10S FEMTOSECOND BUNCH LENGTH MEASUREMENT BASED ON COHERENT TRANSITION RADIATION*

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Abstract

In this paper, we discuss bunch length measurement based on coherent transition radiation for 10s femtosecond electron bunches with of several MeV energy and several pC charge. The ultrashort bunch length is obtained by velocity bunching using a compact dual slot resonantly coupled linac located after an RF photoinjector. Strong focusing with a solenoid is required to enhance the radiation generation. Filters are used to reconstruct coherent transition radiation spectrum. The transverse and longitudinal form factors are also studied with simulation.

INTRODUCTION

Bunch length measurement is a basic issue in beam diagnostic. Traditional methods for bunch length measurements includes using deflecting cavity[1], using radiation based spectrum methods[2] and electro-optic detection methods[3]. By using velocity bunching method, sub picosecond or 10s femtosecond bunch can be generated in several MeV energy and several pC charge regime, for applications such as ultrafast electron diffraction and Thomson scattering. To measure the bunch length at the maximum compression plain, coherent transition radiation (CTR) method is more appropriate than direct methods using deflecting cavity, since the latter measurements are extended in z and can only give an estimate for the average bunch length over the measurement distance. Another advantage of using CTR method for measuring ultrashort bunch is the energy of coherent transition radiation increases significantly as the bunch length decrease, which is favorable to detection.

In this paper, we discuss a bunch length measurement method based on coherent transition radiation, for 10s femtosecond electron bunch length obtained by velocity bunching using a linac. The method and setup are described in the following section. In the end, preliminary experimental results are also presented.

METHOD

For transition radiation generated by electron crossing metal boundary, the process can be viewed as collision process of electron with its image charge. The spectrum and angular distribution of energy generated in the collision can be obtained by calculating the Lienard-Wiechert potential as [4]:

$$\frac{\mathrm{d}E_s}{\mathrm{d}\omega\cdot\mathrm{d}\Omega}=\frac{e^2}{4\pi^2c^3}\left(\frac{\vec{v}\times\vec{n}}{1-\vec{n}\cdot\vec{v}/c}-\frac{\vec{v'}\times\vec{n}}{1-\vec{n}\cdot\vec{v'}/c}\right)^2, \quad (1)$$

where E_s is the radiation energy of single electron,ω is the angular frequency of radiation, Ω is the solid angle, e is the charge of electron, c is the speed of light in vacuum, $\vec{n}$ is the direction of radiation, $\vec{v}$ and $\vec{v'}$ are the velocities of electron and its image charge. It is noted that the angular distribution does not depend on frequency. For a 45 degree collision, the velocity $\vec{v}$ and $\vec{v'}$ are determined by the setup, then we can calculate the energy distribution by integrating over the solid angle collected by an off axis parabolic (OAP).

The total radiation energy of a bunch E_b is the sum of single electrons, taking consideration of phase effect into account. The expression can be written as:

$$\frac{\mathrm{d}E_b}{\mathrm{d}\omega\cdot\mathrm{d}\Omega}=|N\cdot f(\omega)|^2E_s(\omega) \quad (2)$$

$$=\frac{e^2|N\cdot f(\omega)|^2}{4\pi^2c^3}\left(\frac{\vec{v}\times\vec{n}}{1-\vec{n}\cdot\vec{v}/c}-\frac{\vec{v'}\times\vec{n}}{1-\vec{n}\cdot\vec{v'}/c}\right)^2, \quad (3)$$

where $f(\omega)$ is the coherent factor. When the longitudinal size of bunch is much longer than the transverse size and the radiation are concentrated in small angle around beam axis, transverse coherent effect can be neglect and the coherent factor can be written as:

$$f(\omega)=f_L(\omega)=\frac{1}{N}\sum_{j=1}^{N}e^{i\omega t_j}\cong\int_{-\infty}^{+\infty}\rho(t)e^{i\omega t}\mathrm{d}t, \quad (4)$$

where $\rho(t)$ is the normalized distribution function. For wavelength longer than bunch length, the field created by electrons are coherent and the total energy is proportional to the square of number of electrons. In the case of low energy bunch and comparable transverse bunch size and longitudinal size multiplied by γ ($\sigma_x \backsimeq \gamma\sigma_z$), the effect of transverse size of bunch should not be neglected. For a numerical example, the wavelength of CTR corresponding to 40 fs bunch ranges around 12 μm, assuming the transverse spot size is 100 μm, when viewed at the angle larger than 7 degree from the axis, the maximum phase difference of radiation emitting from different transverse position can be larger than one period. Then the coherent factor should be written as:

$$f(\omega)=f_L(\omega)f_T(\omega), \quad (5)$$

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with the transverse coherent factor as:

$$f_T(\omega) \cong \int_{-\infty}^{+\infty} \tilde{\rho}(r) e^{i\omega(\vec{r}\cdot\vec{n}/c)} \mathrm{d}t, \qquad (6)$$

where $\vec{r}$ and $\tilde{\rho}(r)$ are the transverse position and transverse normalized distribution function respectively. To consider the exact coherent effect, we calculate both the longitudinal and transverse coherent factor at given wavelength and angle, for different spot size and different bunch length (assuming Gaussian profiles). Then we integrate the total energy over the solid angle (within 30 degrees from beam axis) and 10 % frequency (FWHM) using numerical method. The result of integration is displayed in Fig. 1.

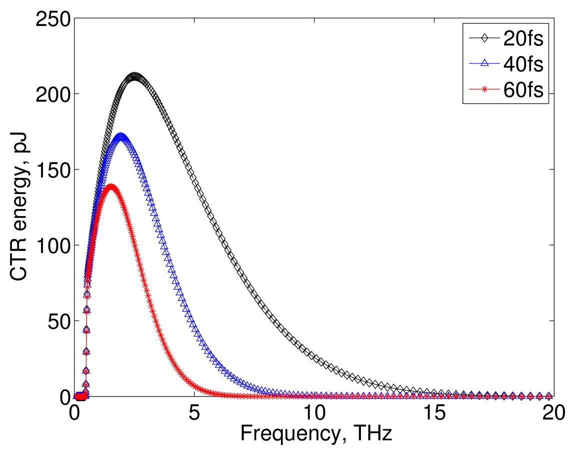

Figure 1: CTR spectrum for rms bunch length of 20 fs, 40 fs, 60fs of energy of 5 MeV, charge of 3 pC and rms spot size of 50 μm.

Figure 1 shows the CTR energy at 3∼5 THz is sensitive to the length of bunch, while the energy at low frequency (1 THz) is relatively insensitive. This characteristic implies we can use the ratio of high frequency CTR energy over low frequency one as a measurement of bunch length.

SETUP

Ultrashort Bunch Generation

The schematic of beam line is shown in Fig. 2. The first solenoid (soleA) right after RF gun is used to match the beam into a standing wave linac, which is operated at compressing phase. After the linac, the bunch drifts and compresses at the CTR target about 1.6 m downstream. The phase of linac determines the compressed point, which should be set coincident with the plain of CTR target. A second solenoid(soleB) is placed about 0.4 m upstream the CTR target to focus the beam to a minimal spot size on CTR target to enhance the transverse coherent effect. The CTR target is a 1/10 wavelength gold mirror of 1cm × 1cm, which can be treated as an infinity perfect boundary for electron of several MeV energy. The distance of CTR target from the cathode of RF gun is 3.78 m.

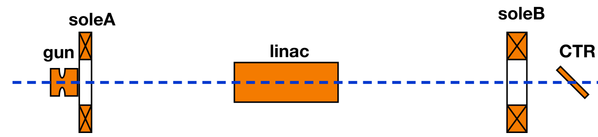

Figure 2: Schematic of beam line.

The energy and energy spread of the linac is calculated with GPT[5], shown in Fig.3. It shows the bunch is compressed to the minimal length at linac phase about 77 degree off crest. The minimal rms bunch length that can be achieved is as low as 21 fs. At the same time the second solenoid can be tuned to achieve spot size of rms 30 μm. It should be noted that there is a tradeoff between the smallest spot size and shortest bunch length, since it is easier to compress or focus in one dimension with a low charge density of the other dimension.

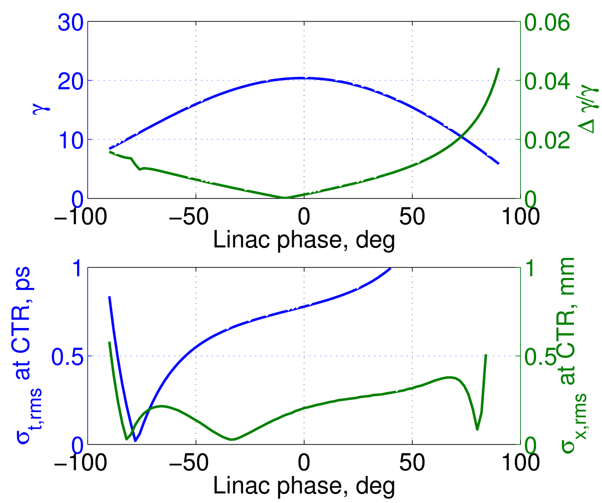

Figure 3: Energy, energy spread, spot size and bunch length with respect to linac phase.

CTR Collection and Spot Size Measurement

The whole setup of CTR collection is placed in a vacuum chamber. A moveable stage can insert the CTR target or a YAG screen onto the beamline. The thickness of YAG is 30 μm with spatial resolution smaller than 5 μm [6]. The measurement of spot size is important for deriving the bunch length. A 90 degree, 1 inch diameter OAP with parent focal length of 1 inch is well aligned and mounted near the CTR target. Two 1.5 inch diameter THz mirrors are used to guide the parallel radiation to a 3 inch diameter OAP with parent focal length of 6 inches. The focused radiation after second OAP passes through a 3 mm thick TPX window[7] on the wall of vacuum chamber and collected by a pyroelectric detector. Filters of different wavelength can be inserted before the detector.

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RESULT AND DISCUSSION

In the first round experiment, the energy of signal is sufficient to be detected with a pyroelectric detector with sensitivity of 0.3 mV/nJ. A solenoid scanning is performed and the total CTR energy is measured under 20 pC charge. The result is shown in Fig. 4.

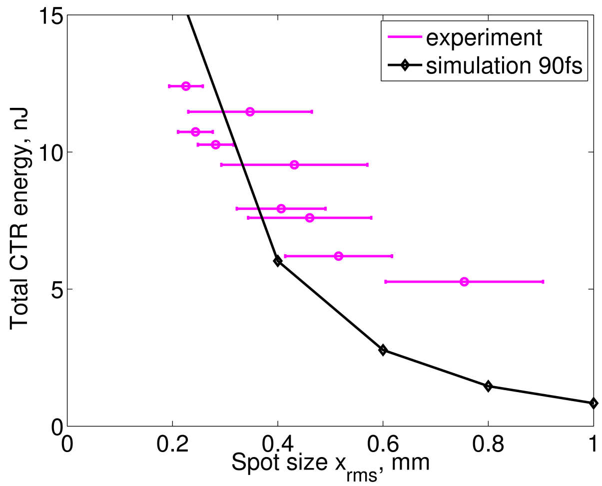

Figure 4: Total CTR energy detected with respect to rms spot size at CTR target under 20 pC charge.

Figure 4 show the total energy decreases as spot size increase, which is in consistent with the degraded transverse coherence of the bunch. However, since this total energy is not sensitive to bunch length, we can estimate a longitudinal bunch size larger than 10s fs order. With lower charge of 5 pC, linac phase scanning is also performed to study the effect of velocity compressing, shown in Fig. 5. Figure 5 shows the compressing point is important to generate CTR.

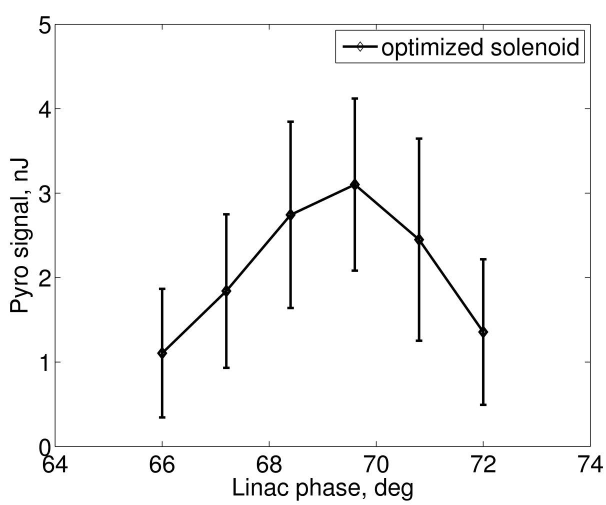

Figure 5: Total CTR energy detected with respect to phase of linac.

Large error bars in both Fig. 4 and Fig. 5 show instability of spot size and CTR energy. This is caused by the jitter of RF system, especially the jitter of gun phase, resulting in the mismatch of compressing point and CTR target. Another challenge is that the calibration of the transmission and detection efficiency for different wavelength. A second round experiment is planned to use more sensitive detectors for lower charge bunch, aiming at measuring the ratio of CTR energy at different frequency and deriving ultrashort bunch length.

CONCLUSION

In this paper, we discuss an CTR based bunch length measurement method for 10s fs bunch of several MeV energy and several pC charge. The CTR energy spectrum is precisely calculated using numerical integration method, considering transverse and longitudinal coherent effect. A relative CTR component ratio measurement is proposed to derive bunch length. Simulation is performed and predicts compressed bunch length of 20 fs (rms), with spot size of 30 μm (rms) at the CTR target. The preliminary experiment shows significant dependence of total CTR energy on spot size and linac phase.

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