POLARIZATION CONTROL OF STORAGE RING FELS USING CROSS POLARIZED HELICAL UNDULATORS *

J. Yan[1,†], H. Hao[1], S. Mikhailov[1], V. Popov[1], S. Huang[2], J. Y. Li[3],
V. N. Litvinenko[4], N. A. Vinokurov[5], Y. K. Wu[1,‡]
[1]DFELL/TUNL, and Department of Physics, Duke University, Durham, NC, USA
[2]Institute of Heavy Ion Physics, Peking University, Beijing, China
[3]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[4]Department of Physics and Astronomy, Stony Brook University, Stony Brook, USA
[5]Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

For more than two decades, accelerator researchers have been working to gain control of polarization of synchrotron radiation and FELs using non-optical means. In 2005, using mixed linear and helical undulators, the first experimental demonstration of polarization control of an FEL beam was realized with the Duke storage ring FEL. With the recent upgrade of the undulator system, the Duke FEL can be operated with up to four helical undulators simultaneously. Using two sets of helical undulators with opposite helicities, for the first time, we have demonstrated full control of the polarization of a storage ring FEL, including helicity switching and rotatable linear polarization. The helicity switching of the FEL beam has been realized with good lasing up to a few Hertz. The generation of a linearly polarized FEL beam using a set of cross polarized helical undulators has been demonstrated with a high degree of polarization ($P_{\text{lin}} > 0.95$). The FEL polarization direction can be fully controlled using a buncher magnet. Furthermore, the use of non-optical means to control the FEL polarization allows us to extend polarization control to γ-ray beams via Compton scattering. For the first time, we have produced linearly polarized Compton γ-ray beams with the rotatable polarization direction using helical undulators.

INTRODUCTION

Control of the polarization of light is of great importance to certain scientific research. For example, in the optical regime, a circularly polarized radiation source with switchable handedness can be used for magnetic dichroism experiments [1, 2]. In addition, some polarization-dependent spectroscopy techniques require the radiation sources to have switchable linear polarizations (typically two orthogonal linear polarizations). Polarization of light can be manipulated using polarizing optics in the visible regime. However, for the short wavelength regions such as vacuum ultraviolet (VUV) or extreme ultraviolet (EUV) where polarizing optics are either not available or have very limited capabilities, controlling polarization without the need of using polarizing optics is critical. In fact, non-optical polarization control of the accelerator based light sources was proposed about 30 years ago, initially for the third-generation storage ring based synchrotron sources. A common approach to realize polarization control is to employ an undulator with multiple arrays of mechanically movable permanent magnets [3–5]. A specific polarization state can be obtained by translating one or more arrays of the magnets to a specific configuration. However, the manufacturing of such an undulator is typically very complicated and costly. Another method to obtain variable polarization is based upon the coherent superposition of two orthogonal polarization states. This idea (referred to as the crossed undulator configuration) was first proposed for planar undulators [6], where two identical planar undulators are used with the first one aligned to produce horizontally polarized radiation and the second one rotated by 90° to produce the vertically polarized radiation. The phase delay between two orthogonally polarized radiation beams is varied using a phase retarder positioned between two undulators, and elliptical polarization with arbitrary ellipticity can be obtained after a monochromator.

Polarization control is also a critical feature for FELs. Since the idea of the crossed undulator configuration was first introduced to the FEL field in the early 2000s [7], FEL polarization control was first experimentally demonstrated on a storage ring FEL at Duke University [8]. Later on, the development of polarization control using crossed undulators was proposed for several linac based FEL projects [9, 10]. In the past few years, some have experimentally realized polarization control using either variable-polarization undulators [11, 12] or crossed planar undulators [13, 14]. In Ref [7], Kim also proposed to use crossed helical undulators to produce linearly polarized radiation with controllable direction of the linear polarization. Its feasibility was theoretically confirmed by Dattoli *et al.* soon after [15, 16]. However, since most FELs do not have the configuration of crossed helical undulators, no experimental demonstration was done until the recent work at FERMI, a linac based high-gain FEL, in 2015 [14].

In 2005, the Duke storage ring FEL achieved polarization control using two planar undulators and two helical undulators [8]. By mixing the linearly polarized radiation from the OK-4 undulators and circularly polarized radiation from the OK-5 undulators with their relative FEL gains controlled by

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† junyan@fel.duke.edu, 1-919-660-2667.

‡ wu@fel.duke.edu, 1-919-660-2654.

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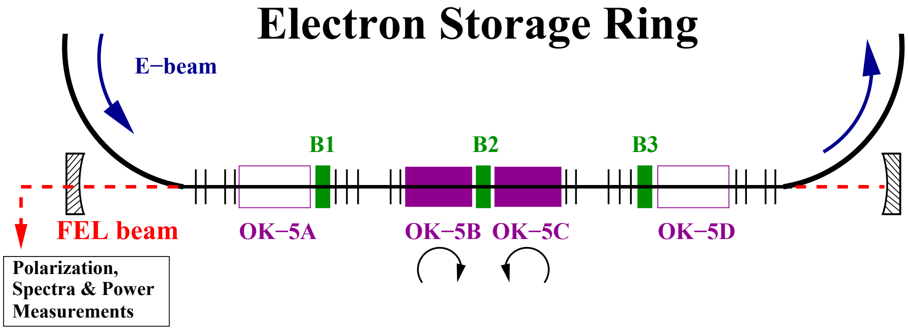

Figure 1: The undulator configuration for the polarization control of FEL beams used for this experimental work. The two helical undulators in the middle of the FEL straight section are turned on with OK-5B and OK-5C operated in normal helicity and reversed helicity, respectively.

buncher magnets, the polarization state of the FEL beams can be continuously tuned between linear and elliptical. However, using this approach, the orientation of the polarization ellipse cannot be independently adjusted. In addition, at that time only two outboard helical undulators (OK-5A and OK-5D) could be used, which unfortunately, were too far apart, and they could not form an effective crossed undulator configuration. Since 2012, with the installation of two additional helical undulators (OK-5B and OK-5C) on an undulator switchyard system in the middle of the FEL straight section [17], up to four helical OK-5 undulators became available for FEL operations (see Fig. 1). This opened up opportunities for the FEL to operate in some novel configurations with variable polarization. To realize control of the FEL beam polarization, two downstream undulators (OK-5C and OK-5D) have been configured with switchable helicity (using a solid-state based dc current switch to change the polarity of current in the vertical coils of the undulators) so that they can produce circularly polarized radiation with either handedness. The two upstream undulators (OK-5A and OK-5B) have a fixed helicity, producing right-handed circularly polarized radiation. Crossed helical undulators can be realized using either two undulators (OK-5B in normal helicity and OK-5C in reversed helicity) or four undulators (OK-5A and OK-5B in normal helicity, and OK-5C and OK-5D in reversed helicity). In this paper, we mainly report the experimental results for the two-undulator configuration, as shown in Fig. 1. Using this configuration, we have achieved the first experimental demonstration of a storage ring FEL with fully controllable polarization, including (1) helicity switching of circularly polarized radiation, and (2) generation of linearly polarized radiation with controllable polarization direction. Using a carefully calibrated polarization diagnostic system, the FEL beam with a high degree of linear polarization can be realized using two cross polarized helical undulators.

HELICITY SWITCHING OF AN FEL BEAM

For the helicity switching, OK-5B (normal helicity) and OK-5C (reversed helicity) undulators, powered by two independent power supplies, are used to produce right- and left-handed circularly polarized FEL beams, respectively (see Fig. 1). The lasing wavelength is typically set to the wavelength which has the minimum round-trip loss of the FEL cavity. Helicity switching is realized by alternately producing lasing of one undulator while preventing the other undulator from lasing. To stop the lasing of a particular undulator, its current is lowered by a few percent so that the center wavelength of the undulator is tuned away from the lasing wavelength and moved to a spectral region where the cavity loss is higher. Meanwhile, the current of the other undulator, which was parked at a lower current, is ramped up to produce FEL lasing. This simultaneous current ramping of two undulators leads to the lasing of one undulator while suppressing the lasing of the other undulator. Using this approach, the helicity switching can be realized at a reasonably fast rate, as high as 5–10 Hz depending on operational parameters. Using a 600 MeV electron beam, helicity switching of circular polarization was experimentally studied with the FEL lasing around 458 nm.

An optical measurement system, as shown in Fig. 2, was developed to characterize FEL beams. A beamsplitter (BS1) was used to split the FEL beam into two arms, with the regular FEL diagnostics lying in its transmission arm and the individual power measurements of the two beams with different circular polarizations located in its reflection arm. To minimize changes of the polarization state of the incident FEL beam due to beamsplitter BS1, this beamsplitter was aligned almost normal to the FEL beam with a small angle (~ 7.5°), which is the minimum angle permitted by the available space on the optical table (Fig. 2). In the reflection arm of BS1, a quarter-wave plate with its fast axis aligned

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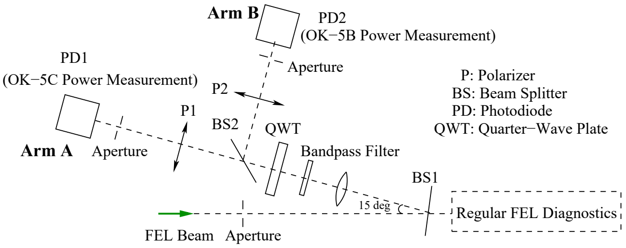

Figure 2: Optical diagnostics to study helicity switching. Power measurement for a particular helicity beam is carried out by selecting a beam of a particular polarization using a quarter-wave plate and a linear polarizer.

horizontally was employed to transform the incoming circularly polarized FEL beams into the linearly polarized ones, with the left-handed (right-handed) circular polarization converted to the 135° (45°) linear polarization. A polarizer in each arm after beamsplitter BS2 was then used to allow the beam of a particular polarization state to pass. Arm A and arm B were chosen to measure the FEL power produced by OK-5C and OK-5B undulators, respectively. The polarizing axis of each polarizer was aligned to minimize intensity leakage when the other undulator was used for lasing.

Helicity switching of a circularly polarized FEL beam was first characterized with a low switching frequency (2.5 mHz). Figure 3 shows a dc power measurement for two cycles of helicity switching during 13.6 minutes. The measured FEL powers produced by two undulators are cross-calibrated using the measured electron beam bunch lengthening. As shown in Fig. 3, the FEL powers are stable without tuning any knobs between two adjacent switchings with a relative rms variation of 0.5% for the right-handed circular beam (OK-5B) and that of 0.6% for the left-handed circular beam (OK-5C). In addition, the average power of the left-handed circular beam is about 7% lower than that of the right-handed circular beam. This may be attributed to the less optimal alignment between the electron beam trajectory and the optical path in OK-5C undulator, compared to that in OK-5B undulator. The tracking of the lasing spectra over the measurement period also shows a good spectral stability with the central wavelength kept nearly constant at 458.06 ± 0.07 nm with the rms spectral width of 0.89 ± 0.02 nm. Furthermore, as shown in the inset of Fig. 3, lowering the undulator current by 8% is sufficient to alternately stop lasing for the detuned undulator. Such a small amount of detuning allows helicity switching to be completed in a very short period of time. With this capability, the lasing processes for fast helicity switching (> 1 Hz) have also been investigated. It is found that as the helicity switching frequency increases, the FEL beam tends to show a more irregular pulsing structure. Therefore, in order to obtain reasonable stability with helicity switching FEL operation, the switching rate should be no greater than 2.5 Hz (for a 600 MeV electron beam), which is limited by the energy damping time of the electron beam circulating in the storage ring.

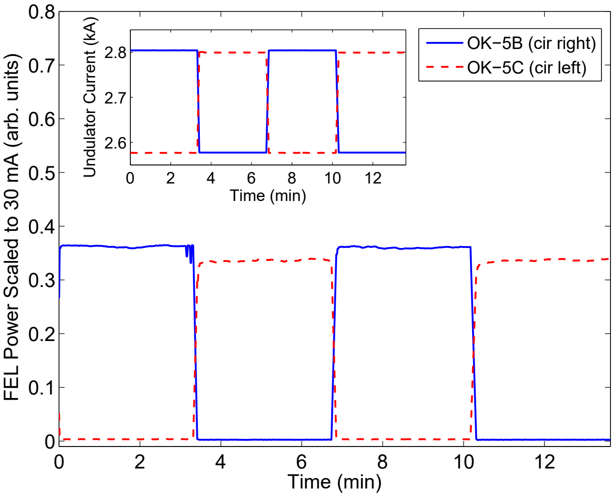

Figure 3: FEL helicity switching using cross polarized helical undulators. The beam current is kept between 29.50 mA and 31.15 mA with top-off injection. The injection occurred once (around $t = 3.2$ min) during the entire measurement. The measured FEL power is linearly scaled to 30 mA for the alternate lasings of OK-5B and OK-5C undulators. The inset shows the undulator currents as a function of time.

LINEARLY POLARIZED FEL BEAM GENERATED USING CROSSED HELICAL UNDULATORS

For the generation of linearly polarized radiation, independently powered OK-5B (normal helicity) and OK-5C (reversed helicity) undulators are used to lase simultaneously at the same wavelength (Fig. 1). With equal intensity, the two circularly polarized FEL beams of opposite handednesses are superposed to result in a linearly polarized beam. As usual, the lasing wavelength of each undulator is mainly tuned by varying the respective undulator magnetic field strength, with the fine adjustments of the wavelength realized by tuning buncher B2 (see Fig. 1). On the other hand, the requirement of equal intensity for the two circularly polarized beams to generate linearly polarized radiation can be met by balancing the FEL gains of the two undulators. The gain balancing is also achieved by tuning the undulator strengths and buncher B2. Furthermore, the direction of the generated linear polarization is determined by the phase difference between the two circularly polarized beams. This phase difference can also be controlled by tuning the field strengths of the two undulators and buncher B2, and consequently, any direction of the linear polarization can be obtained by tuning these three knobs properly. Therefore, in this experiment the strengths of OK-5B and OK-5C undulators and the setting of buncher B2 are three key knobs, which can be used not only to adjust the lasing wavelength, but also to balance the gain between two undulators as well as to manipulate the direction of linear polarization. The other knobs for optimizing the linear polarization of the FEL beam include the FEL mirror settings and the storage ring

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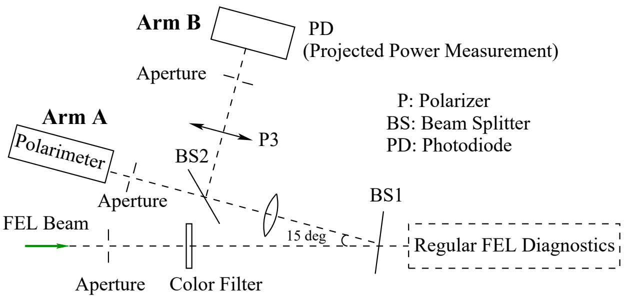

Figure 4: Optical setup for measuring FEL polarization. A polarimeter with a rotating quarter-wave plate is used to measure the polarization ellipse of the FEL beam in arm A. A more precise projection measurement is set up in arm B to measure the degree of linear polarization of the FEL beam.

rf frequency detune. The experimental results reported in this work were obtained using a 550 MeV electron beam and FEL lasing around 548 nm.

As shown in Fig. 4, the optical diagnostics in this work is similar to that shown in Fig. 2 for helicity switching, except for the setup in the reflection arm of beamsplitter BS1, which is modified to characterize the FEL beam polarization by measuring Stokes parameters. In the reflection arm of BS1, the FEL beam is split by a second beamsplitter (BS2) so that one beam is sent to a polarimeter in arm A and the other beam to a polarizer (P3) followed by a photodiode (PD) in arm B. The polarimeter used is Model PA510 from Thorlabs, a device to measure Stokes parameters using the technique of a rotating quarter-wave plate. However, the workable wavelength range of this polarimeter is limited to 450–700 nm. The precision of the polarimeter measurements highly depends on the intensity stability of the incident optical beam. Because the intrinsic power fluctuation of the FEL beam has time constants related to certain harmonics of the polarimeter signal, the polarimeter has been modified to reject FEL beam fluctuation. However, the polarimeter after being modified still has some issues under certain operational conditions. Therefore, we have also developed an independent optical setup to precisely measure the degree of linear polarization using a polarizer and a photodiode. This setup is installed in arm B. The degree of linear polarization can be experimentally obtained by measuring the maximum and minimum intensities of the incoming FEL beam by rotating the polarizer. This setup can be used for a wide spectral range with a properly chosen polarizer.

By scanning the setting of buncher B2 (N_{B2}, representing the relative phase delay between the laser and electron beams), the linear polarization of the FEL beam can be continuously rotated. Figure 5 shows a 360° rotation of the linear polarization (a complete two-period rotation) with N_{B2} varied from 0.33 to 2.33. In the figure, the polarization direction θ_1 (relative to the horizontal direction) and the degree of linear polarization P_{lin} are measured using the polarizer and the photodiode in arm B (Fig. 4). In order to take into account the change of the polarization state caused by the effect of the optics, the whole optical system is carefully calibrated using the Mueller matrix formalism [18], and the measured quantities are corrected accordingly. As shown in Fig. 5(b), with the fine tuning of the operational parameters (N_{B2}, undulator currents, FEL cavity mirrors, ring rf frequency etc.), a high degree of linear polarization has been achieved for all measured polarization directions with $P_{\text{lin}} = 0.94$–0.98. In addition, throughout the process of rotating the direction of the linear polarization, the FEL power is maintained reasonably stable with a relative power variation of 6.8% (rms), and the lasing spectra is also steady with the central wavelength kept at 547.81 ± 0.10 nm.

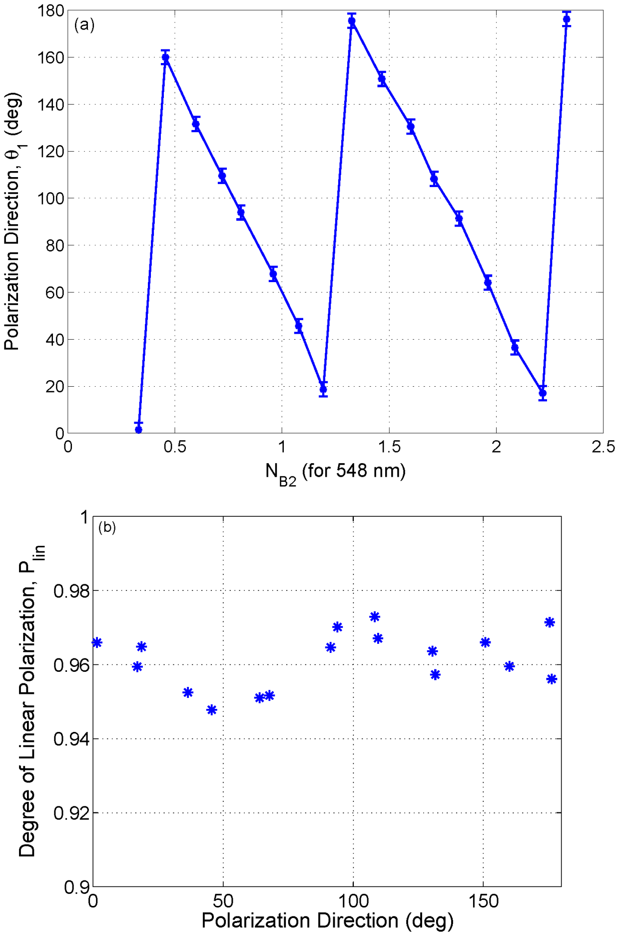

Figure 5: Rotation of the linear polarization by continuously varying buncher B2. (a) The dependency of the polarization direction θ_1 on N_{B2}. All directions (θ_1) have been projected into the range of 0–180°. (b) The measured degree of linear polarization of the FEL beam at the FEL exit window, P_{lin}.

SUMMARY

Using two closely placed helical undulators with opposite helicities and independent power supplies, we have achieved full polarization control for a storage ring FEL. By simultaneously ramping the currents of the two undulators in opposite directions between a lower parking setting and the operational setting, we have realized helicity switching of the circularly polarized FEL beam. In addition, operating these two cross polarized helical undulators to lase simultaneously with well balanced gains, we have experimentally demonstrated the generation of the linearly polarized FEL beam with a high degree of linear polarization (0.94–0.98). The direction of this linear polarization can be rotated by tuning the buncher magnet between the two undulators.

The Duke FEL is mainly used as a laser driver to produce Compton γ-ray beams at the High Intensity γ-ray Source [19, 20]. Since the backscattered γ-rays inherit the polarization of the laser photons, both new capabilities to control FEL polarization can be readily transferred to γ-ray production. The ability to produce γ-ray beams with full polarization control and flexibility will open up a variety of opportunities for experimental nuclear physics research [20,21]. Using the crossed helical undulator configuration, the production of linearly polarized γ-ray beams with the rotatable polarization direction has been recently demonstrated, and further optimization will be carried out as our future work.

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REFERENCES

[1] L. Baumgarten *et al.*, *Phys. Rev. Lett.* **65**, 492 (1990).

[2] A. Agui *et al.*, *Rev. Sci. Instrum.* **72**, 3191 (2001).

[3] S. Sasaki *et al.*, *Nucl. Instr. and Meth. in Phys. Res. A* **331**, 763 (1993).

[4] S. Sasaki *et al.*, *Nucl. Instr. and Meth. in Phys. Res. A* **347**, 87 (1994).

[5] T. Tanaka, K. Shirasawa and H. Kitamura, *Rev. Sci. Instrum.* **73**, 1724 (2002).

[6] K. J. Kim, *Nucl. Instr. and Meth. in Phys. Res. A* **219**, 425 (1984).

[7] K. J. Kim, *Nucl. Instr. and Meth. in Phys. Res. A* **445**, 329 (2000).

[8] Y. K. Wu *et al.*, *Phys. Rev. Lett.* **96**, 224801 (2006).

[9] H. Geng, Y. Ding, and Z. Huang, *Nucl. Instr. and Meth. in Phys. Res. A* **622**, 276 (2010).

[10] Y. Li, B. Faatz and J. Pflueger, *Nucl. Instr. and Meth. in Phys. Res. A* **613**, 163 (2010).

[11] E. Allaria *et al.*, *Phys. Rev. X* **4**, 041040 (2014).

[12] A. A. Lutman *et al.*, *Nat. Photon.* **10**, 468 (2016).

[13] H. Deng *et al.*, *Phys. Rev. ST Accel. Beams* **17**, 020704 (2014).

[14] E. Ferrari *et al.*, *Sci. Rep.* **5**, 13531 (2015).

[15] G. Dattoli, P. L. Ottaviani, and L. Bucci, *Optics Comm.* **195**, 419 (2001).

[16] G. Dattoli, and P. L. Ottaviani, *Nucl. Instr. and Meth. in Phys. Res. A* **479**, 668 (2002).

[17] Y. K. Wu *et al.*, *Proceedings of the 2013 International Particle Accelerator Conference* 267 (2013).

[18] D. Goldstein, Polarized Light. New York: Marcel Dekker, Inc., second edition, 2003.

[19] V. N. Litvinenko *et al.*, *Phys. Rev. Lett.* **78**, 4569 (1997).

[20] H. R. Weller *et al.*, *Prog. Part. Nucl. Phys.* **62**, 257 (2009).

[21] B. E. MacGibbon *et al.*, *Phys. Rev. C.* **52**, 2097 (1995).

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