STUDY ON POLARIZATION CONTROL OF PLANAR UNDULATOR SYSTEM BASED ON MAGNETIC FIELD MODULATION[*]

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Abstract

The fast polarization switching of undulator radiation has attracted more and more attention in recent years. Recently, a new method has been proposed for fast polarization switching up to kilohertz of undulator radiation by using magnetic field modulation generated from low-current electromagnetic coils. Through fast switching the power of coils, the radiation spectra of two undulators can be rapidly shifted into and out of the bandpass of a monochromator, enabling fast polarization switching for the user beamline. In this paper, we have studied the scheme using planar undulators, focusing on the required magnetic field of coils. The performance of the modulated spectrum will also be reported.

INTRODUCTION

In recent years, various types of undulators have been developed to enable controlling of radiation characteristics, including polarization degree, flux distribution, and photon energy. Examples include variable-polarization undulators such as APPLE-II [1] and APPLE-X [2, 3], harmonic-suppressing quasi-periodic undulators, and figure-8 undulators. Fast polarization switching has become increasingly important for experimental techniques like X-ray magnetic circular dichroism and X-ray magnetic linear dichroism, which are used to investigate orbital and spin moments in materials.

To achieve fast polarization switching, some strategies have been taken into consideration. The first involves direct control of the magnetic source. Mechanically adjustable undulators, such as APPLE-type undulators, control polarization by shifting magnetic arrays. Permanent magnet-electromagnet designs, implemented at facilities like SOLEIL [4, 5], enable fast switching of circular polarization by reversing coil currents. When the magnetic source cannot be altered quickly enough, a second strategy, is typically realized using twin-undulator systems and separating the two radiation beams, where two undulators generate radiation with different polarization states .

An innovative third strategy is based on spectral modulation. Instead of physically separate the photon beams with different polarization, this method uses phase shifters between undulators to split the spectrum [6, 7] or applies a modulating magnetic field to slightly detune the undulator harmonics [8, 9]. Cross-undulator schemes also achieve fast polarization switching with the help of phase shifters.

In previous work, we proposed a novel polarization switching scheme based on magnetic field modulation [10]. This scheme has significant advantages, including collinear emission of two photon beams with different polarization states and high stability of the electron beam trajectory. It also ensures high-quality radiation with both high polarization and high photon flux, while maintaining strong engineering feasibility.

The Hefei Advance Light Facility (HALF) [11, 12] is a 2.2 GeV diffraction-limited storage ring developed by the National Synchrotron Radiation Laboratory in China. It features 20 long and 20 middle straight sections. A specialized undulator system has been designed to realize fast polarization switching, where two EPU41 undulators will be installed sequentially and connected by a phase shifter in one straight section.

In this paper, we further investigate the proposed polarization switching scheme. Based on the HALF parameters we studied the performances of this scheme using planar undulators. The paper is organized as follows: First, a theoretical analysis on the required coil field of the proposed scheme is presented using planar undulators. Then, the distribution of the modulated spectrum is studied in detail. Finally, a summary is provided.

POLARIZATION SWITCHING

To illustrate the basic principle of the proposed scheme, in the following we introduce an electron radiation model to accurately calculate the photon energy shift.

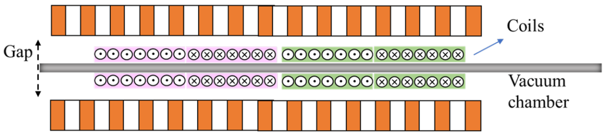

Figure 1: The schematic of the setup of the field modulation linear undulator.

Because the magnetic field of the coils only affects the vertical magnetic field, first we only consider the vertical magnetic field, corresponding to the movement of electrons in the horizontal direction. When an electron beam passes through the system above, the magnet field B_y that it experiences can be expressed as the superposition of the undulator field and the weak field generated by the coils.

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[*] Work supported by the National Natural Science Foundation of China under Grants (No. 12575343 and No. 12241501

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$$B_y = B_{y0}\sin(k_u z) + \alpha B_{y0}\sin\left(\frac{1}{m}k_u z + \varphi_0\right). \tag{1}$$

Here, $k_u = 2\pi/\lambda_u$ with λ_u being the period of the undulator. The period of the coil field is m times that of the undulator. B_{y0} is the peak field of the undulator in the vertical direction and α is the intensity factor of the coil field, representing the ratio of the peak field of the coil to B_{y0}. φ_0 is the phase deviation between the weak field and the undulator field, corresponding to the initial position of the weak field relative to the main field. Calculating the horizontal velocity of electrons and the average velocity of electrons along the undulator direction in a complete period $m\lambda_u$, using the period emitting model one can get the on-axis radiation wavelength with the coil field,

$$\lambda_s = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K_x^2}{2} + \frac{K_y^2}{2}\left(1 + \alpha^2 m^2\right)\right). \tag{2}$$

where K_x is the undulator strength parameter in the horizontal direction. Note that the phase shift φ_0 has no contribution to the average velocity, which implies that the tolerance requirements on the longitudinal position of the coils are not strict.

Here n is the harmonic number of the radiation. When the coil field is off (α=0), the above equation degenerates to the conventional resonance condition. Focusing on the fundamental radiation, namely $n = 1$, the movement of the fundamental wavelength can be written as:

$$\frac{\Delta\lambda}{\lambda} = \frac{K_y^2}{2 + K_y^2}\alpha^2 m^2. \tag{3}$$

The above calculation results give the wavelength shift of the fundamental radiation of the undulator with magnetic field modulation.

To ensure that the main flux of the modulated radiation falls out of the band pass of the monochromator, we need to further discuss the energy distribution of the modulated radiation spectrum. Only when the photon energy shift induced by the coil field is large enough, can the radiation flux through the monochromator be reduced to an extremely low level.

To sufficiently reduce the flux of the modulated spectrum at the original fundamental photon energy to an extremely low level, the required shift of the photo energy ϵ can be described as $\frac{\Delta\epsilon}{\epsilon} = \frac{\Delta\lambda}{\lambda} > \frac{1}{N_u}$, with N_u being the period number of the undulator, then one can obtain the requirement on the product of the weak field and the coil period:

$$\alpha^2 m^2 \geq \frac{1}{N_u K_y^2}\left(2 + K_y^2\right). \tag{4}$$

One can find that $\alpha^2 m^2$ is the main factor that determines the shift of photon energy. Compared with the result of a helical undulator

$$\alpha^2 m^2 \geq \frac{1}{N_u K_y^2}\left(2 + K^2\right). \tag{5}$$

Here $K = \sqrt{K_x^2 + K_y^2}$.

We can observe that, compared with the results of a helical undulator, the modulation factor of a planar undulator is smaller under the same K value. This is because, for a helical undulator, the modulation occurs only in the vertical direction, while the magnetic field in the horizontal direction remains unmodulated. In contrast, for a planar undulator, since its magnetic field exists only in the vertical direction, the entire magnetic field is subject to modulation.

However, what we need to calculate is the minimum magnetic flux density that the coils must generate. For electromagnetic coils, the peak magnetic flux density they can produce is easy to calculate, as it is highly dependent on their structure, number of turns, cross-sectional area, and excitation current. In simple terms, we are more concerned with limiting the excitation current density to avoid excessive heat generation and the need for additional cooling systems.

Use $K = \frac{eB_0\lambda_u}{2\pi m_e c}$, the coil filed can be calculated as

$$B_{coil} \geq \frac{2\pi m_e c}{em\lambda_u}\sqrt{\frac{(2 + K^2)}{N_u}} = \frac{1}{0.934 m\lambda_u}\sqrt{\frac{(2 + K^2)}{N_u}}. \tag{6}$$

Here m_e is the electron mass and c is the light speed in the vacuum. The results show that for both helical and planar undulators, when they operate with the same K value—meaning they work at the same photon energy—the requirements for the magnetic field generated by the electromagnetic coils are identical. This implies that when designing electromagnetic coils for a planar undulator, we can refer to the design scheme used for electromagnetic coils in a helical undulator.

HIGH HARMONIC GENERATION

In addition to the photon energy shift of the fundamental wave, we have also discovered a unique spectral structure in a planar undulator with an additional multi-period electromagnetic coil. The on-axis flux of integer-order harmonics is extremely low, nearly zero.

In the previous theoretical analyses, we derived through calculations that for such an undulator with modulating field, the integer-order harmonics should also be shifted as described by Equation 2. A factor n that specifically describes the harmonic order has been taken into consideration. However, in the simulations, we found that the on-axis flux of these corresponding integer-order higher harmonic radiations becomes exceptionally low, and fractional-order harmonic radiation appears. Among the fractional-order harmonic radiation, the one with the strongest on-axis flux is the fractional harmonic immediately preceding the integer-order harmonic.

In order to investigate the spectra distribution of the linear undulator modulated by coils, we computed the expected performance using the electron beam and undulator parameters listed in Table 1. In the following study, the radiation at a photon energy of 500 eV is taken as an example and the corresponding undulator strength parameter K_y is 1.295. In the simulations, the magnetic field is calculated by combining the undulator and the coils as an integrated system using *Radia* and the radiation spectrum is simulated with the *SPECTRA* code.

Table 1: Parameters Used in Simulations

Parameter	Value	Unit
Electron energy	2.2	GeV
Average beam current	350	mA
Electron beam emittance	100	pm·rad
Undulator period λ_u	50	mm
Number of period N_u	36	–
Undulator parameter K_y	1.295	–
Photon energy	500	eV

We calculated the radiation spectrum of a single conventional planar undulator and the radiation spectrum of the planar undulator after coil modulation. The results are shown in Figure 2. Note that the modulating magnetic field used here is a weak modulating field. At 500 eV, the magnetic field of the conventional planar undulator is 0.277 T. In the simulation, we selected a peak modulating magnetic field of 200 Gs, which is less than 10% of the undulator field. This is relatively easy to achieve for an electromagnetic coil with a large period (m = 4, coil period length is 200 mm).

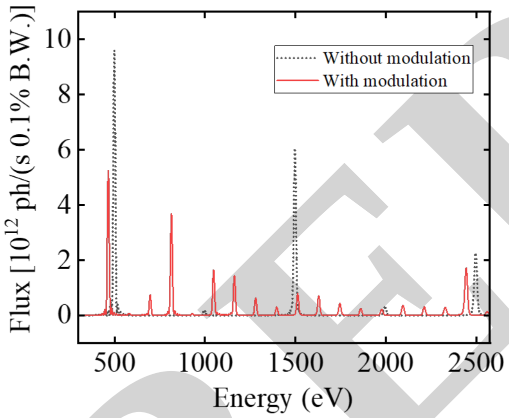

Figure 2: The radiation spectrum of a conventional linear undulator (black short dot) and the radiation spectrum of the linear undulator modulated by coils.

The radiation spectrum of the conventional planar undulator, i.e., the black dashed line in Figure 2, its even-order harmonic radiation is off-axis, and only odd-order harmonics are present on-axis. Now focusing on the modulated undulator radiation, i.e., the red solid line in Figure 2. First, due to the modulating effect of the coil magnetic field, the radiation spectrum undergoes a redshift. The fundamental radiation energy shifts from 500 eV to 465.5 eV. However, at the integer-order harmonic positions, i.e., at 931 eV (n=2), 1396.5 eV (n=3), 1862 eV (n=4), and 2327.5 eV (n=5), the flux is at an extremely low level.

The energy of the harmonics from the modulated undulator are no longer integer multiples of the undulator's fundamental radiation energy. The order *n* of these high harmonics can be expressed by the following Equation 7. Currently, we have only completed an analytical description of the energy of the high harmonics from an helical undulator. The results for a linearly polarized undulator require further analysis. However, based on the simulation results, the expressions for the high harmonic orders appear to be the same for both cases.

$$n = 1 + \frac{1}{m}c, \quad c = 0, 1, 2... \tag{7}$$

Through simulations, we found that compared to the conventional planar undulator, the fundamental radiation flux of the modulated undulator is reduced. Additionally, at the fractional harmonic position immediately preceding an even-order harmonic, the radiation flux is relatively high.

CONCLUSION

In this paper, beside the fast switching method of circular polarization radiation based on magnetic field modulation using electromagnetic coils, we analyzed the performance of this scheme in planar undulators. The results show that the requirements of planar undulators for the modulating magnetic field are the same as those of helical undulators. In addition, we have found an interesting phenomenon in the radiation spectrum of a planar undulator with an additional modulating magnetic field by coils, the on-axis flux of integer-order harmonics is nearly zero, and only fractional-order harmonic radiation exists on the axis.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China under Grants (No. 12575343 and No. 12241501).

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