# DESIGN OF HIGH-FIELD PERMANENT DIPOLE MAGNET WITH ULTRA LOW LEAKAGE FIELD

Zihan Wang, Zhenghe Bai[*], Guangyao Feng[†]
National Synchrotron Radiation Laboratory, USTC, Hefei, China

## *Abstract*

In the fourth-generation light sources, storage ring lattices are typically compact, potentially leading to serious cross-talk effects. Reducing the leakage field of a magnet offers an effective solution. In this paper, a novel permanent dipole magnet structure is proposed to address the magnetic flux leakage in conventional designs. Compared to traditional steel sheet shielding, this structure demonstrates superior performance in reducing leakage fields. Based on this structure, a protective permanent dipole magnet for the front end of a beamline of the Hefei Advanced Light Facility is developed and simulated using the 3D finite element method. The dipole achieves a peak field of 1.49 T with a leakage field significantly reduced to under 10 Gauss at 30 mm. This work offers a viable method to developing future permanent magnets with low magnetic cross-talk.

## INTRODUCTION

The use of permanent magnets (PMs) is one of the new features of the fourth-generation synchrotron light sources [1, 2]. This PM technology has been extensively studied and adopted in some light source facilities, such as ESRF-EBS [3], Sirius [4] and SLS 2.0 [5]. Compared to conventional electromagnets, PMs offer advantages in saving space in the magnetic system, ensuring stable beam operation, and reducing power consumption. However, PM technology is also subject to several limitations. For example, PMs typically lack tunability in their magnetic fields and can suffer from gradual magnetic field degradation when exposed to radiation environments.

Furthermore, in conventional PM designs, an increase in the center field often results in stronger leakage fields, which can lead to serious cross-talk effects and compromise the stability of a light source. To address this issue, this paper proposes a novel PM-based dipole structure designed to effectively reduce leakage fields. By incorporating auxiliary PM blocks, the proposed design generates a counter magnetic flux that opposes the primary leakage flux, thereby reducing leakage fields to very low values. As an application example, a protective dipole based on the proposed structure is designed for the front end of a beamline of the Hefei Advanced Light Facility (HALF) [6]. Simulation results of the magnetic field demonstrate the effectiveness of this new design.

## PM SHIELDING STRUCTURE

Figure 1(a) shows the cross section of a conventional H-shaped PM-based dipole design, where the blue and green areas denote the soft iron and the PMs, respectively. The symmetry of the yoke geometry can compensate the magnetic forces and cancel even-order harmonics. The required dipole field in the gap is established by the magnetic flux generated from the PM blocks. While the designed primary path for this flux is through the adjacent yokes and poles, a portion inevitably leaks into the air around the dipole. Taking the upper half of the dipole as an example, the magnetization directions of all three PM blocks are oriented toward the center. As a result, the combined leakage flux on the front and rear surfaces of the upper half points outward. Similarly, the combined leakage flux on the front and rear surfaces of the lower half points inward, as illustrated in Fig. 1(b). The leakage fields scale with the central field strength, making their control a critical challenge in designing high-field PM-based dipoles.

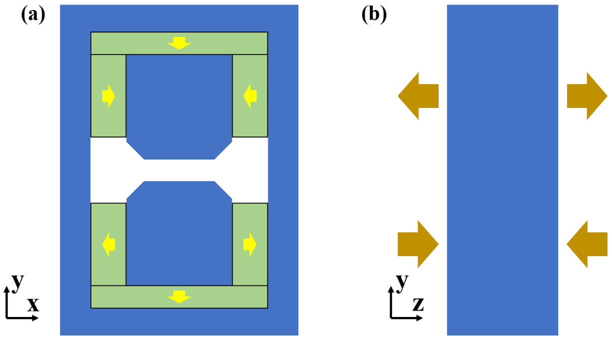

Figure 1: Cross-sectional view of a conventional H-shaped PM-based dipole design (a), and the schematic of its magnetic flux leakage in the longitudinal direction (b). The yellow arrows in the left plot indicate the magnetization directions of the PM blocks.

To address this challenge, this paper proposes a novel magnetic shielding design with auxiliary PM blocks. The design

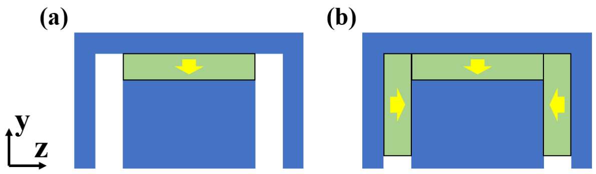

Figure 2: Cross-sectional views in the longitudinal plane for the PM-based dipoles with different magnetic shielding methods: (a) steel sheet shielding and (b) proposed PM shielding. The yellow arrows indicate the magnetization directions of the PM blocks.

---

[*] baizhe@ustc.edu.cn
[†] fenggy@ustc.edu.cn

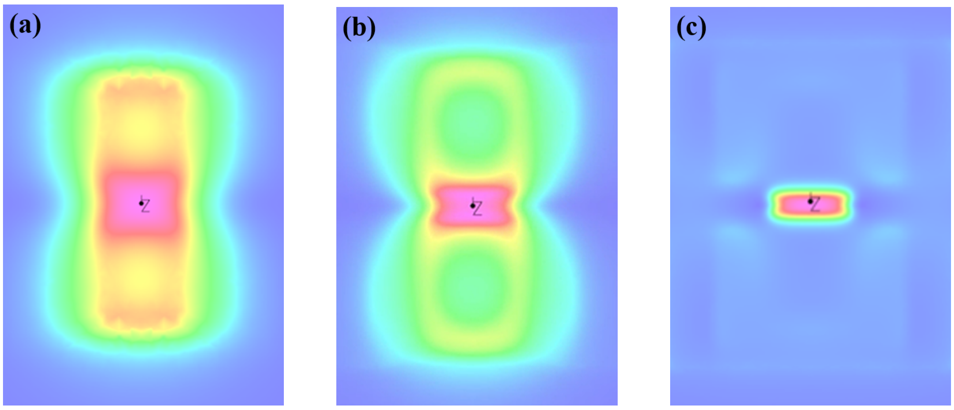

Figure 3: Leakage field distributions near the surface of the PM-based dipole under three cases: (a) without magnetic shielding, (b) with the steel sheet shielding, and (c) with the proposed PM shielding.

relies on the principle of magnetic field superposition. By placing auxiliary PM blocks on regions of the dipole surface where magnetic flux leakage is most significant, counter-fields opposing the combined leakage fields are generated. Through careful design, these counter-fields can effectively cancel out the leakage fields. Consequently, compared to traditional steel sheet shielding, the proposed PM shielding can more precisely and directly suppress leakage fields at the source. The longitudinal cross sections of the PM-based dipoles with steel sheet shielding and PM shielding are shown in Fig. 2. Due to symmetry, only the upper half is illustrated for each structure.

To demonstrate the effectiveness of the proposed PM shielding, the leakage field distributions of the two shielding methods are compared with the case without magnetic shielding, as shown in Fig. 3. While the steel sheet shielding alleviates severe leakage fields in some specific areas, its effectiveness in other regions is rather limited. To achieve further reduction, increasing the thickness of the steel sheets is necessary. This would, however, significantly increase the longitudinal size of the dipole, which is often unacceptable in space-constrained layouts.

In contrast, as shown in Fig. 3(c), the leakage field is significantly reduced when the PM shielding is applied. As a result, the magnetic field becomes well confined to the region close to the magnet center (along the $z$-axis). Moreover, the optimized auxiliary PM blocks are small and placed internally, making the overall dipole without adding substantial size or weight. Therefore, the PM shielding provides superior suppression of leakage fields compared to the steel sheet shielding, while maintaining a compact structural design. In addition, the proposed PM shielding addresses a key drawback of the steel sheet shielding. Using steel sheets alone can lead to a reduction in the center field, because part of the magnetic flux is diverted through the high-permeability steel. However, the addition of auxiliary PM blocks can provide an additional magnetic field at the magnet center, thereby compensating for the integrated field strength loss caused by magnetic shielding. This makes the proposed shielding method a promising alternative for applications where both high center field and low leakage field are critical.

## APPLICATION

In a storage ring, abnormal operation of bending magnets upstream of a straight section can cause the beam to deviate from its design orbit. Such a deviation could cause the beam to enter into the synchrotron radiation beam pipe and potentially damage precision optical components in the beamline station. To mitigate this risk, a protective PM-based dipole will be installed at the front end of a beamline of HALF, which is a diffraction-limited storage ring currently under construction in Hefei, China [6].

Figure 4 shows the model of the protective PM-based dipole with the PM shielding. The magnet design was carried out using the finite element analysis software OPERA 3D [7], with the PM blocks assumed to be made of NdFeB. Although $Sm_2Co_{17}$ offers an excellent temperature coefficient and strong radiation resistance, NdFeB was chosen due to its typically higher remnant magnetic field, which enables a more compact design and saves installation space. Moreover, since the designed dipole incorporates high-permeability soft iron around the PM blocks, the PMs are not directly exposed to radiation. This magnetic shielding structure inherently provides a degree of radiation protection, mitigating concerns over the relatively low radiation resistance of NdFeB.

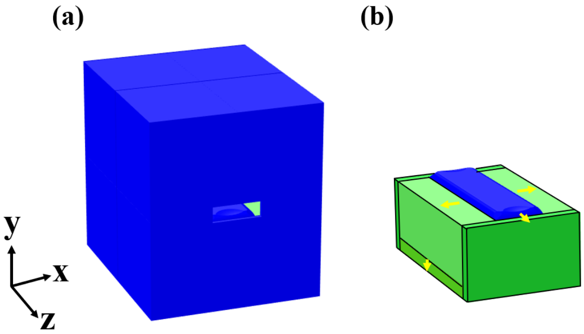

Figure 4: Magnetic model (a) and internal arrangement of PM blocks (b) for the protective PM-based dipole, simulated using OPERA 3D.

The protective PM-based dipole is required to deflect electrons with an energy of 2.2 GeV by an angle of 5°. A comparison of the longitudinal field distributions with and without the PM shielding, designed to meet the requirement, is shown in Fig. 5. It illustrates that PM shielding not only effectively suppresses the fringe field but also significantly enhances the center field. At a longitudinal distance of 30 mm from the dipole, the fringe field is reduced to below 10 Gauss. Figure 6 shows the homogeneity of the integrated field across the horizontal position, indicating a good field region of approximately ±23 mm where the homogeneity is better than 0.1%. The main parameters of the designed dipole are given in Table 1.

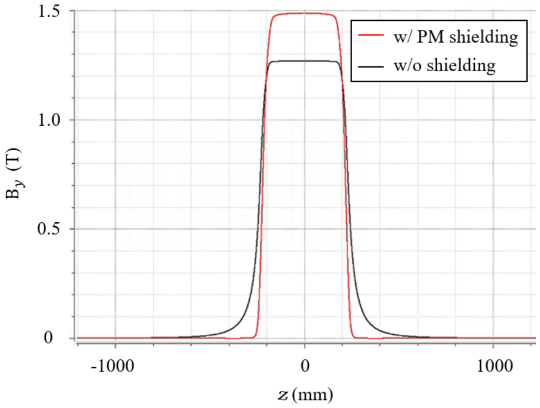

Figure 5: Longitudinal field distributions of the protective PM-based dipoles with the PM shielding (red line) and without magnetic shielding (black line).

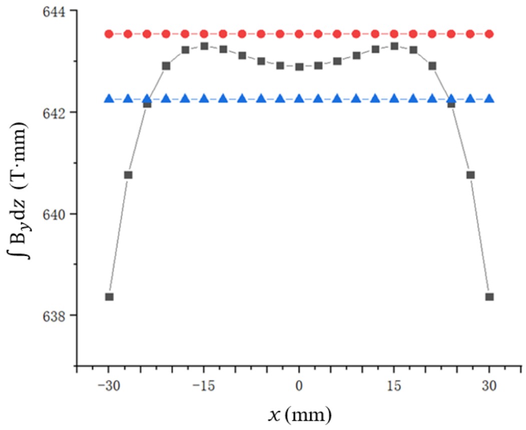

Figure 6: Integrated field distribution as a function of horizontal position for the protective PM-based dipole, shown as the black line. The red and blue lines mark the ±0.1% field homogeneity boundaries.

## CONCLUSION

In this paper, a novel PM-based dipole structure with auxiliary PM blocks was proposed in order to reduce leakage fields. This structure demonstrates superior suppression of leakage fields compared to traditional steel sheet shielding, without significantly extending the longitudinal size of the magnet. Based on the proposed structure, a protective PM-based dipole was designed and modeled, which features a peak field of 1.49 T and maintains a leakage field below 10 Gauss at a longitudinal distance of 30 mm.

Table 1: Main Parameters of the Protective PM-based Dipole

| Parameter | Value | Unit |
|---|---|---|
| Magnet gap | 38 | mm |
| Magnet length | 500 | mm |
| Magnet width | 420 | mm |
| Magnet height | 480 | mm |
| Center field | 1.49 | T |
| Integrated field | 0.64 | T·m |
| Good field region | ±23 | mm |

Furthermore, the proposed shielding method can be generalized. Following the similar design, it is also possible to achieve significant cancellation of the leakage field in PM-based quadrupoles while maintaining a high field gradient. Thus, the proposed shielding method offers a feasible pathway to developing high-field magnets with ultra low leakage field, making it particularly advantageous for fourth-generation synchrotron light sources that generally require highly compact magnet layouts.

## ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China under Grant No. 2024YFA1612200.

## REFERENCES

[1] T. Watanabe, T. Taniuchi, S. Takano, T. Aoki, and K. Fukami, “Permanent magnet based dipole magnets for next generation light sources”, *Phys. Rev. Accel. Beams*, vol. 20, no. 7, p. 072401, 2017. `doi:10.1103/PhysRevAccelBeams.20.072401`

[2] C. Calzolaio *et al.*, “Overview of permanent magnet implementations for advanced light sources”, in *Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, pp. 42–47. `doi:10.18429/JACoW-IPAC2025-MOZN1`

[3] P. Raimondi *et al.*, “Commissioning of the hybrid multibend achromat lattice at the European Synchrotron Radiation Facility”, *Phys. Rev. Accel. Beams*, vol. 24, no. 11, p. 110701, 2021. `doi:10.1103/PhysRevAccelBeams.24.110701`

[4] L. Liu, M. B. Alves, F. H. de Sá, A. C. S. Oliveira, and X. R. Resende, “Sirius commissioning results and operation status”, in *Proc. IPAC’21*, Campinas, SP, Brazil, May 2021, pp. 13–18. `doi:10.18429/JACoW-IPAC2021-MOXA03`

[5] A. Streun *et al.*, “Swiss Light Source upgrade lattice design”, *Phys. Rev. Accel. Beams*, vol. 26, no. 9, p. 091601, 2023. `doi:10.1103/PhysRevAccelBeams.26.091601`

[6] Z. Bai *et al.*, “Progress on the storage ring physics design of Hefei Advanced Light Facility (HALF)”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1075–1078. `doi:10.18429/JACoW-IPAC2023-MOPM038`

[7] Dassault Systèmes, *OPERA-Electromagnetic and Electromechanical Simulation*, `https://www.3ds.com/products/simulia/opera`