DELTA-II Unduator Period Length Selection

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ABSTRACT

The fixed-gap DELTA undulator was operated successfully on the LCLS FEL undulator line between 2014 and 2018 to provide polarized FEL x-ray pulses with adjustable control of the polarization parameters. The device was made resonant to the LCLS FEL undulator segments by choosing an undulator period of 32 mm, larger than the 30 mm period length of the LCLS undulator segments in order to make the weaker magnet structure of the DELTA undulator resonant to the LCLS segments. Now, the LCLS undulator line has been replaced by two new LCLS-II undulator lines, with variable gap undulator segments. There is significant interest to have polarization control on the soft x-ray line (SXR), in which the undulator period is 39 mm, and a project is under way to change it to 56 mm. Also, it turns out that a fixed gap DELTA will not work well with variable gap FEL undulator segments. A new variable gap device, DELTA-II, is required [1]. A 32-mm period DELTA-II can not be made resonant to these new SXR undulator segments over the entire operational range. A longer period device is required. This document describes how the minimum required undulator periods for the DELTA-II undulator has been calculated.

Keywords: Undulator, LCLS-II, LCLS-II-HE, SXR, DELTA-II, Polarization Control

1. INTRODUCTION

The DELTA undulator was used as the last segment of the LCLS FEL undulator line in Afterburner mode [1] to produce x-ray pulses with arbitrary degree and mode of polarization. The Afterburner undulator uses an electron beam that has been micro-bunched by about half a dozen upstream microbunching undulator segments. The latter number needs to be kept sufficiently small to avoid saturation before the electron bunches reach the polarizing Afterburner undulator. The resonant wavelength, λ_r, of the x-ray radiation, that is produced by the Afterburner undulator is determined by the energy, γ, of the electron beam as well as by the period length, λ_u, and strength (which we will characterize with K_{LIN}, the undulator K parameter in linear mode) via the resonant condition

$$\lambda_r = \frac{\lambda_u}{2\gamma^2 n_h}\left(1 + K_{\mathrm{LIN}}^2/2 + \gamma^2\Theta^2\right). \tag{1}$$

n_h is the harmonic number and Θ is the angle between the beam axis and the undulator axis. The Afterburner undulator will only produce significant amounts of radiation if the spacing of the mirobunches matches the resonant wavelength of the Afterburner undulator or a harmonic of it. This becomes an issue due to the fact that the regular LCLS undulator segments have a hybrid magnet structure for increased magnetic strength while the DELTA undulator, based on permanent magnet technology, can only be made using a pure permanent magnet structure and therefore will have a lower K value for the same period and undulator gap. This was solved by increasing the period length of the DELTA undulator. In 2018, the LCLS undulator system was decommissioned and was replaced in 2020 by two new variable gap undulator systems, one to produce hard x-rays (HXR) and the other to produce soft x-rays (SXR). There is significant user demand to provide polarization control on the SXR line. Because the SXR undulator segments have a longer undulator period, the DELTA undulator is too weak to cover the entire photon energy range supported by the SXR undulator line. Shortfalls occur towards the lowest photon energies, which occur at the smallest undulator gaps. Therefore, the DELTA-II undulator, which is being developed instead, will need a larger undulator period. To make matters more complicated, a new project, LCLS-II-HE, is under way to replace the SXR undulator magnet structure with one of an even larger undulator period length, requiring not only an additional increase of the DELTA-II undulator period length but also a decision of how to proceed. There is no magnet structure for a DELTA-II undulator that will cover both SXR undulator period lengths. Options are: to start with a magnet structure appropriate for the current SXR undulator segments and then, when the LCLS-II-HE system is operational, replace it with the longer period structure. Due to the time line (the first version would be

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completed shortly before the LCLS-II-HE upgrade) and resource availabilty (needed undulator resources would be consumed by the LCS-II-HE upgrade) we will likely end up skipping the support for the current SXR line undulator segments and go straight for the support of the LCLS-II-HE version.

2. MAKING THE AFTERBURNER UNDULATOR RESONANT

The objective is to select a period length for the DELTA-II undulator that will allow making the DELTA-II undulator (AB) resonant to the microbunching SXR undulator (mb) over the entire operational range of the latter, i.e., making their resonant wavelengths, Eq. 1, equal

$$\frac{\lambda_{u,\mathrm{AB}}}{2\gamma_{\mathrm{AB}}^2 n_{h,\mathrm{AB}}}\left(1+K_{\mathrm{LIN,AB}}^2/2+\gamma_{\mathrm{AB}}^2\Theta_{\mathrm{AB}}^2\right)=\frac{\lambda_{u,\mathrm{mb}}}{2\gamma_{\mathrm{mb}}^2 n_{h,\mathrm{mb}}}\left(1+K_{\mathrm{mb}}^2/2+\gamma_{\mathrm{mb}}^2\Theta_{\mathrm{mb}}^2\right). \tag{2}$$

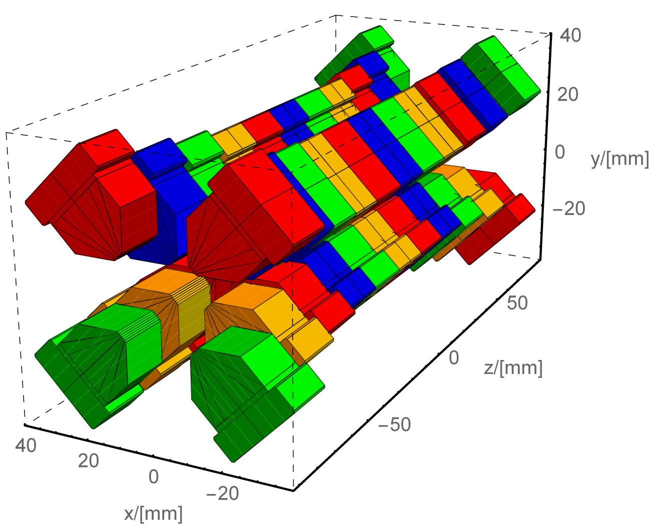
We want to restrict the analysis to radiation traveling parallel to the undulator axis, $\Theta_{\mathrm{AB}}=\Theta_{\mathrm{mb}}=0$, and assume that the energy loss from the microbunching undulator segments is negligible, such that at the entrance of either segment we have $\gamma_{\mathrm{AB}}=\gamma_{\mathrm{mb}}$. In addition, we will only consider the fundamental radiation $n_{h,\mathrm{AB}}=n_{h,\mathrm{mb}}=1$, because we are seeking to make the DELTA-II undulator sufficiently strong to cover the longest wavelength reachable by the mb undulator segments. This will still allow making the DELTA-II undulator resonant to harmonics of the mb undulator as long as $n_{h,\mathrm{AB}}\leq n_{h,\mathrm{mb}}$. Note that $n_{h,\mathrm{mb}}$ is not the harmonic number of the radiation but of the microbunching. This simplifies Eq. 2 to

$$\lambda_{u,\mathrm{mb}}\left(1+K_{\mathrm{mb}}^2/2\right)=\lambda_{u,\mathrm{AB}}\left(1+K_{\mathrm{LIN,AB}}^2/2\right). \tag{3}$$

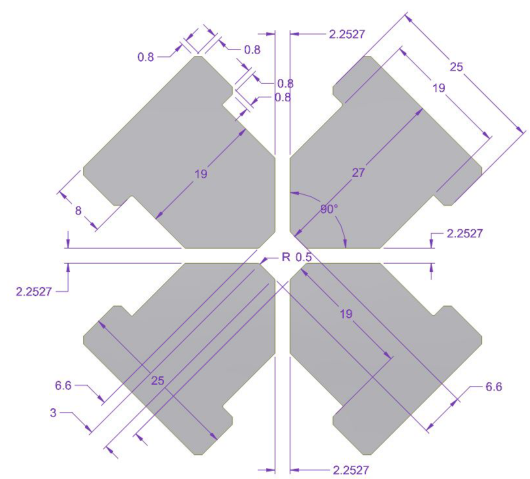
For a given set of mb undulator parameters, K_{mb} and $\lambda_{u,\mathrm{mb}}$, the required strength, $K_{\mathrm{LIN,AB}}$, of the Afterburner undulator is a function of its period, $\lambda_{u,\mathrm{AB}}$

$$K_{\mathrm{LIN,AB}}\left(\lambda_{u,\mathrm{AB}}\right)=\sqrt{2\left(\frac{\lambda_{u,\mathrm{mb}}}{\lambda_{u,\mathrm{AB}}}\left(1+K_{\mathrm{mb}}^2/2\right)-1\right)}. \tag{4}$$

This function needs to be compared with the estimated achievable strength of the Afterburner undulator, $K_{\mathrm{LIN,AB,est}}$. The estimate can be done, for instance, with the magnet computer code, RADIA[2].



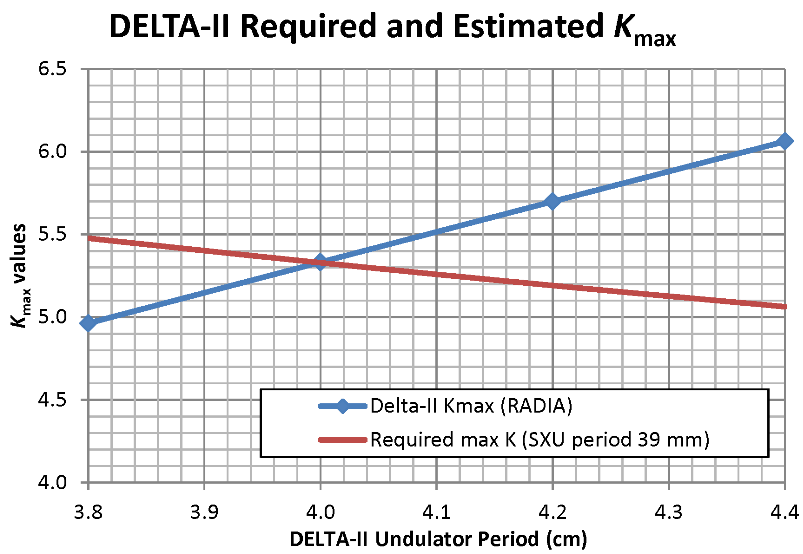
(a) RADIA model (One core period chosen for better visualization)



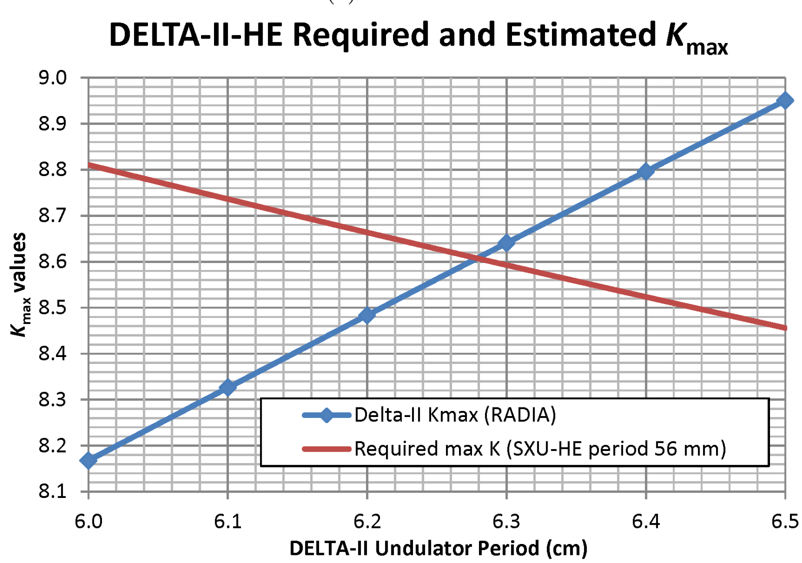
(b) Dimensioned cross section of closed gap core magnet arrangement (F. Peters) used in modelling

Figure 1: DELTA-II Model

Figure 1 shows an example of a RADIA model (with just 1 core period for better visualization). Actual calculations are performed with a larger number of core periods for higher precision calculations of the K parameter. Figs. 2 (a) and (b) show $K_{\mathrm{LIN,AB,est}}$ (blue curves) for the DELTA-II an Delta-II-HE situations, respectively, as function of the undulator period length.



(a) LCLS-SXU



(b) LCLS-SXU-HE

Figure 2: Maximum achievable (blue) and required K (red) values in order to make the DELTA-II undulator resonant to the LCLS-SXU (a) and LCLS-SXU-HE line segments (b).

The maximum value for the undulator parameter of the microbunching undulator, $K_{mb,\mathrm{max}}$, is given by the requirement that a minimum photon energy, $E_{ph,\mathrm{min}}$, needs to be supported at the highest electron energy, $E_{e,\mathrm{max}}$ and is calculated via

$$K_{\mathrm{mb,max}} = \sqrt{2\left(\frac{2\,h\,c\,\gamma_{\mathrm{max}}^2}{E_{ph,\mathrm{min}}\lambda_{u,\mathrm{mb}}} - 1\right)}. \tag{5}$$

Here, h is the Planck constant and c is the speed of light in vacuum. Table 1 summarizes the parameters used by Eq. 5 and the results of the equation.

Table 1: Undulator Line Parameters.

FEL	$E_{ph,\mathrm{min}}$		$E_{e,\mathrm{max}}$	γ_{max}	$\lambda_{u,\mathrm{mb}}$	$K_{\mathrm{mb,max}}$
	[eV]	[aJ]*	[GeV]	[]	[mm]	[]
LCLS-II SXR	250	40	4.0	7827.8	39.0	5.401
LCLS-II SXR-HE	250	40	8.0	15655.6	56.0	9.211

Inserting Eq. 5 as K_{mb} in Eq. 4 results in Eq. 6. We get for the maximum required Afterburner K value as function of undulator period length

$$K_{\mathrm{LIN,AB}}\left(\lambda_{u,\mathrm{AB}}\right) = \sqrt{2\left(\frac{2\,h\,c\,\gamma_{\mathrm{max}}^2}{E_{ph,min}\lambda_{u,\mathrm{AB}}} - 1\right)}, \tag{6}$$

which gives the red lines in Figs. 2 (a) and (b). The intersections between the red and blue lines in these figures give the minimum values of $\lambda_{u,\mathrm{AB}}$. The period lengths for the actual afterburner should be chosen a few percent larger to allow for differences between the estimated parameters and the actual parameters of the device.

3. SUMMARY

This note discusses the calculation of the maximum K parameter for an Afterburner undulator for both, the LCLS-II and the LCLS-II-HE period lengths.

References

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*1 aJ=10^{-18} J