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FORCE-NEUTRAL ADJUSTABLE PHASE UNDULATOR*

J. Z. Xu†, M. Qian, Y. Piao
Advanced Photon Source, Argonne National Laboratory, Lemont, IL, USA

Abstract

We report the design, construction, and testing of a Force-Neutral Adjustable Phase Undulator (FNAPU) at the Advanced Photon Source. The FNAPU is a 2.4-meter-long planar hybrid permanent magnet undulator with a 27-mm period length and a fixed 8.2-mm gap. It consists of two magnetic assemblies with matching periods: one featuring an undulator magnetic structure and the other a simpler structure that compensates for the forces of the undulator. The performance parameters of the undulator are presented.

INTRODUCTION

Since the introduction of the adjustable phase undulator (APU) concept [1], numerous APUs have been designed, constructed, and commissioned [2-4]. The APUs offer several advantages over adjustable gap undulators (AGUs), including compactness in size and the flexibility of rotating orientations to produce vertically polarized radiation. Additionally, with their fixed gap, APUs can be stacked together to form undulator arrays. Unlike AGUs, APUs maintain a constant field roll-off throughout their operating range, the same as that of an AGU at the minimum gap setting. This allows for a narrower pole and magnet design, further contributing to the APU's compactness.

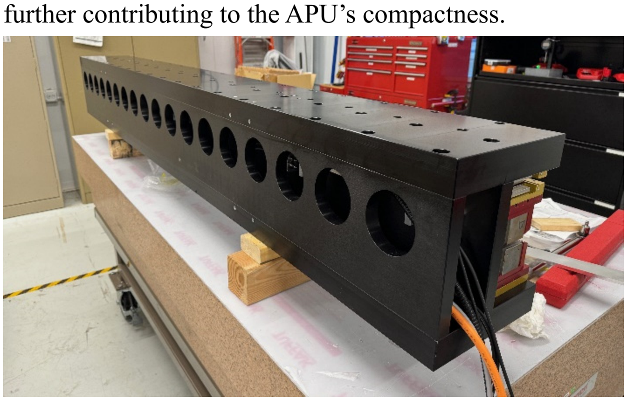

Figure 1: An APS 2.4-meter-long FNAPU with a 27-mm period length.

The majority of APUs constructed so far are pure permanent magnet devices. We present a design for a hybrid permanent magnet force-neutral adjustable phase undulator (FNAPU) based on the concept proposed in reference [5] as shown in Fig. 1. This design utilizes an existing 2.4-meter-long planar hybrid permanent magnet undulator (HPMU) magnetic structure from the Advanced Photon Source (APS) with a 27-mm period length. The FNAPU incorporates an adjustable phase undulator mechanism with an additional set of magnets to neutralize the magnetic forces.

In the following sections, we discuss the magnetic force simulation, the mechanical design of the FNAPU, and the measurement results of the device.

MAGNETIC FORCE OPTIMIZATION

The FNAPU utilizes a legacy 2.4-meter-long planar HPMU with a 27-mm period length from the APS. The gap of the undulator was set to 8.2 mm to fit onto the APS vacuum chamber. The force compensation magnets used in the system are generic grade N42 NdFeB magnets with dimensions of 50.8 mm × 6.35 mm × 12.7 mm (x, y, and z, respectively). To correct interference with the charged particle beam from the magnetic field generated by the force compensation magnets at the beam center, the volume of the end magnets is half that of the body magnets. Therefore, the dimensions of 25.4 mm × 6.35 mm × 12.7 mm (x, y, and z) were chosen for the end magnets. Each magnet has two countersunk holes for mounting. These magnets are readily available at a very low cost.

A 10-period 3D Opera model was built to simulate and optimize the system's forces. The design parameters of the FNAPU are listed in Table 1.

Table 1: The FNAPU Parameters*

Undulator gap (mm)	8.2
Period length (mm)	27
Undulator length (m)	2.4
Pole material	Vanadium Permendur
Magnet material	NdFeB-N42SH
Pole x*y*z (mm)	44.00*42.25*4.20
Magnet x*y*z (mm)	67.00*51.41*9.15
Pole tip chamfer x*y (mm)	2.00*2.00
Pole chamfer on the slope edge in x*y plane (mm)	0.89*0.81
Magnet chamfer x*y (mm)	5.72*5.72
Magnet chamfer z*y (mm)	1.75*0.76
Magnet y recess (mm)	0.5
Effective peak field (T)	0.913
K	2.30
Force comp. mag. gap (mm)	3.2
Force comp. mag. material	NdFeB-N42
Force comp. mag. x*y*z (mm)	50.80*6.35*12.70

* x is horizontal and y is vertical on the component dimensions when the undulator is in its vertical-gap configuration.)

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† x@anl.gov

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Figure 2 shows the forces acting on the system with a gap of 8.2 mm for the undulator magnetic structure and 3.2 mm for the force compensation magnet structure. The longitudinal forces (Fz) are shown in solid curves, and the transverse forces (Fy) are shown in dashed curves. The blue curves represent forces in the undulator magnetic structure, and the red curves represent forces in the force compensation magnet structure. The black curves represent the system's net forces.

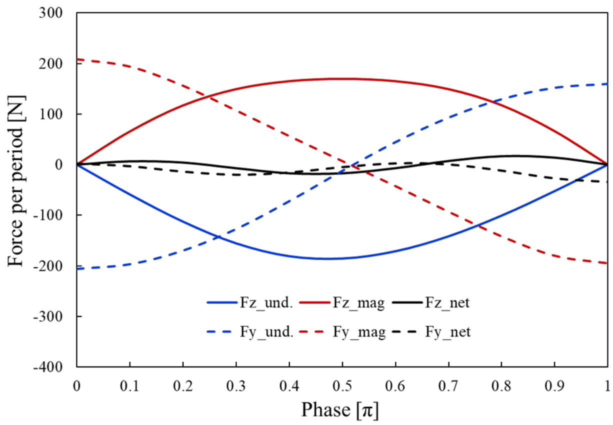

Figure 2: The longitudinal forces F_z (solid lines), and the transverse forces F_y (dashed lines) vs. phase along a half period of the FNAPU.

The residual net forces arise from the discrepancies between the undulator's hybrid magnet pole profile and the simpler magnet surface geometry of the force compensation magnets. This difference stems from the use of a hybrid magnet structure in the undulator compared to the purely permanent magnet structure of the force compensation magnets.

MECHANICAL DESIGN

The 2.4-meter-long FNAPU with a 27-mm period length is shown in Fig. 3. It consists of two parallel magnetic structures with the same period length: an undulator magnetic structure and a force compensation magnet structure. The motor, actuator, encoder, and limit switches are integrated within the frame for a compact design.

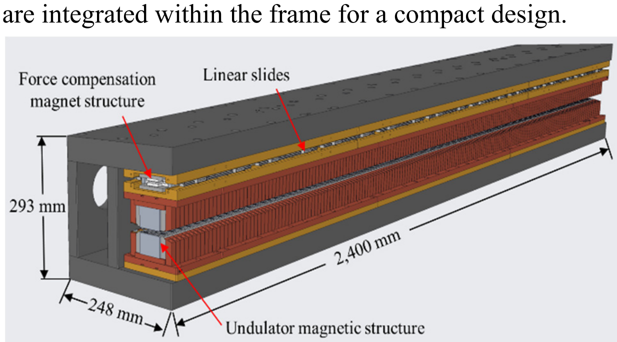

Figure 3: The 2.4-meter-long FNAPU with 27-mm period length and 8.2-mm fixed gap.

The undulator magnetic structure is a legacy 2.4-meter-long, 27-mm period length APS planar HPMU designated APS27#3, as shown in Fig. 4. Each magnetic array consists of five longitudinal sections. To prevent undulator pole movement during operation under strong dynamic magnetic forces, epoxy glue was used to partially fill the air gaps between the poles and magnets.

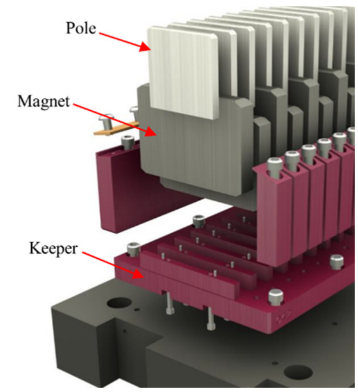

Figure 4: Legacy 2.4-meter-long, 27 mm period length APS planar HPMU magnetic structure design.

APS27#3, designed in 2000, has been in operation in the APS storage ring for over 18 years. We chose this legacy undulator to identify areas for improvement in the magnetic structure design for future FNAPUs.

Precise alignment and spacing adjustments between sections of the undulator magnetic structure proved challenging. Despite significant efforts, the results haven't been fully satisfactory. A new design is necessary to address these alignment and spacing issues.

MEASUREMENT RESULTS

Tuning and measurements were performed on the 6-meter bench of the magnetic measurement laboratory at the APS. Trajectory errors were corrected using magnetic shims, while phase errors were addressed by reshaping the gap profile with mechanical shims [6].

B_{eff} and K

The measured effective magnetic field, B_{eff}, and the deflection parameter, K, are shown in Fig. 5, exhibiting good agreement with the model.

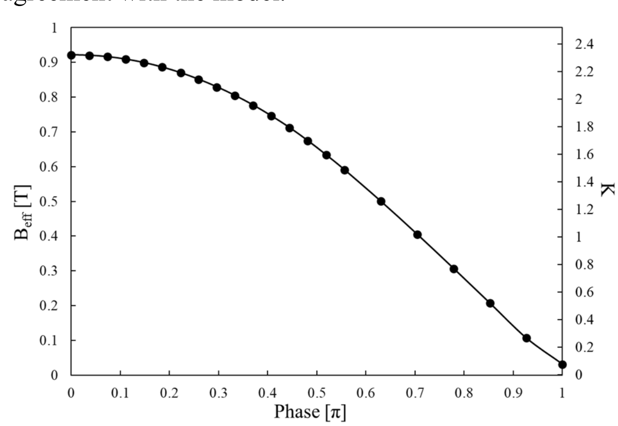

Figure 5: Measured effective transverse field (B_{eff}) and deflection parameter (K) vs. phase.

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Hysteresis

Figure 6 shows the hysteresis effects of the undulator. All measurements begin at the π phase. The first measurement sweeps the phase from π to zero and then back to π. The difference between the forward and backward sweeps (“π → 0” – “0 → π”) is plotted in black. The second measurement sweeps the phase from π to 0.1 π and back, with the difference plotted in red. This process is repeated for the third and fourth measurements ending at different phases. The underlying measurements themselves are reproducible within a tolerance of better than one Gauss.

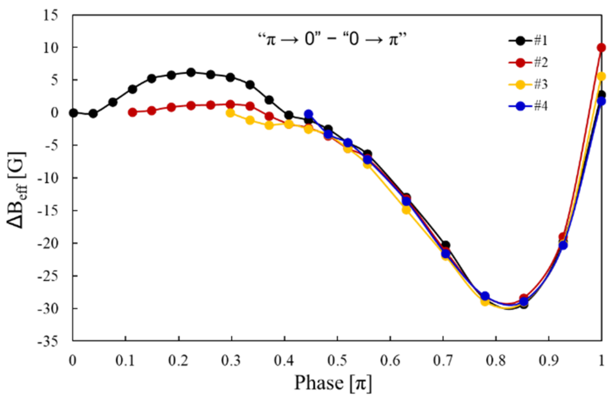

Figure 6: Hysteresis effects.

Despite its insignificance for synchrotron applications, a clear hysteresis effect is observed. This is primarily caused by the movement of the poles due to dynamic magnetic forces in the longitudinal direction during phase changes. This effect can be mitigated by improving the longitudinal reference for the pole surface position within the structure.

RMS Phase Error

Figure 7 shows the RMS phase error of the device as a function of phase. The curve peaks around a phase of 0.6 π. This is primarily caused by two factors: errors in the initial pole positions and the movement of the poles under dynamic magnetic forces in the longitudinal direction during phase changes. These errors can be mitigated by tightening the tolerances for the pole positions and improving the method for securing the poles.

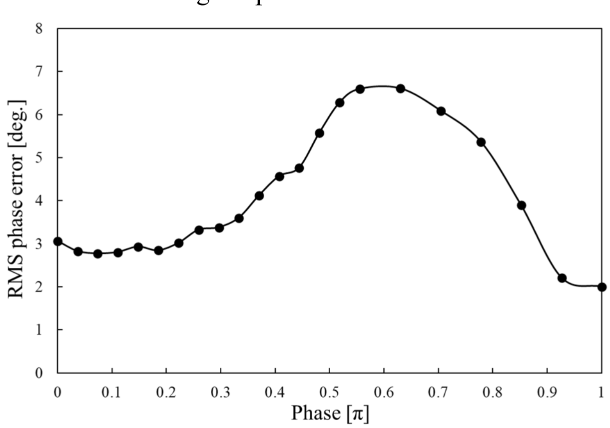

Figure 7: RMS phase errors vs. phase.

Entrance and Exit Angles

Figure 8 shows the entrance and exit angles of the particle beam relative to the radiation beam axis, plotted as a function of phase for a particle beam energy of 6 GeV. The entrance and exit angles remain within ±2.3 μrad and ±2.0 μrad, respectively. These values meet the ±3.9 μrad requirement for APS insertion devices (IDs).

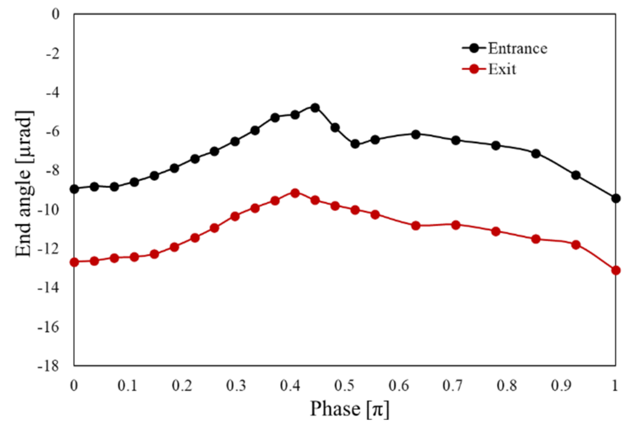

Figure 8: Entrance and exit angles vs. phase.

SUMMARY

We report the design, construction, tuning, and testing of a 2.4-meter-long FNAPU with a 27-mm period length and a fixed 8.2-mm gap at the APS. This design utilizes a cost-effective force compensation magnet structure to neutralize magnetic forces. Performance measurements demonstrate that the FNAPU meets the requirements for APS insertion devices (IDs).

Construction of a second 2.4-meter-long FNAPU with a 17.2-mm period and 8.2-mm fixed gap is underway at the APS. Upon completion, a two-unit FNAPU array will be assembled and tested.

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