CHIRPED PULSE AMPLIFICATION USING A FREE-ELECTRON LASER *

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Abstract

It is proposed that a chirped pulse can be amplified using a free-electron laser. Chirped pulse amplification (CPA) technology is one of the major ways to get high power and ultra short FEL pulse. Linear chirped pulse amplification at single pass FEL amplifier is studied through numerical simulations using our 1D time-dependent code GOFEL-P. The processes of chirped pulses with different chirped parameters being amplified by normal FEL amplifier or the FEL amplifier with energy-chirped electron beam are studied. The peak power and width of the final compressed pulse with different chirped parameters have been calculated. The results show that, the normal FEL amplifier can amplify the chirped pulse, the peak power of the final compressed pulse can reach 10s GW and the width of the pulse can be 10s fs with the parameters of TTF. In the case of using the energy-chirped electron beam to amplify chirped pulse, the gain bandwidth of the FEL amplifier will be wider and the chirped parameter will be larger more. The peak power of the final compressed pulse can even reach near 10 times larger and the width of the pulse 10 times shorter than that with normal electron beam.

INTRODUCTION

Utilizing the CPA techniques in solid-state lasers [1], it is now possible to build compact lasers that produce both ultrashort pulses (⩽50 fs) and intensities as high as 10^{18} w/cm^2, which has facilitated important areas of scientific research such as strong-filed physics. However, the wavelength range below 200nm is essentially inaccessible to current solid-state lasers, since the materials used in conventional laser amplifiers have a short wavelength cutoff near 180 nm. The CPA techniques can also be used in FELs to obtain shorter wavelength even in X-ray range, ultrashort pulse high power lasers.

As early as 1988, Moore suggested the chirped-pulse FEL as an oscillator can be operated with enhanced energy extraction efficiency [2]. The subpicosecond laser pulses (down to 200 fs) have been produced and measured with CLIO FEL oscillator at a wavelength around 8.5 μm [3]. However, they did not use any dispersive elements to provide optical pulse compression, and they found that the frequency-time relationship inside the main laser pulse becomes distorted due to saturation processes and leads to pulses unsuitable for compression techniques.

Generating short pulses by frequency chirping FEL output in SASE FEL configurations has been proposed [4, 5]. The idea is to send an energy-chirped electron beam through the long undulator to produce frequency-chirped output. A monochromator is then used to select a narrow bandwidth. Since the radiated frequency is correlated with the temporal position along the pulse, a short segment of the original radiation is transmitted. In LEUTL experiment at ANL [6], properties of chirped SASE were studied using the frequency-resolved optical gating technique. It was observed that the spikes in the SASE output have a positive frequency chirp even in the absence of an energy chirp in the electron beam. It was also confirmed that an electron energy chirp mapped directly into the frequency chirp of the FEL output, and under proper conditions the two chirps were made to cancel each other within a spike.

However, to create a chirped output radiation pulse that can be compressed to a short pulse, the pulse must be very accurately chirped, i.e., from the head to the tail of the pulse the pulse the optical phase relationship should be as coherent as if it had been originally stretched from a compressed short pulse. It is difficult to generate such coherence starting from noise, as occurs in oscillator or SASE FEL configurations. Hence from the standpoint of phase coherence, the choice of a chirped pulse seeded single pass FEL amplifier seems the most promising configuration to pursue. Yu has suggested that utilizing CPA techniques with an HGHG FEL the 4 fs pulses with 0.3 mJ at a central wavelength of 88 nm can be yielded [7].

In this paper, we come back to simple and basic case. Linear chirped pulse amplification at single pass FEL amplifier is studied through numerical simulations using our 1D time-dependent code GOFEL-P [8-10]. The processes of chirped pulses with different chirped parameters being amplified by normal FEL amplifier or the FEL amplifier with energy-chirped electron beam are studied. The peak power and width of the final compressed pulse with different chirped parameters have been calculated. The results show that, the normal FEL amplifier can amplify the chirped pulse, the peak power of the final compressed pulse can reach 10s GW and the width of the pulse can be 10s fs with the parameters of TTF. In the case of using the energy-chirped electron beam to amplify chirped pulse, the gain bandwidth of the FEL amplifier will be expanded and the chirped parameter will be larger. The peak power of the final compressed pulse can even reach near 10 times larger and the width of the pulse 10 times shorter than that with normal electron beam.

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SIMULATION RESULTS

The envelope of a linear frequency chirped Gaussian pulse can be expressed as [10, 11]:

$$a_s(z=0,t)=a_{s0}\exp\left(-\frac{1+iC}{2}\frac{t^2}{\tau_0^2}\right) \quad (1)$$

where a_{s0} and τ_0 is the maximum optical field amplitude and the width of the Gaussian pulse, C is the chirp parameter. C > 0 for positive chirp which means the frequency will become large along the pulse whereas C < 0 for negative chirp. The width of the pulse will be compressed to about 1/C and the power to C times of the original values as a_{s0} and τ_0 by a idea compression dispersive element such as GVD material.

A linear frequency chirped Gaussian optical pulse expressed as Eq. 1 is inputted our 1D time-dependent code GOFEL-P [8-10]. As an example, the parameters of TTF experiment at DESY [12] as shown in Table 1 are used in all numerical simulations. The energy spread and emittance of the electron beam are neglected in simulations. The initial power of the optical pulse is 1 kW over the duration of 2.3 ps.

Table 1: TTF Parameters used in Simulations

Electron beam	
energy (MeV)	270
peak current (A)	600
micro bunch (ps)	2.2
transverse beam size (μm rms)	100
Undulator	
period (cm)	2.73
peak field strength (kG)	4.6
length (m)	9.83
Optical	
wavelength (nm)	82.2

Normal FEL Amplifier

First we studied the simplest case, in which linear frequency chirped optical pulses pass an FEL amplifier with normal gain bandwidth. The averaged power over the radiation pulse varies with the undulator length at different initial chirp parameters is shown in Fig. 1. One can see that the optical power decreases as initial C increases since the portion with different frequency to the resonant frequency, at which the optical pulse can obtain the maximum amplification by the electron beam, becomes more and more. One can also see that the saturation reaches at almost same undulator length of about 5.6 m with different C.

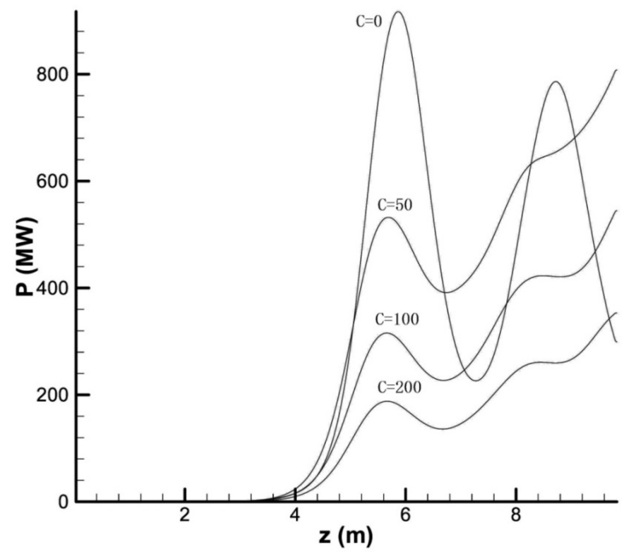

Figure 1: Averaged power of the optical pulse as a function of the undulator length with different initial chirp parameters.

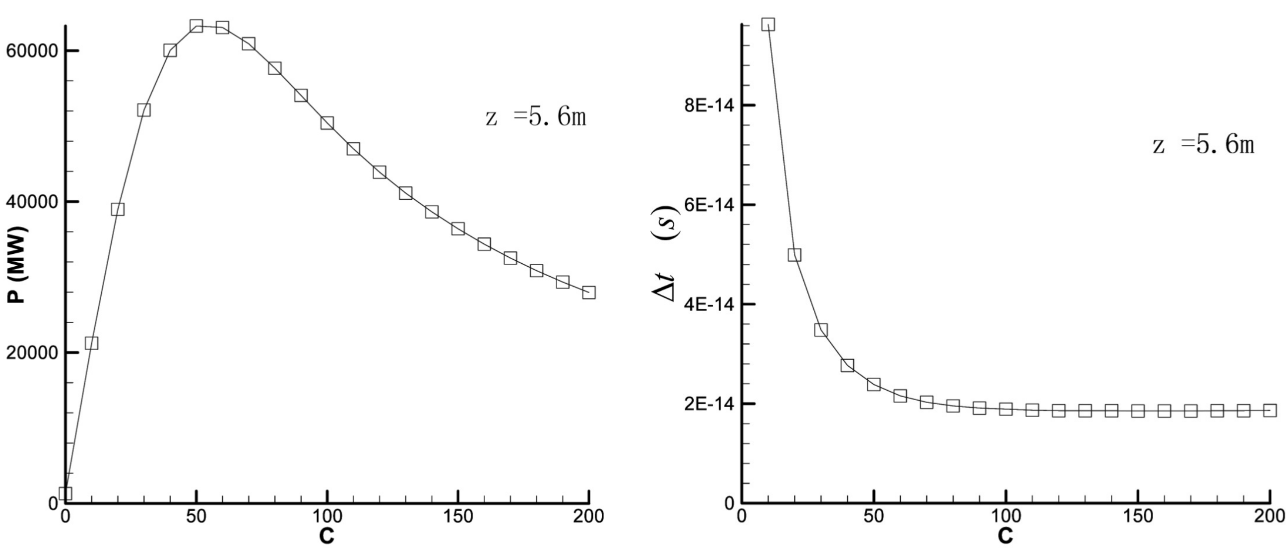

Figure 2: Peak power and FWHM width of the compressed optical pulse *vs* initial chirp parameter.

We output the optical pulse at the undulator length of 5.6 m. The Fourier transform method is used to calculate the peak power and width of the final compressed pulse by an idea linear compression element [11, 13]. The calculated power and width (FWHM) as functions of the initial chirp parameter are shown in Fig. 2. We can see that the optical power reaches the maximum value of 63.3 GW at C = 50. The power of the compressed pulse increases as C increases but the amplification of the chirped optical pulse by the electron beam reduces as shown in Fig. 1. The balance is achieved at the point of C = 50 and so be the maximum power. The width of the compressed pulse decreases rapidly with increased chirp parameter when C < 50, as shown in Fig. 2, which implies the phase coherent is kept perfect during the chirped pulse is amplified by the electron beam in the 5.6 m length undulator as chirp parameter is small. Whereas C > 50, the frequency region of the chirped optical pulse exceeds the gain bandwidth of the FEL amplifier and that portion cannot be amplified by the electron beam with the same energy, and so the pulse cannot be further compressed even with larger and larger initial chirp parameter. As shown in Fig. 2, the width of the final compressed pulse becomes a constant of about 18.5 fs and does not change as C continue increasing.

If one want to obtain shorter optical pulses, the gain bandwidth of the FEL amplifier must be expanded, which can be attained using energy chirped electron beams [2-7].

Amplifier with Energy Chirped Electron Beam

A FEL amplifier's gain bandwidth is approximately given by a Pierce parameter ρ [4, 7, 8], which is typical about 0.1 % for an ultraviolet FEL. Therefore, to amplify a chirped pulse with a few percent bandwidth, the energy of the electron beam should be chirped to match the resonance condition:

$$\gamma^2(t) = \frac{\lambda_u\left(1+K^2\right)}{4\pi c}\omega(t) \qquad (2)$$

where $\gamma(t)$ is the electron beam energy, λ_u is the undulator period and K the undulator parameter, and $\omega(t)$ is the frequency of optical pulse. The time t is used to denote the longitudinal position along the radiation and electron pulse.

Differentiating Eq. 2 and Eq. 1, the energy of the electron beam must be chirped as:

$$\frac{\gamma(t)-\gamma(0)}{\gamma(0)} = \alpha\frac{t}{T_b} \qquad (3)$$

where $\alpha = \frac{CT_b}{2\tau_0^2\omega(0)}$, T_b is the length of the electron beam, α is typical in the range of 0.1% to 1%.

By dephasing the RF wave relative to the electron bunch in the accelerator section, the bunch can be made to accelerate off the crest of the accelerating wave. The electron bunch will acquire an energy slope such that electrons at the start of the bunch will have a lower energy than the later ones [3]. This energy slope is approximately linear for a proper dephased from the crest, and so matches the linear frequency chirped optical pulse according Eq. 3.

The averaged power over the optical pulse varies with the undulator length at different initial chirp parameters is shown in Fig. 3. One can see that the optical power decreases as initial C increases, but not as rapidly as the case of unchirped electron beam as shown in Fig. 1 since the energy of electron beam is chirped to match the frequency chirped. A much larger chirp parameter C can be used and the power only reduce to half of the maximum even C as large as 600. However, due to the slippage that is caused by the different between the speeds of the optical and electron pulses, the optical pulse exceeds the electron beam continually when they go through the undulator together, which leads to a detuning of each frequency to the formerly matched energy of electron slice and so the reduction of the averaged power over the optical pulse.

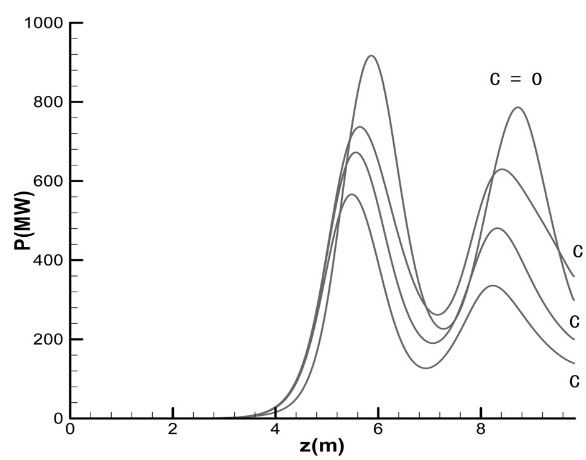

Figure 3: Averaged power of the optical pulse as a function of the undulator length with different initial chirp parameters.

Although the saturation point shifts slightly to shorter interaction length for a chirped pulse with an energy chirped electron beam, we still output the optical pulse at the undulator length of 5.6 m. The calculated power and width as functions of the initial chirp parameter are shown in Fig. 4. We can see that the optical power reaches the maximum value of 568.5 GW at C = 300, which is near 10 times larger than that of normal FEL. The power of the compressed pulse increases almost linearly as chirp parameter increases but the amplification reduces slowly due to the detuning caused by the slippage. The balance is achieved at a much larger chirp parameter of C = 300. The width of the compressed pulse also decreases rapidly with increased chirp parameter when C < 100, as shown in Fig. 4. When C > 100, the effects of the detuning caused by the slippage become more and more important and so the pulse cannot be further compressed even with larger and larger initial chirp parameter. As shown in Fig. 4, the width of the final compressed pulse reaches the minimum of 2.29 fs at C = 350, which is near 10 times shorter than that of normal FEL. With the energy-chirped electron beam, the gain bandwidth of the FEL amplifier will be expanded and much larger initial chirped parameter can be taken, and much higher power, much shorter width laser pulse can be obtained.

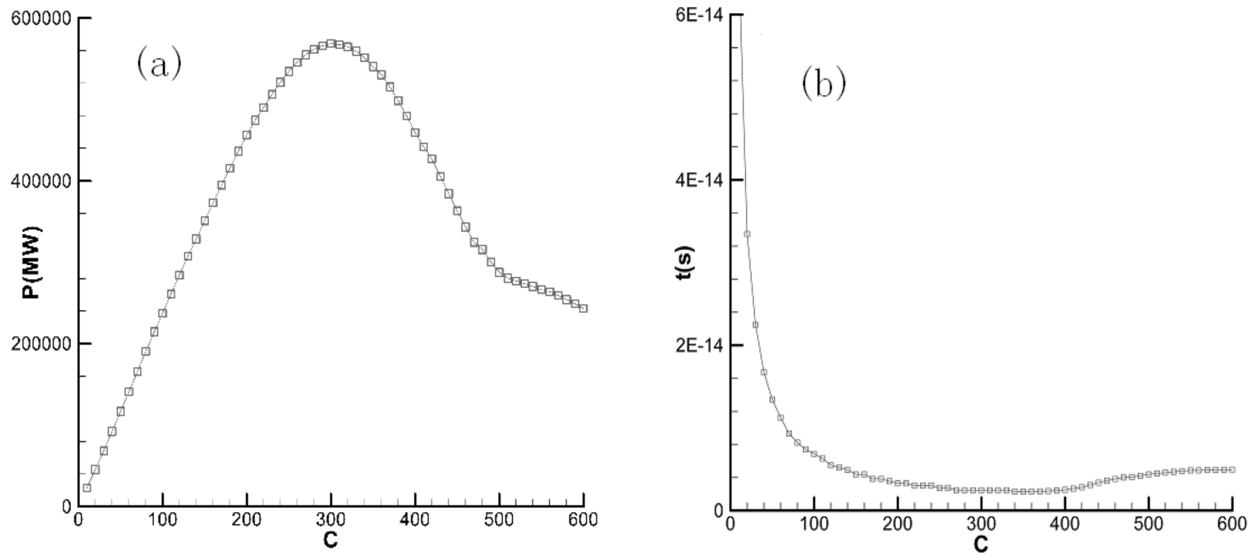

Figure 4: Peak power and FWHM width of the compressed optical pulse *vs* initial chirp parameter.

CONCLUSION

In this paper, it is proposed that a chirped pulse can be amplified using an FEL. Linear frequency chirped pulse amplification at single pass FEL amplifier is studied through numerical simulations. The processes of chirped pulses with different chirped parameters being amplified by normal FEL amplifier or the FEL amplifier with energy-chirped electron beam are studied. The peak power and width of the final compressed pulse with different chirped parameters have been calculated. The results show that, the normal FEL amplifier can amplify the chirped pulse, the phase coherent is kept perfect during amplification as chirp parameter is small, the peak power of the final compressed pulse can reach 10s GW and the width of the pulse can be 10s fs with the parameters of TTF. In the case of using the energy-chirped electron beam to amplify chirped pulse, the gain bandwidth of the FEL amplifier will be expanded and the chirped parameter will be larger. The peak power of the final compressed pulse can even reach near 10 times larger and the width of the pulse 10 times shorter than that with normal electron beam.

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