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Monitoring of electron bunch length by using Terahertz coherent transition radiation

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ABSTRACT

In this paper, ultrashort bunch length monitoring was demonstrated based on Terahertz (THz) coherent transition radiation (CTR) in Tsinghua Thomson scattering X-ray (TTX) source. The radiation produced by electron bunch is split into three paths: one of them is used to detect the total energy, while the other two paths are filtered with different THz band-pass filters before detection. The bunch length variation can be obtained by calculating the ratio between the filtered energy and the total energy. The bunch is compressed by a chicane and via changing the current of chicane, the ratio of filtered energy and total energy changed correspondingly. It is a simple supplemental approach to monitor the bunch length during beam conditioning and facility operation. Bunch arrival-time jitter and nonlinear effects in chicane are observed in the experiment during the measurement of filtered energy and total energy.

1. Introduction

Ultrashort electron bunches are required in various applications e.g. high gain free electron laser (FEL), wake field acceleration, ultrafast electron diffraction (UED), coherent transition radiation (CTR) and coherent synchrotron radiation (CSR) [1,2,3]. The bunch length of the ultrashort electron bunch can be measured and monitored by several ways. One way is to use a deflecting cavity to convert the longitudinal distribution into transverse coordinate [4]. Another common way, which is time consuming for the autocorrelation measurement, is to reconstruct the electron distribution by coherent transition radiation [5]. The electro-optic method [6] can measure the bunch length with the temporal resolution limited to 60 fs [7]. Electron bunch compression monitors based on CDR are studied in SwissFEL to monitor the bunch length as well as the RF phase [8].

In this paper, a simple method based on coherent transition radiation is used to monitor the bunch length in Tsinghua Thomson scattering X-ray (TTX) source. The bunch was compressed by chicane after 30° off the maximum acceleration in a 3 meters linac. The bunch length varied as the chicane current changed. THz transition radiation was generated when the ultrashort electron bunch cross the aluminium film and split into three paths. The total energy of one path and the energy of two different spectral region selected by band-pass filters were detected simultaneously. The ratio between the narrow band energy and the total energy is useful to reveal the bunch length and to monitor the facility working status, which will be discussed in detail.

The paper is structured as follows. The principle, the experimental methods are introduced in Section 2. The layout of the experiment and GPT simulation results are displayed in Section 3. Section 4 analyses the experimental results. In the end, a summary is given in Section 5.

2. Principle and experimental methods

2.1. Coherent transition radiation

Transition radiation (TR) is generated when a charged particle crosses the interface between two media even in the case of its rectilinear motion [9]. The TR is caused by a change in the optical properties of the medium along the path where the charge particle is moving. By solving the Maxwell equations, the transition radiation can be analysed by Ginzburg–Frank equation under the assumption of infinite size target, infinitely thin and ideally flat, perfectly conducting material and far-field radiation [11]. The spectral angular distribution of emitted radiation from a single electron is then described by the formula

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$$\frac{d^2 I_{sp}}{d\omega d\Omega} = \frac{e^2}{4\pi^3 \varepsilon_0 c} \frac{\beta^2 \sin^2 \theta}{(1-\beta^2 \cos^2 \theta)^2} \tag{1}$$

where θ is the angle measured against the backward direction, c is light velocity in vacuum, $\beta = v/c$. For relativistic electrons, the equation is a good assumption for inclined incidence as well and it is not related to frequency [9].

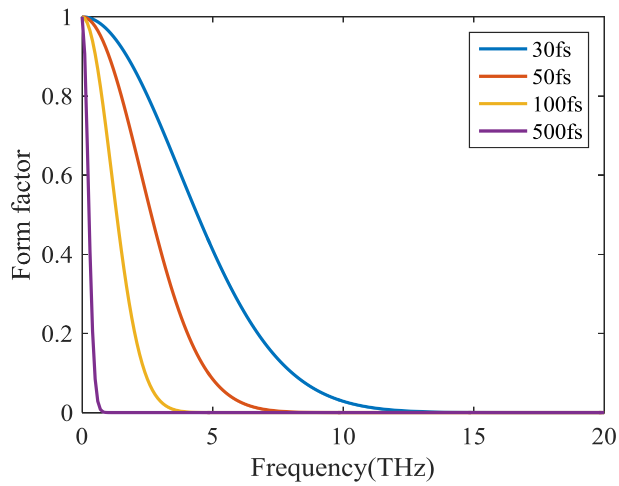

Fig. 1. Comparison of form factor of Gaussian distribution electron bunch with different rms bunch length.

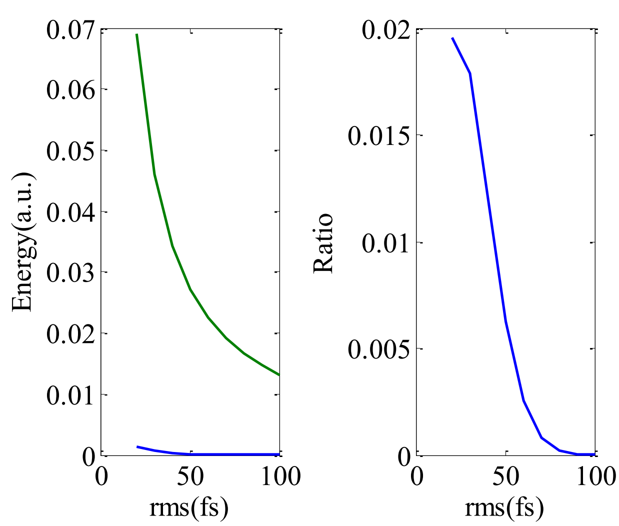

Fig. 2. (Left) Calculated results of total energy (green, integrated from 0.1 to 15 THz) and high frequency energy (blue, integrated from 4.9 to 5.1 THz) of CTR radiated by Gaussian bunch with different bunch length. The X-axis is the rms bunch length and Y-axis is the radiation energy. (Right) The ratio between high frequency energy and total energy mentioned above.

When the electron bunch length is comparable (or shorter) to the wavelength, coherent transition radiation is emitted. The energy spectrum of coherent radiation is expressed in

$$\frac{d^2 I}{d\omega d\Omega} = \frac{d^2 I_{sp}}{d\omega d\Omega}[N + N(N-1)F(\omega)] \tag{2}$$

where $\omega = 2\pi c/\lambda$ is the angular frequency of the emitted light, N is the number of electrons in a bunch. $F(\omega)$ is the bunch form factor, which can be defined as the square of the Fourier transform of the particle distribution within the bunch when the transverse size and observation angle are small [10]. In the setup, the transverse size is less than 100 μm and the observation angle is small thus the approximation is reasonable.

2.2. Bunch length vs radiation energy

As the energy spectrum of single electron transition radiation is independent from frequency, the total radiation energy of CTR is decided by form factor when bunch charge is constant. For Gaussian distribution with rms bunch length σ_t, the form factor is

$$F(\omega) = \exp\left[-(\omega\sigma_t)^2\right] \tag{3}$$

Form factor of different bunch length is shown in Fig. 1. The X-axis in Fig. 1 is frequency instead of angular frequency for convenience. For a Gaussian bunch of constant charge but different rms length, the high frequency energy and the ratio between high frequency energy and the total energy increase as the bunch length decreases, as shown in Fig. 2. It is obvious that the bunch longitudinal distribution has significant effects on the ratio. In our experiment, the ratio when bunch length changed at different R56 of chicane was measured.

3. Experimental layout and simulation results

Fig. 3 shows the main components of the experimental layout, which is part of the Tsinghua Thomson scattering X-ray (TTX) source. A modified version of the BNL/KEK/SHI type 1.6 cell photocathode radio-frequency (RF) gun and a 3 m SLAC-type traveling wave accelerating section are used to generate ultrashort, high charge, and low-emittance electron pulses [12]. A Ti:sapphire laser system generates ultraviolet driving laser for the photocathode RF gun. A chicane is installed to compress the bunch length. More detailed description of the whole system can be found in Refs. [13,14].

The THz generation and measurement setup is shown in Fig. 4. An Al film on YAG oriented at 45 degrees with respect to the beam line is installed to generate CTR, offering the possibility to measure CTR energy and beam size. After going through a diamond exit window, the CTR is filtered by a 14.3THz low pass filter from Tydex. An off-axis parabolic mirror (OAP2) is installed with the focal point at the CTR target to collimate the radiation. Two HRFZ-Si spliters (S1 and S2) split the radiation into three paths

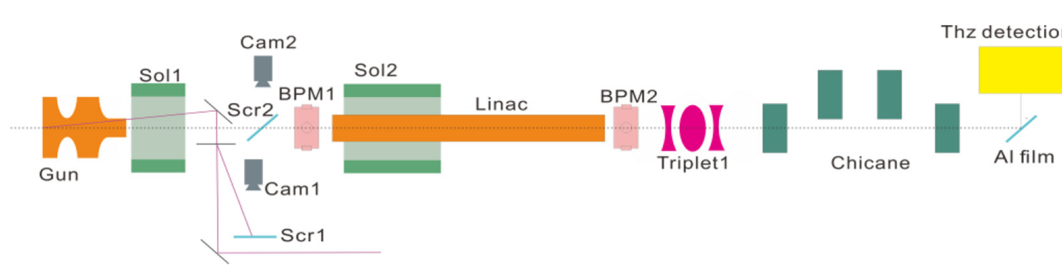

Fig. 3. Schematic of the beam line for Terahertz CTR.

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