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CHIRPED-BEAM TWO-STAGE SASE-FEL FOR HIGH POWER FEMTOSECOND X-RAY PULSE GENERATION

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Abstract

We present a method for generating femtosecond duration x-ray pulses using a single-pass free-electron laser (FEL). This method uses an energy-chirped electron beam to produce a frequency-chirped x-ray pulse through self-amplified spontaneous emission (SASE). After the undulator we consider passing the radiation through a monochromator. The frequency is correlated to the longitudinal position within the pulse, and therefore, by selecting a narrow bandwidth, a short temporal pulse will be transmitted. The short pulse radiation is used to seed a second undulator, where the radiation is amplified to saturation. In addition to short pulse generation, this scheme has the ability to control shot-to-shot fluctuations in the central wavelength due to electron beam energy jitter. We present calculations of the radiation characteristics produced by a chirped-beam two-stage SASE-FEL, and consider the performance of the chirped-beam two-stage option for the Linac Coherent Light Source (LCLS).

1 INTRODUCTION

A single-pass free-electron laser (FEL) has the ability to extend the energy range of lasers into the x-ray regime. The Linac Coherent Light Source (LCLS) is a proposal [1] to construct a single-pass FEL which generates x-rays through self-amplified spontaneous emission (SASE). A SASE-FEL, such as the LCLS, can be modified to produce short duration (femtosecond) radiation. High power femtosecond x-ray pulses have many applications such as biological and material imagery, holography, and analysis of ultrafast processes.

The proposed scheme for short duration radiation generation consists of two undulators separated by a monochromator and an electron beam bypass. An energy-chirped electron beam is injected into the first undulator. The first undulator operators in the high-gain linear regime of amplification and produces frequency-chirped radiation with the usual SASE properties. After the first undulator, the radiation is passed through a monochromator which transmits a narrow bandwidth. Since the radiation frequency is correlated to the longitudinal position within the beam, a short temporal radiation pulse will be transmitted through the monochromator. A single superradiant spike in the temporal distribution may be selected by this method [2]. After the first undulator a chicane is used to delay the electron beam, compensating the path delay introduced in the radiation pulse by the monochromator. At the entrance to the second undulator, the radiation is recombined with the electron beam. The second undulator acts as an FEL amplifier and amplifies the short-pulse radiation to saturation.

This two-stage FEL scheme is similar to proposals to develop a monochromatic x-ray laser [3]; although we are interested in short-duration x-ray generation and not Fourier transform limited monochromatization.

The proposed scheme offers two advantages over the standard SASE-FEL. First it provides control of the radiation pulse length, and allows the possibility of producing short-duration radiation pulses. The short-duration pulse will reach saturation in the second undulator, and therefore, will have the same peak power as the standard SASE-FEL. Second it provides stability of the shot-to-shot fluctuations in the central wavelength due to shot-to-shot electron energy jitter.

The discussion in this paper is focused on the parameters for the LCLS. Table 1 lists the basic LCLS FEL parameters.

Table 1: LCLS FEL Parameters

Radiation wavelength	1.5 Å
FEL parameter, ρ	5×10^{-4}
Electron beam energy	14.35 GeV
Undulator type	planar
Undulator period	3 cm
Undulator parameter, K	3.71

2 RADIATION CHARACTERISTICS

The radiation wavelength λ of an FEL depends on the beam energy measured in rest mass units γ as $\lambda = (\lambda_u/2)(1+K^2)\gamma^{-2}$, where λ_u is the undulator period and K is the undulator strength parameter (the average normalized vector potential of the undulator magnetic field). Therefore, chirping the electron beam (i.e., providing an energy spread that is correlated to the longitudinal position of the electrons within the beam) before the beam enters the first undulator allows control of the frequency distribution of the radiation pulse generated in the first undulator. Chirping of the electron beam may be accomplished by acceleration the electron bunch in the linac at an off-crest RF phase. We will consider a linear energy chirp on the electron beam such that $(\delta\gamma/\gamma) = \alpha(z/L_b)$, where L_b is the FWHM electron bunch length, and z is the longitudinal deviation from the beam centroid. This energy chirp will pro-

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duce a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma = 2\alpha z/L_b$.

The temporal structure of the radiation produced by a SASE-FEL [4] will consist of randomly distributed spikes (or wavepackets) of root-mean square (rms) duration $\sigma_\tau = 1/(2\sigma_\omega) \approx (\lambda/4\pi\rho c)(N_u\rho)^{1/2}$, determined by the rms FEL bandwidth σ_ω, where the ρ is the FEL parameter, $\lambda/4\pi\rho$ is the cooperation length, and N_u is the number of undulator periods. The FEL process saturates at about $N_u \approx 1/\rho$. There is full longitudinal coherence of the radiation within one spike, but no phase correlation between spikes. The number of spikes in the distribution is approximately given by $N_s \approx L_p/2\pi c\sigma_\tau$, where L_p is the FWHM radiation pulse length. For the LCLS case, the spike duration is $2\pi\sigma_\tau \sim 1$ fs. The basic SASE-FEL properties of the radiation will be unaffected by the chirp provided the energy chirp over one cooperation length is much less than the FEL parameter $\alpha/L_b \ll \rho^2/\lambda$.

The width of the spectral distribution of the SASE radiation will be determined by the frequency chirp (for $\delta\omega > \sigma_\omega$). The spectral distribution will also consist of N_s random spikes (modes). For LCLS parameters, the rms FEL bandwidth is $\sigma_\omega/\omega \sim 10^{-4}$.

2.1 Femtosecond Pulse Generation

The monochromator may be used to select the pulse duration, due to the correlation between frequency and longitudinal position in the electron beam introduced in the radiation. The rms pulse length of the transmitted radiation will be $\sigma_z \simeq L_b(\sigma_m/\omega)/2\alpha$, for a Gaussian line monochromator with rms bandwidth σ_m. The minimum duration which may be selected by this method is limited by the properties of wavepackets (Heisenberg uncertainty principle) $\sigma_z \geq c/2\sigma_m$. For example, if we consider a 0.5% chirp ($\alpha = 5 \times 10^{-3}$) over the LCLS beam and a monochromator bandwidth $\sigma_m/\omega = 4.3 \times 10^{-5}$, then a FWHM pulse duration of $L_p/c \simeq 3.2$ fs is transmitted.

If we choose the monochromator bandwidth to be larger than the spectral interval of coherence, then the temporal distribution of the radiation will contain many spikes, i.e., $\sigma_z > c\sigma_\tau$. For this case, the probability distribution of the peak radiation power after the monochromator tends to a gamma distribution with rms power fluctuations $\sigma_P \approx (2\pi c\sigma_\tau/L_p)^{1/2}$.

2.2 Frequency Stabilization

We expect shot-to-shot fluctuations in the mean electron beam energy due to jitter throughout the linac. This will lead to fluctuations in the frequency of the radiation. Provided the correlated energy chirp is larger than the mean energy fluctuations, the resulting frequency-chirped radiation pulse will span the deviation due to the jitter. This will allow the monochromator to select the desired frequency, and therefore, stabilize the shot-to-shot jitter. For LCLS, the expected mean beam energy jitter from the linac is 0.1%.

Table 2: Undulator 1 Parameters

Length, $L_u^{(1)}$	43.2 m
Input electron beam:	
Peak current	3.4 kA
Bunch duration, FWHM	233 fs
Correlated energy spread	0.5%
Uncorrelated energy spread	0.006%
Output radiation:	
Resonant frequency chirp	1%
Mean peak radiation power	13 MW
FEL bandwidth (FWHM)	2.7×10^{-4}
Rayleigh range, Z_R	40 m

3 CHIRPED-BEAM TWO-STAGE FEL

In this section we investigate the requirements for each stage of the device.

3.1 First Undulator

The first undulator operates as a SASE-FEL, starting from noise in the beam and amplifying the spontaneous emission. The input beam and output radiation parameters for the first undulator are listed in Table 2. The first undulator is required to be of sufficient length such that the power transmitted through the monochromator and seeded into the second undulator is much larger than the effective power of the electron beam bunching. Since we propose to reuse the electron beam in the second undulator, the length of the first undulator is limited by the growth of the uncorrelated energy spread. The uncorrelated energy spread in the electron beam increases during the SASE process as $\sigma_\gamma \simeq \rho(P_{\rm out}^{(1)}/P_{\rm sat})^{1/2}$, where $P_{\rm out}^{(1)}$ is the output radiation power from the first undulator and $P_{\rm sat}$ is the saturation power. The growth rate of the amplification becomes negligible when $\sigma_\gamma > \rho$. Therefore, in order to reuse the electron beam in the second undulator and have significant amplification, the first undulator must terminate before saturation. We consider terminating the first undulator such that $P_{\rm out}^{(1)}/P_{\rm sat} \simeq 10^{-3}$. For LCLS parameters, this corresponds to a first-undulator length of $L_{\rm u}^{(1)} = 43.2$ m, with mean output peak radiation power $\langle P_{\rm out}^{(1)}\rangle = 13$ MW.

3.2 Monochromator

We consider Bragg diffraction as the method of bandwidth selection. Utilizing a 4-bounce scheme, the transmitted radiation remains in the same direction and transverse position. This method also allows the path delay introduced in the photon beam to remain constant over the tunability range. For example, one can consider Si(111) crystals, which transmit about 80% of the incident x-rays. Using Si(111), 1.5 Å photons are transmitted with an rms bandwidth of $(\sigma_m/\omega) = 4.3 \times 10^{-5}$.

3.3 *Electron Beam Bypass*

The distance between the undulators is defined by the electron beam bypass. A chicane has been designed for LCLS parameters to bypass the electron beam and provide a path delay to the electron beam to compensate for the photon beam path delay induced in the monochromator. The parameters for the chicane are listed in Table 3. The length of the bypass includes the chicane and optics to match the betatron functions from the exit of the first undulator to the entrance of the second undulator. The achromatic chicane is non-isochronous and compresses the energy-chirped beam. For an energy chirp of 0.5%, the beam is compressed about 14%. The compression also increases the current and the uncorrelated energy spread of the electron beam entering the second undulator. By selecting the nominal frequency in the monochromator and providing equal path delay for both the photon and electron beams, the short pulse radiation will recombine at the entrance of the second undulator with the resonant electrons.

The radiation power into the second undulator must be much greater than the effective power of bunching in the electron beam. Therefore the bunching produced by the FEL interaction in the first undulator should be destroyed in the bypass before the second undulator. This demodulation of the electron beam on the scale of the radiation wavelength is easily accomplished by passing the beam (with uncorrelated rms energy spread after the first undulator of 0.007%) through the non-isochronous chicane.

3.4 *Second Undulator*

The second undulator operates as an FEL amplifier and is seeded by the radiation pulse selected in the monochromator. The parameters for the second undulator are listed in Table 4. We require that the input radiation power at the entrance of the second undulator dominate over the effective power of the beam shot noise. The peak input radiation power at the entrance of the second undulator is $P_{\rm in}^{(2)} \approx P_{\rm out}^{(1)} T_{\rm diff} T_m \gg P_{\rm shot}$, where $T_m \approx (0.8)^4 \simeq 0.41$ is the power loss in the monochromator, and $T_{\rm diff} = [1 + (L_{\rm by}/Z_R)^2]^{-1} \simeq 0.6$ is the power loss due to diffraction of the radiation pulse between the first and second undulators. The input radiation pulse is amplified in the second undulator to saturation. For the input electron and photon beam parameters listed in Table 4, saturation occurs at $L_u^{(2)} = 51.84$ m. The fluctuations of the output radiation are dramatically reduced because the FEL amplifier operates in the non-linear regime.

Table 3: Electron Beam Bypass Parameters

Total length, $L_{\rm by}$	32.4 m
Path delay	5.0 mm
Off-axis displacement	20.5 cm
R_{56}	3.6 mm
Bending angle	1.68 deg
Dipole magnetic field	0.4 T

Table 4: Undulator 2 Parameters

Length, $L_u^{(2)}$	51.84 m
Input electron beam:	
Peak current	4.0 kA
Bunch duration (rms)	200 fs
Uncorrelated energy spread	0.008%
Beam shot noise power	3.3 kW
Input radiation:	
Pulse duration (FWHM)	3.2 fs
Radiation bandwidth (FWHM)	10^{-4}
Mean radiation power	3.2 MW
Power fluctuations (rms)	58%
Output radiation:	
Pulse duration (FWHM)	3.2 fs
Radiation bandwidth (FWHM)	10^{-4}
Mean peak radiation power	23 GW
Power fluctuations (rms)	9%

4 CONCLUSION

The chirped-beam two-stage SASE-FEL provides the possibility to generate high-power femtosecond x-rays, as well as stabilizing the radiation frequency. The seeding of the second undulator has a number of advantages compared to a single undulator followed by x-ray optics (i.e, the standard SASE-FEL). By seeding the radiation into a second undulator, any power loss in the monochromator is recovered and the radiation intensity fluctuations are reduced. The peak power after the first undulator is much less than the saturation power, and therefore, damage to the optical elements of the monochromator will be reduced.

We have examined a system which is compatible with the LCLS design parameters. The characteristics of the output radiation for LCLS design parameters are listed in Table 4. The final choice of parameters for such a device will be determined by the users of femtosecond duration x-ray pulses.

5 REFERENCES

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