NUMERICAL STUDIES OF THE INFLUENCE OF THE ELECTRON BUNCH ARRIVAL TIME JITTER ON THE GAIN PROCESS OF AN XFEL-OSCILLATOR FOR THE EUROPEAN XFEL

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Abstract

The superconducting linac of the European XFEL Laboratory in Hamburg will produce electron bunch trains with a time structure that allow in principle the operation of an XFELO (X-ray FEL-Oscillator). The electron bunches of the European XFEL have an expected length between 2 and 180 fs (FWHM) with an expected arrival time jitter of about 30 fs (RMS). A jitter of the electron bunch arrival time leads to a detuning between the electron and photon pulse. Since an XFEL-Oscillator relies on a spatial overlap of electron and photon pulse, the influence of a lack of longitudinal overlap is studied. The simulations are performed for different bunch lengths and levels of arrival time jitter. The results of a simulation are presented where angular, transversal and arrival time jitter are taken into account simultaneously, assuming parameters expected for the European XFEL Linac.

INTRODUCTION

The recently proposed concept of an XFELO described in [1, 2] potentially offers performance complementary to a SASE (self-amplified spontaneous emission) based FEL. The proposed XFELO uses a crystal cavity to provide narrow band feedback of the SASE radiation and has the potential to produce hard x-rays with energies between 5 and 20 keV. While the extracted peak power of such an XFELO (about 50 MW) is predicted to be lower by about 3 orders of magnitude compared to SASE-FELs, the bandwidth will be in the order of $\Delta\nu/\nu \approx 10^{-5}$ - 10^{-7} which is 2 - 4 orders of magnitude more narrow than the bandwidth of a SASE-FEL ($\Delta\nu/\nu \approx 10^{-3}$). The pulses of an XFELO will have a significantly larger longitudinal coherence up to full longitudinal coherence along the photon pulse [3]. Building an XFELO requires components which have to perform on the edge of today's technical feasibility, including the production and acceleration of high-brightness electron beams, the optimization of radiation generation in the undulator and the electron and x-ray beam guidance so as to overlap the electron bunch with the x-ray pulse to obtain optimal FEL gain. In this paper the influence of a lack of overlap is studied, whereby the focus rests on the arrival time jitter between electron bunch and x-ray pulse. The currently lowest arrival time jitter of 30 fs was achieved with a synchronization system reported in [4] using 60 fs (RMS) long electron bunches. At the European XFEL a synchronization system similar to that is planned to be implemented [5] and it is assumed that the arrival time jitter will decrease for bunches shorter than 60 fs. At the European XFEL electron bunches with a length between 180 fs and 2 fs are planned to be generated. Due to the fact that the arrival time jitter of the electron bunches at the European XFEL will be of the order of the bunch length some impact on the XFELO operation can be expected. To quantify the impact of the arrival time jitter on the XFELO operation simulations using the code GENESIS 1.3 [6] have been performed. The simulations have been performed for bunch lengths of 178 fs and 18.8 fs (FWHM) with three levels of arrival time jitter each. Since not only the arrival time is subjected to jitter exemplarily a simulation has been performed that incorporates bunch position and angular jitter as well. The jitter levels used in this exemplary simulation are the levels expected for European XFEL Linac.

Table 1: Input Parameters of the Simulations

Parameter	unit	Setup 1	Setup 2
Electron energy	GeV	14.5	14.5
Bunch charge	nC	1	0.1
Bunch length (FWHM)	fs	178	18.8
Peak current	kA	4.9	5
Normalized emittance	µm	1	0.3
Slice energy spread	MeV	1.5	2.04
Beta function at waist	m	7.5	7.5
Radiation wavelength	Å	1.027	1.027
Undulator length	m	15	15
Undulator period	m	0.03	0.03
Cavity length	m	66.62	66.62
Outcoupled radiation	%	4	4
Cavity losses	%	4	4

SIMULATIONS

The simulations where performed with the single pass FEL code GENESIS 1.3 together with an oscillator extension code [7] which calculates the propagation of the output radiation field in the cavity of one GENESIS run and use it as the seed radiation for a subsequent GENESIS run. The calculation of the field propagation inside the cavity comprises the free space propagation, the spectral filtering due to the Bragg reflection, the transformation due to the focusing elements and the outcoupling of a fraction of the radiation at one of the crystal mirrors. The spectral bandpass filter that is applied to the radiation to simulate the Bragg reflection (4 4 4) at a Diamond crystal has a width of $\Delta\lambda/\lambda \approx 1.66 \cdot 10^{-6}$ (FWHM) which corresponds to a Fourier-limited pulse duration of about 180 fs (FWHM).

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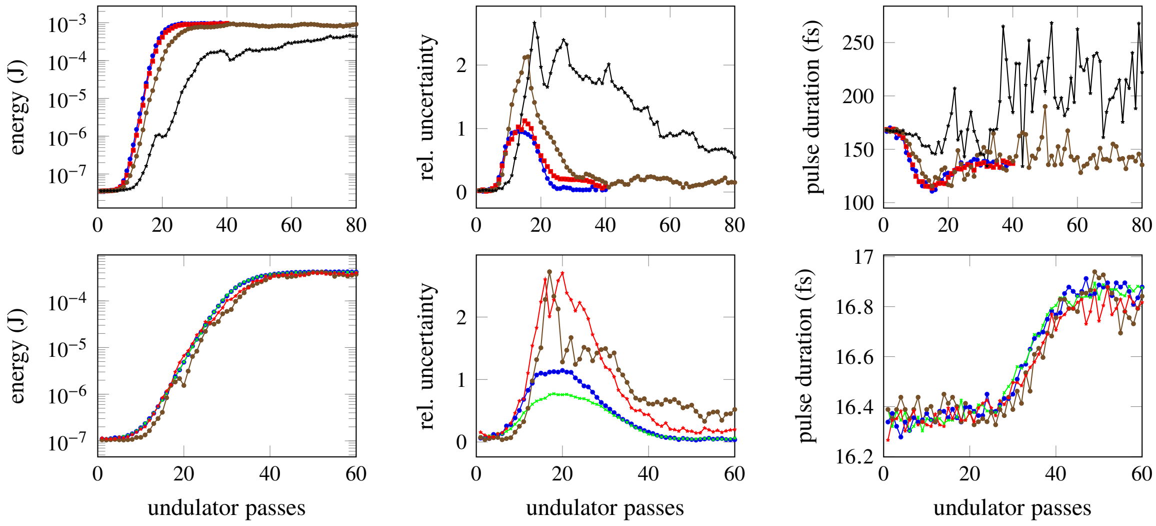

Figure 1: Effect of the arrival time jitter on the XFELO process for jitter levels of 0 fs (blue), 6.3 fs (green), 30 fs (red), 60 fs (brown), and 120 fs (black). In the top row the results of the simulation with 178 fs long electron bunches are shown. In the bottom row the results of the simulation with 18.8 fs long electron bunches are shown. The plots on the left show the mean pulse energy versus the number of undulator passes for the different jitter levels. The centered plots show the relative deviation of the mean pulse energy and the plots on the right show the mean pulse duration of the x-ray pulses.

For the generation of the arrival time jitter a script was written that shifts the radiation pulse by the deviation in the arrival time relative to a reference point within the simulated time window. The value of the deviation in the arrival time is generated by a random number generator that generates Gaussian distributed random numbers. Since GENESIS has input variables for angular and positional deviations of the electron beam the implementation of this kind of jitter could be done in a different way. Hence a script was written generating uniformly distributed random numbers and writing these numbers into the GENESIS input file. Both scripts have to be executed for each cavity round trip to generate the respective jitter. The input parameter of the simulations are shown in Table 1. One run of a jitter simulation presented here starts with a first electron bunch that generates an x-ray pulse via the SASE process and continues until the XFELO has reached saturation. Since jitter is a statistical process the simulations presented here consist of 25 runs, allowing to calculate the mean and variance of the results.

RESULTS

The arrival time jitter simulations have been performed for two different setups shown in Table 1. The essential difference in these two setups is the electron bunch length of 178 fs and 18.8 fs respectively. The results of the simulations are shown in Figure 1. The top row shows the results of setup 1. The first plot of the top row shows the mean pulse energy versus the number of undulator passes and the center plot in the top row shows the corresponding deviation of the mean for the jitter levels (RMS) of 0 fs (blue), 30 fs (red), 60 fs (brown) and 120 fs (black). For the jitter levels of 30 fs and 60 fs the impact on the gain process is quite low whereas at 120 fs the impact is significant. This result is in good agreement with the expectation that a jitter significantly shorter than the bunch length should only have a low effect on the gain process. In the plot of the energy deviation from the mean pulse energy it is noticeable that the deviation of the mean has a maximum roughly at the point where the gain is maximum. The reason for that is that at high gain levels a relatively small disturbance gets amplified and thus broadens the relative uncertainty. At saturation, lower pulse energies get amplified more than higher pulse energies and this leads to a narrowing of the relative uncertainty. The right picture in the top row shows the pulse duration versus the number of undulator passes. The pulse duration has a minimum about the point of the maximum gain. The reason for that could be that the amplitude of the electrical field in the center of the x-ray pulse is higher than at the head or the tail. If an electron bunch meets the circulating x-ray pulse it should therefore take longer for the microbunching to form at positions where the amplitude of the electrical field is lower compared to positions where the amplitude is higher. This should lead to a higher gain in the center of of the x-ray pulse until saturation is reached. Intensifying the center of the pulse more than the tails should thus shorten the over-all pulse duration. Furthermore the plot shows that the pulse duration increases with increasing jitter and that the fluctuation of the pulse duration increases with increasing jitter as well. The reason for the increase in the pulse duration is that due to the jitter the circulating pulse in the cavity and the electron bunch do not overlap completely, which leads to an asymmetrical growth of the x-ray pulse and thus the pulse duration increases.The plots in the bottom row show

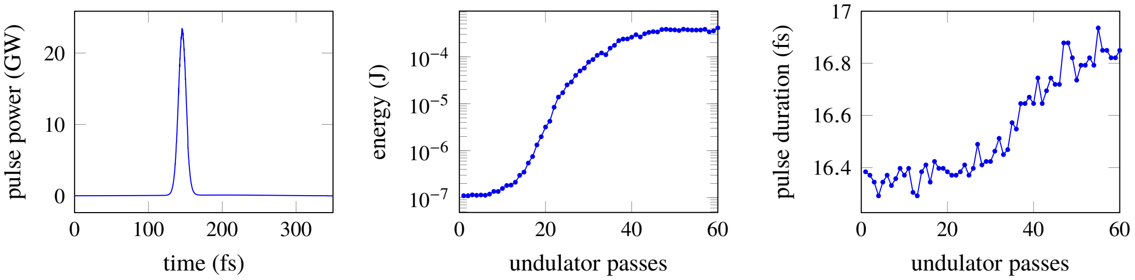

Figure 2: Performance of an XFELO considering the arrival time jitter (30 fs), angular jitter (100 nrad) and positional jitter (1 µm) expected for the European XFEL Linac. The left plot shows an exemplary pulse at saturation. The center plot shows the mean pule energy as a function of the number of undulator passes and the right plot shows the mean pulse duration as a function of the number of undulator passes.

the results of setup 2 (see Table 1). It should be noticed that in the bottom row the assumed jitter levels, if compared to the bunch length, are much bigger than in the top row. However, as the first and second plot (bottom row) show, the gain process at the same jitter levels is almost as stable as in the simulations using 178 fs electron bunches. The reason for that is the constant length of the circulating x-ray pulse. As mentioned above the Fourier-limited pulse length is due to the Bragg-reflection about 180 fs (FWHM). If a shorter pulse is generated only that fraction of the pulse within the bandwidth of the Bragg-reflection will be reflected. That leads to a circulating pulse much longer than the pulse generated in the undulator. Taking the circulating x-ray pulse of about 180 fs into account it becomes clear that the jitter sensitivity of an XFELO run with 18.8 fs electron bunches is almost the same as for an XFELO run with 178 fs electron bunches. Apart from this interesting fact the first two plots in the bottom row show the same characteristic like the first two plots in the top row. The right plot in the bottom row shows the mean pulse duration versus the number of undulator passes. All curves show a slight increase in pule duration and depending on the jitter level the pulse duration fluctuates more or less.The results of the simultaneous simulation of arrival time jitter, angular jitter and positional jitter are shown in Figure 2. For the simulation the setup 2 (see Table 1) has been used. The jitter levels are with 30 fs for the arrival time jitter, 100 nrad for the angular jitter and 1 µm for the positional jitter chosen like expected for the European XFEL Linac. The first plot shows an exemplary x-ray pulse at saturation. The pulse has an almost Gaussian shape with only some spikes on top which indicates a high level of longitudinal coherence. Even though it cannot be recognized very well it should be noticed that the 17 fs (FWHM) pulse has the weak circulating pulse of 180 fs (FWHM) as a background. The plot in the center shows the mean pulse energy versus the number of undulator passes. The curve has some small spikes and saturates at a mean pulse energy of about 300 µJ. The plot on the left shows the mean pulse duration as a function of the undulator passes. It can be seen that the mean pulse duration increases during the gain process and after saturation it stabilizes at about 16.8 fs. Overall this simulation shows a very similar characteristic to the simulation of setup 2 only taking arrival time jitter into account (see Figure 1).

CONCLUSION

In this paper the influence of electron beam jitter on the XFELO gain process was studied. An interesting result of the simulations is that for bunch lengths below the Fourier-limited pulse length of the mirrors the sensitivity to arrival time jitter does not significantly increase when the bunch length decreases. Therefore it turned out that the levels of arrival time jitter which can be achieved with today's technology are low enough to allow stable XFELO operation for all electron bunch lengths. At arrival time jitter levels significantly below the duration of the circulating pulse the jitter has only a weak impact on the mean gain, the mean saturation energy, and the mean pulse duration. However the fluctuation of these quantities increase noticeable. The simultaneous simulation of arrival time jitter, angular jitter and positional jitter have shown that it should be possible to run an XFELO under jitter conditions expected for the European XFEL Linac. Even though the fluctuations of the pulse energy and pulse duration are noticeably increased by the jitter the operation can be considered stable.

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