracted from perpendicular-field M(H) measurements was found to be significantly higher than predicted by Ginzburg–Landau theory. The study attributes this enhancement of H_{c1} to the dominant role of flux pinning in perpendicular geometry, whereas measurements performed with the magnetic field parallel to the filaments, where proximity coupling is largely absent, except for the thinnest sample, yield H_{c1} values consistent with Ginzburg–Landau expectations.

These findings align directly with the established reasons for the industrial dominance of NbTi. The alloy's exceptional ductility enables the fabrication of fine multi-filamentary composites required for AC applications, where reducing filament diameter is essential for minimizing losses. At the same time, decades of metallurgical optimization, especially through the controlled precipitation of α-Ti, have produced nearly ideal pinning centers, with precipitate thicknesses ($\approx$5 nm) and spacing matched to the NbTi coherence length. This microstructural engineering is precisely what ensures strong, uniform flux pinning, and the magnetization study confirms that pinning remains the principal mechanism governing the critical magnetic behavior of NbTi, particularly the elevated H_{c1} observed in perpendicular field.

Ultimately, the study reinforces the central design compromise inherent to NbTi conductors: while ductility allows the production of ultra-fine filaments that suppress AC losses, excessively reducing filament size increases proximity coupling, which reintroduces the very losses one intends to avoid. The optimal performance of NbTi in high-field magnets therefore results from balancing filament refinement with sufficient spacing to prevent proximity-induced coupling, while leveraging the α-Ti microstructure to achieve the high pinning forces required in demanding applications such as MRI systems, particle accelerators, and Maglev trains.

6.2 High Temperature superconductors (HTS)

High-temperature superconducting (HTS) materials[16], instead, discovered in 1986 as copper-oxide ceramics, have been considered essential for technological competitiveness in the 21st century, since their critical temperature (Tc) is higher than the boiling point of liquid nitrogen (77 K). This crucial point makes it possible to use liquid nitrogen as a refrigerant instead of liquid helium, which is expensive and of limited availability.
The main HTS compounds used in maglev applications are based in Yttrium-

Barium-Copper Oxide (YBCO) with a T_c of approximately 90 K, Bismuth-Strontium-Calcium-Copper Oxide (BSCCO) with a T_c of approximately 110 K. Although other thallium- and mercury-based compounds exhibit high T_c values, the toxicity associated with their components means that they are considered developmental materials.

Regarding HTS Maglev trains, the application is based on the use of HTS material bulks.The performance of these bulks, as in the case of LTS materials, will depend on three critical parameters: temperature (T_c), magnetic field (H_c), and the critical current density (J_c) they can carry.

The critical current density (J_c) is the parameter that will define current transport in a polycrystalline superconductor, mainly due to intergranular boundaries. Instead of flowing uniformly and continuously, the current must find a "path" or network of efficient connections among all grains in order to traverse the material. This phenomenon, known as Weak Links, is particularly notable in the family of YBCO ($YBa_2Cu_3O_{7-\delta}$).

The control of magnetic fields will be crucial, since most practical applications (such as motors, generators, transformers, and Maglev) involve the integral presence of an external magnetic field. This external magnetic field penetrates the superconductor in the form of discrete bundles of flux lines, called vortex. As long as these flux lines remain pinned, the HTS retains its superconducting properties. However, when an electric current is applied, the Lorentz force causes these flux lines to move or drift (Flux Creep), resulting in energy dissipation and loss of conduction properties. The current-carrying capability of a material is limited by the so-called Irreversibility Line, which is a crucial boundary within the magnetic-field–temperature (H–T) phase diagram. This parameter depends directly on the anisotropic nature of the material, as BSCCO is considerably more anisotropic than YBCO, its irreversibility line will lie lower.

7 Maglev Trains application

7.1 Introduction and history of Maglev trains

Along with the increase of population and expansion in living zones, automobiles and air services cannot afford mass transit anymore. Accordingly, demands for innovative means of public transportation have increased.
In order to appropriately serve the public, such a new-generation transportation system must meet certain requirements such as rapidity, reliability, and safety. In addition, it should be convenient, environment-friendly, low maintenance, compact,light-weight, unattained, and suited to mass-transportation.
The magnetic levitation (Maglev) train is one of the best candidates to satisfy those requirements. While a conventional train drives forward by using friction between wheels and rails, the Maglev train replaces wheels by electromagnets and levitates on the guideway, producing propulsion force electromechanically without any contact.
The Maglev train can be reasonably dated from 1934 when Hermann Kemper of Germany patented it. Over the past few decades since then, development of the Maglev train went through the quickening period of the 1960s, the maturity of the 1970s–1980s, and the test period of the 1990s, finally accomplishing practical public service in 2003 in Shanghai, China. Since the Maglev train looks to be a very promising solution for the near future, many researchers have developed technologies such as the modeling and analysis of linear electric machinery, superconductivity, permanent magnets, and so on.
The Maglev train offers numerous advantages over the conventional wheel-on-rail system: 1) elimination of wheel and track wear providing a consequent reduction in maintenance costs ; 2) distributed weight-load reduces the construction costs of the guideway; 3) owing to its guideway, a Maglev train will never be derailed ; 4) the absence of wheels removes much noise and vibration; 5)noncontact systempreventsit from slipping and sliding in operation; 6) achieves higher grades and curves in a smaller radius; 7) accomplishes acceleration and deceleration quickly; 8) makes it possible to eliminate gear, coupling, axles, bearings, and so on; 9) it is less susceptible to weather conditions.
However, because there is no contact between rails and wheels in the Maglev train, the traction motors must provide not only propulsion but also braking forces by direct electromagnetic interaction with the rails. Secondly, the more weight, the more electric power is required to support the levitation force, and it is not suitable for freight. Thirdly, owing to the structure of the guideway, switching or branching off is currently difficult. Fourthly, it cannot be overlooked that the magnetic field generated from the strong electromagnets for levitation and propulsion has effects on the passenger compartment.
Without proper magnetic shielding, the magnetic field in the passenger compartment will reach 0.09 T at floor level and 0.04 T at seat level. Such fields are probably not harmful to human beings, but they may cause a certain amount

of inconvenience. Shielding for passenger protection can be accomplished in several ways such as by putting iron between them, using the Halbach magnet array that has a self-shielding characteristic, and so on.
Figure 6a shows the comparison of Maglev and wheel-on-rail systems. In all aspects, Maglev is superior to a conventional train. Figure 6b represents the comparison of characteristics of the mass transportation systems provided by the Ministry of Transportation in Japan.
It is appreciable from the tables that the tendency of global transportation is toward the Maglev train. Accordingly, it is necessary to be concerned and understand all technologies including magnetic levitation, guidance, propulsion, power supply, and so on.[17]

TABLE I
COMPARISON OF MAGLEV AND WHEEL-ON-RAIL SYSTEMS

	Maglev System	Iron Wheel-on-Rail System
Vibration & Noise	No mechanical contact 60~65 [dB]	Contact between wheels and rails, 75~80 [dB]
Safety	No possibility of derailment	Derails from a minor defect
Guideway	Light vehicle & distributed load → light-weight	Heavy & concentrated load → Hardy structure
Maintenance	Very little	Periodic replacement of wheels, gear, rails, etc
Grade	About 80~100/1000	About 30~50/1000
Curve	In 30 [m] in radius	In 150 [m] in radius

(a) Comparison of maglev and wheel-on-rail systems

TABLE II
COMPARISON OF CHARACTERISTICS OF THE MASS TRANSPORTATION SYSTEMS

Type	Rapidity	Environment-friendly	Grade and Curve
Iron wheel-on-rail	○		○
Linear Motor Car (Iron wheel-on-rail)		○	◎
Maglev	◎	◎	◎
Rubbered tire			◎
Monorail		◎	◎

93' Ministry of Transportation, Japan
( ) average (○) good (◎) very good

(b) Comparison of characteristics of mass transportation systems

7.2 Superconductivity in maglev trains

Maglev systems are generally classified into 3 groups [17]: Electro-Magnetic Suspension (EMS), Electro-Dynamic Suspension (EDS), and High-Temperature Superconducting (HTS) pinning Maglev systems. Today, commercially operating Maglev systems do not employ superconducting materials, they rely on conventional magnet technology (EMS). These EMS systems operate using electromagnets mounted on the train, oriented upward toward a ferromagnetic rail, typically made of steel. These electromagnets generate an attractive force that pulls the vehicle upward, allowing it to levitate slightly below the guide way. Since the magnetic attraction varies inversely with the square of the levitation distance, small variations in the air gap lead to large changes in force, making the system inherently dynamically unstable.

In contrast to the electromagnetic suspension system (EMS), which achieves levitation through magnetic attraction force, the Electrodynamic Suspension System (EDS) employs repulsive force for vehicle lift. Its operation is based on the principle of electromagnetic induction: when the magnets integrated on board the vehicle move over inductor coils or conductive plates housed in the guide way Figure 7, induced currents are generated to simultaneously produce a magnetic field, whose repulsive interaction provides the necessary levitation force. A significant advantage of EDS lies in its magnetic stability. The system is so magnetically stable that it eliminates the need for precise control of the air gap (typically around 100 mm) [17], granting it high reliability against load variations and making it highly suitable for high-speed operation. However, the EDS system requires reaching a minimum speed (around 100 km/h) [17] to generate sufficient induced currents, obliging EDS-type trains to incorporate wheels (such as rubber tires) for guidance and vehicle support at low speeds.

Regarding this second group, on which the present work focuses, the most relevant developments are those from the Japanese company JR Central, which implements this technology in the pioneering MLX and MLU models, and in the current SCMAGLEV project (Linear Chuo Shinkansen) [18], with the L0 Series and L0 Series Improved Version models that incorporate NbTi coils Figure 8. To this day, all in the prototypal phase, although the commercial opening of the Yamanashi Maglev Line that will connect Shinagawa (Tokyo) and Nagoya is currently projected for the year 2034 [1], which, if so, would represent the first successful case of using superconductors in passenger railway transport. In fact, tests with passengers have already been carried out on the 42 km of track built so far, with speeds exceeding 500 km/h, the maximum speed of conventional Shinkansen being 320 km/h [19].

Japanese high-speed Maglev trains, including the MLX and the later L0 Series, use the air-core Linear Synchronous Motor (LSM) with superconducting magnets, instead of the alternative Linear Induction Motor (LIM), due to its higher efficiency and better power factor. The lateral guidance of the vehicle is achieved through a repulsive magnetic force, where the connection of the levitation coils to the sidewalls of the guide way induces circulating currents when the train moves laterally, generating the force that keeps it centered Figure 7. This centering system entails the need to implement vibration detectors, one of the most recurrent issues with this technology.

On the other hand, the main limitation of SCM-EDS systems lies in the use of

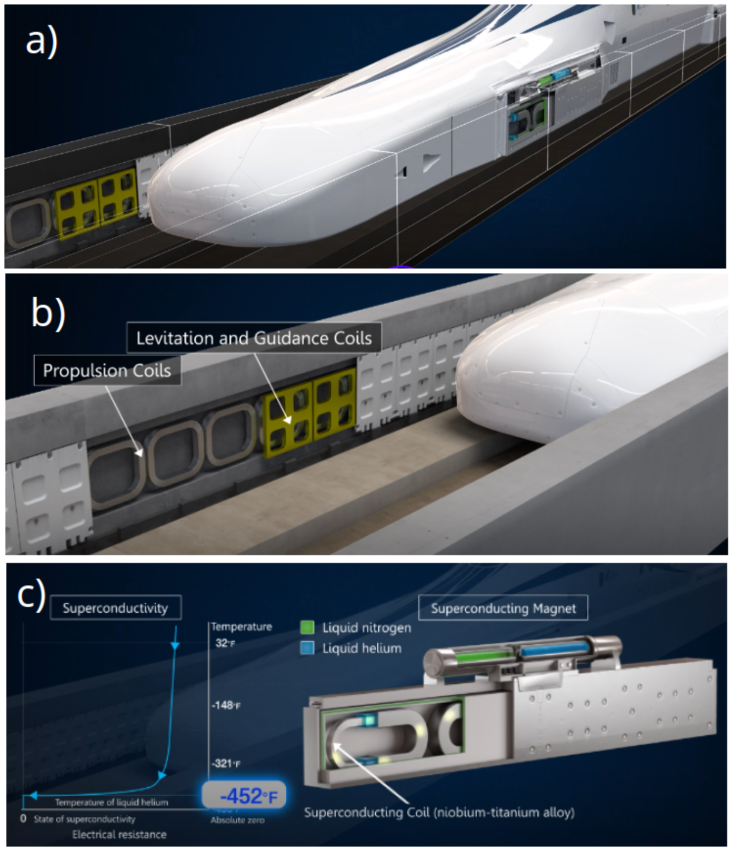

Figure 7: a) general view of the L0 Series JR Central train construction. b)Schematic view of the propulsion and guidance coils c)Schematic view of the NbTi coils and the refrigeration system [18]

Figure 8: From right to left SCMGLEV Series L0 Improved Version and Series L0 [18]

LTS materials such as NbTi or Nb_3Sn, with a low T_c (below 20 K) [14], and in the need to manage the cryogenic requirements of these magnets. The heat generated by the induced currents (associated with energy losses) can cause the evaporation of the liquid helium, raising the operating temperature above the Tc of the material, with the consequent extinction of the superconducting state. This phenomenon is known as quenching, and makes it indispensable for all SCM systems to incorporate an on-board helium refrigerator, increasing the structural complexity of the system.

Limitations that, in recent years, have led to study a third category, still at the experimental stage, of models based on the use of High Temperature Superconductors (HTS) in bulk form [17][20]. The High Temperature Superconducting (HTS) Maglev train system is based on the physical principle of flux pinning. Levitation is achieved through the flux-pinning force between the HTS bulk mounted on the vehicle in liquid nitrogen cryogenic containers called Dewars and a permanent magnet (PMG) array Figure 9.

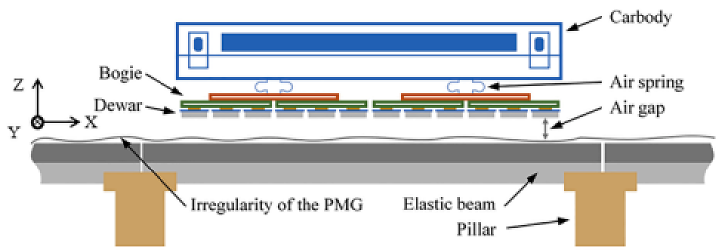

Figure 9: Schematic representation of an HTS maglev vehicle [20]

The levitation system itself is considered a self-stabilizing mechanism that integrates levitation together with lateral guidance, offering a relatively simple configuration compared with SCM-EDS models, and helping reduce the levitation distance (gap between the HTS material and the guide way) to 10 mm [20], an important factor for the safety and stability of train operation. This simplification of the vehicle structure translates into a lighter mass compared with EDS. In fact, in the high-speed domain, the vertical vibration acceleration of its car body often remains below 0.1 m/s^2, outperforming conventional wheel trains and comercial EMS vehicles [20].

At the cryogenic implementation level, the increase in T$_c$ resulting from working with HTS materials such as YBaCuO (YBCO) allows HTS maglev systems to use liquid nitrogen as a refrigerant, which is significantly less expensive. HTS Maglev technology has demonstrated great research potential and practical value worldwide. Southwest Jiaotong University (China) developed the world's first manned HTS Maglev vehicle in 2000, and in 2021 commissioned the world's first high-speed HTS Maglev engineering prototype, with a design speed of 620 km/h [20] [21]. Other countries such as Germany, Brazil, and Italy have also developed similar test lines or experimental devices.

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