ATTOSECOND PULSES FROM X-RAY FEL WITH AN ENERGY-CHIRPED ELECTRON BEAM AND A TAPERED UNDULATOR

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Abstract

We present a new scheme for generation of attosecond pulses in X-ray SASE FEL. A short slice in the electron beam is strongly modulated in energy by a few-cycle laser pulse in a short undulator, placed in front of the main undulator. Gain degradation within this slice is compensated by an appropriate undulator taper while the rest of the bunch suffers from this taper and does not lase. Three-dimensional simulations with the code FAST predict that short (200 attoseconds) high-power (up to 100 GW) pulses can be produced in Angstrom wavelength range with a high degree of contrast. A possibility to reduce pulse duration to sub-100 attosecond scale is discussed.

INTRODUCTION

Generation of attosecond pulses would significantly increase scientific potential of future hard X-ray FELs such as European XFEL [1] and Linac Coherent Light Source [2]. Up to now several schemes for generation of attosecond pulses from X-ray SASE FELs have been proposed [3, 4, 5, 6, 7, 8]. In this paper we study a new scheme making use of energy chirp in the electron beam and a tapered undulator. The impact of energy chirp on SASE FEL performance was studied in details in [9]. It was found that FEL gain degradation can be perfectly compensated by undulator tapering. An application of the compensation effect for generation of attosecond pulses from X-ray FELs was conceptually proposed in [9]. In this paper we present the results of numerical simulations demonstrating that the scheme works very well in a realistic situation. We also discuss a possible extension of this scheme that can allow to generate high-power, high-contrast hard X-ray pulses with a duration in 10-100 attosecond range.

ENERGY CHIRP AND UNDULATOR TAPERING

The energy chirp parameter [9]

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0\omega_0\rho^2} \quad (1)$$

is defined such that, for positive sign of $\hat{\alpha}$, particles in the head of the bunch have larger energy than those in the tail. Here $\rho = \lambda_{\mathrm{w}}\Gamma/(4\pi)$ is the efficiency parameter, $\Gamma^3 = \pi j_0 K^2 A_{JJ}^2/(I_A\lambda_{\mathrm{w}}\gamma_0^3)$, j_0 is the beam current density, $I_A = mc^3/e \simeq 17$ kA, γ_0 is relativistic factor, $K = e\lambda_{\mathrm{w}}H_{\mathrm{w}}/(2\sqrt{2}\pi mc^2)$ is rms undulator parameter, $A_{JJ} = J_0(Q) - J_1(Q)$ is the Bessel function factor, $Q = K^2/[2(1+K^2)]$, Relativistic factor γ_0 and reference frequency ω_0 are connected by the FEL resonance condition: $\omega_0 = 2ck_w\gamma_0^2/(1+K^2)$. It is also useful to define normalized detuning [11]: $\hat{C} = [k_w - \omega(1+K^2)/2c\gamma_0^2]/\Gamma$.

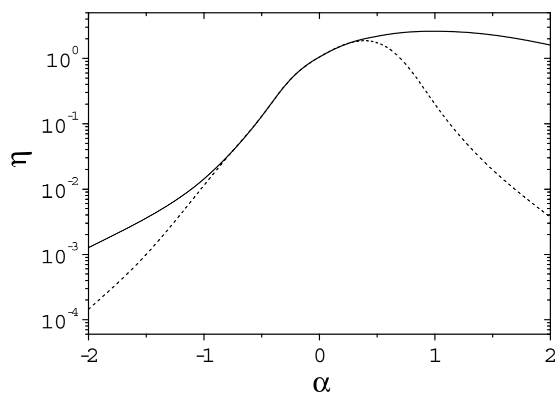

Figure 1: Normalized output power versus parameter $\hat{\alpha}$. Solid: $\hat{z} = \hat{z}_{\mathrm{sat}}(\hat{\alpha})$; dash: $\hat{z} = \hat{z}_{\mathrm{sat}}(0) = 13$.

A high-gain linear regime of a chirped SASE FEL operation was studied in [10, 9]. The main results of the simulations of the nonlinear regime [9] with 1-D version of the code FAST [11, 12] are presented in Fig. 1. Saturation length and power are functions of two parameters, $\hat{\alpha}$ and N_{c}. For our simulations we have chosen $N_{\mathrm{c}} = 3 \times 10^7$ - a typical value for VUV SASE FELs. Note, however, that the results, presented in Fig. 1, very weakly depend on N_{c}. In Fig. 1 the output power is plotted versus chirp parameter for two cases: when undulator length is equal to a saturation length for a given $\hat{\alpha}$ and when it is equal to the saturation length for the unchirped beam case ($\hat{z} = 13$). One can see sharp reduction of power for negative $\hat{\alpha}$ while a mild positive chirp ($\hat{\alpha} < 0.5$) is beneficial for SASE.

Let us consider now the case when there is no energy chirp ($\hat{\alpha} = 0$) and the detuning parameter changes linearly along the undulator [11]: $\hat{C}(\hat{z}) = \hat{b}_1\hat{z}$. This change can be due to variation of undulator parameters ($K(\hat{z})$ and/or $k_{\mathrm{w}}(\hat{z})$), or due to an energy change $\gamma_0(\hat{z})$.[1] We have found from numerical simulations [9] that in such case the effect on FEL gain is exactly the same as in the case of energy chirp and no taper if $\hat{\alpha} = 2\hat{b}_1$ for any value of $\hat{\alpha}$ (Figure 2 shows an example).

A symmetry between two considered effects (energy chirp and undulator tapering) can be understood as follows.

[1] An effect of undulator tapering (or energy change along the undulator) on FEL gain was studied in [13] in the limit $\hat{b}_1 \ll 1$.

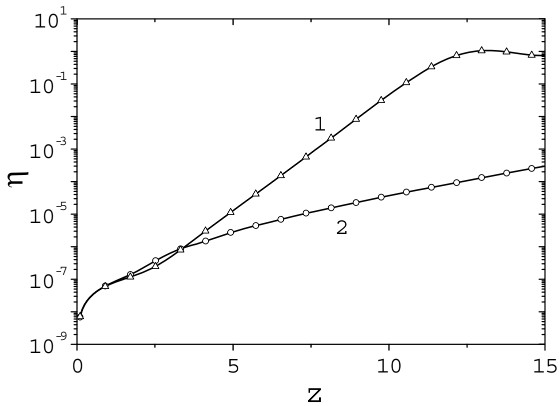

Figure 2: Normalized power versus undulator length. Solid line 1: $\hat{\alpha} = 0$, $\hat{b}_1 = 0$; triangles: $\hat{\alpha} = 4$, $\hat{b}_1 = -2$; solid line 2: $\hat{\alpha} = 4$, $\hat{b}_1 = 0$; circles: $\hat{\alpha} = 0$, $\hat{b}_1 = 2$.

If we look at the radiation field acting on some test electron from an electron behind it, this field was emitted at a retarded time. In the first case a back electron has a detuning due to an energy offset, in the second case it has the same detuning because undulator parameters were different at a retarded time. The question arises: can these two effects compensate each other? We give a positive answer based on numerical simulations (see Fig. 2 as an example): by setting $\hat{b}_1 = -\hat{\alpha}/2$ we get rid of gain degradation, and FEL power at any point along the undulator is the same as in the case of unchirped beam and untapered undulator. This holds for any value of $\hat{\alpha}$. For instance, if one linearly changes magnetic field H_w of the undulator, the compensation condition can be written as follows (nominal values of parameters are marked with subscript '0'):

$$\frac{1}{H_{\mathrm{w0}}}\frac{dH_{\mathrm{w}}}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{cdt} \qquad (2)$$

Of course, in such a case we get frequency chirped SASE pulse. Since compensation of gain degradation is possible also for large values of $\hat{\alpha}$ (there is no theoretical limit on the value of chirp parameter, except for above mentioned condition $\rho\hat{\alpha} \ll 1$), one can, in principle, organize a regime when a frequency chirp within an intensity spike is much larger than the natural FEL bandwidth (given by $\rho\omega_0$).

GENERATION OF ATTOSECOND PULSES

A new scheme looks similar to those considered in [5, 6] making use of energy modulation of a short slice in the electron bunch by a high-power few-cycle optical pulse in a two-period undulator. Due to energy modulation the frequency of SASE radiation in X-ray undulator is correlated to the longitudinal position within the few-cycle-driven slice of the electron beam. The largest frequency offset corresponds to a single-spike pulse in time domain (about

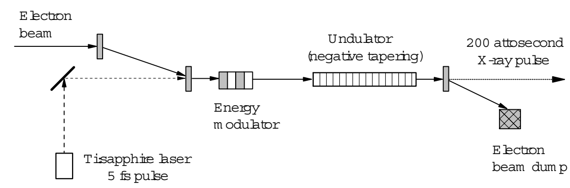

Figure 3: Schematic diagram of attosecond X-ray source. Energy modulator performs slice energy modulation of the electron bunch (see Fig. 5). Undulator tapering leads to complete suppression of the amplification process in the most fraction of the electron bunch, and output X-ray pulse has 200 attosecond pulse duration.

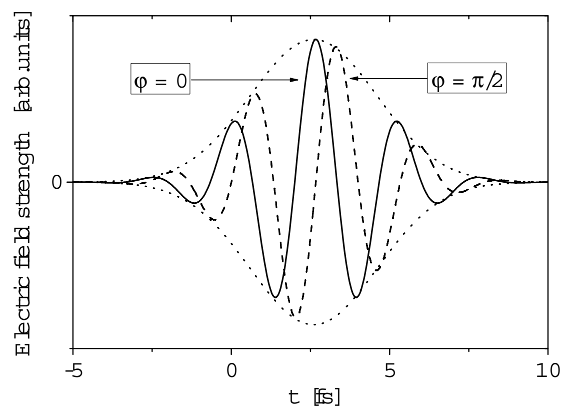

Figure 4: Possible evolutions of the electric field in the 5-fs pulse. carried at a wavelength 800 nm for two different pulse phases ($\phi = 0, \pi/2$)

300 attoseconds). The selection of single-spike pulses is achieved by using a crystal monochromator after the X-ray undulator [5], or with the help of the other undulator tuned to the offset frequency [6].

In this paper we consider a new scheme (see Fig. 3) that makes use of the compensation effect, described in the previous Section. Indeed, there is a strong energy chirp around zero-crossing of energy modulation. If one uses appropriate undulator taper then only a short slice around zero-crossing produces powerful FEL pulse. The main part of the bunch is unmodulated and suffers from strong negative undulator tapering (see Fig. 1). One should also note that for large negative taper the SASE FEL gain is very sensitive to longitudinal velocity spread. Therefore, a high-contrast attosecond pulse is directly produced in the undulator.

Operation of attosecond SASE FEL is illustrated for the parameters close to those of the European XFEL operating at the wavelength 0.15 nm [1]. The parameters of the electron beam are: energy 15 GeV, charge 1 nC, rms pulse

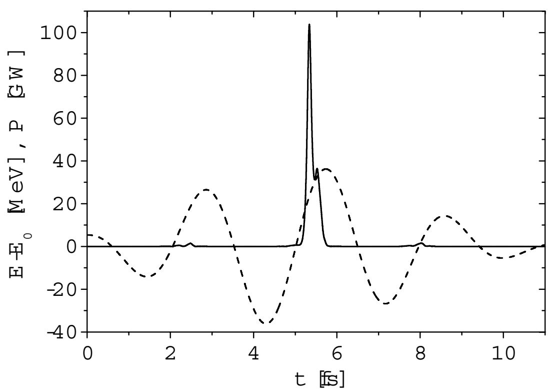

Figure 5: Energy modulation of the electron beam at the exit of the modulator undulator (dotted line) and a profile of the radiation pulse at the undulator length 100 m

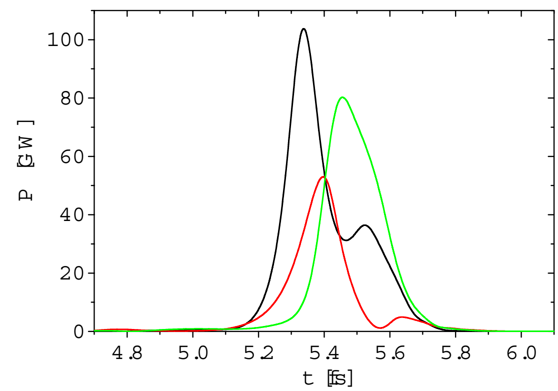

Figure 6: Temporal structure of the radiation pulse (three different shots) at the undulator length 100 m.

length 25 μm, rms normalized emittance 1.4 mm-mrad, rms energy spread 1 MeV. Undulator period is 3.65 cm, and the rms K-value is 2.5.

The parameters of the seed laser are: wavelength 800 nm, energy in the laser pulse 3 mJ, and FWHM pulse duration 5 fs (see Fig. 4). The laser beam is focused onto the electron beam in a short undulator resonant at the optical wavelength of 800 nm. Optimal conditions of the focusing correspond to the positioning of the laser beam waist in the center of the modulator undulator. It is assumed that the phase of laser field corresponds to ”sine” mode (dashed line with $\varphi = \pi/2$, see Fig. 4). Parameters of the modulator undulator are: period length 50 cm, peak field 1.6 T, number of periods 2. The interaction with the laser light in the undulator produces a time-dependent electron energy modulation as it is shown in Fig. 5. This modulation corresponds to the energy chirp parameter $\hat{\alpha} \simeq 2$ at zero crossing ($t = 5$ fs in Fig. 5).

Optimization of the attosecond SASE FEL has been performed with the three-dimensional, time dependent code FAST [12] taking into account all physical effects influencing the SASE FEL operation (diffraction effects, energy spread, emittance, slippage effect, etc.). Three-dimensional simulations confirmed the predictions of the one-dimensional model: the energy chirp and the undulator tapering compensate each other, there is strong suppression of the amplification in the case of uncompensated negative taper.

Undulator tapering is performed by changing the gap of undulator modules [1] such that magnetic field increases linearly along the undulator length ($\hat{b}_1 < 0$). We performed the scan of tapering depth $\hat{b}_1$ in order to maximize the power in the main peak on one hand, and to minimize contribution of the background, on the other hand. We ended up with the value of taper which is about 20 % smaller than that required for a perfect compensation of chirp at $t = 5$ fs. Note that the chirp is not linear in the region of interest. In addition, a mild net positive chirp is beneficial for SASE, as it was discussed above (see Fig. 1).

A typical radiation pulse at the undulator length 100 m is shown in Fig. 5. One can see a high-power spike in the region where the energy chirp is well compensated by the taper and two weak side peaks at $t \simeq 2$ fs and $t \simeq 8$ fs where the net effect is negative taper. In the rest of the bunch a large negative taper together with velocity spread and 3-D effects completely suppresses amplification. In Fig. 6 we present three different shots illustrating the properties of the main peak. Typical pulse duration is about 200 attoseconds (FWHM) and peak power ranges from several tens up to hundred GW. To estimate the contrast (which we define as the ratio of energy in the main peak to the total radiated energy at the experiment) we assume that an angular collimation is used in order to reduce spontaneous emission background. A collimator with half-angle 3 μrad allows the entire intensity in the main peak to be transmitted. The contrast is influenced by SASE intensity in two side peaks and by spontaneous emission in the first harmonic from the rest of the bunch. For the charge of 1 nC, as in our numerical example, the contrast is about 95 %. Higher harmonics of undulator radiation (if they disturb an experiment) can be cut, for instance, by a multilayer monochromator with a bandwidth of the order of 1 %.

BEYOND ”FUNDAMENTAL LIMIT”

It is generally accepted that the shortest pulse, that can be obtained from a SASE FEL, is given by a duration of intensity spike in time domain, i.e. it is defined by inverse FEL bandwidth $(\rho\omega_0)^{-1}$. However, the fact that a SASE FEL can operate with a strong chirp parameter (in combination with undulator tapering) without gain degradation, opens up a possibility of a conceptual breakthrough: one can get from SASE FEL a radiation pulse which is much shorter than the inverse FEL bandwidth. Indeed, in the case of $\hat{\alpha} \gg 1$, the frequency chirp inside an intensity spike is much larger than FEL bandwidth. Thus, one can use a monochromator to reduce pulse duration. By an appropriate choice of the monochromator bandwidth one can select an X-ray pulse that is shorter by a factor of $\sqrt{2\hat{\alpha}}$ than the inverse FEL bandwidth. The only theoretical limit in this case is given by the condition $\rho\hat{\alpha} \ll 1$. Note that for hard X-ray FELs the parameter ρ is in the range $10^{-4} - 10^{-3}$.

To illustrate a possible technical realization of this idea, we can suppose that the energy modulation by a few-cycle optical pulse is increased by a factor 3 so that $\hat{\alpha} \simeq 6$. In combination with undulator tapering and a monochromator, this would allow to obtain sub-100-GW coherent X-ray pulses with a duration below 100 attoseconds and a contrast above 90 %. Note that the contrast remains high because the spectrum of spontaneous emission from the rest of the bunch gets broader due to the stronger taper.

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