CIRCULAR POLARIZATION CONTROL BY REVERSE UNDULATOR TAPERING

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Abstract

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. As a cheap upgrade one can consider an installation of a short helical (or cross-planar) afterburner, but then one should have an efficient method to suppress powerful linearly polarized background from the main undulator. We propose a new method [1] for such a suppression: an application of the reverse taper in the main undulator. The method is free and easy to implement, it can be used at different X-ray FEL facilities, in particular at LCLS after installation of the helical afterburner in the near future. The theoretical background of the method as well as detailed numerical simulations are presented in [1]. In this note we discuss qualitatively the physics of the effect discovered in [1].

METHOD DESCRIPTION

In a short-wavelength SASE FEL the undulator tapering is used for two purposes: to compensate an electron beam energy loss in the undulator due to the wakefields and spontaneous undulator radiation; and to increase FEL power (post-saturation taper). In both cases the undulator parameter K decreases along the undulator length. The essence of our method is that we use the opposite way of tapering: parameter K increases which is usually called reverse (or negative) taper. We discovered [1] 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, our 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.

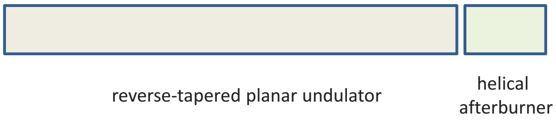

Figure 1: Conceptual scheme for obtaining circular polarization at X-ray FELs.

QUALITATIVE DISCUSSION

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

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

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 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). Note that there were already two proposals for making use of the reverse taper in FELs: to improve the efficiency of FEL oscillators [2], and to use it in combination with an energy chirp in order to produce attosecond X-ray pulses [3]. Here we discuss a new useful feature of the reverse taper: a possibility to generate a strongly modulated electron beam at a pretty much reduced level of the radiation power.

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 stron bunching) is not seen in this regime. For this reason we will consider the asymptote of large $|\beta|$ 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

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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). 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 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 $|\hat{C}|^2$.

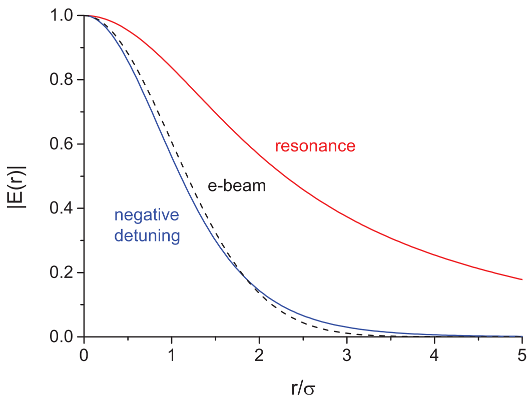

Figure 2: Field distribution of the FEL eigenmode at the exact resonance (red) and at a large negative detuning (blue). The diffraction parameter [5] equals 0.1. The detuning parameter for the blue curve equals -20 in 3D notations [5]. Dashed curve shows the electron beam profile.

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 high gain linear regime (or, the exponential gain regime).

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 is smaller than in case of the FEL amplifier operating in steady-state regime with a constant negative detuning.

v) Up to now we have discussed the considered effect in the frame of 1D theory. It is interesting to note that 3D simulations give us even stronger suppression of FEL power (at the same level of bunching) than one could anticipate from 1D theory. The 3D "bonus" can be explained as follows. In the case when diffraction plays a significant role (i.e. when the diffraction parameter B [5] is smaller than one), the radiation mode size is larger than the electron beam size when an FEL operates close to the resonance (see Fig. 2). However, the field distribution shrinks in the case of a large negative detuning (this can be explained by a shorter effective formation length, see ii)). As a result, for the same FEL power, the field acting on the beam is stronger in the latter case, i.e. it leads to a stronger energy modulation, and, therefore, to a stronger density modulation (bunching) - in addition to the 1D effect discussed in ii).

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. In particular, 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 orders of magnitude (or more), and the increase of the saturation length is about 20-30 %. Thus, the effect is not only very attractive for the polarization control as discussed above but can also be efficiently used in other FEL schemes.

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