LASER WAVELENGTH TUNING BY VARIABLE-GAP UNDULATORS IN SACLA

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Abstract

Wavelength tunability by variable-gap in-vacuum undulators is one of the features of SACLA. To fully utilize this advantage, it is important to suppress gap-dependent magnetic field errors down to the tolerance level, namely sub-microradian per undulator segment, which assures high SASE amplification gain enabling XFEL power saturation. For this purpose, we introduced a "feed-forward correction" scheme, which is a well-known technique in third-generation light sources. However, in linac-based XFELs, it was not easy to make sufficiently accurate correction tables of steering magnets to cancel out error fields due to shot-by-shot beam orbit and energy fluctuations propagating from the accelerator. By using a linear accelerator model, we so far succeeded in suppressing the gap-dependent orbit deviation down to a 10-μm level over the undulator section. Owing to this effort, experimental users at SACLA can quickly change the laser wavelength in a few seconds according to their demands by setting only the undulator K-value. In this paper, we report the present status of wavelength tuning by the undulator gap in SACLA and problems to be solved towards better accuracy.

INTRODUCTION

The Japanese x-ray free-electron laser (XFEL) facility SACLA has started public user operation on March 2012 [1-3]. Currently, high-power stable XFEL light with pulse energies of 100-400 μJ is generated and provided for experimental users in a wavelength range from 5 keV to 15 keV.

Since SACLA adopted variable-gap in-vacuum undulators, a laser wavelength can be changed either by the electron beam energy or the undulator gap. In order to achieve the laser wavelength tuning by controlling the undulator gap, a "feed forward correction" scheme, which is familiar in third-generation light sources, is introduced. In the storage ring, the beam orbit deviation may affect the pointing stability of synchrotron radiation, however intensity of radiation, in principle, does not change. On the other hand in linac-based XFELs, the orbit deviation directly degrades the laser performance. To maintain high SASE amplification gain, the electron beam orbit in the undulator section should be straight and its deviation needs to be less than several-microns [4]. Therefore, the preparation of precise correction tables is indispensable to tune the laser wavelength by the undulator gap.

Here, we report the present status of wavelength tuning by the undulator gap in SACLA, which is the world's first attempt in linac-based SASE FELs.

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PRECISE MEASUREMENT OF BEAM ORBIT DEVIATION IN UNDULATOR SECTION

For the electron beam orbit measurements, RF cavity type BPMs are used in SACLA [5, 6]. In the undulator section, there are 18 undulators and 17 BPMs are located in between two undulators. In addition, there are 4 BPMs downstream of the undulator section before the beam dump. Although the resolution of these BPMs can reach sub-micron, the dynamic range is limited within ±100 μm. Therefore careful attention should be paid to their usage.

In order to accurately measure the beam orbit deviation in the undulator section, the fluctuation of the injection orbit should be precisely measured for each electron bunch by using two BPMs installed upstream of the first undulator. The two BPMs are separated by a 7.8-m long drift space to determine the position and angle of the injection beam orbit. To eliminate the effect of environmental magnetic fields, the passage of the beam between the two BPMs is magnetically shielded using high-μ metallic-sheets. The components around the drift space are made of low-μ metals. The magnetic fields from ion pumps and cold cathode gauges are confined by iron-plates. After these efforts, the residual magnetic field at the beam passage is suppressed to less than 4 mG, which is 1/100 of the environmental fields. The photograph of the drift space with two BPMs is shown in Fig. 1.

Before the orbit measurements, the bunch charge is reduced to less than 100 pC to avoid BPM signal saturation. Also an orbit and beam energy feedback is applied with an interval of several seconds to suppress slow drift of the injection orbit and beam energy.

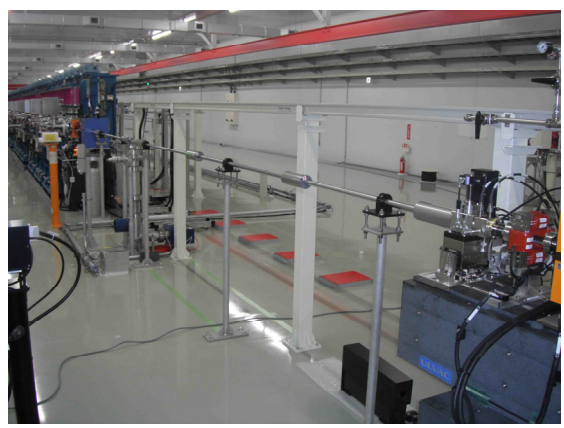

Figure 1: Injection section of the undulator line.

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ISBN 978-3-95450-123-6

The injection orbit error propagating from the accelerator is subtracted from the measured beam positions by the BPMs using linear transfer matrices. The position error at the BPMs is described as follows,

$$\Delta x = M_H(1, 1)\,\Delta x_0 + M_H(1, 2)\,\Delta x_0',$$

$$\Delta y = M_V(1, 1)\,\Delta y_0 + M_V(1, 2)\,\Delta y_0',$$

where Δx_0 and Δy_0 are the positions of the injection orbit, Δx_0' and Δy_0' are their angles. M_H and M_V are the elements of the transfer matrix from the first undulator to the corresponding BPM. Since the transfer matrix is already known, the influence of the injection orbit fluctuation can be subtracted from shot-to-shot. Fig. 2 shows an example of a distribution of the raw BPM position data. By subtracting the shot-to-shot fluctuations, the spread of the measured data is reduced to sub-micron level as shown in Fig. 3.

After excluding the data that exceed the BPM dynamic range, this subtraction procedure is applied and the data are averaged for 100 shots.

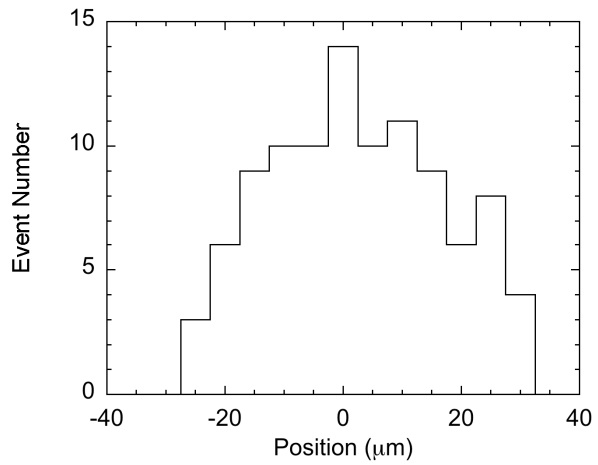

Figure 2: Distribution of raw BPM data including injection orbit fluctuations.

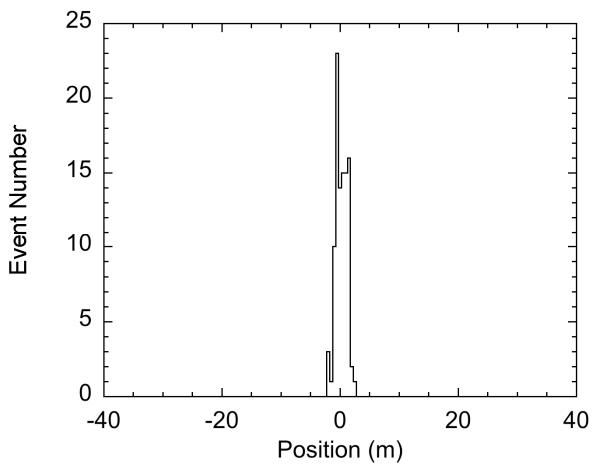

Figure 3: Distribution of BPM data after subtraction of the injection orbit fluctuations.

LASER WAVELENGTH TUNING BY UNDULATOR GAP

In order to correct the position and angular deviations of the electron orbit due to the gap-dependent error fields, two steering magnets are at least necessary. In SACLA, a pair of steering magnets is attached at the entrance and the exit of each undulator. Correction tables of the steering magnets are made for each of 18 undulators.

The reference beam orbit is set at the undulator gap of 10 mm, and then the orbit deviation is measured as a function of the undulator gap. At each undulator gap, the steering currents are determined so that the orbit deviation at the BPMs located downstream of the corresponding undulator becomes minimal. The steering current is calculated based on the measured orbit response of each steering magnet.

The orbit deviation for the gap movement of one undulator from 10 mm to 3.5 mm is typically within 2 μm. Figure 4 shows an example of correction tables in horizontal direction. The data are taken at a gap step of fine enough. Particularly at small gaps, the field errors rapidly change, so the correction table is made at a 20-μm interval at the gap close to the minimum.

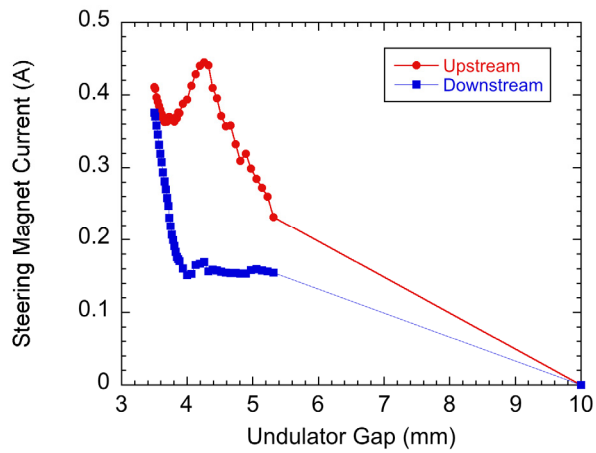

Figure 4: An example of the steering currents to correct the orbit deviation as a function of the undulator gap.

In addition to the orbit correction tables for the undulator gap, the correction tables for each phase-shifter are also necessary. In SACLA, 17 permanent-magnet phase-shifters are installed in between the undulators to match radiation phases of each undulator.

Since SACLA uses small-gap in-vacuum undulators, gap-taper is an important parameter to cancel beam energy loss due to wake fields and to maximize the FEL output. While the optimal gap-taper depends on the conditions of the electron beam and the undulator gap, it is typically at the order of 20 microns, corresponding to $\Delta K \sim 10^{-3}$, between two consecutive undulators. Fig. 5 shows the laser pulse energy as a function of the gap-taper at 8.4-keV photon energy. Optimal taper values are measured for several gaps and different beam energies,

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and then the taper value is determined for specific beam energy and undulator gap by linear interpolation.

When the undulator gap is changed, the gap-taper and phase-shifter are tuned to the optimal values. Simultaneously the feed-forward corrects the orbit deviation originated to these parameter change.

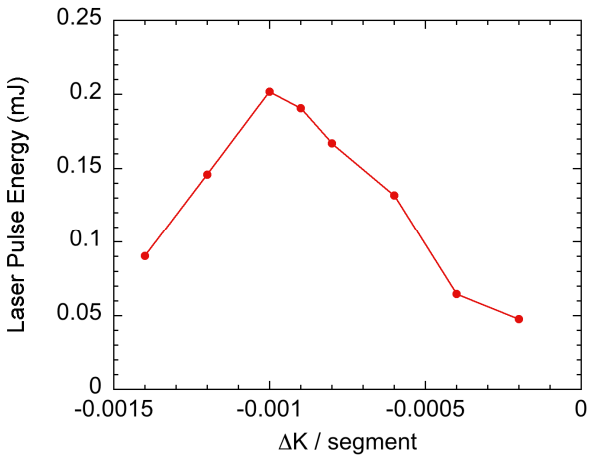

Figure 5: FEL outputs as a function of gap-taper at 8.4-keV photon energy.

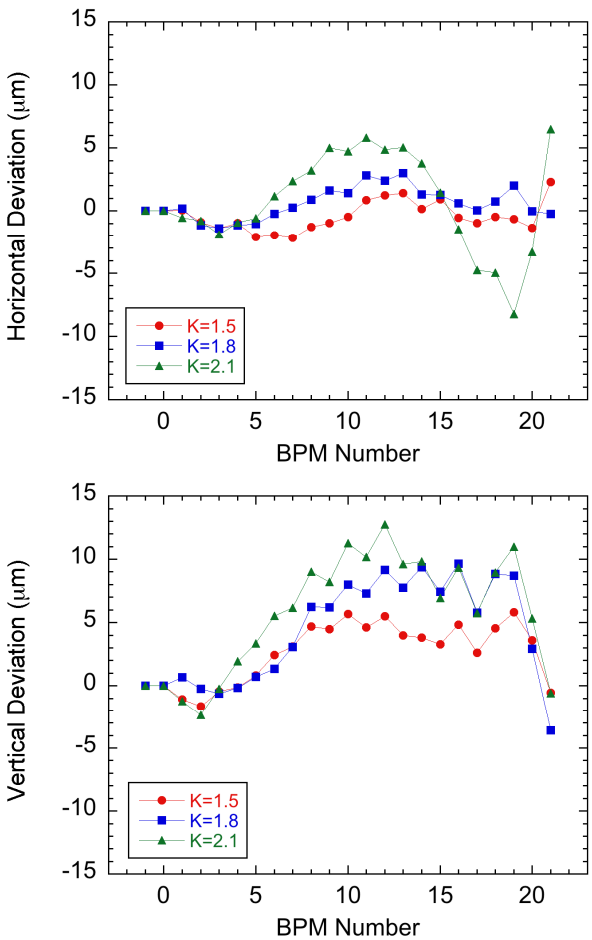

Figure 6: Orbit deviation from the reference orbit for various K-values. The reference is taken at 10-mm gap.

Figure 6 shows the measured orbit deviation by changing the all undulator gaps. The beam orbit with 10-mm gap is taken as a reference orbit. The orbit deviation at the maximum undulator K-value (minimum gap) is suppressed within 10 μm. However, the deviation becomes large as the gap closed. Especially, the orbit deviation at the latter half of the undulator section stands out. An improvement for making more precise correction table will be discussed in the next section.

The steering fields correct the absolute error fields of the undulators and phase-shifters. Once the correction tables are created, the same correction tables can be used for any electron beam energies. Laser pulse energy as a function of the photon energy are shown in Fig. 7 for various electron beam energies. At each beam energy, the photon energy is scanned by changing the undulator K-value. The laser pulse energy more than 100 μJ/pulse is currently available for a photon energy range from 5 to 15 keV.

Owing to these efforts, experimental users can quickly change the laser wavelength by setting only the undulator K-value without any accelerator tuning. The GUI display for setting the K-value is shown in Fig. 8.

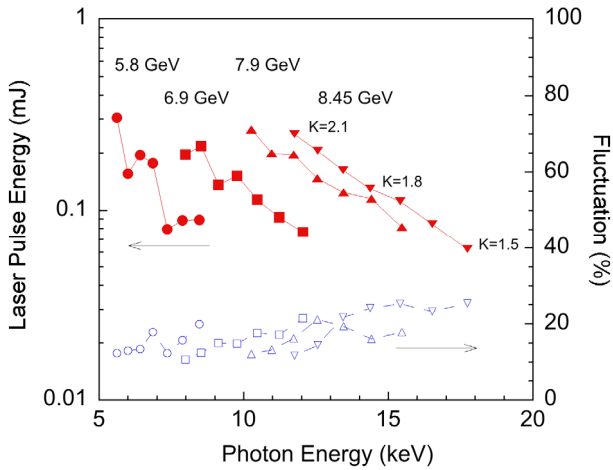

Figure 7: Laser pulse energy as a function of photon energy for various electron beam energies.

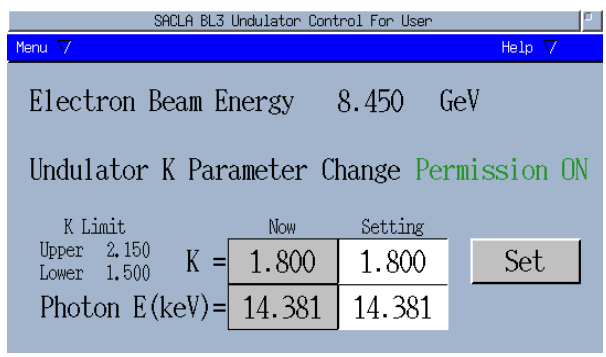

Figure 8: GUI display for setting the K-value. Experimental users can quickly change the laser wavelength without any accelerator tuning.

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TOWARDS BETTER ACCURACY OF WAVELENGTH TUNING

In the present method, both upstream and downstream steering strengths are determined to minimize the deviation of the beam orbit after the corresponding undulator. In order to determine the angle of the electron beam in the undulator more precisely than that determined by the BPMs, spontaneous radiation of the undulator can be used. Supposing a straight orbit inside the undulator, the upstream steering strength can be determined by observing the spontaneous radiation axis on a target locating downstream far from the undulator. The downstream steering corrects the orbit so that the orbit deviation at the BPMs becomes minimal in the same way as the present method.

One more important point is an available number of BPMs for the orbit measurements. Although the undulators located upstream can use enough number of BPMs, it decreases as going downstream, then the accuracy of the correction table becomes worse. To compensate this, the spontaneous radiation can be used to improve the accuracy of the measurements.

ACKNOWLEDGMENTS

We thank to the SACLA operators: Mr. Yutaka Kano, Mr. Yasuyuki Tajiri, Mr. Shinichiro Tanaka, Mr. Taichi Hasegawa, Mr. Takuya Morinaga, and Mr. Ryo Yamamoto for the contribution of machine operation and beam analysis. We also thank to all of the SACLA members.

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ISBN 978-3-95450-123-6