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Generating quasi-single-cycle THz pulse from frequency-chirped electron bunch train and a tapered undulator

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Abstract

We propose a proof-of-principle experiment to test a new scheme to produce a single-cycle radiation pulse in free-electron lasers (FELs). Here, a few α-BBO crystals will be first used to produce an equally spaced laser pulse train. Then, the laser pulse train illuminates the cathode to produce a frequency-chirped electron bunch train in a photocathode rf gun. Finally, the frequency-chirped electron bunch train passes through a tapered undulator to produce a quasi-single-cycle THz pulse. This experiment should allow comparison and confirmation of predictive models and scaling laws, and the preliminary experimental results will also be discussed.

Keywords: electron bunch train; single-cycle THz pulse; tapered undulator

1. Introduction

Fast time-dependent phenomena are typically studied with a pump–probe technique in which the dynamics are initiated by a pump laser and then probed by a delayed pulse. Because the temporal resolution depends on the duration of the pump and probe beams, there is continuous interest in the free-electron laser (FEL) community to produce radiation pulses with shorter and shorter duration to meet the demands of the studies of faster and faster processes.

There are many ways to reduce the pulse duration in FELs. For instance, one may just reduce the beam charge to produce a very short electron bunch that naturally produces a very short FEL pulse[1–3]. Alternatively, one may use the so-called 'slotted foil' in the center of a chicane to spoil the transverse emittance for most of the portions of the electron beam such that an ultrashort x-ray pulse is produced only from the short slices of unspoiled beam that passes cleanly through the slot[4–6]. Instead of using a slotted foil for the selection of a short beam slice for lasing, one may also use a few-cycle laser to manipulate the electron beam energy or divergence distribution for producing an ultrashort FEL pulse[7–14]. Comprehensive reviews and comparisons of various methods can be found in Refs. [15, 16].

However, in all these methods, the FEL slippage length limited the shortest duration that can be obtained in FELs. For SASE FELs, because a long undulator is needed for lasing the minimal pulse duration is typically on the order of 100 as. For seeded FELs, because the beam is prebunched one can use a short undulator to produce intense radiation and the pulse duration may be pushed to tens of attoseconds (for instance, an isolated radiation pulse with about 20 as duration has been predicted in Ref. [13]).

Recently, a novel scheme based on coherent emission from a chirped microbunch passing through a strongly tapered undulator has been proposed to produce a single-cycle radiation pulse in order to counteract the slippage effect[17]. Before applying this idea to large scientific facilities, we feel it is necessary to perform a proof-of-principle experiment to demonstrate its underlying physics. The main purpose of this paper is to discuss a proof-of-principle experiment to test this idea at THz wavelength range.

2. Methods

In this section, we discuss how one may generate a quasi-single-cycle THz pulse by superposition of chirped radiation pulse trains. The idea is to adjust the separation of the electron microbunch (which determines the separation of the radiation pulse train) and the tapering of the undulator

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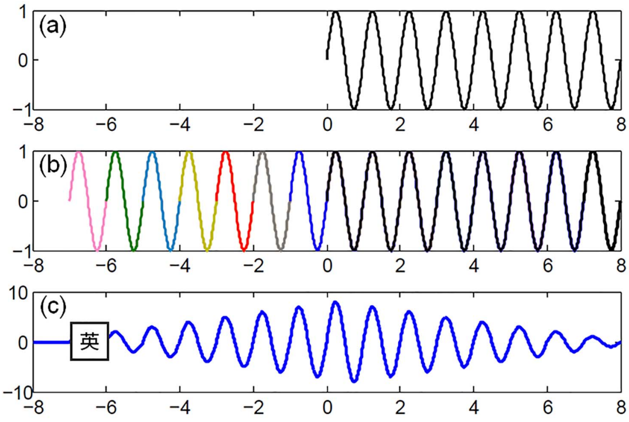

Figure 1. (a) Radiation field of a single bunch; (b) superposition of radiation fields from the whole electron beam (eight bunches). (c) Total radiation field from the eight bunches. The horizontal axis is the longitudinal position normalized to the radiation wavelength (bunch head to the left) and the vertical axis is the amplitude of the radiation field normalized to that of a single bunch.

(which determines the frequency chirp of the radiation pulse) such that all the radiation pulses will coherently add up at only one radiation cycle while destructively interfering at all other cycles[17].

When an electron microbunch passes through an undulator with strength K, period λ_u, and number of periods N, a radiation pulse with N cycles and central wavelength at $\lambda = (1 + K^2/2)\lambda_u/2\gamma^2$ will be produced, where γ is the relativistic factor of the electron beam.

We first study what kind of radiation pulse one may get for a bunch train with uniform separation and an untapered undulator. Figure 1 shows the radiation field produced in an eight-period undulator with eight equally separated bunches when the bunch separation equals the radiation wavelength. One can see that, because all the radiation pulses are in phase, they coherently add up to form a field of which the amplitude is eight times larger than that from a single bunch. Yet, the pulse duration is limited by the slippage length in the undulator and only a multiple cycle pulse can be obtained.

Now, we consider the case when the undulator is tapered, e.g., K is a function of z. Figure 2 shows the radiation field produced in an eight-period tapered undulator with eight equally separated bunches. Here, one can see that a frequency-chirped radiation pulse is produced as K decreases along the beam propagation direction (Figure 2(a)). However, the radiation pulse produced from each bunch is no longer in phase, so the radiation pulses randomly add up to form a long pulse with field amplitude that is neither enhanced nor reduced.

Finally, we consider the case where the bunch train is also chirped, e.g., the separation of adjacent bunches linearly changes along the longitudinal direction. Analysis shows that when the chirp of the bunch train matches that of the tapered undulator (in this case the bunch separation increases from bunch head to bunch tail), constructive interference only occurs for one cycle while those at other cycles are destructive (Figure 3(b)), resulting in a quasi-single-cycle radiation pulse (Figure 3(c)) as first proposed in Ref. [17].

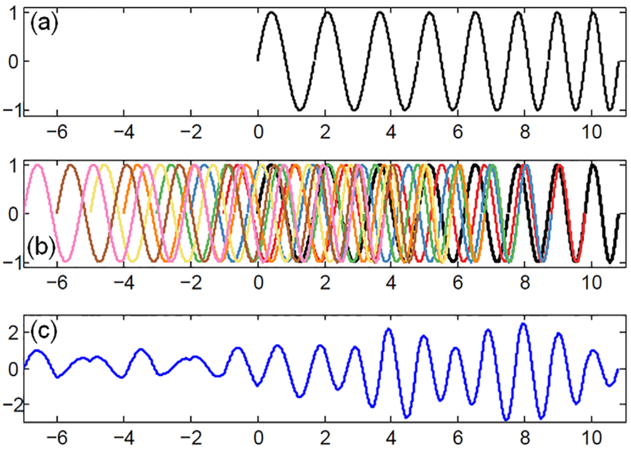

Figure 2. (a) Frequency-chirped radiation from a single bunch; (b) superposition of radiation fields from the whole electron beam (eight bunches). (c) Total radiation field from the eight bunches.

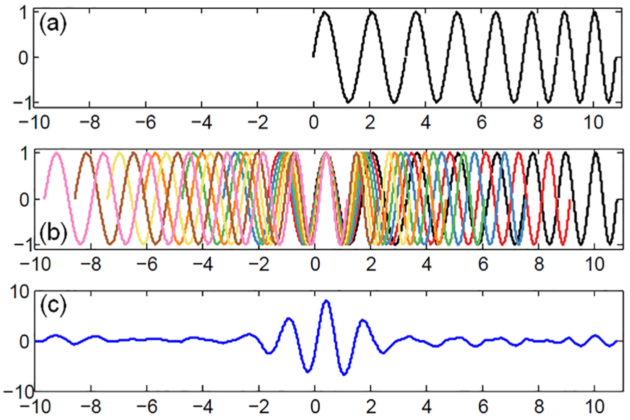

Figure 3. (a) Frequency-chirped radiation from a single bunch; (b) superposition of radiation fields from the whole electron beam (chirped bunches). (c) Total radiation field from the chirped bunches when the bunch chirp matches the undulator tapering.

Note that the pulse width is eventually determined by the bandwidth of the radiation pulse. Thus, a bunch train with strong chirp and a strongly tapered undulator are required to get a truly single-cycle radiation pulse. It should also be noted that to match the tapering of the undulator, a bunch train with a strong energy chirp instead of a frequency chirp may be used as well[18].

3. Generation of a chirped bunch train

The electron bunch train can be produced with a laser pulse train in a photocathode rf gun, taking the advantage of the promptness of photoemission. Furthermore, because

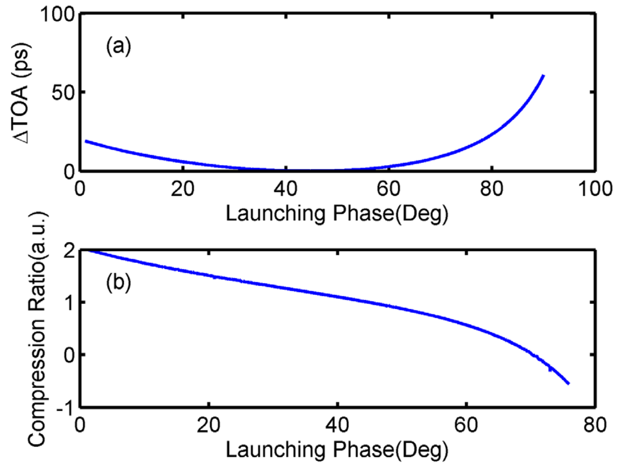

Figure 4. (a) Difference in time-of-flight for electrons launching at various rf phases in a photocathode rf gun; (b) compression ratio of the electron bunch launching at various rf phases.

the time-of-flight of electrons from cathode to the exit of the gun depends on rf phase, a frequency-chirped electron bunch train can be produced by properly choosing the laser launching phase. Figure 4 shows the simulated time-of-flight for electrons launching at various rf phases and also the corresponding compression ratio defined as the ratio of the initial bunch length to the final bunch length. Due to the linearly varying compression ratio, a frequency-chirped electron bunch train with linearly increasing separation may be produced by setting the launching phase at about 30°.

Figure 5 shows the measured electron bunch train in a preliminary experiment. Here, three α-BBO crystals with temporal walk-off of 4.8, 2.4 and 1.2 ps, are used to produce an eight-laser pulse train; then the equally spaced laser pulse train is converted into a frequency-chirped electron bunch train in the photocathode rf gun. This technique uses the group velocity mismatch (GVM) of the ordinary and extraordinary rays such that a laser pulse becomes two after passing though a birefringent crystal with the temporal walk-off determined by the thickness and GVM of the crystal (see Refs. [19–22]. As can be seen from Figure 5(b), the separation of the adjacent bunches changes nearly linearly from about 0.9 to 1.3 ps. Sending this beam through a strongly tapered undulator would yield a quasi-single-cycle THz pulse.

It is worth mentioning that in addition to generating bunch trains, the α-BBO crystals can also be used to produce a flat-top electron beam. For instance, when the temporal walk-off is smaller than the laser pulse width, the laser pulses will overlap. This allows stacking the input short laser pulse into a long flat-top output, leading to a flat-top electron beam (see Refs. [19, 22]).

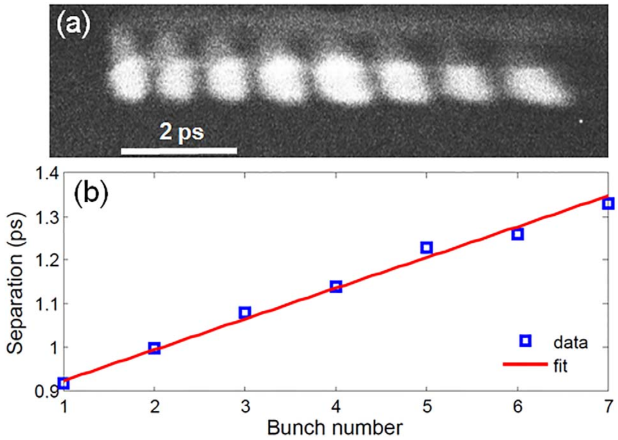

Figure 5. (a) Measured frequency-chirped electron bunch train (bunch head to the left); (b) separation of the bunch train.

4. Proposed experiment

We propose to conduct a proof-of-principle experiment to test this novel scheme for the generation of a single-cycle radiation pulse at Shanghai Jiao Tong University where a photocathode rf gun is available[23]. The electron beam energy at the exit of the photocathode rf gun is about 3.3 MeV. To produce a THz pulse with wavelength matching the separation of the chirped electron bunch train, an undulator with a period of about 24 mm will be needed. The K value of the undulator should be changed from about 0.8 to 1.3 by varying the gap of the undulator. Simulation shows that we can produce up to about 150 pC charge in the eight bunch trains without causing significant distortion to the bunch shape from longitudinal space charge force. In this proposed experiment, a quasi-single-cycle THz pulse with central wavelength at about 0.3 mm and peak power in the order of MW will be produced. The temporal distribution of the quasi-single-cycle THz pulse will be measured through electro-optic sampling (see Ref. [24]). The spectrum of the THz pulse will be measured with an interferometer to further confirm the relatively large bandwidth of the quasi-single-cycle pulse.

5. Summary and outlook

In conclusion, we have proposed a proof-of-principle experiment to test the recently proposed novel scheme to produce a single-cycle radiation pulse in FELs. The underlying physics of this method and the feasibility of the experiment at THz wavelength have been discussed based on calculations and simulations. A frequency-chirped electron bunch train has been successfully produced in our photocathode rf gun. In future, we will build a strongly tapered undulator to produce a quasi-single-cycle THz radiation. We anticipate that this proof-of-principle experiment will mark a great step toward generation of shorter and shorter radiation pulses in FELs.

Acknowledgments

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