Operation of a fast polarization-switching source at the Photon Factory

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Abstract. We have been developing a fast polarization-switching source for the vacuum ultraviolet and soft X-ray region at the B15-16 straight section of the 2.5-GeV Photon Factory (PF) storage ring. The source consists of two tandem APPLE-II-type elliptically polarizing undulators (EPUs), namely, U#16-1 and U#16-2, and a fast kicker system. The target frequency of polarization switching is 10 Hz. As the first step, we installed U#16-1 and five identical bump kickers in the PF ring in March 2008. Then, we constructed U#16-2 and installed it in August 2010. The orbit switching operation at 10 Hz, for user experiments, started in January 2012. We describe the details of the operation status of two EPUs and the fast local bump system in this report.

1. Introduction
At the 2.5-GeV Photon Factory (PF) storage ring, renovation for upgrading the straight sections for insertion devices was completed in 2005.[1] In an attempt to utilize the extended straight section effectively, we have been developing a fast polarization-switching source in the vacuum ultraviolet (VUV) and soft X-ray region at the B15-16 straight section.[2] This is one of the two longest (8.9 m) straight sections in the PF ring. The source consists of two tandem APPLE-II-type elliptically polarizing undulators (EPUs), namely, U#16-1 and U#16-2, and a fast kicker system. These two EPUs are identical and designed to produce soft X-rays in the energy region from 200 eV to 1 keV under various polarization states. Figure 1 shows a schematic view of the polarization switching system.

We adopted an APPLE-II-type magnetic arrangement to enable the EPU to achieve circular (left- and right-handed) as well as linear (horizontal, vertical, and in the ±45° direction) polarization states.[3,4,5] The target frequency of polarization switching is 10 Hz for using a lock-in technique, and a 0.3 mrad bump angle is required to separate the photons from the two undulators.

As the first step, we installed U#16-1 and five identical bump kickers in the PF ring in March 2008. Then, we constructed U#16-2 and installed it in August 2010. After the installation of U#16-1 and U#16-2, the operation of the EPUs for user experiments has continued steadily without any orbit switching. The available polarization modes are circular (Bx/By = 1), elliptical (Bx/By = 1/2), and linear in the horizontal and vertical directions. Figure 2 shows a photograph of U#16-1 and U#16-2 installed in the BL15-16 straight section. In 2011, we succeeded in polarization switching at 10 Hz.
with an orbit distortion of less than 10% of the beam size outside of the bump. The polarization switching operation at 10 Hz for user experiments was started in January 2012.

Figure 1. Schematic view of the polarization switching system.

Figure 2. Photographs of U#16-1 and U#16-2 in the BL15-16 straight section.

2. Characteristic of U#16-1 AND U#16-2

U#16-1 and U#16-2 are identical EPUs with an APPLE-II-type magnetic arrangement. The period length of the EPU is 56 mm and the periodicity number is 44, which satisfies the requirements for an energy region from 200 eV to 1 keV with the first harmonic in the 2.5 GeV PF ring. As magnet material we employed a Nd-Fe-B alloy with a remanent field of \( B_r = 12.5 \text{ kG} \) and coercivity of \( H_c = 25.0 \text{ kOe} \) (NEOMAX 38VH, manufactured by NEOMAX Co., Ltd.). The magnet blocks are coated with TiN (5 \( \mu \text{m} \) thick). Both undulators have four variable rows of magnetic arrays to change the polarization states and a gap-driving mechanism to change the photon energy. The typical operation modes include an EPU symmetric and an EPU antisymmetric mode. In the EPU symmetric mode, we displace a pair of rows diagonally opposite to one another. The EPU symmetric mode plays a major role in achieving circular (left- and right-handed) and linear (horizontal and vertical) polarization. In the EPU antisymmetric mode, we can achieve linear polarization with an arbitrary polarization angle.

Figure 3 shows the spectral properties of U#16-1 and U#16-2 in the EPU symmetric mode.

By individually shifting the four rows of magnetic arrays, we can use U#16-1 and U#16-2 as normal APPLE-II type EPUs as well as adjustable phase undulators (APUs) [6,7,8]. In the APU mode, we shift the upper pair of magnetic rows longitudinally with respect to the lower pair; however, the gap is kept fixed in order to change the photon energy. Figure 4 shows a schematic view of the magnetic arrangement of the APU symmetric mode. We define the present additional phase as the "pair phase." In the APU symmetric mode, the pair phase tunes the photon energy while maintaining a constant polarization state. In contrast, in the APU anti-symmetric mode, we can control the angle of the linear polarization plane by controlling the pair phase with constant photon energy radiation.[8]

We adjusted the magnetic field distribution of U#16-1 in its planar undulator configuration using the original position of four rows with a minimum gap of 21 mm. We used two moving Hall probes to measure the horizontal and vertical magnetic fields individually. The sampling ratio for data acquisition was 50 kS/s, and the speed of the Hall probes was 5 mm/s. We obtained magnetic field data in 0.1-mm steps after an averaging process for noise reduction. To adjust the field, we swapped the magnets and inserted shims to adjust the horizontal positions of individual magnets. We optimized the kick angle at each pole of the calculated electron orbit on the basis of the measured field data.

For the magnetic adjustment of U#16-2, we developed a procedure for optimizing the arrangement of its magnetic arrays.[9] We estimated the properties of the total magnetic field distribution of the EPU by superposing the individual fields of each of the magnets constituting the EPU. We measured the magnetic field distribution of each magnet block in advance, and we determined a suitable arrangement of the magnetic arrays by a simulated annealing method using the measured field data of the magnets. After we assembled the magnet blocks according to the simulated arrangement, we measured the magnetic field distribution of U#16-2 in the planar undulator mode for the original positions of the four rows with a minimum gap of 21 mm. The standard deviation of the phase errors
was 1.5° in the first measurement without any adjustment. For the distribution of the first integrals of the magnetic field at individual magnetic poles, we adjusted the horizontal positions of the magnetic blocks using shims.

**Figure 3.** Spectral properties of U#16-1 and U#16-2 in the symmetric mode.

**Figure 4.** Schematic view of the magnetic arrangement for the APU symmetric mode.

### 3. Operation of U#16-1 and U#16-2

We operated the two EPUs in the APU symmetric mode for tuning the photon energy by changing the pair phase with a fixed gap of 21 mm. The typical available polarization modes are circular ($B_x/B_y = 1$), elliptical ($B_x/B_y = 1/2$), and linear in the horizontal and vertical directions. In the case of the APU mode, the closed orbit distortion (COD) and the tune shift are small as compared to the gap change. Then, we can correct the COD easily by using steering magnets located at both ends of the undulator; the control system is simple and can be used to tune the photon energy and the polarization states. We correct the tune shift using quadrupole magnets on both sides of the straight section. In addition, we correct the skew quadrupole moment using a correction magnet installed downstream from the two EPUs. The corrected skew quadrupole moment is 270 G.

In the first operation of U#16-1 after commissioning, it was used as a circular polarized source in the APU symmetric mode. The measured spectra have different features compared to the usual EPU symmetric mode in which the photon energy is controlled by the combination of the gap and the row phase. The intensity of photon flux decreases by about half, and the bandwidth of the first harmonic peak increases in the APU symmetric mode. By a numerical analysis of the spectral properties in the APU symmetric mode, we found that the horizontal field non-uniformity of the EPU and the horizontal beam size (640 μm) of the PF-ring were mainly responsible for the reduction of flux intensity. Instead of intensity degradation, we observed a slight difference between the measured degrees of the circular polarization in these two modes; further, APU-mode operation with circular polarization and the obtained spectrum were sufficient for the experiments at BL16. The APU symmetric mode offers a highly useful feature, which allows the polarization state and the photon energy to be controlled during usual static operation as well as during fast polarization-switching operation because the disturbance of the electron beam is extremely small in this mode.

### 4. Fast local bump system

To achieve a fast local bump, five identical bump kickers were installed in a long straight section (B15-16) in the spring of 2008. The control system for the local bump was developed until the installation of U#16-2 in the summer of 2010. Figure 5 shows a schematic view of the configuration of the B15-16 straight section.

K1-K5 are the kicker magnets for the local bump. HVs are slow steering magnets to adjust the beam trajectory in two insertion devices, and FHVs are fast steering magnets for feed-forward correction in both the horizontal and vertical directions. Fast beam position monitors (FPMs) are used to adjust the fast bump, and PMs are normal beam position monitors for the COD correction.

The designed bump frequency is 10 Hz, and the required bump angle is 0.3 mrad to separate the photons from the two undulators. Each bump magnet has a length of 15 cm and an individual bipolar power supply. The capacity of the power supplies is 50 V and 100 A. The magnetic current waveforms
are sinusoidal with a DC offset. As a design goal, the amplitude of the unwanted beam oscillations around the ring should be suppressed to one-tenth of the beam sizes, which are about 30 μm in the horizontal direction and 3 μm in the vertical direction. The angles of the photon beam axes of U#16-1 and U#16-2 should be fixed within 1 μrad at the user beamline.

The actual magnetic field of the individual kicker magnet contains amplitude errors and phase errors in contrast to an ideal sinusoidal waveform. The amplitude errors generate beam oscillations with the same phase as the bump itself. However, the disturbances from the phase errors have a phase difference of 90°. We corrected both errors for all kicker magnets by measuring the beam oscillation outside of the bump with the phase information. The bump control system has four 2-channel arbitrary function generators and a voltage-controlled 6-channel attenuator module. The accuracy of the correction is 1 mA for the amplitude error and 0.01° for the phase error.

In addition, the four FHVs for the horizontal and vertical directions are used for feed-forward correction to suppress the remaining oscillations after the adjustment of the kicker magnets. The feed-forward controller has sixteen 16-bit ADCs and eight 16-bit DACs. The signal processing clock is set at 20 kHz, which is sufficiently fast for suppressing the 10 Hz orbit movement. After feed-forward correction, the vertical and horizontal oscillations are also suppressed within 3 μm around the ring with 10 Hz polarization switching. Figure 6 shows an example of beam position measurement by FPMs at the bump. During the fast polarization switching operation, the intensity of the photon beam at the monochrometer differs according to the distances from the two EPUs but the focused x-ray beam position is stable sufficiently. At other beamlines, the fluctuation of the photon beam linked the bump switching is not detected.

This fast local bump system is developed under the APU circular polarization modes of the EPUs. For the other APU symmetric modes and the transition states of the EPUs, we measured the unwanted 10 Hz beam oscillation around the ring with fast local bump and confirmed that feed-forward correction worked well with the same accuracy as in the circular polarization mode. We could use the same data table for feed-forward correction in all APU symmetric modes of the EPUs. The fast polarization switching operation at 10 Hz was started successfully in April 2012. Experiment users can change the photon energy and the polarization state of both U#16-1 and U#16-2 independently at any time during the fast polarization switching operation and during static operation.

![Figure 5. Schematic view of the configuration of the B15-16 straight section.](image)

![Figure 6. Example of the fast beam position measurement by FPMs.](image)

**References**

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