Segmented Undulator for Extensive Polarization Controls in $\leq 1$ nm-rad Emittance Rings

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We designed a segmented undulator composed of four units of an APPLE undulator, such as an APPLE-II, and three phase-shifters. By simulating the optical performance in a 1-nm-rad emittance ring of synchrotron radiation, the novel undulator generates various polarized light that have high flux, high polarization, and fast-switching with a marginal perturbation to an electron beam in the storage ring. Varieties of polarization combinations in undulator segments allow for novel research, such as experiments using orbital angular momentum in X-ray photons. Furthermore, they provide a high flux third harmonic beam for both linear and circular polarizations, extending the photon energy range significantly at a beamline. The high degree of freedom in polarization controls of the segmented undulator provides opportunities for new experiments with low-emittance synchrotron radiation or X-ray free electron lasers.

Keywords Undulator; Soft X-ray; Polarization; Synchrotron radiation

I. INTRODUCTION

Polarization dependence in soft X-ray spectroscopy has been a direct probe for investigating electronic states in materials [1–8]. Polarization controls have been a central issue in technology for soft X-ray synchrotron radiation [9–27]. While in general, polarizers have been adopted in optical experiments, those of the soft X-ray polarizer have had limits in degree of polarization and in photon energy [28, 29]. This is because a polarizer functions by photoabsorption in magnetic materials. Polarization controls at beamlines in synchrotron radiation facilities have been carried out, for example, with an Advanced Planar Polarized Light Emitted (APPLE) undulator, such as APPLE-II [9, 10]. By mechanically arranging magnet arrays in the undulator, light with circular and linear polarizations is generated by helical and tortuous trajectories of electrons, respectively. The polarization change typically takes an order of minutes at synchrotron radiation facilities.

Nowadays, much faster switching of polarizations has become necessary at the beamline for nanobeam experiments or modulation spectroscopies. For example, measurements of X-ray magnetic circular dichroism (XMCD) have been made in nanometer scale so that it should be completed before any possible spatial drift on a sample. Highly sensitive XMCD measurements using locking amplification have also become necessary to capture faint spin signals in spintronic materials. Moreover, recent developments in detectors and in machine learning simulations, such as sparse-modeling [30], have made measurements so fast that controls of undulators are approaching their temporal limit in the user beamtime.

In synchrotron radiation facilities, various techniques have been developed to realize the fast polarization switching in the soft X-ray region. The cross undulator, which was the first to be proposed [17] and tried [16], is composed of two undulators having orthogonal field components placed in tandem in the same straight section; specifically, one generates horizontally polarized radiation while the other generates vertically polarized radiation, resulting in various
polarization states depending on the relative phase between the two optical waves. The polarization state can be controlled by tuning the phase using the so-called phase shifter (one-period undulator) inserted between the two undulators. The phase shifter is usually made of electromagnets, so that the phase can be quickly varied, and the polarization state can be quickly switched.

The most serious problem in using cross undulators is that the degree of polarization \( P \) attainable under practical conditions is rather low. This is because the polarization states (Stokes parameters) of radiation emitted from the cross undulator strongly depend on the observation angle. As a result, \( P \) rapidly drops with the increasing aperture angle in the beamline to obtain higher photon flux. In practice, it was reported in Ref. 16 that \( P \) actually measured with a polarimeter was lower than 50%. It should be emphasized that reducing the emittance of the electron beam does not overcome the difficulty; even with a single electron (zero emittance), we cannot achieve a high degree of polarization with a cross undulator due to the large aperture angle. Because of this problem, the cross undulator is not realistic for synchrotron radiation sources, and thus is not actually used in any facilities to our knowledge.

Another scheme for the fast polarization switching was proposed and developed in SPring-8 [22]. This is based on two undulators as well as a cross undulator, which generate circularly polarized radiation with opposite helicities and are combined with kicker magnets to kick the electron beam at the entrance of either of the two undulators. As a result, only one of the two polarization states is observed on the axis, which can be switched by changing the bump orbit. Although the kicker magnet system has been used in SPring-8 with a maximum switching speed of 10 Hz for more than 15 years, and has enabled a variety of experiments, it can induce a large fluctuation in the electron beam trajectory and disturb the stable operation of the storage ring. This comes from the large kick angle (hundreds of micro radians) required to completely separate the two photon beams that have opposite helicities. This problem can be more serious when low-emittance storage rings become available, thus increasing the switching speed is not realistic.

A third scheme for fast polarization switching has been proposed in SPring-8 [18, 19] and installed in BL07LSU [20] to overcome the above difficulties. This is an extension of the cross undulator and is referred to as a segmented cross undulator; the undulator is divided into many segments to form a series of cross undulators as shown in Figure 1(a). Specifically, all the segments have the same undulator parameters, but the polarization property at the even numbered segments is orthogonal to that at the odd numbered segments. By tuning the phase shifters inserted between segments, the polarization state can be controlled. What is important in this scheme is that the dependence of the Stokes parameters of radiation is much weaker than that of a cross undulator having the same specifications. Thus, \( P \) can be kept relatively high even with a large aperture angle. In addition, the effects on the electron beam trajectory are much lower than those of the kicker-magnet system. Summarizing the above discussions, a segmented cross undulator is the best choice to realize polarization switching with a speed exceeding 10 Hz in future storage rings where the electron beam trajectory should be highly stable.

We now note that the segmented cross undulator in BL07LSU of SPring-8 is composed of (horizontally and vertically polarized) figure-8 undulators; this is to reduce the heat load near the optical axis as much as possible. This is critically important for optical elements in soft X-ray beamlines, particularly in SPring-8, which has a high electron energy of 8 GeV. Thus, fast polarization switching is basically limited to that between the left- and right-handed circular polarizations (and optionally between tilted linear polarizations at +45° and −45°). In principle, however, it is possible to switch horizontal and vertical polarizations by using helical undulators for each segment as mentioned in Ref. 18. In other words, we can expect a flexible operation of the cross undulator if the polarization of each segment is variable. In practice, this is possible by adopting the APPLE undulator [9], in which arbitrary polarization states are made available by the “phasing” operation (longitudinal mechanical motion of the magnetic array). It should be emphasized that operating the APPLE undulator in linear-polarization

![Figure 1](image)
mode can bring a high heat load, which should be seriously considered.

In this technical report, we present a segmented cross undulator design composed of APPLE undulators, which can be installed in a storage ring with an emittance of 1 nm rad and an electron energy of 3 GeV, which are typical of (or similar to) those in many synchrotron radiation facilities under operation or construction. Our simulation indicates that the novel segmented undulator exceeds the performance of the cross type, including characters that have never been achieved with existing insertion devices in facilities. The present segmented undulator generates polarization-tunable soft X-ray beams with high flux, high polarization, fast-switching, a wide photon energy range, and great potential.

II. SIMULATION

A. Design

A segmented cross undulator is composed of four segments and three phase shifters, as schematically drawn in Figure 1(a). The segment is an APPLE undulator, such as an APPLE-II type [9, 10], that produces linear or circular polarized light by magnetically regulating electron motions in the insertion device. The phase shifter is composed of a pair of electromagnetic coils; its role is to add electron trajectory between the neighboring segments so that one can control a phase shift (phase difference) between electromagnetic waves generated individually. The source provides light with varieties of polarization depending on the choice of undulator-types for the segments.

The example in Figure 1(a) corresponds to the extension of a cross undulator that consists of two planar or figure-8 undulators that create photons with horizontally or vertically linear polarization [16, 17]. When a cross undulator is segmented, it is a “segmented cross undulator” [18–21]. Figure 1(b) illustrates an evolution of the light polarization from the segmented cross undulator with horizontal linear segments (#1 and #3) and vertical linear segments (#2 and #4). In this case, all the three phase shifters take the same amount of change but opposite in sign between the center one and the other two. By sinusoidal variation of a phase shift amplitude between π/2 and −π/2 by time with a frequency, ν, the light switches between left- and right-handed circular polarizations through the 45°-tilted linear polarization in one cycle, 1/ν [8]. It is noteworthy that the tilted linear polarization appears in a frequency of 2ν. For another example, when two types of helical undulators, (#1, #3) left-handed and (#2, #4) right-handed circular polarized light are chosen in a two types of helical undulators, (#1 and #3) left-handed and (#2, #4) right-handed circular polarized light are chosen in a two types of helical undulators, (#1 and #3) and the opposite helical (−h). Linear polarized light is produced with the helical (±h) undulators (#1 and #3) and the opposite helical (−h) were simulated by the synchrotron radiation calculation code, SPECTRA, developed by Tanaka [31–35]. Parameters used in the simulation are listed in Table 1. We assume an insertion device is in a 1-nm-rad emittance storage ring of synchrotron radiation with electron energy of 3 GeV. The total length of the segmented (cross) undulator is set at 4.2 m, including four 0.784-m-long segments and three phase shifters, each with a length of 0.15 m. The magnetic period is 56 mm to generate soft X-rays in the 3 GeV storage ring and there are 14 periods in each undulator segment. For a comparison, we also made a simulation on a 4.2-m-long undulator with 75 periods of the 56-mm magnetic unit. The fundamental (first-order) photon energy was set at hv1st = 700 eV to demonstrate L-shell absorption edges of transition metal elements that have been typically adopted in polarization dependent X-ray absorption experiments. The corresponding K-values of undulator segments are shown in Table 1.

C. Results and discussion

Table 2 shows examples of a segmented cross undulator (U), a segmented U, and a long U. Circular polarized light is generated in a segmented cross U with the horizontal linear undulators (#1 and #3) and the vertical linear undulators (#2 and #4). Linear polarized light is produced with the helical (+h) undulators (#1 and #3) and the opposite helical (−h)

| Table 1: Parameters used in the simulation at hv1st = 700 eV. |
|-----------------------------------------------|
| Parameters for a Storage Ring |
| Parameter | Value |
| Electron energy (GeV) | 3 |
| Average current (mA) | 400 |
| Natural emittance (nm rad) | 1 |
| Coupling constant | 0.002 |
| Parameters for Undulators |
| Segment (Cross) Undulator |
| Parameter | Value |
| Total length (m) | 4.2 |
| Number of segments | 4 |
| Number of phase-shifters | 3 |
| Magnet period (mm) | 56 |
| Number of periods in one segment | 14 |
| K (helical mode) | 1.1 |
| K (linear mode) | 1.5 |
| Long Undulator |
| Parameter | Value |
| Total length (m) | 4.2 |
| Magnet period (mm) | 56 |
| Number of periods | 75 |
| K (helical mode) | 1.1 |
| K (linear mode) | 1.5 |
undulators (#2 and #4). Segmented U, defined in this present simulation, takes a configuration in which all the segments are the same type: for example, circular polarized light by four helical (+h) undulators (#1−#4) or linear polarized light by the four linear (horizontal) undulators (#1−#4). Thus, a long U is solely a helical or linear undulator.

In Table 2, simulated values of partial power at the beam center are shown for individual combinations. Simulations for a long U indicates that the power of a linear undulator is almost three times larger than that of a helical undulator. This power dependence is consistent with the segmented U. These results indicate that when designing a beamline with an APPLE undulator, one has to consider possible damage or deformation of the optical elements by the heat load when using a linear polarized light. However, the power of the linear polarized light is reduced for a segmented cross U because the segments are helical undulators. This is one benefit of using the segmented cross U.

For polarization-controlled undulators, the switching time of the light polarization is a significant factor during a beamtime experiment. Table 2 lists switching times for the individual undulator types at current synchrotron radiation facilities. The time for a segmented U and a long U is determined by mechanical change of the magnet arrangement in an APPLE undulator. For example, it typically takes longer than 5 min when one switches between left- and right-handed circular polarization or between horizontal and vertical linear polarization at a synchrotron radiation facility. On the other hand, light polarization in a segmented cross U can be switched in milliseconds because it is now controlled by the user-defined AC current pattern, e.g., sine-wave or square-wave, through electromagnetic coils in phase shifters. As shown in Figure 1, the polarization change of a segmented cross U is much advanced than those of a segmented U and a long U. A segmented cross undulator in SPring-8 BL07LSU can attain polarization switching of 13 Hz (a period of 77 ms) at the experimental station during user operation mode of the storage ring [8]. Moreover, the phase shifter itself has been reported to work even at frequencies higher than 30 Hz (a period of 33 ms) [36]. Thus, the segmented cross U attains 10000 times faster switching than that of an APPLE undulator.

Figure 2 shows examples of simulated energy spectra of photon flux for the segmented cross U, segmented U, and long U. The light is set at $h\nu_{1st} = 700$ eV with the slit size ($\Delta\sigma_x, \Delta\sigma_y$) that correspond to $4\sigma_x \times 4\sigma_y$ of a spot profile of the long U. Number labels of the segments are shown in Figure 1(a).

| Undulator type | Polarization mode | Segment | Power (W) | Switching time |
|----------------|-------------------|---------|-----------|----------------|
| Segmented Cross U | Advanced circular | #1 linear (horizontal) | 20 | ms (phase shift) |
| | | #2 linear (vertical) | | |
| | | #3 linear (horizontal) | | |
| | | #4 linear (vertical) | | |
| | Advanced linear | #1 helical (+h) | 7 | ms (phase shift) |
| | | #2 helical (−h) | | |
| | | #3 helical (+h) | | |
| | | #4 helical (−h) | | |
| Circular | #1 helical (+h) | 7 | min (mechanical) |
| | #2 helical (+h) | | |
| | #3 helical (+h) | | |
| | #4 helical (+h) | | |
| Segmented U | Linear | #1 linear (horizontal) | 20 | min (mechanical) |
| | | #2 linear (horizontal) | | |
| | | #3 linear (horizontal) | | |
| | | #4 linear (horizontal) | | |
| Long U | Circular | #1 linear (horizontal) | 10 | min (mechanical) |
| | Linear | linear (horizontal) | 26 | min (mechanical) |
consistent with the experimental spectra of a segmented cross undulator reported in our previous study [20]. Figure 3(a, b) compares energy spectra of photon flux and the amount of circular polarization for a first-order undulator beam of $h\nu_{1st} = 700$ eV. The present simulation revealed that the peaks individually have different degrees of light polarization. The circular polarization is as large as 1 but the signs are inverted between the main and side peaks.

As shown in Figure 3(c), the simulation shows the apparent energy spectra for the third harmonics with a photon flux that is almost comparable to that of the fundamental beam [Figure 4(b)]. This is in sharp contrast to a helical undulator that has negligible photon flux for the third order. The generation with the segmented cross undulator is because beams from the linear undulator segments create high radiation in the third harmonics. As a consequence, the segmented cross U has the advantage of significantly extending the available photon energy range for beamline users, even for circular polarized light. The polarization spectrum in Figure 3(d) again shows that the sign is inverted between the main and the side peaks. Furthermore, polarizations of the main peaks are also opposite in the sign between the fundamental and the third harmonic beams. Because the spectra in Figure 3 show differences in the amount of photon flux and polarization, it is necessary to map their quantitative relationships at the spectral peaks.

**Figure 4** summarizes the amount of photon flux and absolute values of polarization for various undulators with (a) linear and (b) circular polarizations. As shown in Figure 3, the simulation found that a side peak at a higher energy has a larger degree of polarization than that at a lower energy, which has also been reported previously for a segmented cross undulator [20]. Thus, we present values for main peaks and side peaks at high energy, as labeled in Figure 2. To make comparisons in Figure 4, the photon flux was evaluated with a slit size of $(\Delta \sigma x, \Delta \sigma y)$, which corresponds to $4\sigma_x \times 4\sigma_y$ of a spot profile of the long U under Poisson distribution. The sequential four points on curves for a seg-

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**Figure 2:** Simulated photon energy spectra with circular polarization for (a) segmented cross undulator, (b) segmented undulator, and (c) long undulator. The photon energy was set at $h\nu_{1st} = 700$ eV. The slit size was set at $(\Delta \sigma L_x, \Delta \sigma L_y)$, as defined in the text.

**Figure 3:** Simulated (a, c) photon energy spectra and (b, d) circular polarization for a segmented cross undulator with linear undulator segments. The spectra in (a, b) were simulated with the first-order beam at $h\nu_{1st} = 700$ eV, while those in (c, d) with the third-order beam at $h\nu_{3rd} = 2100$ eV. The slit size was set at $(0.25\Delta \sigma x, 0.25\Delta \sigma y)$. 
mented cross undulator are simulated at \((\Delta \sigma_{Lx}, \Delta \sigma_{Ly})\), \((0.75\Delta \sigma_{Lx}, 0.75\Delta \sigma_{Ly})\), \((0.5\Delta \sigma_{Lx}, 0.5\Delta \sigma_{Ly})\), and \((0.25\Delta \sigma_{Lx}, 0.25\Delta \sigma_{Ly})\). For linear polarization [Figure 4(a)], a long-U and a segmented U make the high flux fundamental and third harmonic light with \(P_L = 1\). Reduction of the photon flux from long-U to segmented-U can essentially be understood by a decrease in the number of the magnet period. Concerning the segmented cross U, \(P_L\) of the side peak is better than 0.91 and it is larger than that of the main peaks. By reducing the slit size, the polarization becomes even larger and can reach 0.97 in a simulation.

In a case with circular polarization [Figure 4(b)], a long-U and a segmented U make the high flux fundamental light with \(P_C = 1\). It is noteworthy that the photon flux is larger for circular polarized light than for linear polarized light. This is because a helical undulator generates a higher flux beam than a planar undulator. Another feature is that the photon flux of a segmented U is apparently different from that of a segmented cross U for circular polarization [Figure 4(b)], while they are comparable for linear polarization [Figure 4(a)]. This is again because helical undulators generate a higher flux beam than planar undulators in a segmented cross U.

A side peak of the fundamental light from a segmented cross U has a circular polarization \(P_C\) better than 0.90. By reducing the slit size, \(P_C\) becomes large and reaches 0.97 at the minimum slit size in the calculation. The photon flux of the third harmonic beam is as large as the fundamental one. A value of \(P_C\) is better than 0.85 for the side peak in the third harmonics and approaches 0.9 when the slit size is reduced. The data in Figure 4 show that the photon flux of the main peak is larger than that of the side peak. However, the amount of the polarization is better for the side peak but becomes similar in the small slit size. For reference, values of the SPring-8 soft X-ray (SX) undulators are plotted in the figure with the \(4\sigma_x \times 4\sigma_y\) slit size of the SPring-8 photon beam. The comparison in Figure 4 demonstrates the expected performance of the soft X-ray segmented undulator in a 1-nm-rad emittance ring. It is worth mentioning that an XMCD image contrast can be obtained in nanometer scales at \(P_C = 0.38\) [29] and magnetic moments of atomically thin films are quantitatively determined by applying the sum rules of the XMCD spectra taken at \(P_C = 0.57\) [37] and \(P_C =

**Figure 4:** Comparisons between the photon flux and the absolute polarization values for (a) linear polarization and (b) circular polarization in various types of undulators. The photon flux values of a low-emittance long undulator (U) and low-emittance segmented U were taken with the slit size \((\Delta \sigma_{Lx}, \Delta \sigma_{Ly})\), which corresponds to \(4\sigma_x \times 4\sigma_y\) of a spot profile of the long U. The sequential four points on the curves of a low-emittance segmented cross U are simulated at \((\Delta \sigma_{Lx}, \Delta \sigma_{Ly})\), \((0.75\Delta \sigma_{Lx}, 0.75\Delta \sigma_{Ly})\), \((0.5\Delta \sigma_{Lx}, 0.5\Delta \sigma_{Ly})\), and \((0.25\Delta \sigma_{Lx}, 0.25\Delta \sigma_{Ly})\). For reference, values of the SPring-8 soft X-ray (SX) U are plotted in the figure with the \(4\sigma_x \times 4\sigma_y\) slit size of the SPring-8 photon beam.
0.65 \[38\]. The circular polarization modes of the segmented undulator in Figure 4(b) are sufficient to characterize magnetic materials.

Segments of the APPLE undulator leave a potential to combine a set of the different types of polarization modes. For example, one can suppose one type of the segments to be in helical mode and the other type to be in linear mode. This configuration allows us to conduct experiments on the photon vortex, the light with a topological polarization mode \[39–42\]. High harmonics, generated in a helical undulator, have been known to have singularities at the beam center and to carry orbital angular momentum (OAM), which can be defined by a topological number. Recently, soft X-ray photon beams with OAM have been observed in the second harmonic off-axis radiation of a helical undulator at a third-generation synchrotron radiation in low-emittance mode \(e = 1.66 \text{ nm rad} \) \[39\]. The photon vortex was evidenced by detecting the spiral patterns of photon intensity, which are a consequence of interference between the second harmonics \(2\nu\) of a helical undulator and the fundamental light of a planar undulator \(\nu\). Thus, a combination of a helical unit and a planar unit in the segmented undulator generates a photon vortex and allows us to characterize it. Photon beams carrying OAM have been predicted to make intriguing experiments, such as the separation of quadrupolar from dipolar transitions in X-ray photoabsorption in a material \[40\]. A segmented undulator with APPLE-type units provides a constant opportunity for novel experiments using the photon vortex.

The present segmented undulator also provides a new potential for experiments at soft-X-ray free electron lasers (SXFEL) \[38–40\]. Polarization controls at SXFEL have been a central issue in XFEL technology because there is no appropriate polarizer in this photon energy. This is in sharp contrast to experiments with hard X-ray FEL. Recently, a cross undulator has been considered for the polarization control for SXFEL \[43–45\]. The researchers studied the effectiveness of SXFEL and examined the stable operation \[45\]. Moreover, recent developments in a phase shifter proposed to switch circular (linear) polarizations for individual shots generated in a typical frequency range of 10 Hz \[36\]. By applying the present research, one can produce many extensive experiments using varieties of polarizations if the present segmented undulator is set with APPLE-type units at the end of a SXFEL.

III. CONCLUSION

We studied the optical performance of a segmented (cross) undulator with four units of an APPLE undulator and three phase-shifters by means of spectral simulation. The light source generates various types of polarizations, linear or circular, in both fundamental and third harmonic beams with high flux and fast switching. The undulator beamline is expected to make varieties of experiments possible at low-emittance synchrotron radiation and at XFEL facilities. Moreover, the great potential in a combination of segments leave many possibilities for developing novel research, such as experiments using orbital angular momentum in X-ray photons.

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References

[1] M. Niibe, N. Takehira, and T. Tokushima, e-J. Surf. Sci. Nanotechnol. 16, 122 (2018).
[2] K. Amemiya and M. Sakamaki, e-J. Surf. Sci. Nanotechnol. 16, 186 (2018).
[3] H. Watanuki, K. Mitsuhashi, and M. Takizawa, e-J. Surf. Sci. Nanotechnol. 16, 79 (2018).
[4] M. D’Angelo, R. Yukawa, K. Ozawa, S. Yamamoto, T. Hirahara, S. Hasegawa, M. G. Silly, F. Sirotii, and I. Matsuda, Phys. Rev. Lett. 108, 116802 (2012).
[5] R. Yukawa, S. Yamamoto, K. Ozawa, M. D’Angelo, M. Ogawa, M. G. Silly, F. Sirotii, and I. Matsuda, Phys. Rev. B 87, 115314 (2013).
[6] M. Ogawa, S. Yamamoto, Y. Kousa, F. Nakamura, R. Yukawa, A. Fukushima, A. Harasawa, H. Kondoh, Y. Tanaka, A. Hakizaki, and I. Matsuda, Rev. Sci. Instrum. 83, 023109 (2012).
[7] K. Takubo, K. Yamamoto, H. Hirata, Y. Yokoyama, Y. Kubota, S. Yamamoto, S. Yamamoto, I. Matsuda, S. Shin, T. Seki, K. Takahashi, and H. Wadati, Appl. Phys. Lett. 110, 162401 (2017).
[8] Y. Kubota, Y. Hirata, J. Miyawaki, S. Yamamoto, H. Akai, R. Hobara, Sh. Yamamoto, K. Yamamoto, T. Someya, K. Takubo, Y. Yokoyama, M. Araki, M. Taguchi, Y. Harada, H. Wadati, M. Tsunoda, R. Kinjo, A. Kagemiha, T. Seike, M. Takeuchi, T. Tanaka, S. Shin, and I. Matsuda, Phys. Rev. B 96, 214417 (2017).
[9] S. Sasaki, Nucl. Instrum. Methods Phys. Res. A 347, 83 (1994).
[10] S. Sasaki, K. Kakuno, T. Takada, T. Shimada, K. Yanagida, and Y. Miyahara, Nucl. Instrum. Methods Phys. Res. A 331, 763 (1991).
[11] T. Tanaka, T. Hara, M. Oura, H. Ohashi, H. Kimura, S. Goto, Y. Suzuki, and H. Kitamura, Rev. Sci. Instrum. 70, 4153 (1999).
[12] T. Tanaka and H. Kitamura, Nucl. Instrum. Methods Phys. Res. A 364, 368 (1995).
[13] T. Tanaka, and H. Kitamura, J. Electron Spectrosc. Relat. Phenomena 80, 441 (1996).
[14] T. Tanaka, H. Kitamura, J. Synchrotron Radiat. 3, 47 (1996).
[15] T. Tanaka, X.-M. Mare’chal, T. Hara, T. Tanabe, and H. Kitamura, J. Synchrotron Radiat. 5, 459 (1998).
[16] J. Bahrdt, A. Gaupp, W. Gudat, M. Mast, K. Molter, W. B. Peatman, M. Scheer, Th. Schroeter, and Ch. Wang, Rev. Sci. Instrum. 63, 339 (1992).
[17] K. J. Kim, Nucl. Instrum. Methods Phys. Res. 219, 425 (1984).
[18] T. Tanaka and H. Kitamura, Nucl. Instrum. Methods Phys. Res. A 490, 583 (2002).
[19] T. Tanaka and H. Kitamura, AIP Conf. Proc. 705, 231 (2004).
[20] S. Yamamoto, Y. Senba, T. Tanaka, H. Ohashi, T. Hiroto, H. Kimura, M. Fujisawa, J. Miyawaki, A. Harasawa, T. Seike, S. Takahashi, N. Nariyama, T. Matsushita, M. Takeuchi, T. Ohata, Y.
Furukawa, K. Takeshita, S. Goto, Y. Harada, S. Shin, H. Kitamura, A. Kakizaki, M. Oshima, and I. Matsuda, J. Synchrotron Radiat. 21, 352 (2014).

[21] Y. Senba, S. Yamamoto, H. Ohashi, I. Matsuda, M. Fujisawa, A. Harasawa, T. Okuda, S. Takahashi, N. Narita, Y. Moto, T. Hara, Y. Furukawa, T. Tanaka, K. Takeshita, S. Goto, H. Kitamura, A. Kakizaki, and M. Oshima, Nucl. Instrum. Methods Phys. Res. A 649, 58 (2011).

[22] T. Hara, K. Shirasawa, M. Takeuchi, T. Seike, Y. Saito, T. Muro, and H. Kitamura, Nucl. Instrum. Methods Phys. Res. A 498, 496 (2003).

[23] T. Hara, T. Tanaka, T. Tanabe, X.-M. Marechal, K. Kumagai, and H. Kitamura, J. Synchrotron Radiat. 5, 426 (1998).

[24] T. Muro, T. Nakamura, T. Matsuhashita, H. Kimura, T. Nakatani, T. Hirono, T. Kudo, K. Kobayashi, Y. Saitoh, M. Takeuchi, T. Hara, K. Shirasawa, and H. Kitamura, J. Electron Spectrosc. Relat. Phenomena 144–147, 1101 (2005).

[25] K. J. S. Sawhney, F. Senf, M. Scheer, F. Schaefers, J. Bahrdt, A. Gaupp, and W. Gudat, Nucl. Instrum. Methods Phys. Res. A 390, 395 (1997).

[26] K. Amemiya, M. Sakamaki, T. Koide, K. Ito, K. Harada, T. Aoto, T. Shioya, T. Obina, S. Yamamoto, and Y. Kobayashi, J. Phys.: Conf. Ser. 425, 152015 (2013).

[27] H.-W. Luo, T.-Y. Chung, C.-H. Lee, and C.-S. Hwang, J. Synchrotron Radiat. 26, 59 (2019).

[28] F. Schafer, H.-C. Mertins, A. Gaupp, W. Gudat, M. Mertin, I. Packe, F. Schmoll, S. D. Fonzo, G. Soulie, W. Jark, R. Walker, X. L. Kann, R. Nyholm, and M. Eriksson, Appl. Opt. 38, 4074 (1999).

[29] B. Pfau, C. M. Gunther, R. Konnecke, E. Guehrs, O. Hellwig, W. F. Schlotter, and S. Eisebitt, Opt. Express 18, 13608 (2010).

[30] Y. Yokoyama, T. Arima, M. Okada, and Y. Yamasaki, J. Phys. Soc. Jpn. 88, 024009 (2019).

[31] T. Tanaka and H. Kitamura, J. Synchrotron Radiat. 8, 1221 (2001).

[32] T. Tanaka, Phys. Rev. ST Accel. Beams 17, 060702 (2014).

[33] T. Tanaka, Opt. Lett. 42, 1576 (2017).

[34] T. Tanaka, Phys. Rev. Accel. Beams 21, 110704 (2018).

[35] http://spectrax.org/spectra/