Fast polarization switching of undulator radiation up to kilohertz with magnetic field modulation

Nanrui Yang, Zhouyu Zhao, and Heting Li*

National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, 230029, Anhui, People's Republic of China

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The fast polarization switching of undulator radiation has attracted more and more attention in recent years. In this paper, a new method is proposed for fast polarization switching of undulator radiation by using magnetic field modulation generated from low-current electromagnetic coils. The key point is that we propose to use the coils with a period length of an integral multiple of the undulator period, which can significantly reduce the required coil field. 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. Based on this advantage, this method has strong potential to be implemented in a storage ring and a high switching frequency up to kilohertz can be expected.

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I. INTRODUCTION

Polarization control of undulator radiation has attracted wide attention in recent years, and some extremely important experimental techniques in the field of materials and chemistry have put forward huge demands for fast polarization switching of radiation. For example, x-ray magnetic circular dichroism (XMCD), utilized to measure the spin and orbital magnetic moment of materials, necessitates a high switching frequency between left-hand circular polarization (LCP) and right-hand circular polarization (RCP). In general, the implementation of very fast polarization switching not only serves to decrease the total acquisition time per experimental spectrum but also contributes to a considerable enhancement in the signal-to-noise ratio.

A variety of techniques have been proposed to achieve polarization control and fast polarization switching of undulator radiation. Some permanent magnet undulators and electromagnet undulators have been designed to realize arbitrary polarization states. Some kinds of undulators, such as APPLE-II [1,2], APPLE-X, and DELTA [3–5], can adjust the polarization states by shifting the magnet arrays mechanically. Undulators that use both permanent magnets and electromagnets, such as the Electromagnetic/Permanent Magnets Helical Undulator in SOLEIL [6,7] and ESRF [8], are also specifically engineered to enable fast polarization switching. By inverting the direction of the coil current, the switching of circularly polarized radiation can be realized.

Twin-undulator systems that generate radiations in different polarization states can enhance the alternation frequency. The radiation of the two undulators can be separated and selected alternately. Many techniques such as electromagnetic switching [9,10], photon beamline switching [11–14], electron beam orbit switching [15–17], and nature close orbit switching [18] have been developed. Another method to achieve fast polarization switching is to modulate the output spectrum. This can be achieved by using phase shifters between undulators to split the spectrum [19–23] or using modulating magnetic field to detune the undulator harmonic slightly [18,24,25]. In Ref. [24], the method of modulating magnetic field by adding electromagnet coils has been originally mentioned.

In this paper, inspired by the previous works, a method for fast polarization switching of undulator radiation based on magnetic field modulation is developed. As illustrated in Fig. 1, two identical elliptically polarized undulators are positioned along the same beamline and operated with different polarization states. The field modulation is generated by thin electromagnetic coils placed on the upper and lower surfaces of the vacuum chamber. In each undulator, the coils are fed with a pulsed current. When the current is on, a weak magnetic field is generated, resulting in a modulation of the output spectrum and making the main radiation flux shift out of the bandpass of the monochromator. Through alternately feeding current pulses to the coils of the two undulators, fast polarization switching of radiation after passing through the monochromator can be achieved. The key point of this method is

*Contact author: liheting@ustc.edu.cn

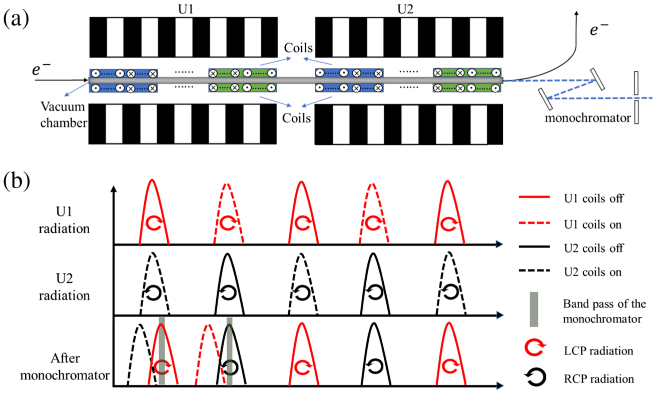

FIG. 1. The schematic of (a) the setup of the device and (b) the polarization switching.

that the period of the coils is set to an integral multiple of the undulator period, which can significantly reduce the required coil field and make it possible to use a low current to generate the modulation field. This method can enable fast switching between two selected polarization states at a frequency of several hundreds or even kilohertz while maintaining a high photon flux with a high polarization degree.

The rest of this paper is organized as follows: First, the theoretical analysis of this method is given. Then the radiation performance with modulation coils is studied in detail. Additionally, constraints on the switching frequency are evaluated and discussed. Finally, we make a summary.

II. PRINCIPLE

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 generated by the magnetic field of the coils. The coil field only affects the vertical magnetic field, therefore, first, we 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 vertical magnet field B_y that it experiences can be expressed as the superposition of the undulator field and the weak coil field.

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

Here, k_u is $2\pi/\lambda_u$ 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 coil 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, one can obtain

$$\beta_x = \frac{K_y}{\gamma}\left[\cos(k_u z) + \alpha m\cos\left(\frac{1}{m}k_u z + \varphi_0\right)\right], \quad (2)$$

where $K_y = \frac{eB_{y0}}{m_e c k_u}$ is the undulator strength parameter in the vertical direction. Considering $m \geq 2$, the average velocity of electrons along the undulator direction in a complete period $m\lambda_u$ can be deduced as

$$\beta_{z0} = 1 - \frac{1}{2\gamma^2} - \frac{K_x^2}{4\gamma^2} - \frac{K_y^2}{4\gamma^2}(1 + \alpha^2 m^2), \quad (3)$$

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. For $m = 1$, the above equation keeps correct only when φ_0 equals to odd multiple of $\pi/2$, otherwise, the contribution of φ_0 should be taken into account.

Using the undulator emitting model, one can get the on-axis radiation wavelength

$$\lambda_s = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K_x^2}{2} + \frac{K_y^2}{2}(1 + \alpha^2 m^2)\right). \quad (4)$$

Here, n is the harmonic number of the radiation. When the coil field is off ($\alpha = 0$), the above equation degenerates to the conventional resonance condition. Focusing on the fundamental radiation, namely $n = 1$, comparing with the result of a conventional undulator with $K = \sqrt{K_x^2 + K_y^2}$, the movement of the fundamental wavelength can be written as

$$\frac{\Delta\lambda}{\lambda} = \frac{K_y^2}{2 + K^2}\alpha^2 m^2. \quad (5)$$

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 bandpass of the monochromator, we need to further discuss the distribution of the modulated radiation spectrum. Only when the photon energy shift induced by the coil field is large enough, the radiation flux after passing through the monochromator can be reduced to an extremely low level. Considering the undulator radiation bandwidth, the required shift of the photon energy can be described as $\frac{\Delta\varepsilon}{\varepsilon} = \frac{\Delta\lambda}{\lambda} \geq \frac{1}{N_u}$, 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,

$$\alpha^2 m^2 \geq \frac{1}{N_u K_y^2}(2 + K^2). \quad (6)$$

One can find that $\alpha^2 m^2$ is the main factor that determines the shift of photon energy.

For example, for two identical undulators with $\lambda_u = 50$ mm, $N_u = 36$, and $K_x = K_y = 1.11$, using the above equations, we can find $\alpha^2 m^2$ need to be larger than 0.104. First considering the period of the coils is twice of the undulator, namely $m = 2$, the peak field of coils should be at least 0.038 T, which is rather difficult for a small coil with a low current. As for 4-time-period coils, the peak field of the coils needed reduces to 0.019 T, obviously easier to realize. And when $m = 6$, the required coil field is only 0.013 T. Moreover, as m increases, there is more longitudinal space for the coils, allowing for an increase in the number of coil turns and a decrease in the exciting current. This is beneficial to generate the required coil field with a lower current.

III. SIMULATION RESULTS

A. Basic radiation performance

To validate the theoretical analysis above, simulations based on the parameters of the XMCD undulator of Hefei Advanced Light Facility (HALF) [26,27] have been carried out. HALF is a 2.2 GeV diffraction-limited storage ring based light source under construction in the National Synchrotron Radiation Laboratory in China. The parameters used in simulations are presented in Table I.

Each of the two identical undulators is designed with a period length of 50 mm and a period number of 36. Considering that the height of the vacuum chamber is 10 mm and the coils occupy a vertical gap of 4 mm on each side, the minimal gap of each undulator is 20 mm. There are four coils in each complete period. Considering the limitation of the vertical gap, each coil is composed of two layers, and the number of turns in each layer is determined by one-fourth of the coil period length. For example, for $m = 4$, one-fourth of the coil period length is 50 mm. Assuming using the wire with a cross-sectional size of 2 mm × 2 mm, each layer of the coil has about 24 turns.

Here, first, we take the radiation at the photon energy of 411 eV as an example and the corresponding undulator strength parameter K_x/K_y is 1.11/1.11.

TABLE I. 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
Period number of each undulator N_u	36	⋯
Undulator parameter K_x/K_y	1.11/1.11	⋯
Photon energy	411	eV
The ratio of period m	2/3/4/6/9	⋯
Turns of coils in each period	25/36/48/74/100	⋯

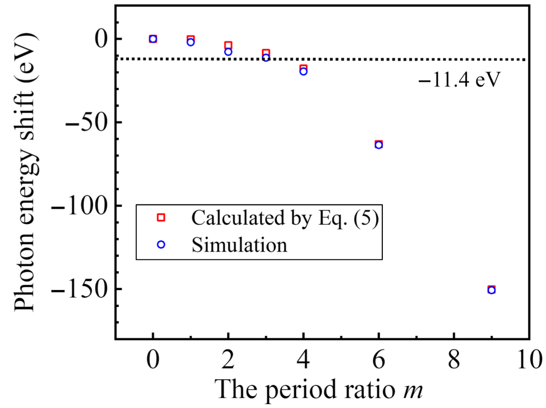

FIG. 2. The calculation and simulation results of the photon energy shift of fundamental radiation at max flux for different ratios of coil period to the undulator period. For $m = 1$, the phase shift φ_0 is $\pi/2$.

In the simulations, the magnetic field is calculated by combining the undulator and the coils as a whole with RADIA [28] and the spectrum is simulated with the SPECTRA [29] code. Figure 2 illustrates the photon energy shift of the fundamental radiation with coil field modulation from theoretical calculation and simulation. Here, the coil period is an integral multiple of the undulator period, and from the comparison, it is obvious that the simulation results agree with the theoretical value very well for different coil periods. It should be noted that, with the increase of the period ratio m, there is more longitudinal space allowing the coils to have more turns, thus more turns in each coil are used when m is bigger. However, the exciting current for the coils with different period length is fixed at 12 A. From Fig. 2, as the period ratio m increases, the photon energy shift increases rapidly. Since the fundamental radiation bandwidth is about 11.4 eV, the period factor m should be larger than 4 for sufficiently reducing the flux of the modulated spectrum at 411 eV. Actually, when m becomes extremely large, the coil field severely distorts, deviating from the sine wave, and leading to distortion of the modulated spectrum. When $m = 1$, the magnetic field that the coils can provide is only about 0.004 T, which is too small to generate enough photon energy shift.

The radiation spectrum has been simulated and given in Fig. 3. At the point of the photon energy of 411 eV, which is the fundamental energy of the undulator radiation and also the center of the bandpass of the monochromator, the radiation flux of the undulator with 4-time-period coils reduces to less than 1%, and it will be less than 0.1% for 6-time-period coils. It also can be found that the main flux of the modulated radiation decreases obviously with the increase of m. This is because more components of high order harmonics appear when m becomes larger.

When the target photon energy of the radiation increases, the undulator strength parameter decreases. From Eq. (6), one can find that, to shift the radiation out of the bandpass

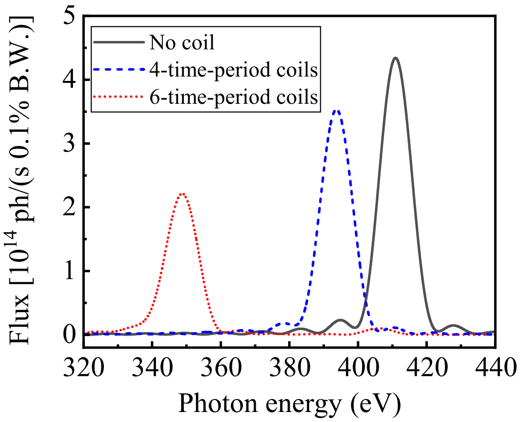

FIG. 3. The radiation spectra without modulation (black solid) and radiation spectra modulated by coils with period ratio of $m = 4$ (blue dash) and $m = 6$ (red dot).

of the monochromator, the required coil field also decreases. The calculating results of the photon energy shift for different target photon energies using Eq. (5) based on 4-time-period coils are shown in Fig. 4. Here the peak field of the coils is fixed at 0.02 T, corresponding to the minimal coil field calculated by Eq. (6). The results show that, for higher photon energy, this method can work more comfortable because lower coil current is required. To cover lower photon energy such as 250 eV, one need to choose larger undulator period and/or larger period ratio m. However, the determination of the ratio m should be considered combining with the total period number of each undulator and the undulator period number should be an integral multiple of m.

The effect of the phase deviation between the coil field and the undulator field has also been checked and it was found that it had nearly no influence on the photon energy shift of the radiation from the modulated field. This suggests that the proposed scheme exhibits a lower sensitivity to the assembly accuracy of the coils in practice.

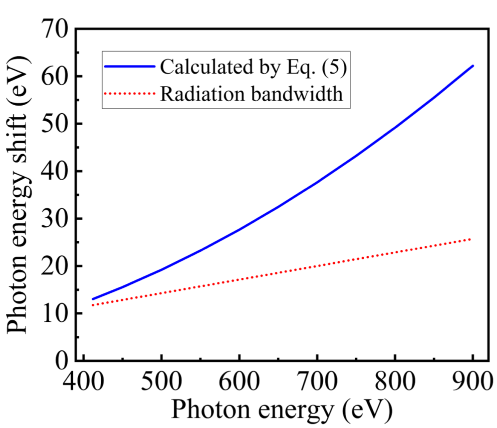

FIG. 4. The photon energy shift (blue solid) of using 4-time-period coils with peak field fixed at 0.02 T for different working photon energies and the radiation bandwidth (red dot) that is also the required minimal photon energy shift.

B. The switching frequency

The polarization switching frequency of permanent magnet undulators is limited to a few Hz, because magnet arrays are driven by a mechanical motion system and operated within an environment of strong magnetic forces. Currently, various force compensation schemes are being developed [30–32] and this may be beneficial to increase the switching frequency. For undulators with full or partial electromagnets, the switching frequency is limited by the coil self-inductance and the induced eddy currents in the vacuum chamber wall. To reduce the effect of eddy current, the vacuum chamber material should have a large resistance. It is also important to avoid employing excessively high exciting current of the coils.

As mentioned above, for radiation of 411 eV, the coil field should be at least 0.02 T for using the 4-time-period coils. For the coils described in the previous subsection, the inductance of each coil is about several μH, which has little impact on the polarization switching frequency. What we shall refer to as the main type of distortion is the field penetration delay caused by eddy currents when the magnetic field passes through the vacuum chamber.

Figure 5 illustrates how different kinds of vacuum chambers influence the pulsed magnetic field of the coils. The impact of the vacuum chamber material as well as the inductance of the coils on the time delay of the pulsed magnetic field has been evaluated employing the *CST Studio Suite* [33]. A square-wave exciting current pulse with a width of 4 ms was used to feed the coils as an example. Faster rise times result in longer duration at maximum values and quicker responses. As shown in Fig. 5, the four curves represent the results of vacuum

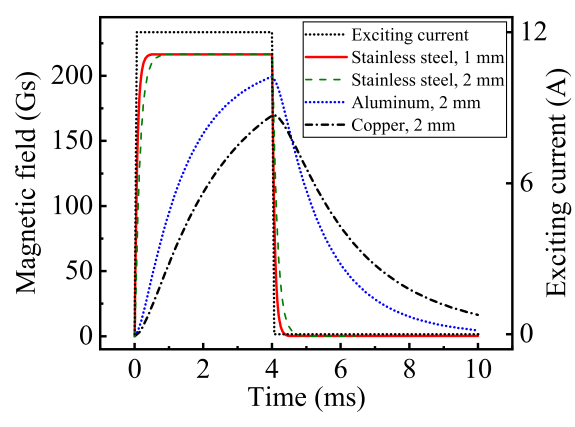

FIG. 5. The square wave exciting signal (black dot) and the response of the magnetic field on the beam orbit for different kinds of vacuum chambers. Red solid: stainless steel with 1 mm thickness; Olive dash: stainless steel with 2 mm thickness; Blue dot: aluminum with 2 mm thickness; Black dash dot: copper with 2 mm thickness.

chamber material of copper, aluminum, and stainless steel, respectively. Obviously, when using the stainless-steel vacuum chamber with the wall thickness of 1 mm, the sum of the rise time and fall time of the coil field is less than 0.2 ms. It indicates that the rise and fall process of the coil field can be finished in less than 0.2 ms for every current pulse, which means the fast polarization switching of the system at a frequency of kilohertz can be expected.

IV. SUMMARY

In this paper, a method was proposed to control the undulator radiation polarization using magnetic field modulation. The output radiation of the undulator after the monochromator can be modulated by adding thin hollow electromagnetic coils in a twin-undulator system. Using coils with a period length of an integral multiple of the undulator period makes it possible to generate enough photon energy shift with low exciting current. Calculation and simulation results demonstrate that the scheme can achieve fast switching of polarization at a frequency of several hundreds or even kilohertz and exhibits high engineering feasibility. The electromagnetic coils can be integrated and uniformly installed on the vacuum chamber of existing undulators, such as two APPLE-II undulators. This approach allows researchers to easily turn on or off the coil groups to achieve fast polarization switching or to use specific polarized radiation. Due to the relatively low exciting current for the coils, no additional cooling system is required. Furthermore, these coils can correct the first and second integrals of magnetic fields themselves without requiring additional correction magnets so that they have little impact on electron beam orbits. In summary, with strong potential for engineering application, this scheme holds promise for providing more options in future related beamline design and construction.

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