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Research Article

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System Energy Analysis and COMSOL Simulation of a Superconducting Shielding Model

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Abstract

This article proposes a superconducting shielding magnetic field model based on the Meissner effect of superconductors, which blocks magnetic fields. By utilizing the shielding effect of the superconductor on the magnetic field during the phase transition, the model achieves intermittent shielding of electromagnetic force, allowing the electromagnetic force to work intermittently on the moving magnet within the model during its operation. The model is analyzed on the basis of superconducting thermodynamic theory, with a focus on the electromagnetic energy of the system. It is concluded that the energy is not conserved during the operation of the model. To verify the correctness of the analysis, electromagnetic simulations and data analysis were conducted via the COMSOL electromagnetic module and Ampère's law superconducting model parameters, which yielded identical results.

Keywords: Superconducting Thermodynamics, Meissner Effect, Superconducting Shielding, Energy Conservation, COMSOL Simulation

1. Background Technology

Thermodynamics is based on the concept of reversible phase transitions. Before the discovery of the Meissner effect, superconductors were always considered ideal conductors, with the normal state appearing when superconductivity is destroyed, resulting in resistance and heat generation from currents associated with magnetic fields. Therefore, superconducting phase transitions are viewed as nonequilibrium processes, making it impossible to understand them via thermodynamics. However, Keesom (1924), disregarding the premise of thermodynamic application, established a series of thermodynamic formulas for superconducting phase transitions, which were found to align well with a significant amount of experimental data. Gorter (1933) noted that the success of these early thermodynamic treatments strongly suggests that superconducting phase transitions should be reversible[1].

The discovery of the Meissner effect revealed that the disappearance of supercurrents in superconductors does not involve any irreversible processes. Gorter and Casimir (1934) noted that the thermodynamic treatment of superconducting phase transitions is entirely similar to that of other phase transitions, confirming the correctness of the early thermodynamic approach, and they proposed the two-fluid model[1].

The two-fluid model explains that the formation of superfluid electrons (later known as Cooper pairs) is due to the system's tendency toward the state of lowest free energy, aligning with the thermodynamic principle of minimizing free energy. The subsequent BCS theory provided a microscopic quantum explanation for Cooper pairs, describing them as pairs of electrons that condense into a lower energy state, further verifying the thermodynamic driving force behind superconductivity.

In 1935, the London brothers expanded on the two-fluid theory and, on the basis of the hypothesis of superconducting electrons and classical Maxwell equations of electromagnetism, derived the London equations. These equations demonstrate that superconducting electrons form superconducting currents in magnetic fields, which generate opposing magnetic fields that cancel out external magnetic fields. They noted that the formation and disappearance of superconducting currents are lossless, providing a strong explanation for the Meissner effect. Later, the BCS theory explained the Meissner effect on a microscopic level through the lossless motion of Cooper pairs. The London equations and BCS theory confirmed that the Meissner effect in superconductors under a magnetic field occurs without generating heat or energy loss. Conversely, when the magnetic field is removed, the disappearance of the superconducting current also occurs without energy loss. Conversely, when the magnetic field is removed, the disappearance of the superconducting current also occurs without energy loss. Under the influence of a varying magnetic field, the supermagnetic field in the Meissner state has a completely reversible transformation among the electromagnetic energy flowing into the supermagnetic field, the internal magnetic field energy, and the kinetic energy of superconducting electrons. There are no losses within the super magnetic field[2].

Superconducting shielding is a physical function formed by the Meissner effect in superconductors. In a magnetic field, the superconductor in the superconducting state generates superconducting currents in the thin layer on its outer surface (with a thickness of 10^{-2} to 10^{-1} micrometers), creating an opposing magnetic field that expels the internal magnetic flux (magnetic field lines), resulting in zero magnetic flux within the superconductor, effectively achieving magnetic field isolation[1,4,5]. As shown in Figure 1, the superconductor isolates the magnetic field, thereby altering the distribution and pathways of the original magnetic field[1,3-5].

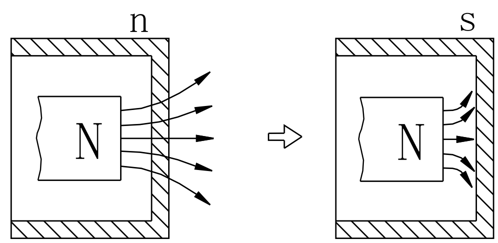

Figure 1: The Magnetic Field Distribution Generated by a Real Magnetic Field Around a Superconductor

1.1 Thermodynamic Analysis of a Superconducting Magnetic Shielding Model

First, let us introduce the thermodynamic Gibbs free energy formula[1,6]:

A superconductor in a magnetic field HHH, as shown in the second step of Figure 2, becomes magnetized in the superconducting state. The superconductor works under the influence of an external magnetic field, producing an opposing magnetic moment MMM and a superconducting current. The amount of work done is $dW = \mu_0 HdM$, where μ0 is the permeability of free space.

The differential form of the Gibbs free energy in the presence of a magnetic field is as follows:

$$dG = dU - TdS - SdT + pdV + Vdp - \mu_0 HdM - \mu_0 MdH \qquad (1)$$

In this equation, the symbols represent the volume V, entropy SSS, pressure P, temperature T, magnetic field strength HHH, and magnetic moment M.

The Gibbs free energy in the absence of a magnetic field is as follows:

$$G = U - TS + PV \qquad (2)$$

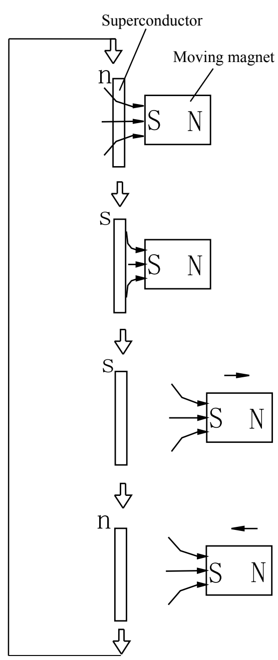

Figure 2: Basic Model

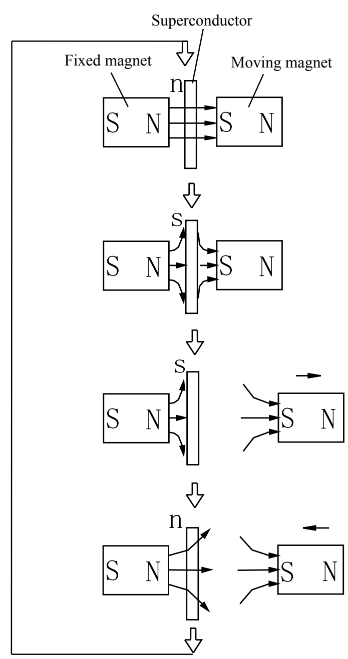

Figure 3: Superconducting Phase Transition Model with an Added Moving Magnet

Note: In the figures, "s" represents the superconducting state, "n" represents the normal state, and the arrows indicate the direction of displacement.

The model in this paper, as shown in Figure 3, is similar in form to the basic superconducting thermodynamic model depicted in Figure 2. The difference is the addition of a moving magnet, which introduces a variable magnetic field. The model represents a dynamic cyclic process in which the superconductor undergoes phase transitions from the normal state to the superconducting state and then returns to the normal state.

The specific structure of the model consists of a fixed permanent magnet (referred to as the "fixed magnet") and a movable permanent magnet (referred to as the "moving magnet") placed on either side of a disc-shaped superconductor. The detailed motion of the model follows this sequence:
a) The superconductor starts in the normal state, with the moving magnet positioned away from the superconductor;
b) The moving magnet approaches the superconductor, At this time, the superconductor in the normal state behaves as a paramagnetic material, and when a moving magnet approaches, it is considered to have no effect on the superconductor[1,7]; Cooling induces a phase transition in the superconductor to the superconducting state, at which point the superconductor shields the fixed magnetic field;
c) The moving magnet moves away from the superconductor;
d) Heating causes the superconductor to return to the normal state.
The above steps complete one cycle.

Since the model presented in this paper involves a cyclic process, where superconductors transition from the normal state to the superconducting state and then revert back to the normal state, according to the thermodynamic theory of superconductivity, all the parameters, including electromagnetic energy, are reversible for superconductors that return to their original state. Therefore, any thermodynamic effects on the superconductors themselves can be offset and disregarded during the model's thermodynamic analysis. However, within this model, there is a moving magnet that, during operation, will be electromagnetically influenced by the diamagnetic field of the superconductor. Therefore, we need to reanalyze the electromagnetic energy changes between the components of the model while disregarding other parameters, such as V, S, P, and T.

According to equations (1) and (2), in the presence of a magnetic field, two additional terms are included in the system's free energy: $\mu_0\, HdM + \mu_0\, MdH$. These two terms represent the work done by the external magnetic field HHH during the phase transition of the superconductor and the response of the superconductor's opposing magnetic field to changes in the external magnetic field. In fact, the first term corresponds to the work done by the magnetic field on the superconductor, generating the opposing magnetic field, whereas the second term represents the work (or potential energy) performed by the opposing magnetic field on the external field.

The thermodynamic analysis of the model in this paper considers not only the changes in the thermodynamic parameters of the superconductor but also those of the two permanent magnets. A comprehensive analysis of the three components is necessary to achieve a complete thermodynamic understanding of the model.

Next, we analyze only the changes in the thermodynamic parameters of the system caused by the external magnetic field.

2. Comparative Group Analysis of the Basic Model

Since the three objects in the model mainly interact and transform through electromagnetic energy, placing the superconductor alone in an adiabatic chamber ensures that no heat energy is exchanged between them—only electromagnetic energy. This approach makes the analysis of free energy changes among the three objects straightforward and clear.

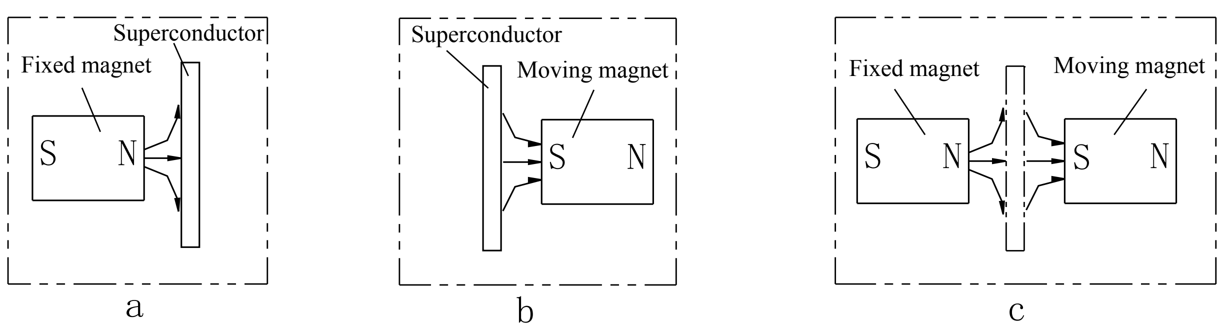

Figure 4: The Model is Divided into Three Combination Diagrams

Three objects are divided into three groups, with each pair forming one group. As shown in Figure 4, analyze the energy transformation for each group of objects in each step according to the motion sequence of the model. Based on the model setup, the superconductor initially starts in the normal state, and the moving magnet is placed far away from the superconductor.

1.1 Superconductor and Permanent Magnet: The interaction between the permanent magnet and the superconductor is relatively simple. When the superconductor is in the normal state, there is no effect between them. When the superconductor transitions into the superconducting state, according to the free energy equation (1), the permanent magnet does work on the superconductor, and the superconductor generates a diamagnetic field that creates potential energy doing work on the permanent magnet. When the superconductor returns to the normal state, the diamagnetic field disappears, and the potential energy vanishes as well. At this point, the model completes one cycle. In this process, the work and potential energy are exchanged between the superconductor and the permanent magnet. Ultimately, neither object experiences a change in energy, and each obeys the law of energy conservation.

1.2 Superconductor and Moving Magnet: Starting from the initial state, the moving magnet approaches the superconductor, and while the superconductor is in the normal state, there is no effect between them. When the moving magnet gets closer, the superconductor undergoes a phase transition to the superconducting state. According to the free energy equation (1), the superconductor generates a diamagnetic field due to the magnetic field of the moving magnet. The moving magnet does work on the superconductor, while its magnetic field is shielded. As the moving magnet moves away from the superconductor, the superconductor's diamagnetic field does work on the moving magnet. At the same time, the diamagnetic field disappears, and the free energy decreases. In the entire process, the moving magnet does work on the superconductor first, and then the superconductor does work on the moving magnet. The energy is exchanged twice, but over the course of one cycle, neither object undergoes a change in energy, and the total energy of the two objects remains constant.

1.3 Permanent Magnet and Moving Magnet: Initially, the superconductor is in the normal state. When the moving magnet approaches the superconductor, it also gets closer to the permanent magnet. Since the superconductor cannot shield the magnetic field of the permanent magnet, the permanent magnet exerts a magnetic force on the moving magnet, doing work on the moving magnet as they approach each other[8,9]. Further, when the superconductor enters the superconducting state, according to the Meissner effect, the superconductor shields the magnetic fields of both permanent magnets, eliminating the magnetic force between them. At this point, the moving magnet moves away from the permanent magnet. As the moving magnet moves away, the permanent magnet no longer exerts a magnetic force on the moving magnet, and thus cannot do work on it. Thus, in one cycle, the permanent magnet does positive work on the moving magnet.

Based on the steps above, in the whole model, the free energy of the superconductor and the permanent magnet remains unchanged, consistent with the thermodynamic theory of superconductors. However, the free energy of the moving magnet changes because it is subjected to the unilateral electromagnetic force from the permanent magnet.

Through the pairwise analysis of the objects in the model, we find that during one cycle, the free energy of the superconductor and the permanent magnet is conserved, while the free energy of the moving magnet increases due to the work done by the unilateral magnetic field force from the permanent magnet. This seems inconsistent with the thermodynamic formulas for superconductors and the reversibility of phase transitions.

2. Equivalent Analysis by Changing the Position of the Moving Magnet

One way to analyze the system is shown in Figure 5, where the moving magnet and the fixed magnet are placed on the same side of the superconductor at an equal distance relative to the original position. According to the superposition principle, the combined magnetic field strength of the two permanent magnets remains unchanged, and the effect on the superconductor is equivalent. The moving magnet also undergoes reciprocating motion, but in this case, over one full cycle, the work done by the fixed magnet on the moving magnet is zero. This is because this arrangement does not utilize the magnetic shielding function of the superconductor. When the moving magnet moves away, it is still subjected to the opposing electromagnetic force of the fixed magnet, and the total work done by the fixed magnet on the moving magnet before and after is zero. Therefore, the energy of the entire model is conserved.

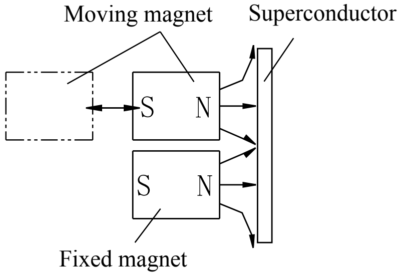

Figure 5: Schematic Diagram of Changing the Position of the Moving Magnet

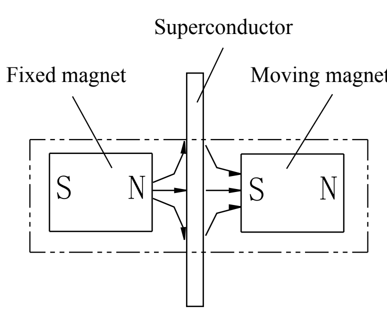

Figure 6: Schematic Diagram of the Overall Analysis

However, in the case of Figure 3, owing to the effect of superconducting shielding, the total work done by the fixed magnet on the moving magnet before and after is greater than zero. As a result, in the model shown in Figure 3, energy is not conserved during cyclic operation, and the system gains energy.

3. Overall Analysis Based on the Meissner Effect

The new model, which includes a moving magnet, is essentially a variation of the basic Meissner effect model. The external magnetic field acting on the superconductor is provided by two permanent magnets. According to the principle of superposition, this can be considered a combined external magnetic field, as shown in the shaded part inside the dashed box in Figure 6. As the moving magnet moves away, the magnetic field decreases, which still conforms to the Meissner effect. As the external magnetic field decreases, the opposing magnetic field of the superconductor also decreases accordingly.

For the entire model, the superconductor and the two permanent magnets exchange energy due to electromagnetic interactions, and their mutual energy influences are conserved overall. The only remaining factor is the electromagnetic work done by the fixed magnet on the moving magnet. Since this work is not zero over one complete cycle of the model, the total energy of the system is not conserved.

On the basis of the above steps, the moving magnet ultimately retains the electromagnetic work done by the fixed magnet on it.

Through separate analysis of the three objects in the model, it can be concluded that during one cycle, the energy of the superconductor and the fixed magnet is conserved, whereas the moving magnet gains a net amount of work. Therefore, the system's total energy is not conserved and increases. To further confirm the correctness of these results, we analyze the system from different perspectives.

4. Electromagnetic Simulation Analysis via COMSOL

1. Software Adaptation Selection

COMSOL is one of the best software tools available for analyzing physical theories, offering comprehensive, rigorous, and highly reliable internal physical formulas, especially with its well-developed logical functions for electromagnetism. Therefore, COMSOL is used in this work to perform electromagnetic and thermodynamic analyses of the model.

For this specific model, the AC/DC module in COMSOL, which is suitable for electromagnetic field analysis, is applied. The parameters are set according to the characteristics of the superconductor's Meissner effect, including the magnetic permeability, electrical conductivity, and dielectric constant, to simulate the model.

2. Model Movement Process

As shown in Figure 7, the movement process of the model is as follows:

1. A cylindrical fixed magnet is placed inside a cylindrical superconductor, which is in the normal state, with the moving magnet positioned 52 mm away from the superconductor.
2. From 0 to 5 s, the moving magnet moves at a constant speed of 1 cm per second along the negative x-axis, approaching the superconductor. After 5 s, the moving magnet stops and is now 2 mm away from the superconductor.
3. At 5 s, the superconductor begins its phase transition to the superconducting state, and by 6 s, the phase transition is complete, with the superconductor in a fully superconducting state.
4. From 5 to 8 s, the moving magnet remains stationary.
5. At 8 s, the moving magnet starts moving again at a constant speed of 1 cm per second along the x-axis. By 13 s, the moving magnet returns to its initial position in the model.

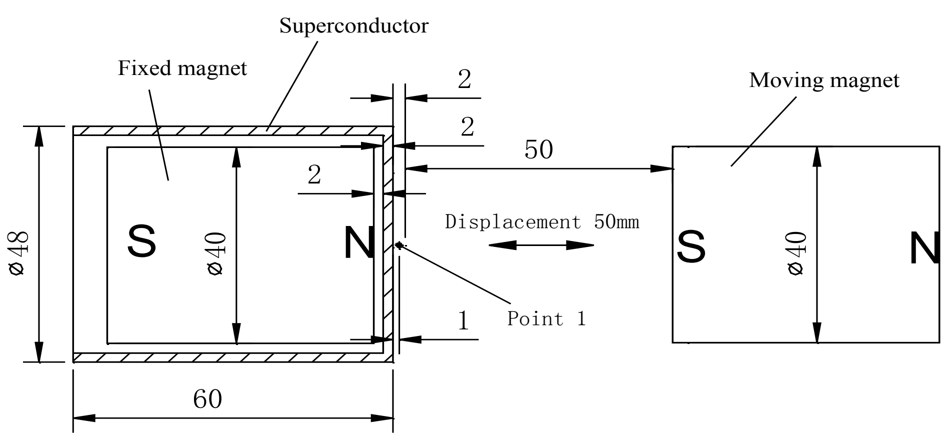

Figure 7: Geometric Model

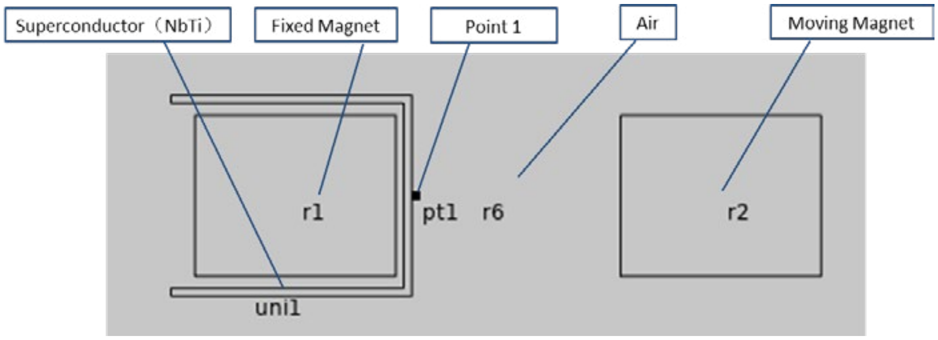

Figure 8: Simulation Model

The simulation model is built on the basis of the geometric model shown in Figure 8.

3. Parameter Settings

Owing to significant differences in the properties of various superconducting materials, it is necessary to first select a material for the superconductor in this model before setting the parameters. To simplify the analysis, this model is based on a Type I superconductor and uses the parameters of a well-known material, niobium-titanium alloy (NbTi).

The parameter settings for the superconductor model are based on superconducting theory: the magnetic flux inside the superconductor is zero, and the current experiences no resistance. In other words, when the superconductor is in the superconducting state, its relative magnetic permeability is 0, and its electrical conductivity is infinite.

The theoretical foundation follows Ampère's law, making the "magnetic fields" (mf) physics module the most suitable for simulating superconducting shielding. The "magnetic fields" module is specifically designed on the basis of Ampère's law to build electromagnetic fields. The internal equations within "magnetic fields" adhere to existing electromagnetic theory, including the London equations from superconducting theory, which are based on Maxwell's electromagnetic equations. Therefore, the use of "magnetic fields" for simulating superconducting shielding is both appropriate and correct.

For the superconductor in the superconducting state, the relative magnetic permeability is set to 0, and the electrical conductivity is set to infinity. However, in COMSOL, the relative magnetic permeability cannot be set to 0. According to superconductivity theory and the paper on superconducting shielding, for simulations, the relative magnetic permeability is typically set between 10^{-2} and 10^{-5}, and the electrical conductivity is generally set to 10^{5}[1,2]. In this model, the relative magnetic permeability of the superconductor is set to 10^{-5}, and in the normal state, the superconductor is typically paramagnetic, so its relative magnetic permeability is set to 1. The superconductor in this model is assumed to be a niobium–titanium (NbTi) alloy. In the normal state, the electrical conductivity of the superconductor has little effect on the electromagnetic properties of paramagnetic materials, so the electrical conductivity is also set to 10^{5}.

The physics interface for the superconductor uses the "Ampere's law in solids" interface from COMSOL's "magnetic fields" module, with the relative magnetic permeability and electrical conductivity set according to the values mentioned above.

For the permanent magnets in the model, the parameters are set according to commonly used permanent magnetic materials in the software. Both the fixed and moving magnets are assigned the material N54 (sintered NdFeB), with the magnetic flux density modulus slightly reduced to 0.2 T. When the moving magnet is replaced with a ferromagnetic material, its relative magnetic permeability is set to 40,000. The surrounding environment is modeled using air.

4. Simulation Process

After the materials, physical fields, and interface parameters are determined, the mesh size and precision are set to ensure that the model calculations converge. Since the model is dynamic, to simplify the process and reduce the computation time, the parametric sweep function in COMSOL is used. The time cycle for the model is set to 13 seconds.

5. Explanation of the Contour Plot

After running the model, the simulation results are shown in Figure 9, which presents electromagnetic distribution contour plots at six key time points.

The results indicate that during the movement process, from 0 to 5 s, the superconductor is in its normal state, behaving as a paramagnetic material, and thus has no effect on the magnetic fields of the two permanent magnets. Between 5 and 6 s, the model is in a transitional state, which can be considered an intermediate state of superconductivity. Since a parametric sweep was used, the intermediate state is not physically accurate (in reality, the phase transition temperature range of Type I superconductors is very narrow, as small as 10^{-3}). Therefore, there is no need to analyze the intermediate state.

From 6 to 13 s, the superconductor is in the superconducting state, the internal magnetic flux is expelled, and the magnetic flux inside the superconductor becomes zero. A counteracting magnetic field forms on the inner and outer surfaces of the superconductor, opposing the external magnetic field, which is consistent with superconducting theory. At this point, the superconductor not only shields the magnetic field of the fixed magnet from its interior but also generates an opposing magnetic field outside, which exerts a positive electromagnetic repulsive force in the x-direction on the moving magnet.

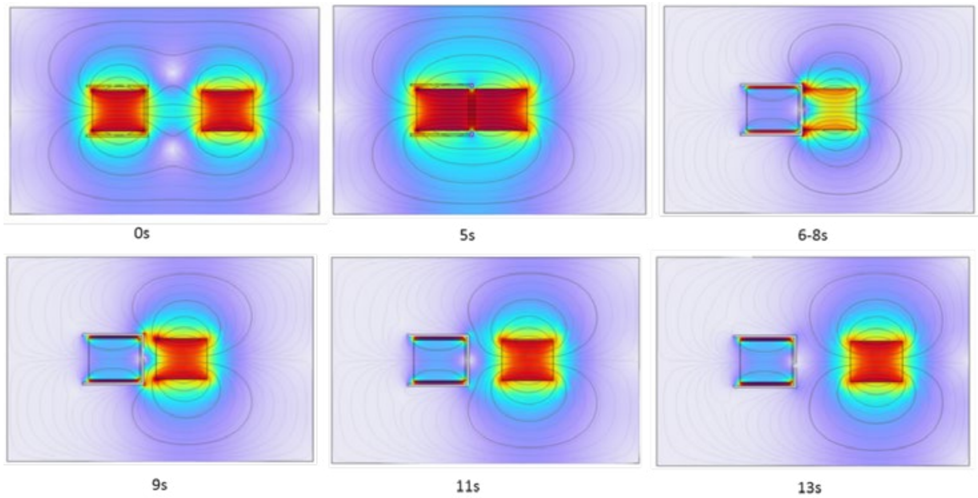

Figure 9: Electromagnetic Field Distribution at Various Time Points in the Model

To facilitate observation, the moving magnet remains stationary during the period from 5--8 seconds. At 8 s, the moving magnet begins to move away from the superconductor, and the opposing magnetic field outside the superconductor starts to weaken. This behavior is fully consistent with the Meissner effect of the superconductor (excluding the pinning effect of Type II superconductors here).

The contour plots of the model during the movement process align perfectly with the theoretical analysis of the model discussed earlier.

6. Data Analysis

After completing the simulation of the full model, the first step is to verify whether the model satisfies the principle of electromagnetic superposition. Using COMSOL, simulations were performed for the combination models described in Part 3, and the results were analyzed through superposition.

From the simulation results of the three combination models, two important electromagnetic parameters are extracted for analysis:
1. The x-direction electromagnetic force is exerted on the moving magnet during the operation of the model.
2. The magnetic flux density modulus at point 1 of the model is shown in Figure 8.

By comparing the variation curves of these two parameters across the three combination models, the applicability of the superposition principle to this model is analyzed. Figures 10 and 11 show the two combinations of the moving magnet and superconductor and the fixed magnet and superconductor, respectively. Figures 12 and 13 display the simulation result contour plots for these two combinations.

After the model is broken down, one more combination involving the fixed magnet and moving magnet remains, which considers only the interaction between the two without involving the superconductor. This will not be discussed at this stage and will be addressed separately later.

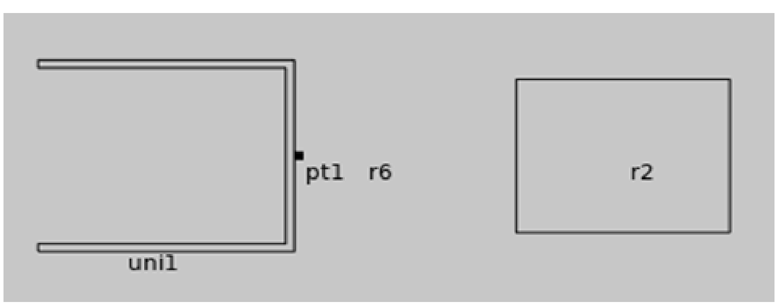

Figure 10: Model Without Fixed Magnet

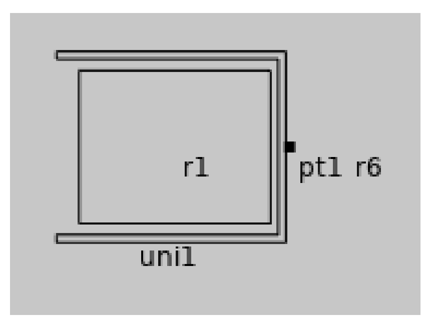

Figure 11: Model Without Moving Magnet

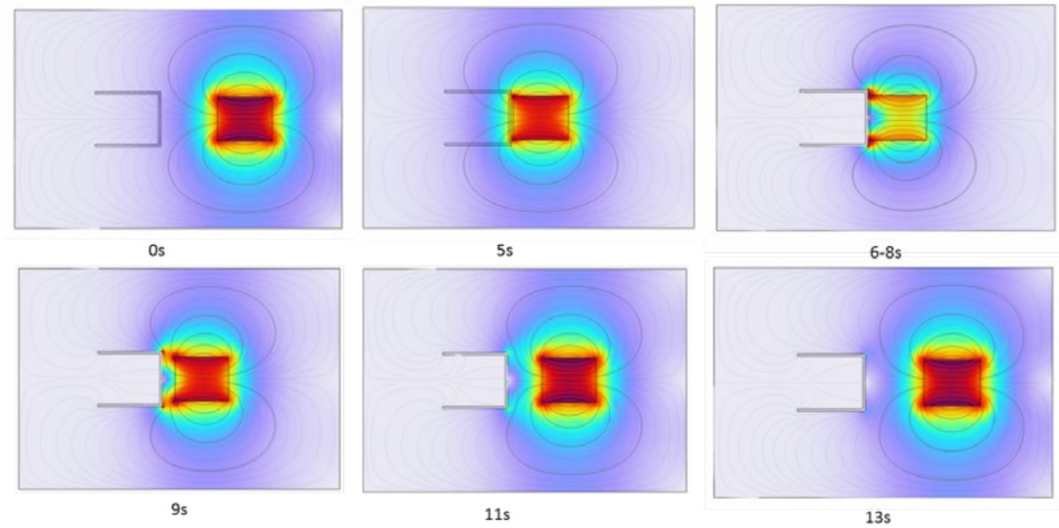

Figure 12: Electromagnetic Field Distribution at Various Time Points in the Model Without a Fixed Magnet

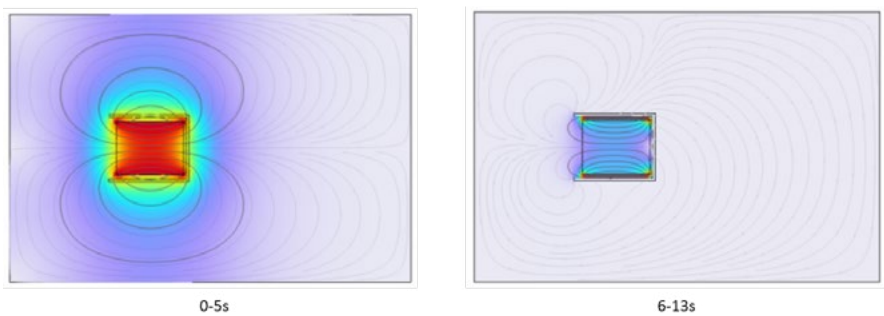

Figure 13: Electromagnetic Field Distribution at Various Time Points in the Model Without Moving Magnets

After the simulation results are computed, the parameter curves are extracted. Figure 14 compares the magnetic flux density modulus curves at Point 1 for the complete model and the model without the permanent magnet.

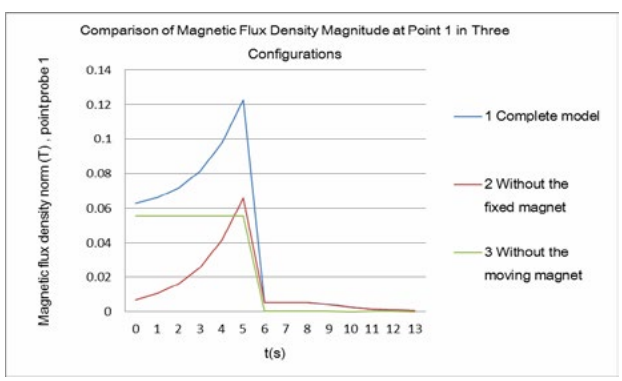

Figure 14: Comparison of Magnetic Flux Density Modulus Curves at Point 1 for the Three Combinations

By comparing the magnetic flux density modulus curves at Point 1, it is evident that when the superconductor is in the superconducting state, it indeed shields and isolates the magnetic flux of the field. Furthermore, the values align with the principle of magnetic field superposition. Notably, between 0 and 5 seconds, the magnetic flux density modulus at Point 1 in the complete model exactly equals the superposition of the cases without the permanent magnet and without the moving magnet.

Next, we further analyze the model's energy change by examining the electromagnetic force experienced by the moving magnet.

Figure 18 shows the electromagnetic force curve for the complete model, Figure 15 shows the curve for the model without the fixed magnet, and Figure 20 compares the electromagnetic force curves for the two models.

The electromagnetic force provides a more intuitive explanation of the superposition principle. After 6 s, when the superconductor shields the fixed magnet, the two curves almost overlap, indicating that the electromagnetic force on the moving magnet is nearly the same in both models. This confirms that the electromagnetic force acting on the moving magnet in the complete model at that point is entirely provided by the superconductor's opposing magnetic field, which aligns with the previous superposition theory analysis.

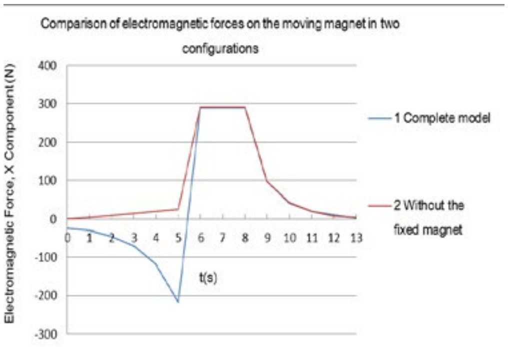

Figure 15: Electromagnetic Force on the Moving Magnet for the Two Combinations

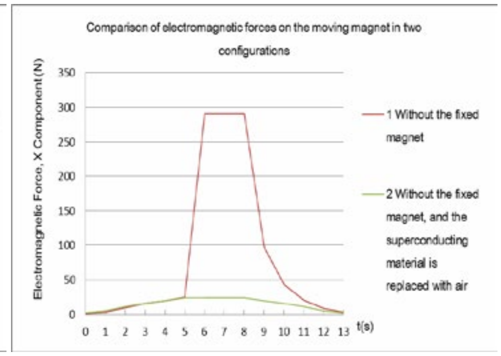

Figure 16: Electromagnetic Force on the Moving Magnet for the Other Two Combinations

Figure 16 shows that in the model without the fixed magnet, the electromagnetic force curve during the 0–5 second interval is small and gradually increases in the positive x-direction electromagnetic force. Initially, it was thought that there might be a parameter discrepancy in the superconductor settings, causing the superconductor in its normal state to exert some electromagnetic force on the moving magnet. To verify the correctness of the superconductor parameter settings, the model was modified by setting the superconductor material to air. After running the simulation and outputting the electromagnetic force curve, it was found to match exactly with the curve where the relative magnetic permeability of the superconductor in the normal state was set to 1. This demonstrates that even if an object is set as air in COMSOL, it still exerts a small electromagnetic force on the magnet. Importantly, this proves that the superconductor parameter settings in the normal state were correct. This finding also suggests that solid paramagnetic materials exert a slight electromagnetic force on permanent magnets.

The electromagnetic force analysis further confirms the correctness of the electromagnetic superposition principle in the model, supporting the accuracy of the earlier theoretical analysis.

By using the electromagnetic force curves, the work done by the electromagnetic force can be calculated through integration over the displacement variable. Since COMSOL does not directly offer the functionality to integrate electromagnetic force along the displacement direction, this paper extracts the electromagnetic force data from the model and uses EXCEL or MATLAB to perform displacement integration for each segment of the curve, obtaining the electromagnetic work for each time interval. As shown in Figures 17 to 20, excluding Figure 17, which shows the electromagnetic work of the superconductor on the moving magnet, Figure 19 displays the remaining work. Figure 20 shows the cumulative numerical results for Figure 19.

When comparing Figure 18 with Figure 17, the values are almost identical, indicating that during the 8–13 second interval, the superconductor completely shields the magnetic field of the fixed magnet, and the electromagnetic work exerted on the moving magnet is entirely provided by the opposing magnetic field of the superconductor. The fixed magnet no longer exerts any negative work on the moving magnet.

The simulation model not only confirms the correctness of the electromagnetic superposition principle but also directly calculates the remaining work generated during the model's operation.

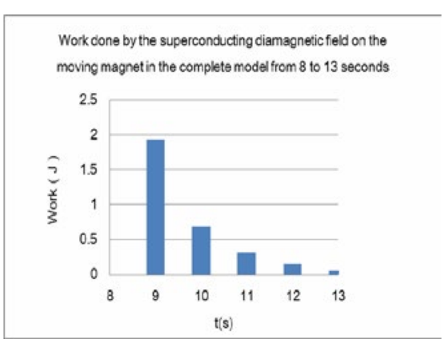

Figure 17: Electromagnetic Work on the Moving Magnet in the Complete Model During 8–13 Seconds

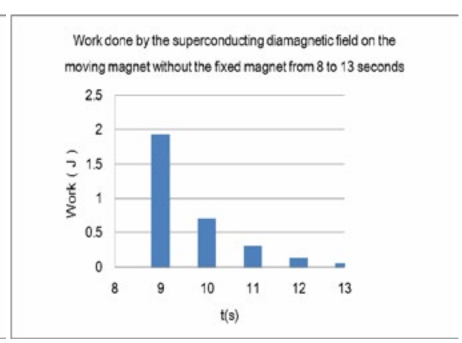

Figure 18: Electromagnetic Work on the Moving Magnet Without the Fixed Magnet During 8–13 Seconds

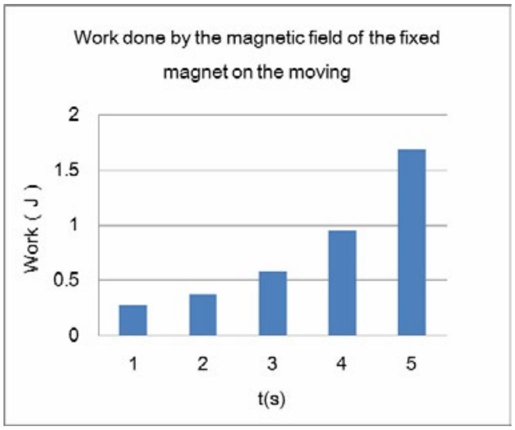

Figure 19: Electromagnetic Work on the Moving Magnet in the Complete Model During 0–5 Seconds

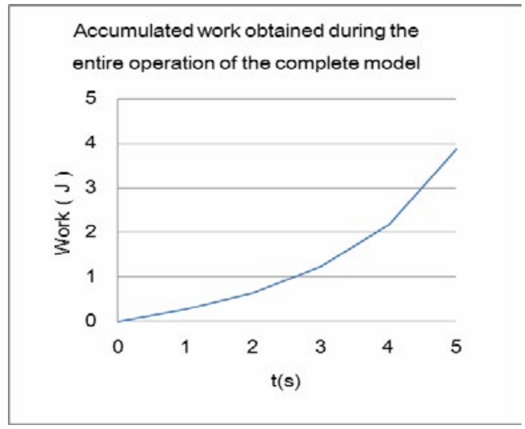

Figure 20: Cumulative Electromagnetic Work on the Moving Magnet in the Complete Model During 0–5 Seconds

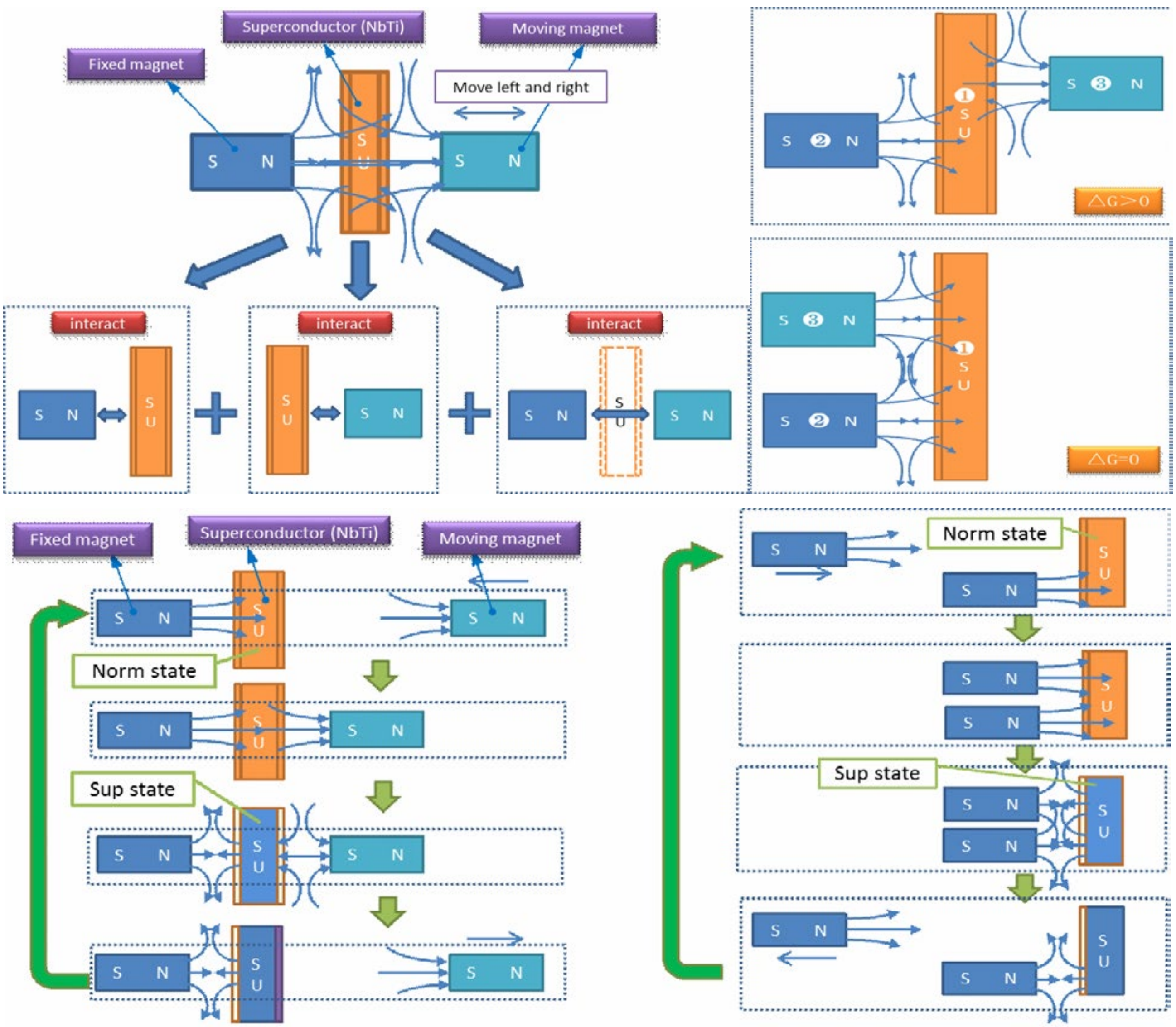

Figure 21: Schematic Diagram of the Group Analysis Process

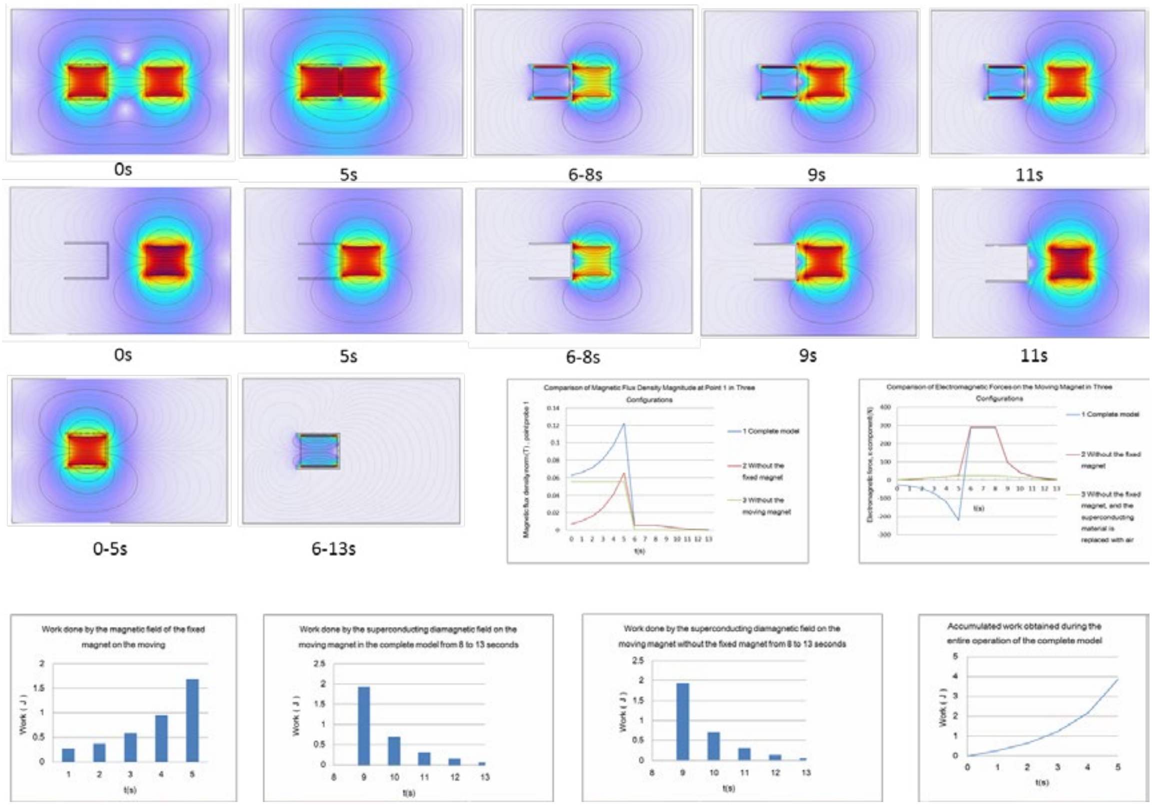

Figure 22: Summary of the Simulation Data

7. Simulation Conclusion

The simulation analysis results show that the electromagnetic interactions between the superconductor and the two permanent magnets conform to the principle of electromagnetic superposition, proving that the derivations and analysis in the second part of this paper are entirely correct. Additionally, the simulation directly calculates the positive work done by the fixed magnet on the moving magnet, indicating that the model produces positive work during operation, leading to an increase in energy. Figure 21 presents an Schematic diagram of the group analysis process, and Figure 22 presents an integration of the simulation contour plots and the calculated data.

8. Experimental Setup

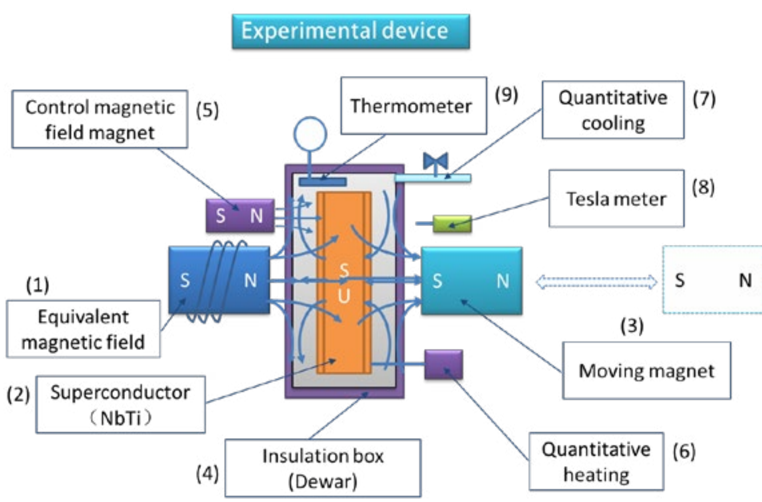

Figure 23: Experimental Setup for Model Verification

The experimental setup for model verification is shown in Figure 23. Currently, the necessary conditions for constructing the experimental setup are not available. Once the conditions for building the setup are met, experimental verification is conducted. Although the model cannot be experimentally tested at the moment, both theoretical derivations and simulation analysis have yielded completely consistent results.

9. Conclusion

This work, which is based on superconducting thermodynamic theory and other superconducting theories, analyzes the thermodynamic energy of the model from different perspectives and uses several different methods. The analysis revealed that the thermodynamic energy of the model system is not conserved. COMSOL simulations were used to verify this conclusion, which not only qualitatively confirmed the correctness of the theoretical analysis but also yielded the same results quantitatively. In the end, the superconducting shielding model presented in this paper does not conserve thermodynamic energy, indicating that there are situations where the first law of thermodynamics may not be applicable.

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