STUDY ON EFFECT OF PHASE SHIFTER ON FEL INTENSITY AT PAL-XFEL

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Abstract

In the PAL-XFEL, the phase shifters are installed between the undulator modules to match the phase of the electron beam and the FEL radiation field at the entrance of next undulator. By varying the phase shifter gap, the FEL intensity measured at the QBPM oscillates and sine curve fitting can be applied to it for optimizing the FEL intensity. However, the optimal gap determined from fitting result is slightly different from the gap at which the maximum intensity is measured because distorted shapes are appeared from some phase shifters. In this presentation, we report and discuss the experimental results of phase shifter gap scanning with simulation results.

INTRODUCTION

Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL) is one of X-ray free electron laser facilities which utilize the long undulator lines to generate powerful X-ray FEL radiation [1]. Electron beam is oscillated and delayed as long as resonant wavelength per each undulator period due to the magnetic field of undulator. Therefore, phase of electron beam and radiation is well matched along the undulator according to the resonance condition. But undulator length cannot be infinitely long and diagnostics, such as quadrupole and beam position monitor, have to be installed at somewhere, the intersection is required between the undulator modules as shown in Fig. 1.

Because the electron beam does not oscillate and just goes straight in the intersection, so the phases of the electron beam and the FEL radiation is mismatched at the entrance of next undulator module after the intersection. However, such mismatch can be corrected by using phase shifter [2, 3] which applies magnetic field to the electron beam, as shown by yellow dashed box in Fig. 1.
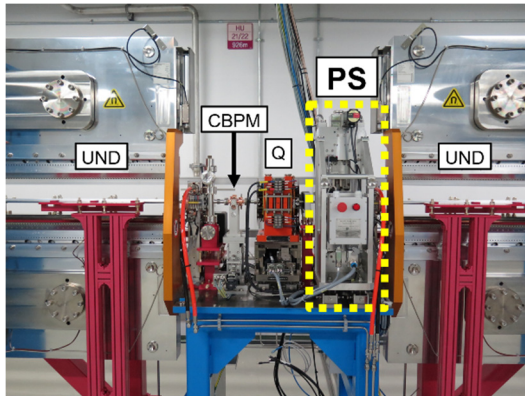

Figure 1: Intersection between undulator modules. Cavity beam position monitor (CBPM), quadrupole (Q) and phase shifter (PS) has been installed.

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PHASE MATCHING WITH PHASE SHIFTER

Phase shifter makes the electron beam to oscillate and be delayed according to the FEL radiation by applying the magnetic field. Retarded distance of the electron beam in the intersection between undulator modules is expressed in Eq. (1) [3].

$$s = \frac{1}{2\gamma^2}\left(L_{\text{int}} + \left(\frac{e}{mc}\right)^2 \cdot PI_{\text{PS}}\right) = n \times \lambda_{\text{r}} \qquad (1)$$

γ is Lorentz factor of the electron beam, L_{int} is the length of intersection, e and m is the electron charge and mass, c is speed of light and PI_{PS} is phase integral of phase shifter which is expressed in Eq. (2) [3].

$$PI_{\text{PS}} = \int_{-\infty}^{\infty}\left(\int_{-\infty}^{z''} B_{\text{Y}}(z')dz'\right)^2 dz'' \qquad (2)$$

To make the phase of electron beam and radiation well matched at the entrance of the next undulator module after the intersection, retarded distance of the electron beam has to be multiple of resonant wavelength, λ_{r} by changing some parameters in Eq (1) and PI_{PS} is easily varied by changing the gap of phase shifter.
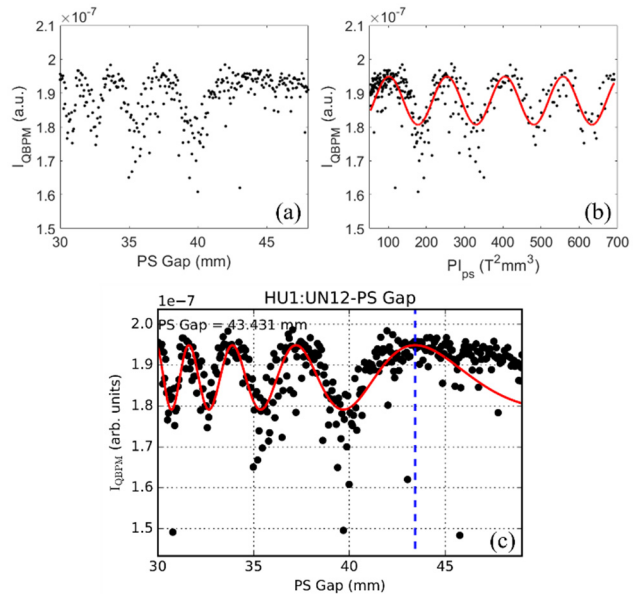

Figure 2: (a) Measured FEL intensity at the QBPM according to the gap of phase shifter. (b) Measured FEL intensity (black dots) and sine curve fitting result (red solid line) according to the phase integral of phase shifter. (c) Converted fitting data from sine curve fitting result (red solid line) and determined optimal gap of phase shifter (blue dashed line) are plotted over the measured FEL intensity according to the gap of phase shifter.

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When the phase shifter gap is changing, we assume that the FEL intensity at the end of undulator line oscillates like sine curve and sine curve fitting can be applied to the measured FEL intensity by using Eq. (3)

$$I_{QBPM} = A \sin\left(\frac{2\pi}{T} \cdot PI_{PS} + B\right) + C \qquad (3)$$

I_{QBPM} is the FEL intensity measured at the QBPM, T is the phase integral period of FEL intensity and A, B and C are fitting coefficients. QBPM is a kind of photon diagnostic which is located in the optical hutch after the undulator line at PAL-XFEL, and the measured value from it also reflects the FEL intensity. With fitting results, phase shifter can be optimized as shown in Fig. 2, which will be explained in next section.

EXPERIMENTAL RESULTS OF PHASE SHIFTER GAP SCANNING

Practical procedure of phase shifter gap scanning is shown in Fig. 2. At PAL-XFEL, 20 undulators with self-seeding section and 19 phase shifters are installed in HU1 undulator line as shown in Fig. 3. FEL intensity according to the phase shifter gap is measured at the QBPM as shown in Fig. 2(a). Actually, we can directly control the gap of phase shifter at the PAL-XFEL, not the phase integral of

phase shifter. Therefore the phase shifter gap has to be converted to the phase integral and sine curve fitting is applied as shown in Fig. 2(b). Finally, the fitting results are re-converted to the phase shifter gap from phase integral and the optimal gap of phase shifter is determined as shown in Fig. 2(c).

To optimize the intensity of FEL radiation by matching the phase of electron beam and radiation between the undulator modules, phase shifter gap scanning which is introduced in Fig. 2 is proceeded for all phase shifters. Measured data and fitting results for every phase shifter according to phase integral of each phase shifter are shown in Fig. 4. Main parameters measured at PAL-XFEL are summarized in Table 1.

Table 1: Main Parameters Measured at PAL-XFEL

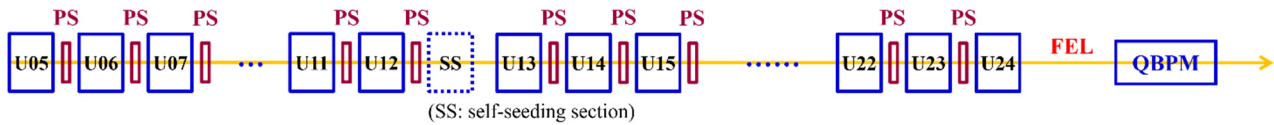| Parameter	Value	Unit
Electron beam energy	8.54	GeV
Bunch charge	180	pC
Undulator parameter, K	1.87	
Undulator period	26	mm
FEL wavelength	1.28	Å
Photon energy	9.7	keV

Figure 3: Schematic layout of HU1 undulator line at PAL-XFEL.
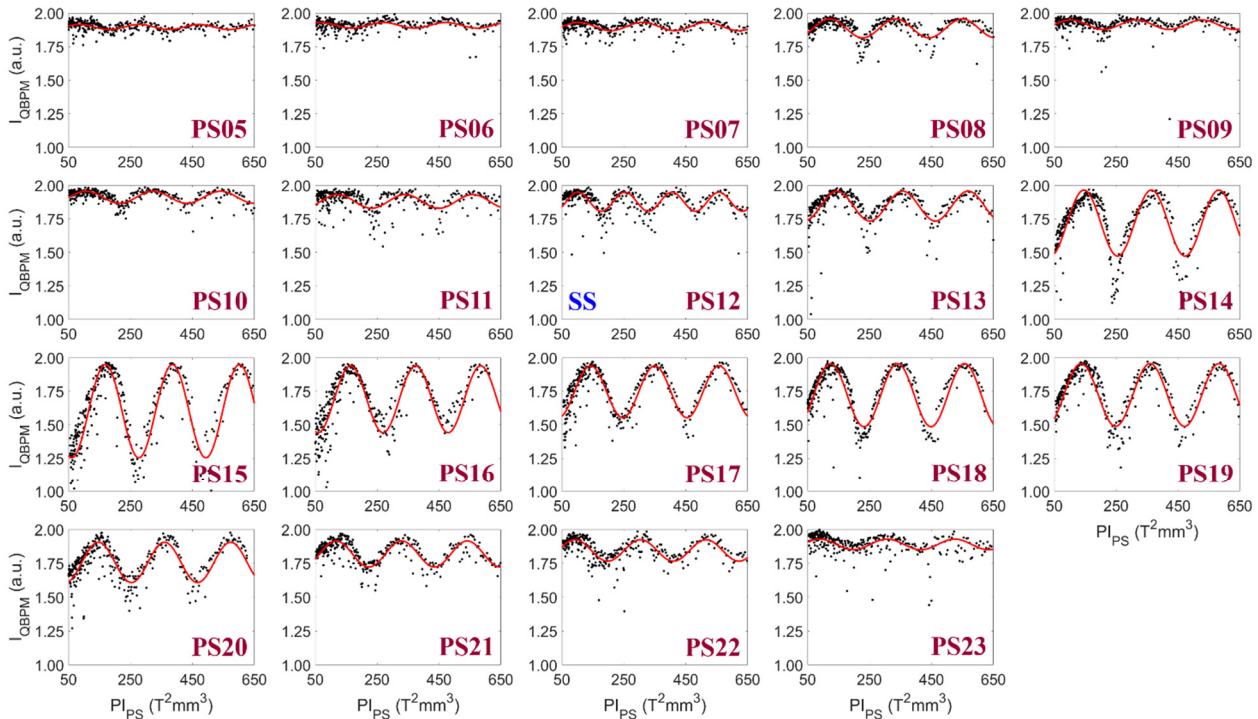

Figure 4. Measured FEL intensity at the QBPM (black dots) and sine curve fitting results (red solid line) according to the phase integral of each phase shifter. 'SS' means that phase shifter is located at self-seeding section.

COMPARISION WITH SIMULATION RESULTS

When the results which is shown in Fig. 4 are glanced over roughly, fitting results reflect well with the measured data and optimal gap of phase shifter is correctly deter-mined. However, some fitting results are slightly different from the gap at which the maximum intensity is measured owing to a distorted shape of measured data. Therefore, FEL simulation [4] is carried out to investigate such phe-nomena.

Reference case of which results are shown in Fig. 5 (re-sistive wall wake field included, optimal undulator taper-ing for obtaining maximum radiation power is applied) is found and used to compare with experimental results. Vir-tual undulator parameter, K_D, is used to reflect a function of phase shifter which delay the electron beam by oscillat-ing the electron beam in the intersection in GENESIS 1.3 [4]. Main parameters used in simulation are summarized in Table 2.
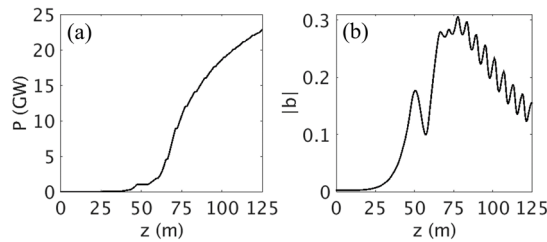

Figure 5: Simulation results of reference case to compare with experimental results which are shown in Fig. 4. (a) Averaged radiation power and (b) averaged bunching factor along the undulator line.
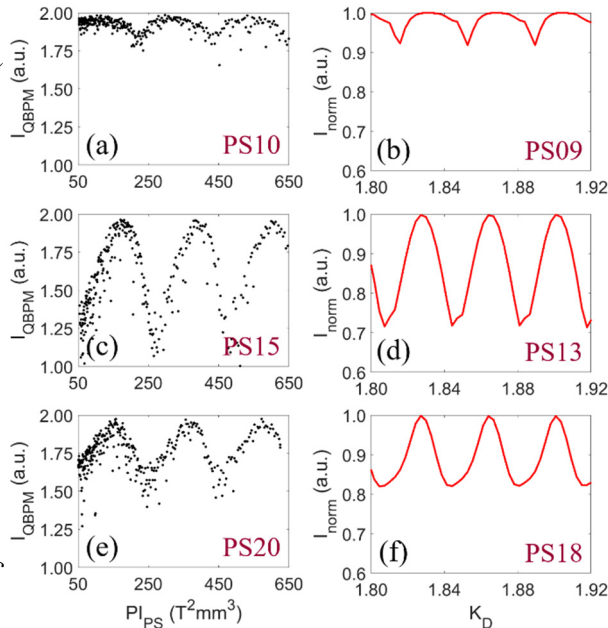

Figure 6: (a, c, e) Measured FEL intensity at the QBPM according to the phase integral of phase shifter and (b, d, f) normalized FEL intensity at the end of undulator line obtained from simulation results according to the virtual undulator parameter in the intersection.

Table 2: Main Parameters used in Simulation

Parameter	Value	Unit
Electron beam energy	8.54	GeV
Peak current (flat-top)	3	kA
Normalized slice emittance	0.4	mm·mrad
Undulator parameter, K	1.87	
Undulator period	26	mm
FEL wavelength	1.28	Å
Photon energy	9.7	keV

Representative cases are shown in Fig. 6. Simulation results which look similar with measured data are selected. Different location (about 1 or 2 undulator modules) is originated from ideal beam properties in simulation. As shown in Fig. 6, phase shifter gap scanning on some phase shifter results in a distorted shape of result, therefore, inaccuracy of phase shifter gap scanning can be caused.

Another feature in Fig. 6 is that the widths of oscillating results get smaller as the lasing is proceeding along the undulator. Considering that microbunching of the electron beam along the undulator is also proceeding as shown in Fig. 5, it seems that phase shifter gap scanning can be a potential detector for microbunching structure of electron beam in the undulator line.

SUMMARY

At the PAL-XFEL, variable gap phase shifters are installed in every intersection between undulator modules to match the phase of electron beam and radiation by delaying the electron beam. By phase shifter gap scanning to determine the optimal gap of phase shifter, phases of electron beam and radiation can be well matched between undulator modules. However, determined gap from sine curve fitting results is slightly different from the gap at which the maximum intensity is measured because measured data looks like a distorted shape. Therefore, other fitting strategies have to be considered to increase the phase shifter gap scanning accuracy in the future. It will be also investigated that a degree of microbunching structure of the electron beam can be analogized from phase shifter gap scanning results.

REFERENCES

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