MEASUREMENT OF ELECTRON BUNCH LENGTH VIA A TUNABLE-GAP UNDULATOR*

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Abstract

A THz undulator with widely tunable gap is constructed and installed at Tsinghua University beamline, which is applied for narrow-band THz radiation and measurements of electron bunch longitudinal structure. This is a planar electromagnetic device with 8 regular periods, each 10 cm long. The field range B=0.15- 0.99 T peak field on axis while changing the gap from 75mm to 23mm. In the experiments, we scanned the undulator gap to measure the radiation intensity at different resonant frequency, thus we can get the bunch length even form factor of the bunch. The demonstrated experimental results show that the bunch of 220pC compressed by chicane in Tsinghua beamline is about 120fs (rms), which agree well with the simulations. The resolution of bunch length measurement with this method can be attoseconds by optimized undulator. Furthermore, the form factor of electron bunch train can also be measured.

INTRODUCTION

The longitudinal distribution of relativistic electron beams is one of the main property of the electron bunch. Ultrashort bunch have applications including high gain free electron laser (FEL)[1], wake field acceleration[2], ultrafast electron diffraction (UED)[3], and for production of beam-based high power, coherent radiation in the terahertz (THz) spectral range[4]. Bunch trains with a large number of equally spaced electron microbunches, have potential application in the resonant excitation of the wakefield accelerators[5], and for production of narrow-band terahertz radiation[6]. Electron bunch form factor derived from the Fourier transform of the longitudinal electron density in the bunch, defined as:

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

where $S(z)$ is the distribution function for particles in the bunch, measured relative to the bunch centre, c is light velocity in vacuum. The form factor uncovers the bunch distribution and is the essential parameter in coherent radiation[7].

The bunch longitudinal distribution or form factor can be measured by several methods. One way is to use a deflecting cavity to convert the longitudinal distribution into transverse coordinate[8]. Reconstruction of bunch distribution from autocorrelation curve of coherent transition radiation is another common method[9]. The electro-optic method can measure the bunch length with the temporal resolution limited to 60fs[10]. Electron bunch compression monitors based on CDR and CTR are also studied in SwissFEL[11] and Tsinghua beam line[12]. Resonant at Far IR wavelength based on undulator was demonstrated at FLASH[13].

In this paper, a THz undulator with widely tunable gap was used to diagnose the bunch form factor so as to evaluate the bunch longitudinal distribution. The radiation energy is

$$W = W_e[\mathrm{N}+\mathrm{N}(\mathrm{N}-1)\,\mathrm{F}(\omega)], \tag{2}$$

where N is the number of electrons in the bunch, W_e is the radiation energy of a single electron. During the experiment, the undulator gap was scanned so as to change the resonant frequency and the total radiation energy intensity at different frequency was measured. The bunch length of ultrashort bunch or longitudinal structure of bunch train can be measured.

EXPERIMENTAL LAYOUT

The experimental layout is shown in Figure 1, which is part of the Tsinghua Thomson scattering X-ray (TTX) source. A Ti:sapphire laser system generates ultraviolet driving laser for the modified version of BNL/KEK/SHI type 1.6 cell photocathode radio-frequency (RF) gun. The longitudinal structure of the electron bunch can be modulated by the driving laser and the bunch charge varies from a few pC to ~1nC according to the laser energy. After acceleration of 3 m SLAC-type traveling wave accelerating section, the bunch energy increases up to 45MeV. A chicane is installed to compress the bunch longitudinal distribution. More detailed description of the whole system can be found in Refs.[14].

An 8-period widely tunable permanent magnetic planar undulator is installed in the beamline. Parameters of the undulator is listed in Table 1. According to Halbach's fitting equation, the fitted curve of magnetic field and undulator parameter are show in Figure 2.

The electron bunch passed through the undulator after beam manipulation and generated terahertz radiation. The radiation energy was detected by Golay cell detector after collection by OAP as shown in Figure 1. An aluminium

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film on YAG oriented at 45 degrees with respect to the beam line is installed after chicane to generate CTR, offering the possibility to measure the autocorrelation curve by Michelson interferometer. Measurement of CTR spectrum is a general method to diagnose bunch longitudinal distribution, which could be compared with undulator measurement.

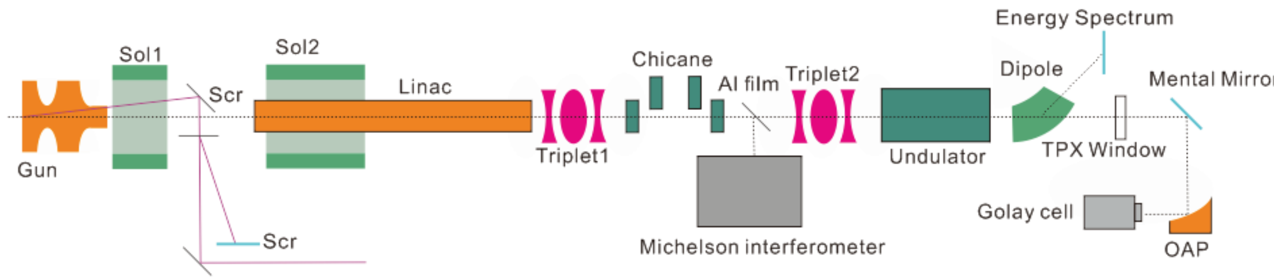

Figure 1: Layout of the Tsinghua beam line and THz system.

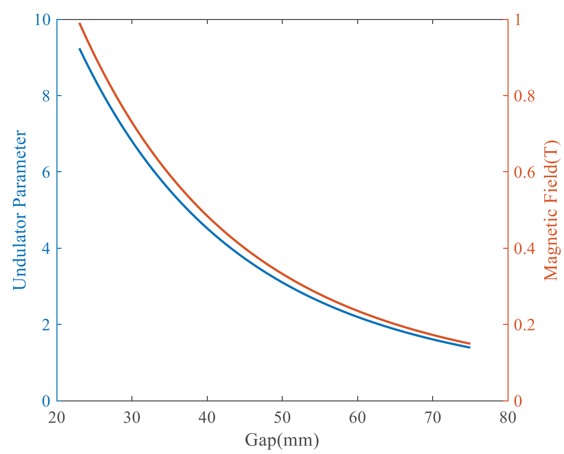

Figure 2: Fitted curve of undulator parameter and magnetic field in the middle plane.

Table 1: Parameters of the Tunable Undulator

Parameter	Value
Undulator period	100 mm
Number of periods	8
Magnetic gap range	23-75 mm
Peak magnetic field	0.991-0.150 T
Undulator parameter	9.24-1.39

EXPERIMENTAL RESULTS

Parameters of the ultrashort electron bunch generation are shown in Table 2. After acceleration with energy chirp, the bunch was compressed with magnetic chicane. The rms bunch length varied from picoseconds to tens of femtoseconds while the magnetic field of chicane changed[12]. We changed the chicane current so as to change the rms bunch length. For ultrashort Gaussian bunch, the total undulator radiation energy approximately scales like:

$$W \propto Q^2 \cdot \omega_0 \cdot \exp[-\omega_0{}^2 \sigma_t{}^2] \quad (3)$$

where W is the total radiation energy, Q is bunch charge, ω_0 is the radiation angular frequency, σ_t is the rms bunch length[4]. The total energy is related to bunch length and resonant frequency. At low frequency, the radiation energy is limited by diffraction effects while at high frequency radiation energy is limited by bunch form factor.

The total radiation energy measured as we scanned the undulator gap, i.e. the resonant frequency was shown in Figure 3. Simulation results of chicane compression from GENERAL PARTICLE TRACER (GPT) code[15] show that as chicane current increases, the bunch varies from under-compression through the point of full-compression and to over-compression. For under-compression status, the bunch distribution is Gaussian. The theoretical radiation energy of 100fs and 140fs Gaussian bunch are also shown for comparison with measurement. For shorter Gaussian bunch, the radiation energy peaks at higher resonant frequency. The measurement agreed well with theoretical results. The bunch length was shorter with chicane current 36A than 33A, so the peak energy appeared at higher resonant frequency. The measurement revealed that rms length of the ultrashort bunch of 220pC compressed by chicane in Tsinghua beamline was 120fs with uncertainty 20fs.

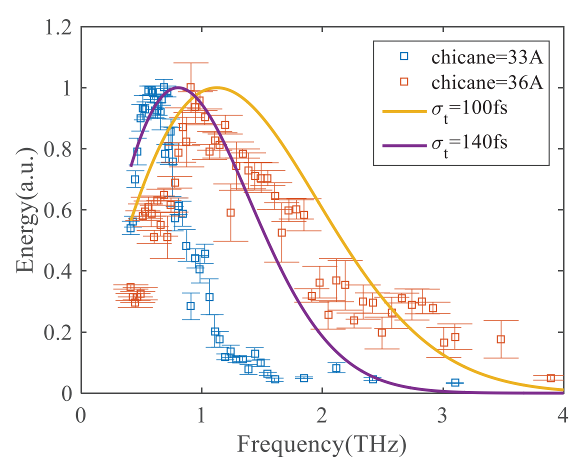

Figure 3: Radiation energy at different resonant frequency. The solid curves are the theoretical radiation energy of 100fs and 140fs Gaussian bunch predicted by theory.

Table 2: Parameters of Ultrashort Bunch Generation

Parameter	Value
Laser duration	8 ps (FWHM)
Phase of RF gun	30 °
TW accelerator phase	-45 °
Charge	220 pC
Bunch energy	28 MV

CONCLUSION

In this paper, ultrashort bunch length measured by undulator with widely tunable gap was demonstrated. The radiation energy was measured when undulator gap changed. The measured results agree well with theoretical predictions. During the experiment, the rms length of the bunch of 220pC compressed by chicane is 120fs with uncertainty 20fs. For the current undulator and beam energy, bunch length as short as 15fs can be measured. With optimized undulator for bunch length measurement, attosecond bunch measurement will be possible.

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