ECHO-ENABLED TUNABLE TERAHERTZ RADIATION GENERATION WITH A LASER-MODULATED RELATIVISTIC ELECTRON BEAM*

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Abstract

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 is demonstrated numerically with a start-to-end simulation using the beam parameters at 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. We also briefly discuss how one may retrieve the beam longitudinal phase space through measurement of the THz density modulation.

INTRODUCTION

As been widely used in radar, security, communication, medical imaging etc, THz radiation has drawn a lot of attention all over the world. A lot of studies have been done on the generation of THz radiation. Accelerator-based free electron laser (FEL) technology, such as the 4^{th} 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 [1] and experimentally tested [2] to generate high harmonics of FEL radiation, and the bunching coefficients of this scheme was also analyzed in detail [3] to give us 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 Ref. [4, 5]. In this scheme, the relativistic electron beam is firstly 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 non-zero 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 (OPA) 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 [5], 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 $k_1 = C_1k_0$ 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 passing through the second dispersion section, the energy modulation is converted into density modulation at the final wave number $k = nC_1C_2k_0 + mC_2k_0$, where n and m are non-zero integers. It is easy to find out that one may vary the final frequency of density modulation continuously by varying the chirp of the beam or R_{56} of the first dispersion section.

GENERATION OF DENSITY MODULATION IN THEORY

As introduced in Sec. I (more details, see Ref. [4]), 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 Figure 1(a1), which consist 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

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section, the energy modulation is converted to density modulation at wave number

$$k = nk_1 + mk_2. \tag{1}$$

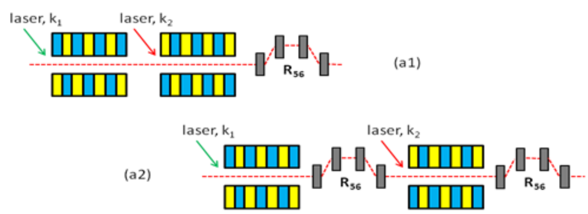


Figure 1: (color) layout of two schemes to generate THz density modulation in a relativistic electron beam.

Consider an initial Gaussian energy distribution as

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

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 $_E$. After the beam passes through the dispersion section, the distribution function becomes

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

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

The bunching factor $b_{n,m}$ at each harmonic, defined as $< [N(z)/N_0] e^{-ik_{n,m}z} >$ is

$$b_{n,m} = \big| J_n[(n + Km)A_1 B] \times J_m[(n + Km)A_2 B] e^{-(1/2)[(n+Km)B]^2} \big|. \tag{4}$$

As a comparison, we show the new scheme to generate THz density modulation, which is briefly mentioned in [5], in Figure 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 (EEHG) 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

$$k = nC_1 C_2 k_1 + mC_2 k_2, \tag{5}$$

where C_1 and C_2 are the bunch compression factor provided by the first and the second dispersion section.

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 the 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

$$f_0(p,\xi) = \frac{N_0}{\sqrt{2\pi}} \exp\Bigg\{ -\frac{(p - H\xi)^2}{2} \Bigg\}. \tag{6}$$

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. [6] shows the bunching factor at the harmonic factor a after the beam, without an energy chirp, passing through two modulators and two dispersions as

$$b = \frac{1}{N_0} \Bigg| \int_{-\infty}^{+\infty} dp e^{-iapB} f_0(p) \Big\langle \exp\{-ia\xi - iaA_1 B \sin\xi\} \times \exp\{-iaA_2 B_2 \sin(K\xi + KB_1 p + KA_1 B_1 \sin\xi + \Phi)\} \Big\rangle \Bigg|. \tag{7}$$

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 $B = B_1 + B_2$.

By changing the integration variable from p to $p' = p - H\xi$, and for the two identical wavelengths, define $k_0 = k_1 = k_2$, therefore in Eq. 7, $K = 1$, we conclude that the angular bracket denoting averaging over ξ does not vanish only if

$$a = \frac{n + m(1 + HB_1)}{1 + HB}, \tag{8}$$

and the bunching factor becomes

$$b_{n,m} = \Bigg| J_m\Bigg(\frac{n + m(1 + HB_1)}{1 + HB} A_2 B_2\Bigg) J_n\Bigg(\frac{A_1(nB + mB_2)}{1 + HB}\Bigg) \Bigg| \times \exp\Bigg\{ -\frac{(nB + mB_2)}{2(1 + HB)^2} \Bigg\}^2. \tag{9}$$

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

$$k = nC_1 C_2 k_0 + mC_2 k_0, \tag{10}$$

it is straightforward to see that with $n = 1$, $m = -1$, and $(C_1 - 1)C_2 \sim 10^{-2}$, if an 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.

GENERATION OF DENSITY MODULATION IN A START-TO-END SIMULATION AND THZ RADIATION

The beam line of SDUV FEL facility, which is used to carry out the Echo-Enabled Harmonic Generation (EEHG)

Table 1: 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 & 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 & U2 (cm)	5
number of periods of U1 & 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

experiment [2], is shown in Figure 2. 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 seed laser in those two modulators is 1047 nm.

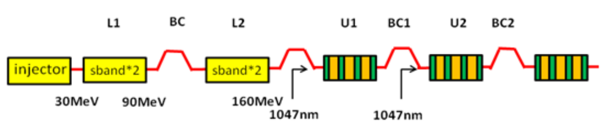
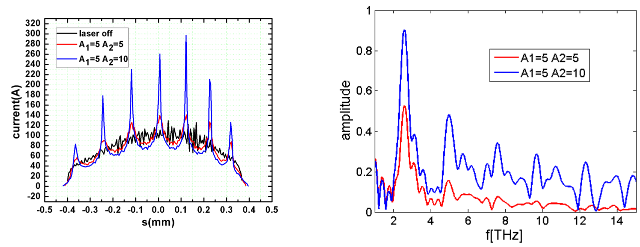


Figure 2: (Color) Layout of SDUV FEL facility for generation of THz density modulation in a chirped electron beam.

We use ASTRA 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 (consist of 2 S-band) and finishes after the beam passing through the second dispersion section (BC2, seen in Figure 2). After being accelerated to 160 MeV, the beam with energy chirp $h = 11.22\ \mathrm{m}^{-1}$ is sent into the modulator to interact with a 1047 nm laser. To gain the maximal bunching according to the theory, it is optimal to regulate the laser power at $\Delta E_1 = 25$ keV while the slice energy spread of the beam is about 5 keV. So is the same with the second modulator at$\Delta E_2 = 50$ keV. The main parameters in the simulation are listed in Table 1.

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 Figure 3, 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 Figure 3, 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 harmonic linearizer (e.g. an X-band cavity in FEL linac) in 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 dispersion.



(a) (Color) beam currents for $A_2 = 5$ (red) and $A_2 = 10$ (blue) when $A_1 = 5$ and initial current without laser modulation (black).

(b) (Color)FFT image of beam current for $A_2 = 5$ (red) and $A_2 = 10$ (blue) when $A_1 = 5$

Figure 3: (Color) beam current and its Fast-Fourier-Transform (FFT) image.

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-micron FEL radiation, therefore it is hard to match the resonance condition because the period and the magnet field of the undulator are both too large.

Therefore, TR is the only but even better choice because it is relatively easy and convenient to operate in our scheme. 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 μJ/THz and peak power at 4.5 THz was about 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 Figure 3(b).

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