UNDULATOR COMMISSIONING STRATEGY FOR SPRING-8 XFEL

T. Tanaka*
RIKEN SPring-8 Joint Project for XFEL, Koto 1-1-1, Sayo, Hyogo 679-5148, Japan

Abstract

The undulator commissioning, i.e., tuning of components in the undulator beamline to correct errors that can lead to FEL gain reduction, is crucially important to realize lazing in the x-ray region. In the SPring-8 x-ray FEL, the commissioning is to be made by monitoring the characteristics of the spontaneous or amplified radiation. The angular profile at a certain photon energy is measured in the former, while the radiation intensity is monitored in the latter. A lot of calculations and simulations have been carried out to investigate the tuning resolution and accuracy and to study the feasibility of the undulator commissioning based on this concept.

INTRODUCTION

In order to achieve FEL saturation in the x-ray region, the undulator should be long enough, e.g., 100 m or longer. From a practical point of view, the long undulator is divided into a large number of segments, and diagnostics tools and focusing magnets are installed in between. Such segmentation can cause non-negligible errors, i.e., the trajectory error, K-value discrepancy between segments, and phase mismatch in the drift sections, which cause FEL gain reduction. These errors should be corrected carefully by alignment of the components in the undulator beamline such as the beam position monitors (BPMs), undulators, and phase shifters.

In principle, careful magnetic measurement of the undulator and phase shifter gives correct information necessary to adjust the K value and phase shift. As for the alignment of BPMs, the electron [2] and/or X-ray [1] beam based alignment can be applied. The former measures the dispersion function by changing the electron energy and detect the trajectory variation to deduce the BPM offset, while the latter directly measures the BPM offset by means of the x-ray beam produced in the upstream undulator (alignment undulator).

In case one of the above procedures does not work well due to uncertain reasons, we have to specify the cause and correct it by an alternative method so that the FEL output power reaches saturation. This procedure will mainly be based on synchrotron radiation (SR) emitted from the undulators and is called the undulator commissioning.

It should be noted that we have two forms of SR to be applied to the undulator commissioning, i.e., spontaneous radiation and amplified radiation. It is therefore possible to select one of the two forms according to the target of the undulator commissioning. The selection can be done by changing the number of undulator segments to be enabled: if we need to monitor the spontaneous radiation, the number of segments should be so small that the resultant undulator length is at lease shorter than several times the gain length, and vice versa.

The commissioning with spontaneous radiation is different from that with amplified radiation in terms of the target error source, method to characterize the radiation, and requirement on the electron beam. In this paper, details of the commissioning strategy in both cases are explained together with the results of calculations and simulations performed to check the feasibility of the undulator commissioning using the SPring-8 XFEL electron beam parameters. The computations have been done with computer codes SPECTRA [3] and SIMPLEX [4] that have been developed in SPring-8.

ESTIMATION OF THE GAIN REDUCTION

Before describing the undulator commissioning strategy, let us estimate the gain reduction rate of the respective error sources. As mentioned in introduction, we have three kinds of errors to be concerned: trajectory error, K-value discrepancy, and phase mismatch.

In the initial stage of commissioning, the electron beam is steered so that it goes through the origins of BPMs installed in the drift sections between undulator segments. In this case, we have two sources that give rise to the trajectory error. One is the undulator field error and the other is the misalignment of the BPMs. The former can be corrected by careful field correction during the manufacturing process and thus the trajectory in the undulator can practically be regarded to be straight. Now, we can define the trajectory error only by the horizontal and vertical positions of the BPMs, x_i and y_i at the i-th drift section.

The gain reduction due to the trajectory error has been estimated by FEL simulations as follows. First, a trajectory error model is created by

$$x_i = R(j_x)\Delta x, y_i = R(j_y)\Delta y,$$

where $R(j)$ is the uniform random number generated by a seed number j_x and $\Delta x, y$ are the maximum position offsets of the BPMs in the horizontal and vertical directions, respectively. In other words, they indicate the alignment accuracy of the BPMs. The electron trajectory over the whole undulator is defined so that it goes through the transverse position (x_i, y_i) at the longitudinal position of the i-th BPM, and FEL simulation is carried out to get the FEL output $P(j_x, j_y)$ at the undulator exit. Then, the above procedure is repeated 30 times with different seed numbers. The

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* ztanaka@spring8.or.jp

reduced gain with the alignment accuracy Δx and Δy is then defined by $G_r = P_m/P_0$, where P_m denotes the minimum output among the 30 sets of $P(j_x, j_y)$, and P_0 is the ideal FEL output without any errors. Now we can calculate the reduced gain as the function of the BPM alignment accuracy by repeating the above process with different values of Δx and Δy.

In the same manner, we can calculate the reduced gain for the other two error sources, the K-value discrepancy ΔK and phase mismatch $\Delta\phi$. Note that the K-value error model should be defined by $K_i = K_n + R(j_K)\Delta K$, where K_n is the nominal K value.

Figure 1 shows the reduced gain for the three error sources. Note that the BPM alignment accuracies in the horizontal and vertical directions have been assumed to be identical, i.e., $\Delta x = \Delta y$.

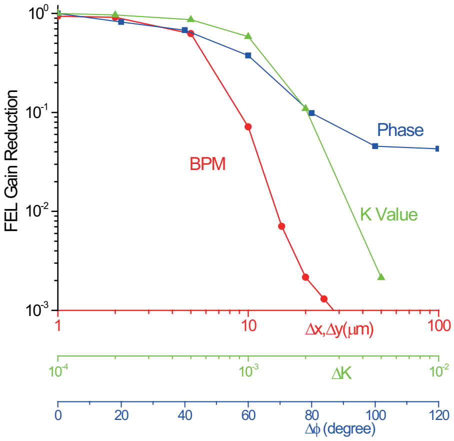

Figure 1: FEL gain reduction due to the respective errors.

If we impose that the gain reduction for the individual error sources should be less than 20%, then we roughly have criteria on the tolerance, i.e., $\Delta x, y < 5\mu$m, $\Delta K < 10^{-3}$, $\Delta\phi < 40^o$. Note that under these criteria, the resultant reduced gain is at least larger than $0.8^3 \sim 0.5$.

COMMISSIONING WITH SPONTANEOUS RADIATION

Now let us describe the undulator commissioning with spontaneous radiation. We take advantage of the characteristics intrinsic to undulator radiation that the spectrum and angular profile of the photon flux density have a sharp peak when the resonant condition is satisfied. In this sense, we have two possibilities. One is to measure the spectrum after passing through a pinhole with an angular acceptance small enough not to broaden the sharp peak. The other is to measure the angular profile of photons monochromatized at a certain energy. If the electron beam is completely stable in terms of the pointing and energy stability as in the storage ring, we can take both the methods. In practice, however, the electron beam accelerated by the linac is not necessarily stable.

In the x-ray region where a crystal monochromator is used to monochromatize the photon beam, the spectrum is measured by scanning the Bragg angle. This necessarily requires a larger number of shots of the electron beam to take a single spectrum, and thus the measurement is quite sensitive to the electron beam stability. On the other hand, the angular profile can be in principle measured by a single shot and is less sensitive to the beam stability. From this point of view, the angular profile measurement is more reliable.

Measurement Setup

Figure 2 shows the measurement setup for the undulator commissioning. As explained in the following sections, two or three undulator segments are enabled (close the gap), and the emitted spontaneous radiation is monochromatized by the crystal monochromator and the image of the monochromatic beam is taken by the X-ray CCD. In the following sections, the K value is assumed to be 1.9, and thus the fundamental energy is set at 12037 eV.

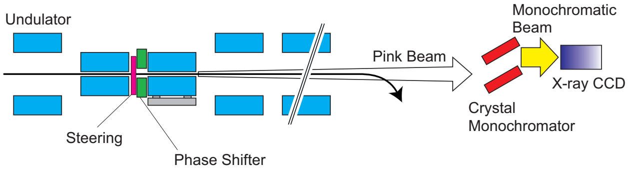

Figure 2: Measurement setup for the undulator commissioning with spontaneous radiation.

Trajectory Correction

In order to perform the trajectory correction, i.e., alignment of the BPM, two adjacent undulators are enabled. Then, the steering magnet current in between is changed. This imposes a single kick error (SKE) between the two undulators. It is found that the SKE induces an asymmetry of the angular profile if the photon beam is monochromatized at a photon energy slightly lower than the fundamental energy, as shown in Fig. 3(a), where the angular profile at the photon energy of 11950 eV is plotted for different SKE angles.

The ratio of the photon intensity at the two peak positions is plotted as a function of the SKE angle in Fig. 3(b). The steering current is then optimized so that the two peak intensities are consistent.

K-value Adjustment

In order to perform the K-value adjustment, i.e., to determine the optimum gap, two adjacent undulators are enabled and a SKE is intentionally introduced in between to separate the angular profile. Next, the gap of one of the two undulators is changed so that the shapes of the angular profile coincide with each other. Fig. 4(a) shows an example

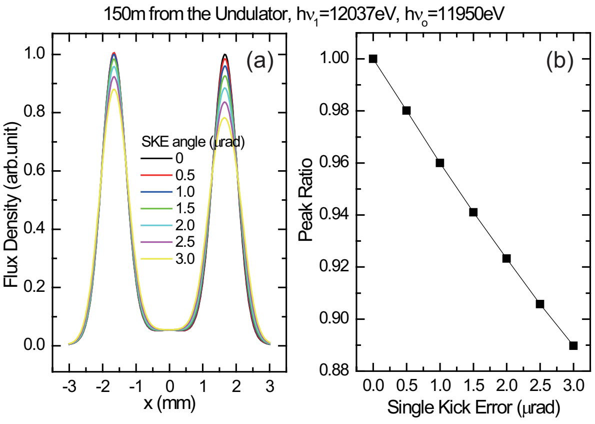

Figure 3: (a) Angular profiles at different SKE angles. (b) Peak ratio as a function of the SKE angle.

of the angular profiles at different K-value deviations between the two undulators. The photon energy is assumed to be 12000 eV, slightly lower than the fundamental energy.

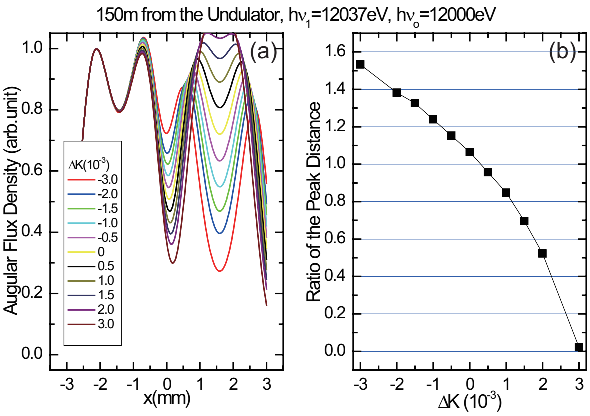

Figure 4: (a) Angular profiles at different K-value deviations. (b) Ratio of the peak distances in the positive and negative coordinates as a function of the K-value deviation.

In this example, a horizontal SKE of -20 μrad has been introduced, and the K value of the upstream undulator has been changed. Thus the angular profile in the positive x coordinate, which corresponds to radiation from the upstream undulator, varies with the K-value.

In order to look for the optimum K value, we have to define a figure of merit that specifies “similarity” between the two angular profiles in the positive and negative x coordinates. In this example, we can calculate the ratio of the distances between the two peak positions in the positive and negative x coordinates. The result is plotted as a function of the K value deviation in Fig. 4(b). The ratio is found to become almost unity when $\Delta K = 0$.

Phase Matching

In order to optimize the phase between segments, three adjacent undulators are enabled and a SKE is introduced between the 2nd and 3rd segments to separate the angular profile. The photon beam is monochromatized exactly at the fundamental energy. Then the phase shift between the 1st and 2nd segments is changed by the phase shifter. Fig. 5(a) shows an example of the angular profiles at different phase shifts. The direction and angle of the SKE are the same as those in the previous section.

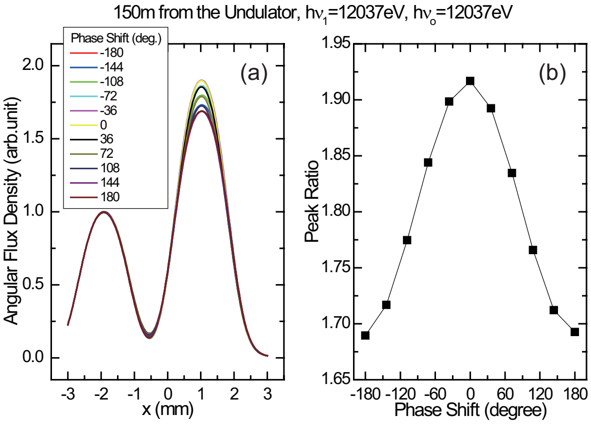

Figure 5: (a) Angular profiles at different phase values. (b) Ratio of the peak photon counts.

We find that the peak intensity of the angular profile corresponding to the 1st and 2nd undulators becomes the maximum when $\Delta\phi = 0$, as shown in Fig. 5(b), where the intensity is normalized by that corresponding to the 3rd undulator. The reason why the 3rd undulator is enabled is to introduce a reference signal so that the measurement is less sensitive to the bunch charge.

Accelerator Stability Issue

Let us now consider the effects of the accelerator stability on the reliability of the undulator commissioning described above. We have three points to be concerned about, i.e., bunch-charge stability, pointing stability and energy stability.

Apart from the total photon counts and the centroid position, variation in the bunch charge and beam injection angle do not change the angular profile. This means that the figure-of-merit functions to look for the optimum parameters, as indicated in Figs. 3(b)-5(b), do not also change. This means that the undulator commissioning described in the former sections is not sensitive to the bunch-charge and pointing stabilities, as far as a single-shot measurement is assumed. On the other hand, the fundamental energy varies with the electron energy, which results in the angular profile change. Thus the electron energy fluctuation can spoil the reliability of the commissioning.

In order to study the effects due to the energy fluctuation, we have repeated calculations shown in Figs. 3-5 at the two different electron energies 0.1% higher and lower than the nominal one. The results are shown in Fig. 6 in terms of the figure-of-merit functions to look for the optimum parameters.

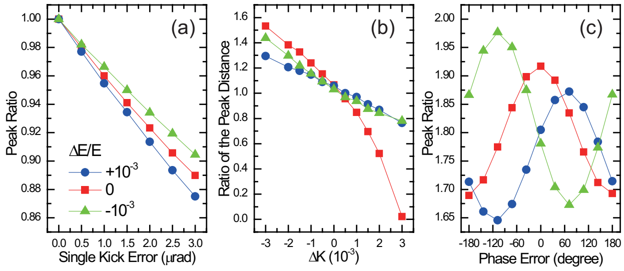

Figure 6: Effects due to the energy variation on the reliability of the undulator commissioning: (a) trajectory correction, (b) K-value adjustment, (c) phase matching.

In the case of the trajectory correction and K-value adjustment, the effects are not very large. What we have to do is just to look for the conditions when the figure of merit becomes unity. On the other hand, the phase matching condition is greatly changed due to the energy variation. Thus we may have to reduce the energy fluctuation by energy filter or equivalent to do phase matching with this method.

COMMISSIONING WITH AMPLIFIED RADIATION

After the undulator commissioning with spontaneous radiation, it is expected to observe FEL amplification with enough number of undulator segments and thus the amplified radiation can be used as a probe for the undulator commissioning. What we have to do first is to optimize the undulator tapering, which compensate the energy loss of the electron beam by the wakefield and interaction with radiation. Figure 7 shows the dependence of the FEL gain on the undulator tapering at the exit when all (18) undulator segments are enabled. It is found that the FEL gain at the optimum tapering is increased by a factor of 30 compared to that without tapering.

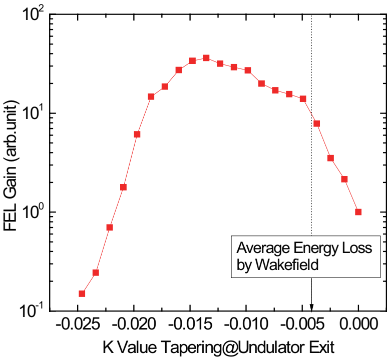

Figure 7: Effects of the undulator tapering to compensate the wakefield-induced energy loss.

In principle, we can do the same thing at every undulator segments to correct the errors that have been mentioned in the former sections. Namely, the parameters of components relevant to the N-th segment are changed with only the first N undulator segments enabled. It should be noted, however, that the response of the FEL gain is dependent on the number of undulator segments N to be enabled. The response becomes maximum when the FEL process is in the exponential growth region. Figure 8 shows the FEL response to the respective errors for different numbers of undulator segments. It is found that the response is small when N is too small (spontaneous radiation) or too large (near saturation).

We have to take care of the fluctuation of the FEL output intrinsic to the SASE process when considering the undulator commissioning with amplified radiation. In addition, the accelerator stability is also an issue. Rough estimation shows that the intensity fluctuation, including 10% peak current fluctuation, reaches 40% in the exponential growth region. Compared with the response function in Fig. 8, we have to say that an extremely stable accelerator operation is needed to do the error correction at individual undulator segments, although this is not the case for the tapering optimization because the response is much larger.

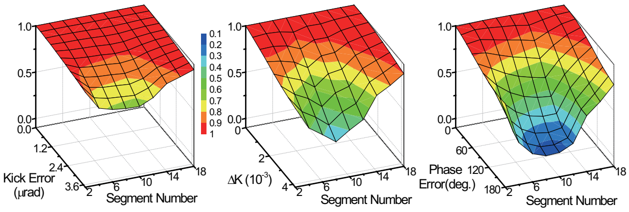

Figure 8: Response of the FEL gain for different numbers of undulator segments: (a) trajectory error, (b) K-value deviation, (c) phase error.

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