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SCIENCE AND ART FACULTY

PHYSICS DEPARTMENT

UNDERGROUND THESIS

Superconductors in Space Missions: Magnetic Shielding, Radiation Protection and Other Applications

MERT GÜRLEK
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Supervisor

Prof. Dr. Çiğdem NUHOĞLU

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This graduation study was prepared by me under the supervision of **Prof. Dr. Çiğdem Nuhoğlu**. In this study titled "**Superconductors in Space Missions: Magnetic Shielding, Radiation Protection and Other Applications**", I declare that I have obtained the necessary legal permissions for data collection and use in this study, that I have fully presented the information I received from other sources in the main text and references, that I have not distorted and/or forged the research data and results, and that I have acted in accordance with the principles of scientific research and ethics throughout my study. I accept any legal consequences in case of proof of the contrary of my statement.

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Mert GÜRLEK

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Mert GÜRLEK

Content

Abstract

Superconductors in Space Missions: Magnetic Shielding, Radiation Protection and Other Applications

Mert Gürlek

Physics Department

Graduation Study

Supervisor: Assoc. Prof. Dr. Süreyya Aydın Yüksel

The intense radiation, microgravity, and extreme temperature fluctuations in space pose significant risks to both astronaut safety and the sensitive equipment of spacecraft. This thesis comprehensively examines active magnetic shielding methods based on the Meissner effect to mitigate the aforementioned radiation issue. Utilizing high-temperature superconductors, it has been demonstrated that an alternative to the high mass and limited protection level of passive shielding materials can be provided. Notably, hybrid shielding systems (passive + active) have been validated through projects such as SR2S to significantly reduce radiation doses by minimizing secondary particle formation and controlling critical magnetic field exceedances. Consequently, superconducting shielding systems developed using the Meissner effect are shown to offer distinct advantages in long-term deep-space missions, not only in protecting astronaut health but also in terms of energy efficiency and cost-effectiveness.

Key Words: Superconductivity, Meissner Effect, Active Magnetic Shielding, High-Temperature Superconductors (HTS), Radiation Protection, Long-Duration Space Missions, Hybrid Shielding (Passive + Active), Secondary Particles, Astronaut Safety, Microgravity, Vacuum Environment, Energy Efficiency, Critical Magnetic Field, Space Radiation

YILDIZ TEKNİK ÜNİVERSİTESİ

FİZİK BÖLÜMÜ

1

Introduction

Today, space exploration has evolved beyond satisfying mere scientific curiosity to encompass comprehensive projects that aim to ensure humanity's long-term survival in extraterrestrial environments. The goal of establishing permanent bases on celestial bodies like the Moon and Mars necessitates effective management of the high-energy radiation and extreme conditions astronauts will encounter. While conventional "passive" shielding materials (e.g., aluminum, polyethylene) are currently employed to counter radiation and temperature fluctuations, these materials often prove impractical for space missions due to their additional mass and limited protection against high-energy particles.

At this point, superconductors stand out with their properties of zero electrical resistance and magnetic field exclusion (Meissner effect). A superconductor operating below its critical temperature (T_c) can carry current with almost no energy loss while also preventing external magnetic fields from penetrating its interior. This phenomenon, known as "magnetic shielding," opens the door to utilizing superconducting materials in next-generation shielding systems against space radiation and cosmic rays.

However, the challenges posed by the space environment—such as vacuum, microgravity, intense radiation, and extreme temperature fluctuations—directly impact the performance of superconductors under these harsh conditions. Questions such as how to cool these materials, which require low operating temperatures, how to maintain their mechanical stability over long durations, and how radiation damage affects superconductivity remain subjects of ongoing research. Despite these challenges, recently developed high-temperature superconductors (HTS) have emerged as a promising alternative for space projects due to their ability to be cooled with liquid nitrogen, relatively low weight, and high critical current-carrying capacities.

This study begins by addressing the fundamental properties of superconductors and then examines the effects of space conditions on these materials. It further delves into the advantages and disadvantages of different types of superconductors for magnetic shielding. The concept of creating a shield against space radiation with advanced magnetic shielding systems is becoming increasingly significant for both protecting astronaut health and enhancing the reliability of sensitive electronic systems in spacecraft. Therefore, this thesis focuses on key topics such as the properties of Type I and Type II superconductors, the role of the Meissner effect in radiation protection, and the optimization of superconducting materials. Additionally, other important applications of superconductors in space (superconducting cables, SMES systems, sensor technologies, etc.) will be briefly discussed to shed light on future research and projects.

This thesis aims to evaluate both theoretical and practical studies as an integrated whole. The contribution of superconducting materials to space radiation shielding, with their high magnetic field tolerance and zero resistance property, is anticipated to be a critical technological breakthrough in near-future deep space missions. Consequently, the information and discussions presented here aim to contribute to a better understanding and further development of the potential applications of superconducting principles in the space sector.

2

GENERAL OVERVIEW OF SUPERCONDUCTIVITY

2.1 Fundamental Concepts

2.1.1 Definition And Historical Background

Superconductivity is a phenomenon characterized by the complete disappearance of electrical resistance and the exclusion of magnetic fields (Meissner effect) in materials cooled below a certain critical temperature (T_c). This phenomenon was first discovered in 1911 by Dutch physicist Heike Kamerlingh Onnes. Onnes observed that when mercury was cooled to 4.2 Kelvin using liquid helium, its electrical resistance vanished entirely. This groundbreaking discovery marked a significant milestone in understanding the behavior of matter at low temperatures.

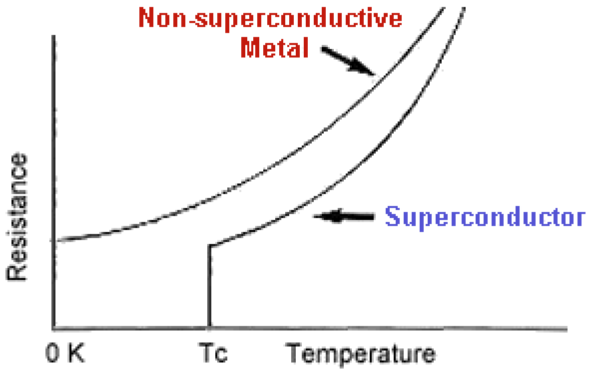

Figure 1. Electrical resistance depending on temperature [22]

The microscopic explanation of superconductivity was introduced in 1957 through the BCS Theory, developed by John Bardeen, Leon Cooper, and Robert Schrieffer. This theory explained that at low temperatures, electrons form special structures known as Cooper pairs through interactions mediated by phonons, and this pairing forms the foundation of the superconducting phase [8].

2.1.2 Fundamental Properties Of Superconductivity

The most prominent characteristics of superconducting materials include zero electrical resistance and the Meissner effect, which enables the exclusion of magnetic fields. Zero electrical resistance allows superconductors to carry electric current without energy loss, offering significant advantages for energy transmission and storage systems [6]. The Meissner effect, which describes the expulsion of external magnetic fields from the material, plays a critical role in applications such as radiation protection and magnetic shielding in space environments.

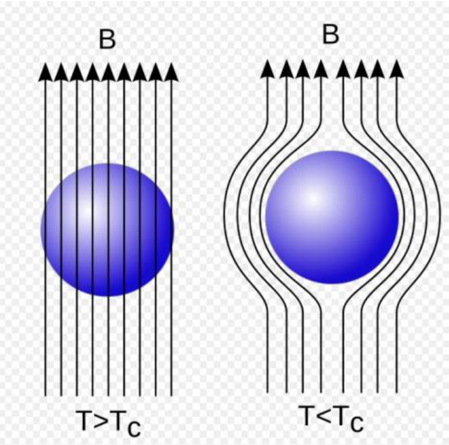

Figure 2. Meissner effect of superconductor below critical temperature [23]

Superconductivity requires materials to operate within specific boundary conditions, defined by critical parameters: critical temperature (T_c), critical magnetic field (H_c), and critical current density (J_c). T_c represents the temperature below which a material transitions into the superconducting state, while H_c denotes the maximum magnetic field strength under which superconductivity can persist. J_c defines the maximum current density a superconductor can carry without resistance. These critical parameters directly influence the performance and application domains of superconducting materials [14], [16].

2.2 Classification Of Superconducting Materials

Superconducting materials are classified into different categories based on their physical and chemical structures. These classifications depend on parameters such as operating temperatures, magnetic field tolerances, and structural characteristics. The most common types are low-temperature superconductors (LTS) and high-temperature superconductors (HTS). These materials offer specialized performance advantages for specific applications and play a critical role in implementing superconductivity theories in practical settings.

2.2.1 Low-Temperature Superconductors (LTS)

Low-temperature superconductors (LTS) are typically composed of metals and alloys with critical temperatures below 20 Kelvin. One of the first discovered superconductors, mercury ($T_c \approx 4.2$ K), is considered a historical cornerstone of superconductivity. Other metals, such as lead and niobium-titanium, also fall into this category [8].

These materials are notable for their zero electrical resistance and magnetic field exclusion properties. However, due to their low critical magnetic field (H_c) values, they are limited in applications involving high magnetic fields. Despite this limitation, LTS materials are widely used in technologies requiring precise magnetic fields, such as magnetic resonance imaging (MRI) systems, particle accelerators, and energy storage systems [13].

The requirement for cryogenic cooling necessitates more intensive energy and cost planning for low-temperature superconductors. Nevertheless, their high thermal stability and energy density make them indispensable for scientific research and industrial applications [18].

2.2.2 High-Temperature Superconductors (HTS)

High-temperature superconductors (HTS) are a class of materials with critical temperatures above 30 Kelvin, typically composed of cuprate-based ceramic compounds. One prominent example is $YBa_2Cu_3O_7$ (YBCO), which exhibits superconductivity up to approximately 90 Kelvin, enabling operation with more cost-effective coolants like liquid nitrogen [2], [14].

HTS materials exhibit the properties of Type II superconductors, making them notable for their high magnetic field tolerance. This characteristic provides significant advantages in applications such as space exploration, magnetic levitation systems, and energy transmission [13], [6]. Additionally, their radiation resistance and low-density cryogenic requirements make them a preferred choice for space missions [14].

The complex crystal structure of HTS materials necessitates high precision during the manufacturing process. However, advanced ceramic processing techniques and nanostructuring are among the methods used to enhance the critical current density of these materials. For instance, graphene-doped YBCO derivatives offer improved performance and durability [21].

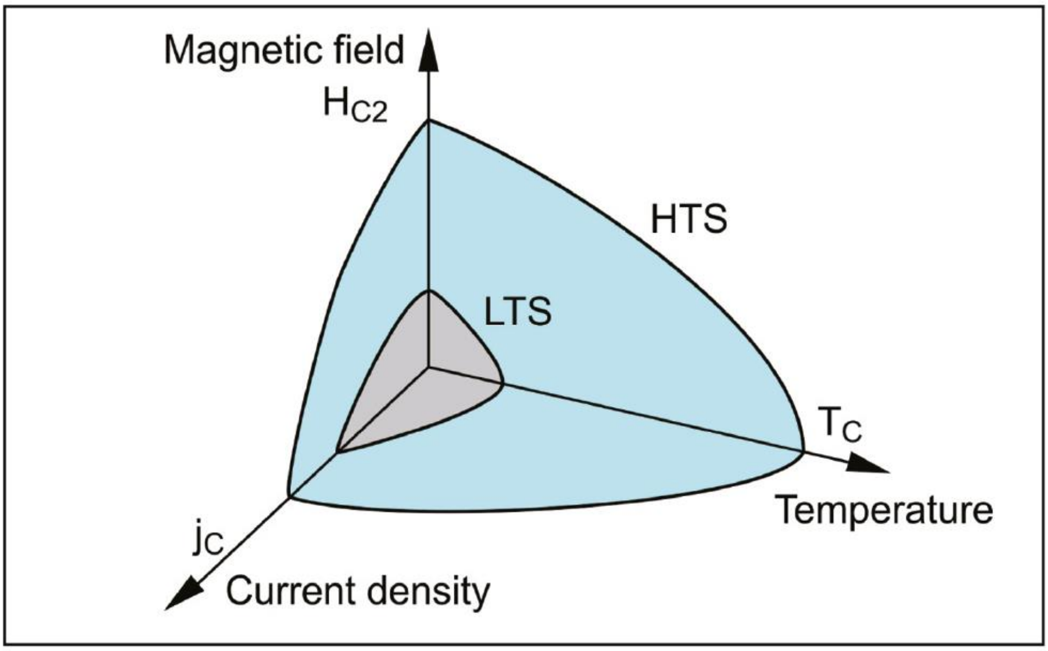

Figure 3. Schematic diagram of the critical parameters (critical temperature T_c, critical current density j_c, and upper critical magnetic field H_{C2}) of a superconductor (LTS, low-temperature superconductor; HTS, high-temperature superconductor) [24]

2.2.3 Type I And Type II Superconductors

Superconductors are divided into two main categories based on their behavior under magnetic fields: Type I and Type II superconductors.

- **Type I Superconductors:**

  These superconductors are typically composed of pure metals and maintain the Meissner effect up to low magnetic field strengths. However, when the critical magnetic field (H_c) is exceeded, superconductivity is entirely lost. Examples of Type I superconductors include lead and mercury [8].Due to their lower critical field values, Type I superconductors have a narrower range of practical applications [20].

- **Type II Superconductors:**

  Type II superconductors consist of complex materials such as alloys and cuprate-based ceramics. These materials exhibit a "mixed state" phase between the lower critical field (H_{c1}) and the upper critical field (H_{c2}). In this phase, magnetic fields partially penetrate the material, forming vortex structures. Niobium-titanium and YBCO are examples of this class [12], [6]. The high magnetic field tolerance of Type II superconductors enables broader applications in areas such as energy storage systems and magnetic shielding [20].

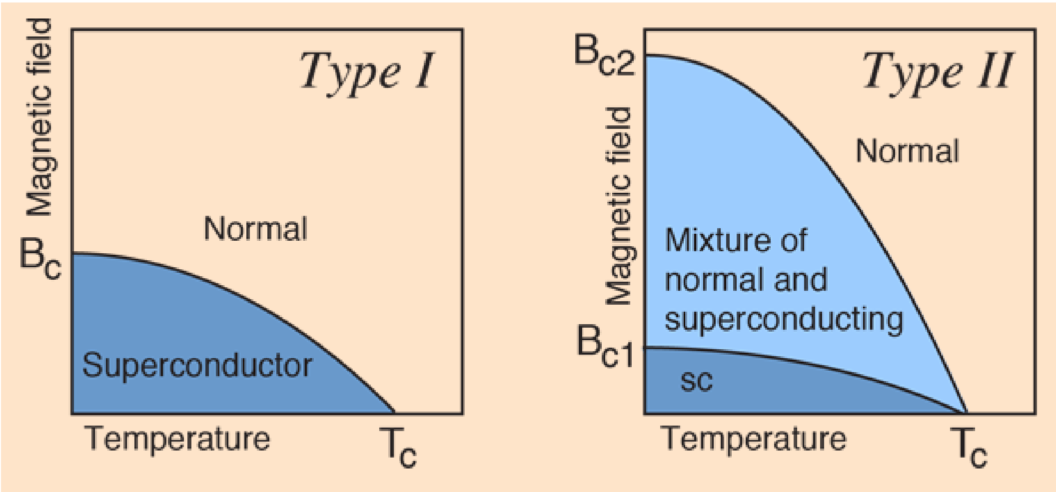

Figure 4. Reactions of type 1 and type 2 superconductors to temperature and magnetic field changes [25]

2.3 Theories Of Superconductivity

Superconductivity is a complex quantum phenomenon that has been explained through various theoretical frameworks. These theories enable a deeper understanding of the microscopic mechanisms underlying superconductivity and help to elucidate the properties of superconducting materials.

One of the first comprehensive explanations, the BCS Theory, proposes that superconductivity arises from electron-phonon interactions. In contrast, the Ginzburg-Landau Theory provides a more macroscopic perspective. The London Equations mathematically describe the relationship between magnetic fields and superconductors. Together, these theories are critical for understanding both the physical behaviors of superconducting materials and their technological applications.

This subsection will delve into the fundamental theories of superconductivity in detail. It will begin by focusing on the microscopic foundations of the BCS Theory and its explanation of the fundamental principles of superconductivity.

2.3.1 BCS Theory

Developed in 1957 by John Bardeen, Leon Cooper, and Robert Schrieffer, the BCS Theory provides the first comprehensive theoretical framework to explain the microscopic foundations of superconductivity. This theory posits that, at low temperatures, electrons interact through vibrations in the crystal lattice of a material (phonons), forming bound pairs known as "Cooper pairs" [8].

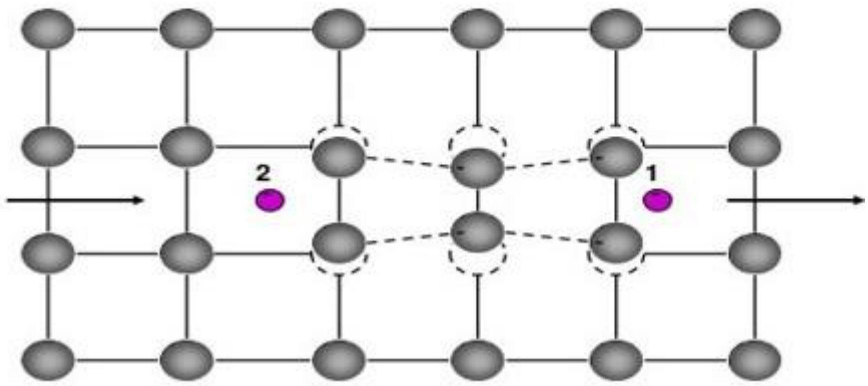

Figure 5. In this figure, a schematic representation is given of how Cooper pairs (pink circles), which carry current without resistance in superconductivity, interact with the crystal lattice (gray circles). Briefly, Cooper pairs are pairs of electrons that move together due to a mutual attraction mediated by lattice vibrations (phonons). This pairing makes them more resistant to scattering within the lattice, enabling them to conduct current without resistance. [26]

This pairing process reveals that electrons do not behave as independent classical particles but instead move coherently due to quantum mechanics. This phenomenon underpins the state of superconductivity and the ability to carry current without resistance. Cooper pairs are formed by an attractive force mediated by phonons, resulting in the creation of an energy gap in the material's energy band. This energy gap plays a critical role in explaining the onset of superconductivity and the exclusion of magnetic fields (Meissner effect) [8].

The BCS Theory mathematically demonstrates that the superconducting transition temperature (T_c) is dependent on the strength of electron-phonon interactions within the material. Beyond explaining the absence of electrical resistance, the theory also aids in understanding other critical parameters, such as the critical temperature, critical magnetic field, and critical current density [20].

Although initially developed for low-temperature superconductors, the BCS Theory has also served as a foundational guide for understanding the general behavior of high-temperature superconductors. However, the mechanisms underlying superconductivity in cuprate-based materials require more complex models due to their intricate behaviors [20],[21].

2.3.2 Ginzburg–Landau Theory

Developed in the 1950s, the Ginzburg-Landau Theory provides a macroscopic explanation of the superconductivity phenomenon and serves as a theoretical framework for studying phase transitions. From a thermodynamic and field theory perspective, the theory addresses the superconducting state by introducing the concept of an order parameter, a fundamental variable that defines the superconducting properties of a material [20].

The core approach of the theory involves modeling the spatial variations of the order parameter and the distribution of magnetic flux within a superconducting material. The Ginzburg-Landau equations, derived for this purpose, mathematically express the relationship between the magnetic fields and the order parameter in a superconductor.

- **Mixed Phase and Critical Fields:**

The Ginzburg-Landau Theory is crucial for explaining the mixed phase observed in Type II superconductors. In this phase, magnetic flux vortices form between the lower critical field (H_{c1}) and the upper critical field (H_{c2}), enabling the material to withstand high magnetic fields [20], [21].

- **Applications:**

This theory has been instrumental in optimizing the magnetic properties of superconductors for engineering applications. It has guided advancements in magnetic shielding, energy storage, and magnetic resonance technologies [13].

The Ginzburg-Landau Theory bridges the gap between microscopic and macroscopic approaches, providing a broader framework for understanding superconductivity and laying the groundwork for further advancements in the field.

2.3.3 London Equations

The London Equations, developed in 1935 by Fritz and Heinz London, provide a mathematical framework for understanding the electromagnetic properties of superconductors. These equations describe the interactions between the current-carrying charge carriers (Cooper pairs) and magnetic fields within a superconducting material, offering fundamental insights into the magnetic characteristics of superconductivity [8],[20].

The London Equations form the mathematical basis for explaining the Meissner effect. When a material is cooled below its critical temperature, the magnetic field inside the superconductor rapidly diminishes near the surface and is expelled from the material. This phenomenon is characterized by the London penetration depth ($\boldsymbol{\lambda}_L$), a parameter that determines how deeply the magnetic field can penetrate into the superconductor [14].

The penetration depth is mathematically expressed as follows:

Equation 1.

$$\boldsymbol{B}(\boldsymbol{x}) = \boldsymbol{B_0} \boldsymbol{e}^{-x/\lambda_L}$$

- $\boldsymbol{B}(\boldsymbol{x})$: Magnetic field magnitude at a distance $\boldsymbol{x}$ from the surface of the superconductor,
- $\boldsymbol{B_0}$: Magnetic field magnitude at the surface of the superconductor,
- $\boldsymbol{\lambda}_L$: London penetration depth

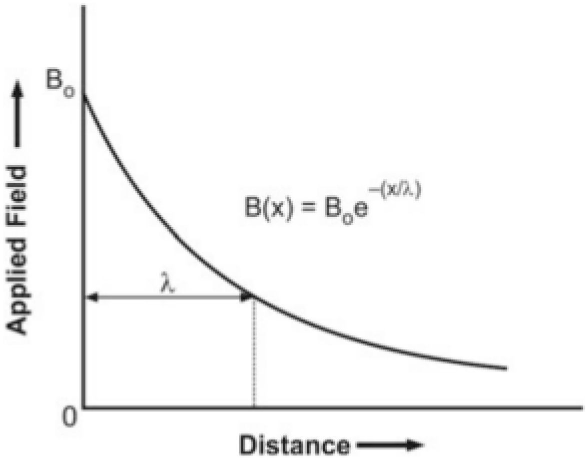

Figure 6. Illustration of the penetration depth of the external magnetic field from the surface of the superconductor [20]

The London Equations are widely used to model the magnetic properties of superconductors and optimize their use in engineering applications. They serve as a key tool in understanding the behavior of superconducting materials for magnetic shielding and radiation protection technologies [6]. In high-temperature superconductors, the anisotropic (direction-dependent) nature of the London penetration depth enhances their magnetic performance [14].

While the London Equations effectively describe the macroscopic behavior of superconductors, they do not account for the microscopic mechanisms or atomic origins of superconductivity. For this reason, they are often considered alongside theories like BCS and Ginzburg-Landau for a more comprehensive understanding [20].

2.4 Critical Parameters İn Superconductivity

Superconductivity is a phase state that can be sustained only within certain critical limits. These limits determine the material's capacity for zero electrical resistance and magnetic field exclusion. Parameters such as the critical temperature (T_c), critical magnetic field (H_c), and critical current density (J_c) define the conditions under which superconductivity can persist [12], [15].

2.4.1 Critical Temperature (T_c)

Superconductivity emerges when a material is cooled below a specific critical temperature (T_c), marking the onset of this unique phase state. This temperature represents a fundamental threshold that enables the material to carry current without electrical resistance. The interaction of electrons with lattice vibrations (phonons), leading to the formation of bound pairs known as Cooper pairs, constitutes the core mechanism of this phase transition [12], [21].

Critical temperature values vary widely depending on the type of superconducting material. In low-temperature superconductors (LTS), materials such as mercury ($T_c \approx 4.2$ KT) and niobium-titanium ($T_c \approx 9.2$ KT) operate using cryogenic coolants like liquid helium and are commonly employed in applications requiring precise magnetic fields [12], [18]. In contrast, high-temperature superconductors (HTS), such as $YBa_2Cu_3O_7$ (YBCO), can operate with more cost-effective coolants like liquid nitrogen, achieving superconductivity up to approximately 90 Kelvin. Similarly, materials like magnesium diboride (MgB_2, $T_c \approx 39$ K) offer medium critical temperature values that provide significant advantages for space applications [3], [12].

When the critical temperature is exceeded, the superconducting state ceases, and the material reverts to its normal conductive properties. This transition results in the reappearance of electrical resistance and the loss of the Meissner effect. The material also loses its ability to shield against external magnetic fields, leading to energy losses. This transition can severely impact the functionality of devices used in space environments or precision energy transmission systems [6], [12], [18].

The critical temperature is of paramount importance in superconducting applications. Technologies utilizing low-temperature superconductors, such as MRI systems and particle accelerators, rely on high precision and reliability. On the other hand, the use of high-temperature superconductors in energy transmission and magnetic levitation applications reduces cryogenic costs, providing economic and operational advantages. In the future, the development of materials with higher T_c values will enable the broader adoption of superconducting technologies across various fields [15], [18].

2.4.2 Critical Magnetic Field (H_c)

Superconductivity can only be sustained below a certain magnetic field threshold. The critical magnetic field (H_c) represents the maximum magnetic field strength a superconducting material can withstand while maintaining its superconducting state. This value depends on the material's type, structural properties, and operating conditions. When the critical magnetic field is exceeded, the material transitions to a normal conducting state, losing its zero electrical resistance and magnetic field exclusion properties entirely [12], [14].

In materials with low magnetic field tolerance, superconductivity ceases abruptly when the critical field is surpassed. However, in some superconductors, multiple transitional states can be observed below the critical magnetic field. In such cases, magnetic flux vortices form, allowing superconductivity to be partially retained. This characteristic highlights the advantages of these materials in high magnetic field applications [13].

The magnetic field tolerance of superconducting materials plays a critical role in applications such as energy storage, magnetic shielding, and space missions requiring high magnetic fields. High-temperature superconductors (HTS) are particularly preferred for these applications due to their ability to operate across a wide magnetic field range. For example, materials like YBCO exhibit magnetic field tolerances exceeding 100 Tesla, while alternatives like MgB_2 offer economical and high-performance solutions [12], [21].

When the critical magnetic field is exceeded, energy losses, performance degradation, and reduced functionality of devices can occur. Therefore, selecting the appropriate material is vital for system design in superconducting applications [6].

2.4.3 Critical Current Density (J_c)

The maximum current density a superconducting material can carry is known as the critical current (J_c), a fundamental parameter that determines the performance of the superconductor in applications. Critical current depends on factors such as the structural homogeneity of the material, electron-phonon interactions, and fabrication methods. If the current density exceeds the J_c value, magnetic flux vortices within the superconductor begin to move. This phenomenon results in energy losses, temperature increases, and a loss of electrical stability, significantly reducing the performance of the superconductor [8], [14].

Critical current can be limited by microstructural defects in the superconducting material and the motion of magnetic vortices. To achieve higher performance, manufacturing techniques have been developed to mitigate these limitations. For example, in materials like MgB_2, nanoscale SiC doping has proven to be an effective method to enhance critical current density. Such additives stabilize magnetic vortex motion, increasing the maximum current the superconductor can carry. Studies have shown that nano-SiC-doped MgB_2 can achieve high values of 25 kA/cm^2 at 4.2 K and a magnetic field of 10 Tesla [5], [12].

When the critical current is exceeded, even if superconductivity is not completely lost, energy losses increase, and device efficiency decreases. Additionally, the heat generated by the transported current can raise the material's temperature closer to its critical temperature (T_c), potentially terminating superconductivity. The loss of electrical stability poses risks, particularly in high-reliability applications such as energy transmission and storage systems [6], [16].

In practical applications, the critical current value determines the potential use of superconductors. High-temperature superconductors (HTS) like YBCO stand out in magnetic levitation systems and energy storage applications due to their high critical current values. Similarly, MgB_2 is notable in space applications for its lightweight and high current-carrying capacity. These materials are commonly employed in satellite systems for magnetic shielding and in energy transmission lines [12],[14]. Advances in fabrication techniques and nanostructuring are continually improving critical current performance, enabling the broader application of superconducting technologies across various domains[21].

2.5 Interrelations Of Critical Parameters And Their Calculation

The performance of superconductors is determined by the interplay between key parameters such as critical temperature (T_c), critical magnetic field (H_c), and critical current density (J_c). These critical values depend on the material's physical and chemical structure and are intricately related. Understanding these relationships is essential for optimizing the performance of superconductors, particularly in space environments.

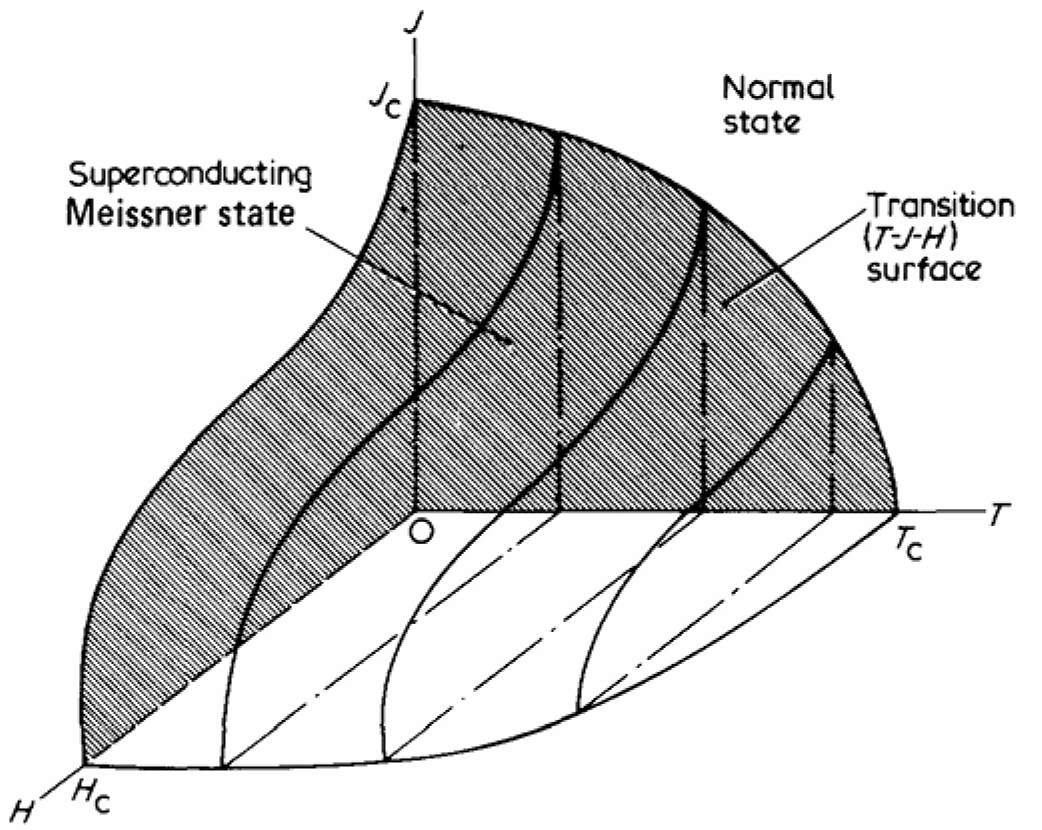

Figure 7. Depiction of the change of critical parameters relative to each other in 3 dimensions [13]

2.5.1 T_c – H_c Relationship

The critical temperature (T_c) is defined as the temperature at which the superconducting state begins, while the critical magnetic field (H_c) represents the maximum magnetic field strength under which superconductivity can persist. As T_c increases, H_c generally tends to decrease. This relationship is particularly evident in high-temperature superconductors (HTS). For example, YBCO has a T_c of approximately 90 K but a lower H_c compared to low-temperature superconductors (LTS). However, the H_c value of YBCO can be enhanced by improving its microstructural properties [12], [21].

Equation 2. The temperature-dependent change of the critical magnetic field value.

$$H_c \approx H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

- H_c: Critical magnetic field,
- T_c: Critical temperature,

2.5.2 H_c – J_c Relationship

The critical current density (J_c) represents the maximum current a superconductor can carry without resistance and is directly related to the critical magnetic field (H_c). As the magnetic field increases, J_c typically decreases because high magnetic fields induce the motion of magnetic vortices, leading to energy losses. REBCO-based superconductors exhibit higher resilience in this relationship, maintaining high J_c values even under strong magnetic fields. REBCO superconductors used in the STEP project are among the best examples of this performance [20], [14].

2.5.3 Mathematical Modeling And Calculation Approaches

Theoretical models such as the London Equations and the Ginzburg-Landau Theory are used to calculate critical values. The London Equations define the relationship between the critical magnetic field and penetration depth, while the Ginzburg-Landau model analyzes energy densities and critical parameters in the superconducting state [6],[18]. For instance, critical current density (J_c) can be expressed as follows:

Equation 3. Calculation of critical current level depending on critical magnetic field and population depth.

$$J_c = \frac{H_c}{\lambda_L}$$

- H_c: Critical magnetic field,
- λ_L: London penetration depth,

These mathematical models provide a foundation for understanding the interdependence of critical parameters and help in designing superconducting systems for advanced applications.[6],[18].

2.6 Josephson Effect

The Josephson effect is a quantum mechanical phenomenon that explains the lossless flow of current between two superconductors separated by a barrier (an insulator or a thin metallic layer) due to the quantum phase difference between them. Predicted in 1962 by Brian D. Josephson, this effect is considered a groundbreaking discovery in the field of superconductivity. It has enabled the transfer of the quantum properties of superconducting materials into practical electronic devices, making it a cornerstone of superconducting electronics [3], [21].

2.6.1 DC Josephson Effect

The Josephson effect is explained by two fundamental mechanisms. The first is known as the direct current (DC) Josephson effect, which describes the flow of a supercurrent (I_s) through the barrier when there is no potential difference between the two superconductors. This current depends on the quantum phase difference ($\emptyset$) between the superconductors and is expressed as:

Equation 4. This expression shows the relationship of the supercurrent in a Josephson junction with the phase difference.

$$I_s = I_c \sin(\emptyset)$$

- I_s: Supercurrent passing through the Josephson joint,
- I_c: The Critical Current,
- $\emptyset$: The phase difference Decoupled between the two superconductors.

Here; I_c represents the maximum critical current the superconducting junction can carry. The DC Josephson effect demonstrates that energy loss-free, resistance-free current can flow through superconducting junctions [8].

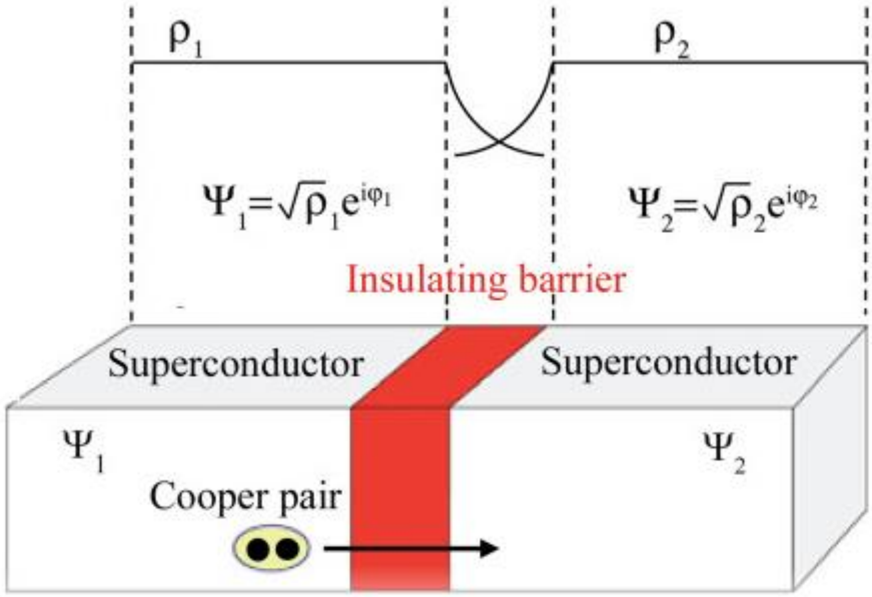

Figure 8. Josephson Junction Diagram: This diagram illustrates a Josephson junction, where two superconductors are separated by a thin insulating barrier. The wavefunctions of the superconductors (Ψ_1 and Ψ_2) carry information about their phase (ϕ) and density. Cooper pairs tunnel through the insulating barrier via quantum tunneling, generating a supercurrent ($I_s = I_c \sin[\phi_1 - \phi_2]$) that depends on the phase difference.

2.6.2 AC Josephson Effect

The second mechanism is the alternating current (AC) Josephson effect. In this case, when a voltage (V) is applied across the superconductors, the current oscillates over time. The oscillation frequency (f) is related to the applied voltage by the following relationship:

Equation 5. $$f = \frac{2eV}{h}$$

- e is the electron charge
- h is Planck's constant.

The AC Josephson effect is widely used in high-precision measurement devices due to the exact relationship between voltage and frequency [20].

2.6.3 Quantum Phase Coherence and Tunneling

The Josephson effect is made possible by the quantum phase coherence of superconductors and the ability of Cooper pairs to tunnel through the barrier. These quantum properties of superconductors not only allow for energy-loss-free current transfer but also enable highly precise voltage and frequency measurements. The physical nature of the Josephson effect depends on the structure of the superconducting materials, the properties of the barrier, and the geometry of the junction. These factors contribute to the wide range of applications of superconducting technologies [18], [21].

2.6.4 Technological Applications and Importance

The importance of the Josephson effect lies not only in understanding superconductivity theory but also in advancing the development of superconducting devices. This phenomenon forms the basis of various technologies, including SQUID’s (Superconducting Quantum Interference Devices), precision voltage standards, and energy-efficient digital circuits. Particularly in space applications, where energy efficiency and high precision are critical, Josephson junctions play a vital role [18], [21].

3

The Effects Of Space Envıronment On Superconductors

3.1 Low Temperatures And Thermal Stress

The space environment, with its extremely low temperatures, provides a natural operating condition for superconducting materials. In regions not directly exposed to sunlight, temperatures can drop to approximately -270°C (3 Kelvin). These conditions are especially favorable for low-temperature superconductors ($T_c < 20$ K). Materials such as mercury, lead, and niobium-titanium can leverage this natural cooling advantage to enhance energy efficiency. For instance, the requirement for liquid helium cooling can be minimized due to the inherently low temperatures in space [12], [15].

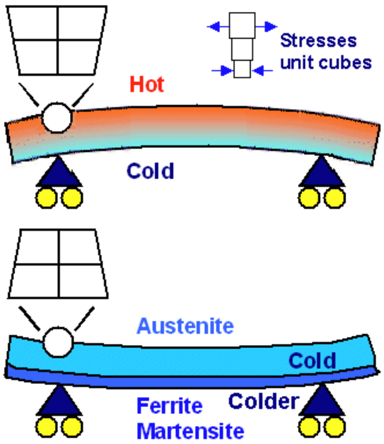

Figure 9. The effect of thermal change on the surface and inner surface of the material on expansion is shown**.** [27]

High-temperature superconductors (HTS), while capable of withstanding low temperatures, offer flexibility to operate across a wider temperature range. Materials like YBCO can perform efficiently at approximately $Tc \approx 90$ K when cooled with liquid nitrogen. This capability makes high-temperature superconductors an economically and operationally advantageous choice [14],[21].

Despite the benefits of low temperatures, the variable thermal cycles in space can induce thermal stress on superconducting materials. In regions exposed to sunlight, surface temperatures can rise to several hundred degrees, potentially challenging the structural stability of these materials. Ceramic-based high-temperature superconductors are more resilient to such thermal cycles, making them a preferred choice for long-term space missions [6], [18].

The low temperatures of space provide a strategic advantage in meeting the energy efficiency and durability requirements of superconductors. However, optimizing these materials to withstand thermal cycles and extreme temperature variations is crucial for maintaining this advantage in the long term [12].

3.2 Vacuum

The near-perfect vacuum conditions of space exert both advantageous and challenging effects on the performance of superconducting materials. Vacuum prevents surface oxidation and chemical degradation of superconductors, enabling long-term stable operation. Furthermore, it facilitates energy transmission without electrical resistance loss, enhancing energy efficiency. Materials such as MgB_2 perform exceptionally well under vacuum conditions, making them a suitable solution for space applications [2], [10].

However, superconductors face certain structural and thermal challenges in a vacuum environment. Vacuum can lead to surface deformations due to gas desorption. Additionally, sudden temperature changes between sunlit and shaded regions cause thermal expansion and contraction, resulting in mechanical stress. These effects can challenge the structural integrity of superconducting materials [7], [21].

Ceramic-based superconductors like YBCO are widely preferred for space missions due to their stable performance in vacuum conditions. Tests of YBCO in vacuum environments have demonstrated its ability to maintain electromagnetic and thermal properties over extended periods. Similarly, MgB_2 superconductors are notable for their resilience to both thermal stress and radiation effects [12], [16].

In conclusion, while vacuum conditions enhance the energy efficiency of superconductors, they also introduce structural challenges. Therefore, durability improvements tailored to vacuum environments are essential in the design of superconducting materials. Such an approach ensures the reliable use of superconductors in space missions [6], [17].

3.3 Microgravity

Microgravity refers to conditions in the space environment where gravitational forces are negligible. This environment creates a range of physical and engineering effects that influence the properties and performance of superconducting materials.

3.3.1 Effects Of Microgravity On Superconductors

1. **Behavior of Magnetic Vortices**:

   The microgravity environment can alter the dynamics of the formation and motion of magnetic vortices in superconductors. In Type II superconductors, the stability of vortices formed under magnetic fields may increase or decrease, impacting energy loss and critical current density [21].

2. **Performance of Cryogenic Liquids**:

   In microgravity, cryogenic liquids cannot flow as efficiently as they do under traditional gravity conditions. This limits the distribution and effectiveness of cryogenic fluids like liquid helium or liquid nitrogen used for cooling superconductors. Alternatively, capillary pump systems and thermal management strategies optimized for microgravity have been developed [18].

3. **Electrical and Thermal Stability**:

   The absence of gravity can have potential effects on the electrical and thermal stability of superconductors. Factors such as thermal expansion may be less pronounced in microgravity, but this can lead to the accumulation of mechanical stress in some materials [12].

3.3.2 Advantages And Limitations

- **Advantages**:

  Microgravity enhances the performance of superconductors in low-density magnetic fields and can limit vortex motion, reducing energy losses. This improves the performance of superconductors in applications such as magnetic shielding and energy storage [6].

- **Challenges**:

  The management of cryogenic liquids poses a significant engineering challenge in microgravity. Additionally, more research is needed to assess the long-term durability and reliability of superconductors in microgravity environments [12].

3.4 High-Energy Radiation And Cosmic Rays

One of the most significant challenges superconducting materials face in the space environment is the impact of high-energy radiation and cosmic rays. These factors can affect the structural integrity and performance of superconducting materials.

3.4.1 Radiation Effects On Superconductors

1. **Structural Damage and Degradation**:

   Cosmic rays and solar-origin particles can cause deformations in the atomic structure of superconducting materials. This can reduce the critical current density and superconducting properties of the material. Such effects must be carefully studied, particularly in high-temperature superconductors like MgB_2 and YBCO [12], [21].

2. **Changes in Electrical and Magnetic Performance**:

   Defects caused by radiation can negatively affect the ability of superconductors to exclude magnetic flux (Meissner effect) and their zero electrical resistance properties. This can lead to increased energy losses and reduced device efficiency [13].

3.4.2 Advantages And Limitations

1. **Doping and Composite Materials**:

   To develop radiation-resistant superconductors, nanoscale additives are incorporated into the material composition. For instance, adding SiC to MgB_2 enhances its resistance to radiation effects [12], [21].

2. **Protective Coatings**:

   Protective coatings can be applied to the surface of superconductors to minimize radiation effects. These layers prevent radiation from directly penetrating the material structure, thereby extending the lifespan of the superconductor [18].

3.5 Magnetic Field

Another critical factor influencing the performance of superconductors in the space environment is magnetic fields. Space encompasses a wide spectrum of magnetic fields originating from both natural sources (planets, the Sun, the galaxy) and artificial sources (spacecraft and equipment). These fields can directly impact the operation and durability of superconductors.

3.5.1 Sources Of Magnetic Fields İn Space

Planetary Magnetic Fields:

Planets with magnetic cores, such as Earth, are the first natural sources of magnetic fields encountered by spacecraft. Earth's magnetosphere partially shields spacecraft and onboard superconducting systems from solar winds and cosmic rays. However, this magnetic field can have varying effects on the magnetic properties of superconductors [14],[21].

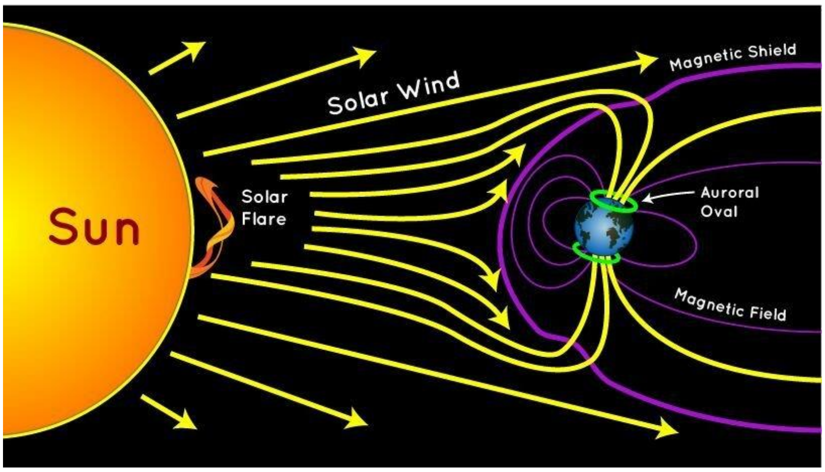

Figure 10. As an example, the depiction of the Earth's magnetic field is shown. [28]

Solar Magnetic Fields:

Solar winds and solar flares create a dynamic magnetic environment. These fluctuations can challenge the critical magnetic fields of superconductors. In particular, they can increase magnetic vortex motion in Type II superconductors, leading to energy losses [14],[6].

Artificial Magnetic Fields:

Magnetic fields generated by electronic systems within spacecraft and satellites can affect the operation of superconducting devices. Sensitive sensors and magnetic shielding systems must be protected from such artificial magnetic fields [9],[13].

3.5.2 Impact On Superconducting Performance

Exceeding Critical Magnetic Field Limits:

Superconductors can exclude magnetic fields (Meissner effect) up to their critical magnetic field (H_c) limit. However, once this limit is exceeded, the superconducting property is lost, and the material transitions to a normal conductive state. In Type II superconductors, this occurs in a state known as the "mixed phase," where magnetic vortices form [14].

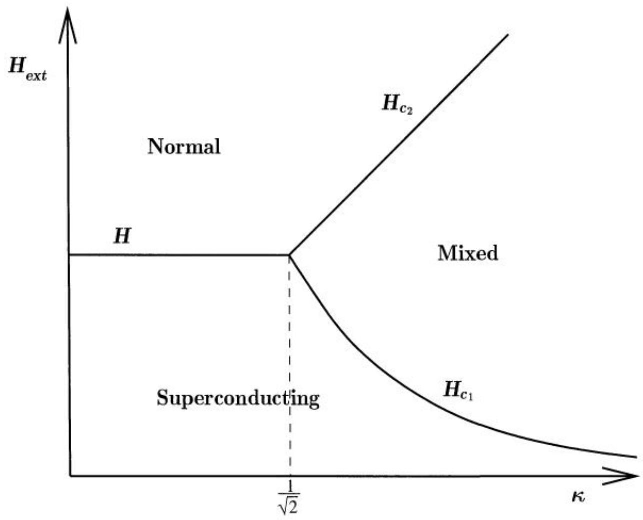

Figure 11. The behavior of type 2 superconductors when they exceed their critical magnetic fields is shown. [29]

Motion of Magnetic Vortices:

In Type II superconductors, magnetic fields partially penetrate the material, forming vortices. These vortices can reduce the critical current-carrying capacity and lead to energy losses. Variable magnetic fields in the space environment can trigger vortex motion, negatively affecting the material's performance [7],[21].

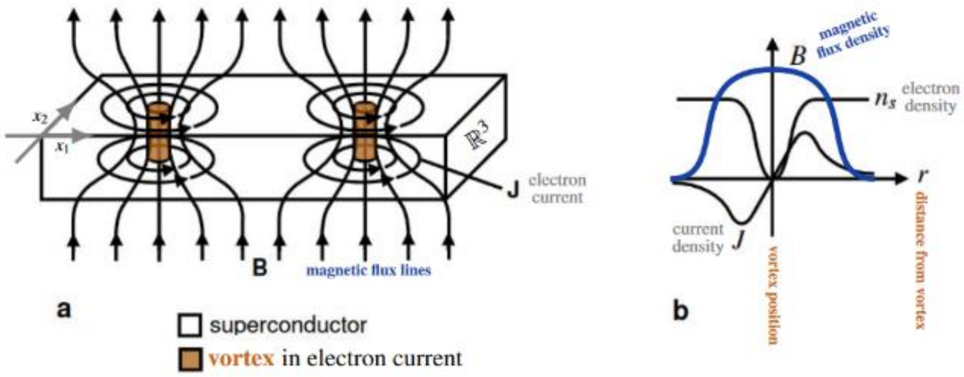

Figure 12. (a) Magnetic flux penetrates type-II superconductors through flux vortices. These vortices form where magnetic flux lines pass through and are surrounded by circulating electron currents.(b) The cross-sectional view shows the distribution of the magnetic field (B), superconducting electron density (n_s), and supercurrent (J) as a function of the distance from the vortex core. The magnetic field and current density are maximum at the core, while the superconducting electron density increases outward. This diagram explains the relationship between magnetic flux and supercurrent in type-II superconductors. [30]

Magnetic Field Resilience:

High-temperature superconductors (HTS), such as YBCO and MgB_2, are notable for their high magnetic field resilience. These materials can operate in magnetic fields exceeding 10 Tesla, offering a wide range of applications in space missions [12], [13].

3.6 Reliability And Long-Term Use Of Superconductors İn Space

The long-term reliability of superconductors in space is directly linked to microstructural durability, the effectiveness of quench protection systems, and material lifespan. While the harsh conditions of the space environment challenge the performance of superconductors, innovations in engineering and material development play a crucial role in enhancing their reliability. In particular, REBCO-based high-temperature superconductors (HTS) offer ideal solutions for space missions due to their thermal and radiation resilience [21], [2].

3.6.1 Influence Of Microstructure On Durability

The microstructure of superconductors significantly influences their durability and lifespan. High-performance REBCO superconductors exhibit resistance to thermal cycles and mechanical stresses due to their microstructural uniformity. Optimizing the microstructure enables improvements in critical parameters such as critical current density (J_c) and critical temperature (T_c) [21], [11].

3.6.2 Quench Protection Systems

To enhance the reliability of superconductors under overload conditions, quench protection systems have been developed. During these transitions, known as quenches, energy accumulation is safely managed and dissipated through passive mechanisms. These systems ensure long-term operational stability, improving the safety of both superconducting systems and the devices they support. Quench protection technologies have become increasingly critical in space missions, as REBCO-based materials demonstrate reliable performance even in high magnetic fields [12], [19].

3.6.3 Lifetime And Robustness

REBCO-based superconductors exhibit exceptional durability against the high-radiation and low-temperature conditions of space. These materials provide long-term reliability in high-radiation environments and energy savings in low-temperature settings, making them indispensable for space missions. For instance, REBCO superconductors used in the STEP project have proven their potential for long-term use in toroidal field coils. Innovative engineering designs that enhance resistance to thermal fluctuations further increase the operational reliability of these materials [21], [12].

Advances in manufacturing methods have expanded the applications of high-temperature superconductors in both energy transmission and magnetic field operations. In this context, the synthesis and optimization of materials such as REBCO and YBCO are critical for space missions. The reliability of superconductors is continuously improved through these advancements in material engineering [21], [12].

4

Meissner Effect And Radiation Protection İn Space

The Meissner effect, characterized by the ability of superconductors to expel magnetic fields, provides a robust foundation for protecting against the harmful effects of radiation and cosmic rays in the space environment. This effect, combined with the energy loss-minimizing properties of superconducting materials, plays a critical role in magnetic shielding systems used in spacecraft. The unique capability of superconductors presents a significant opportunity to enhance both the protection of sensitive equipment and the safety of astronauts during space missions. Detailing the fundamental properties of the Meissner effect and its role in applications is essential to understand the technological potential of superconductors more comprehensively.

4.1 Fundamental Aspects Of Meissner Effect

4.1.1 General Information

The Meissner effect is one of the fundamental properties of superconductivity, occurring when a superconducting material expels external magnetic fields upon being cooled below its critical temperature (T_c). Discovered in 1933 by Walther Meissner and Robert Ochsenfeld, this phenomenon marked a significant step in understanding the magnetic properties of superconductors. In addition to their zero electrical resistance, superconductors create shielding currents on their surface that prevent magnetic fields from penetrating the material, thereby achieving zero magnetic permeability [1], [6].

The mechanism of the Meissner effect involves the formation of supercurrents on the surface of the superconductor, which counteract and neutralize the external magnetic fields. This process prevents magnetic fields from penetrating the material, distinguishing superconductors from classical perfect conductors. In the space environment, this property enables the use of superconducting materials in radiation protection and magnetic shielding systems [6], [14].

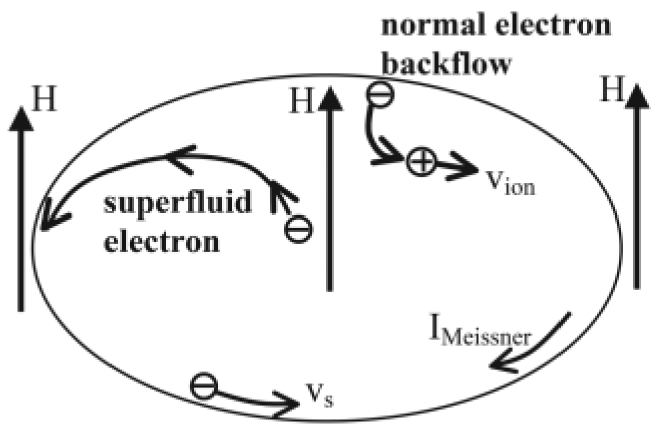

Figure 13. Meissner Effect Diagram: This diagram illustrates the current and magnetic field distribution during the Meissner effect in superconductors. Superfluid electrons generate a Meissner current ($I_{meissner}$) to expel the magnetic field, while normal electrons respond with backflow. The magnetic field (H) is pushed out of the superconductor, accompanied by superfluid velocity (v_s) and ion motion (V_{ion}). The diagram summarizes the interaction between magnetic fields and currents in superconductivity. [31]

4.1.2 London Penetration Depth

The London penetration depth ($\boldsymbol{\lambda_L}$) defines how deeply a magnetic field can penetrate into the surface of a superconducting material. Developed in 1935 by Fritz and Heinz London, the London Equations provide a fundamental model for mathematically describing the behavior of magnetic fields in superconductors. These equations explain the magnetic field expulsion caused by the Meissner effect and the physical basis of the magnetic currents on the surface of superconductors [20].

The penetration depth is defined by the following equation:

Equation 1.

$$\boldsymbol{B(x) = B_0 e^{-x/\lambda_L}}$$

- $\boldsymbol{B(x)}$: Magnetic field magnitude at a distance $\boldsymbol{x}$ from the surface of the superconductor,
- $\boldsymbol{B_0}$: Magnetic field magnitude at the surface of the superconductor,
- $\boldsymbol{\lambda_L}$: London penetration depth.

The London penetration depth itself is expressed by the equation:

Equation 6

$$\boldsymbol{\lambda_L} = \sqrt{\frac{\boldsymbol{m}}{\boldsymbol{\mu_0 n e^2}}}$$

- $\boldsymbol{m}$: Mass of the supercurrent carriers,
- $\boldsymbol{\mu_0}$: Magnetic permeability of free space,
- $\boldsymbol{n}$: Density of supercurrent carriers,
- $\boldsymbol{e}$: Electric charge.

High-temperature superconductors have a larger London penetration depth compared to low-temperature superconductors. For example, materials like YBCO exhibit penetration depths in the range of 200–500 nm, while low-temperature superconductors typically have smaller values ($\boldsymbol{\lambda_L}$~50 nm). This difference allows high-temperature superconductors to operate across a broader range of magnetic fields [20].

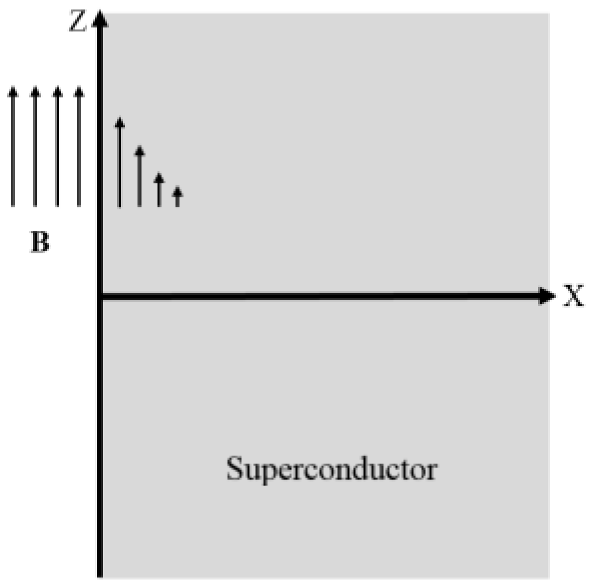

Figure 14. The magnetic field intensity penetrating the superconductor from the surface to the depths is shown. [20]

4.2 Meissner Effect For Spacecraft Magnetic Shielding

4.2.1 General Overview

The Meissner effect, with its ability to expel magnetic fields, provides an effective foundation for radiation protection in spacecraft. Active magnetic shielding systems manipulate external magnetic fields to divert charged particles away from areas occupied by astronauts and sensitive equipment. Superconductors, with their zero electrical resistance, can generate strong magnetic fields without energy loss. This capability enhances energy efficiency and increases the effectiveness of protection systems during long-term space missions [1], [6].

Superconducting materials such as YBCO ($YBa_2Cu_3O_7$) and MgB_2 (Magnesium Diboride) are among the preferred active shielding materials in space environments. YBCO stands out for its high magnetic field tolerance and wide operating temperature range, while MgB_2 offers significant advantages due to its low density and ability to operate at low temperatures. These superconductors are integrated into toroidal or solenoid structures that optimize the redirection of magnetic fields, providing effective protection for spacecraft [17], [21].

4.2.2 The Risk Of Secondary Particles

Cosmic rays and high-energy radiation in the space environment can interact with superconducting materials to produce secondary particles. Neutrons, gamma rays, and light ions are examples of secondary particles that increase radiation doses, posing risks to both astronaut health and the electronic equipment of spacecraft. This is a significant factor that limits the performance of superconducting shielding systems [1], [5].

Electrically neutral particles such as pions and neutrons cannot be directed by magnetic fields, making their control with superconducting systems impossible. Neutrons, in particular, can penetrate the atomic structure of materials, causing mechanical stress and long-term structural damage. This increases the importance of passive shielding materials in managing secondary particles. Low atomic number materials like polyethylene are effective in mitigating the effects of such particles through absorption [9], [14].

To address this challenge, various engineering solutions have been proposed:

- **Toroidal Configurations**: These can enhance the deflection of charged particles, reducing the impact of secondary particles. Additionally, they minimize the effects of magnetic fields on internal modules [9],[14].
- **Hybrid Shielding Systems**: Combining superconducting materials with low atomic number passive shields enhances the absorption of secondary particles and reduces radiation doses [9].

Engineering optimization is crucial for limiting the production of secondary particles in superconducting materials and ensuring effective protection. Geometric designs and careful management of magnetic field intensity will be effective in resolving these issues.

4.2.3 The Importance Of Geometry

In superconducting-based magnetic shielding systems, geometric design emerges as a fundamental factor determining system performance. Changes in geometry alter the redirection, intensity, and interaction of magnetic fields with superconducting materials. These physical mechanisms can either enhance or limit shielding performance. Therefore, geometric configuration is critically important for optimizing radiation protection capacity.

Different geometric designs determine how magnetic fields propagate around a spacecraft. For instance, toroidal geometries confine magnetic fields within the protected region, preventing external leakage. This enhances radiation shielding while supporting energy efficiency. In contrast, solenoid configurations provide a homogeneous magnetic field distribution along the axis, offering broader coverage. However, magnetic field leakage at the edges can limit protection effectiveness [1], [7].

Lorentz forces arise from the interaction between the currents carried by the superconducting material and the magnetic fields. Incorrect geometry can cause uneven distribution of these forces, leading to mechanical stress on the material's surface and compromising structural integrity. An appropriate geometry balances Lorentz forces, enhancing the system's long-term durability [1], [9].

Geometry also directly impacts energy efficiency. Focused geometries concentrate magnetic fields only in required regions, reducing energy consumption while providing high protection in targeted areas. Conversely, geometries designed for broader coverage require more energy, making energy management a critical consideration for the sustainability of long-term space missions [7], [9].

Secondary particle production is another key factor influenced by geometry. Collisions between charged particles and superconducting surfaces can generate secondary particles, such as neutrons and gamma rays. Toroidal configurations minimize such collisions, thereby limiting radiation effects. Solenoid configurations, while advantageous for broad protection, are less effective in reducing secondary particle production [14], [16].

Geometry	***Advantages***	***Disadvantages***
Toroidal	*Completely confines magnetic fields, minimizing environmental interactions.*	*Mechanically complex and requires heavy materials for structural support.*
Solenoid	*Provides homogeneous magnetic fields along the axis, easier to manufacture, and suitable for modular designs.*	*Limited protection effectiveness due to magnetic field leakage at the edges.*
Flat	*Simple design, low production cost, and ease of assembly.*	*Insufficient magnetic field coverage and reduced effectiveness.*

Table 1. In this table, superconducting configurations of different geometries are compared.

4.2.4 Differences Between Type I And Type II For Magnetic Shielding

Type I and Type II superconductors offer distinct features and advantages in magnetic shielding systems. Type I superconductors are characterized by their low magnetic field tolerance and complete Meissner effect. These properties make them suitable for simple shielding applications requiring low magnetic field resistance but insufficient for high magnetic field conditions.

In contrast, Type II superconductors are ideal for modern space missions due to their ability to withstand high magnetic fields and operate in a state known as the "mixed phase." Materials such as YBCO and MgB_2 fall under the Type II category, offering high performance across a wide range of temperatures. Type II superconductors are particularly preferred in environments with high radiation levels and strong magnetic fields, although they require more sophisticated designs and come with higher costs [20], [21].

4.3 Current Research On Spacecraft Protection Through The Meissner Effect

The application performance of the Meissner effect in spacecraft holds significant potential for radiation protection and magnetic shielding system design, primarily due to the ability of high-temperature superconductors (HTS) to expel magnetic fields. Current research focuses on enhancing this effect through optimized geometric configurations and simulation models. The findings from these studies contribute to a deeper understanding of the physical mechanisms of the Meissner effect and the impact of geometric arrangements on performance.

4.3.1 Toroidal Geometry

Toroidal geometry offers an exceptionally effective structure for magnetic shielding systems in spacecraft. This geometry confines magnetic fields within the protected region, enhancing the safety of astronauts and sensitive equipment. Toroidal systems utilizing the Meissner effect optimize radiation protection performance by maintaining control over magnetic fields. High-temperature superconductors (HTS) like YBCO and MgB_2 are widely used in toroidal designs, demonstrating energy efficiency and durability in various projects. For example, the SR2S (Space Radiation Superconducting Shielding) project developed toroidal shields that reduced radiation doses by up to 45%. These systems, designed for long-duration missions such as Mars expeditions, can generate magnetic field strengths of up to 20 Tesla-meters [9] , [1].

Toroidal geometries enable isotropic redirection of magnetic fields and minimize edge field leakage. This creates a homogeneous magnetic field distribution in the protection area, significantly reducing radiation-related risks. However, these systems have complex mechanical structures and require additional engineering solutions to balance internal forces. For instance, ESA's studies on "Double Helix" and "Racetrack" toroidal designs optimized for weight and stress reduction highlight advancements in this area. The Double Helix design improves material efficiency, while the Racetrack design reduces mechanical stress [1], [14]

Figure 15. Racetrack Toroid System: This system utilizes superconductors in a toroidal design. The racetrack shape ensures a uniform distribution of the magnetic field, enhancing radiation protection performance while reducing mechanical stress on the superconductors. It is designed for effective shielding in space missions.[14]

Monte Carlo simulations on toroidal geometry demonstrate superior performance in redirecting magnetic fields. A toroidal structure with a field strength of 11.9 T-m can reduce cosmic radiation doses by up to 40% and efficiently deflect heavy charged particles. However, challenges in manufacturing and addressing secondary particle formation require additional measures. Hybrid systems combining passive shielding materials with toroidal designs are recommended to mitigate secondary particle effects [5], [14].

Mathematical modeling and theoretical analyses are used to optimize the bending strength and protection efficiency of toroidal fields. The London Equations and Ginzburg-Landau theories provide insights into mechanisms that minimize energy losses and enhance critical field resilience. For example, the intensity distribution of the magnetic field in a toroidal system can be expressed as:

Equation 7

$$\Xi = \int_{R_i}^{R_e} B_{\emptyset} dR = \frac{\mu_0 I}{2\pi} \ln\left(\frac{R_e}{R_i}\right)$$

Where;

- Ξ: Magnetic flux linkage (measured in Weber).
- $B_{\emptyset}$: Toroidal magnetic field (magnetic field intensity).
- R_i: Inner radius of the toroidal system.
- R_e: Outer radius of the toroidal system.
- μ_0: Magnetic permeability of free space ($\mu_0 \approx 4\pi \times 10^{-7}$).
- I: Current in the toroidal system (measured in Amperes).

This equation helps analyze and optimize the particle deflection capabilities of toroidal fields [14],[1].

4.3.2 Solenoid Geometry

Solenoid geometry is a widely used magnetic shielding method for spacecraft due to its ability to direct magnetic fields homogeneously along the axis. These structures offer significant advantages in space missions by providing broad coverage areas and modular design possibilities. Solenoid systems utilizing high-temperature superconductors (HTS) like YBCO and MgB_2 enhance spacecraft reliability by optimizing magnetic field generation and radiation protection capabilities [1], [5].

Under the MAARSS (Magnet Architectures and Active Radiation Shielding Study) project, solenoid systems demonstrated the ability to reduce total radiation doses by up to 30%. However, the effectiveness of this protection varies across different types of radiation, such as solar particle events (SPEs) and galactic cosmic radiation (GCR). The higher energy levels of GCR indicate that solenoid systems alone may not suffice, necessitating the integration of passive shielding materials [7],[14].

One key advantage of solenoid geometries is their ability to provide a homogeneous magnetic field distribution, which is critical for space missions requiring broad protection areas. Innovative designs like the "6+1" configuration, which incorporates a central compensation coil, minimize magnetic field leakage and reduce external field effects. These configurations have been optimized for long-duration human space missions, such as Mars and lunar expeditions [14].

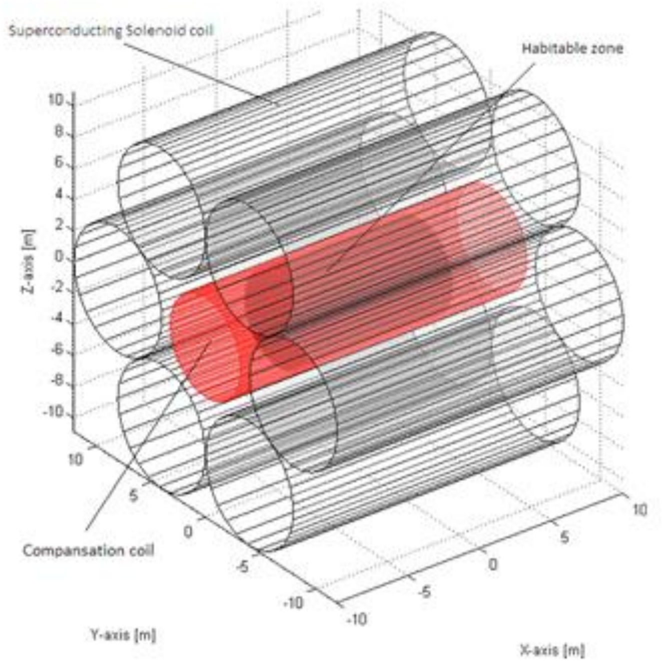

Figure 16. 6 + 1 Expandable Solenoid Shield: This figure illustrates the 6+1 expandable superconducting solenoid shield designed by Westover et al. The shield surrounds a habitable zone intended to protect astronauts from radiation. The main solenoids generate magnetic fields, while compensation coils ensure a uniform field distribution. This design provides effective radiation protection for space missions. [14]

Despite their advantages, solenoid structures also present challenges. The effects of Lorentz forces can create significant mechanical stress, particularly at the coil ends, leading to structural deformation. YBCO-based superconductors have been enhanced with specialized microstructures that improve mechanical stress tolerance. These microstructures extend the elastic limits of superconductors and reduce the risk of mechanical deformation. However, their performance in long-term space missions remains an active area of research [7][9].

Additionally, solenoid systems can produce secondary particles, such as neutrons and protons, through interactions with high-energy particles. This limits shielding effectiveness and requires the integration of passive shielding materials. Low atomic number materials, such as polyethylene, play a critical role in enhancing solenoid systems' efficiency through neutron absorption [16][5].

Mathematical modeling is essential for optimizing solenoid geometries by understanding the distribution of magnetic field intensity along the axis. These models are used to evaluate the particle deflection capacity of magnetic fields and improve radiation protection performance. The magnetic field strength along the axis of a solenoid system can be calculated using the following equation:

Equation 8.

$$\boldsymbol{B_z = \frac{\mu_0 n I}{2}\left[\frac{z - l/2}{\sqrt{(z - l/2)^2 + R^2}} - \frac{z - l/2}{\sqrt{(z + l/2)^2 + R^2}}\right]}$$

Where:

- $\boldsymbol{B_z}$: Magnetic field intensity at distance $\boldsymbol{z}$ along the solenoid axis,
- $\boldsymbol{\mu_0}$: Magnetic permeability of free space,
- $\boldsymbol{n}$: Number of turns per unit length,
- $\boldsymbol{I}$: Current through the solenoid,
- $\boldsymbol{R}$: Radius of the solenoid,
- $\boldsymbol{l}$: Length of the solenoid.

This equation provides critical insights into the magnetic field redirection capabilities of solenoids, aiding in the evaluation and optimization of their radiation shielding performance.

4.3.3 Flat Geometry

Flat geometries offer a straightforward structure in magnetic shielding systems, characterized by simple designs and ease of production. These geometries are particularly preferred in low-cost applications or those with limited space requirements. Superconducting materials used in flat configurations can provide homogeneous magnetic field distribution, making them effective in radiation protection systems. ESA studies have demonstrated that flat YBCO plates possess stable magnetic field redirection capabilities and have shown moderate success in reducing radiation doses [19], [7].

One of the most notable advantages of flat geometries is their simplicity and cost-effectiveness during manufacturing. Compared to the complex mechanical demands of toroidal and solenoid structures, flat geometries optimize mass and volume in spacecraft. YBCO-based superconducting plates enhance the performance of these systems due to their low-temperature requirements and energy efficiency. Additionally, the homogeneous magnetic field distribution offered by flat geometries provides an effective way to control particle deflection within a limited area [7], [14].

However, flat geometries have certain limitations. These configurations may not be adequate for wide protection areas or situations requiring effective deflection of high-energy particles. Particularly in long-duration missions exposed to high radiation levels, flat geometries provide limited magnetic field strength compared to toroidal or solenoid systems. Additionally, the management of secondary particles produced from interactions with radiation can further constrain the performance of flat configurations [14], [1].

Studies conducted under the SR2S project and by ESA suggest that flat geometries could be a cost-effective and simple solution for short-term missions. However, for missions requiring higher performance, it has been emphasized that flat geometries need to be integrated into hybrid systems. These hybrid configurations, combined with flat geometries, could contribute to more complex and efficient magnetic shielding systems [1], [5].

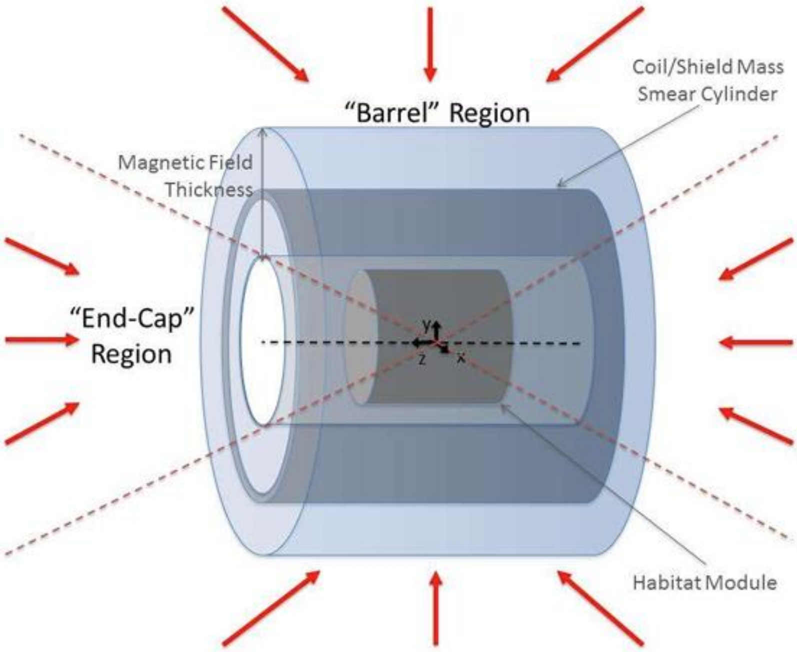

Figure 17. Magnetic Shield Geometry: This structure features a cylindrical design consisting of the "Barrel" and "End-Cap" regions. The geometry ensures a uniform magnetic field surrounds the habitable area. This symmetrical and three-dimensional design provides an effective solution for radiation protection. [7]

4.4 Meissner Effect For Astronaut Suit Shielding

Superconducting shielding based on the Meissner effect offers a promising solution for radiation protection in astronaut suits. However, the feasibility of this technology is constrained by several technical challenges.

The low-temperature requirements of superconducting materials necessitate the integration of cryogenic cooling systems into the suits. This increases energy consumption and impacts the overall weight of the suit. The development of miniaturized cryogenic systems is critical to overcoming this challenge. These systems must be further optimized to maintain sufficient cooling capacity while improving energy efficiency. Lightweight, long-lasting, and modular cooling systems are particularly crucial for addressing this issue [1], [4].

Moreover, high-energy radiation striking superconducting surfaces can produce secondary particles, which limit the effectiveness of protection. Secondary particles (e.g., neutrons and gamma rays) pose biological risks to astronauts by increasing radiation doses and potential health hazards. To mitigate this issue, combining superconducting materials with passive shielding layers made of low atomic number materials such as polyethylene is recommended. Such hybrid systems can reduce the effects of secondary particles, minimizing the biological damage caused by radiation [1], [16].

The technology based on the Meissner effect is expected to find broader applications with advancements in the miniaturization of cryogenic systems and the improvement of material performance. Specifically, the development of this technology for long-term space missions will enhance astronaut safety. Additionally, integrating superconducting shielding systems into astronaut suits in a way that effectively manages magnetic fields can limit the production of secondary particles. Geometric configurations will play a critical role in enhancing protection capacity [1], [9], [16].

4.5 Hybrid Magnetic Shielding Systems

Hybrid magnetic shielding systems offer an innovative solution by combining the strong magnetic field generation capability of superconductors with the durability of conventional materials. These systems provide significant advantages over traditional methods in terms of energy efficiency and mass optimization.

In these systems, superconducting components effectively deflect charged particles due to their zero-resistance properties, while the outer layers of conventional materials absorb part of the radiation, enhancing protection capacity. Hybrid designs incorporating high-temperature superconductors like YBCO and MgB_2 can reduce radiation doses by up to 50%. Research on different radiation types, such as galactic cosmic radiation (GCR) and solar particle events (SPE), has shown some variations in the effectiveness of these systems. While GCR's high-energy nature creates scenarios where hybrid systems cannot provide full protection, SPEs, which consist of lower-energy particles, can be deflected more effectively by hybrid systems [1], [6], [14].

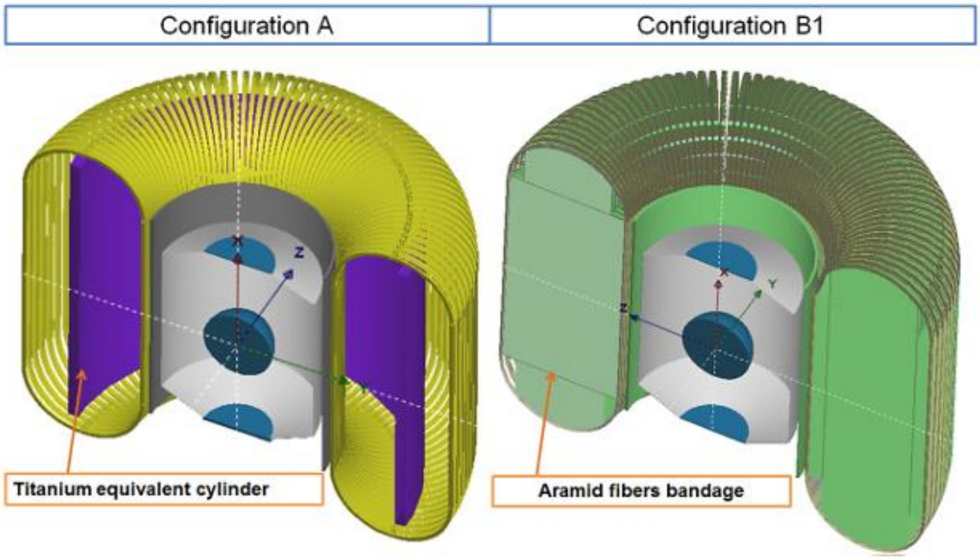

Figure 18. Hybrid Protection System: The image illustrates a hybrid protection system combining passive and active shielding mechanisms. Configuration A utilizes a titanium equivalent cylinder, while Configuration B1 incorporates an aramid fiber bandage. Passive protection is achieved through these materials, while active protection is provided by magnetic fields redirecting radiation. This design offers an effective solution for radiation shielding, particularly for long-duration space missions. [9]

The design of hybrid systems also offers significant advantages in terms of energy and mass optimization. Simulation studies have shown that these systems can reduce total mass by 30% to 50%. Compared to a traditional 315-ton toroidal structure, hybrid systems can achieve the same protection performance with a mass of just 100 tons. Additionally, the zero electrical resistance of superconducting components reduces energy consumption by up to 50%, making hybrid systems a sustainable solution for long-term space missions [6], [9].

However, hybrid systems present some technical challenges: Ensuring structural compatibility between superconducting and conventional materials requires complex engineering solutions. Differences in thermal expansion between materials can challenge mechanical durability during prolonged use. While low atomic number materials like polyethylene play an effective role in radiation absorption, combining such materials with superconducting layers can lead to deformation under long-term thermal stress [5], [14].

The low-temperature requirements of superconducting components pose additional engineering challenges in system design concerning energy efficiency and operational reliability. Miniaturized cryogenic systems play a key role in overcoming these challenges [9].

Hybrid systems are becoming a fundamental technology for future space missions due to their superior radiation protection performance, lightweight structure, and energy efficiency. These systems will increase spacecraft reliability by delivering higher performance at lower costs, especially for long-term deep space missions. Better understanding the performance differences of hybrid systems against different radiation types, such as SPE and GCR, will play a critical role in optimizing these systems [6], [14].

4.6 Comparison With Conventional Shielding Methods

Significant differences exist between traditional passive shielding methods and superconducting-based active shielding systems used for protection against space radiation. These two approaches are evaluated in terms of factors such as protection efficiency, mass savings, and energy efficiency. While traditional methods stand out with their simple designs and low-cost advantages, superconducting systems offer superior protection capacity and weight reduction.

Passive shielding methods typically consist of dense materials like aluminum and polyethylene. Although these materials are effective against low-energy radiation types, they are inadequate for high-energy cosmic rays. For instance, a 10 cm thick aluminum shield can effectively block low-energy radiation, but additional layers are required for high-energy particles. This results in heavy shielding systems that limit spacecraft carrying capacity and increase mission costs. For long-term missions like Mars, the total mass of these systems can exceed 100 tons, making them challenging to transport with current technologies [1], [9].

Superconducting-based active shielding systems provide an innovative solution to overcome these challenges. Using magnetic fields to deflect charged particles away from the protected region, these systems offer both mass savings and superior protection. A toroidal superconducting system with 8 T-m strength can achieve up to 50% mass savings compared to an equivalent passive shielding system. This reduces the total mass from 100 tons to 50 tons, enabling spacecraft to be lighter and more efficient [6], [16]. Superconducting shielding systems can generate magnetic fields up to 23 T-m, reducing the radiation dose inside the habitat to as low as 10 cSv/year, well below the limits set for low Earth orbit [9].

However, superconducting systems also face technical challenges. These systems require cryogenic cooling and advanced engineering solutions to maintain magnetic field stability. Nevertheless, the use of high-temperature superconductors (HTS) like YBCO and MgB_2 has the potential to reduce the burden of cryogenic systems and enhance system efficiency. HTS materials can operate at higher temperatures and be combined with less complex cooling systems [6], [12].

In conclusion, while passive shielding methods are suitable for low-cost and short-term missions, they fall short in meeting the high radiation protection requirements of modern space missions. Superconducting-based active shielding systems stand out as a more effective solution for long-term missions due to their lightweight structures, superior protection capacities, and energy efficiency. These systems will form the foundation of future radiation protection technologies in space missions [1], [6], [16].

5

Other Applications Of Superconductors İn Space Missions

5.1 Superconducting Cables

Superconducting cables offer groundbreaking solutions for energy transmission in space missions. Developed using high-temperature superconductors (HTS), these cables minimize energy loss and enhance overall system efficiency due to their zero electrical resistance. A study conducted at CERN demonstrated that magnesium diboride (MgB_2) superconductors are ideal candidates for long-distance energy transmission, thanks to their high current-carrying capacity. The studies demonstrated that MgB_2 achieved a critical current density of 10^4 A/cm² at temperatures as low as 20 K. This finding emphasizes that MgB_2 can operate effectively without requiring complex cryogenic systems such as liquid helium. This capability significantly enhances energy efficiency and simplifies operations. These advantages make MgB_2 particularly suitable for space missions, where naturally low temperatures are prevalent. [12]

Superconducting cables are especially suitable for deep-space missions involving energy-intensive equipment. For example, simulation studies on a 1-kilometer-long MgB_2 cable system for long-term missions like Mars have shown a reduction in energy loss by over 50%, thereby significantly lowering total energy costs and logistical burdens. In such mission scenarios, reduced energy loss enables the design of spacecraft with lighter energy management systems. Furthermore, the effective redirection of magnetic fields increases the reliability of these cables and ensures their long-term usability [3], [6].

5.2 Superconducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy Storage (SMES) systems represent an innovative technology for energy storage and management in spacecraft. SMES systems store electrical energy in a magnetic field, offering rapid charge and discharge capabilities. These systems stand out due to their energy conversion efficiency exceeding 90% and long operational lifespans. SMES systems provide energy storage capacities ranging from 1 MW to 100 MW, making them suitable for energy-intensive missions [21], [15].

The primary advantage of SMES in space missions is its ability to meet sudden power demands. For instance, a SMES system with a 6 MJ capacity can support short-term high-power energy needs, ensuring the protection of critical loads. Additionally, micro-SMES configurations with compact and lightweight designs optimize the mass and volume requirements of spacecraft [21].

Challenges:

The main challenges in using SMES systems in space include cryogenic cooling requirements and the proper confinement of magnetic fields. However, advancements in high-temperature superconductors (HTS) offer significant opportunities to address these challenges. For example, toroidal designs can prevent magnetic field leakage, while solenoid configurations can provide larger energy storage capacities [21].

5.3 Communication And Sensor

Superconducting technologies play a critical role in space missions, particularly in low-frequency detection and communication systems. Superconducting Quantum Interference Device (SQUID) magnetometers provide exceptional sensitivity and wide bandwidth for magnetic field measurements. These devices have unparalleled capability in detecting variations in solar wind and changes in planetary magnetic fields. For example, SQUID devices, with a sensitivity of 1 pT (picoTesla), have enabled detailed mapping of magnetic field fluctuations on the Martian surface. During the Mars Global Surveyor mission, SQUID devices provided crucial data on the planet's ancient magnetic field structure, shedding light on Mars' geological history. Their high sensitivity makes these devices ideal for studying low-frequency magnetic fluctuations and geomagnetic interactions [21], [18].

Superconducting digital circuits developed with Josephson junctions offer significant advantages in data processing and communication systems on spacecraft. These circuits, with switching speeds of up to 1 picosecond and low energy consumption, optimize data transfer. Specifically, the use of Josephson circuits in digital signal processing and radar applications enhances efficiency in space missions. A NASA study demonstrated that these circuits maintained performance under radiation doses of up to 300 krad (kilo rad), showcasing their long-term reliability in extreme environments. Josephson circuits have been employed in high-radiation missions, such as the Mars Reconnaissance Orbiter, to enhance the reliability of communication systems [3], [21].

5.4 Superconducting Propulsion And Magnetic Levitation System

Superconducting propulsion systems and magnetic levitation represent groundbreaking innovations for space transportation and planetary settlements. Magnetic levitation systems, utilizing powerful superconducting magnets, offer low energy consumption and high-speed advantages for material transport. A mass driver system designed to transport materials from the Moon's surface to Earth's orbit, supported by linear synchronous motors and superconducting magnets, can generate a 3 T magnetic field, enabling the transport of 10 kg of materials per trip. This system significantly reduces costs while enhancing efficiency in space logistics [13], [15].

Superconducting propulsion systems also hold great potential for interplanetary transportation. The high magnetic field generation capacity of superconductors enables long-term transportation missions with low energy consumption. Magnetic bearing technologies used in extended missions increase system durability due to their frictionless operation. For instance, a magnetic levitation system has been demonstrated to operate reliably for 10 years, providing an economical and dependable solution for logistics missions between the Moon and Mars [13], [21].

6

Conclusion and Evaluation

6.1 Summary of Key Findings

6.1.1 Purpose and Problem Restatement

This thesis aimed to deeply examine the capabilities offered by superconducting materials under the challenging conditions of the space environment (vacuum, microgravity, high radiation, etc.) and demonstrate how superconductors could be a key technology, particularly for radiation protection in space and energy applications**.** The advantages of active magnetic shielding systems based on the Meissner effect and high-temperature superconductors (e.g., YBCO, MgB_2) over conventional passive shielding methods (e.g., aluminum, polyethylene) were assessed, along with other applications such as SMES, superconducting cables, sensors, and propulsion systems.

6.1.2 Condensed Summary of Main Findings

1. **Meissner Effect and Active Shielding:** Active superconducting shielding systems, which can partially replace heavy traditional shielding materials in space missions, show significant promise in terms of *mass savings* and *high radiation protection*. Data from certain projects in the literature (e.g., SR2S) confirm that hybrid systems (passive + active) can reduce mass by up to 30–50%.
2. **Role of High-Temperature Superconductors:** Materials like YBCO and MgB_2, which can operate at liquid nitrogen temperatures, reduce cryogenic requirements while offering high magnetic field resistance. This enhances energy efficiency in long-term and deep-space missions.
3. **Other Applications (SMES, Cables, Sensors):** Superconducting Magnetic Energy Storage (SMES) systems, due to their ability to meet *sudden power demands* and provide high conversion efficiency, promise revolutionary solutions for spacecraft energy management. Additionally,

applications such as magnetic levitation and propulsion technologies offer low energy consumption and high-speed advantages for Moon and Mars logistics, as well as interplanetary transportation.

6.1.3 Comparative Evaluation

This study provides a detailed comparison between passive shielding methods and superconducting-based active shielding systems, highlighting the gap addressed by current research. It demonstrates how designs focused on the Meissner effect could be advantageous for long-term missions, as opposed to heavy and costly systems based on traditional materials. One of the most significant contributions of this thesis is showing that hybrid systems are an optimal approach for reducing secondary particle production and preventing critical magnetic field exceedances.

6.2 Theoretical and Practical Implications and Limitations

This thesis aimed to present a comprehensive overview of the potential applications of superconducting materials, particularly high-temperature superconductors like YBCO and MgB_2, in addressing the challenges of space environments such as vacuum, microgravity, and high radiation. The findings and evaluations highlight several key points from both engineering and practical perspectives.

6.2.1 Engineering and Application Opportunities

- **Active Magnetic Shielding:** Active shielding systems leveraging the Meissner effect offer the potential for more efficient solutions in terms of mass and cost. Instead of relying on heavy passive shielding materials, the magnetic field expulsion capability of superconductors can provide radiation protection. This approach can significantly reduce the overall spacecraft mass, especially for long-duration missions to destinations like Mars or the Moon, where *every kilogram is critical*.
- **Superconductivity in Astronaut Suits:** Sources examined in this thesis suggest that the idea of radiation-shielded astronaut suits utilizing the Meissner effect is still in the experimental phase. However, with advancements in miniaturized cryogenic cooling systems, this technology

could become viable in the future. Such systems would allow astronauts to operate more safely in high-radiation environments.

- **SMES (Superconducting Magnetic Energy Storage):** The ability of SMES systems to meet sudden power demands with rapid charge/discharge capabilities has been emphasized in various studies as a valuable asset for space missions.
- **Sensor Technologies:** Superconducting devices like SQUID magnetometers offer unparalleled sensitivity in detecting magnetic field fluctuations on planetary surfaces or the effects of solar wind, enabling precise measurements.
- **Magnetic Levitation and Propulsion:** Superconducting magnets can facilitate efficient material transport with low energy consumption and high speed. These technologies can be utilized for systems like mass launch ramps, supporting transportation from planetary surfaces to orbit.

6.2.2 Limitations and Challenges

- **Material and Method Constraints:** This thesis primarily focuses on widely studied high-temperature superconductors like YBCO and MgB_2. The performance of other superconductors, which remain untested in space or are still in the laboratory stage, is not well understood. Furthermore, the effects of space environmental factors, such as temperature fluctuations and variable magnetic fields, on surpassing the critical limits of superconductivity are not fully predictable.
- **Experimental and Simulation Gaps:** Conducting experiments in space conditions is highly costly, and replicating microgravity environments with complete accuracy is challenging. As a result, building a comprehensive experimental database for superconductors is difficult. Simulation studies are also constrained by the incomplete understanding of superconductivity at the microscopic level, which forces engineering calculations to rely on assumptions and limited modeling frameworks.
- **Generalization Issues and the Need for Hybrid Systems:** Each mission profile (e.g., short- or long-duration, low- or high-radiation) requires distinct design approaches, making a single superconducting shielding or

energy system unsuitable as a "one-size-fits-all" solution. In hybrid shielding (passive + active) systems, risks such as *secondary particle* generation and critical magnetic field exceedances must be mitigated with supplementary passive shielding layers. While this approach is engineering-intensive, it offers a more robust and secure structure.

6.3 Final Remarks and Concluding Observations

This thesis has been prepared to demonstrate how superconductors can play a critical role in radiation protection, energy management, and transportation as the space age accelerates. Active shielding approaches based on the Meissner effect have the potential to mitigate the mass and performance limitations of traditional passive materials. In particular, hybrid shielding systems and high-temperature superconductors (e.g., YBCO, MgB_2) offer promising prospects in terms of cost-effectiveness.

However, the challenges posed by the space environment—variable magnetic fields**,** intense radiation**,** and extreme temperature differentials—remain unresolved with current technologies. Thanks to advancements in artificial intelligence and materials science, even though the *microscopic nature of superconductors cannot yet be fully understood*, statistical modeling and next-generation production techniques are making it increasingly feasible to identify optimal materials and designs.

In conclusion, this thesis underscores once again the revolutionary potential of superconductivity in space missions. When considering critical factors such as preventing radiation overdoses, ensuring astronaut safety, and enhancing energy efficiency for deep-space missions, superconducting-based solutions can propel humanity one step closer to becoming an interplanetary civilization**.**

“The extraordinary properties of superconductors and their synergy with space engineering stand poised to become one of our greatest allies on the journey to the stars.”

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