# COIL ENERGIZING PATTERNS FOR AN ELECTROMAGNETIC VARIABLY POLARIZING UNDULATOR*

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*Abstract*

A new electromagnetic undulator optimized for producing intense soft x-rays of variable polarization is under construction at the Advanced Photon Source. Most of the coil packs are powered by a main power supply; a few are powered separately so that magnetic fields at certain pole positions can be different. The undulator radiation depends sensitively on the chosen magnetic field pattern, and higher spectral harmonics may be shifted in energy. For some beamline experiments, it is important to reduce the so-called higher-order contamination to increase the signal-to-noise ratio. We present spectra and power densities calculated directly from realistic magnetic fields and discuss coil energizing patterns.

## INTRODUCTION

A new all-electromagnetic variably polarizing undulator (EMVPU) optimized for producing intense x-rays in the energy range from 250 eV to 2.5 keV is under construction for sector 29 at the Advanced Photon Source (APS) [1-2]. Values of select parameters of the undulator are given in Table 1. The total power and on-axis power density are both well below the high heat load limits for the APS front-end components. Periodic undulators inherently generate x-rays at rational higher-order harmonics of the fundamental harmonic energy ($E_1$) in linear polarization modes. Those are often desired and often used; however, this beamline requires suppression of the higher-order harmonics of the undulator to enhance the signal-to-noise ratio for certain low-sensitivity x-ray scattering experiments. This undulator has the built-in capability of shifting the rational higher harmonics by energizing the coils at the so called quasi-periodic (QP) pole positions differently from the coils at the regular poles. The "amount" of quasi-periodicity can be turned on *gradually* or be turned off completely by energizing the QP coils with the same current as the regular coils. The theory and applications of quasi-periodic undulators are already described elsewhere in the literature [3].

## SPECTRAL CALCULATIONS

After an extensive study of different coil energizing patterns, we found that the suppression of the third and fifth harmonics did not depend strongly on the choice of the QP parameters $r$ and tan($\alpha$), and we therefore settled on the comparison of two QP patterns: one with 16 QP poles and one with 22 QP poles. The 16-pole pattern derived from $r = 2.1$ and $\tan(\alpha) = 1/\sqrt{15}$, with QP poles every 9th or 10th pole, designates the following pole pairs as the QP poles: (5,6), (14,15), (23,24), (32,33), (41,42), (50,51), (60,61), and (69,70). The 22-pole pattern derived from $r = 1.4$ and $\tan(\alpha) = 1/\sqrt{15}$, with QP poles every 6th or 7th pole, has (5,6), (12,13), (18,19), (25,26), (31,32), (37,38), (44,45), (50,51), (57,58), (63,64), and (70,71) as the QP pole pairs. It is desirable to keep the number of QP poles low because the effective magnetic field depends on the number of QP poles – an important consideration to be able to reach 250 eV in linear horizontal polarization mode. Note that having pairs of QP poles is necessary to avoid overall steering of the electron beam.

The higher harmonic reductions depend sensitively on the magnitude of the magnetic field at the QP poles, and realistic values were chosen to achieve reasonable suppressions. All spectra were calculated directly from magnetic fields derived from optimized magnet design models and adjusted to have the same effective magnetic field independent of the magnitude of fields at the QP poles. Hence the first harmonic energies overlap and a direct comparison of the harmonic intensities is feasible. Flux spectra for the three different modes of operation at the required minimum first harmonic energies are presented in this paper. As a metric we chose to calculate the flux through an aperture that covers the whole central cone of harmonic radiation at the location of the front-end exit mask (25.4 m) using the code SPECTRA for the APS beam emittance and beam energy spread [4].

Table 1: Values of Select Parameters for the 4.8-m-long 12.5-cm-period EM Undulator with 38 Periods (76 poles) for 7.0 GeV Beam Energy and 200 mA Beam Current

| Polarization Mode | K value | Required $E_1$ (eV) | $P_{total}$ (kW) / $P_{dens}$(kW/mrad$^2$) 1) |
|---|---|---|---|
| Linear Hor. ($x$) | 5.27 | 250 | 6.4 / 102 |
| Linear Vert. ($y$) | 3.86 | 440 | 3.4 / 71 |
| Circular | 2.73 | 440 | 3.4 / 2 |

1) From modeled non-sinusoidal magnetic fields taking into account beam emittance and beam energy spread. The total power is ~ 6% higher and the on-axis power density is ~ 10% higher than from a sinusoidal magnetic field. None depends on the chosen QP pattern.

### *Linear Horizontal Polarization*

The flux spectra for the 16-pole and 22-pole QP patterns are compared in Fig. 1. Both clearly suppress the higher harmonics, including the second harmonic, to reasonably low levels. It is desirable to keep the flux reduction of the first harmonic small. However, for

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reasonable higher-harmonic suppression, QP inevitably causes a reduction of the first harmonic by ~ 20%.

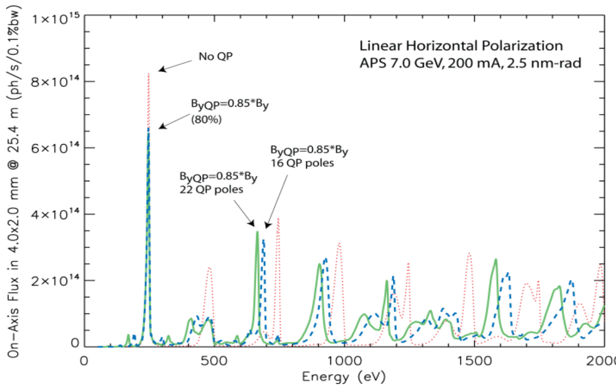


Figure 1: Flux in linear horizontal polarization mode at 250-eV first-harmonic energy for two different QP patterns with reduced magnetic field at the QP poles (85% of regular field). The higher harmonics are shifted to lower energies with the QP turned on. The energy shift is smaller for the 16-pole pattern (blue dashed curve). The flux of the third harmonic is reduced to ~ 8% and the second harmonic is reduced to less than 50% for both patterns. The first harmonic is reduced by ~ 20%.

The energy shift is smaller for the 16-pole QP pattern, but it is sufficiently large and was therefore chosen for the remainder of this study. The effect of changing the magnitude of the magnetic field (coil current) at the QP poles is illustrated in Fig. 2. The flux of the third harmonic decreases rapidly from 39% to 8% and the low-energy side peak grows when the QP field is reduced from 90% to 85% of the regular field. A higher QP field reduction will gradually destroy the first harmonic and will not significantly reduce the third harmonic.

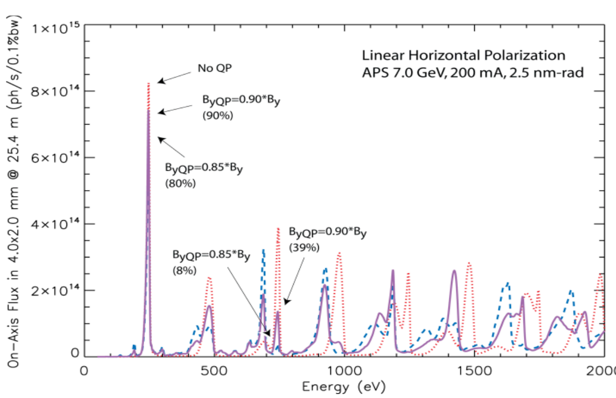


Figure 2: Flux at 250-eV first-harmonic energy for two reductions of the magnetic field using the 16-pole QP pattern. QP field reduction of 15% is near optimum. (The red dotted and blue dashed curves are as in Fig. 1.)

## *Linear Horizontal Polarization Using 2-Axis Field*

A reduced magnetic field at the QP poles introduces a smaller phase advance of the emitted photons than at the regular poles. It has also been suggested that a larger phase advance can be introduced by making the magnetic field larger at the QP pole locations [5-7].

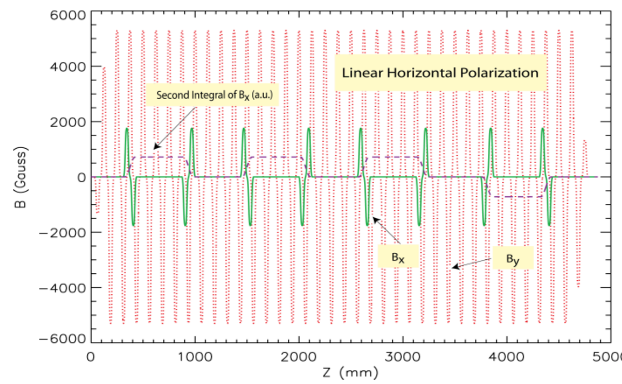


Figure 3: Vertical magnetic field $B_y$ and added horizontal magnetic field $B_x$ of 35% at the QP pole locations for the 16-pole QP pattern for 250-eV first harmonic energy. The second field integral of the $B_x$ field in arbitrary units corresponding to the electron trajectory in the vertical plane is also shown.

For the EMVPU with two perpendicular magnetic fields, the added phase advance may come from the second-axis field – the $B_x$ field. Figure 3 shows the vertical magnetic field ($B_y$) and the added horizontal magnetic field ($B_x$) at the QP poles for the same 16-pole QP pattern as before but with new values of $r = 3.64$ and $\tan(\alpha) = 1/\sqrt{5}$ so that $r\tan(\alpha) > 1$ as required. The vertical trajectory remains on axis at the exit of the undulator for this particular QP pattern.

The spectrum from the 2-axis magnetic field is compared with the previous case in Fig. 4. Due to the beam emittance and the finite size of the aperture, the previous reduced-magnetic field case with $B_{yQP}$ 85% of $B_y$ and $B_x = 0$ gives better performance. Furthermore, the 2-axis field has the undesirable effect of decreasing the degree of linear polarization of the first harmonic slightly from better than 99.9% to ~ 99.1% (not shown).

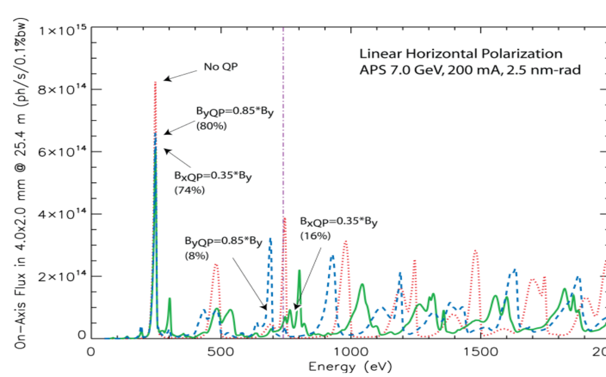


Figure 4: Flux at 250-eV first-harmonic energy for two QP magnetic fields using the 16-pole QP pattern. The 2-axis field with $B_{xQP}$ 35% of $B_y$ shifts the higher harmonics to higher energies off the rational harmonics. The vertical marker indicates the exact location of the third harmonic. (The red dotted and blue dashed curves are as in Figs. 1 and 2.)

### *Linear Vertical Polarization*

The spectra with and without QP turned on with 15% field reductions at the minimum 440-eV first-harmonic energy are shown in Fig. 5.

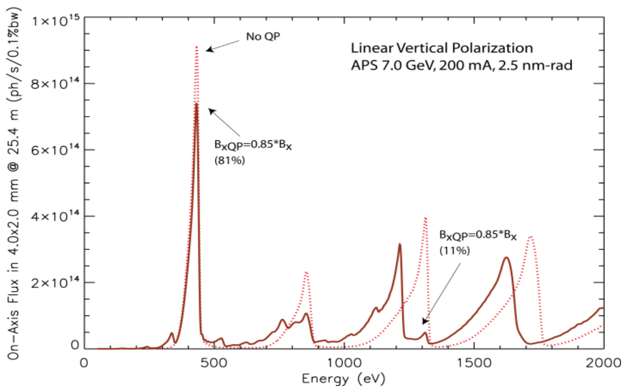


Figure 5: Flux in linear vertical polarization mode at 440-eV first-harmonic energy using the 16-pole QP pattern. A QP magnetic field reduction of 15% ( $B_{xQP}$ 85% of $B_x$) reduces the third harmonic to ~ 11%.

### *Circular Polarization*

The QP for circular polarization may be introduced by changing the magnetic field of both $B_x$ and $B_y$ at the QP poles or by changing only one of them. Figure 6 shows the spectra at the minimum 440-eV first-harmonic energy with a 15% field reduction of both fields. The QP is not particularly important for circular polarization because the higher odd harmonics are already inherently suppressed. The degree of circular polarization of the first harmonic remains near 100% with the QP introduced.

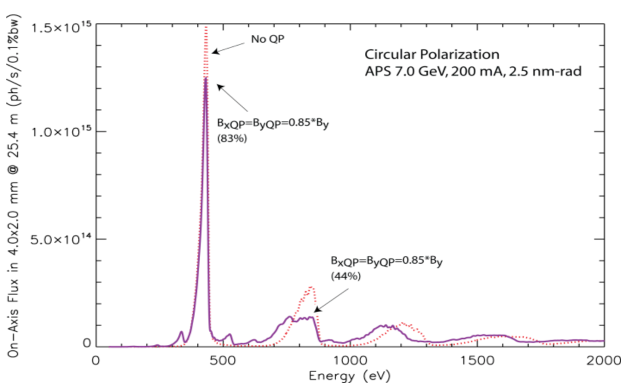


Figure 6: Flux in circular polarization mode at 440-eV first-harmonic energy using the 16-pole QP pattern. A QP magnetic field reduction of 15% for both $B_x$ and $B_y$ provides more than 50% reduction of the second harmonic. The first harmonic is reduced by 17%.

## DISCUSSION

We found that the higher harmonic suppression did not depend sensitively on the actual QP pattern chosen, and we therefore focused on a 16-pole pattern in this study. In contrast, the suppression is sensitive to the phase advance, but it was found to be in only rough agreement with theory, which may be related to the finite number of QP poles used.

We explored the idea of introducing a QP 2-axis field for linear horizontal polarization with $r \tan(\alpha) > 1$; however, it does not seem advantageous due to the beam emittance and the resulting low-energy tail on the harmonic peak. Even the 22-pole QP pattern, which provides a larger shift of the harmonics, does not result in significantly greater suppression of the higher harmonics. For circular polarization, there is no advantage to using enhanced fields at the QP poles. For example, for $B_{xQP} = B_{yQP} = 1.15 * B_y$, the first harmonic is reduced by 23% compared to 17% for the 16-pole pattern (c.f. Fig. 6). One may also introduce the phase advance by increasing one field component only, but it does not seem advantageous because the field change at the QP poles needs to be larger than that of changing both fields simulataneosly. In practice it will become difficult to adjust the $B_x$ and $B_y$ effective magnetic fields to the same value unless the circular polarization rate can be measured accurately. Nevertheless, it would be valuable to measure QP-reduced-field spectra versus QP-enhanced-field spectra once the EMVU is operational.

The magnetic fields scale roughly linearly with current except for the $B_y$ field near its maximum value where the field is beginning to saturate. At the maximum current for $B_y$, the current needs to be reduced by 25% to reduce the magnetic field by 15%.

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