TOLERANCE STUDIES OF A SEEDED REVOLVER-UNDULATOR FEL*

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Abstract

Wide-range wavelength-tunability is one of the key aspects of proposed Free Electron Laser (FEL) facilities. Once the electron beam energy and undulator period length are specified, the span of the available K-values determines the achievable wavelength range. As the usable range of the K-values is limited by technical considerations like minimum acceptable gap or magnet technology etc, alternatives to enlarge the output wavelength range are of high interest. Using revolver-undulator design, different magnetic structures are incorporated into the same undulator module. Thus it is possible to switch between different undulator periods, covering a wider wavelength range at a given FEL-line. Because of the transverse-position dependency of the magnetic field, the alignment reproducibility of the revolver-undulators is of concern, in particular for the APPLE-type devices. Simulation studies have been performed taking the BESSY FEL-lines [1] as examples to investigate the alignment tolerances of these devices, to reveal their limits of applicability.

INTRODUCTION

One of the main features of the FEL facilities recently proposed is the wavelength tunability. The resonant wavelength of an FEL depends on the undulator period length, the K-value, and electron beam energy [2]. Once the undulator is built, the period length is fixed. The tunability can be achieved either by changing the electron beam energy, as proposed for LCLS [3] and XFEL [4], or by varying the K-values, as proposed for BESSY Soft X-ray FEL. Independently of the fact whether the electron beam energy varies or does not the available range of the K-values is limited by technical considerations like minimum acceptable gap or magnet technology etc. Thus, alternatives to enlarge the output wavelength range are of importance.

In a revolver-undulator different magnetic structures are incorporated into the same undulator segment [5, 6]. Therefore, it is possible to switch between different undulator periods, and cover a wider wavelength range at a given FEL-line. For reliable operation of a FEL facility, the reproducibility of the transverse alignment after each switching is essential. Although the transverse offset of an undulator module causes only a second order effect on the K-value, the resulting longitudinal, and transverse jitters, i.e. phase shake and orbit distortions, [7, 8] can be remarkable as an FEL line consists of many undulator modules.

APPLE-type devices as proposed for the BESSY FEL deliver variable polarized radiation by shifting the undulator rows against each other [1]. The magnetic field of these devices changes with the transverse position leading to nonlinear field components which vary with the row shift and provide thus different focussing gradients for different polarization modes. An undulator-module offset in combination with a strong focussing can lead to strong phase shake and orbit distortions reducing the output power. Therefore in particular the APPLE-type devices are sensitive to module-alignment errors.

Simulation studies presented here, take the final amplifier of the high-energy (HE) BESSY FEL as an example to investigate the alignment tolerances for APPLE-type revolver-undulators. The simulations have been performed for APPLE-II and APPLE-III devices [1] using the simulation code GENESIS 1.3 [9].

APPLE-TYPE DEVICE

Generally, an APPLE device consists of four rows of magnets [10]. The principle of its magnetic structure is sketched in figure 1. By moving two diagonal rows, the ratio and phase between horizontal and vertical fields can be varied and thus the photon polarization can be controlled. For a parallel motion the relative phase between the horizontal and vertical fields is 90° which results in helical / elliptical polarization and for the antiparallel motion the phase is 0° which leads to linear polarization of variable orientation.

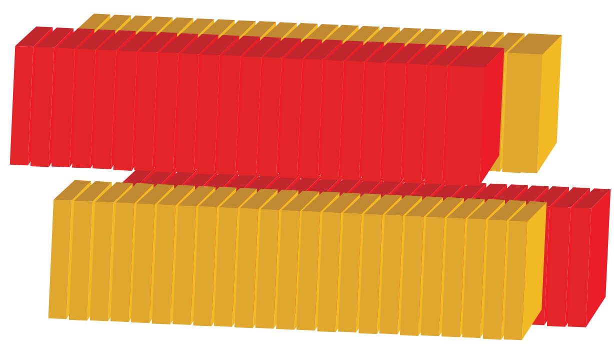

Figure 1: The APPLE undulator consists of four rows of magnets. Variable polarization can be provided by shifting the rows. Shown is an antiparallel shift resulting in tilted linearly polarized radiation.

The APPLE-II and APPLE-III devices differ in the magnetization direction of the transversally magnetized blocks. Compared to the APPLE II, the APPLE III has a tilt angle of magnetization of 45° within the plane prependicular to the main axis. In addition, magnet material is added close

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to the beam pipe providing higher fields at the expense of a reduced access from the side.

The transverse field distribution of the APPLE devices deviates significantly from that of a planar device. In a planar device with wide poles the horizontal roll-off is negligible and the vertical distribution is described by $k_y = \lambda_u/2\pi$. Figure 2 shows the transverse field distribution of APPLE-II, and APPLE-III type undulators. The vertical field has a minimum on the central axis which is due to a 1 mm slit between neighboring magnet rows. The horizontal field has a sharply peaked maximum.

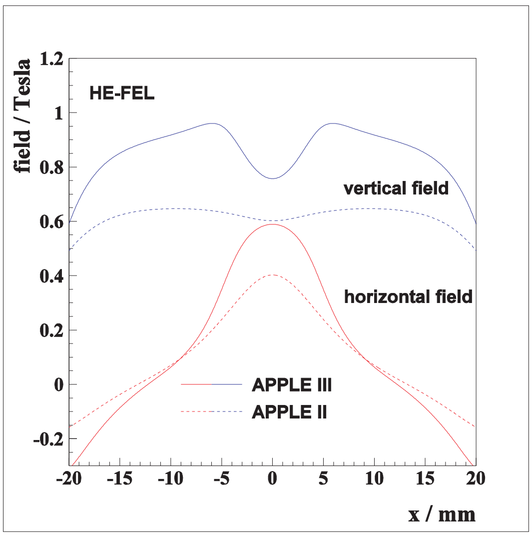


Figure 2: Transverse field profiles for the HE-FEL evaluated for an APPLE-II design (dashed line) and APPLE-III (solid line). The vertical field (blue) is calculated at row shift of 0 and the horizontal field (red) at row shift = $\lambda_u/2$.

The focussing properties of the undulator depend strongly on the row shift. At a shift of 0 mm the device focusses mainly in the vertical direction and only to a small amount horizontally. For larger shifts a horizontal defocussing occurs and the vertical focussing increases. Figure 3 shows the focussing properties of the final amplifier of the HE-FEL at the smallest gap in the parallel mode. For the antiparallel mode, trajectories with various initial conditions are tracked through the undulators and a linear transfer matrix is fitted to the results. The focussing properties are deduced from this matrix. In this way the focussing parameters used in the simulation are calculated. For more details see [1]. The data for the parallel mode are derived analytically.

SIMULATION TECHNIQUES AND RESULTS

The presented studies are restricted to the shortest wavelength, i.e. 1.24 nm, of the high-energy line which is the most sensitive case for BESSY FEL facility. The final amplifier of the HE-FEL consists of five APPLE undulators

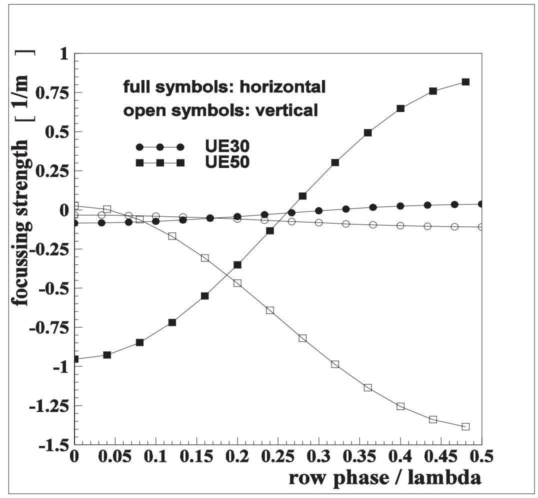


Figure 3: Focussing of the final amplifier of the HE-FEL at the smallest gap in the parallel mode.

with a period length of $\lambda_u = 28.5$ mm. Quadrupole magnets between the undulator modules are included to control the transverse size of the electron beam. The quadrupoles are assumed to be perfectly aligned. However, there is no orbit correction included in the simulation. Therefore the small kicks caused by the module offsets can be amplified by the quadrupoles leading to considerable orbit deviations.

In order to ensure that other error sources play no role, idealized seed radiations and electron beams are used for the simulation. The seeding radiation is Gaussian shaped with a peak power of 150 MW, a pulse duration of 30 fs fwhm and a tranverse rms size of $\sigma_r = 60$ μm. The electron beam has an energy of 2.3 GeV, normalized emittances of $\epsilon_{nx} = \epsilon_{ny} = 1.5$ mm mrad, a relative energy spread of 10^{-4}, and a transverse beam size of $\sigma_x = \sigma_y = 60$ μm.

In the simulation code GENESIS, undulator-module offsets are taken into account by the following analytical expression:

$$K^2 = K_0^2 \cdot \left(1 + \frac{k_x^2}{k^2}(x - x_{offset})^2 + \frac{k_y^2}{k^2}(y - y_{offset})^2\right)$$

where K_0 is the nominal K-value and $k = 2\pi/\lambda$ is the radiation wave number. The strongest focussing parameter is achieved in the case of vertical linear polarization. In this case, the normalized horizontal and vertical focussing parameters amount to $k_x^2/k^2 = -1.044$ and $k_y^2/k^2 = 2.044$ for APPLE-II and $k_x^2/k^2 = -0.494$ and $k_y^2/k^2 = 1.502$ for APPLE-III devices.

The simulations are carried out for APPLE-II and APPLE-III type undulators. The first set of simulations are performed for randomly chosen module-offsets. For the second set of simulations a relative correlated field error of 2×10^{-3} was included in addition. In order to minimize the first and second field integral, GENESIS corrects the field errors for each period, i.e. if the first pole has an error of ΔK the second pole has an error of $-\Delta K$.

Figure 4 shows the output power of the final amplifier as a function of the average module-offset for APPLE-II and APPLE-III devices. An offset up to 30 μm seems to have no effect on the output power. The APPLE-III type devices are slightly less sensitive to module-offsets.

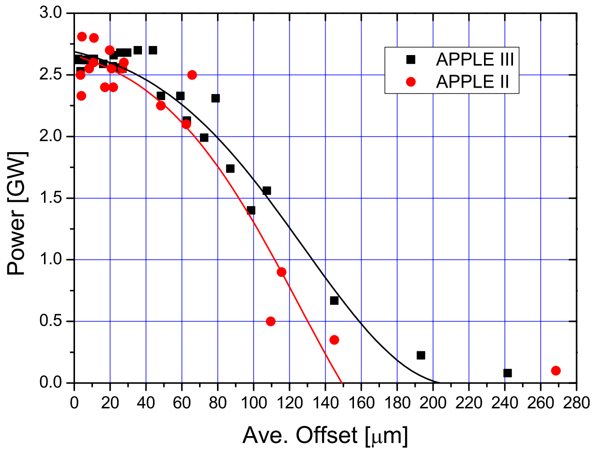


Figure 4: The output power of the final amplifier as a function of average module-offset after 15 m for APPLE-II and APPLE-III devices. The lines are included to guide the eye.

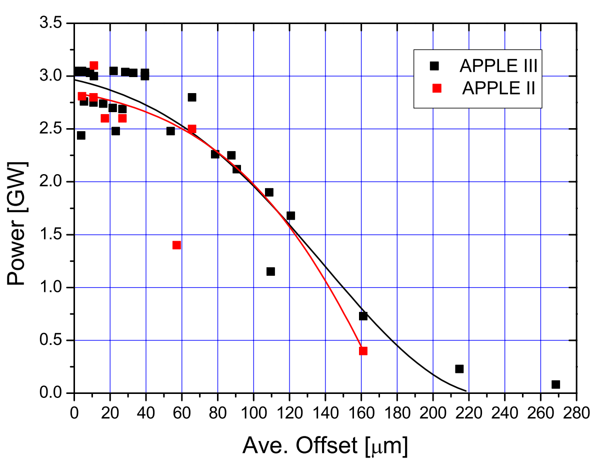


Figure 5: The output power of the final amplifier as a function of average module-offset after 15 m. A relative correlated field error of 2×10^{-3} was included in addition. The lines are included to guide the eye.

The results for the second set of the simulations are shown in figure 5. The correlated field errors increase the scattering of the output power. Also here, the APPLE-III device is less sensitive to module offsets and field errors.

The phase shake is the net fluctuation around a linear change in the phase [7]. Its rms value can be calculated as the phase of the case including the errors minus the phase of the ideal case, squared and summed over all periods. The output power as a function of phase shake is depicted in figure 6 for the APPLE-III device for both simulation sets. The main effect of field errors is an increase in the scattering of the output power. A phase shake less than 0.2 rad seems to be tolerable for both simulation sets.

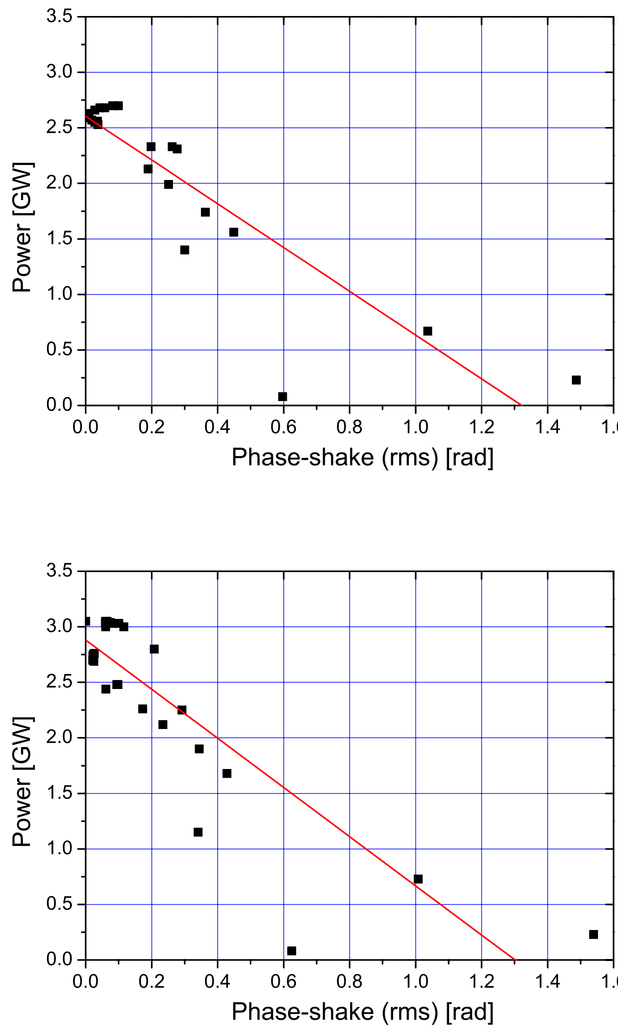
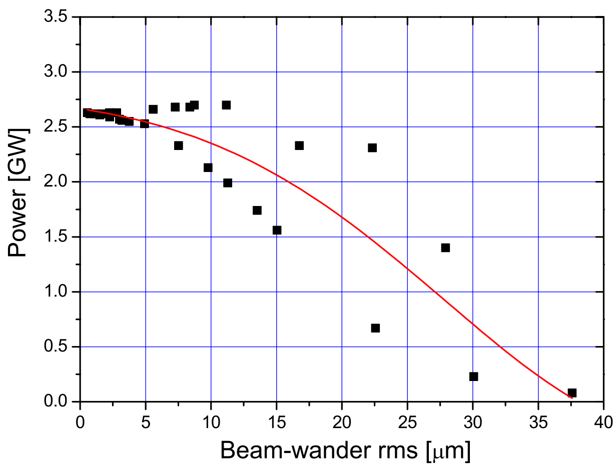


Figure 6: The output power as a function of the phase shake, without (top) and with (bottom) an additional field error of 2×10^{-3} for the APPLE-III device. The lines are included to guide the eye.

The orbit distortion or beam wander deteriorates the overlap between the radiation and electrons. The rms value of the beam wander can be calculated as the deviation from the nominal trajectory squared and summed over undulator length. Figure 7 depicts the output power as a function of the rms beam wander for the APPLE-III device for both simulation sets. The beam wander, i.e. the loss of the overlap between the radiation field and electron beam, affects the results strongly. Already, a beam wander of 7 μm rms leads to a significant power reduction of 5 %. The scattering in the results due to the field errors is clearly visable.



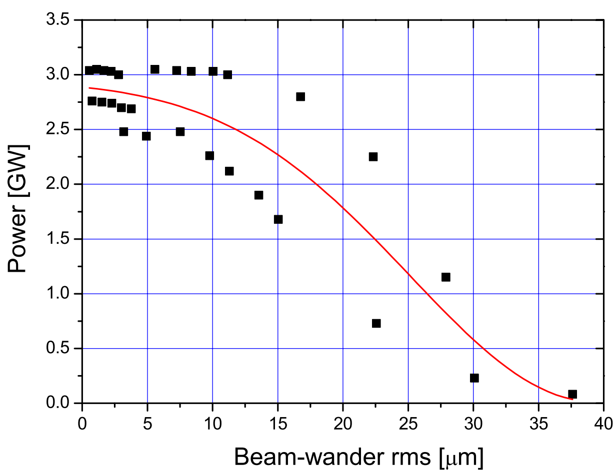


Figure 7: The output power as a function of the beam wander, without (top) and with (bottom) an additional field error of 2×10^{-3} for the APPLE-III device. From the results of the many sets of the randomly distributed module offsets, only upper and lower limit are shown. The lines are included to guide the eye.

DISCUSSION AND CONCLUSION

In the first set of simulation, the phase shake is caused by the orbit deviation. Generally, a distortion in the trajectory changes the path length of electrons and leads thus to a distortion in the phase, i.e. to a phase shake. Due to the transverse field distribution, in the case of an APPLE-type device, a distortion in the trajectory changes not only the path length but also the effective field experienced by the electrons. Therefore the strong effect of the beam wander on the output power is not surprising. Whereas, the correlated field errors do not change the transverse trajectory, they cause a jitter in the phase and increase thus the scattering in the output power.

In view of the large magnetic forces which vary in all directions during the operation the requirements of maintaining offset tolerances in the 30 μm range represent a challenge for the mechanical design of the revolver undulators and its alignments procedure.

Preliminary mechanical considerations show that the tolerance of 30 μm can be meet with an appropriate choice of precise mechanical components. Additionally, the undulator modules will be placed on transverse translation stages which are remote controlled using linear encoders for feedback. These stages are essential for the undulator commissioning where the modules have to be aligned with respect to each other.

As mentioned above, there is no orbit correction included in the simulations. An orbit correction system reduces the beam wander caused by the module-offset and relaxes thus the reproducibility requirements. In order to investigate the benefits of an orbit correction system for revolver-undulator tolerances, included orbit correction is planned for the future simulations.

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