ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP107

POLARIZING AFTERBURNER FOR THE LCLS-II UNDULATOR LINE*

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Abstract

A fixed-gap polarizing undulator (Delta) has been successfully operated in afterburner mode in the LCLS FEL beamline at the SLAC National Accelerator Laboratory (SLAC) from August 2014 to the end of operations of the LCLS facility in December 2018. The LCLS undulator line is currently being replaced by two new undulator lines (as part of the LCLS-II project) to operate in the hard and soft x-ray wavelength ranges. Polarizing afterburners are planned for the end of the soft x-ray (SXR) line. A new polarizing undulator (Delta-II) is being developed for two reasons: (1) increased maximum K value to be resonant over the entire operational range of the SXR beamline (2) variable gap for K value control. It has been shown that using row phase control to reduce the K value while operating in circular polarizing mode severely degrades the performance of a polarizing undulator in afterburner mode. The device is currently scheduled for installation 2020-2021. The paper will explain the need for the variable gap design backed up by beam based measurements done with the LCLS Delta undulator.

INTRODUCTION

The LCLS Delta polarizing afterburner has been successfully operated [1] with the LCLS FEL for user experiments [2–4] until the shutdown of the facility in December 2018. The SLAC National Accelerator Laboratory (SLAC) is now getting ready to commission a new FEL facility with two undulator lines to produce soft x-ray (SXR) and hard x-ray radiation (HXR). It is planned to install up to three polarizing afterburners at the end of the SXR undulator beamline. It was clear that the 32-mm-period LCLS Delta, which is based on a concept developed by Alexander Temnykh [5], could not be made resonant with the SXR undulators over the high K regime of the operating range because the undulator period of the SXR undulator is 39 mm compared to the 30 mm period length of the LCLS undulators. A new Delta undulator with longer period was required. As work on designing the new device started, the team became aware of a PSI paper by Thomas Schmidt et. al [6]. The PSI group had found that line-width broadening occurred to the undulator radiation under certain operating conditions, when operating a fixed gap APPLE-II undulator, which uses 4 independently movable rows of magnets similar to the Delta undulator and has similar properties. The source of the line-width broadening was found to be a transverse gradient of the undulator parameter, K, that appears when operating the undulator in circular polarizing and at reduced strength. This effect is described in the next section.

* Work was supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-AC02-76SF00515.
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TRANSVERSE K GRADIENT

It turns out that polarizing undulators such as the Apple [7] and Delta devices that are basically constructed from 4 rows of permanent magnets, where the longitudinal row positions can be changed during operation to adjust the polarization mode and the undulator parameter, K, will generate a transverse gradient of K for certain combinations of row positions. Such an undulator can be conceptualized as made from two crossed planar pure permanent magnet undulators, each having two rows of permanent magnets in Halbach array [8] configuration mounted on opposite sites of the beam axis. The on-axis field is strongest when north poles at the permanent magnet block end closest the beam axis on one row exactly oppose south poles at the permanent magnet block ends closest to the beam axis on the other row. When the two rows are moved longitudinally with respect to each other by a distance Δz, the on-axis field changes with the cosine of that distance

$$K = K_0 \cos\left(2\pi \frac{\Delta z}{\lambda_u}\right) \quad (1)$$

at constant gap. Here, K_0 is the maximum K value that occurs at $\Delta z = 0$. Such a device is called an Adjustable Phase Undulator [9]. The relative longitudinal position of the two adjustable phase undulators determines the polarization mode, i.e., they will produce planar polarized light when they are aligned and various forms of elliptical, circular or planar light when they are displaced with respect to each other. It turns out that a transverse K gradient occurs in the device when operated in circular mode while $K < K_0$. After the initial observation, this fact was theoretically derived by Zachary Wolf [10] and by Marco Calvi et al. [11]. According to [10], the K gradient can be expressed to first order as

$$\left.\frac{\partial K}{\partial x}\right|_{x=y=0} = \frac{\pm K_{max} k_s^2}{\sqrt{2k_s^2 + 2k_u^2}} \sin\left(\cos^{-1}\left(\frac{K|_{x=y=0}}{K_{max}}\right)\right) \sin\delta,$$

$$\left.\frac{\partial K}{\partial y}\right|_{x=y=0} = 0,$$

where the "+" sign applies when $z_{A,up} > z_{A,dn}$ and $z_{B,up} > z_{B,dn}$ and the "−" sign applies when $z_{A,up} < z_{A,dn}$ and $z_{B,up} < z_{B,dn}$, or

$$\left.\frac{\partial K}{\partial x}\right|_{x=y=0} = 0,$$

$$\left.\frac{\partial K}{\partial y}\right|_{x=y=0} = \frac{\pm K_{max} k_s^2}{\sqrt{2k_s^2 + 2k_u^2}} \sin\left(\cos^{-1}\left(\frac{K|_{x=y=0}}{K_{max}}\right)\right) \sin\delta,$$

where the "+" sign applies when $z_{A,up} > z_{A,dn}$ and $z_{B,up} < z_{B,dn}$ and the "−" sign applies when $z_{A,up} < z_{A,dn}$ and $z_{B,up} > z_{B,dn}$.

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Here $z_{A,up}$, $z_{A,dn}$, $z_{B,up}$, $z_{B,dn}$ are the z positions of the upper and lower rows of crossed undulators A and B, respectively. The parameter, k_s, depends on the transverse structure of the pole tips. For the SLAC Delta undulator, it has been measured magnetically to $k_s = 186\ \text{m}^{-1}$. Reduction of this parameter is possible to some degree but reducing it to zero seems not to be possible without loosing most of the undulator strength. The parameter $k_u = 2\pi/\lambda_u$ is the undulator wavenumber, with the undulator period λ_u=32 mm. The parameter, δ, is the polarization control phase, which is $\pm\pi/2$ for the full left or right circular polarization mode and 0 for the linear polarization mode. Thus, in circular polarization mode with $z_{A,up} > z_{A,dn}$ and $z_{B,up} > z_{B,dn}$ the predicted relative on-axis K gradient should be:

$$\frac{1}{K_{\max}}\frac{\partial K}{\partial x} = \frac{k_s^2}{\sqrt{2k_s^2 + 2k_u^2}} \sin\left(\cos^{-1}\left(\frac{K}{K_{\max}}\right)\right) \quad (2)$$

While for individual undulators in a storage ring, this horizontal gradient of the K parameter can cause different parts of the beam to produce different wavelength resulting in linewidth broadening, the situation is quite different when operated as afterburner in an x-ray FEL. When the undulator is operating as afterburner [1], the radiation will be generated from a highly micro-bunched beam modulated by half a dozen undulators just upstream of the afterburner undulator, which causes the electron density to be peaked periodically along the electron bunch. If the K value of the afterburner undulator is set such that the radiation wavelength,

$$\lambda_r = \frac{\lambda_u}{2h\gamma^2}\left(1 + \frac{1}{2}K^2\right), \quad (3)$$

is the same or an integer fraction of the micro-bunching period, the radiation amplitude will be strongly enhanced due to constructive interference. Otherwise, the radiation amplitude will be suppressed. In Eq. 3, γ is the relativistic Lorentz factor and h is the harmonic number. A consequence for the radiation intensity from such a micro-bunched electron beam traveling through an undulator with transverse K gradient is that there is one path line through the device on which radiation is strongest while electrons traveling at a distance to that path line will radiate at a lower amplitude. Therefore, if the transverse beam dimensions are too large or the beam is transversely displaced, the number of electrons contributing to the x-ray intensity can be significantly reduced. This behavior was experimentally tested with the Delta afterburner undulator at the end of the LCLS undulator line in 2015.

MEASUREMENT OF THE EFFECT OF A *K* GRADIENT ON AFTERBURNER RADIATION

At the last position of the LCLS undulator line, the Delta polarizing afterburner was mounted on a remotely movable girder. Among other modes, the moving mechanism allowed the girder, and thus the Delta undulator, to be moved relative to the incoming electron and x-ray beams in any transverse direction, while its axis remained parallel to the beams. This capability was used in 2015 to study the effect of the transverse K gradient on radiation produced by the Delta undulator. The experiment made use of the fact that the maximum K value, to which the fixed gap Delta undulator could be set by aligning opposite magnet rows, was larger than the K value needed for resonance with the also fixed gap LCLS undulators.[1] In order to make the Delta afterburner undulator resonant to the LCLS undulators a value of $K/K_0 = 0.942$ was needed. During the experiment, the girder was first moved in horizontal direction across the distance range of -0.5 mm to +0.5 mm relative to the beam axis and than in vertical direction across the same distance range. For this scan, the parameter δ (see above) was set to $+\pi/2$ to produce circular polarized radiation. During the scan, the total intensity of the x-ray radiation leaving the Delta afterburner undulator was measured with the LCLS gas detectors (GDET) and recorded.

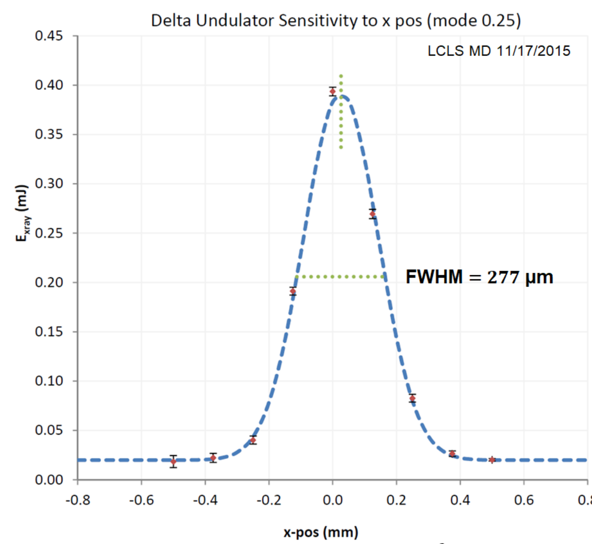

Figure 1: Intensity profile of the x-ray radiation coming from the Delta afterburner undulator at LCLS during a horizontal position scan of the device.

The error bars in Fig. 1 show the results of that scan. For large values of the x position distance, the radiation level is constant. This is mostly the radiation produced by the upstream LCLS undulators. Not much radiation is produced by the Delta afterburner undulator at these large displacements. As the x position is reduced, the total intensity rises, peaking around a position of about 0.023 mm. The dashed line is the result of a Gaussian fit:

$$E_{\text{xray}} = E_{\text{xray},0}\, e^{-\frac{(x-x_{\text{res}})^2}{2\,\sigma_x^2}} + E_{\text{xray,bg}} \quad (4)$$

with fit constants: $E_{\text{xray},0} = 0.3667$ mJ, $E_{\text{xray,bg}} = 0.0201$ mJ, $x_{\text{res}} = 23.1\ \mu$m, $\sigma_x = 117.5\ \mu$m.

[1] The pole planes of the upper and lower jaws of the fixed gap LCLS undulators were slightly canted with respect to each other around the beam axis, which allowed small K adjustments of order 0.1 % by remotely controlling the transverse position of the undulator.

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In order to determine the sensitivity of the x-ray intensity to the K value of the Delta afterburner undulator, an independent scan of K was performed over the range $3.29 \le K \le 3.40$. For this scan, the transverse position was kept constant at $x_{pos} = y_{pos} = 0$ mm and the parameter δ (see above) was set to $+\pi/2$ to produce circular polarized radiation. The total intensity of the x-ray radiation leaving the Delta afterburner undulator was measured with the LCLS gas detectors and recorded.

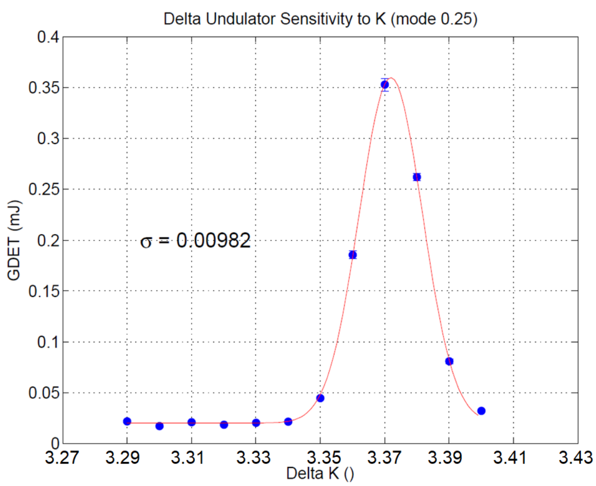

Figure 2: Intensity profile of the x-ray beam coming from the Delta afterburner undulator at LCLS during a scan of the K value ('Delta K') of the Delta undulator.

The error bars in Fig. 2 show the results of that scan. The curve looks similar to that in Fig. 1. The red line connecting the error bars is the result of a Gaussian fit:

$$GDET = GDET_0 \, e^{-\frac{(K-K_{res})^2}{2\,\sigma_x^2}} + GDET_{,bg}, \qquad (5)$$

with fit constants: $GDET_0 = 0.3386$ mJ, $GDET_{bg} = 0.0201$ mJ, $K_{res} = 3,3727$, $\sigma_K = 0.00982$.
A comparison of Fig. 1 and Fig. 2 leads to the conclusion that the change in x-ray intensity during the horizontal scan of the device comes from the fact that the K value changes in the device as function of x, such that the electron beam experiences a change in K as the device is moved horizontally with respect to the beam. Also, the similarity of the two curves leads to the conclusion that the $K(x)$ is roughly linear over the width of the resonance. The gradient can then be estimated by

$$\frac{\partial K}{\partial x} \approx \frac{\sigma_K}{\sigma_x} = \frac{0.00982}{117.5\ \mu\text{m}} = 0.0000836/\mu\text{m} \qquad (6)$$

or

$$\frac{1}{K_{\max}}\frac{\partial K}{\partial x} \approx 2.63 \times 10^{-5}/\mu\text{m}. \qquad (7)$$

This is in quite good agreement with Eq. 2, which gives a value of $3.0 \times 10^{-5}/\mu$m when evaluated with the parameters given in the text.

According to the equations given on page 1, there should not be a K gradient in y direction if there is one in x direction. To test this, a scan similar to the one shown in Fig. 1 was done in the y directions. The result is shown as error bars in Fig. 3.

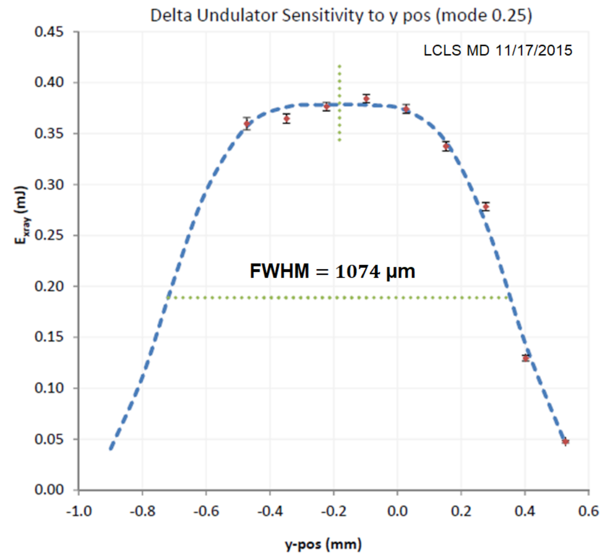

Figure 3: Intensity profile of the x-ray beam coming from the Delta afterburner undulator at LCLS during a vertical position scan of the device.

Figure 3 does look different from Fig. 1 but it is not completely flat, as one might expect at first. The reason is that the magnetic undulator field increases with distance from the beam axis following a hyperbolic cosine function. The dashed line shows a fit to the data points of function:

$$E_{xray} = E_{xray,0} \, e^{-\frac{K_{res}^2(\cosh(k_y(y-y_{res}))-1)^2}{2\,\sigma_x^2}} + E_{xray,bg}, \qquad (8)$$

with fit constants: $E_{xray,0} = 0.3590$ mJ, $k_y = 165\ m^{-1}$, $y_{res} = -180\ \mu$m, $E_{xray,bg} = 0.0201$ mJ. The values of K_{res} and σ_K have been taken from the fit in Fig. 2. When comparing the fits in Fig. 1 and Fig. 2 it appears that the horizontal gain width can be approximated by

$$\sigma_x \approx \frac{5}{4} \frac{\rho_{1D}}{\frac{1}{K_{\max}} \frac{\partial K}{\partial x}\Big|_{x=y=0}}. \qquad (9)$$

Equation 9, in which ρ_{1D} is the Pierce parameter, allows a prediction of the afterburner performance for smaller K values introduced by changing the row phases of the two crossed undulators.

Figure 4 illustrates the result of Eq. 9 for the entire LCLS-II SXR operational range as functions of electron energy and photon energy. Only at the lower right hand side corner of the plot, i.e., for large electron energy and low photon energy (at high values of the K parameter) is the gain window wider than the rms of the electron beam (purple to green colors). For photon energies above about 450 eV the gain window is too narrow and is expected to severely reduce afterburner performance. SLAC is now developing a new polarizing undulator, Delta II, which is based on the original

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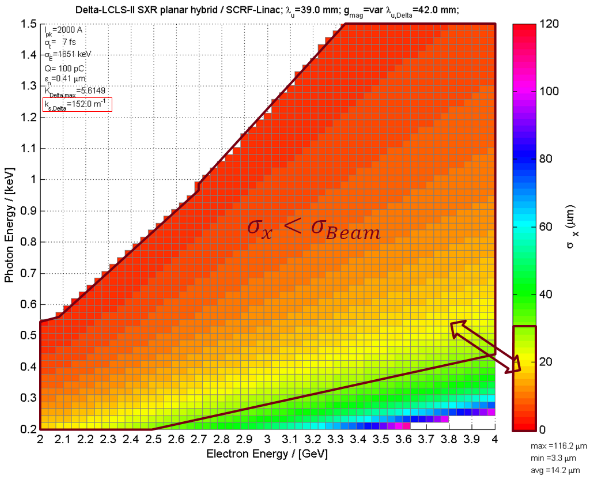

Figure 4: Estimated horizontal gain width for a 42-mm period Delta operating on the LCLS-II SXR line. (The Delta II undulator that is currently under development at SLAC is using a 44 mm period length.) The gain width for most of the operational range is smaller that the rms width of the electron beam, which is expected to significantly reduce the intensity of the radiation from the Delta afterburner undulator.

SLAC Delta undulator but with added variable gap capability, which will be used to set the K value. The row phases will only be used to set the polarization mode.

CONCLUSION

Measurements with the Delta polarizing undulator, operated on the LCLS beamline in afterburner mode, support earlier observations and theoretical work of the occurrence of a transverse variation of the K parameter (K gradient) in 4-row permanent magnet undulators operated in circular or elliptical polarization modes when row phase is used to set the K value of the device. These K gradients will broaden the radiation linewidth in a stand-alone device and limit the generation of radiation and of FEL gain to parts of the electron bunch that falls within a narrow transverse window, thus severely reducing output intensity of the device. While a transverse K gradient might be useful in certain situations to, for instance, combat the effects of a large energy spread, in most situations it is not desirable. Then, it must be avoided by adding variable gap capability to the device, such that gap variations can be used for K adjustments and row phase variations will only be used for adjusting the polarization mode of the radiation.

ACKNOWLEDGMENTS

The author thanks Alberto Lutman and James MacArthur for their support during the data acquisition for this paper.

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