A SIMPLE METHOD FOR GENERATING A FEW FEMTOSECOND PULSES IN SEEDED FELS*

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Abstract

We propose a simple method to generate a few femtosecond pulses in seeded FELs. We use a longitudinal energy-chirped electron beam passing through a dogleg where transverse dispersion will generate a horizontal energy chirp, then in the modulator, a seed laser with narrow beam radius will only modulate the centre part of electron beam and short pulses in high harmonics will be generated in the radiator. Using a representative realistic set of parameters, we show that 30 nm XUV pulse with duration of 8 femtoseconds (FWHM) and peak power of GW level can be generated from a 180 nm UV seed laser with beam waist of 75 μm.

INTRODUCTION

There is a rapidly growing interest in the availability of extremely short pulses, which have facilitated the rapid development of ‘‘ultrafast science’’, including structural studies of single biomolecules, femtosecond chemistry, etc [1]. In recent years, free-electron lasers (FELs) researchers have explored various ways to produce high-power, ultrashort pulses at XUV and shorter wavelengths with a particular emphasis on temporal synchronism with external lasers to facilitate pump-probe experiments [2].

A definition of the ultra-short X-ray pulses in Ref. [3] is the pulse duration of the order of few femtoseconds and shorter. A rather natural way to obtain such pulses is to use ultra-short electron bunches. However, most of short pulse schemes rely upon manipulating one or more properties of an ultrashort temporal portion of a much longer electron bunch, such as transverse emittance, energy or current [4-7]. These manipulations generally use a few-cycle, near-IR laser pulse to energy-modulate the e-beam so that, when combined with other transport elements such as chromatic chicanes, foils, specially tuned undulators, the FEL emission will predominately arise from the modulated portion.

In this paper, we propose a new simple method to generate a few femtosecond pulses in seeded FELs. A both longitudinal and transverse energy-chirped electron beam is obtained from a dogleg section and modulated by a seed laser with a narrow beam radius, thus only the short centre portion of electron bunch is modulated and then generate short pulses emission in the radiator. This is an easy-to-implement scheme for an existed seeded FEL configuration.

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METHODS

Our scheme, as shown in Fig. 1 in which we place a high-gain harmonic generation (HGHG) configuration as an example for seeded FELs, does not require any other hardware or special properties of electron beam. The unique difference is the use of dogleg, however, there usually be one or several doglegs in the transport line between the linac and undulators. This scheme can be combined with other kinds of seeded FELs, such as echo-enabled harmonic generation (EEHG) [8], phase-merging enhanced harmonic generation (PEHG) [9] and so on.

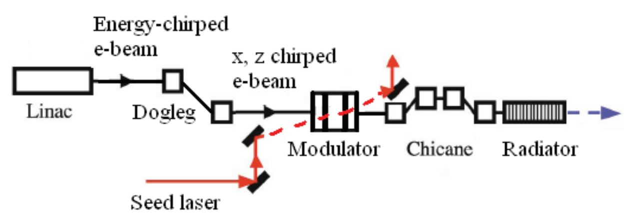

Figure 1: A schematic of the proposed scheme for short pulse production.

We assume an energy-chirped beam at the exit of Linac. The energy chirp parameter

$$h = \frac{d\gamma/\gamma}{dz} \tag{1}$$

is defined such that, for positive sign of h, electrons in the head of the bunch have larger energy than those in the tail, where γ is the relativistic factor and z is the bunch length coordinate. Using the electrons with the average energy γ_0 as the reference particles, for an electron (x_0, z_0), after passing through the dogleg with a momentum compaction R_{56} and a transverse dispersion η, we have its new coordinates (x, z) as

$$z = z_0 + R_{56}(hz_0 + \delta\gamma_0) \approx (1 + hR_{56})z_0 \tag{2}$$

$$x = x_0 + \eta(hz_0 + \delta\gamma_0) \approx \eta hz_0 \tag{3}$$

Here, we use the condition that the initial slice energy spread $\delta\gamma_0$ is much smaller than the chirped energy deviation and the initial beam transverse size is much smaller than that after dogleg. This approximation is reasonable because here the dogleg has a considerable dispersion strength and, to obtain short pulse, we need to extend the transverse size to an enough big level.

In this case, we can give the RMS bunch length and x-plane beam size after dogleg as

$$\sigma_z \approx (1 + hR_{56})\sigma_{z0} \tag{4}$$

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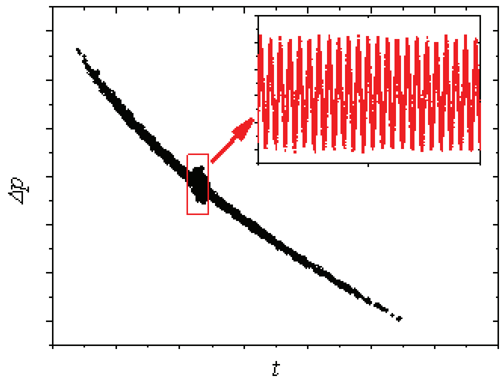

Figure 2: The longitudinal phase space of the electron bunch after modulated by a seed laser with narrow waist.

$$\sigma_x \approx \eta h \sigma_{z0} \tag{5}$$

where σ_{z0} means the RMS bunch length prior dogleg. In addition, the peak current of electron beam changes

$$I_p \approx \frac{1}{(1+hR_{56})} I_{p0} \tag{6}$$

Till here the situation is very similar to that in Ref. [1] where a slotted foil will be used next and the manipulated electron beam will be accelerated again, while in our scheme, next the electron bunch will be sent through the HGHG configuration.

We assume a seed laser with a small beam radius of r_s to modulate the electron bunch. The transverse beam size of the seed laser is much smaller than the electron beam's, therefore only the electrons that locate in the optical field of the seed laser will be modulated as Fig. 2 shows, and then bunch at the fundamental wavelength and its harmonics after passing a chicane. The length of the modulated portion bunch can be written as

$$\sigma_{z\,\mathrm{mod}} \approx (1+hR_{56}) \frac{r_s}{\eta h} \tag{7}$$

In fact, we do not need a very accurate energy chirp from Linac, especially for the bunch head and tail. A roughly energy-chirped electron beam also can achieve that only the centre portion of bunch is modulated by the seed laser.

SIMULATIONS

To show the feasibility of the proposed scheme, as mentioned above, we take an HGHG scheme to generate XUV short pulses as an example. We consider a set of parameters based on Hefei soft x-ray FEL proposal [10]: E=800 MeV, I_p=600 A, ε_n=2 mm · mrad, slice energy spread: $\delta\gamma$=0.01%, RMS bunch length σ_{z0}=0.5 ps, and initial energy chirp: h=67 at the exit of Linac. The HGHG process is simulated by the GENESIS code [11]

Assuming a dogleg with a momentum compaction R_{56}=-7 mm and a transverse dispersion η=0.6 m, after passing the dogleg, the electron bunch is compressed by a factor of 1.875, therefore, the peak current becomes to be about 1125 A. We have roughly designed the dogleg settings using the transport matrix method and the assuming is reasonable and easy to be implemented. In addition, it is worth pointing out that we do not expect to compress the chirped bunch too much through the dogleg, because when the compression factor is large, the slice energy spread will grow dramatically and a large energy modulation will be needed, thus, a very powerful seed laser will be needed as the modulator is very short. Therefore, the bunch is only compressed by a factor less than two. The current profiles before and after the dogleg are given in Fig. 3. The elements R_{51} and R_{52} of the transport matrix are neglected here, as these two elements can be optimized to a very small level by adding one or several quadrupoles in the dogleg and we will discuss the affection in the next part.

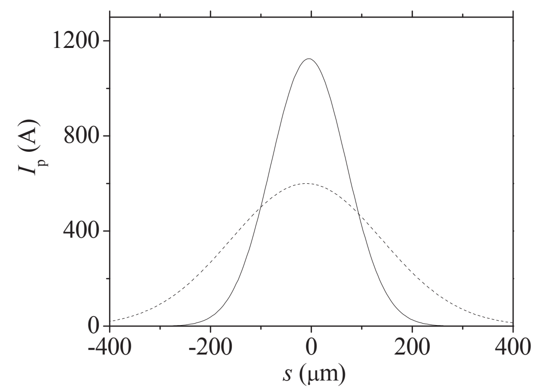

Figure 3: The current profiles at the entrance(dash line) and exit (line) of dogleg.

To generate short pulses, a 180 nm seed laser with a narrow beam waist of 75 μm is used. The rayleigh length of seed laser can be calculated as:

$$z_r = \pi \omega_0^2 / \lambda_s \tag{8}$$

where ω_0 is the radius of the optical beam waist. Here, z_r is about 0.1 m. Obviously, this short Rayleigh length will lead a rapid growth of the laser beam radius in the modulator. Considering this, we use a short undulator with 6 periods and period length λ_u=5.4 cm to provide period magnetic field for energy modulation. The waist position of the seed laser is the centre of the modulator. On this condition, the laser beam radius at the entrance and exit of the modulator is about twice beam waist. This will lead a spread of the length of the modulated portion. However, as the electrons in different transverse position will obtain different energy modulation, we can suppress this spread effect by carefully optimizing the dispersive strength of the chicane. The following simulation results imply that the modulated portion is much longer than that from Eq.(7), but when after chicane the bunched portion and radiation pulse have a nearly equal length with that from Eq.(7).

According to Eq.(7), we can roughly calculate the length of the modulated portion to be $\sigma_{z\mathrm{mod}}$=1μm (3.3 fs) and the FWHM length 7.8 fs. We take the sixth harmonic for the HGHG scheme. Figure 4 shows the bunching factor of 6th harmonic along the electron bunch at the exit of chicane. From Fig. 4, it can be found that the FWHM

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length of the bunched portion is about 8 fs that is a little longer than the result of analytical calculation. We give the 30 nm radiation pulse in Fig. 5. The FWHM length of the radiation pulse is about 8 fs. The peak power is about 0.9 GW.

These results agree with the analysis very well. The little extending of radiation pulse length should be attributed to the rapid variation of the seed beam radius.

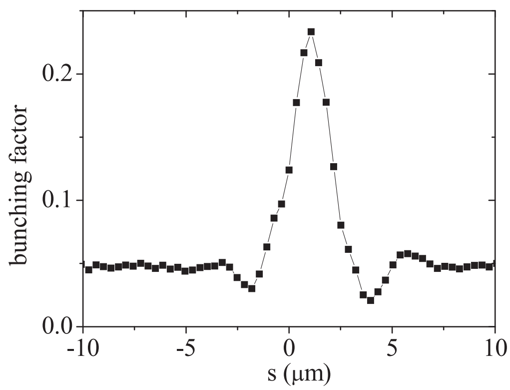

Figure 4: The bunching factor of 6th harmonic along the electron bunch at the entrance of radiator.

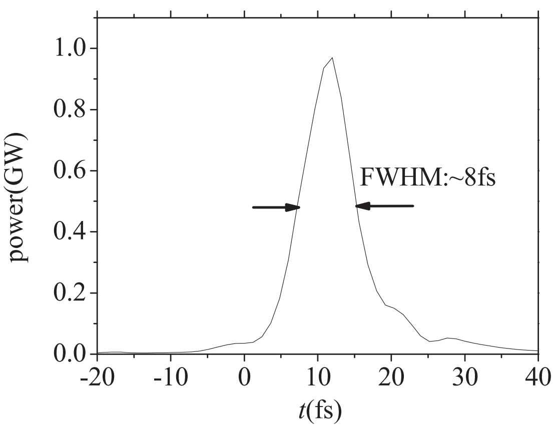

Figure 5: Pulse structure of 30 nm radiation. The pulse length is 8 fs (FWHM).

DISCUSSIONS

Obtaining the electron bunch chirped in both longitudinal and transverse directions is a critical issue in this scheme. The initial energy chirp is easy to be achieved from the Linac and as mentioned above, it does not need to be very accurate. We only care the properties of the centre portion bunch. When passing through the dogleg, the transport matrix elements R_{51} and R_{52} may extend the centre portion length by $\Delta z = R_{51}x + R_{52}x'$, and we should control $\Delta z \ll \sigma_{zmod}$. In a two-dipole dogleg, usually the first term is very small enough to be ignored, but in the second term, the element R_{52} is equal to η, and this may lead a degradation of the quality of the centre portion bunch. We have simulated the physical process in the dogleg with full matrix, and the results show that it does not degrade the FEL performance too much with above parameter settings. However, one should optimize the transport matrix to minimize R_{52} for experiments.

Another important point is controlling the beam radius of seed laser, which directly determine the radiation pulse length. Limited to the seed wavelength, the seed beam radius is also limited since the rayleigh length will be too short if the seed beam radius is too small. Besides, due to the low up-frequency conversion efficiency, the radiation wavelength of the single stage HGHG scheme is limited and this may finally lead that the radiation pulse length can not be much shorter than the single spike condition. Maybe if we combine this scheme with the EEHG scheme, the radiation pulse length can be sub-femtosecond level.

CONCLUSION

In conclusion, we have described a simple scheme for generating sub 10 fs pulse in seeded FELs. This scheme is easy to be implemented because for an existing seeded FEL facility, the hardware requirement is already satisfied. An extra demand is a seed laser with narrow beam waist. Using the HGHG scheme as an example, we have shown that 30 nm XUV pulse with duration of 8 fs (FWHM) and peak power of GW level can be generated from a 180 nm seed laser with beam waist of 75 μm.

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