

A FORCE-NEUTRAL ADJUSTABLE PHASE UNDULATOR FOR A COMPACT X-RAY FEL*

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Abstract

The magnetic and mechanical designs of a force-neutral adjustable phase undulator (FNAPU) are presented. The FNAPU combines two magnetic assemblies with equal periods, one with an undulator magnetic structure and one with a force compensation magnet structure. The latter is used to neutralize the magnetic force affecting the undulator magnetic structure and vice versa in all undulator phases. Assembling in proximity a group of different FNAPUs is discussed.

INTRODUCTION

The adjustable phase undulator (APU) is a fixed-gap undulator in which one row of the magnets of the undulator magnetic structure can be longitudinally shifted with respect to the second row to adjust the undulator magnetic field [1]. It is more compact than a conventional adjustable-gap undulator (AGU), requires less air space between the vacuum chamber and the magnetic structure, and can be assembled with vertical or horizontal orientation of the magnetic structures to produce a light with horizontal or vertical polarization. Many APU designs have been explored since its inception [2-4]. However, the APU's practical use so far has been limited to short devices because of the insurmountable difficulty of dealing with the magnetic force growing with the undulator length.

We propose a solution for this problem. It consists of adding to the primary APU a magnet structure to neutralize the magnetic forces of the APU. The strength of the magnetic force is proportional to the square of the magnetic field. The magnetic field depends on the gap between the two rows of the magnet structure exponentially. The smaller the gap, the higher the magnetic field. Since the APU is a fixed-gap undulator, using two additional rows of weaker magnets at a smaller gap, as shown in Fig. 1, will fully neutralize the magnetic forces when both structures have the same period length and are arranged to have the offset in z by a half period.

The lower rows of the force compensation magnet structure and the undulator magnetic structure are fixed to the supporting frames. The upper magnet rows of both structures are mechanically coupled.

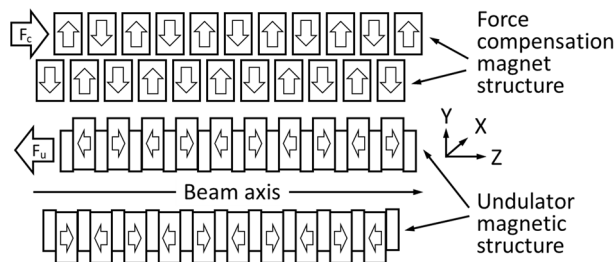


Figure 1: A schematic of the FNAPU. The force compensation magnet structure is at the top and the primary undulator magnetic structure is at the bottom. Arrows show the direction of the easy axis in the magnets. F_c and F_u are the longitudinal magnetic forces of the two structures shown here for the FNAPU with the phase selected to be $\pi/2$. The x , y , and z arrows on the right define the coordinate system.

In the following sections we discuss the magnetic and mechanical designs of the FNAPU. As a concrete design goal, we use undulator parameters with the undulator length of 2 m adapted for a compact x-ray free-electron laser (XFEL) facility under consideration in Argonne National Laboratory [5]. We show that similar approaches to the undulator design can be used for much longer FNAPUs.

MAGNETIC DESIGN

With a beam aperture of 2 mm in a collinear wakefield accelerator considered in [5], we can accommodate the FNAPU with a fixed gap of 2.7 mm by using a vacuum chamber with an inside diameter of 2.0 mm and an outside diameter of 2.4 mm, and by using only a 0.3-mm air-gap tolerance between the undulator gap and the vacuum chamber outside diameter. This is a 26% smaller gap comparing to an AGU, which requires at least a 1.0-mm airgap. To reach a maximum undulator parameter $K > 1.1$, undulator design parameters have been optimized as shown in Table 1.

Figure 2 shows the Opera model with the vertical-gap configuration. On the left side is the quarter-period model and on the right side is the de-magnetization on the magnet surface. The worst de-magnetization on the magnet is 14,700 Oe.

* Work supported by U.S. Department of Energy, Office of Sciences, under Contract No. DEAC02-06CH11357.

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Table 1: The FNAPU design parameters (Note that x is horizontal and y is vertical on the component dimensions when the undulator is in its vertical-gap configuration.)

Parameters	Value
Gap (mm)	2.7
Period length (mm)	10.6
Undulator length (m)	2.0
Pole material	Vanadium Permendur
Magnet material	NdFeB-N42SH
Pole x*y*z (mm)	22.00*20.00*2.28
Magnet x*y*z (mm)	32.00*25.00*2.97
Pole tip chamfer x*y (mm)	4.00*10.00
Pole chamfer on the slop edge in x*y plane (mm)	0.25*0.25
Magnet chamfer x*y (mm)	2.00*2.00
Magnet chamfer z*y (mm)	0.80*0.80
Magnet y recess (mm)	0.10
Effective peak field (T)	1.144
K	1.132

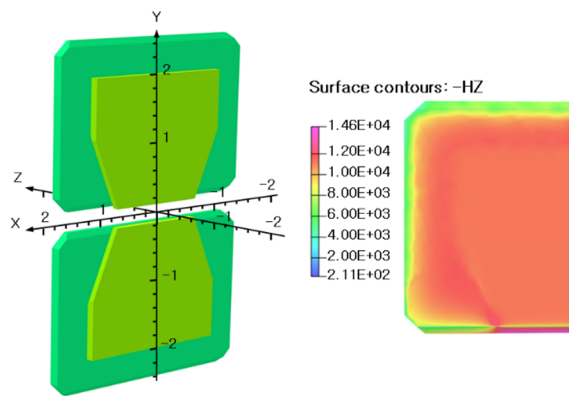


Figure 2: The quarter-period Opera model of the 10.6-mm-period miniature FNAPU. On the right is the de-magnetization (in units of Oersted) on the magnet surface. Other dimensions are listed in Table 1.

The main field and longitudinal field profiles at different phase are shown in Fig. 3.

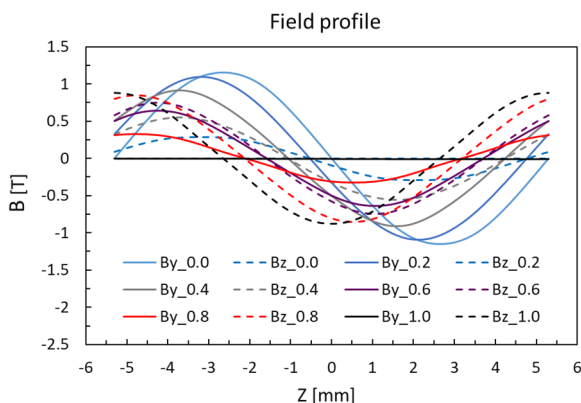


Figure 3: The transverse magnetic field, B_y (solid lines), and the longitudinal magnetic field, B_z (dotted lines), are plotted along one period of an FNAPU, with six phases depicted at intervals of 0.2 Pi.

The force compensation magnets used in the system are grade N42 NdFeB magnets with dimensions of 20 mm \times 5 mm \times 5 mm in x, y, z. These magnets are readily available at a low cost. The system's forces are illustrated in Fig. 4 at a gap of 1.3 mm in a force compensation magnet structure.

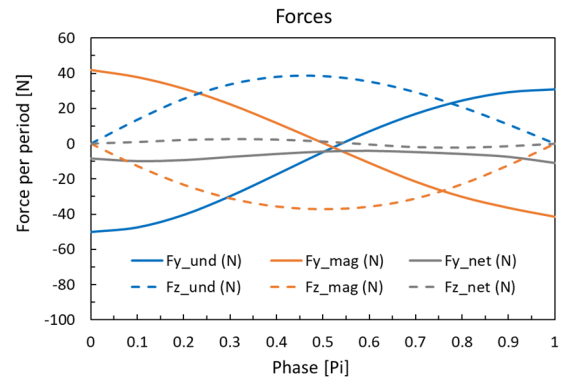


Figure 4: The longitudinal force, F_z (dotted lines), and the transverse forces F_y (solid lines) vs. phase along half period of FNAPU.

The forces in the undulator magnetic structure are represented by the blue-colored curves, while the orange-colored curves indicate the forces in the force compensation magnet structure. The grey-colored curves represent the system's net forces. The longitudinal forces are neutralized, while the transverse forces remain relatively constant. The constant net force results from the discrepancy between the undulator hybrid magnetic structure and the force compensation pure permanent magnet structure.

The magnetic field generated by the force compensation magnet structure at the beam center can cause interference with charged particles. However, a model indicates that the magnetic field appears only at both ends of the structure and is independent from the phase shift. At each end of the structure, the field integral is about 19 G-cm. This problem can be corrected by replacing the end force compensation magnets with half-volume magnets. The field integrals reduced to zero.

MECHANICAL DESIGN

A 2-m-long FNAPU with a 10.6-mm period and a 2.7-mm fixed gap has been designed as shown in Fig. 5. The lower row of the force compensation magnet structure is attached to the frame's top plate with the links as shown in Fig. 5, while the upper row is coupled to the upper row of the undulator magnetic structure. By achieving force neutralization, industry-standard components that are precise, reliable, compact, and cost-effective can be utilized. Consequently, the undulator's cross-sectional area is limited to just 135 mm \times 135 mm.

The frame structure has a modular design comprised of two vertical and two horizontal plates. Each plate is divided into sections longitudinally, specifically two horizontal and three vertical sections in this design. Additionally, the undulator magnetic and force compensation

magnet structures also are sectional. During assembly, these structures are arranged in-phase and separated with nonmagnetic spacers. The force compensation magnet structure is clamped a half period out of phase (aligned longitudinally), and the lower row links are subsequently fastened to the top plate of the frame to complete the assembly process.

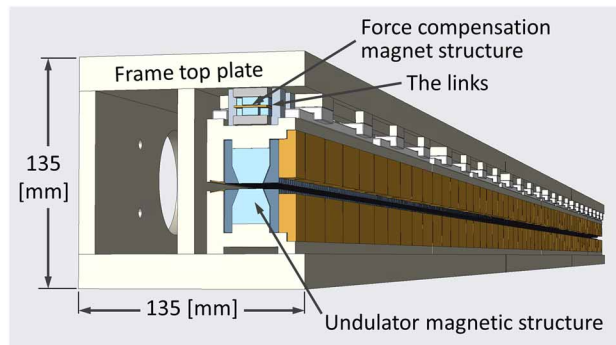


Figure 5: An FEL FNAPU that is 2 meters long, has a 10.6-mm period, and a fixed 2.7-mm gap. The FNAPU can be rotated by 90 degrees to function as a horizontal gap vertical polarizing undulator (HGVPU) [6].

The tuning of the undulator is based on the effective tuning technologies that have been developed at the Advanced Photon Source over the past three years [7]. The trajectory tuning is corrected using magnetic shims, and phase errors are corrected by reshaping the gap profile with mechanical shimming. These technologies have been successfully applied to more than 30 permanent magnet undulators and superconducting undulators.

The undulator design presented above allows multiple FNAPUs to be stacked together as shown in Fig. 6, in which case multiple FEL undulator lines can be accommodated in one tunnel as considered in [5]. FNAPUs with different period lengths could be used.

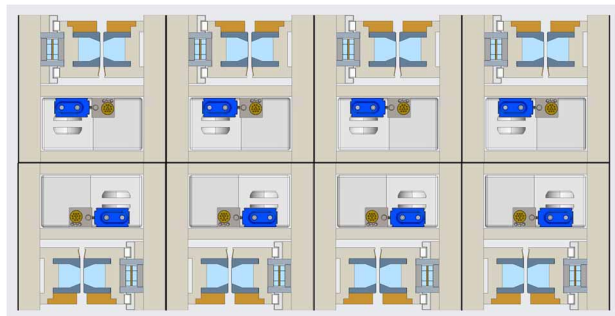


Figure 6: An illustration showing eight FNAPUs with the horizontal gaps being arranged in the closest proximity using $540 \text{ mm} \times 270 \text{ mm}$.

SUMMARY

The design of a 2-m-long compact-size and lightweight FNAPU with a 10.6-mm period, a 2.7-mm fixed gap, and a maximum undulator parameter $K=1.13$ has been presented. By utilizing a readily available force compensation magnet structure to neutralize the dynamic forces, the FNAPU length can be scaled up as needed. This mod-

ular design can be oriented vertically or horizontally to produce radiation with horizontal or vertical polarizations. It is safer to operate due to the limited range and freedom of motion, which eliminates pinch hazards. Multiple FNAPUs can be packed together to form a matrix undulator array, covering a larger X-ray energy range. This cost-effective design is simple to fabricate and easy to operate and maintain, making it beneficial for all existing and future synchrotron and FEL facilities. Another FNAPU with a 2.4-m length, a 27-mm period, and an 8.5-mm fixed gap is currently in the process of fabrication at the Advanced Photon Source.

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