X-RAY BASED UNDULATOR COMMISSIONING IN SACLA

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Abstract

The undulator commissioning such as the precise K value tuning and trajectory correction is the important step toward realization of x-ray free electron lasers. In the SPring-8 Angstrom Compact free electron LAser (SACLA) facility, the undulator commissioning has been carried out by means of characterization of x-ray radiation. The details of the commissioning methods and actual results, together with the evaluation of the achieved accuracy, are presented.

INTRODUCTION

SACLA, the SPring-8 Angstrom Compact free electron LAser, achieved the first lasing in June 2011 at the wavelength of 0.12 nm, which soon got down to 0.08 nm [1]. After further beam tuning aiming at higher laser power and more stable operation, the user operation started in March 2012.

In order to achieve FEL saturation in the angstrom-wavelength region, 18 segments of in-vacuum undulators (IVUs) have been installed in SACLA. Each segment is 5-m long and placed with a 1.15-m long interval to install the devices for electron diagnostics, and steering and quadrupole magnets. Because of such a segmented structure, there exist many error sources that can lead to FEL gain reduction even if each undulator segment is perfect. In addition, the narrow-gap operation of IVUs can lead to unwanted effects that reduce the FEL gain. In order to correct or compensate all these errors and effects, we have to align or tune a number of components related to undulator operation and optimize many parameters so that all the undulator segments work coherently. Such an optimization process is referred to as undulator commissioning.

In SACLA, the undulator commissioning has been carried out based on the characterization of spontaneous or amplified x-ray radiation. In this paper, details of the commissioning procedure and the achieved results are reported.

ERROR SOURCES AND THEIR TOLERANCES

Before describing the details of the undulator commissioning carried out in SACLA, let us first mention the error sources that affect the FEL gain. We have mainly three sources related to utilizing a long undulator composed of more than one segment: trajectory error, K-value discrepancy, and phase mismatch. In addition, the wakefield-induced energy loss is another point to be concerned in SACLA, where narrow-gap IVUs are used. In order to suppress the FEL gain reduction due to these error sources, respective components related to undulator operation should be finely tuned or well aligned. The tolerances specified by a numerical study based on FEL simulations assuming the SACLA beam parameters are summarized in Table 1. Note that all the simulations have been performed with the FEL simulation code SIMPLEX [2].

Table 1: Error Sources and Their Tolerances

Tuning Item		Tolerance
Trajectory		
	BPM Center	2.2 μm
	Injection Angle	0.50 μrad
K Value	Total	5×10^{-4}
	(in Gap)	1.9 μm
	(in Height)	60 μm
Phase Slippage		30 degree
Undulator Taper		10^{-4}/segment

The tolerance of the trajectory error is given in two forms. One gives that of the center of the BPMs installed in the drift sections and the other gives that of the injection angle of the electron beam into undulator segments. As explained later, the injection angle of the electron beam is measured and corrected in SACLA by characterization of monochromatized spontaneous radiation.

The K value deviation, which comes from the tuning error of the gap and misalignment of the undulator height, should be less than 5×10^{-4} in total. Based on the magnetic measurement of the SACLA undulator, this number is converted to the tolerances of 1.9 μm in gap and 60 μm in height.

METHODS AND RESULTS OF COMMISSIONING

In order to align or tune the components within the tolerances as listed in Table 1, characterizations of spontaneous and SASE radiations have been carried out in SACLA. The details are presented in the following sections.

Photon Diagnostics

The photon diagnostics system in SACLA is schematically illustrated in Fig. 1. The slit assembly placed 80 m far from the exit of the last (18th) undulator is used for shaping the photon beam, whose aperture size is variable and

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selected according to the purpose of measurement. After passing through the slit, the radiation pulse energy is measured by the photon BPM [3], which also works as a photon intensity monitor. Then, the radiation is monochromatized by a double-crystal monochromator and detected by a photodiode to measure the photon flux, or by a 2-dimensional x-ray profiler to measure the spatial profile.

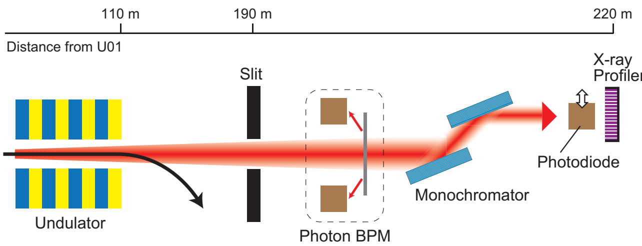

Figure 1: Schematic illustration of the photon diagnostics system in SACLA.

Trajectory Correction

In SACLA, the angle of beam injection to a specific undulator segment is estimated from the measurement of the spatial profile of monochromatized spontaneous radiation, and then corrected by a steering magnet installed in front of the undulator. An x-ray CCD detector having a high photon counting efficiency and a high spatial resolution was chosen as the x-ray profiler, which has been originally developed for imaging experiments at SACLA. A clear image of monochromatized spontaneous radiation from a single undulator segment has been obtained with a single-shot measurement, as indicated in Fig. 2. Note that the slit is fully opened in this process to take the image as wide as possible.

The center of the mass of the measured spatial profile reflects the injection angle of the electron beam. It is therefore possible to correct the trajectory error by adjusting the injection angle so that all the spatial profiles of spontaneous radiation from individual undulator segments have the identical central positions. What is important in this procedure is the pointing stability of the monochromatized spontaneous radiation, which have been found to be 0.22 μrad and 0.48 μrad in the horizontal and vertical directions, respectively, being less than the tolerance of 0.50 μrad. It is thus feasible to apply this procedure for the trajectory correction, at least in SACLA.

K-value Tuning

It is possible to estimate the undulator K value by measuring the spectrum of spontaneous radiation and detecting the peak energy. It is well known that the spectral bandwidth of undulator radiation becomes wider for a larger angular acceptance. Therefore, it seems that the slit aperture size should be as small as possible for a better resolution. Contrary to this general approach, the slit is fully opened to increase the angular acceptance during the K-value tuning in SACLA in order to reduce the number of parameters

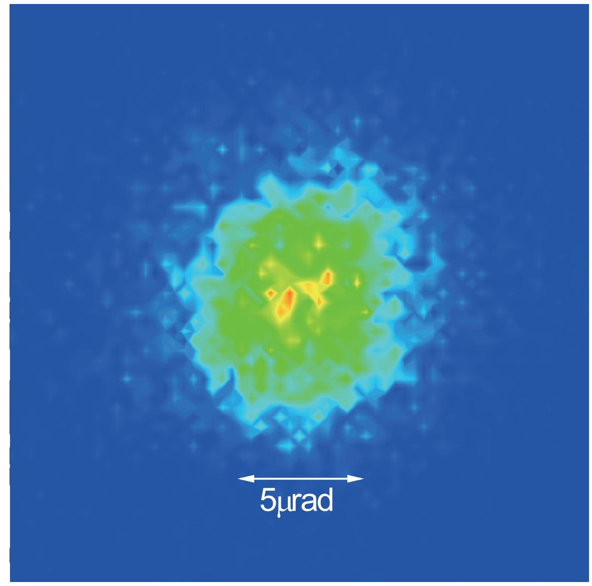

Figure 2: Example of a single-shot image of monochromatized spontaneous radiation from the 1st undulator segment, taken by the CCD detector.

affecting the spectral measurement. For example, Figs. 3 (a) and (b) show the variations in spectrum with horizontal injection angle when the slit aperture is opened to 10 mm (maximum) and 0.5 mm in both directions, respectively, which have been calculated with the spontaneous synchrotron radiation code SPECTRA [4].

The spectra with the aperture size of 10 mm are found to be insensitive to the injection angle. This also applies to other parameters such as the beam emittance, twiss parameters, and undulator-slit distance, i.e., when the slit is fully opened, the resultant spectrum is insensitive to these conditions, unlike the spectra with a small aperture. The advantage of using a large angular acceptance is obvious from this example.

It is well known that the undulator K value is a function of not only the undulator gap but also the vertical offset between the electron beam and the magnetic center. This means that the undulator gap should be finely tuned and the undulator height should be well aligned. In the following sections, the detailed procedures are given.

Gap Tuning In order to tune the undulator gap, the photon flux at a specific photon energy is measured as a function of the gap. The higher energy edge of the spectral profile (spectral edge) that corresponds to the undulator fundamental energy ω_1 is shifted from higher to lower energies when the undulator gap is closed. The resultant measurement data is similar to the spectral profile as in Fig. 3 (a). The result is then analyzed to look for the optimum gap that corresponds to some specific K value. This optimization process is repeated for all the undulator segments and several different K values to calibrate the relation between the gap and K value. An example of the measurement result

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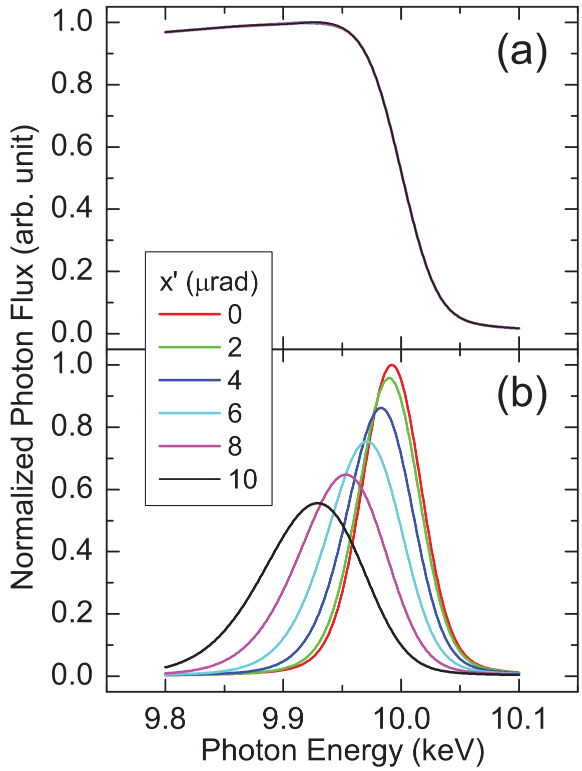

Figure 3: Example of calculated spectra of spontaneous radiation emitted from the 1st segment in two different slit aperture sizes: (a) 10 mm and (b) 0.5 mm.

is shown in Fig. 4, in which the electron energy is fixed at 7.8 GeV and the monochromator energy is fixed at 10 keV, and thus the K value is nearly 2.1.

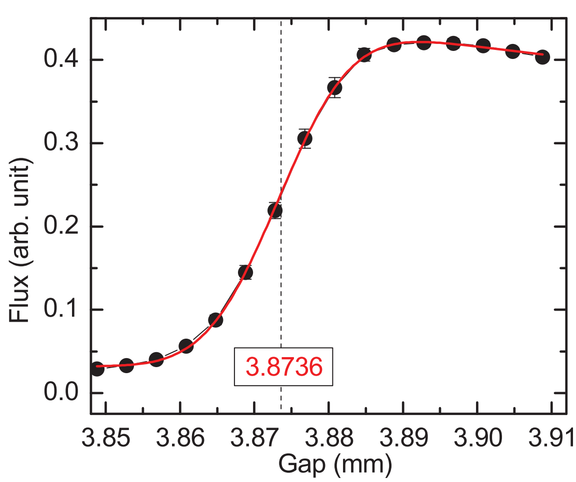

Figure 4: Photon flux of spontaneous radiation from the 1 st segment measured at 10 keV as a function of the gap (black circle). The results of fitting is also indicated (red line).

The photon flux was found to drastically change around the gap between 3.88 mm and 3.87 mm, which roughly corresponds to the K value of 2.1. In order to exactly specify the optimum gap to give the K value of 2.1, we have introduced an empirical fitting function defined as

$$f(g) = (a_1 + a_2 g)\mathrm{erf}\left(\frac{a_3 - g}{a_4}\right) + a_5, \tag{1}$$

where erf is the Gauss error function and $a_1 \sim a_5$ are the fitting parameters, among which a_3 gives the central position of the spectral edge and thus this can be regarded to be the optimum gap. The red line in Fig. 4 indicates the fitting function and the optimum gap in this example was found to be 3.8736 mm. Repeating this process, all the undulator segments can be precisely tuned to have the identical K value within some tolerance.

Height Alignment In order to align the undulator height and to eliminate the vertical offset between the electron beam and magnetic center, the photon flux is measured as a function of the undulator height as in the gap tuning. The K value depends almost quadratically on the vertical offset under realistic conditions and thus the spectral edge is shifted from higher to lower energies when the offset increases. The photon flux is thus maximized when the offset vanishes if the gap and monochromator are set appropriately.

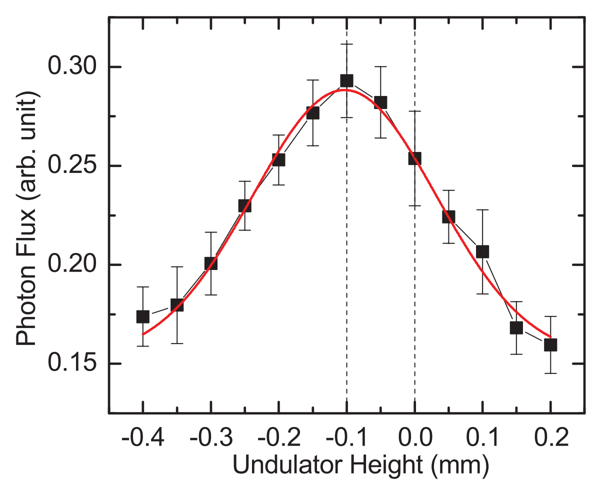

Figure 5: Photon flux of spontaneous radiation from the 1 st segment measured at 10 keV as a function of the undulator height (black square). The result of Gaussian fitting is also indicated (red line).

Figure 5 shows an example of the photon flux measured as a function of the undulator height. In this example, the undulator height was found to be misaligned by 0.1 mm, which was corrected by a remotely controlled elevation system attached to the undulator.

Phase Matching

In order to satisfy the phase matching condition, the spectral characteristics of spontaneous radiation emitted from two undulator segments has been utilized. Figure 6 (a) shows the variation in spectra with the phase slippage

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between the 1st and 2nd segments, which was varied by changing the gap of the the phase shifter installed in between. The undulator gap values of the two segments have been set to have the identical K values of 2.1. The spectral edge becomes steeper at the phase shifter gap of 30.4 mm, meaning that this gap is closer to the optimum condition for the phase matching. In order to look for the optimum phase shifter gap, the photon flux at 9.988 keV, as indicated by the dashed line in Fig. 6 (a), has been measured as a function of the phase shifter gap, the result of which is shown in Fig. 6 (b). The phase slippage has been calculated from the magnetic measurement of the phase shifter and indicated in the relative value with respect to the phase slippage at the phase shifter gap of 30.4 mm. The sinusoidal oscillation was found as expected, and the optimum phase shifter gap was found to be 30.4 mm.

Taper Optimization

The most straightforward way to compensate the wakefield effect is to optimize the undulator tapering so that the SASE intensity is maximized. In order to do so, it is necessary to get the SASE signal or at least the indication of FEL amplification, which is not very promising in the early stage of undulator commissioning. We have therefore tried to measure the wakefield-induced energy loss by means of measuring the variation of the spontaneous radiation spectrum for different wakefield conditions. For this purpose, the K value and the gap of the 17th undulator segment were fixed at 1.4 and 5.66 mm, while those from the 1st to the 16th undulator segments were varied to change the wakefield condition. It is worth noting that such an operation to vary the wakefield condition is possible only for IVUs but not for the conventional out-vacuum devices.

The spectrum of spontaneous radiation from the 17th segments was measured to investigate the effects due to the wakefield. Note that the 18th segment was disabled by fully opening the gap because of the availability at the time of measurement. Also note that the electron beam was intensionally kicked by the steering magnet located just in front of the 1st undulator segment to suppress the SASE process, in order to investigate the effects due to the wakefield alone. The measurement results are shown in Fig 7.

The spectral edge was found to shift to lower energies and become more gradual when the wakefield was enhanced by closing the gap of the upstream 16 segments, meaning that the average electron energy decreased and energy spread increased. Using this experimental result, it is possible to roughly estimate the undulator taper to compensate the electron energy loss. For example, we need to apply an undulator taper of -6×10^{-5}/m at the K value of 2.1, meaning that the undulator K value should be decreased by 3×10^{-4} from segment to segment. It is worth noting that this value is about 1/3 of the optimum taper of -10^{-3}/segment, which has been determined to maximize the SASE intensity. This discrepancy may be attributable to the difference in impact of the energy loss between the spectrum of spontaneous radiation and intensity of SASE.

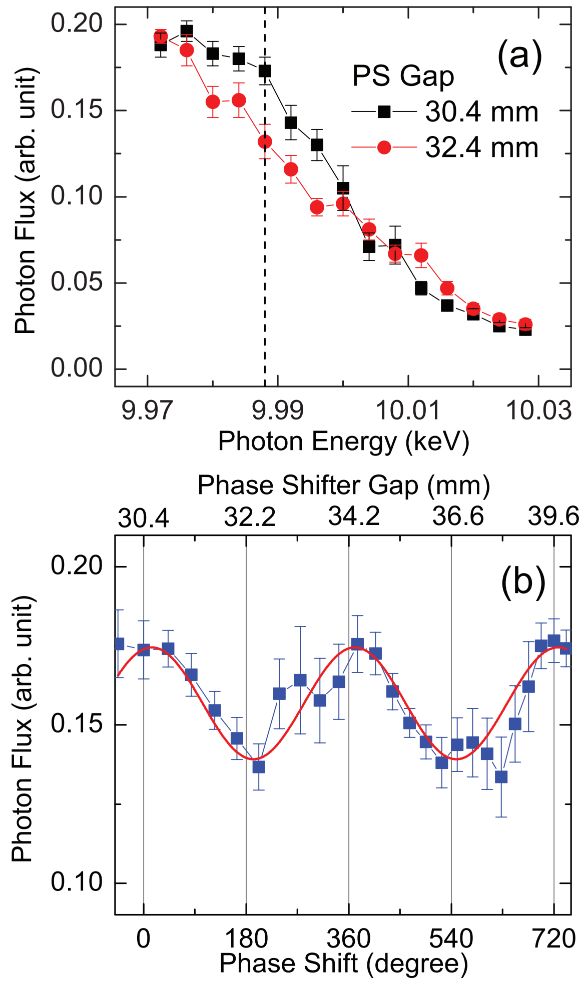

Figure 6: Phase matching example. (a) Spectra of spontaneous undulator radiations for two different gap values of the phase shifter installed in between, when the 1st and 2nd segments have the identical K values of 2.1. (b) Photon flux at 9.988 keV measured as a function of the relative phase shift (blue square). The phase shifter gap corresponding to the phase shift of $n\pi$ is indicated in the top scale. The sinusoidal fitting of the measured result is also shown (red line).

EVALUATION OF ACHIEVED ACCURACY

Now let us consider the achievable accuracies of the alignment and tuning procedures described above. Needless to say, the accuracy can be in principle improved by increasing the averaging number at each data point. On the other hand, it is better to reduce the number of shots for data averaging to save the time for commissioning and to avoid the possible ambiguity due to the long-term drift of accelerator operation. It is thus important to evaluate the expected accuracy, when no averaging is made, i.e., only one shot is recorded at each data point. For the trajectory correction, it is reasonable to define the accuracy as the pointing stability of the photon beam. For the other com-

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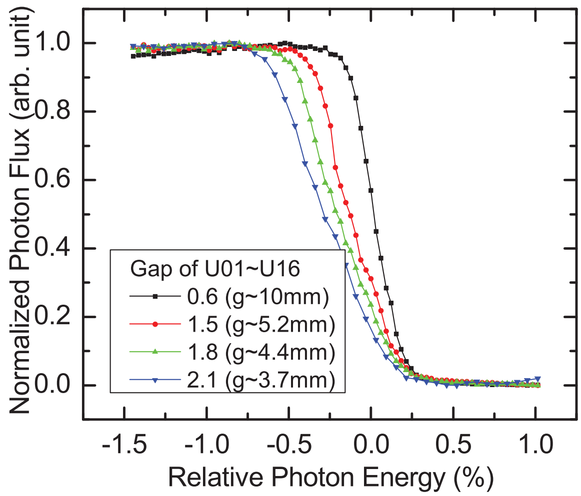

Figure 7: Spectra of spontaneous radiation for difference wakefield conditions.

missioning procedures, let us define the accuracy as the deviation of the relevant fitting parameters in the functions to fit the measured data, such as those indicated by red lines in Figs. 4 and 5. By means of a numerical study based on the statistics of the actual measurement results, the deviations of the fitting parameters have been estimated, the results of which are summarized in Table 2 as the achieved accuracy, together with the pointing stability to define the accuracy of the trajectory correction. In any of the commissioning procedures, the achieved accuracy was found to be less than the tolerance, showing the validity of the schemes using x-ray characterization for undulator commissioning in SACLA.

Table 2: Required and Achieved Accuracies in the Undulator Commissioning Using Characterization of Radiation. *Requires SASE signal

Target Item		Accuracy Required	Achieved
Trajectory (Injection Angle)		0.50 μrad	0.22 μrad (x) 0.48 μrad (y)
K Value	Total	5×10^{-4}	1.8×10^{-4}
	Gap	1.9 μm	0.6 μm
	Height	60 μm	10 μm
Phase Slippage		30 degree	15 degree
Taper*		10^{-4}/segment	4×10^{-5}/segment

SUMMARY

The undulator commissioning procedures based on the x-ray characteristics measurement have been presented together with the actual results. The achieved accuracies have been found to be within the tolerances. All of the commissioning processes are now routinely being carried out in SACLA to offer the best performance to users, whose frequencies depend on the target item. Among them, the trajectory correction should be done most frequently, e.g., every two or three weeks, because the ground level of the SACLA undulator building, which is just 3 years old, is still moving slightly.

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REFERENCES

[1] T. Ishikawa et al., Nature Photon. 6 (2012) 540

[2] T. Tanaka, Proc. 26h Int. Free Electron Laser Conf. (2004) 2283; http://radiant.harima.riken.go.jp/simplex/

[3] K. Tono et al., Rev. Sci. Instrum. 82 (2011) 023108

[4] T. Tanaka and H. Kitamura, J. Synchrotron Radiation 8 (2001) 1221; http://radiant.harima.riken.go.jp/spectra/

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