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RECENT EXPERIMENTAL RESULTS ON HIGH-PEAK-CURRENT ELECTRON BUNCH AND BUNCH TRAINS INTERACTING WITH A THz UNDULATOR*

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Abstract

In this paper, experimental results based on THz undulator with widely tunable gap installed at Tsinghua Thomson scattering X-ray (TTX) beamline are introduced. This is a planar permanent magnetic device with 8 regular periods, each 10-cm long. The undulator parameter varies from 9.24–1.39 by changing the magnetic gap from 23 mm to 75 mm. The coherent undulator radiation can be used as a narrow-band THz source with central frequency ranging from 0.4 THz to 10 THz. The bunch length was determined from the radiation intensity at different undulator gaps, agreeing well with simulations. Furthermore, slice energy modulation was directly observed when high-peak-current bunch trains based on nonlinear longitudinal space charge oscillation passed through the undulator. The demonstrated experiment in the THz regime provides a significant scaled tool for FEL mechanism exploration owing to the simplicity of bunch modulation and diagnostics in this range.

INTRODUCTION

High-peak-current electron bunch and bunch trains have many important applications in accelerator research. Ultrashort bunches are widely used in high-gain free electron lasers (FEL) [1], wake-field acceleration [2], ultrafast electron diffraction (UED) [3] and high-power coherent radiation in the terahertz (THz) spectral range [4]. The resonant excitation of wakefield accelerators [5] and production of narrow-band terahertz radiation [6] rely on the development of bunch trains with a large number of equally spaced electron micro bunches. The measurement of ultrashort bunch length and bunch train distribution is of vital importance for these frontier applications.

the electron-bunch form factor, defined as:

$$F(\omega)=\left|\int_{-\infty}^{\infty} e^{i\omega z/c} S(z)\,dz\right|^2 \quad (1)$$

is derived from the Fourier transform of the longitudinal electron density in the bunch, where $S(z)$ is the distribution function for particles in the bunch, measured relative to the bunch centre, c is light velocity in vacuum. Form factor is closely related to the bunch longitudinal distribution, both for ultrashort bunch and bunch trains. There have been several methods for bunch form factor or longitudinal distribution measurement. Deflecting cavity is one of the most useful tool for beam diagnostics, converting the longitudinal distribution into transverse coordinate [7]. Electro-optic method can measure bunch length with temporal resolution limited to sub-ps level [8]. Moreover, spectrum and intensity of coherent radiation are used for bunch longitudinal distribution diagnose or monitoring, including coherent diffraction radiation (CDR), coherent transition radiation (CTR) [9], and coherent Smith-Purcell radiation [10]. In this paper, ultrashort bunch length and bunch train distribution are derived from THz radiation energy of a tunable-gap undulator.

Moreover, radiation spectrum and energy from the tunable-gap undulator were measured, which is an intense narrow-band THz source. Terahertz sources have many potential applications in biophysics, medical, industrial imaging, nanostructures, and metal science [11]. Intense THz radiation has been utilized as probes of low-frequency excitations, which is a powerful tool to improve the fundamental understanding of matter. THz sources based on relativistic electrons are usually with high power and have various properties based on emission mechanisms. Coherent undulator radiation is naturally narrow-band, which is of great advantage for scientific research. The resonant frequency is defined as:

$$f=\frac{2\gamma^2 c}{\left(1+K^2/2\right)\lambda_u}, \quad (2)$$

where γ is the Lorentz factor, K is the undulator parameter, and λ_u is the period.

When electron bunch train with the same period passes through undulator, the radiation from bunch tail slips ahead the bunch and interact with the electron ahead. Furthermore, if the resonant wavelength is the same with bunch train period, the radiation from micro bunches add coherently and interact with electron bunch. Bunch energy modulation was observed at Terahertz spectrum during the experiment. The beamline and experimental results are introduced in the following sections.

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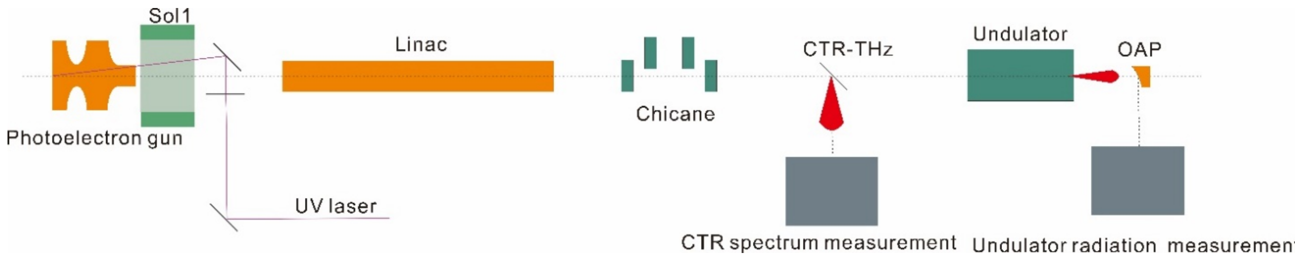

Figure 1: Layout of the Tsinghua beam line and THz system.

EXPERIMENTAL LAYOUT

The experiment was performed at Tsinghua Thomson scattering X-ray (TTX) beamline, which is illustrated in Figure 1. A Ti:sapphire laser system generates ultraviolet driving laser for the photocathode radio-frequency (RF) gun. For ultrashort bunch generation, the laser is a 10-ps quasi flat-top distribution and the bunch train is generated by modulated driving laser from laser stacking using birefringent α-BBO crystals. Bunch charge varies from a few pC to ~1 nC according to the laser energy. After acceleration by a 3-m SLAC-type traveling wave accelerating section, the bunch energy increases up to 45 MeV. The bunch is compressed by a magnetic chicane to change bunch length or period of electron bunch train.

The undulator is installed downstream the chicane, and it is an widely tunable permanent magnetic planar undulator with eight regular periods, each of which are 10 cm long. The magnetic gap is widely tunable from 23 to 75 mm. According to Halbach's fitting equation, the peak magnetic field is:

$$B_0[\mathrm{T}] = 3.0255\times e^{-5.2255(\frac{g}{\lambda_u})+1.6202(\frac{g}{\lambda_u})^2}, \quad (3)$$

where g is the magnetic gap. The undulator parameter,

$$K = \frac{eB_0\lambda_u}{2\pi mc} = 0.934\lambda_u[cm]B_0[T], \quad (4)$$

varies from 9.24 to 1.39 continously. The undulator parameter is plotted as a function of undulator magnetic gap in Figure 2.

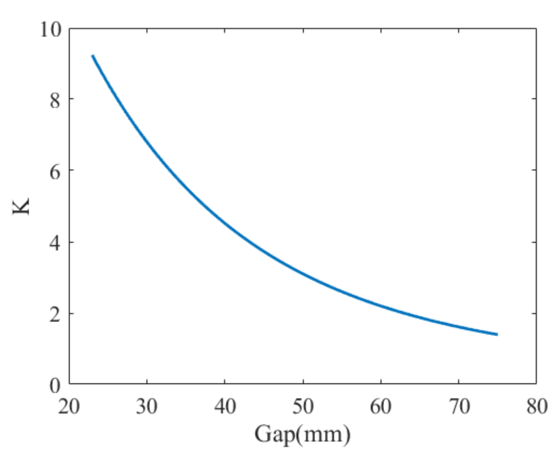

Figure 2: Undulator parameter as a function of undulator magnetic gap.

EXPERIMENTAL RESULTS

Radiation Energy and Spectrum Measurement

An ultrashort Gaussian bunch was generated by 10-ps quasi-flat-top driving laser and compressed by chicane. The radiation energy was collected by off-axis parabolic mirrors and measured by Golay cell detector. The radiation spectrum was measured by Michelson interferometer. The measured autocorrelation curve and corresponding energy spectrum, when undulator gap was 30 mm and bunch energy 28 MeV, are shown in Figure 3. The central frequency is about 0.73 THz, which agrees well with theoretical calculation. The measured energy was μJ level depending on central frequency and bunch properties.

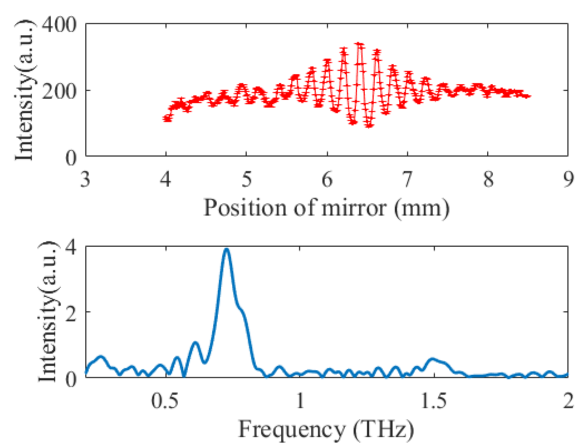

Figure 3: Measured autocorrelation curve (top) and the converted radiation spectrum (bottom).

Bunch Length Measurement

Coherent radiation intensity is closely related to form factor, which is determined by bunch length. For undulator radiation, the radiated energy is mainly influenced by diffraction effects at low central frequency but limited by form factor at high frequency. The radiation energy curve was measured as we scanned undulator gap continuously. The curve shape is determined by bunch length, as shown in Figure 4. The bunch length was delivered from fitting of Gaussian bunch radiation energy. From the radiation energy curve, the ultrashort bunch length was 110 fs. The resolution is determined by bunch energy and undulator parameters.

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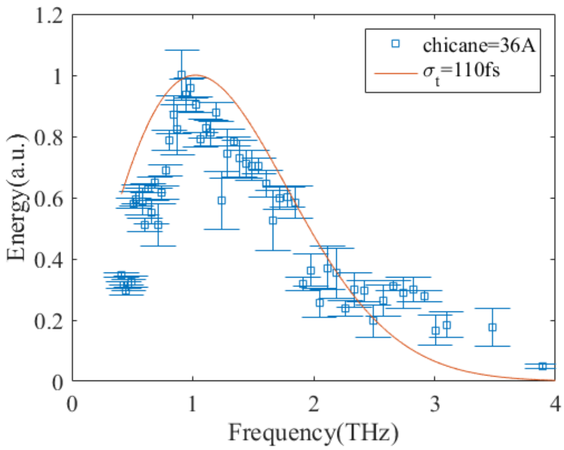

Figure 4: Radiation energy as a function of central frequency. The square was measured and solid line was from theory.

Observation of Bunch-Train Energy Modulation

A high-intensity electron bunch train, based on a nonlinear longitudinal space charge oscillation, was generated with about 1-ps separation (corresponding to a frequency of 1 THz) [12]. If the undulator resonant frequency was close to bunch train separation, the radiation from micro bunch in the tail slipped ahead per resonant wavelength every undulator period. The slipped radiation added coherently with radiation from the micro bunch ahead and interacted with the bunch, resulting in much higher radiation energy due to coherence and bunch modulation from beam and field interaction. The measured energy spectrum was presented in Figure 5, when radiation from micro bunches added coherently, the bunch in the head is modulated obviously.

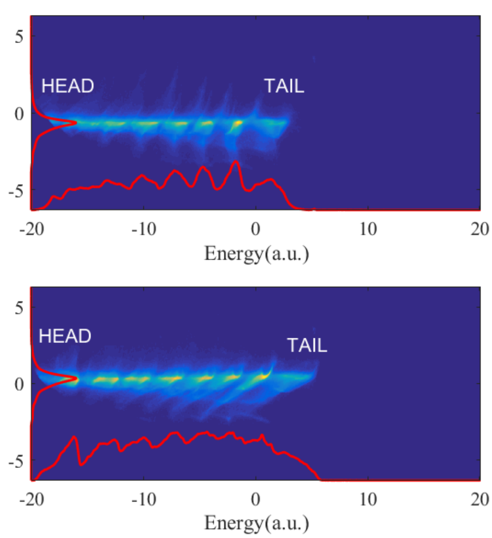

Figure 5: Energy spectrum when radiation from micro bunches added (Top) uncoherently and (Bottom) coherently.

CONCLUSION

Recent experimental results on high-peak-current electron bunch and bunch trains interacting with a THz undulator are introduced in this paper. The narrow-band THz radiation energy and spectrum were measured. Bunch length were delivered from energy undulator gap curve. Furthermore, bunch trains based on nonlinear longitudinal space charge oscillation were generated and passed through the tunable-gap undulator. Slice energy modulation were observed directly, providing a significant scaled tool for FEL mechanism exploration.

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