DESIGN OF AN X-UNDULATOR*

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Abstract

The Advanced Photon Source Upgrade (APS-U) will deliver a new storage ring based on a multi-bend achromat (MBA) lattice featuring swap-out on-axis injection, enabling the use of small-diameter insertion device vacuum chambers. To leverage this advantage, we designed an X-undulator similar to the APPLE-X undulator but with a fixed gap and additional, simpler magnet arrays for force compensation. The X-undulator is a pure permanent-magnet-based variable polarization undulator with a 30-mm period length and an 8.5-mm diameter bore in the beam center. Variation of the radiation wavelength and polarization is achieved using the longitudinal motion of the undulator magnetic arrays. This paper covers the magnetic and mechanical design, as well as the optimization of this X-undulator.

INTRODUCTION

Pure permanent-magnet (PM)-based elliptically polarized undulators (EPUs) are used to deliver photons for polarization-dependent spectroscopy, scattering, and imaging experiments at synchrotron radiation (SR) light sources. Most EPUs built for third-generation storage-ring-based SR sources have magnetic structures designed without axial symmetry because the vacuum chamber has a horizontal dimension much larger than the vertical dimension, a necessary condition for off-axis injection. Due to the round vacuum chamber in free-electron laser sources, different types of EPUs with axial symmetry were developed, such as the delta undulator for LCLS-II [1] and the Apple-X undulator for SwissFEL and European XFEL [2, 3]. The highly symmetrical configuration allows for more magnetic material to be placed adjacent to the round beam chamber, and a stronger on-axis magnetic field could be achieved. The transition to on-axis electron injection for the Advanced Photon Source Upgrade (APS-U) storage ring enables the use of small-diameter round vacuum chambers, and hence a similar EPU could be implemented. In this paper, we present an EPU design of this kind that we call the X-undulator (XU), featuring axially symmetric PM arrays that utilize longitudinal movements to control polarization and adjust the K value, and a force compensation mechanism, similar to that for the planar adjustable phase undulator [4], which significantly reduces the forces between the arrays. A configuration for fast polarization switching is also discussed.

MAGNETIC DESIGN

The functional part of the XU, defined as the magnetic structure that generates usable magnetic fields on the axis, comprises four identical 30-mm-period Halbach PM arrays symmetrically positioned around the electron beam axis, each named after its quadrant, as shown in Fig. 1. For the planned 1.0 m prototype, there are 33 periods in total. Each array period contains four blocks magnetized radially or longitudinally.

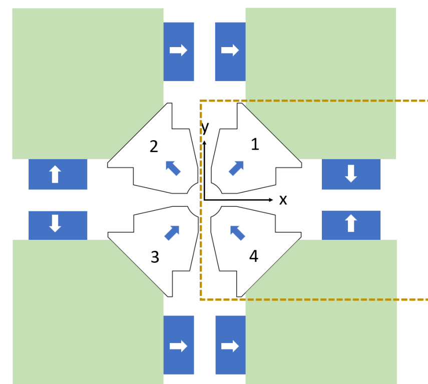

Figure 1: Diagram of the XU consisting of four functional magnet arrays of Delta-shaped magnets and eight force compensation magnet arrays represented by blue blocks. The arrows indicate the direction of magnetization. The functional and force compensation magnet arrays in the same quadrant are co-mounted on one magnet array jaw (in light green). The magnet arrays enclosed by yellow dashed lines are modeled for force compensation calculation.

The four functional arrays, moving independently in the longitudinal direction, are paired as follows: Arrays #1 and #3 face each other and produce a similar on-axis field, forming one pair, while Arrays #2 and #4 form the second pair. Displacement within a pair alters the value of K, while displacement between pairs varies polarization. This configuration enables the realization of all polarization states within the designed K range.

The magnets are of NdFeB material with a remanence of 1.28 T. The round vacuum chamber has inner and outer diameters of 6 mm and 7.5 mm, respectively, so the bore diameter of the XU magnet arrays is determined to be 8.5 mm. A 3-mm gap between the neighboring magnet arrays is required for side access and magnetic measurement using a Hall probe. The optimization goals for the magnets include increasing the maximum K, minimizing the magnetic force between the arrays, and simplifying the installation. Magnetic field calculations and dimensional optimization were performed using the RADIA simulation code [5]. Removal of material on the magnet sides significantly reduces magnetic forces while preserving the maximum K. As a result, the optimized undulator magnet design features transversely tapered gaps, as depicted in Fig. 2.

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The maximum effective field for all polarization modes is 0.928 T, corresponding to a K value of 2.6 and a minimum photon energy of 2.6 keV with the 6 GeV APS-U electron beam.

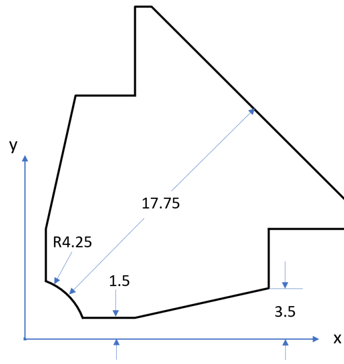

Figure 2: Optimized undulator magnet profile (dimensions in mm). The coordinate origin indicates the electron beam center.

Force Compensation

Two compensation magnet arrays are installed on each jaw to compensate for the forces experienced by the functional array installed on the same jaw. The compensation array consists of NdFeB-N42 magnets with a remanence of 1.32 T, each with two countersunk holes for mounting, measuring 25.4 mm×12.7 mm×12.7 mm (x, y, and z). The adjacent blocks in the compensation array are oriented in opposite directions and are spaced by 2.3 mm, forming a 30-mm period. The compensation magnet arrays of the neighboring jaws face each other, and the phase between them is 180° different from their respective functional arrays, as indicated in Fig. 1. Force compensation optimization focuses solely on the neighboring jaw interactions, with the task being to ensure the forces between the compensation arrays and the force between the functional arrays cancel out by adjusting the gap between the compensation arrays.

Four magnetic arrays in quadrants #1 and #4 centered on the y=0 mm plane, as indicated by the dashed line in Fig. 1, were modeled. The Maxwell stress tensor method described in the following was used for the precise calculation of the forces over a magnet period.

$$\mathbf{F} = \frac{1}{\mu_0} \iint \mathrm{d}A\ \mathbf{S} \cdot \mathbf{n}, \qquad (1)$$

with $\mathbf{n}$ being the normal of the surface and

$$\mathbf{S} = \begin{bmatrix} B_x^2 - B^2/2 & B_x B_y & B_x B_z \\ B_y B_x & B_y^2 - B^2/2 & B_y B_z \\ B_z B_x & B_z B_y & B_z^2 - B^2/2 \end{bmatrix}, \qquad (2)$$

where $B^2 = B_x^2 + B_y^2 + B_z^2$. Integrating the right-hand side of Eq. (1) over the surface of a rectangular volume for y≥0 and 0<z<30 mm calculates the force for one period in the upper half of the model. Given the zero field in $+y$, $-x$, and $+x$ planes and $\mathbf{F}|_{z=0\,\mathrm{mm}} = -\mathbf{F}|_{z=30\,\mathrm{mm}}$, it is sufficient to do the integration over the $y = 0$ mm and $0<z<30$ mm plane to compute the forces.

The optimized gap between the compensation arrays is 4.0 mm and the resulting forces are shown in Fig. 3. With the introduction of force compensation arrays, the longitudinal and vertical net forces between two neighboring jaws were reduced by a factor of 10. The forces between neighboring jaws will be less than 300 N for the planned 1-m XU prototype.

The compensation magnets are of lower cost than the functional magnets. Placing them near the functional array reduces the mechanical structure size, but may impact the on-axis field due to errors in them. A 43.8-mm separation between the compensation magnet and the beam centerline is chosen as a compromise after taking into account the errors.

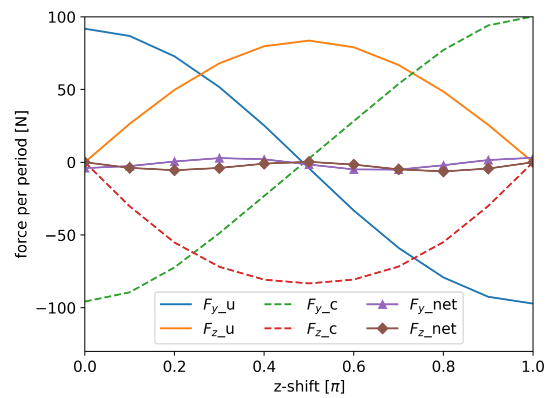

Figure 3: Force optimization results. In the legends, "_u" stands for the undulator magnet array forces (solid lines), "_c" stands for the compensation magnet array forces (dashed lines), and "_net" stands for the net forces after combining the undulator magnet array and the compensation array (lines with markers).

Fast Polarization Switching

Switching between left and right circular polarization requires a 7.5-mm quarter-period motion. A 1 Hz switching rate with a 50% duty cycle is feasible, considering mechanical properties such as net forces, eddy current forces, mass of moving parts, and motor and actuator capabilities. To further increase the polarization switching rate, a dual inline XU configuration is utilized as depicted in Fig. 4. The XUs generate left-polarized (upstream) and right-polarized (downstream) x-ray radiation at energy E. Introducing a minor phase displacement Δ into the downstream XU's four jaws in a K-altering manner shifts its energy outside the monochromator's bandwidth, delivering only left-polarized radiation. Alternately applying the displacement to the two XUs switches the polarization states at the user end. This method also enables rapid switching between orthogonal linear polarizations.

For lower harmonic energy radiation, the undulator K shows reduced sensitivity to phase shifts, necessitating larger motion distances. Thus we conducted a spectra simulation to estimate the motion distance for fast polarization switching at the XU's lower spectral range. As shown in Fig. 5, reducing K by 3%, corresponding to a 0.6-mm phase shift per

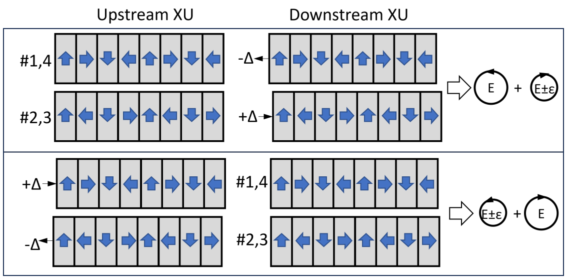

Figure 4: Diagram of fast polarization switching mechanism. The configuration in the top panel generates left-polarized radiation and the bottom panel configuration generates right-polarized radiation at the target energy E.

jaw, displaces the undulator harmonic by twice its FWHM, resulting in a reduction of flux at the original energy by a factor of 200. Given this small motion distance, a 5-Hz polarization switching rate with a 50% duty cycle is feasible. In this scenario, the jaw accelerates from rest to 24 mm/s at 0.96 m/s^2 over 25 ms and then decelerates to zero in the following 25 ms. In addition to the motion distance, another potential limitation of fast polarization switching arises from the eddy currents generated in the presence of the ID vacuum chamber. Investigating the impact of these eddy currents with the help of a dummy vacuum chamber will be a task of the prototyping project.

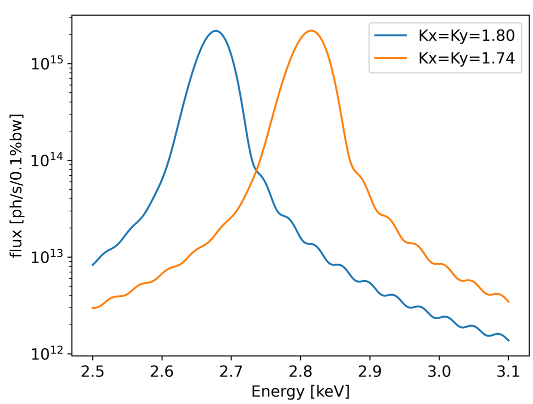

Figure 5: Pinhole flux spectra simulation of two 2.2-m XUs with opposite circular polarizations and undulator K values of 1.80 and 1.74, respectively. The calculation assumed APS-U beam, and the radiation is collected with a 1×1-mm pin-hole at 25 m downstream of the device center.

MECHANICAL DESIGN

A functional magnet array and two compensation arrays were mounted on a 1-m-long aluminum girder, forming a magnet array jaw, as depicted in Fig. 6. The girder has a recessed top that provides space for a longitudinal motion drive system, comprising a servo motor, a planetary gearbox, a linear actuator, limit switches, and a linear encoder for positional feedback. This configuration with an embedded drive system compacts the transverse dimensions. During rapid polarization switching, the motor's recurrent motion could potentially cause heat buildup, affecting the thermal conditions, girder deformations, and the magnetic performance of the XU. A cooling channel, which circulates water to dissipate motor heat, is introduced to improve localized temperature control. The jaw design allows fine positional adjustments of functional magnets for on-axis field tuning. The jaw is mounted on 16 pairs of precision rail slide pairs directed z (eight per side) on a compact, strong C-shaped aluminum frame, as shown in Fig. 7. The overall dimension of the assembled XU prototype is 300 mm×280 mm×1000 mm (x, y, and z). The C-Frame opening allows for easy installation of the vacuum chamber and facilitates magnetic measurements using Hall sensors from the side. This structure also offers gap-shimming capability, so that the tuning of phase errors by introducing small gap deformations is possible after the device is assembled.

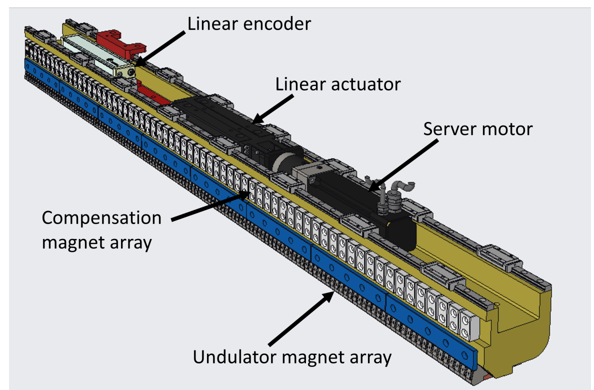

Figure 6: One of the magnetic jaws of the 1-m XU prototype.

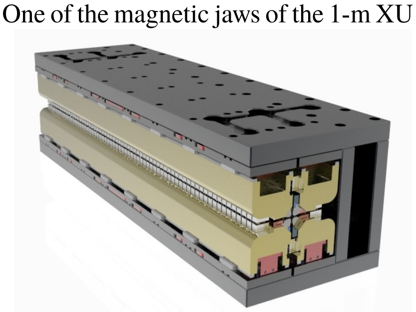

Figure 7: 3D model of the assembled 1-m XU prototype.

SUMMARY

We presented the magnetic and mechanical design of the 1-m prototype X-undulator featuring four symmetric magnetic array jaws around the APS-U's round beam chamber and jaw movement for both K tuning and x-ray polarization control. It is also equipped with a magnet-based force compensation mechanism for reducing the forces among jaws, compacting the overall size, and facilitating faster polarization switching. Ongoing prototyping will validate the design and identify potential issues.

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