GENERATION OF NARROW-BAND, COHERENT, TUNABLE TERAHERTZ RADIATION USING A LASER-MODULATED ELECTRON BEAM*

M. Dunning†, C. Hast, E. Hemsing, K. Jobe, D. McCormick, J. Nelson, T.O. Raubenheimer,
K. Soong, Z. Szalata, D. Walz, S. Weathersby, D. Xiang
SLAC, Menlo Park, CA, USA

Abstract

The technical layout and initial results of an experiment to generate narrow-band, coherent, tunable terahertz (THz) radiation through the down-conversion of the frequency of optical lasers using a laser-modulated electron beam are described. In this experiment, a 120 MeV electron beam is first energy modulated by two lasers with different wavelengths. After passing through a dispersive section, the energy modulation is converted into a density modulation at THz frequencies. The central frequency of the THz modulation can be tuned by varying the wavelength of one of the two lasers or the energy chirp of the electron beam. The density-modulated beam will be used to generate narrow-band THz radiation using a coherent transition radiator inserted into the beam path. The experiment is being performed at the Next Linear Collider Test Accelerator (NLCTA) at SLAC, and will utilize the existing Echo-7 beamline, where echo-enabled harmonic generation (EEHG) was recently demonstrated.

INTRODUCTION

Generation of density modulation in relativistic electron beams with varying periods ranging from Ångstroms to millimeters is of fundamental interest in accelerator physics. This density modulation allows the electrons to radiate in phase, which leads to orders of magnitude enhancement in the radiation power compared to the spontaneous radiation. A free-electron laser (FEL) is an example where the electrons are packed into narrow bunches with equal spacing from the sustained electron-radiation interaction in a long undulator [1, 2, 3].

In the optical to ultraviolet wavelength region, the classic way to introduce density modulation in an electron beam is through laser modulation [4, 5, 6, 7]. In these schemes, typically a laser is first used to interact with the beam in a short undulator to generate energy modulation at the laser frequency ω; then the energy modulation is converted into density modulation after the beam passes through a dispersive section (i.e. 4-dipole chicane). Because of the nonlinear transformation, the beam density is modulated at both the laser frequency and its harmonics, namely $h\omega$, where h is an integer. The density modulated can be very useful. For example, it can be used for phase-stable net acceleration in staged laser accelerators [8, 9], for driving seeded FELs to generate fully coherent radiation at high harmonic frequencies of the seed laser [5, 6, 7, 10], or for amplifying a coherent seed in the x-ray wavelength to generate mode-locked multichromatic x-rays [11].

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† mdunning@slac.stanford.edu

The principle of generating periodic THz structure in the beam charge density by modulation with two optical lasers is relatively straightforward [12]. After interacting with a laser with wavenumber k_1 in an undulator, and then another with wavenumber k_2 in a second undulator and then passing through a downstream chicane, in general, the beam density distribution will consist of modulations at the wavenumber

$$k_{n,m} = nk_1 + mk_2, \tag{1}$$

where n and m are integers. It is straightforward to see that by choosing $n = 1$ and $m = -1$ (or vice versa), density modulation at the difference frequency of the two lasers can be generated. This allows one to generate long-scale density modulation in electron beams through short-scale energy modulations.

One important parameter that characterizes the density modulation is the bunching factor $b_{n,m}$, which is found to be independent of the laser phase difference, and can be written as [12]

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

where $J_{n,m}$ is the Bessel function of the first kind, $A_{1,2} = \Delta E_{1,2}/\sigma_E$ is the dimensionless energy modulation in the first and second modulators, $\Delta E_{1,2}$ is the energy modulation amplitude, σ_E is the uncorrelated beam energy spread, $B = R_{56}k_1\sigma_E/E_0$ is the dimensionless momentum compaction of the chicane, E_0 is the reference particle energy, and $K = k_2/k_1$.

EXPERIMENT LAYOUT

An experimental test of this scheme was carried out using the echo-enabled harmonic generation (EEHG) beamline [13, 14] at SLAC's NLCTA. The layout of the beamline is schematically shown in Fig. 1. The electron beam is generated in a 1.6 cell S-band photocathode rf gun and further accelerated to 120 MeV with two X-band linac structures. The main elements of the beamline are 3 chicanes (C0, C1 and C2), 2 undulators (U1 and U2), an rf transverse cavity (TCAV), several quadrupoles for beam matching and focusing, and several optical transition radiation (OTR) and Yttrium Aluminum Garnet (YAG) screens for measuring the position and distribution of the lasers and electron beams.

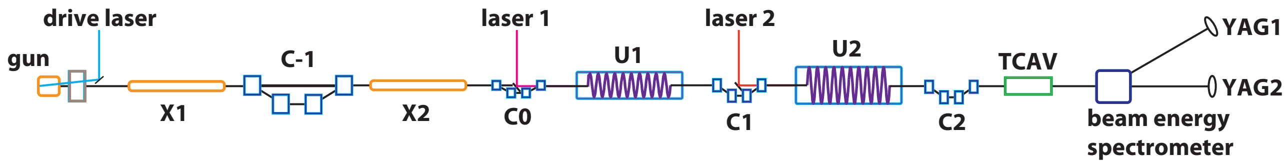

Figure 1: Schematic layout of the beamline for generation of THz density modulation in a relativistic electron beam through laser modulation at SLAC's NLCTA.

Table 1: Main Experiment Parameters

Beam energy	120 MeV
Normalized emittance	2 μm
Bunch charge	40 pC
Laser wavelength in U1	800 nm
Laser wavelength in U2	1550 nm
$N_p \times \lambda_u$ for U1	10 × 3.3 cm
$N_p \times \lambda_u$ for U2	10 × 5.5 cm
Peak energy modulation in U1	40 keV
Peak energy modulation in U2	50 keV
R_{56}, C1	1.0 mm
R_{56}, C2	10.0 mm

The experiment aimed to generate density modulation at 12 THz, corresponding to $n = -1$ and $m = 2$ for two lasers with wavelengths at 800 nm and 1550 nm. In Fig. 1, the first chicane C0 is used only for laser injection into the first undulator U1, where the 800 nm laser (1 ps FWHM, Ti:Sapphire) interacts with the electron beam to imprint energy modulation. While chicane C1 is not necessary for generation of THz density modulation, it is required for injection of the 1550 nm laser (0.55 ps FWHM, produced by an optical parametric amplifier (OPA) system pumped by the same Ti:Sapphire laser) into undulator U2. In this experiment, the momentum compaction of C1 is set to $R_{56}^{(1)} = 1.0$ mm, the minimal value required for the electron beam to bypass the laser injection mirror. While the presence of chicane C1 slightly changes the optimal values of the laser energy modulation for maximizing the density modulation, it does not change the underlying physics.

The bunching factor $b_{-1,2}$ as a function of the energy modulation amplitudes from the two lasers is calculated and shown in Fig. 2a. The optimal energy modulations that maximize the bunching are found to be $\Delta E_1 \approx 40$ keV and $\Delta E_2 \approx 140$ keV. In this experiment, the energy of the 1550 nm laser was limited to ~ 10 μJ which limited the achievable ΔE_2. To see if noticeable density modulation at THz frequencies could still be generated with limited energy modulation, the beam distribution was simulated with various energy modulations from the 1550 nm laser, and the results are shown in Fig. 2b (in the simulations $\Delta E_1 = 40$ keV was assumed). The simulation indicates that about 10% density modulation at 12 THz may be generated with $\Delta E_2 = 50$ keV. The modulation is present in only part of the beam since the laser pulse width is shorter than the electron bunch length.

After temporal and spatial overlap of the laser and the electron beam, the energy modulation from the 1550 nm laser was maximized. The energy modulation is measured at the YAG1 energy spectrometer screen, where the dispersion is 1.5 m. The energy resolution was estimated to be approximately 10 keV.

A representative beam image measured at YAG1 with lasers off is shown in Fig. 3a. With laser modulation, the horizontal beam size at YAG1 will increase due to the increased energy spread. In this experiment, the beam energy, laser timing and the electron-laser spatial overlap were finely adjusted to maximize the energy modulation from the 1550 nm laser; the energy-modulated beam image at YAG1 is shown in Fig. 3b. Analysis of the images shows that the peak energy modulation from the 1550 nm laser was about ΔE_2 =50 keV. After determining ΔE_2, the energy of the 800 nm laser was adjusted with a wave plate to provide approximately 40 keV energy modulation to maximize the density modulation in accordance with Fig. 2.

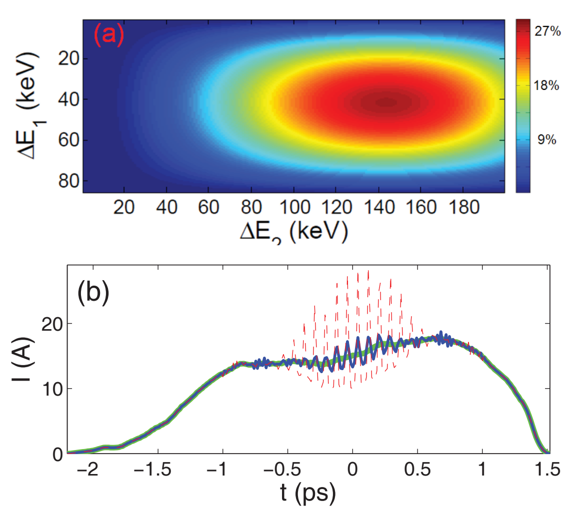

Figure 2: (a) THz bunching as a function of laser energy modulations; (b) Simulated beam density distribution for $\Delta E_2 = 50$ keV (blue line) and $\Delta E_2 = 140$ keV (dashed red line). The initial beam distribution without laser modulations is shown as a solid green line.

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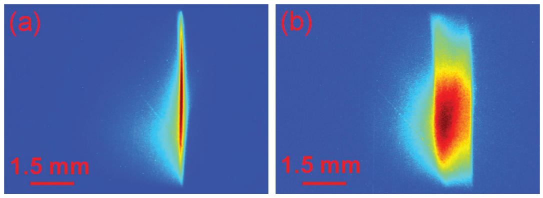

Figure 3: Raw images of beam transverse profile measured at YAG1 with lasers off (a) and with 1550 nm laser on (b)).

INITIAL RESULTS

The density modulation was measured at the YAG2 screen with a 27-cell TCAV, an rf structure which essentially maps the temporal profile of the beam to transverse position [15, 16]. The temporal resolution of the TCAV was calculated to be about 30 fs. Representative beam images measured at YAG2 with lasers off and lasers on are shown in Fig. 4a and Fig. 4b, respectively. The density modulation is clearly seen in Fig. 4b with both lasers on. Figure 4c shows the projected beam density distribution. Because the laser pulse is shorter than the electron bunch, density modulation is only present for part of the beam, similar to the simulation in Fig. 2b.

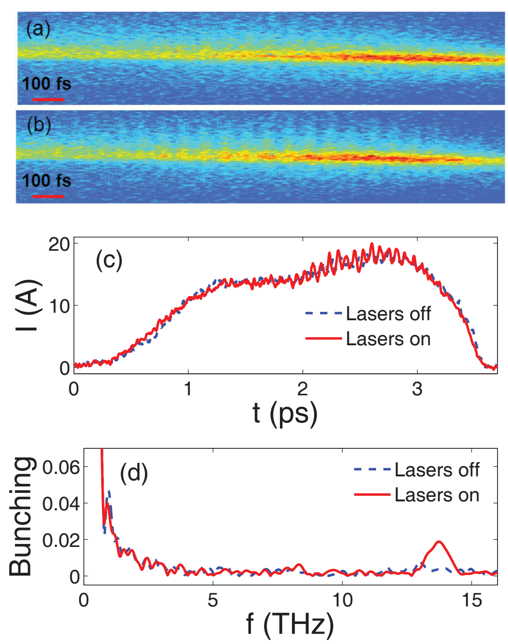

Figure 4: Raw images of beam density distribution (only part of the beam distribution is shown for purposes of visualization) measured with the TCAV with lasers off (a) and lasers on (b); Projected beam current distribution (c) and the corresponding spectrum (d).

The bunching factor is obtained from Fourier transformation of the beam density distribution and is shown in Fig. 4d. From the figure, the central frequency of the density modulation is quantified to be about 13.6 THz, which slightly deviates from the theoretical value of 12 THz. This discrepancy could be attributed to the uncertainty of the wavelength of the 1550 nm laser, of which the wavelength was measured using a spectrometer with a resolution of about 5 nm. A deviation of about 6 nm in the laser wavelength would result in a difference of 1.6 THz for the density modulation. The energy chirp (correlation of energy and longitudinal position) of the beam from wake fields and RF curvature from the x-band linac structures may also shift the central frequency of the modulation, similar to that in the EEHG technique [13, 17].

CONCLUSION

In summary, density modulation at THz frequencies was observed in a relativistic electron beam through down-conversion of the energy modulations from two lasers. One of the many advantages of the demonstrated technique is the flexibility it offers to tune the central frequency of the modulation, which can be achieved through tuning of laser wavelengths or beam energy chirp. In principle, it allows one to generate density modulation in the beam covering the whole THz range. Once the density modulation is formed, it is straightforward to use the beam for generation of coherent, narrow-band THz radiation. The NLCTA OPA is currently being upgraded, which will increase the energy modulation from the second laser, thereby increasing the depth of the density modulation in the beam. The strongly density-modulated beam will then be sent through an OTR foil to generate coherent THz radiation, which will be spectrally characterized with a Michelson interferometer and a cryogenically cooled bolometer.

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