

# INTEGRATING PERMANENT MAGNETS AND ELECTROMAGNETS: A HYBRID DIPOLE MAGNET DESIGN

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## Abstract

In this study, we designed a hybrid dipole magnet that integrates both permanent magnet and electromagnet technologies. The primary magnetic field is generated by the permanent magnets, while the coils enable fine-tuning of the field. The design carefully considers the placement of the permanent magnets and coils to optimize performance. Additionally, an outer plate mechanism is incorporated for coarse magnetic field adjustments, and a NiFe compensator is employed to mitigate the effects of temperature variations on the magnetic field. Given the challenges and risks associated with assembling strong magnets, we also developed a detailed assembly procedure and a set of specialized fixtures to ensure safe and efficient assembly. The integration of permanent and electromagnetic technologies in this hybrid design provides a robust and adaptable solution, paving the way for innovative applications in advanced accelerator technologies.

## INTRODUCTION

The demand for high-performance, compact, and energy-efficient magnetic elements in modern accelerators has driven interest in hybrid magnet designs that combine the advantages of permanent magnets (PMs) and electromagnets (EMs). In traditional accelerator lattice systems, most magnets are electromagnets. They offer excellent controllability and operational flexibility, but also come with drawbacks such as high power consumption, significant heat generation, and large physical size. In recent years, many accelerator facilities [1-3] around the world have started exploring the use of permanent magnets to replace electromagnets. PMs can generate magnetic fields without requiring any power, resulting in lower operational costs. However, pure permanent magnets also have limitations. They provide fixed magnetic strength, are susceptible to demagnetization, and offer limited adjustability.

To address these issues, we developed a hybrid dipole magnet that combines the energy efficiency of PMs with the tunability of electromagnets. This paper presents the engineering development of such a hybrid magnet, focusing on its design rationale, structural integration, temperature compensation strategies, and safe assembly solutions.

## HYBRID DIPOLE MAGNET CONCEPT

The hybrid dipole magnet design integrates permanent magnets (PMs) and a trim coil to create a compact, energy-efficient, and tunable magnetic field system. A typical hybrid dipole magnet (Fig. 1) consists of DT4E poles, yokes, Sm<sub>2</sub>Co<sub>17</sub> permanent magnet blocks, a copper trim coil,

outer tuning plates, NiFe alloy plates, and aluminum structural parts.

In this configuration, the PM blocks provide the main magnetic field, while the trim coil allows for fine adjustment of the field strength within a limited range. This design significantly reduces power consumption compared to traditional electromagnets, while still preserving operational flexibility. To improve adaptability, an outer iron plate mechanism [4] is incorporated for coarse field tuning. This is especially useful during initial installation or maintenance. When multiple hybrid dipole magnets are fabricated, the outer plate can be used to pre-adjust each magnet to a similar magnetic field before installation. Once installed in the accelerator, the trim coil can then be used for final fine-tuning during operation.

Additionally, to address the negative temperature coefficient of permanent magnets, NiFe alloy plates are placed near the magnet poles. These act as passive compensators to stabilize the magnetic field against temperature variations. The magnetic circuit is designed to ensure efficient flux paths while maintaining sufficient thermal and mechanical isolation between components.

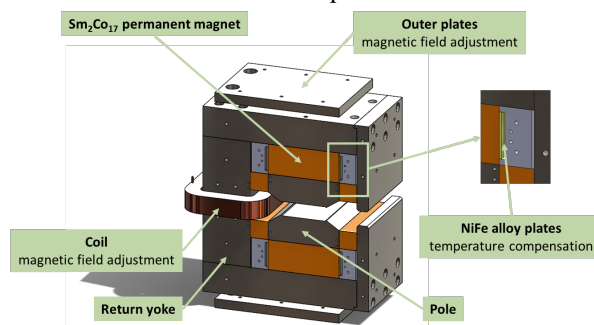


Figure 1: Mechanism design of a hybrid dipole magnet.

## Permanent Magnet Blocks

The Sm<sub>2</sub>Co<sub>17</sub> permanent magnet blocks ( $B_r > 1.08$  T) were manufactured in Taiwan. These blocks (Fig. 2) are not formed as a single piece, but are assembled by gluing smaller magnetized units together. This method allows us

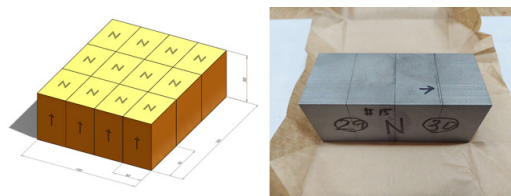


Figure 2: The large magnet is made of smaller magnets glued together.

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to fabricate magnets in flexible sizes and shapes, while maintaining field performance. Dimensional tolerances and flux consistency were kept within acceptable ranges based on simulation results.

### Magnet Assembly

There are two methods for assembling permanent magnets: with magnetic force, or without. In magnetic-force assembly, the PM blocks are first attached to the pole, then the rest of the components are assembled. In non-magnetic assembly [5], the yoke and pole are first aligned and fixed, and the PM blocks are inserted afterward. In this project, we used the first method, with magnetic force. Because the magnetic attraction during assembly can exceed several hundred kilograms, this process presents engineering and safety challenges.

To address this, we developed a systematic and repeatable assembly process using custom-designed fixtures. We also found that applying a reverse magnetic field during the process can help reduce the attractive force and make the assembly smoother. The fixtures include mechanical guides, magnetic shielding, and locking mechanisms to ensure safe, controlled, and staged installation.

## MAGNETIC FIELD MEASUREMENT

The magnet prototype is 150 mm in length. At room temperature (20 °C), the measured central magnetic field is 0.7545 T, and the integrated field is 0.13964 T·m. These measurements (Fig. 3) closely align with the simulation predictions, confirming the accuracy of both the magnetic and mechanical design.

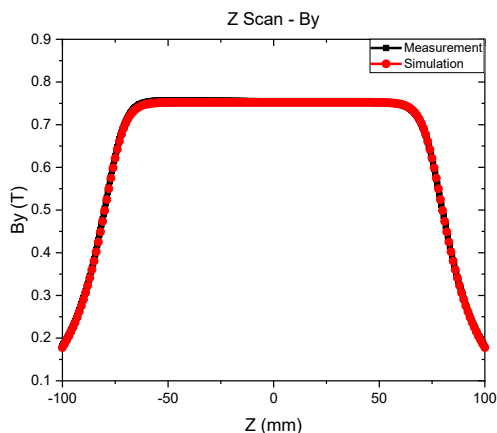


Figure 3: Z scan of magnetic field measurement.

### Trim Coil

The trim coil is made of  $2 \times 3 \text{ mm}^2$  copper wire and contains 42 turns. The main magnetic field of the magnet is directed downward. When the coil generates an upward field, it increases the total magnetic field; when it generates a downward field, it reduces the total field. The integrated magnetic field increases by approximately 0.086% for every 1 A of coil current (Fig. 4). With a coil current range of  $\pm 15 \text{ A}$ , the magnetic field can be adjusted by approximately  $\pm 1.25\%$ .

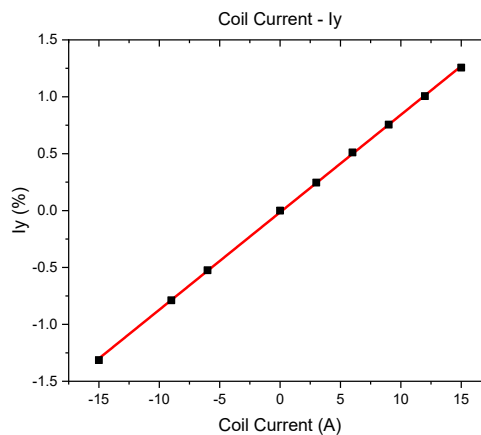


Figure 4: The coil current can be adjusted to meet the magnetic field requirements.

### Outer Plates

The magnetic field strength is affected by the gap between the outer plates and the yoke. This gap is adjusted using aluminum spacers of different thicknesses. A smaller gap results in a stronger magnetic field, while a larger gap reduces it (Fig. 5). When the outer plate gap is reduced from 10 mm (baseline) to 0 mm, the integrated field increases by about 1.85%. Conversely, when the gap increases to 20 mm, the integrated field decreases by around 0.14%. This coarse tuning method is simple yet effective during magnet pre-alignment and calibration.

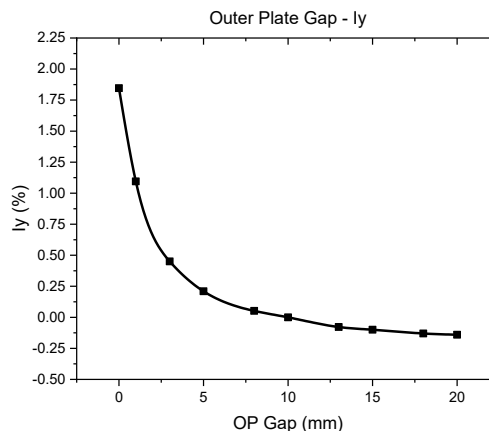


Figure 5: The magnetic field decreases with increasing outer plate gap.

### NiFe Alloy Plates

$\text{Ni}_{30}\text{Fe}_{70}$  alloy plates are used to passively compensate for the temperature dependence of the PMs. These plates are placed near the magnet blocks and tested in a temperature-controlled environment (Fig. 6) that includes heaters, fans, and acrylic covers. At 20 °C, every 2 mm increase in NiFe plate thickness (Fig. 7) reduces the integrated magnetic field by 0.4%. Without NiFe plates, the field drops by 0.043% per degree Celsius. With 4 mm thick NiFe plates, this drop is reduced to 0.027% per degree. These results

confirm that NiFe alloy plates are effective in stabilizing the magnetic field against temperature variations.

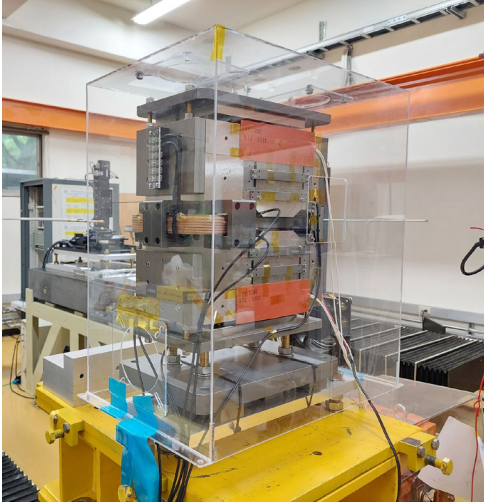


Figure 6: The hybrid dipole magnet in a temperature-controlled environment.

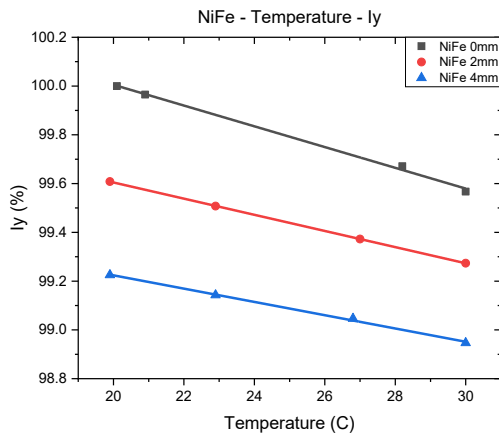


Figure 7: The variation of magnetic field with temperature for various thickness of NiFe.

## CONCLUSION

We presented a hybrid dipole magnet integrating permanent magnets and a trim coil. The system also features outer plates for coarse field adjustment, trim coil for fine field adjustment and NiFe alloy plates for thermal compensation. By assembling magnets from smaller units, we gain flexibility in design. Measurement results are consistent with simulation, validating both mechanical and magnetic performance. Looking ahead, we aim to reduce magnetic force during assembly and optimize the placement of poles and NiFe plates. This development marks a key milestone in localized accelerator magnet technology.

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