Echo-enabled tunable terahertz radiation generation with a laser-modulated relativistic electron beam

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A new scheme to generate narrow-band tunable terahertz (THz) radiation using a variant of the echo-enabled harmonic generation is analyzed. We show that by using an energy chirped beam, THz density modulation in the beam phase space can be produced with two lasers having the same wavelength. This removes the need for an optical parametric amplifier system to provide a wavelength-tunable laser to vary the central frequency of the THz radiation. The practical feasibility and applications of this scheme are demonstrated numerically with a start-to-end simulation using the beam parameters at the Shanghai Deep Ultraviolet Free-Electron Laser facility (SDUV). The central frequency of the density modulation can be continuously tuned by either varying the chirp of the beam or the momentum compactions of the chicanes. The influence of nonlinear rf chirp and longitudinal space charge effect have also been studied in our article. The methods to generate the THz radiation in SDUV with the new scheme and the estimation of the radiation power are also discussed briefly.

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I. INTRODUCTION

As has been widely used in radar, security, communication, medical imaging, etc., THz radiation has drawn a lot of attention all over the world. Many studies have been done on the generation of THz radiation [1–4]. Accelerator-based free electron laser (FEL) technology, such as the fourth generation light source, can produce radiation with high intensity, high peak power, and coherence, which might be a great candidate for the generation of THz radiation. In recent years, a new scheme of employing the echo effect previously observed in hadron accelerators was proposed [5] and experimentally tested [6] to generate high harmonics of FEL radiation, and the bunching coefficients of this scheme were also analyzed in detail [7] to give us a clearer picture of the mechanism behind it. Providing the advantages of the echo-enabled harmonic generation FEL such as compact size, tunable frequency, etc., a method of using two lasers to modulate the electron beam to generate density modulation at THz frequency has been proposed and analyzed in Refs. [8–10]. In this scheme, the relativistic electron beam is first sent into a modulator to interact with a

laser with the wave number k_1 . Then the beam is transmitted into the following modulator to interact with another laser with the wave number k_2 . The energy modulation will be converted into density modulation when the beam passes through a dispersion section. In this situation, the density modulation at wave number $k = nk_1 + mk_2$ can be achieved, where n and m are nonzero integers. By varying the wavelength of those two lasers and the parameter of dispersion, one can vary the central frequency of the beam density modulation conveniently. In this scheme, an optical parametric amplifier is needed to provide two different lasers (e.g., 800 nm and 1560 nm in this scheme) to modulate the electron beam, respectively.

As briefly mentioned in [9], one may generate the continuously tunable density modulation with two lasers having the same wavelength, which is different from the scheme mentioned above, if there is a chicane between the two modulators, similar to the echo-enabled harmonic generation scheme. A chirped electron beam is modulated in the modulator at wave number k_0 . The wave number of the beam density modulation will be compressed to $k_1 = C_1 k_0$ and its high harmonics when the beam passes through the first dispersion section with small R_{56} . Then the beam will be sent into another same modulator to interact with a laser at the same wave number k_0 . After the beam passes through the second dispersion section, the energy modulation is converted into density modulation at the final wave number $k = nC_1 C_2 k_0 + mC_2 k_0$, where n and m are nonzero integers. It is easy to find out that one may vary the final

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frequency of density modulation continuously by varying the chirp of the beam or R_{56} of the first dispersion section.

In this article, the result of the generation of density modulation is discussed theoretically in Sec. II. Then in Sec. III, the simulation results of the scheme to generate THz density modulation are presented. The THz generation in SDUV via the new scheme is briefly discussed in Sec. IV. Summaries and conclusion are given in Sec. V.

II. GENERATION OF DENSITY MODULATION IN THEORY

As introduced in Sec. I (for more details, see Ref. [8]), the layout of the scheme to generate THz density modulation in a relativistic electron beam with two different lasers at wave numbers k_1 and k_2 is shown in Fig. 1(a1), which consists of two modulators and a dispersion section. The beam is modulated by two different lasers at wave numbers k_1 and k_2 when the beam passes through two modulators, respectively. After the beam passes through the dispersion section, the energy modulation is converted to density modulation at wave number

$$k = nk_1 + mk_2. \quad (1)$$

Consider an initial Gaussian energy distribution as

$$f_0(p) = \frac{N_0}{\sqrt{2\pi}} e^{-p^2/2}, \quad (2)$$

where N_0 is the number of electrons per unit length, $p = (E - E_0)/\sigma_E$ represents the dimensionless energy deviation with central energy E_0 and slice energy spread σ_E . After the beam passes through the dispersion section, the distribution function becomes

$$f_f(z, p) = \frac{N_0}{\sqrt{2\pi}} \exp \left\{ -\frac{1}{2} [p - A_1 \sin(k_1 z - Bp) - A_2 \sin(k_2 z - KBp + \phi)]^2 \right\}, \quad (3)$$

where $A_1 = \Delta E_1/\sigma_E$, $A_2 = \Delta E_2/\sigma_E$ represent the energy modulation amplitude of each modulator and $B = R_{56}k_1\sigma_E/E_0$, $K = k_2/k_1$.

FIG. 1. Layout of two schemes to generate THz density modulation in a relativistic electron beam.

The bunching factor $b_{n,m}$ at each harmonic, defined as $\langle e^{-ik_{n,m}z} \rangle$ is

$$b_{n,m} = |J_n[(n + Km)A_1B] \times J_m[(n + Km)A_2B] e^{-(1/2)[(n+Km)B]^2}|. \quad (4)$$

We show the phase space evolution of the beam at each section in Fig. 2 with $\lambda_1 = 800$ nm, $\lambda_2 = 900$ nm, $A_1 = 5$, $A_2 = 5$, and $R_{56} = 2$ mm to illustrate the dynamics occurring when the beam passes through the beam line. We can easily see that energy modulations at wave number k_1 and $k = nk_1 + mk_2$ are achieved at the exit of modulator 1 and modulator 2, respectively. The energy modulation is converted to density modulation after the beam passes through the dispersion section and the microbunching forms at THz frequency if we take the suitable parameters. The asymmetry of the beam density distribution comes from the lack of electrons at both sides of the phase space.

As a comparison, we show the new scheme to generate THz density modulation, which is briefly mentioned in [9], in Fig. 1(a2). It is easy to find out that there is a dispersion section between two modulators, which is similar to the echo-enabled harmonic generation scheme. Based on Eq. (1), the density modulation in the beam is achieved at the exit of the second dispersion section at the wave number

$$k = nC_1C_2k_1 + mC_2k_2, \quad (5)$$

where C_1 and C_2 are the bunch compression factor provided by the first and the second dispersion section, and the distribution function is [11]

FIG. 2. Phase space evolution of the electron beam at various locations, where p is the dimensionless energy derivation in Eq. (2). (a) Exit of modulator 1; (b) exit of modulator 2; (c) exit of dispersion; and (d) final density profile.

$$f_f(\xi, p) = \frac{N_0}{\sqrt{2\pi}} \exp \left[-\frac{1}{2} \{ p - A_2 \sin(k\xi - KB_2 p + \phi) - A_1 \sin[\xi - (B_1 + B_2)p + A_2 B_1 \sin(K\xi - KB_2 p + \phi)] \}^2 \right], \quad (6)$$

where $B_{1,2} = R_{56}^{(1,2)} k_1 \sigma_E / E_0$, $C_1 = 1/(1 + hR_{56}^{(1)})$, and $C_2 = (1 + hR_{56}^{(1)})/[1 + h(R_{56}^{(1)} + R_{56}^{(2)})]$.

The bunching factor $b_{n,m}$ is thus written as

$$b_{n,m} = |J_n \{ -A_1 [nB_1 + (n + Km)B_2] \} \times J_m [-(n + Km)A_2 B_2] e^{-(1/2)[nB_1 + (n + Km)B_2]^2}|. \quad (7)$$

In this scheme, the R_{56} of the first dispersion is very small (about 1–2 orders of magnitude smaller than the R_{56} of the second dispersion). That is to say we can ignore nB_1 in Eq. (7) for $nB_1 \ll nB_2$ so that Eq. (7) becomes the same with Eq. (4). It is easy to point out that for an electron beam without energy chirp, the bunching factors of those two schemes are almost the same. The central frequency of density modulation in the beam for those two scheme are the same as well for $h = 0$ leading to $C_1 = 1$ and $C_2 = 1$.

The advantage of this new scheme over the old one is that we can use one laser with the beam split into two identical pulses to modulate the electron beam twice in two modulators, respectively, when there is energy chirp in the beam. As a result, the complexity of the whole apparatus is reduced. In the following, we will discuss the detail of the new scheme.

Consider an initial Gaussian energy distribution function with a linear energy chirp h as

$$f_0(p, \xi) = \frac{N_0}{\sqrt{2\pi}} \exp \left\{ -\frac{(p - H\xi)^2}{2} \right\}, \quad (8)$$

where $H = \frac{h}{k_0 \sigma_E / E_0}$ is the dimensionless energy chirp and $\xi = k_0 z$, and $h = \frac{d\gamma}{\gamma dz}$ is defined as the energy chirp along the beam.

The derivation in Appendix A of Ref. [11] shows the bunching factor at the harmonic factor a after the beam, without an energy chirp, passing through two modulators and two dispersions as

$$b = \frac{1}{N_0} \left| \int_{-\infty}^{+\infty} dp e^{-iapB} f_0(p) \langle \exp \{ -ia\xi - iaA_1 B \sin \xi \} \times \exp \{ -iaA_2 B_2 \sin(K\xi + KB_1 p + KA_1 B_1 \sin \xi + \Phi) \} \rangle \right|. \quad (9)$$

Again, $K = k_1/k_2$ and $k_{1,2}$ are the seed laser wave numbers of each modulator, $A_{1,2} = \Delta E_{1,2}/\sigma_E$ and $B = B_1 + B_2$.

According to Ref. [12], by changing the integration variable from p to $p' = p - H\xi$, for the two identical wavelengths $k_1 = k_2$, it is computed that $K = 1$ in Eq. (9). Therefore we conclude that the angular bracket denoting averaging over ξ does not vanish only if

$$a = \frac{n + m(1 + HB_1)}{1 + HB}, \quad (10)$$

and the bunching factor becomes

$$b_{n,m} = \left| J_m \left(\frac{n + m(1 + HB_1)}{1 + HB} A_2 B_2 \right) J_n \left(\frac{A_1 (nB + mB_2)}{1 + HB} \right) \right| \times \exp \left\{ -\frac{(nB + mB_2)^2}{2(1 + HB)^2} \right\}, \quad (11)$$

where $J_{n,m}$ is the Bessel function of the first kind.

According to Eq. (5), when $k_1 = k_2 = k_0$, we have

$$k = nC_1 C_2 k_0 + mC_2 k_0. \quad (12)$$

It is straightforward to see that with $n = 1$, $m = -1$, and $(C_1 - 1)C_2 \sim 10^{-2}$, if a 1047 nm laser is employed to modulate the beam, an about 3 THz density modulation can be generated and its THz radiation spectrum can be easily measured by the interferometer.

Based on the preliminary simulation with ELEGANT [13], we make the beam energy chirp $h = 11.22 \text{ m}^{-1}$, $R_{56}^{(1)} = 0.477 \text{ mm}$, and $R_{56}^{(2)} = 40 \text{ mm}$, where R_{56} is the momentum compaction of each dispersive section. The bunching factor $b_{1,-1}$ vs the energy modulation amplitudes of each modulator is calculated and shown in Fig. 3. It is easy to point out that the bunching factor maximizes its value when $A_1 = 5$ and $A_2 = 10.5$.

Similarly, we make $A_1 = 5$, $A_2 = 10$ and vary R_{56} of two dispersions to calculate the value of the bunching factor. The central frequency of density modulation in the beam varies as well when the R_{56} of two dispersions change. We show the result of our calculations in Fig. 4, from which we can see that it is easier to vary the central frequency of density modulation in the beam by varying

FIG. 3. The bunching factor vs laser energy modulation amplitudes.

FIG. 4. Bunching factor and central frequency (THz) of density modulation vs R_{56} of each dispersion. (a) Bunching factor vs R_{56} of each dispersion. (b) Central frequency of density modulation vs R_{56} of each dispersion.

R_{56} of the first dispersion section than that of the second one.

As we show in Fig. 2, we use an electron beam with linear energy chirp to interact with the 1047 nm laser in those two modulators and show the phase space evolution in Fig. 5 in this scheme with two modulators and two dispersions. The beam density distribution and its Fourier

FIG. 5. Phase space evolution of the electron beam with linear energy chirp at various locations, where p is the dimensionless energy derivation in Eq. (2). (a) Exit of modulator 1; (b) exit of modulator 1, closer look; (c) exit of modulator 2; (d) exit of modulator 2, closer look; (e) exit of dispersion 2; and (f) exit of dispersion 2, closer look.

FIG. 6. Beam density distribution and its fast-Fourier-transform (FFT) image (small peaks in FFT image come from the uniform electron beam with finite length). (a) Beam density distribution. (b) FFT image of beam density.

transform images are shown in Fig. 6. The mechanism of allowing a chirped electron beam to interact with two lasers of the same wavelength can be explained as follows: the beam is modulated by the laser in the first modulator and generates energy modulation at wave number k_0 ; then the energy modulation is compressed to $C_1 k_0$ with the compression of the whole beam; the modulated beam interacts with the laser again in the second modulator to produce a superimposed energy modulation; finally the energy modulation is converted to density modulation at wave number $(C_1 - 1)C_2 k_0$ when the beam passes through the second dispersion.

III. GENERATION OF DENSITY MODULATION IN A START-TO-END SIMULATION

The beam line of SDUV FEL facility, which is used to carry out the Echo-Enabled Harmonic Generation experiment [6], is shown in Fig. 7. It consists of the injector, linear accelerator, two modulators, two dispersions, and a radiator. The beam at peak current 50 A is accelerated to 160 MeV with 5 S-band (2856 MHz RF frequency) linac structures. The bunch compressor chicane in the linac is turned off in this scheme. The wavelength of the seed laser in those two modulators is 1047 nm.

We use the particle tracking code ASTRA [14] to generate a Gaussian beam with the charge of 200 pC and the peak current of about 50 A from the photocathode rf gun and is accelerated to about 30 MeV with an S-band linac structure, considering the strong space charge effect in the injector. Simulation with ELEGANT code begins when the beam passes through L1 (consists of 2 S-bands) and finishes after the beam passes through the second dispersion section (BC2, seen in Fig. 7). After being accelerated to 160 MeV, the beam with energy chirp

FIG. 7. Layout of SDUV FEL facility for generation of THz density modulation in a chirped electron beam.

FIG. 8. Longitudinal phase space of the beam at two important locations. (a) Exit of modulator 1; and (b) exit of modulator 2.

$h = 11.22 \text{ m}^{-1}$ is sent into the modulator to interact with a 1047 nm laser. To gain the maximal bunching according to the theory (seen in Fig. 2), it is optimal to regulate the laser power at $\Delta E_1 = 25 \text{ keV}$ while the slice energy spread of the beam is about 5 keV. The same is true with the second modulator at $\Delta E_2 = 50 \text{ keV}$. The phase space of the beam is shown in Fig. 8 and the main parameters in the simulation are listed in Table I. The images of phase space are different from those in Fig. 5 because the head of the beam is on the left in ELEGANT.

According to Fig. 3, the optimal energy modulations is $A_1 = 5$ and $A_2 = 10$. In the following simulation, we make a comparison among the laser off, $A_1 = 5$, $A_2 = 5$ and $A_1 = 5$, $A_2 = 10$. The beam currents and their Fourier transform images are shown in Fig. 9, from which we could see that the scheme could provide fundamental frequency of THz when $A_2 = 5$ and higher harmonic when $A_2 = 10$ to satisfy the needs of various users. In Fig. 9, we could also see that the wavelength of density modulation in the left side is longer than that in the right side. The reason is that there is not a higher harmonic linearizer (e.g., an X-band RF cavity) to linearize the longitudinal phase space of the beam in the SDUV facility so that a nonlinear curvature exists in the longitudinal phase space, and as a result the electrons in the head are compressed differently to that in the tail when the beam passes through the second

FIG. 9. Beam current and its fast-Fourier-transform image. (a) Beam currents for $A_2 = 5$ (red) and $A_2 = 10$ (blue) when $A_1 = 5$ and initial current without laser modulation (black). (b) FFT image of beam current for $A_2 = 5$ (red) and $A_2 = 10$ (blue) when $A_1 = 5$.

dispersion. The spectrum is not single frequency compared to that in Fig. 6.

All the simulations above with ELEGANT are conducted without considering the longitudinal space charge (LSC) effect. According to Refs. [15–18], the LSC effect, as the main effect driving microbunching instability, may degrade

FIG. 10. Comparison between LSC effect off (left) and on (right). (a) Slice energy spread at the entrance of modulator 1, LSC off. (b) Slice energy spread at the entrance of modulator 1, LSC on. (c) Beam current at the exit of dispersion 2, LSC off. (d) Beam current at the exit of dispersion 2, LSC on. (e) Longitudinal phase space at the exit of dispersion 2, LSC off. (f) Longitudinal phase space at the exit of dispersion 2, LSC on.

TABLE I. Main parameters in the ELEGANT simulation.

Parameter	Value
Bunch charge (nC)	0.2
Beam energy (MeV)	160
Transverse beam size (rms, mm)	0.2
Slice energy spread (keV)	5
Laser wavelength in U1 and U2 (nm)	1047
Laser power in U1 (MW)	4.5
Laser power in U2 (MW)	20
Laser waist size (mm)	1.7
Period of U1 and U2 (cm)	5
Number of periods of U1 and U2	10
Energy modulation amplitude in U1 (keV)	25
Energy modulation amplitude in U2 (keV)	50
R_{56} in U1 (mm)	0.477
R_{56} in U2 (mm)	40

the quality of the electron beam when the beam passes through the bunch compressor chicane. A comparison is made to illustrate the influence on the slice energy spread and the current of the beam with the LSC effect. The result is shown in Fig. 10, from which we could see that energy modulation is accumulated (spikes in the slice energy spread with LSC on) because of the initial density modulation coming from shot noise and drive laser, and the peak current of the electron beam at the exit of dispersion 2 reduces. The position of the peaks move a little and the number of the peaks changes (from 7 to 6); this is because the energy chirp of the beam is reduced because of the longitudinal space charge force (the electrons in the head gain energy and the electrons in the tail lose their energy; see the phase space in Fig. 10), leading to the difference between the LSC effect off and on. So the LSC effect may degrade the quality of the beam. Nevertheless, considerable density modulation at THz frequency is still produced with the LSC effect taken into account.

IV. GENERATION OF THZ RADIATION

Transition radiation (TR), undulator radiation, diffraction radiation, and synchrotron radiation are all good methods to generate THz radiation. Considering the THz density modulation in the electron beam, transition radiation and undulator radiation are the better choices for us. In SDUV, the electron beam energy is about 160 MeV and the undulator is dedicated to generate sub- μm FEL radiation; therefore, it is difficult to match the resonance condition because the period and the magnetic field of the undulator are both too large.

Subsequently, TR is the only, but even better, choice because it is relatively easy and convenient to operate in our scheme. As an example, a round TR target made of a metallic foil with radius r is placed at the end of the linac in SDUV, and the THz radiation is generated when the beam passes through the target [8]. The TR spectral angular distribution for a single electron with a round TR target follows:

$$\frac{d^2U}{d\Omega d\omega} = \frac{e^2}{4\pi^3\epsilon_0 c} \frac{\beta^2 \sin^2\theta}{(1 - \beta^2 \cos^2\theta)^2} [(1 - \Upsilon(\zeta))^2], \quad (13)$$

where

$$\Upsilon(\zeta) = \frac{\zeta}{\beta\gamma \sin\theta} [J_1(\gamma \sin\theta \zeta) K_2(\zeta) - \gamma \theta J_2(\gamma \sin\theta \zeta) K_1(\zeta)], \quad (14)$$

and $\Upsilon = 2\pi r/\gamma\lambda\theta$ is the polar angle, $K_{1,2}$ is the modified Bessel function of the second kind.

For the beam with energy 160 MeV, charge 200 pC, and bunch length 2 ps, and the round TR target with radius 5 mm, we calculated that the peak radiation intensity was about 0.12 $\mu\text{J}/\text{THz}$ and peak power at 4.5 THz was

approximately 0.06 MW. The low charge of the beam leads to a low peak power of the radiation. The shape of the radiation spectrum is identical to the FFT curve shown in Fig. 9(b).

Compared to the regular methods of THz generation such as the optical rectification of a laser or production by gyrotrons, although the peak power provided by our new method is relatively low, it brings us a fast and convenient way to adjust the radiation frequency in a considerably wide range, which is requested in the research areas such as biophysics, structure biology, material science, and so on. Therefore, we believe this new method will open a new door for THz research and application.

V. CONCLUSIONS

Considering the wide applications of THz radiation in recent years, we analyzed the scheme to generate tunable THz density modulation by a 1047 nm seed laser at the SDUV FEL facility in theory and simulation, which turned out to be feasible for future experiments at the SDUV facility. With the scheme, the central frequency of the density modulation of the beam can be continuously tuned in at least 1–5 THz, which could be measured by an interferometer conveniently. The influence of nonlinear rf chirp and longitudinal phase space charge effect have also been studied. Our results show that this new scheme is feasible and easily applied in the Shanghai Deep Ultraviolet Free-Electron Laser facility.

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