PHASING OF TWO UNDULATORS WITH DIFFERENT *K* VALUES AT THE ADVANCED PHOTON SOURCE*

R. Dejus# and I. Vasserman, ANL, Argonne, IL 60439, U.S.A.

Abstract

Two full-length 2.4-m-long undulators, with period lengths 2.3 cm and 2.7 cm, were installed in tandem in the 5.6-m-long straight section on the storage ring in sector 14. One part of the user research program requires that both undulators be tuned to 12.0 keV and the x-ray intensity maximized. The total intensity is sensitive to the phasing between the undulators, so the distance between the devices must be optimized and the ends tuned appropriately. Because of the different period lengths, the gaps and K values of the undulators will be different: 10.6-mm gap and a K value of 1.17 for the shorter-period device and 15.7-mm gap and a K value of 0.93 for the longer-period device. A special shield was designed and installed between the devices to eliminate interference. Results of magnetic measurements, tuning, and computer simulations of the spectral performance are presented.

INTRODUCTION

An overview of general issues related to longitudinal phasing of two collinear undulators with the same period length were reported earlier [1]. In this work, we report on recent magnetic measurements and computer calculations of the on-axis brilliance and flux for two collinear undulators with different period lengths, installed in the 5.6-m-long straight section in sector 14 at the Advanced Photon Source (APS). Both undulators are 2.4 m long; the 2.3-cm-period device (U2.3) has 103 periods, and the 2.7-cm-period device (U2.7) has 88 periods. Both undulators are planar permanent magnet hybrid devices with vanadium permendur poles [2], designed to reach 12.0 and 7.0 keV, respectively, in the first harmonic at minimum gap (~ 10.6 mm). The user research program requires optimized brilliance and flux when both undulators operate simultaneously at 12.0 keV. The total intensity is sensitive to the phasing between the devices, and because active phasing was not implemented the break length was optimized (58 mm) and the ends tuned appropriately. The measured slippage distance versus gap follows very closely the expression in a field-free region [3], which means that one whole period in phase corresponds to an energy change of E_0/n, where E_0 is the phased energy (12.0 keV), and n is an integer number of slippage periods (here $n = 3$). Computer simulations were performed to predict the spectral performance when the undulators operate together at 12.0 keV and above.

MAGNETIC END SHIELDS

Special magnetic end shields were used to limit the extension of the magnetic field from the two insertion devices into the break section. Figure 1 shows the measured magnetic fields at the exit of the U2.7 for two different gaps. Because the distance between devices is only 58 mm, the magnetic end field from one device reaches the other device. Due to the existence of nonlinear elements (vanadium permendur poles) and different fringe fields at different gaps, the field in the break section becomes coupled, which implies that magnetic tuning of individual devices is not feasible. To eliminate this, a μ-shield was inserted. It reduces the fringe field to acceptable levels in the middle of the break section, and both devices may therefore be tuned independently. (Some coupling still remains, but the change of field integrals is smaller than the storage ring requirements and can be neglected.) The effect depends on the period length of the device (the larger the period length, the larger the fringe field) and, in particular, on the device termination. For example, the most recent magnet strength termination pattern (30%, 80%, 100%), gives significantly weaker end fields and a thinner shield may be used. For the U2.3 and the U2.7, the thickness was ~ 1 mm, whereas longer-period devices, e.g., 3.3-cm-period devices, required twice the thickness.

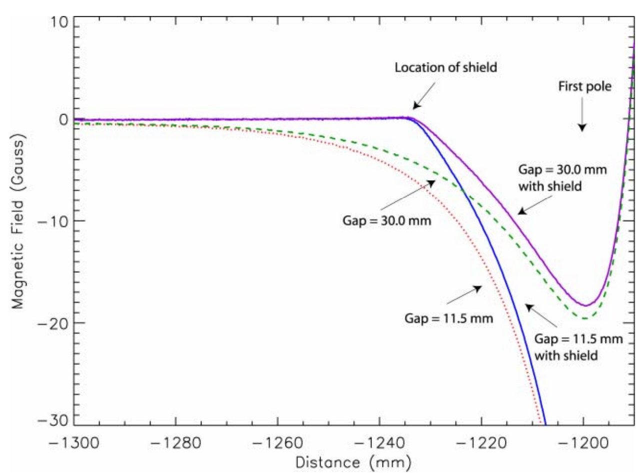

Figure 1: Magnetic field measurements near the middle of the break section for the 2.7-cm-period device at 11.5-mm and 30.0-mm gaps. The solid curves show the measurements with the μ-shield installed and the dotted and dashed curves without the μ-shield.

*Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
#dejus@aps.anl.gov

1-4244-0917-9/07/$25.00

SPECTRAL CALCULATIONS

Computer calculations were performed using the code UR [4] and Hall probe measurements of the magnetic fields at different gaps. The APS standard operating low-emittance lattice in top-up mode was assumed, which has a beam emittance of 2.5 nm-rad, a coupling of 1.0%, and a beam energy spread of 0.1%. The beam energy was 7.0 GeV, and the beam current was 100 mA. The undulators were tuned to be in-phase at 12.0 keV and individually tuned to show high spectral performance as measured by the small rms phase errors: 3.3° (at 10.6 mm gap) for the U2.3 and 2.3° (at 15.7 mm gap) for the U2.7. The predicted on-axis brilliance is shown in Fig. 2 for phased and unphased undulators. The maximum loss is about 34%, hence this shows the importance of phasing the devices correctly for brilliance-sensitive experiments at select energies. The *K* values of the phased undulators must be matched within ~ $2*10^{-3}$ in $\Delta K/K$ (gap change ~ 15 µm for the U2.3 and 17 µm for the U2.7) to lose less than 2% of the intensity.

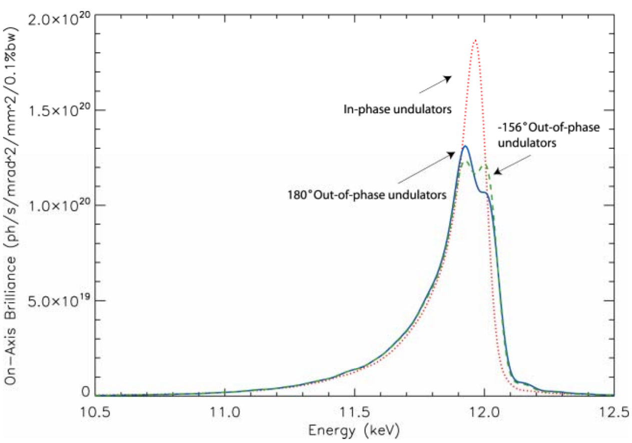

Figure 2: First harmonic on-axis brilliance for the two undulators tuned to be in phase at 12.0 keV (red dotted curve). The blue solid curve shows the performance for undulators 180° out of phase (70% of the intensity of perfect phasing) and the green dashed curve shows the performance for a -156° phase shift (66% of the intensity of perfect phasing). The *K* value is 1.17 (10.6-mm gap) for the U2.3 and 0.93 (15.7-mm gap) for the U2.7.

Once the undulators are set to be in phase at E_0, they will move 180° out of phase at $E_0 + E_0/(2n) = 14.0$ keV for $n = 3$, which is the number of slippage periods applied. Figure 3 shows the results of a series of calculations as a function of the first-harmonic energy to confirm the anticipated behavior. The hypothetical in-phase undulator intensities are also shown for comparison, and Fig. 4 shows the on-axis brilliance ratios of the data shown in Fig. 3. The undulators clearly show a periodicity of 4.0 keV with a maximum loss of intensity of 30% at 14.4 keV. The asymmetry is expected because of the emittance, which causes maximum loss to occur off 180° phase shift.

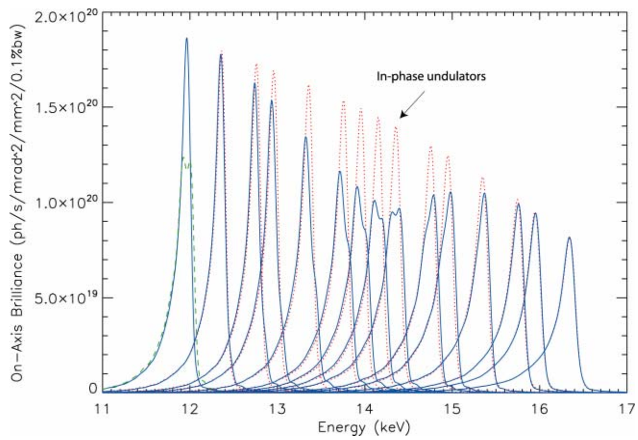

Figure 3: First harmonic on-axis brilliance for the two undulators tuned to be in phase at 12.0 keV and their energy dependence for a fixed break length. The red dotted curves show the in-phase intensity and the blue solid curves show the real performance with a fixed break length between them. The green dashed curve is the same as in Fig. 2.

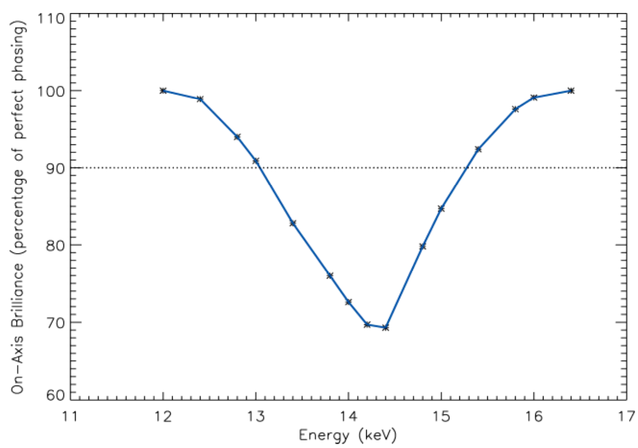

Figure 4: On-axis brilliance ratio of real intensity to perfectly phased undulators (data from Fig. 3) for the first harmonic. There is a clear asymmetry, i.e., worst case at 70% occurs at about 14.4 keV rather than 14.0 keV, corresponding to the off-180° phase shift noted in Fig. 2. The performance is better than 90% of perfect phasing below 13.0 keV and above 15.2 keV.

Interestingly, and perhaps somewhat counterintuitively, undulator gap tapering will improve the situation, as seen in Fig. 5. The preferred way would be to taper the U2.3 and U2.7 in *opposite* directions by the same amount in $\Delta K/K$ to gain intensity. The optimum taper would be about $1.4*10^{-2}$ in $\Delta K/K$, which corresponds to a difference in gap of 200 µm over the whole length of the undulator for the U2.3 and 230 µm for the U2.7. The on-axis brilliance will improve from about 70% to 85% of in-phase intensity at 14.4 keV, which represents the worst case. Thus, the maximum loss in the first harmonic will be only about 15%, which is the reason why active phasing may not be necessary.

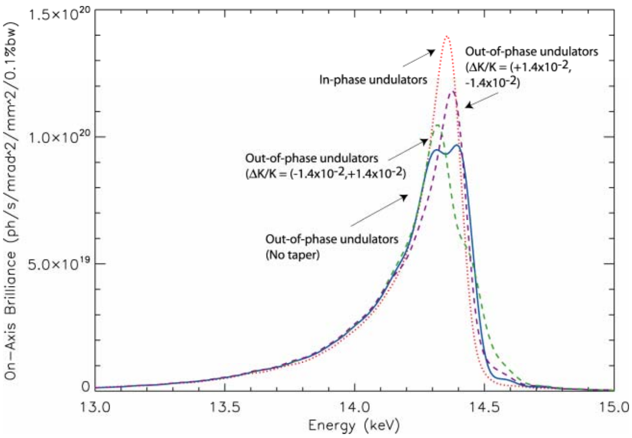

Figure 5: First harmonic on-axis brilliance for the two undulators at 14.4 keV (blue solid curve; initially tuned to be in phase at 12.0 keV). The red dotted curve shows the in-phase performance. The dashed curves show the effect of linear taper expressed as *ΔK/K* over the undulator half-length for the U2.3 and U2.7, respectively. A positive value indicates smallest gap (highest field) downstream. The intensity improves from about 70% to 85% of the in-phase intensity for optimum tapering by making both gaps smaller in the break section (purple dashed curve).

Contrary to the loss of on-axis brilliance, which may be important under some circumstances, the loss of aperture-limited flux is typically very small for unphased undulators as is seen in Fig. 6. For a typical aperture, 2.0 mm (h) * 1.0 mm (v) at 30 from the source, the loss is only about 4% and may be ignored. Thus, for experiments sensitive to flux rather than the brilliance, undulator phasing is not important.

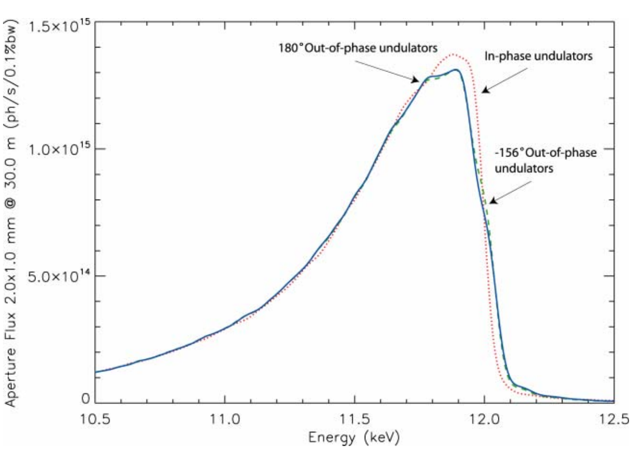

Figure 6: First harmonic flux through a 2.0 mm (h) * 1.0 mm (v) aperture at 30 m for the two undulators tuned to be in phase at 12.0 keV (red dotted curve). The out-of-phase undulators both show about 96% of the intensity of perfect phasing.

DISCUSSION

The two undulators were magnetically tuned to be in phase at 12.0 keV. The total number of slippage periods from undulator center-to-center was verified numerically from the measured magnetic fields to find the proper break length between them. Because the undulators have different period lengths, the following phasing condition $\lambda_{u1}\left(1+K_1^2/2\right)=\lambda_{u2}\left(1+K_2^2/2\right)$ applies in the field-free region, where λ_{u1} is 2.3 cm and λ_{u2} is 2.7 cm. This sets the relationship between the two K values. The minimum practical break length was chosen, which satisfied the phasing condition for three slippage periods (n = 3). The calculated spectra of the first harmonic on-axis brilliance showed modulations in intensity with a periodicity of 4.0 keV, as expected from the chosen break length. Because the undulators were phased at 12.0 keV, we observe a loss of about 30% at 14.4 keV. About half of this may be recovered by undulator gap tapering, and the loss would be only about 15%. For aperture-limited photon flux experiments, the phasing of undulators is even less important, and we found that the loss was only about 4%.

The intensity modulation of the higher harmonics showed the same periodicity, i.e., 4.0 keV, but the losses were less than 10% for the third harmonic and negligible for the fifth harmonic.

If a magnetic chicane were to be installed between the undulator to implement active phasing, the undulators would need to be shortened by about 15 cm. The intensity ratios in this work did not take this into account; hence, if active phasing were to be implemented, the in-phase intensities would be less and the losses described would be a few percent less. Thus, the losses were conservatively calculated in this work.

REFERENCES

[1] R. Dejus, Proceedings of 2005 Particle Accelerator Conference, May 16 – 20, 2005, p. 764, http://www.jacow.org.
[2] J. Grimmer and R. Kmak, Proceedings of 2005 Particle Accelerator Conference, May 16 – 20, 2005, p. 889, http://www.jacow.org.
[3] R. Dejus, unpublished.
[4] R.J. Dejus and A. Luccio, Nucl. Instrum. Methods A 347 (1994) 61.