DESIGN OF A COMPACT HYBRID PLANAR UNDULATOR*

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Abstract

Undulators are key insertion devices in synchrotron radiation and free-electron laser facilities, where reducing the period length is an effective approach to achieving shorter radiation wavelengths and more compact systems. For short-period operation, the magnetic field of conventional hybrid planar undulators is limited by the efficiency of magnetic flux utilization, while highly closed magnetic structures, although capable of providing higher fields, often suffer from increased structural complexity and limited tunability. In this work, a compact hybrid planar undulator scheme is proposed based on a high-field magnetic structure. By removing part of the side magnets, the proposed design significantly reduces structural complexity while retaining the capability of field tuning via gap variation. Three-dimensional finite element simulations are performed to systematically investigate the influence of key structural parameters on the effective field and field quality. In addition, a combination of NdFeB magnets with different grades is adopted to mitigate demagnetization in critical regions. The results demonstrate that the proposed compact hybrid structure can achieve relatively high magnetic field levels under short-period conditions, while maintaining good engineering feasibility and operational reliability. This design provides a promising approach for next-generation compact high-performance undulators.

INTRODUCTION

Undulators generate high-brightness synchrotron radiation and free-electron laser radiation by inducing small-amplitude oscillations of an electron beam through a periodic magnetic field. For a given electron beam energy, the radiation wavelength is primarily determined by the undulator period length and the deflection parameter. Therefore, reducing the period length is an effective approach to achieving shorter wavelengths and improving the compactness of the facility. In recent years, short-period undulators have attracted significant attention in next-generation synchrotron light sources and free-electron laser facilities.

At present, several technical approaches have been developed for short-period undulators, including in-vacuum undulators, cryogenic permanent magnet undulators, and superconducting undulators. In-vacuum undulators are technologically mature; however, further reduction of the gap is constrained by beam lifetime and radiation damage. Cryogenic permanent magnet undulators can provide enhanced magnetic fields, but at the cost of increased system complexity [1]. Superconducting undulators offer even higher field potential, yet challenges remain in terms of operational stability and engineering implementation [2]. Therefore, within the framework of room-temperature permanent magnet technology, improving the performance of short-period undulators through magnetic structure optimization remains an important and practical approach.

DIFFERENT MAGNETIC STRUCTURE CONFIGURATIONS

To enhance the magnetic field performance of short-period planar undulators, various novel magnetic structures have been developed in recent years. These designs mainly aim to improve the magnetic field by optimizing the magnetic flux distribution, increasing the degree of magnetic circuit closure, or modifying the arrangement of magnets. From the perspective of magnetic circuit topology, these structures can be understood as an evolution from conventional open magnetic circuits toward highly closed configurations. Figure 1 shows schematic diagrams of different magnetic structures.

The conventional hybrid planar undulator, consisting of alternating permanent magnets and ferromagnetic poles, features a simple structure, mature fabrication technology, and good field tunability, and has been widely adopted in synchrotron radiation facilities. However, under short-period conditions, its magnetic field strength is limited by the relatively low efficiency of magnetic flux utilization in the gap region. To address this limitation, additional magnets can be introduced at the sides and above the poles (Type-a), which enhances the magnetic flux concentration near the beam channel. This type of structure can improve the magnetic field while maintaining good engineering feasibility, although the improvement remains moderate due to the partially open magnetic circuit [3].

Further enhancement can be achieved by increasing the degree of magnetic circuit closure. For example, quasi-ring or quasi-circular magnetic structures can be formed around the beam channel (Type-b and Type-c), significantly reducing magnetic flux leakage and improving flux concentration, thereby enabling higher magnetic field strength. However, such configurations are typically associated with fixed apertures and limited field tunability. To overcome this limitation, more complex configurations, such as dual-ring structures (Type-d) or designs with increased numbers of magnetic blocks (Type-e), can be introduced to enable field adjustment through changes in magnetization orientation or structural parameters. Nevertheless, these approaches generally lead to increased structural complexity, a larger number of magnetic components, and greater challenges in fabrication, assembly, and magnetic error control. In addition, their operational flexibility may still be constrained in practical applications.

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In summary, different magnetic structure configurations involve a clear trade-off between magnetic field performance and engineering feasibility. Conventional hybrid structures offer excellent tunability and technological maturity but relatively lower magnetic field strength; side-magnet-enhanced structures provide moderate field improvement while maintaining good practicality; highly closed high-field structures can achieve significantly higher magnetic fields, but at the cost of increased complexity and reduced tunability.

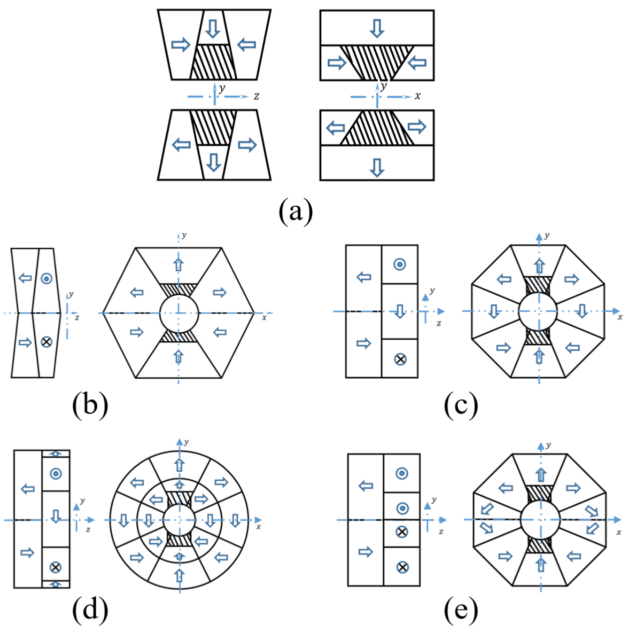

Figure 1: Different magnetic structure configurations, (a) Type-a; (b) Type-b; (c) Type-c; (d) Type-d; (e) Type-e.

MAGNETIC STRUCTURE OPTIMIZATION AND ANALYSIS

In previous studies, the feasibility of the Type-c structure has been experimentally validated using a prototype segment [4]. Compared with conventional hybrid undulators, this structure can achieve a significant enhancement in magnetic field strength, demonstrating its strong potential for high-field applications. However, the large number of magnetic blocks and the structural complexity introduce challenges in fabrication, assembly, and magnetic error control, which limit its practical implementation.

To balance magnetic performance and engineering feasibility, a simplified configuration is proposed in this work based on the previously developed high-field structure. Specifically, part of the side magnets are removed (as shown in Fig. 2), leading to a substantial reduction in structural complexity. Although this modification results in a moderate decrease in magnetic field strength, the structure retains the capability of field tuning via gap variation, thereby achieving a better compromise between performance and practicality.

The magnetic field is evaluated using three-dimensional finite element simulations, in which a complete magnetic circuit model is established, including permanent magnets, poles, and the yoke, with nonlinear material properties taken into account. The results indicate that the magnetic field behavior of the simplified structure is generally consistent with that of the Type-c configuration. As key geometric parameters (e.g., side dimensions) increase, the magnetic field strength initially increases and gradually approaches saturation. The pole height and thickness exhibit a near-parabolic relationship with the effective magnetic field. In addition, the magnetization orientation not only affects the field strength but also has a significant impact on the good-field region.

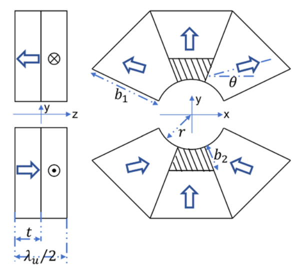

Figure 2: Selected magnetic structure configuration, where arrows indicate the magnetization direction and shaded regions denote the poles.

Under short-period and high-field conditions, local magnets may experience strong demagnetizing fields. In previous work, grain boundary diffusion (GBD) processing was employed to enhance coercivity; however, this approach significantly increases the cost. Further analysis shows that the demagnetization level strongly depends on the magnetization direction. Magnets magnetized along the z direction, especially those located near the gap, are subjected to higher demagnetizing fields, while magnets magnetized along the x and y directions experience relatively lower demagnetization.

Based on this observation, a combined magnet configuration using NdFeB magnets with different grades is adopted. High-coercivity magnets are employed in critical regions with strong demagnetizing fields to ensure stability, while high-remanence magnets are used in regions with lower demagnetization to maintain overall field strength. This strategy enables a simultaneous optimization of magnetic performance and demagnetization safety margin.

Specifically, the pole material is CoVFe, and NdFeB is used for the permanent magnets. Different magnet grades are selected according to the magnetization direction. Magnets magnetized along the z direction use grade 35EH (remanence ~1.2 T, coercivity > 2388 kA/m), those along the x direction use grade 45SH (remanence ~1.35 T, coercivity > 1592 kA/m), and those along the y direction use grade 50H (remanence ~1.4 T, coercivity > 1353 kA/m). The calculated demagnetizing fields on the magnet surfaces are shown in Fig. 3. The values are 2113 kA/m for the z-oriented magnets, 1205 kA/m for the x-oriented magnets, and 1134 kA/m for the y-oriented magnets. All magnets operate within safe demagnetization limits under working conditions. Under a period length of 16 mm and an aperture of 5 mm, the magnetic field reaches approximately 1.21 T.

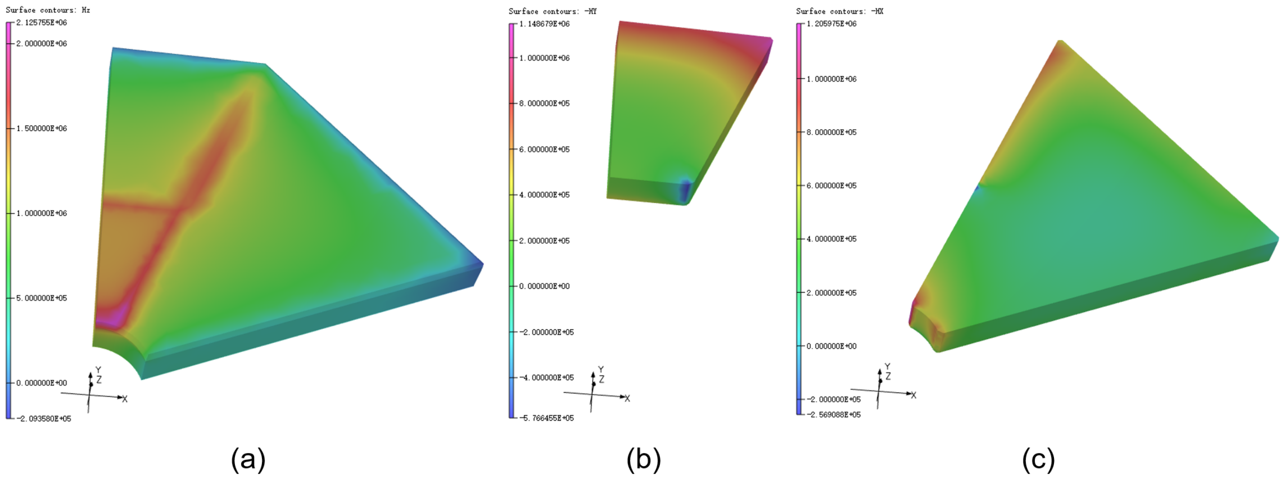

Figure 3: Demagnetizing fields on the magnet surfaces: (a) z-oriented magnets, (b) y-oriented magnets, (c) x-oriented magnets.

A center-symmetric termination structure is adopted, resulting in a zero first field integral, and only the second field integral requires optimization [5]. The termination consists of one end pole and two adjacent end magnets, as shown in Fig. 4. The end magnets (and pole) have the same height and width as the regular units, with only the thickness being adjusted. A Radia model and the corresponding on-axis magnetic field distribution are shown in Fig. 5.

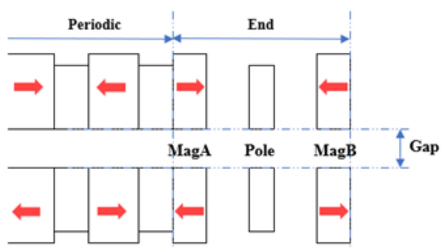

Figure 4: Schematic of the termination structure.

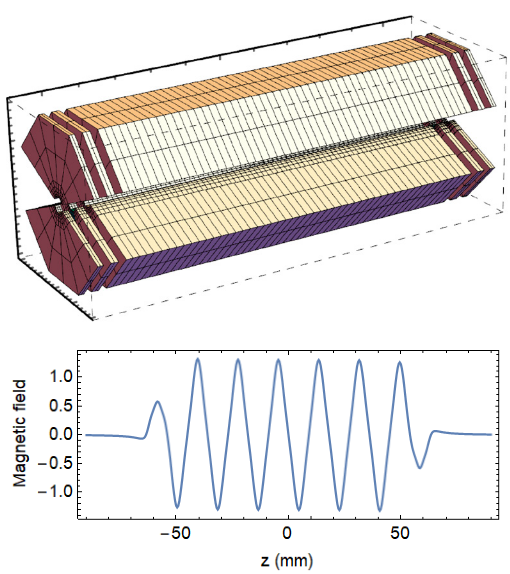

Figure 5: Radia model and on-axis magnetic field distribution.

CONCLUSIONS

A compact hybrid planar undulator structure has been proposed and optimized for short-period applications. Based on a high-field closed magnetic circuit configuration, a simplified scheme is developed by removing part of the side magnets, which significantly reduces structural complexity while preserving the capability of field tuning via gap variation. This design achieves a better balance between magnetic performance and engineering feasibility.

Three-dimensional finite element simulations have been carried out to investigate the magnetic characteristics and parameter dependencies of the proposed structure. The results show that the structure can achieve a magnetic field of approximately 1.2 T at a period length of 16 mm and an aperture of 5 mm, demonstrating its capability for high-field operation under short-period conditions.

To address demagnetization effects, a graded magnet configuration using NdFeB magnets with different coercivities and remanence values is adopted according to the magnetization direction. This approach effectively reduces the demagnetization risk in critical regions while maintaining overall magnetic field strength. The calculated demagnetization levels remain within safe limits under operating conditions.

In addition, a center-symmetric termination structure is employed to ensure a zero first field integral, allowing efficient optimization of the second field integral. The termination design further improves the field quality and facilitates practical implementation.

Overall, the proposed compact hybrid structure provides a feasible solution for achieving high magnetic fields with manageable complexity, and offers a promising approach for next-generation compact undulators.

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