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SEEDED FREE-ELECTRON LASERS DRIVEN BY A TRANSVERSE TILTED ELECTRON BUNCH*

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Abstract

A transverse tilt of the electron bunch is normally unwanted in free-electron laser (FEL) since only a portion of the bunch can contribute to the FEL radiation. However, the recent researches demonstrate that the tilted bunch can be used to generate FEL with some special features. In this work we investigate the generation of a large tilt of the bunch by using a corrugated structure and a dogleg separately. Based on the tilted bunch, the creation of ultra-short pulse and multi-color pulses are demonstrated in high-gain harmonic generation (HGHG) FEL.

INTRODUCTION

The growing demands on studying the ultrafast science greatly promote the development of FEL with ultra-short pulse, and some of them further require another FEL pulse or external laser which have a different wavelength but with good temporal synchronism to facilitate pump-probe experiments. FEL community has developed various methods to create ultra-short pulses, such as using a slotted foil, employing the enhanced self-amplified spontaneous emission scheme, using optimized nonliear bunch compression and so on [1–4]. For the generation of multi-color FEL, many methods are developed to achieve separated pulses at different wavelengths, which may need several seed lasers with different wavelengths or several e-bunches with different energies or several undulator sections with different strengths [5–7].

The transverse tilt of the bunch was once thought of harmful to the normal FEL device since only a portion of e-bunch can emit radiation. However, the recent studies show that the tilted bunch can be applied at some specific fields, including generation of broad-bandwidth radiation and ultra-short pulses and muti-color pulses, etc [7–9].

This paper proposes to create the bunch tilt by using a corrugated structure and a dogleg separately. After that, based on high-gain harmonic generation (HGHG) principle, a seed laser with narrow beam radius is used to modulate the center portion of the tilted bunch and then short pulses at harmonics will be generated in the radiator [10]. In contrast, we investigate the creation of multi-color pulses by using a seed laser with large beam radius to modulate the total bunch and then emit radiations at different harmonic based on employing the field gradient of the radiator [11]. Numerical simulations including the generation of the tilted bunch and FEL radiation confirm the validity and feasibility of these schemes at short-wavelength region. It can provide an optional operation mode to meet the requirement of short-pulse FEL or multi-color FEL for some users.

GENERATION OF BUNCH TILT

The tilted bunch can be characterized by the transverse offset x of electrons in proportion to its longitudinal position s. Several methods have been developed to obtain such a bunch tilt including the transverse wakefields in the corrugated structure, the residual dispersion from dispersion structure, the RF deflecting cavity which is developed as the electron bunch diagnostic. Here we investigate the generation of a large bunch tilt in a corrugated structure and a dogleg separately.

Corrugated Structure

Corrugated structure is widely known for cancelling the bunch energy chirp introduced by Linac accelerator. However, when passing the bunch off-axis through the corrugated structure, it will excite transverse wakefields and then couple the longitudinal position and transverse position of the electrons. Assuming a driving electron at (x_0, y_0) and a trailing electron at (x, y), with $|x - x_0|$ small compared to the gap size, the short-range transverse point wakes can be approximately given by [12]

$$w_x(s,x) = w_d(s,x_0) + w_q(s,x_0)(x - x_0) \tag{1}$$

$$w_y(s,x) = w_q(s,x_0)(y_0 - y) \tag{2}$$

where $w_d(s,x_0)$ and $w_q(s,x_0)$ are the dipole and quadrupole wake functions on the offset x_0, respectively. The dipole wake offers the transverse momentum kick to create the bunch tilt with focusing in y and defocusing in x introduced by the quadrupole wake.

Subsequently, through convolving the point wakes with the longitudinal bunch shape $\lambda(s)$, the wakes along the whole bunch can be given as

$$W(s,x) = \int_0^\infty w(s',x)\lambda(s-s')\,ds' \tag{3}$$

For a corrugated structure with the corrugation parameters much smaller than the gap size, but with the depth greater than the period, the transverse wakes exhibits an impact of parabolic relationship on s. The wakes at the head of the bunch are negligible but the tail experiences strong wakes. In this feasibility study, we calculate the wakes including

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the "zero order" and the "first order" wakes to ensure the accuracy of the calculation [12].

According to the wake theory above, we numerically investigated the bunch evolution in the corrugated structure in three dimensions. Parameters of corrugated structure are given in Table 1. The e-bunch with beam energy of 400 MeV, slice energy spread of 20 keV, normalized transverse emittance of 1.0 mm.mrad, peak current of 800 A and full width of 1 ps.

Table 1: Parameters of corrugated structure.

Parameter	Specification	Units
Nominal half aperture, a	3	mm
Period length, p	0.5	mm
Depth, d	0.6	mm
Longitudinal gap, t	0.25	mm
Plate width, w	20	mm
Plate length, L	1.7	m

In Fig. 1, with the offset $x_0 = 1.5$ mm, the tail of the bunch experiences dipole wake of 0.6 kV/pC and quadrupole wake of 0.63 MV/pC/m. Such wakes introduce a horizontal deviation of 1 mm. Obviously, such tilt will increase the projected emittance of the bunch, nevertheless, the slice emittance is almost constant and thus do not have influence to the final FEL performance. The non-negligible issues are the introduced horizontal velocity of the bunch combined with the increase of horizontal beam size. In vertical direction, the bunch will suffer a transverse focusing introduced by the quadrupole wake and thus decreasing the vertical beam size. In order to further increase the bunch tilt without increasing transverse velocity of the electrons, a drift section can be adopted after the corrugated structure.

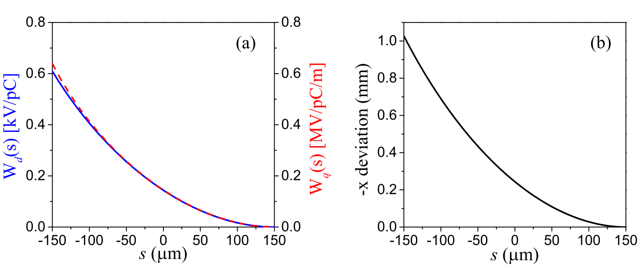

Figure 1: (a) Dipole bunch wake $W_d(s)$ and quadrupole bunch wake $W_q(s)$. (b) Bunch deviation of x.

Dogleg

The dogleg is consisted of two dipole magnets which can be regarded as a transport matrix in the calculations. We assuming an energy-chirped beam at the exit of Linac. The energy chirp parameter can be given as

$$h = \frac{d\gamma/\gamma}{ds} \tag{4}$$

where γ is the relativistic factor. After passing through the dogleg, the chirped bunch is transversely dispersed, its coordinates can be deduced as

$$s \approx (1 + hR_{56})s_0 \tag{5}$$

$$x \approx \eta h s_0 \tag{6}$$

where R_{56} is the momentum compaction, η is the transverse dispersion of the dogleg and s_0 is the initial electron coordinate. We use the condition that the initial slice energy spread is much smaller than the chirped energy deviation and the initial bunch transverse size is much smaller than that after dogleg. This approximation is reasonable because here the dogleg has a considerable dispersion strength.

Assuming the e-bunch has an initial energy chirp $h = 60\,\mathrm{m}^{-1}$ at the exit of Linac, after passing the dogleg with a momentum compaction $R_{56} = -7.8$ mm and a transverse dispersion $\eta = 0.6$ m, the e-bunch is compressed by a factor of 1.9, therefore, the peak current becomes to be about 1500 A and the transverse deviation of the bunch is about 11 mm. We have roughly designed the dogleg settings using the transport matrix method and the assuming is reasonable and easy to be implemented.

Note that, the tilted bunch generated by the dogleg and the corrugated structure both have a large transverse velocity and will spread quickly at the transverse direction and may degrade the following FEL process. Therefore several quadrupole magnets can be used to suppress the transverse velocity by taking advantage of the variation of the magnetic field in the offset orbit.

FEL PERFORMANCE

With such tilted bunch, we investigated the generations of an ultra-short pulse and multi-color pulses based on HGHG FEL.

Ultra-short Pulse

This scheme employs a 240 nm seed laser with narrow beam waist r_s of 70 μm to modulate the center portion of the tilted bunch. We can roughly calculate the length of the modulated portion to be $\sigma_{mod} \approx (1 + hR_{56})r_s/h\eta = 1\,\mu$m (FWHM∽ 7.85 fs). Here, the rayleigh length is about 0.07 m, and will inevitably increase the laser beam radius in the modulator. Therefore we use a short undulator with 6 periods and period length of 5 cm to provide the magnetic field for energy modulation. Only a small portion of the e-bunch can be modulated by this narrow seed laser.

Next, we consider the generation of sixth harmonic based on the HGHG scheme. Figure 2 shows the time structure of 40 nm radiation pulse. The peak power is about 400 MW and the FWHM length is about 8.2 fs that is a little longer than the modulated portion. In this scheme, we only care about the properties of the center portion bunch. When passing through the dogleg, the transport matrix elements R_{51} and R_{52} may extend the center portion length by $\delta s = R_{51}x + R_{52}x'$, and lead to a degradation of the quality of the center portion bunch. Thus, we should control $\delta s \ll \sigma_{mod}$.

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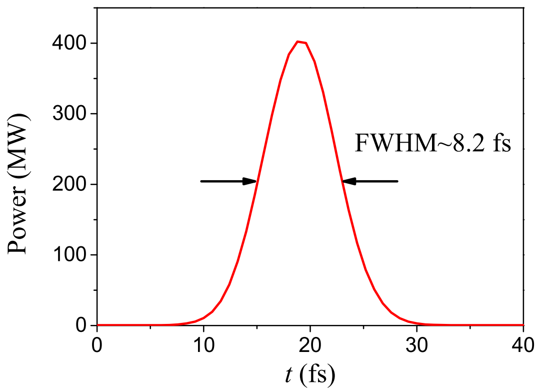

Figure 2: The time structure of the radiation pulse of the 6th harmonic based on HGHG scheme.

Multi-color Pulses

To generate multi-color pulses, a 240 nm seed laser with large beam waist of 3 mm is used to ensure the adequate energy modulation inside the tilted bunch. Following the modulator and dispersive section with optimized parameters, the bunching at harmonics are generated. Another difference from the former scheme is that, a transverse gradient undulator (TGU) is adopted as the radiator in this proposed scheme. In such a radiator, different portion of the bunch will experience different undulator magnetic field and if the ΔK is large enough to cover two resonant conditions at adjacent harmonics along the bunch, it can emit two pulses at different harmonics simultaneously. In this feasible study, a TGU radiator with undulator parameter of 1.25 on the axis and field gradient of 50 m^{-1} is adopted. For the tilted bunch with transverse modulated size of 5 mm which is symmetrical to the radiator axis, $K(x)$ varies from 1.41 to 1.09, and then can cover 5th (1.39) and 6th (1.13) resonant conditions along the bunch. Figure 3 shows the time structure and the spectrum of two-color FEL pulses. The peak power of 48 nm pulse (5th harmonic) and 40 nm pulse (6th harmonic) are about 82 MW and 156 MW, respectively. Both the FWHM pulse widths of the two pulses are closed to 10 fs and can be tuned by changing the tilt amplitude and the beam waist of the seed laser as well as the time separation between them. In addition, the TGU radiator has the potential to be replaced by using the nature transverse gradient of a normal planar undulator to carry on multi-color FEL in this scheme [13, 14].

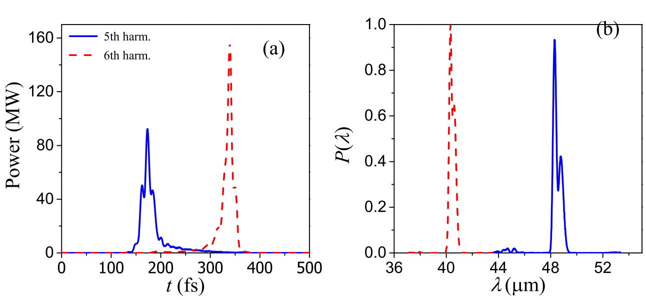

Figure 3: Time structure (a) and spectrum (b) of two-color FEL pulses at 5th and 6th harmonics.

SUMMARY

This paper demonstrated the generation of a tilted bunch by using a corrugated structure and a dogleg separately. Based on a large tilted bunch and HGHG principle, an ultra-short pulse or multi-color pulses can be achieved. These schemes have the potentials to be implemented in a normal seeded FEL device. However, it seems difficult to produce a pulse length shorter than a few femtoseconds with this scheme. In the multi-color scheme, only one electron bunch, one seed laser and one radiator section are required, however, the tunability of the pulse width and separation are also limited especially for producing more colors.

REFERENCES

[1] P. Emma *et al.*, Femtosecond and subfemtosecond X-ray pulses from a self-amplified spontaneous-emission based free-electron laser, *Phys. Rev. Lett.*, 92, 074801, 2004.

[2] A.A. Zholents, and G. Penn, Obtaining attosecond x-ray pulses using a self-amplified spontaneous emission free electron laser, *Phys. Rev. Accel. Beams*, 8, 050704, 2005.

[3] W.M. Fawley, Production of ultrashort FEL XUV pulses via a reverse undulator taper, *Nucl. Instrum. Methods A*, 593, 111, 2008.

[4] S. Huang *et al.*, Generating Single-Spike Hard X-Ray Pulses with Nonlinear Bunch Compression in Free-Electron Lasers, *Phys. Rev. Lett.*, 119, 154801, 2017.

[5] T. Hara *et al.*, Two-colour hard X-ray free-electron laser with wide tunability, *Nat. Commun.*, 4, 2919, 2013.

[6] E. Ferrari *et al.*, Widely tunable two-colour seeded free-electron laser source for resonant-pump resonant-probe magnetic scattering, *Nat. Commun.*, 7, 10343, 2016.

[7] A.A Lutman *et al.*, Fresh-slice multicolour X-ray free-electron lasers, *Nat. Photonics*, 10, 745, 2016.

[8] E. Prat *et al.*, Efficient generation of short and high-power x-ray free-electron-laser pulses based on superradiance with a transversely tilted beam, *Phys. Rev. ST Accel. Beams*, 18, 100701, 2015.

[9] E. Prat *et al.*, Generation of ultra-large-bandwidth x-ray free-electron-laser pulses with a transverse- gradient undulator, *J. Synchrotron Rad.*, 23, 874, 2016.

[10] H. Li and Q. Jia, Generation of a few femtoseconds pulses in seeded FELs using a seed laser with small transverse size, *Nucl. Instrum. Methods A*, 830, 309, 2016.

[11] Z. Zhao *et al.*, Generation of coherent two-color pulses at two adjacent harmonics in a seeded free-electron laser, *Phys. Rev. Accel. Beams*, 21, 020701, 2018.

[12] K. Bane *et al.*, Analytical formulas for short bunch wakes in a flat dechirper, *Phys. Rev. Accel. Beams*, 19, 084401, 2016.

[13] H. Li and Q. Jia, Normal planar undulators doubling as transverse gradient undulators, *Phys. Rev. Accel. Beams.*, 20, 020707, 2017.

[14] Z. Zhao *et al.*, Phase-merging enhanced harmonic generation free-electron laser with a normal modulator, *J. Synchrotron Rad.*, 24, 906, 2017.