Radiation Pulse Compression for a SASE-FEL

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1. Introduction

In a SASE-FEL the radiation is emitted in spikes of length L_c -the cooperation length- [1], with a line-width

$$\Delta\lambda/\lambda=\lambda/L_c\,, \qquad (1)$$

or

$$\Delta\omega=2\pi c/L_c. \qquad (1')$$

The total radiation pulse consists of N_S spikes, and the total pulse length is $L_P=N_S L_c$. In a normal configuration all the spikes have the same line-width and the same central frequency.
Chirping the pulse, i.e. changing the frequency of each spike by a quantity proportional to the spike longitudinal position inside the pulse, allow us to compress the pulse using a pair of diffraction gratings. The pulse length can then be changed between $N_S L_c$ and L_c.
In the case of an X-ray SASE-FEL like LCLS [2] with about 250 spikes in a pulse, this would allow us to change the X-ray pulse length, in an ideal case, from about 230 fs to the length of one spike. The system peak power would thus be increased by a factor of more than 100 to the Terawatt level, while the intensity fluctuations and the line width remain unchanged.
Since the radiation wavelength depends on the beam energy as

$$\lambda=\lambda_W(1+K^2)/2\gamma^2, \qquad (2)$$

chirping of the radiation pulse can be obtained by chirping the electron bunch energy before it enters the undulator, by accelerating the bunch in the whole or part of the linac at an RF phase different from 90^o. In this way we can obtain total control of the electron energy chirping, and thus of the frequency distribution inside the radiation pulse. We assume that the frequency variation within one spike is negligible, or

$$d\omega/ds<<\Delta\omega/L_c\,, \qquad (3)$$

where $\Delta\omega$ is given by (1'), or

$$(1/\omega)(d\omega/ds) << \lambda/L_c^2 . \qquad (4)$$

We assume that the central frequency variation per spike is a fraction α of the spike line-width

$$\Delta\omega/\omega = \alpha(\lambda/L_c), \qquad \alpha<1. \qquad (5)$$

so that the total frequency chirping in the bunch is $N_s\alpha(\lambda/L_c)$.

2. The grating compressor

In this section we discuss the characteristics of the gratings compressor. The geometry of the compressor is shown in Fig. 1. The incidence angle, θ_0, is assumed to be small compared to 1, but large 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*.

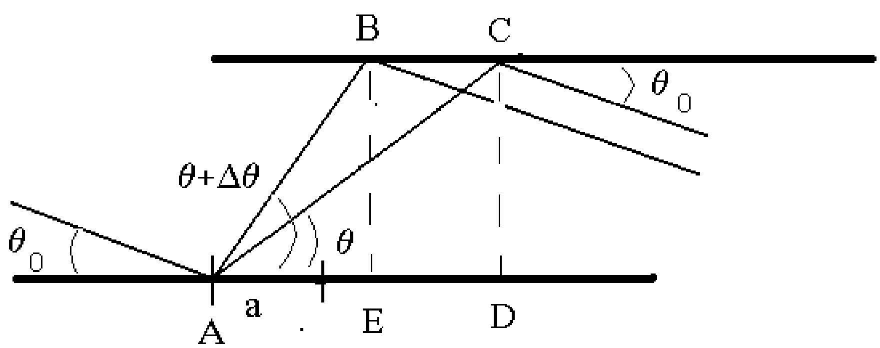

Fig. 1

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

$$a(\cos\theta_0 - \cos\theta) = \lambda. \qquad (6)$$

The angle θ is a function of the incident angle and the ratio λ/a. We define $x=\lambda/a$, and $x+\Delta = (\lambda+\Delta\lambda)/a$. The angle θ is then

$$\theta(x,\theta_0) := \mathrm{acos}(\cos(\theta_0) - x) \qquad (7)$$

Considering the rays with wavelength λ, and $\lambda+\Delta$, 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 half the bunch length, $N_S L_{c/2}$. Let $AC=s$, $AD=L$. Then

$$s(x,\theta_0,D) := \frac{D}{\sin(\theta(x,\theta_0))} \qquad (8)$$

$$L(x,\theta_0,D) := \frac{D}{\tan(\theta(x,\theta_0))} \qquad (9)$$

The distance δ=BC, which gives the minimum grating length, is

$$\delta(x,\Delta,\theta_0,D) := L(x,\theta_0,D) - L(x+\Delta,\theta_0,D) \quad , \quad (10)$$

and the compression factor is

$$F(x,\Delta,\theta_0,D,L_c) := \frac{\left(s(x,\theta_0,D) - s(x+\Delta,\theta_0,D) - \delta(x,\Delta,\theta_0,D)\cdot\cos(\theta_0)\right)}{L_c\cdot\frac{N_S}{2}} \quad .(11)$$

Another important quantity for a grating is the diffraction angle, the bunch length over the incident angle, the bunch image length on the grating, divided by the grating step:

$$\Theta_d(\theta_0) := \frac{(\theta_0\cdot a)}{L_c\cdot N_S} \quad . \qquad (12)$$

We require this angle to be smaller than the change in the angle due to chirping:

$$\Theta_{chirp}(x,\Delta,\theta_0) := \theta(x+\Delta,\theta_0) - \theta(x,\theta_0) \quad . \qquad (13)$$

3. The LCLS case

We consider now an example based on the LCLS [2], with

$\lambda := 1.4 \cdot 10^{-10} \cdot m$

$L_c := 3.4 \cdot 10^{-7} \cdot m$

$N_S \equiv 154$

and a spike line-width of $4x10^{-4}$. We assume for the grating

$a := 0.055 \cdot 10^{-4} \cdot m$

and find the gratings separation for different values of chirping and compression. We define the quantities:

$$x := \frac{\lambda}{a}$$

$$\Delta\lambda := \frac{\lambda^2}{L_c}$$

$$\Delta := \left(\frac{\Delta\lambda}{a}\right) \cdot N_S$$

and plot the angle, θ , the compression factor, and d . A plot of the angle versus the incident angle is shown in Fig. 2.

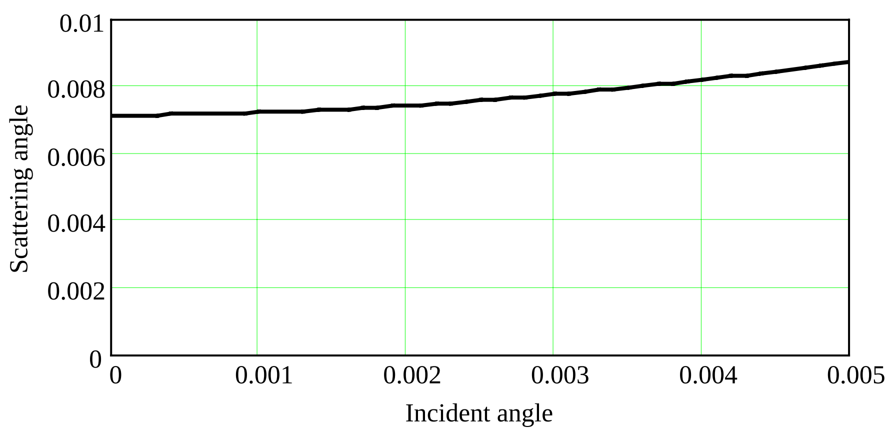

Fig. 2

In Fig. 3 we plot the diffraction angle and the spread in chirping angle.

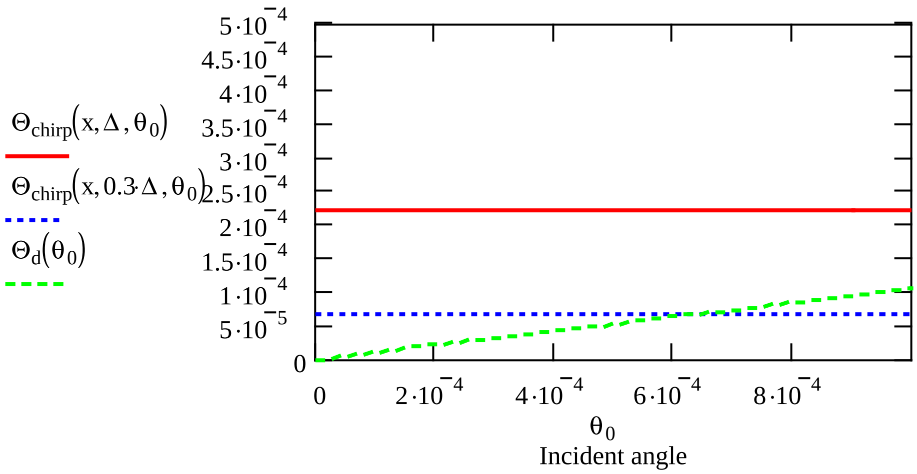

Fig. 3 Chirping and diffraction angles

The power density in the incident beam is reduced by the factor θ_0. We assume that the X-ray pulse spot size at the grating is 100µm and the peak power is 20GW, corresponding to an energy per pulse of 3 mJ, and an energy density of 5J/cm^2. The energy density incident on the grating is then 5θ_0 J/cm^2. For θ_0=0.001 the incident energy density is smaller than 5 mJ/cm^2, small enough to avoid damaging the grating. Since the X-ray pulse is diffraction limited, its angular spread is about 10^{-7} rad, so any value of θ_0 larger than 10^{-5} is acceptable.

For the remaining of this paper we assume the incident angle to be

$\theta_0 := 0.0002$

and plot the compression factor, and the quantity BC, defining the grating length, versus D, and for different values of α.

$D := 0 .. 3$

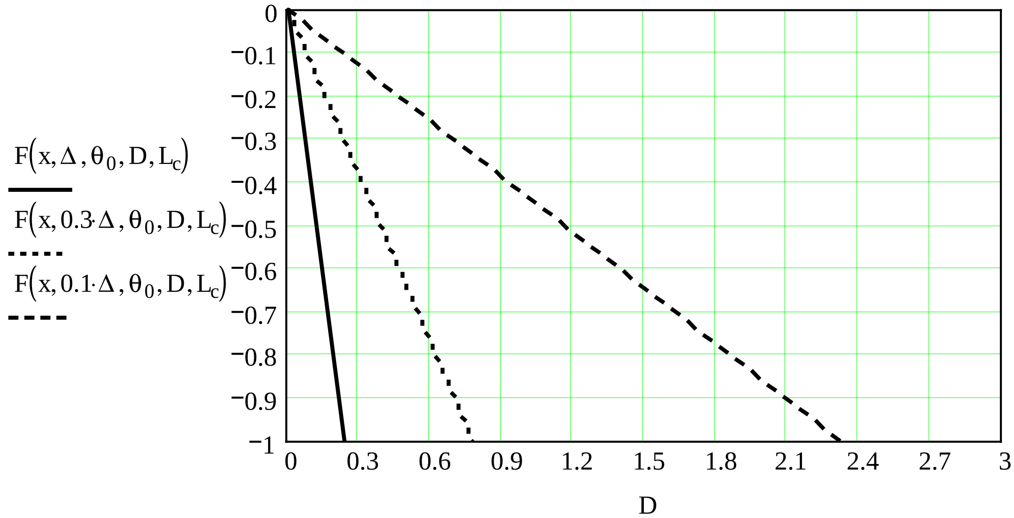

Fig. 4

The three curves in Fig. 4 correspond to the case of chirping equal to $N_S \Delta\omega$, $0.3 N_S \Delta\omega$, and $0.1 N_S \Delta\omega$, 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 $N_S \Delta\omega = 154 x 4 x 10^{-4} = 6 x 10^{-2}$. To obtain this chirping we would need a 3% energy chirping in the electron bunch, to large to avoid electron phase-space dilution due to chromatic effects. A value one third of that, corresponding to the dotted line, is acceptable. From Fig. 4 we see that to obtain full compression we need $D=0.75m$,

Fig. 5 shows the value of δ for the case of chirping equal to $N_S \Delta\omega$, full line, and $0.3 N_S \Delta\omega$, dotted line. The last case give a value δ ~1m, again an acceptable value.

$D := 0 .. 3$

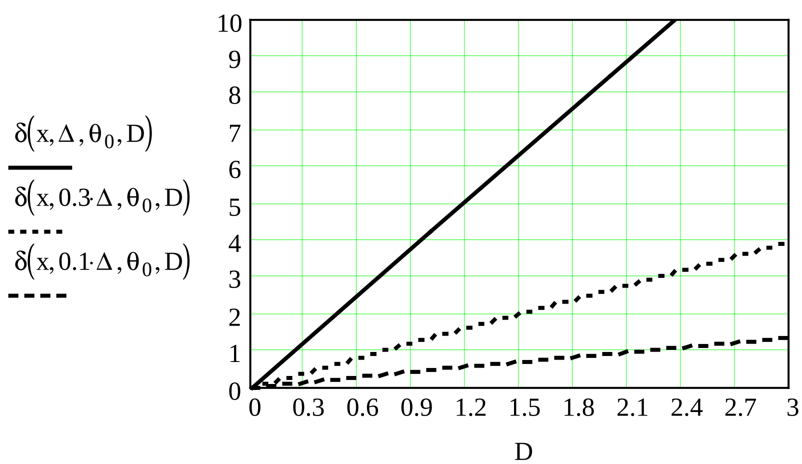

Fig. 5

4. 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 then compress the X-ray pulse with a pair of diffraction grating, and reduce the length of the LCLS X-ray. While in the ideal case the pulse length can be reduced to about 1fs, thus increasing the peak power to about 1 TW, in the real case there are other limitations that have to be taken into account, like the short LCLS pulse length and imperfections in the optical elements. The transmission efficiency of the double grating system has also to be evaluated, and could be quite low. However the possibility of obtaining short pulses is very attractive and justifies further attention to this and other similar systems.
The case that we consider to be of possible practical application is the case corresponding to an energy chirp of 0.3D, or 1% electron energy spread, with a=5.5μm, an input angle on the first grating of 0.2mrad, an exit angle from the first grating of about 7mrad, grating length of about 1m, transverse grating separation of about 0.75m, and longitudinal separation of about 107m.

Acknowledgements

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References

[1] R. Bonifacio et al., Phys. Rev. Lett. 73, 70 (1994).

[2] Linac Coherent Light Source Design Study Report, LCLS Design Study Group, SLAC-Report SLAC-R-521 (1998).