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Chirped pulse amplification in a free-electron laser amplifier

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ABSTRACT

Linear chirped pulse amplification at single pass free-electron laser (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 the 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 FEL amplifier can amplify the chirped pulse, the peak power in the final compressed pulse can reach 10 s GW and the width of the pulse can be 10 s 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 in the final compressed pulse can even reach near 10 times larger and the width of the pulse 10 times shorter than that without electron-beam energy chirped.

1. Introduction

Utilizing the chirped pulse amplification (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 200 nm 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]. 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 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 [7]. 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]. The impact of an initial energy chirp and an initial energy curvature of the electron beam on a seeded FEL has be studied analytically by Lutman et al. [8].

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 [9–11]. A single pass FEL can be operated successfully only at the case using high current electron beam, in which the well focused electron beam guides the optical beam through the long undulator with the almost constant transverse size the same that of the electron beam due to the optical guide effects [12]. In this realistic case, the 1D simulations can give quite good results.

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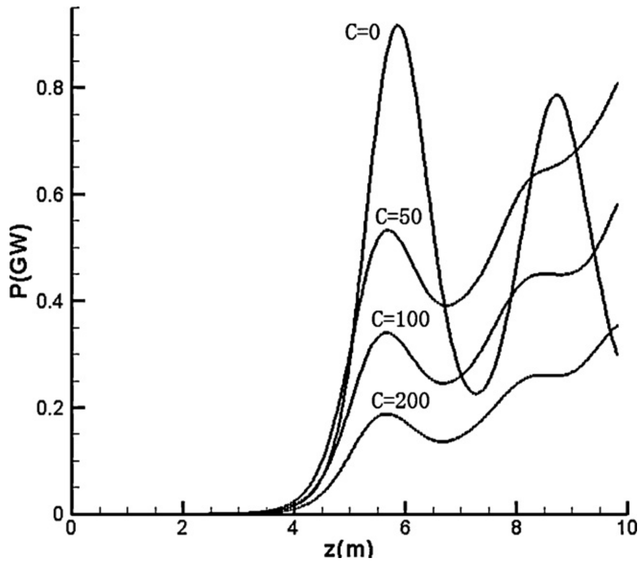

Fig. 1. Averaged power of the optical pulse as a function of the undulator length with different initial chirp parameters.

2. Simulation results

The envelope of a linear frequency chirped Gaussian pulse can be expressed as [11,13]:

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

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 [9–11]. As an example, the parameters of TTF experiment at DESY [14] as shown in Table 1 are used in all numerical simulations. The energy spread and emittance of the electron beam are neglected in simulations, but the radius of the electron beam in Table 1 is matched to the emittance and the undulator field to keep the envelope of the electron beam constant along the undulator [12,15]. The transverse size of the optical pulse is chosen the same value as the results of the optical guide effects. The initial averaged power of the optical pulse is 1 kW over the duration of 2.3 ps and $\tau_0 = 0.49$ 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

We studied the simplest case, in which linear frequency chirped optical pulses pass an FEL amplifier. The central wavelength is chosen to match the parameters of the electron beam and undulator to obtain maximum gain. 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.

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 [11,13,16]. The calculated power and width (FWHM) as functions of the initial chirp parameter are shown in Fig. 2. We can see that the peak power in the compressed pulse reaches the maximum value of 63.3 GW at $C = 50$. The peak power increases as C increases but the amplification of the chirped optical pulse by the electron beam reduces. The balance is achieved at the point of $C = 50$ and so be the maximum peak 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 opti-

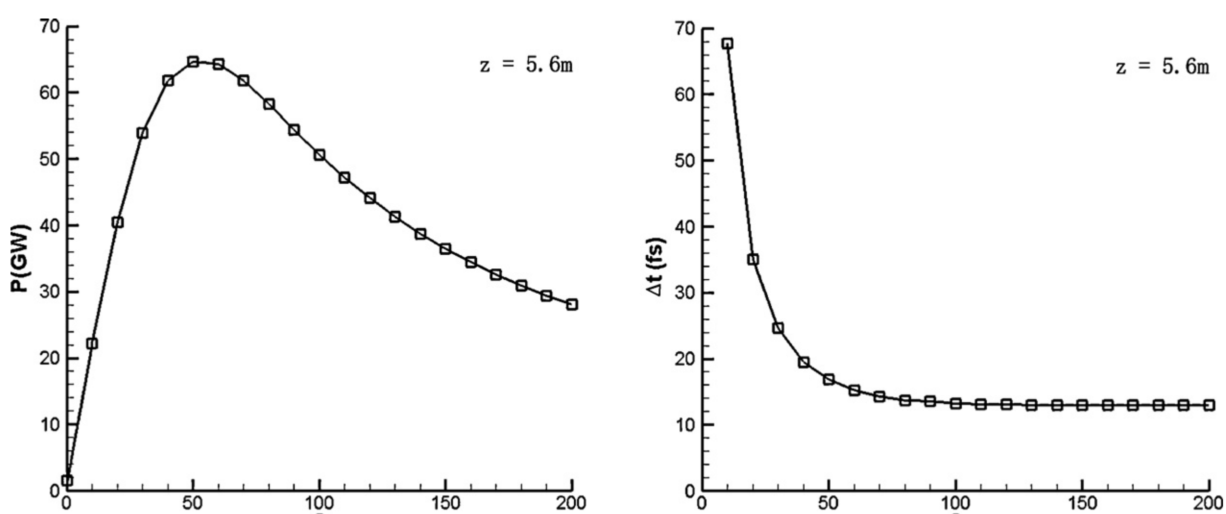

Fig. 2. Peak power and FWHM width of the compressed optical pulse *vs* initial chirp parameter.