# SPECTRAL PERFORMANCE OF CIRCULAR POLARIZING QUASI-PERIODIC UNDULATORS FOR SOFT X-RAYS AT THE ADVANCED PHOTON SOURCE*

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*Abstract*

Comprehensive magnet design modeling and calculations of the spectral performance of an electromagnetic undulator design and a pure permanent magnet undulator design were performed in the process of selecting a new x-ray source for the Advanced Photon Source. Both undulators incorporate variable polarization control and reduction of the magnetic fields at so-called quasi-periodic pole locations for the purpose of suppressing the higher-order radiation harmonics. The introduction of quasi-periodicity shifts the higher spectral harmonics to lower energies, dramatically reducing the higher-order intensities at multiples of the fundamental. The flux in the first harmonic, however, is reduced by 15 – 20% for realistic harmonic suppression. For circular polarization, the higher-order suppression is less important as those are inherently suppressed by the design. The spectral performance of the different undulator designs and the reasoning leading to the selection of an electromagnetic undulator for this beamline are presented.

## INTRODUCTION

A new beamline for soft and intermediate-energy x-rays, slated for construction in sector 29 at the Advanced Photon Source (APS), will cover photon energies from 200 eV to 2.5 keV. This beamline will contain one x-ray source with variable polarization feeding two branch lines that employ two different techniques for studying low-energy electron excitations in matter. An important requirement of this x-ray source is the capability to suppress higher-order radiation harmonics to improve the signal-to-noise ratio in low-sensitivity scattering experiments.

Two different types of circular polarizing undulators were studied for this beamline. The choice was between an APPLE-II type design [1] consisting of pure permanent magnets, and an electromagnetic (EM) design. The undulator period length for each design was optimized for maximum flux at 200 eV for linear horizontal polarization and 400 eV for linear vertical and circular polarization. For both, the suppression of higher-order harmonics can be achieved by either using circularly polarized radiation, which inherently suppresses higher harmonics, or by introducing a perturbation of the magnetic field at select pole locations – the quasi-periodic (QP) pole locations.

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After comprehensive magnet design modeling and calculations of the spectral performances of the two designs, the EM undulator was eventually chosen. The decision was based on the fact that i) the EM is considerably more flexible, as the quasi-periodicity may be gradually turned on or off, whereas the APPLE-II would always have to remain quasi-periodic (at a fixed value); and ii) the EM can be built as one single 4.8-m-long segment, hence removing the issue of phasing between multiple undulator segments. (Although there were no fast polarization switching requirements, the EM can be switched much faster than the APPLE-II.) The APPLE-II can easily produce the required magnetic field strength, and a period length of 11.0 cm was chosen in these studies to keep the total power reasonably low. The EM undulator's magnetic field is, however, weaker, and the shortest period length that can meet the tuning requirement at the 11.0-mm pole gap is 12.0 cm when installed on the APS standard vacuum chamber.

The detailed mechanical design and thermal analyses of a short four-period EM prototype are near completion. A split view of the pole and coil assembly in the center of one jaw is shown in Fig. 1.

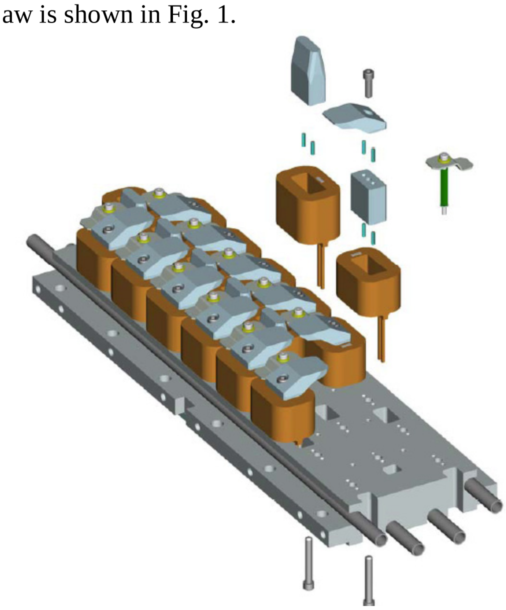

Figure 1: Split view of approximately two periods of one jaw of the EM. Both the off-centered horizontal and the centered vertical poles (blue) and the coils (brown) are shown. The poles are made of vanadium permendur. The full-length undulator is 40 periods long (4.8 m). Two end poles at each end and the quasi-periodic poles will be powered separately.

Three-dimensional magnet modeling was performed using large-scale 24-period models to obtain realistic representations of the magnetic fields in the center of the EM [2] and the APPLE-II [3]. The calculated magnetic fields of both regular and quasi-periodic fields of the EM are shown in Fig. 2 for the case of circular polarization.

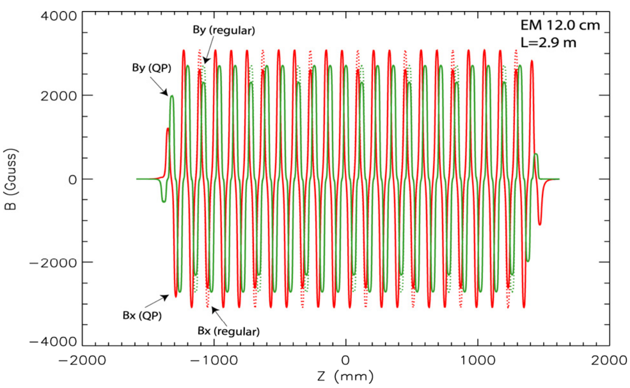


Figure 2: Calculated horizontal ($B_x$) and vertical ($B_y$) magnetic fields in the center of the 24-period EM model with 12.0-cm period at a vertical pole gap of 11.0 mm. The undulator will generate circularly polarized x-rays at a first harmonic energy of 400 eV for the APS beam energy of 7.0 GeV. The solid curves show the 15% reduced field strengths at the quasi-periodic pole locations (5,6), (12,13), (18,19), (25,26), (31,32), (37,38), and (44,45). Although the peak field in the $x$ direction is clearly higher than that in the $y$ direction, the effective magnetic fields in the two directions are the same.

## SPECTRAL CALCULATIONS

### *Non-quasi-periodic Magnetic Fields*

The aperture-limited flux was calculated at the location of the front-end exit mask at 25.4 m from the center of the undulator [4]. To achieve the highest flux, one in general wants to make the period length as short as possible, within existing constraints due to maximum allowable heat load on beamline components and energy tuning range requirements. It was therefore surprising to discover that the longer-period EM produces higher flux than the APPLE-II at 200 eV as is seen in Fig. 3. The field profile along the axis of the EM has a pronounced flat top compared to the field profile of the APPLE-II, which is nearly sinusoidal. This flat top results in a higher flux when the $K$ value ($K_y = 6.1$) is large. For smaller $K$ values ($K_x = K_y = 2.9$) and circular polarization at 400 eV, the EM is expected to produce 8% lower flux.

### *Quasi-periodic Magnetic Fields*

The introduction of reduced magnetic fields at select quasi-periodic (QP) pole locations shifts the higher spectral harmonics to a lower energy. Since they are no longer at an energy that is a multiple of the first harmonic, they do not pass through the monochromator, thereby dramatically reducing the higher-order "contamination" in the photon spectrum [5].

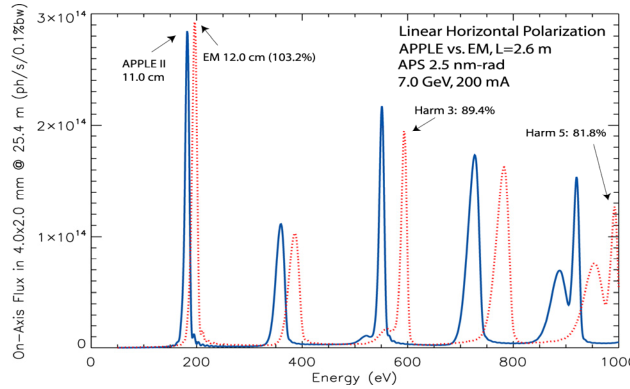


Figure 3: Flux comparison between the APPLE-II and the EM undulator for non-quasi-periodic magnetic fields for an optimized aperture size (4.0 ($h$) x 2.0 ($v$) mm at 25.4 m) for linear horizontal polarization at 200 eV in the first harmonic. Both undulators are 2.6 m long. The longer-period-length EM produces higher flux in the first harmonic due to the large deviation from a sinusoidal shape of the magnetic field at a large $K$ value. The EM-to-APPLE-II flux ratios are shown explicitly. The spectra are offset due to slightly different effective magnetic fields.

The two parameters $r$ and $\alpha$, which select the QP pattern, were chosen such that the QP poles would occur at every 6th or 7th pole ($r$ = 1.4 and $\tan(\alpha) = 1/\sqrt{15}$), see also Fig. 2. The flux spectra of the EM for linear horizontal polarization, with and without quasi-periodicity applied, are shown in Fig. 4. The corresponding flux spectra of the APPLE-II are shown in Fig. 5. The two undulators behave quite similarly when the QP field reductions are applied, although their sensitivity is different.

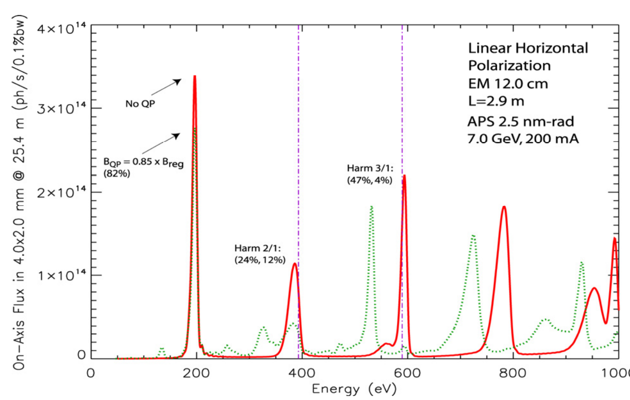


Figure 4: Flux of the EM in linear horizontal polarization mode at 200-eV first-harmonic energy using calculated realistic magnetic fields, with and without quasi-periodicity turned to a 15% field-strength reduction at the QP poles. The intensity reduction of the first harmonic due to quasi-periodicity and the intensities of the higher-order harmonics relative to the first harmonic are shown. The vertical lines mark the higher-order harmonic energies. The monochromotor energy bandpass may be represented by the narrow widths of the vertical lines.

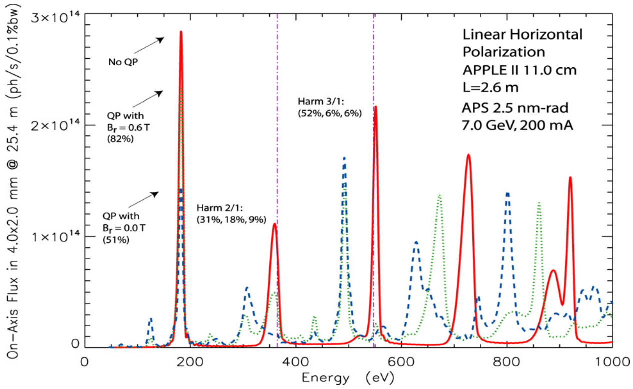


Figure 5: Flux of the APPLE-II with two quasi-periodic field-strength reductions. The reduced remanence fields $B_r$ of 0.6 and 0.0 Tesla near the QP poles give rise to magnetic field reductions at the QP poles of 8% and 15%, respectively. Other conditions are the same as in Fig. 4.

The spectra of the EM in circular polarization mode at 400 eV are shown in Fig. 6. Although not as important in this case, it may still be worthwhile to apply quasi-periodicity because, in addition to shifting the higher harmonics, the quasi-periodicity reduces the intensity of the second harmonic at a faster rate than the first.

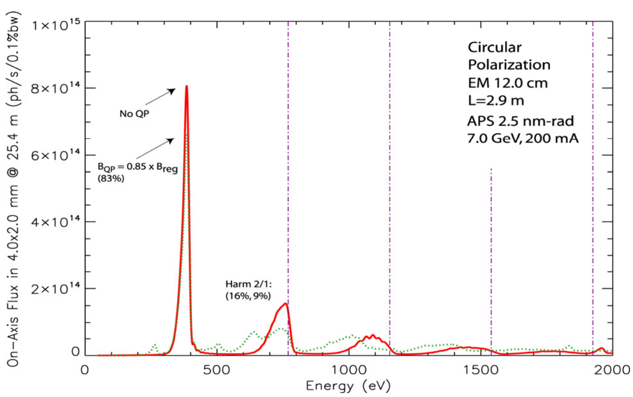


Figure 6: Flux of the EM in circular polarization mode at 400-eV first-harmonic energy. The intensity at the 5$^{th}$ harmonic arises primarily from the non-sinusoidal shape of the magnetic field. The other higher orders are primarily due to the size of the aperture and the beam emittance. Other conditions are the same as in Fig. 4.

## DISCUSSION

A circular polarizing electromagnetic (EM) undulator will be built for the new soft and intermediate-energy range beamline slated for construction at the APS. It can reach 200 eV in the first harmonic and it will be the first undulator at APS providing photons with energies below 500 eV. It was surprising to discover that the EM with 12.0-cm period would produce approximately the same flux in the first harmonic as the APPLE-II with 11.0-cm period, despite its longer period length (see Fig. 3). However, that "feature" worked in favor of the EM in the undulator selection process.

A four-period-long prototype will be fabricated and evaluated magnetically, mechanically, and thermally. Once completed, the full-length 4.8-m-long undulator will be fabricated. Spectra were calculated for a beam current of 200 mA. (For the APS normal beam current of 100 mA, and the final length compared to the model, multiply the EM-flux spectra above by $1/2 \times 4.8/2.9 = 0.83$.) Realistic magnetic fields were derived from three-dimensional magnet modeling of insertion devices that contained no magnetic field errors. The measured flux of the higher-order radiation harmonics of real devices may therefore be smaller by a few percent due to such errors.

It was found that the introduction of quasi-periodicity dramatically suppresses the higher-order radiation harmonics in linear polarization mode and that EM and APPLE-II undulators behave quite similarly, despite different magnetic field shapes (the APPLE-II magnetic fields are near-sinusoidal whereas the EM shows a large fraction of higher-order field harmonics). They show different sensitivity to the magnetic field strength reductions; however, both may easily suppress the higher-order radiation harmonics by reducing the magnetic field strengths by about 15% at the QP poles. A larger field reduction will gradually destroy the radiation, including the first harmonic.

The quasi-periodic pattern for the final EM undulator may change, but it appears that a reasonable choice has already been found. We found that the third-harmonic radiation was reduced from 47% of the first harmonic to only 4% while the first-harmonic intensity dropped by 18% for linear horizontal polarization at 200 eV (see Fig. 4). The quasi-periodicity also suppresses the even harmonics and may even be desirable in the case of circular polarization to suppress the second harmonic (see Fig. 6).

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