FINE TUNING OF THE K-PARAMETER OF TWO SEGMENTS OF THE EUROPEAN XFEL UNDULATOR SYSTEMS

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Abstract

For large and segmented undulator systems of the European X-ray Free Electron Laser (XFEL) [1] a non-destructive, *in situ*, radiation diagnostics method would strongly compliment e-beam diagnostics. If such a method would allow fine tuning of the K parameter of individual undulator segments with an accuracy set by the Pierce parameter ρ, which is on the order of $2\sim3\times10^{-4}$, it would provide a very helpful tool for the FEL commissioning. This paper provides a first analysis of a strategy to tune the K parameter of two adjacent undulator segments. The spontaneous, monochromatic on axis intensity of x-rays is analysed as a function of the phase delay set by the fully characterized phase shifter placed between undulator segments. The method makes use of the diagnostic equipment that will be available at the European XFEL.

INTRODUCTION

Recent successful developments in the technologies of photon guns, accelerators, and undulator systems pushed the wavelength limit of FELs to the x-ray region (XFEL). There are several XFEL facilities already under operation or under construction [1-3]. So far, all XFELs use the principle of self-amplified-spontaneous-emission (SASE) [4,5]. SASE XFEL requires long undulator systems: the typical saturation length of SASE XFEL is several tens of meters but could be more than 100 m. In order to constrain the electron beam within a proper size through such long undulator systems and also due to the technical convenience, the undulator must be separated into many segments. The space between two segments accommodates the required focusing quadrupoles, the diagnostic equipment, and, in the case of the gap-adjustable undulator, the phase shifter. This additional device is needed to maintain the phase delay of the electron relative to the radiation wave equal to an integer number of 2π for all different gaps.

K parameters of all undulator segments must be equal because the difference of *K* parameter induces phase error and thus increases the saturation length. Therefore, in order to minimize the saturation length for a given wavelength, or to achieve the shortest wavelength for the fixed undulator length, it is critical to equalize *K* parameters of all undulator segments.

K values as a function of gaps are measured for each undulator segment at the magnet measurement facility prior to the segment installation and undulator commissioning. But the ultimate test is their radiation performance, and, therefore, there are proposals to measure *K* values by detecting the spontaneous radiation [6-9]. The detected spontaneous radiation could be either emitted from a single undulator segment [6-8] or be the combined radiations from two nearby segments [9]. This paper focuses on the second option: on-axis intensity of the spontaneous radiation from two undulator segments. The intensity as a function of the difference of *K* parameters of two segments was analysed and simulated. These analyses and simulations support the newly proposed method of fine tuning of *K* parameters of two undulators. The method implies the precise characterization of the phase shifter by magnetic measurements.

The European XFEL is designed to cover 0.05 nm - 4 nm wavelength range by using 17.5 GeV electrons. As a part of the project, a total of ninety-two 5-m-long undulator segments will be constructed. All undulators are out of vacuum type and with an adjustable gap. For photon diagnostics the monochromator is designed and planned to be installed at the exit of the hard x-ray undulator [8]. Therefore, on-axis spontaneous radiation from one or several undulator segments can be measured.

THEORY AND METHOD

Analytical Studies

An accelerated relativistic electron emits radiation. The Fourier harmonics of the real part of the radiation electric field $\vec{A}(\omega)$ is given by [10]:

$$\vec{A}(\omega)=\left(\frac{e^2}{8\pi^2 c}\right)^{\frac{1}{2}} i\omega\int_{-\infty}^{+\infty}\vec{n}\times[\vec{n}\times\vec{\beta}(t)]\exp\left[i\omega(t-\frac{\vec{n}\cdot\vec{r}(t)}{c})\right]dt. \quad (1)$$

where c is the light speed, ω is the radiation frequency, and $\omega=2\pi c/\lambda_r$, λ_r the radiation wavelength. $\vec{n}$ is the radius-vector of observation, $\vec{r}(t)$ is the position of electron and $\vec{\beta}(t)$ is the normalized electron speed $\vec{\beta}=\vec{v}/c$. In this paper the study is limited to on-axis radiation: $\vec{n}=\hat{z}$, for the fundamental wavelength only.

Consider now radiation emitted from two undulators with K parameters, K_1 and K_2. From Eq. (1) one can deduce the expression for on-axis intensity I of radiation at the fundamental wavelength:

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$$I \propto \left| 1 + \exp\left[i\left(\varphi_p + N\pi\mu\delta\right)\right] \frac{\sin\left(N\pi\mu\delta\right)}{N\pi\mu\delta} \right|^2 \tag{2}$$
$$\approx 2(1+\cos\varphi_p) - 2\sin\varphi_p (N\pi\mu\delta) - \frac{1+4\cos\varphi_p}{3}(N\pi\mu\delta)^2$$
$$+ \frac{2\sin\varphi_p}{3}(N\pi\mu\delta)^3 + \frac{12\cos\varphi_p + 2}{45}(N\pi\mu\delta)^4,$$

where N is the number of periods in the undulator segment, φ_p - phase shift between radiation Fourier harmonics, parameter $\mu=K_1^2/(1+0.5K_1^2)$, parameter $\delta=(K_2- K_1)/ K_1$. For these studies δ is assumed to be on the order of few units of 10^{-4}.

According to Eq. (2) the intensity I against δ is a linear function of δ in case of $\sin(\varphi_p)\neq 0$. This phase detuning condition provides a good opportunity to increase the sensitivity of K tuning process. But it is quite important to know accurately enough φ_p—the value of the phase shift with contributions from the phase shifter and non-regular parts of undulator segments. This value could be obtained from the magnetic measurements of undulator segments and phase shifter.

An important factor that influences the intensity at the fundamental wavelength is the electron beam energy jitter. The relative energy jitter $\delta_\gamma=\Delta\gamma/\gamma$ is a small value on the order of 10^{-4}.Therefore, the intensity as a function of the phase delay φ_p and the relative beam energy jitter δ_γ could be expanded up to the second order as follows:

$$I \propto 2(1+\cos\varphi_p) + 4\sin\varphi_p(\varphi_p + 2N\pi)\delta_\gamma$$
$$-4\left(\frac{14\cos\varphi_p + 2}{3}N^2\pi^2 + \varphi_p^2\cos\varphi_p + 4N\pi\varphi_p\cos\varphi_p\right)\delta_\gamma^2. \tag{3}$$

From Eqs. (2) and (3) normalized differentials of the intensity against δ or δ_γ could be deduced:

$$\frac{1}{I_0}\frac{\partial I}{\partial\delta} \propto \frac{N\pi\mu\sin\varphi_p}{1+\cos\varphi_p} = N\pi\mu\tan\frac{\varphi_p}{2}. \tag{4}$$

$$\frac{1}{I_0}\frac{\partial I}{\partial\delta_\gamma} \propto 2(\varphi_p + 2N\pi)\tan\frac{\varphi_p}{2} \approx 4N\pi\tan\frac{\varphi_p}{2}. \tag{5}$$

where $I_0=2(1+\cos\varphi_p)$.

Equations (4) and (5) show that the optimum value φ_p should be selected to maintain high enough sensitivity against δ and minimize the effect of the energy jitter. For the purpose of further analysis $\varphi_p=120^\circ$ is chosen.

Simulations

The numerical simulations that use parameters of the European XFEL listed in Table 1 follow the analytical analysis above. The spontaneous radiation is calculated by the code Spectra 8.1 [11].

The magnetic field for the simulation is shown in Fig. 1. The field of the two undulators is cos function with the abrupt end. The field of the phase shifter is presented by a double sin function [12]. The phase delay is tuned by changing the amplitude of the sin function.

Table 1. Parameters Used in the Simulations

Parameter	Value	Unit
Undulator gap	19	mm
Undulator period λ_u	48	mm
Undulator peak field B_0	0.68	T
Undulator parameter K	3.04769	
Number of periods N	100	
e^- energy E_e	17.5	GeV
Pulse per second	30000	
Pulse length σ_z	0.0238	mm
Bunch charge q	1	nC
Peak current I	5000	A
Norm. emittance ε_n	1.4	mm mrad
Emittance $\varepsilon_{x,y}$	4.088×10^{-11}	m rad
e^- energy spread	2	MeV
Relative energy jitter	0.01%	
Beta function β	30	m
Fund. wavelength λ_r	0.115	nm

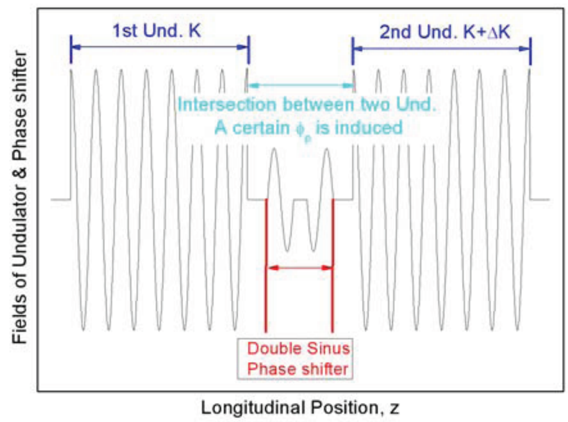

Figure 1: Magnetic field used in the simulations.

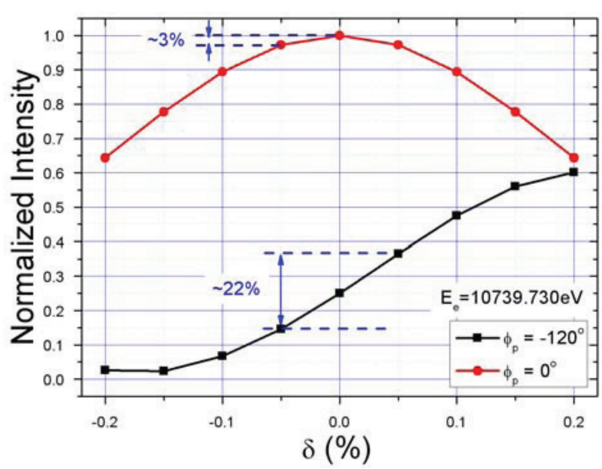

Figure 2: Radiation intensity against δ. Two different φ_p are simulated: φ_p=-120° (black square line) and φ_p=0°[same as 2π] (red dot line).

Figure 2 illustrates the radiation intensity against δ. The black square line corresponds to the phase delay φ_p= -120°, and the red dot line corresponds to φ_p=0. It is clearly seen that the variation of the intensity against δ is

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much larger with a nonzero phase delay φ_p. For example, as shown in Fig. 2, the intensity changes 22% in the range of $-0.05\%<\delta<0.05\%$ with $\varphi_p=-120^\circ$ but only - 3% in the same range with $\varphi_p=0$, i.e., more than 7 times smaller. Consequently, in the case of nonzero φ_p it is much easier to detect the slight difference of the K parameter in the two undulators.

Method of the Fine Tuning of K Parameter

According to Eqs. (2) and (3) the intensities for two phase delays with opposite signs have the same value at $\delta=0$, but their differentials $\partial I/\partial\delta$ [Eqs. (4) and (5)] have the opposite sign. Therefore, the crossover of two intensity curves obtained from two gap scans for one of segments under phase delays, φ_p and $-\varphi_p$, would identify the gap at $\delta=0$. Figure 3 illustrates this approach: simulated intensity curves have the crossover at $\delta=0$. It should be pointed out that practical implementation of this method could explore different approaches.

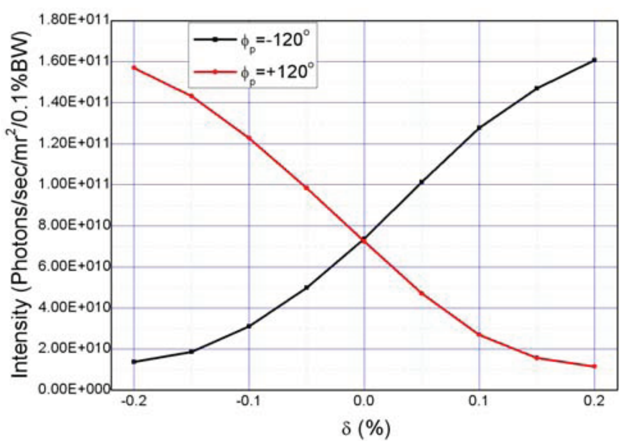

Figure 3: The intensity against δ under two opposite phase delays, $\varphi_p=\pm120^\circ$.

TOLERANCE ANALYSIS

The viability of the proposed above method depends on several factors. The two most important of them are analysed here. The first factor relates to the effect of the phase delay accuracy on the intensity. The second factor is the relative energy jitter and its impact on the intensity.

Tolerance to the Phase Delay Error

Results of intensity simulations for different values of the phase delay with the error spread of 5° are shown in Fig. 4.

Simulations are performed for four phase delays: $\varphi_p=\pm125^\circ$ and $\varphi_p=\pm115^\circ$.The shift of $\pm5^\circ$ in the phase delay results in 0.04% error to δ. It is in a good agreement with the simple estimate $\Delta\delta=2\Delta\varphi_p/(N\pi\mu)$.

The uncertainty of δ in the order of 0.04% leads to the 10% reduction of the total FEL radiation power [13] that is the accepted tolerance for the FEL performance.

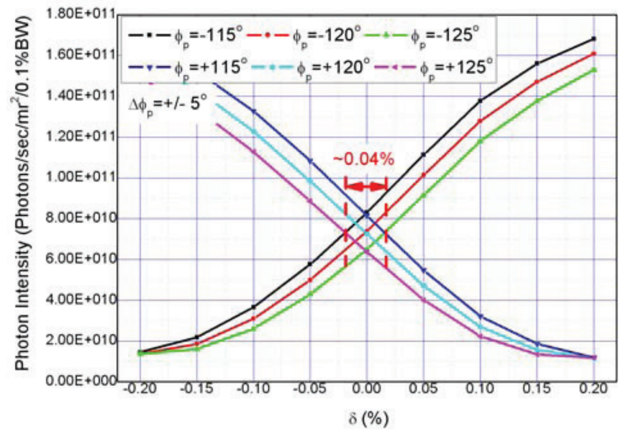

Figure 4: Intensity against δ for several phase delays with the spread of $\Delta\varphi_p$.

Tolerance to the Energy Jitter and Compensation

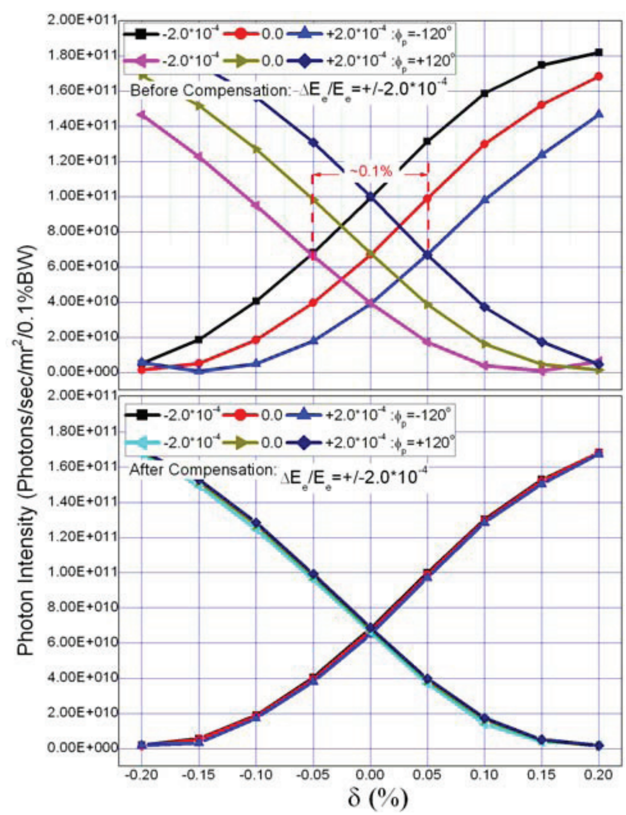

Figure 5: Intensity versus δ without and with the compensation of the jitter. The jitter is in the range of $\pm2\times10^{-4}$.

According to Eq. (2) and Eq. (3), the relative energy jitter δ_γ results in the K value error $\Delta\delta=4\delta_\gamma/\mu$. The top plot in Fig. 5 illustrates the impact of the beam energy jitter on the intensity. The range of the jitter is $\pm2\times10^{-4}$, two times larger than the shot-to-shot jitter specified for the European XFEL. That jitter level leads to 0.1% error of δ that is prohibitively high for the European XFEL.

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There is a way to overcome this problem. First, the spontaneous radiation is measured as the averaged value over many shots. And the averaged energy deviation is smaller than the shot-to-shot jitter. Therefore, in practice the impact of the beam energy jitter should be smaller than shown in Fig. 5 (top plot). Second, since the energy deviation could be calculated according to Eq. (3), as long as the energy jitter is monitored and measured, its influence could be compensated by correcting δ values. After such a correction procedure is applied the error of δ is very well compensated. (Fig. 5, bottom plot).

CONCLUSION AND OUTLOOK

This paper introduces a new method of fine tuning the K parameters of two adjacent undulator segments. It is based on the measurement of the on-axis radiation intensity generated from both segments. It is shown that the sensitivity of the intensity against the difference of K parameters of segments significantly increases when the phase shifter is detuned away from the matching condition. According to this phenomenon it is proposed to measure radiation intensities versus one segment's gap for two detuned phase delays φ_p and $-\varphi_p$. The crossover of two measured curves would provide the gap value where K values of both segments are equal.

The tolerance study shows that this method requires knowledge and control of the phase delay in high accuracy. Because the phase shifter and non-regular parts of undulator segments contribute the phase delay, very accurate magnetic measurements of both these systems are required.

Besides the error of the phase delay, the electron beam energy jitter induces errors as well. It is shown that the compensation procedure would minimize the impact of the energy jitter, and will keep the measurement accuracy of the K value at the acceptable level.

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