REVERSE UNDULATOR TAPERING FOR POLARIZATION CONTROL AT XFELS

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Abstract

The standard approach to obtaining variable polarization at X-ray FELs is to use a short afterburner with controlled field polarization behind a baseline planar undulator. A method for suppression of an intense linearly polarized background from that undulator was proposed recently [1]: an application of the reverse taper. In a certain range of the taper strength, the density modulation (bunching) at saturation is practically the same as in the case of non-tapered undulator while the power of linearly polarized radiation is suppressed by orders of magnitude. Then strongly modulated electron beam radiates at full power in the afterburner. The method was successfully tested at LCLS and is routinely used in user operation. In this contribution we present the qualitative description of the effect as well as the results of the experiment with reverse taper at FLASH2. A contrast in excess of 200 between the radiation from last two undulator sections (played the role of an afterburner) and from the reverse-tapered undulator was demonstrated at the wavelength of 17 nm.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) opens up new horizons for photon science. One of the important requirements of FEL users in the near future will be polarization control of X-ray radiation. Baseline design of a typical X-ray FEL undulator assumes a planar configuration which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from using a circularly polarized radiation (generally speaking, a full polarization control is required).

As a cheap upgrade one can consider an installation of a short helical afterburner as it was done at LCLS where a so called DELTA undulator was installed behind the main undulator [2]. However, to obtain high degree of circular polarization one needs to suppress powerful linearly polarized radiation from the main undulator. A method for suppression of the linearly polarized background from the main undulator was proposed in [1]: an application of the reverse undulator taper. It was shown that in some range of the taper strength the bunching factor at saturation is practically the same as in the reference case of the non-tapered undulator, the saturation length increases slightly while the saturation power is suppressed by orders of magnitude. Therefore, the proposed scheme is conceptually very simple (see Fig. 1): in a tapered main (planar) undulator the saturation is achieved with a strong microbunching and a suppressed radiation power, then the modulated beam radiates at full power in a helical afterburner, tuned to the resonance. This method (in combination with the spatial separation) was used at LCLS to obtain a high degree of circular polarization [2] and is routinely used now in user operation.

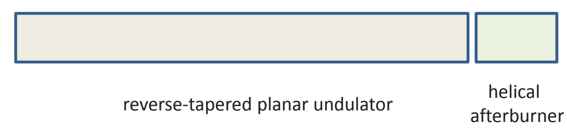

Figure 1: Conceptual scheme for obtaining circular polarization at X-ray FELs.

In this paper we give a qualitative description of the considered effect and present experimental results from FLASH2 [3] where a high contrast between the radiation from the "afterburner" (two last undulator sections) and from the reverse-tapered undulator was demonstrated recently.

DESCRIPTION OF THE EFFECT

The theoretical background of the method as well as detailed numerical simulations are presented in [1]. Here we would like to discuss qualitatively the physics of the considered effect assuming that the reader is familiar with the main results of Ref. [1].

We characterize the strength and the sign of linear taper by the taper strength parameter:

$$\beta = -\frac{\lambda_{\mathrm{w}}}{4\pi\rho^2}\,\frac{K(0)}{1+K(0)^2}\,\frac{dK}{dz}\,. \qquad (1)$$

Here z is the coordinate along the undulator length, ρ is the well-known FEL parameter, λ_{w} is the undulator period, and K is the rms undulator parameter with its initial value denoted as $K(0)$.

When the undulator parameter decreases along the undulator length, β is positive and we deal with a standard (positive) taper. In the opposite case the taper is reverse (or negative).

As for the magnitude of $|\beta|$, one can consider two asymptotes. When $|\beta|$ is small, the undulator tapering leads to a small correction to the FEL gain length which was studied in [4]. Note that the tendency we would like to demonstrate (low power at strong bunching) is better seen in the asymptote of large $|\beta|$, that is why we will consider it in our qualitative discussion (even though in practical examples we deal with intermediate values of $|\beta|$).

Let us consider the high gain linear regime of the FEL operation and make the following consideration:

i) Consider the evolution of the SASE FEL frequency band which should depend on the sign and the magnitude of β. It was found in [4] that for small $|\beta|$, the central frequency of the amplified band moves half as fast as does the resonance frequency (corresponding to the current value of the undulator parameter K). We have found that situation is quite different in the case of strong taper, i.e. when $|\beta| \gg 1$. In the case of positive β the central frequency completely follows the changes of K, while in the case of a reverse taper, $\beta < 0$, the central frequency remains to be close to the resonance at the beginning of the undulator, i.e. it does not follow the changes of K at all. In other words, in the latter case the detuning from resonance continuously increases along the undulator length, and the detuning parameter $\hat{C}$ [1, 5] has a large absolute value and is negative.

ii) For a better understanding it is instructive to consider a steady-state FEL amplifier with a large constant negative detuning rather than SASE FEL with a linearly changing detuning. In the former case one can relatively easily solve an initial value problem [1, 5]. Here we can discuss the main results. At the resonance the normalized field gain length (inverse normalized growth rate [5]) is close to one. In the considered asymptote (large negative detuning) it is much larger and scales as $\sqrt{|\hat{C}|}$, as one can find from the solution of the eigenvalue equation. Thus, the field of the electromagnetic wave has more time to modulate the beam in energy, and the latter is larger than the former by the factor $\sqrt{|\hat{C}|}$ when we consider the properly scaled quantities [5] (in contrast, at the resonance they have comparable magnitudes), see phasor diagram in Fig. 2. The energy modulations are converted into density modulations also on the scale of the gain length, so that the ratio between the latter and the former is again $\sqrt{|\hat{C}|}$. Therefore, the ratio between the bunching amplitude and field amplitude (using the standard scaling of these quantities) is given by $|\hat{C}|$. Closing the picture, the constructive interference from the retarded positions of particles happens on the scale of $1/|\hat{C}|$ due to the large offset from resonance, so that the effective formation length is much smaller than the gain length (in contrast with the resonance case). Thus, the solution of the initial value problem gives us a consistent picture. Note also that the phasors of the field amplitude and of the bunching are almost orthogonal in the considered asymptote of a large negative detuning (see Fig. 2) which indicates a weak energy exchange between the beam and the electromagnetic field. Finally, let us note that the ratio between squared bunching and the normalized FEL power [5] (what counts in the end) scales as $|\hat{C}|^2$.

iii) From the consideration in ii) it might not be clear why the field efficiently modulates the beam in energy despite a large detuning from the resonance. The explanation of this fact is as follows. From the eigenvalue equation we can find not only the real part of the eigenvalue (or, the inverse field gain length) but also an imaginary part that is responsible for the effective change of the wavenumber. The ratio of the frequency (which is given) and the wavenumber is the phase velocity. In the considered case of a large negative detuning we have found from the solution of the eigenvalue equation that the change of the wavenumber is such that the phase velocity slows down, and, as a result, the synchronism between particles and the amplified wave effectively exists in the exponential gain regime.

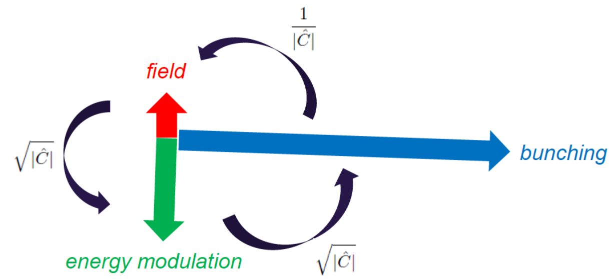

Figure 2: Phasor diagram for an FEL with reverse-tapered undulator.

iv) Let us now return to the SASE FEL case. As we know from i), in the case of a large negative β the central frequency of the amplified band remains to be close to the resonance at the beginning of the undulator, i.e. the detuning from resonance continuously moves towards large negative values as the undulator K increases along the undulator length. Thus, the situation is similar to the case discussed in ii). We have found that the main result is also similar: the ratio between the ensemble averaged squared modulus of the bunching factor and the ensemble averaged normalized power is approximately given by the squared modulus of the detuning parameter at a given position along the undulator length. We should also note that the FEL gain length is short initially, but then it increases as square root of the undulator length. Thus the total increase of the saturation length in case of the SASE FEL with reverse-tapered undulator is smaller than in case of the FEL amplifier operating in steady-state regime with the constant negative detuning.

vi) We have discussed here the high gain linear regime. However, the numerical simulations, performed in [1], confirm that the main effect of the reverse taper (strong bunching at a pretty much reduced radiation power) also takes place at the FEL saturation. We have also found that three-dimensional effects help to improve the contrast. As a result, one can have the situation when the bunching is about the same as in the reference case of no taper, the FEL power is suppressed by two or three orders of magnitude, and the increase of the saturation length is about 20-50 %.

REVERSE TAPER EXPERIMENT

FLASH2 is the second branch of the soft X-ray FEL user facility FLASH [3]. FLASH2 is equipped with gap-tunable undulator with the period 3.14 cm, the maximal K of 2.7 (i.e. the rms value is 1.9), and the net magnetic length of 30 m. The undulator consists of 12 sections, and the value of K can be independently adjusted. In the reverse taper experiment on January 23, 2016 we used the first 10 sections as a main undulator with reverse tapering, and the last two

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sections played the role of the afterburner, i.e. they could be tuned to a resonance with the incoming microbunched beam. The electron energy during the measurements was 715 MeV, and the FEL wavelength was 17 nm. The rms value of K in the first section was 1.06 (corresponding to the undulator gap of 14.5 mm), and the depth of reverse taper over 10 undulator sections was 10 % (note that the step-tapering was used, i.e. the parameter K was constant inside each section). The bunch charge was 0.3 nC, and the other parameters of electron beam (peak current, emittance etc.) were not measured due to a parallel operation with the other undulator line, FLASH1. For this reason we present here only experimental results without a comparison with simulations.

In Fig. 3 the gap scan of the two last undulator sections ("afterburner") is shown. When the undulators are completely open, the pulse energy (measured with gas monitor detector and with MCP detector) is slightly below 1 microjoule. When they are tuned to the resonance with the incoming microbunched beam, the pulse energy becomes 200 microjoules (to be compared with 260 microjoules in an untapered undulator with 12 undulator sections). Note that the rms K parameter in this case is 1.11 which is the mean of the initial value, 1.06, and the final value, 1.17, of the rms K in the reverse-tapered undulator section. This result is in agreement with the predictions of the theory of an FEL with slowly varying parameters [4].

We also measured the FEL gain curve in this configuration, it is shown in Fig. 4. One can see again that the high contrast (in excess of 200) between the radiation intensity from the "afterburner" and from the reverse-tapered undulator is measured. The gain curve in Fig. 4 looks similar to that simulated in [1] for the European XFEL.

We repeated the reverse taper experiment at the same wavelength but at a higher electron energy (930 MeV) on March 12, 2016. Rms undulator parameter was 1.6, and the ten undulator sections were reverse-tapered by 5 %. In this case the pulse energy was 0.25 microjoules, while after tuning the 11th and the 12th sections to the resonance it reached 60 microjoules, i.e. the contrast above 200 was demonstrated again. Since we had a larger K value in this experiment, we could tune the "afterburner" to the second harmonic and measure 1.8 microjoules (i.e. about 3 % of the fundamental). This is an important demonstration because a harmonic afterburner with variable polarization will be installed in FLASH2 as a part of the future upgrade. Reverse tapering in the main undulator will provide background-free radiation from the afterburner since the fundamental as well as high harmonics in the main undulator will be strongly suppressed.

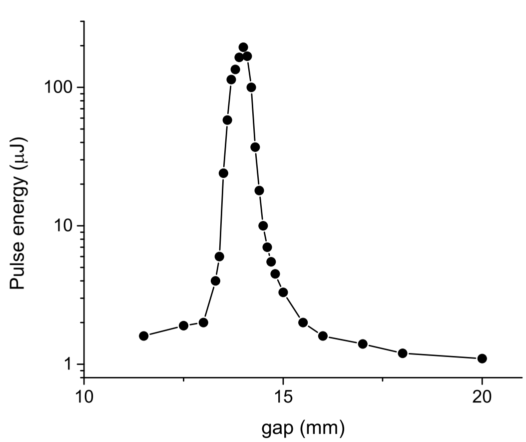

Figure 3: Gap scan of the "afterburner" (last two undulator sections). For a completely open gap the pulse energy is below 1 uJ.

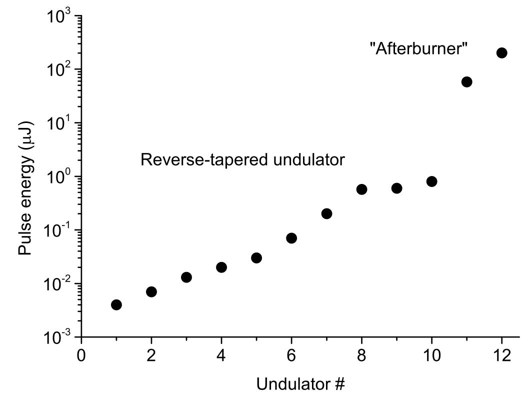

Figure 4: FEL pulse energy versus undulator number. First ten undulators are reverse-tapered, last two sections are tuned to the resonance with the incoming microbunched beam.

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