ON THE ISSUE OF PHASING OF UNDULATORS AT THE ADVANCED PHOTON SOURCE*

R. Dejus[#], ANL, Argonne, IL 60439, U.S.A.

Abstract

Placing two collinear undulators in the 5-m-long straight sections at the Advanced Photon Source (APS) can answer the demand for increased brilliance. Whether longitudinal phasing needs to be taken into account for optimum spectral performance has been investigated. A comprehensive computer simulation study was completed to study the effect of the electron beam emittance, the magnetic field quality of the undulators, and the magnetic field strength (*K* value) on the spectral performance. For a zero-emittance beam, the radiation spectra exhibit strong interference that depends sensitively on the phase between the undulators. For a realistic APS-emittance beam and beam energy spread, the strong and phase-sensitive interference is substantially smoothed. A summary of the key findings including intensity losses due to unphased undulators is reported in this paper.

INTRODUCTION

The concept of phasing can be readily understood by looking at the distance the electrons fall behind the photon beam when traversing an undulator. Well outside the undulator, in the magnetic-field-free region of the undulators, highly relativistic electrons that follow a photon beam will lag the photon beam by $L/2\gamma^2$, where L is the distance traveled by the electrons, and γ is the relativistic factor for the electrons, $\gamma = 1957\,E(GeV)$; E is the energy of the electrons. Inside a planar undulator, the electrons move on a sinusoidal-like path and the electrons' average velocity projected onto the photon-beam direction becomes less than that in the field-free region. Therefore, the lag increases and it becomes $L(1+K^2/2)/2\gamma^2$, where L is the distance traveled by the electrons along the direction of the photon beam, and K is the effective K value of the undulator. Thus, for every undulator period λ_w traversed by the electrons, they slip exactly the distance $\lambda_w(1+K^2/2)/2\gamma^2$ behind, which is the same as the fundamental wavelength of the emitted radiation, and is generally referred to as one slippage period. When the slippage distance from one undulator to the next corresponds to an integral number of slippage periods, they are said to be in phase (resonance). Further, in a field-free region, once in resonance, the slippage distance is periodic with a periodicity of $\lambda_w(1+K^2/2)$. The slippage distance for resonance depends on the K value, which means that, if the undulator gap is changed (K value is changed), the resonance condition will change. They are 180° out of phase if the distance becomes an odd integer multiple of $\lambda_w(1+K^2/2)/2$.

In practice, one can use a magnetic chicane to change the delay of the electrons to set and maintain the phase between the undulators. (In the computer simulations, the length of the drift space between the undulators was changed to change the phase between them.) The key issue for this study was to investigate whether such a phasing would be worth implementing due to the complexity of extra hardware, additional controls and software, maintenance and cost involved.

The issue of phasing of undulator segments has been investigated earlier at both synchrotron radiation and linac-based free-electron laser (FEL) facilities. For the synchrotron radiation facilities, different approaches have been taken. At the European Synchrotron Radiation Facility (ESRF), pure permanent magnet devices are primarily used, and those have special magnetic end structures to provide proper phasing [1]. At the SPring-8 light source, a 25-m-long undulator was put in vacuum, with the segments in close contact [2-3]. An active magnetic phase shifter is used at the BESSY light source [4]. At FEL facilities, a magnetic phase shifter may be installed between variable-gap undulator segments as proposed for the TESLA project [5-6]. Or the segments may be operated at a fixed gap, where the ends are magnetically tuned to provide the proper phasing between them, an idea used for the LEUTL project at the APS [7], and adopted for the LCLS project [8-10].

SIMULATION ISSUES

The reduction of the on-axis brilliance depends strongly on several parameters, most notably the beam emittance (including the beam energy spread), the undulator magnetic field quality (as a measure of this, we use the rms phase error), and the undulator point of operation, i.e., its gap setting or K value. To study the effect of all three parameters, we made hundreds of simulation runs using the code UR [11]. We used the measured magnetic field data for two undulators A (each 2.4 m long with period length 3.3 cm) that had better than average rms phase errors (about 4° at 10.5 mm gap, and 2° at 18.5 mm gap) to minimize the effect of smearing due to magnetic field errors, i.e., to maximize the effect of unmatched phasing. Eight undulator gap settings were examined overall to study the effect of the K value. The APS standard operating low-emittance lattice in top-up mode was used for all simulations with a beam emittance of 2.5 nm-rad and a coupling of 1.0%. For all runs, a beam energy of 7.0 GeV and a beam current of 100 mA were used. If a magnetic phase shifter were to be inserted to maintain perfect phasing, the undulators would have to be shortened by ~ 15 cm or 5 periods. We ignore that in all comparisons that follow.

*Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.
[#]dejus@aps.anl.gov

RESULTS

For a zero-emittance beam, the radiation spectrum exhibits strong interference, which depends sensitively on the phase between the two undulators (a phase shift of a few degrees is easily discernable). In fact, the undulators can be set to destructive interference so that almost complete loss of intensity occurs at the harmonic energies due to the near-ideal sinusoidal magnetic fields. (The high quality of the undulator magnetic fields, small rms phase errors, was clearly evident because the radiation side lobes off the harmonics were almost equal in intensity up to the 5th harmonic.)

For the APS beam emittance and beam energy spread, the on-axis brilliance for perfectly phased undulators scales with the number of periods N as N^p, where $0.9 < p < 1.5$. For a very small beam emittance, the dependence on N is dominated by the radiation diffraction-limited angular spread, which scales $\sim N^{-1/2}$ in both transverse directions. But the actual dependence on N is intricate and also depends specifically on the radiated harmonic energy and the magnetic field errors. Interestingly, the exponent p may be less than 1.0 for high harmonics due to magnetic field errors and the beam energy spread.

The calculated on-axis brilliance for the first harmonic is shown in Fig. 1 at an undulator gap of 13.5 mm for in-phase and out-of-phase undulators. A clear interference pattern can be seen in the spectrum. Calculations at other gaps show that the reduced intensity is largest for a large K value (small gap) and for the first harmonic. The double peaks seen in Fig. 1 are only present in the first harmonic. This is primarily a consequence of the beam energy spread, which contributes a substantial smoothing of the higher harmonics.

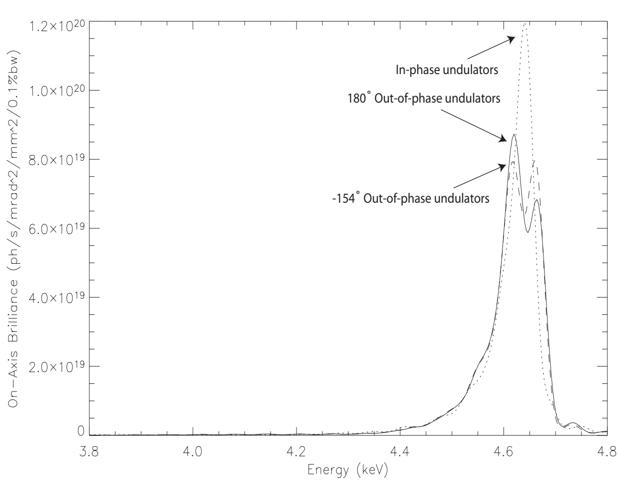

Figure 1: On-axis brilliance of the first harmonic for two undulators in series at an undulator gap of 13.5 mm (K = 2.02). The dotted line is for perfectly phased undulators, and the solid line is for undulators 180° out of phase. The dashed line shows the performance for a -154° phase shift, which represents the worst case. The brilliance is reduced to 73% / 66% (at the peak; solid and dashed line) of the brilliance for in-phase undulators.

The reduction of the higher harmonics (third and higher) due to unmatched phases is, in general, not significant. This is demonstrated in Fig. 2, which summarizes the results for the first, third, and fifth harmonics. We also scanned the phase for the first harmonic, and, when the two peaks became of equal intensity (see Fig. 1), it was recorded and shown as the "variable phase" curve in Fig. 2. In practice, the undulators can be tuned to be in phase at their smallest gap (10.5 mm), which would put them 180° out of phase at approximately 13.5 mm. Thus, the lowest brilliance fraction a user would encounter would be that at 13.5 mm. For the variable phase case at 13.5 mm (i.e., the overall worst case), the brilliance drops to ~ 66% in the first harmonic, ~ 88% in the third harmonic, and ~ 98% in the fifth harmonic.

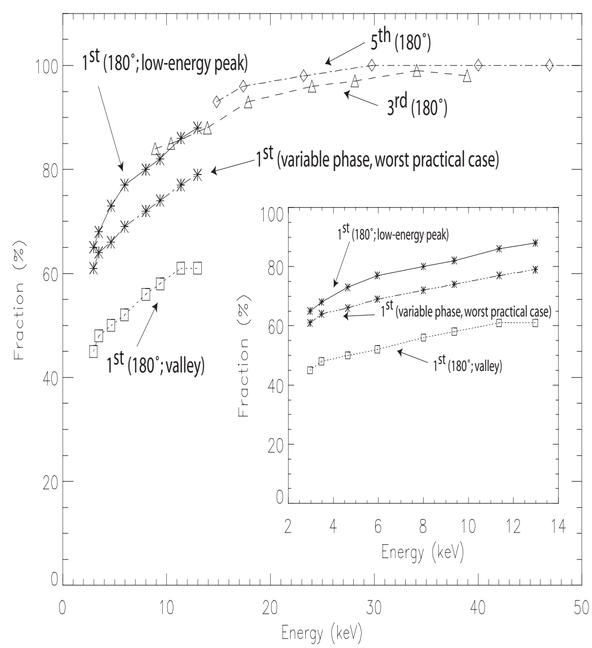

Figure 2: On-axis brilliance fractions versus energy for two undulators that change their gaps in unison (same K value). The curves are from top to bottom: fifth harmonic at 180° phase shift (diamonds/dash-dotted line); third harmonic at 180° phase shift (triangles/dashed line); first harmonic (three curves follow): stars/solid line is the intensity of the low-energy peak of the double peak at 180° phase (see Fig. 1: solid line); stars/dash-dotted line is the intensity for equal intensity of the double peak for varying phases from -170° at 10.5 mm gap to -120° at 30.0 mm gap (see Fig. 1: dashed line); squares/dotted line is for the valley of the double peak at 180° phase (see Fig. 1: solid line). The insert shows a close up of the first harmonic.

For many beamlines at the APS, the phase between the undulators is not important because of a large angular acceptance of the beamline optics. For a typical aperture-limited flux of the first harmonic at 3.0 keV, only a 5% reduction is observed for a phase shift of 180°; see Fig. 3.

0-7803-8859-3/05/$20.00 ©2005 IEEE

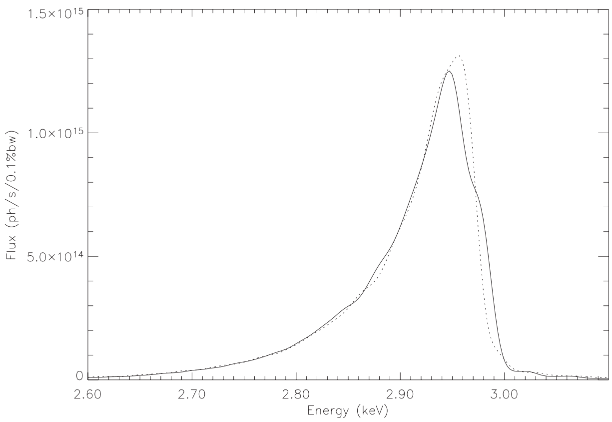

Figure 3: Flux through a 2.0 mm (h) x 1.0 mm (v) aperture at 30 m (first harmonic) for two collinear undulators at 10.5 mm gap (K = 2.74) with the APS beam emittance and beam energy spread taken into account. The dotted line is for perfectly phased undulators, and the solid line is for undulators 180° out of phase.

Both one-undulator and two-undulator linear taper in the magnetic field were simulated. In either case, it improved the on-axis brilliance for unphased undulators. This can be understood because tapering acts as if a range of K values is present, and the condition for destructive and constructive interference becomes less well defined. The spectra for the optimum *two-undulator* taper for the first harmonic energy at 4.6 keV are shown in Fig. 4. The on-axis brilliance becomes 84% of the in-phase brilliance for the optimum taper of ~ 120 μm; the amount of undulator taper is equal but in *opposite* directions. (The same fraction was obtained for a -154° phase shift for a slightly larger taper.)

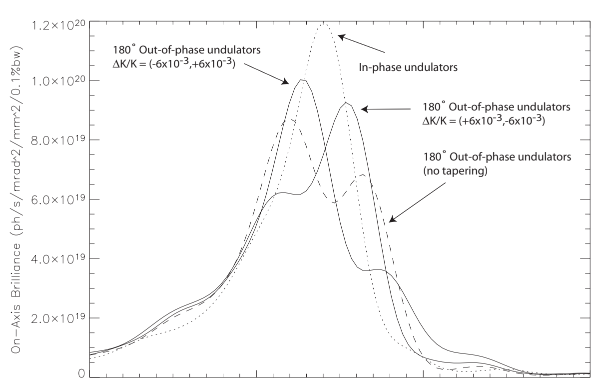

Figure 4: On-axis brilliance of the first harmonic for tapering both undulators compared to two untapered undulators set in phase at 4.64 keV (gap 13.5 mm, K = 2.02, dotted line). The dashed line is for untapered undulators at 180° phase shift. The solid curves show the effect of tapering; the first value in the parenthesis is the amount of linear taper expressed as $\Delta K/K$ for the first undulator over its half-length, and the second value is for the second undulator; a positive value means smallest gap (highest field) downstream.

Undulator gap tapering must not be used for the higher harmonics because it destroys the harmonic intensities quickly. The on-axis brilliance of the third and fifth harmonic were reduced to < 50%; a value that depends on the amount of tapering. The K values of the two undulators must be matched within ~ 1×10^{-3} in $\Delta K/K$ (~ 10 μm in gap) to avoid spectral degradations.

SUMMARY

Proper phasing becomes increasingly important for small beam emittance and beam energy spread, small undulator gap settings (large K values), small magnetic field errors, “small” (low) order odd harmonics. Unless experiments use the first harmonic and are truly sensitive to brilliance over a large range of small gaps (as opposed to flux), active phasing of the undulators is not necessary. Moreover, the loss of on-axis brilliance for the first harmonic can be partly recovered by tapering the gaps. For the worst-case scenario at 13.5 mm, the loss was estimated at only ~ 15% for the first harmonic using tapered devices. The loss was deemed small enough to not justify the complexity and cost of installing a magnetic phase shifter in a new beamline, which is near in completion.

ACKNOWLEDGMENTS

I wish to thank I. Vasserman, S. Sasaki, L. Moog, E. Gluskin, P. Den Hartog, J. Maser, and B. Stephenson for stimulating discussions and ideas.

REFERENCES

[1] J. Chavanne, P. Elleaume, and P. Van Vaerenbergh, J. Synchrotron Rad. **3**, (1996) 93.

[2] H. Kitamura, et al., Nucl. Instrum. Methods, **A467 – 468** (2001) 110.

[3] X.-M. Maréchal, et al., Nucl. Instrum. Methods, **A467 – 468** (2001) 134.

[4] J. Bahrdt, et al., Nucl. Instrum. Methods, **A467 – 468** (2001) 21.

[5] M. Tisher, et al., Nucl. Instrum. Methods, **A483** (2002) 418.

[6] P. Elleaume, J. Chavanne, and B. Faatz, Nucl. Instrum. Methods, **A455** (2000) 503.

[7] I. Vasserman, R. Dejus, N. Vinokurov, AIP Conf. Proc. **521** (AIP, 2000) 368.

[8] R.J. Dejus, Editor, ”LCLS Prototype Undulator Report,” Argonne National Laboratory Report, ANL/APS/TB-48, January 2004.

[9] I. Vasserman, et al., “LCLS Undulator Design Development”, Proc. of the 26th Int. FEL Conference, Aug. 29 – Sept. 3, 2004, Trieste, Italy. http://www.jacow.org.

[10] E. Gluskin, et al., Nucl. Instrum. Methods, **A475** (2001) 323.

[11] R.J. Dejus and A. Luccio, Nucl. Instrum. Methods, **A347** (1994) 61.