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High power femtosecond pulses from an X-ray SASE-FEL

C. Pellegrini*

UCLA, Department of Physics and Astronomy, 405 Hilgard Avenue, Los Angeles, CA 90095-1547, USA

Abstract

We discuss how to use the large-gain bandwidth of an X-ray SASE-FEL to produce femtosecond long pulses by chirping and compressing the output FEL radiation. We consider the power level, spectral width, and intensity fluctuations of the compressed X-ray pulses, compared to the case with no compression. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

An FEL in the high-gain regime has a rather large-gain bandwidth [1]. When starting from noise in a SASE-FEL, the gain bandwidth leads to the presence of spikes in the temporal distribution of the amplified radiation [2–4], if the electron bunch length is larger than the spike length. The existence of spikes and the statistical properties of the photons emitted in a SASE-FEL have been recently verified experimentally in the infrared region of the spectrum [5,6], with good agreement between theory and observations.

In a SASE-FEL operating at the wavelength λ, the r.m.s. spike length at saturation is σ_c, the cooperation length, given by Refs. [2–4].

$$\sigma_c \approx \frac{\lambda}{4\pi\rho} \tag{1}$$

where ρ is the FEL parameter, related to the 1D gain length by $L_G = \lambda_u/2\sqrt{3}\pi\rho$ [1].

The FWHM line width of a spike is

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{2\pi\sigma_c}. \tag{2}$$

For a radiation pulse of r.m.s length σ_P, the pulse consists of a number of spikes, N_S, each one occupying a length $2\pi\sigma_c$. We evaluate the number of spikes by dividing the FWHM pulse length by $2\pi\sigma_c$.

$$N_S \approx \frac{2.35\sigma_P}{2\pi\sigma_c}. \tag{3}$$

For a same pulse length FEL, not starting from noise, but from a coherent uniform signal longer than the pulse length, the Fourier transform limited line width would be

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{2\pi\sigma_P} \tag{4}$$

* Tel.: + 310-206-1677; fax: 310-206-5251.
E-mail address: pellegrini@physics.ucla.edu (C. Pellegrini).

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smaller than Eq. (2) by a factor N_S. Hence for experiments needing high-frequency resolution, it is important to try to reduce the line width near to value (4), as proposed and discussed in Refs. [7,8]. For other experiments, like pump–probe and/or non-linear effect studies, it would be convenient to reduce the pulse length to that of one spike. Achieving this result isolating a single spike has two disadvantages: (a) a reduction in the total intensity in the pulse; (b) a large intensity fluctuation, since the intensity in a single spike fluctuates as the negative exponential distribution [2–4]. In this paper we propose a method to reduce the pulse length to that of a single spike by superimposing all the spikes. This system has the advantage that there is no intensity reduction, and the additional advantage that the intensity fluctuation is still that of a SASE-FEL, of the order of the inverse of the square root of the number of spikes.

The method we propose is based on chirping the radiation pulse, i.e. changing the frequency of each spike by a quantity proportional to the spike longitudinal position inside the pulse, and compressing the pulse using a pair of diffraction gratings. The pulse length can then be changed between σ_P and σ_c. In the case of an X-ray SASE-FEL like LCLS [9], this allows us to change the X-ray pulse length from about 200 fs to about 1 fs. The system peak power is thus increased by a factor of about 200 to the Terawatt level, while the intensity fluctuations and the line width remain unchanged.

2. Chirping

The radiation wavelength of an FEL depends on the beam energy, γ, measured in rest mass units as

$$\lambda = \frac{\lambda_w}{2\gamma^2}(1 + K_{ave}^2) \tag{5}$$

where λ_w and K_{ave} are the undulator period and the average undulator normalized vector potential. A correlated frequency distribution along the radiation pulse chirping can be obtained by changing the electron energy along the electron bunch, i.e. chirping the electron bunch energy before it enters the undulator. This energy variation can be produced by accelerating the bunch in the full linac, or in part of it, at a RF phase different from 90°. By properly choosing the RF accelerating phase, and controlling the wakefields effects, we can obtain total control of the electron energy chirping, and thus of the frequency distribution along the radiation pulse.

In what follows, we will make an initial estimate of the frequency chirping needed to compress the bunch, and of the grating pair needed to transform the frequency chirping into a bunch length reduction. For this initial evaluation we assume that the wavelength variation that we introduce is small over a spike or

$$\frac{d\lambda}{ds} \ll \frac{\Delta\lambda}{\sigma_c} \tag{6}$$

where $\Delta\lambda$ is the spike line width (2). We can also rewrite this condition, using (2), as

$$\frac{1}{\lambda}\frac{d\lambda}{ds} \ll \frac{\lambda}{2\pi\sigma_c^2}. \tag{7}$$

We now assume that we produce a central wavelength variation per spike, equal to a fraction α of the spike line width $(\delta\lambda/\lambda)_{spike} = \alpha\lambda/2\pi\sigma_c$, with $\alpha < 1$. We call α the chirping parameter. The resulting total chirping, total wavelength variation along the bunch, is then

$$\frac{\delta\lambda_T}{\lambda} = \alpha N_s \frac{\lambda}{2\pi\sigma_c} \tag{8}$$

with the chirping parameter $\alpha < 1$.

3. The grating compressor

In this Section we discuss the characteristics of the grating compressor. The geometry of the compressor is shown in Fig. 1. The incidence angle, θ_0, is assumed to be smaller than unity, but larger compared to the angular spread in the radiation beam. The grating lines are separated by the distance a, and the two gratings are separated by d.

Considering first-order diffraction, the scattering angle, θ, is related to the incident angle, θ_0, by

$$a(\cos\theta_0 - \cos\theta) = \lambda. \tag{9}$$

The angle θ is a function of the incident angle and of the ratio λ/a. For two rays with wavelength λ, and $\lambda + \delta\lambda$, corresponding to the angles θ and $\theta + \delta\theta$, the difference in path length is $AC - AB - BC\cos\theta_0$. We define the compression factor, F, as the difference in path length divided by the rms pulse length, σ_P. We also define $x = \lambda/a$, $x + \delta = (\lambda + \delta\lambda)/a$. Let $AC = s$, $AD = L$, $BC = l$. Then

$$s(x, \theta_o, d) = \frac{d}{\sin\theta(x, \theta_o)} \quad (10)$$

$$L(x, \theta_o, d) = \frac{d}{\tan\theta(x, \theta_o)}. \quad (11)$$

The distance $BC = l$, giving the minimum grating length, is

$$l(x, \delta, \theta_o, d) = L(x, \theta_o, d) - L(x + \delta, \theta_o, d). \quad (12)$$

The compression factor is then given by

$$F(x, \delta, \theta_0, d, L_c) = \{s(x, \theta_o, d) - s(x + \delta, \theta_o, d) - l(x, \delta, \theta_o, d)\cos\theta_o\}/\sigma_P. \quad (13)$$

4. The LCLS case

We consider now an example similar to the LCLS [6], with $\lambda = 1.5 \times 10^{-10}$ m, $\rho = 2.4 \times 10^{-4}$, $\sigma_P = 2 \times 10^{-5}$ m. We then have $\sigma_c \sim 5 \times 10^{-8}$m, $N_S \sim 150$. The spike line width is then $\Delta\lambda/\lambda \sim 5 \times 10^{-4}$. The Fourier transform limit of the line width is about 10^{-6}. We assume for the grating $a = 10^{-7}$ m, and evaluate the X-ray energy density incident on the first grating, and the separation of the two gratings for different values of chirping and compression. The power density in the incident beam is reduced by the factor θ_0. Respect to the normal incidence case. To estimate the energy density at the compressor we assume that the spot size is increased from the original 30 to 100 μm, by proper choice of the distance of the undulator exit to the first grating. The LCLS peak power is about 10 GW, corresponding to an energy per pulse of 3 mJ, and an energy density of 10 J/cm^2 for normal incidence. The energy density incident on the grating is then $10\theta_0$ J/cm^2. For $\theta_0 < 0.1$ the incident energy density is smaller than 1 J/cm^2,

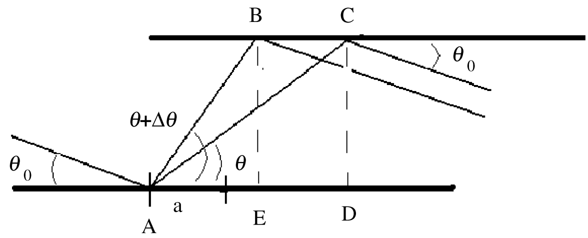

Fig. 1. Schematic representation of the compression system.

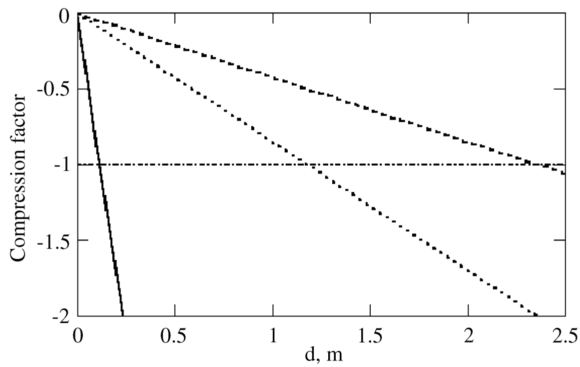

Fig. 2. Compression factor versus grating separation d for $\alpha = 0.5$ (solid line), $\alpha = 0.05$ (dotted line), $\alpha = 0.025$ (dashed line).

small enough to avoid damaging the grating. Since the X-ray pulse is diffraction limited, its angular spread is about 4×10^{-7} rad, so any value of θ_0 larger than 10^{-5} is acceptable. For what follows, we will assume as an example $\theta_0 = 0.05$. The corresponding value of θ is $\theta = 0.07$.

In Fig. 2 we plot the compression factor versus the separation of the two gratings, d, for different values of the wavelength chirping introduced in the X-ray pulse, $\delta\lambda_T$ (8). The three curves in Fig. 2 correspond to a value of the chirping parameter $\alpha = 0.5$, 0.05, 0.025, full, dotted and dashed lines, respectively. A full compression to a bunch length equal to the spike length is obtained for $F = -1$.

For the LCLS case we have $N_S\Delta\lambda/\lambda = 150 \times 5 \times 10^{-4} = 7.5 \times 10^{-2}$. To obtain this chirping we would need a 3.7% energy chirping in the electron bunch, too large to avoid electron phase-space dilution due to chromatic effects. A value one tenth of that corresponding to the dotted line, is acceptable. From Fig. 2 we see that to obtain full compression we need $d \sim 1.2$ m, a value leading to a possible, practical design.

The value of l, the grating minimum length, for the case of $\alpha = 0.05$, $d = 1.2$ m, is $l \sim 15$ cm, again an acceptable value.

5. Conclusions

We have shown that by chirping the electron bunch longitudinal energy distribution in the linac it is possible to correlate the frequency with the longitudinal position of the spikes in a SASE-FEL. Using the line-width of a single spike we can compress the X-ray pulse with a pair of diffraction grating, and reduce the length of the LCLS X-ray pulse to about 1 fs, increasing the peak power to more than 1 TW.

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