TUNABLE HIGH-INTENSITY ELECTRON BUNCH TRAIN PRODUCTION BASED ON NONLINEAR LONGITUDINAL SPACE CHARGE OSCILLATION*

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Abstract

High-intensity trains of electron bunches with tunable picosecond spacing are produced and measured experimentally with the goal of generating terahertz (THz) radiation. By imposing an initial density modulation on a relativistic electron beam and controlling the charge density over the beam propagation, density spikes of several-hundred-ampere peak current in the temporal profile, which are several times higher than the initial amplitudes, have been observed for the first time. We also demonstrate that the periodic spacing of the bunch train can be varied continuously either by tuning launching phase of a radio-frequency gun or by tuning the compression of a downstream magnetic chicane. Narrow-band coherent THz radiation from the bunch train was also measured with μJ-level energies and tunable central frequency of the spectrum in the range of ~0.5 to 1.6 THz.

INTRODUCTION

Bunch trains, consisting of a large number of equally spaced electron microbunches, have been considered for the resonant excitation of the wakefields in plasma and dielectric wakefield accelerators [1–3], and for production of beam-based high power, narrow-band radiation in the terahertz (THz) spectral range [4].

Several methods have been proposed and studied to generate ps and sub-ps spaced bunch trains. These include the conversion of transverse modulation into a periodic longitudinal distribution with the use of dispersive beam line and initial energy chirp [5], or the emittance-exchange technique [6]. The generation of transverse modulation using a mask will always lead to particle loss. Another possibility is to introduce an energy modulation by self-excited wakefields [7, 8] and then convert it to density modulation through a magnetic chicane [9]. The difference-frequency method based on the electron-laser interaction [10, 11] can be also used to generate THz structures although the implementation will be slightly more complex. In addition, many authors have proposed a straightforward method, imposing modulation on the beam directly at the cathode and trying to maintain it as the beam propagates [4, 12, 13]. This method suffers from the smearing effect of longitudinal space charge forces and the initial modulation might blur and tend to disappear for large beam currents. Some improved methods have been considered to compensate this effect and recover the initial modulation [14, 15].

As opposed to trying to reduce the effect of longitudinal space charge forces, Musumeci *et al.* proposed to take advantage of it to magnify the initial density modulation through strengthening the space charge forces and letting the beam distribution evolve in the nonlinear regime [16]. A proof-of-principle experiment with a few pC beam charge (up to ~ 20 pC) was carried out a few years ago [16] and this scheme was proposed to generate high peak current bunch trains [17]. For a large enough initial density modulation, the linear theory, which predicts a periodic evolution of the beam density with the periodicity set by the relativistic plasma frequency, breaks down and the dynamics is more complicated due to the appearance of harmonics of the modulation frequency along the beam propagation. The harmonics interfere constructively after 1/2 plasma oscillation period (π phase advance) leading to the formation of high peak current spikes.

EXPERIMENT SETUP

In this paper, we explore experimentally the possibility of using this technique to generate ps spaced bunch trains with large charge and high peak currents. The experiment was performed at the Tsinghua Thomson Scattering X-ray Source [18]. A schematic of the experiment is presented in Fig. 1. The cathode in a 1.6 cell rf photoinjector is illuminated by a train of 8 equally spaced laser pulses created using 3 α-BBO birefringent crystals of thickness 5.68, 2.84 and 1.42 mm, respectively. The induced separation between neighboring pulses is 1 ps with frequency content of 1 THz. The beam charge after the crystals can be varied from a few pC up to ~ 1 nC. The beam modulation can be observed directly by an rf deflector and can also be confirmed by the measurement of the autocorrelation function of coherent transition radiation (CTR) produced when the beam passes through a foil.

Bunch Train Measurement

A typical measurement of the bunch train with high beam charge by the deflector (~ 700 pC) is presented in Fig. 2. The laser spot on the cathode was optimized to be ~ 4 mm in diameter and the full width at half maximum (FWHM) of the single laser pulse before stacking was ~ 500 fs. The phase of the gun was set at 30° with maximum acceleration

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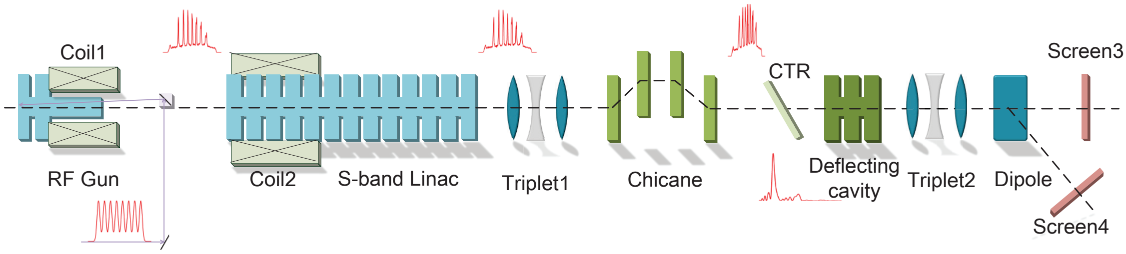

Figure 1: Schematic layout of the beam line for bunch train generation (not to scale). The inset plots are the longitudinal profile of the laser and electron beams, and the THz spectrum. The deflecting cavity is used to streak a portion of the beam across a luminescent screen to measure the beam's longitudinal profile.

gradient 106 MV/m. The gun solenoid was set to 2230 Gs and linac solenoid was ~ 800 Gs. The acceleration section was set at on-crest and the chicane was turned off. For a large beam charge, as the beam experiences strong focusing at low energy, it is difficult to get very small unstreaked beam size by using the current focusing system in the beam line, which limits the temporal resolution of the deflector. In order to resolve the temporal profile, we implemented a 70-μm horizontal slit before the deflector to cut the beam transversely and so that a small fraction of charge could be streaked. We varied the position of the slit and the measured distributions were similar. We observed 7 bunches with ~ 250 A peak current (150 A for the head sub-bunch) and ~ 1 ps periodic spacing. Compared with the initial modulation (peak current ~ 130 A), the modulation is enhanced by the longitudinal space charge forces.

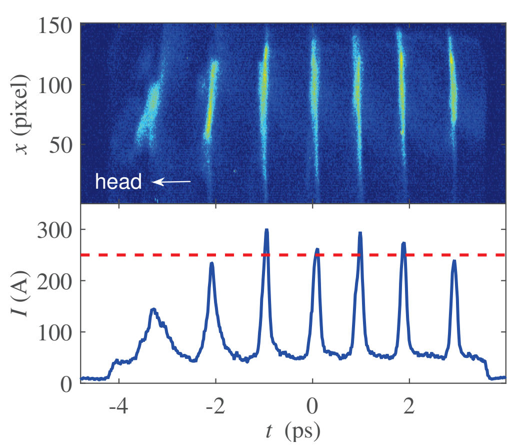

Figure 2: Measured longitudinal distribution (top) and projected density profile (bottom) of the bunch train with a horizontal slit before the deflector.

Auto-correlation Measurement

The modulation in the temporal profile was confirmed by the CTR radiation from the beam. We analyzed the time structure of the signal with a Michelson interferometer using a Golay cell as the detector (not shown in Fig. 1) that characterizes the periodicity of the electron bunch. A typical autocorrelation function is shown in Fig. 3. With the dc offset subtracted, the Fourier transform of the autocorrelation function gives the power spectrum of the THz radiation, also shown in Fig. 3. The central frequency of the spectrum, corresponding to the average spacing of the bunch train, is ~ 0.85 THz since the launching phase in the gun of the electron beam was set at 40° for this measurement. A train of N electron bunches results in an interferogram with $2N - 1$ peaks. The number of peaks of the autocorrelation function is 13, in agreement with with the expected 7 bunches.

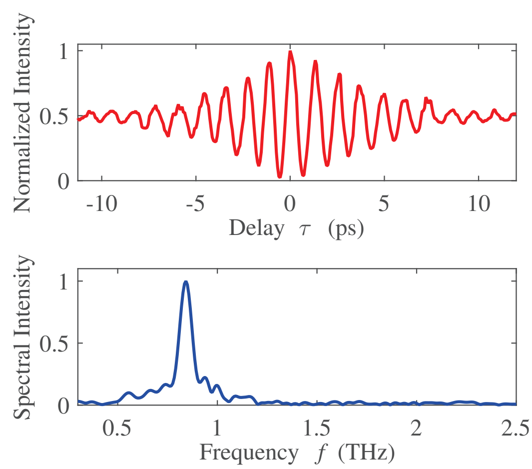

Figure 3: Normalized autocorrelation function of the CTR THz radiation (top) and the THz spectrum (bottom). The central frequency of the spectrum is ~ 0.85 THz as the launching phase of the gun is 40°.

Frequency Adjustment

One could control the central frequency of the CTR radiation by changing the launching phases, which influence the overall bunch compression or stretching due to the velocity bunching. The results of experimental measurements and GENERAL PARTICLE TRACER (GPT) code [19] simulations are presented in Fig. 4. In these measurements, the acceleration section was set at maximum acceleration. By changing the launching phase from 50 ° to 25 °, we observed the central frequency changing from ~ 0.7 THz to ~ 1 THz, which agrees very well with the GPT simulations.

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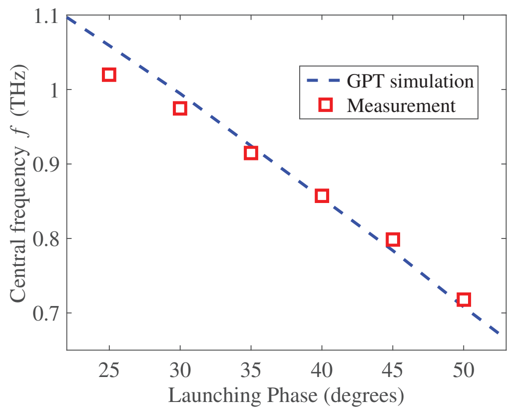

Figure 4: Central frequency of the THz radiation as a function of the launching phase in the gun.

The central frequency can be varied continuously by the chicane as well. If the electron beam was accelerated off-crest to induce an energy chirp, the central frequency of the radiation spectrum would be a function of the chicane current. The measurement results are shown in Fig. 5 with -37° off-crest phase. The launching phase of the electron beam was fixed at 45° during the measurements. The inset gives the corresponding R_{56} of the chicane for different exciting currents. In the experiment, the central frequency was increased by a factor of 2 by the bunch compression. In addition to compressing the bunch, we can also stretch it to decrease the central frequency. The frequency range of the CTR radiation obtained in the experiment was from ~ 0.5 THz to ~ 1.6 THz, which means the average spacing of the bunch train was from ~ 0.6 ps to ~ 2 ps.

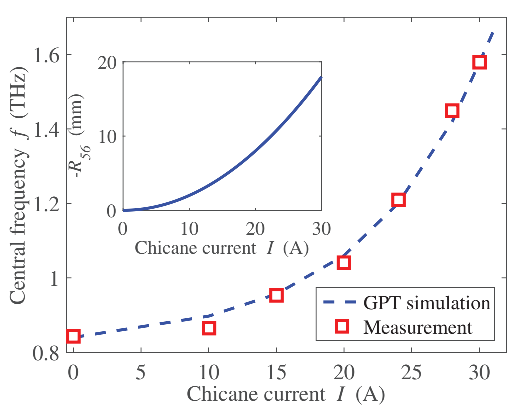

Figure 5: Central frequency of the THz radiation as a function of the chicane current. The inset shows the R_{56} of the chicane for different exciting currents.

SUMMARY

In summary, we have observed high-charge high peak current electron bunch trains based on the nonlinear longitudinal space charge oscillation, orders of magnitude higher than previous results. We imposed a ps initial modulation on the beam at the cathode and controlled its oscillation phase advance over the propagation by the external focusing. The bunch train was measured both by a deflector directly and CTR radiation. The peak current of the current spikes in the temporal profile was up to ~ 250 A, enhanced by a factor of 2 compared with the initial modulation. Narrow-band coherent THz radiation was also generated from the bunch trains. The central frequency of the radiation spectrum can be varied continuously by the overall bunch compression or stretching. The frequency range achieved in the experiment was from ~ 0.5 THz to ~ 1.6 THz.

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