Bunch length measurement at Tsinghua Thomson scattering X-ray source*

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Abstract: The length of electron beam from a photocathode RF gun is determined by a spectrometer, according to the relative energy spread induced by the bunch length during the acceleration in a linac. For a photocathode RF gun, different laser injected phase and beam charge are studied. The compression is changed for the different laser phases, as from 10° to 30°, and the bunch length is lengthened due to the strong longitudinal space charge force, caused by the increased charge.

Key words: bunch length measurement, energy spread, photocathode RF gun

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1 Introduction

In recent years, motivated by dynamic studies of a variety of physical, chemical, and biological process with a temporal resolution of several hundreds of femtoseconds, the fundamental time scale of atomic motions [1], interest in the development of the next generation X-ray light source, which aims to achieve picosecond and sub-picosecond hard X-ray pulses, is rapidly growing. Several concepts or methods, such as Ka X-ray source with an intense laser [2], X-ray FEL [3, 4], synchrotron radiation with slicing technique [5], and Thomson scattering (or inverse Compton scattering) by a relativistic electron beam [6], have been proposed and demonstrated to generate suitable X-ray pulses. Among these sources, the X-ray source based on Thomson scattering may lead to a novel femtosecond time light source facility. It can generate ultra-short, high flux, monochromatic and tunable hard X-ray pulses, and provide a means of performing hard X-ray pump-probe experiments on a sub-picosecond time scale. And compared with the X-ray FEL facility and the synchrotron light source, it is more compact and affordable, and can generate more hard X-rays. Enticed by these prospects, the Accelerator Laboratory of Tsinghua University proposed the Tsinghua Thomson Scattering X-ray Source (TTX) in 2001 [7].

A high quality electron beam with high charge, low emittance and short bunch length is crucial for a Thomson scattering X-ray source. Especially for ultra-short X-ray pulse generation, the bunch length should be subpicosecond [8]. Generally, such an electron beam is generated with a photocathode RF gun and accelerated to the expected energy with linac sections. The transverse and longitudinal properties from the photocathode RF gun determine the beam qualities exiting the linac. While the transverse emittance exiting the gun is studied extensively, the longitudinal distribution is still poorly understood.

The longitudinal distribution exiting the gun is influenced by several factors. The drive laser and the photoemission process on the cathode determine the beam's initial distribution near cathode. For normal cathode material, such as copper and magnesium, the photoemission time is several femtoseconds, which is much shorter than the drive laser pulse duration, therefore the initial bunch distribution is the same as

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the drive laser. The photoelectrons are accelerated to relativity in a short distance by a high RF field, and compressed during acceleration [9, 10]. The longitudinal space charge force also affects the beam's longitudinal distribution. It increases the energy spread and elongates the bunch length.

In this paper, the bunch length exiting the gun at TTX is measured by a simple method, which uses a spectrometer to measure the time correlated relative energy spread. We study the bunch compression in the gun with different laser injected phases, and the bunch lengthening due to the longitudinal space charge force. The method and experimental setup are described in Sec. 2. The bunch length with the different laser injected phases and the beam charge are measured. The experimental results are given in Sec. 3 and some conclusions are drawn in Sec. 4.

2 Description of the experiment

The TTX beam line is shown in Fig. 1. It consists of a 1.6 cell S-band photocathode RF gun of the BNL/KEK/SHI type, a 3 m SLAC section, a spectrometer for energy spectra measurement, three quadrupole magnets, and some YAG screens for beam profile measurement. The laser system is a Ti: Sapphire CPA laser with a regenerative amplifier, and two multi-pass amplifiers, which provide both the drive UV pulse for the photocathode and the 800 nm IR pulse for Thomson scattering. The UV laser pulse irradiates the cathode nearly perpendicularly and generates electron pulses with corresponding spatial distribution. The laser system and the RF system are synchronized through a timing circuit with a timing jitter of less than 500 fs.

In the experiment, the linac operation phase strays away from the minimum energy spread phase, which can introduce a time-correlated energy deviation along the beam bunch. The corresponding energy spread is measured with a spectrometer. Based on the achieved energy spectra, the bunch length could be determined.

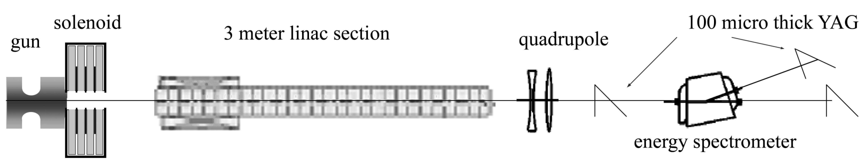

Fig. 1. A schematic drawing of the TTX beam line.

The analytical expression for bunch length can be derived as a function of the linac phase and the measured relative energy spread. Assuming the linac with a simple $V_{\rm linac}\cos\phi_0$ energy boost to the bunch, the R-matrix of the linac is

$$R_{\rm linac}=\begin{pmatrix}1 & 0\\ -V_{\rm linac}\sin\phi_0 & 1\end{pmatrix},$$

where ϕ_0 is the phase of the reference electron at the bunch center. The transformation of the beam matrix through the linac is given by

$$\tau(1)=R_{\rm linac}\tau(0)R^{\rm T}_{\rm linac}, \qquad (1)$$

where

$$\tau=\begin{pmatrix}\tau_{11} & \tau_{12}\\ \tau_{12} & \tau_{22}\end{pmatrix}$$

is the beam matrix, which defines the longitudinal ellipse, $\tau_{11}=\sigma_t^2$ and $\tau_{22}=\sigma_E^2$ are the rms bunch length squared and the rms energy spread squared, respectively. Multiplying the matrices gives the rms energy spread exiting the linac,

$$\sigma_E^2=\tau_{22}(0)-2\tau_{12}(0)V_{\rm linac}\sin\phi_0+\tau_{11}(0)(\sin\phi_0)^2. \quad (2)$$

Assuming the intrinsic energy spread or the width of the longitudinal ellipse can be neglected compared with the total energy spread, the energy deviation of an electron in the linac entrance can be written as $\delta_E=k\Delta z$, where Δz is the distance to the reference electron, and k is the slope of the longitudinal phase space ellipse. Therefore, the rms energy spread at the linac exit can be written as $\sigma_E=\sigma_t V_{\rm linac}\sin\phi_0+k\sigma_t$, and the relative energy spread is

$$\sigma_t\frac{V_{\rm linac}\sin\phi_0+k}{V_{\rm linac}\cos\phi_0+E_0},$$

where E_0 is the beam energy at the entrance of the linac.

At the exit of the spectrometer, the beam size is given by

$$\Omega=\sqrt{\beta\varepsilon+\eta^2\frac{(\sigma_i^2+\sigma_E^2)}{(V_{\rm linac}\cos\phi_0+E_0)^2}}, \qquad (3)$$

where β is the Courant-Snyder β function, η is the dispersion function at the spectrometer viewer, and σ_i and σ_E are the intrinsic and bunch length induced energy spreads, respectively. By tuning the quadrupole magnets upstream, the dipole magnet to produce a small value of the β function, the beam size due to its transverse emittance is negligibly small compared with that due to the relative energy spread. And the intrinsic energy spread is usually much smaller than the bunch length induced energy spread. Then the transverse rms beam size Ω measured at the spectrometer can be written as

$$\Omega=\sigma_t\eta\left(\frac{V_{\rm linac}\sin\phi_0+k}{V_{\rm linac}\cos\phi_0+E_0}\right), \tag{4}$$

$V_{\rm linac}$, E_0 and ϕ_0 can be experimentally determined in experiment, but k is unknown. To overcome this problem, the profiles are measured at ϕ_0 and $-\phi_0$ of the RF waves, which alter the sign of correlated energy spread from the linac. Therefore, the rms bunch length is

$$\sigma_t=\Omega^+\frac{V_{\rm linac}\cos\phi_0+E_0}{\eta(V_{\rm linac}\sin\phi_0+k)}=\Omega^-\frac{V_{\rm linac}\cos\phi_0+E_0}{\eta(V_{\rm linac}\sin\phi_0-k)}, \tag{5}$$

where Ω^+ and Ω^- are the measured rms beam size with the linac phase at $+\phi_0$ and $-\phi_0$, respectively. Notice that all rms values are positive and $V_{\rm linac}\sin\phi_0$ is usually larger than $|k|$. Therefore the rms length and the initial correlated energy spread are given by

$$\sigma_t=\frac{(\Omega^++\Omega^-)(V_{\rm linac}\cos\phi_0+E_0)}{2\eta V_{\rm linac}\sin\phi_0}, \tag{6}$$

and

$$|k| = \frac{(\Omega^+-\Omega^-)(V_{\rm linac}\cos\phi_0+E_0)}{2\eta\sigma_t} = \frac{(\Omega^+-\Omega^-)}{(\Omega^++\Omega^-)}V_{\rm linac}\sin\phi_0. \tag{7}$$

The sign of phase space slope can be determined from the sign convention of the RF wave.

Similarly, the longitudinal distributions can also be derived from the measured beam profiles at the spectrometer using the corresponding correction factor given by Eq. (6). In practice, these distributions from both cases are usually different, which should be identical in principle. The differences between the two distributions result from the deviations of the assumptions from the real distributions, and these can be used to evaluate the error of the measurement.

We test the formula and measurement procedure using PARMELA computer simulations. The numerical measurement results and the simulated bunch lengths are in excellent agreement over bunch length in the range of 100 fs to several ps, with less than 8% offset while the space charge effect can be estimated, indicating that the assumptions are good.

3 The experimental results

During the measurement, the RF field on the photocathode RF gun cathode is ~70 MV/m and the electron beam energy at the linac entrance is about 3 MeV. The rms duration of the drive UV laser is 2.4 ps. The energy boost of the linac measured by the spectrometer is 29.0 MeV, and the maximum energy gain is used to define the zero RF phase. The beam profiles are measured with linac phase $-24°$ and $24°$ off crest.

It should be noticed that there is about 5°–7° phase slippage during acceleration in the linac, which simply shifts the $V_{\rm linac}\cos\phi_0$ RF waveform by this amount in phase. However, this slippage has little effect on the measurement results, since the maximum energy gain is used to define the zero RF phase. The Parmela simulation also indicates approximately 5%–10% change in pulse length during acceleration, it has little effect on the length measurement since the elongation or compression is canceled in Eq. (6), but it has a significant impact on the results of the correlated energy spread.

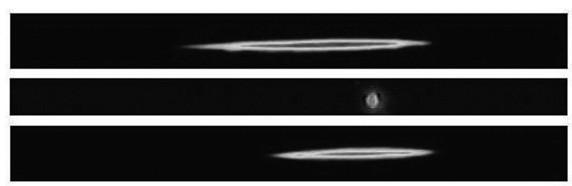

Fig. 2. Typical beam profiles measured on the spectrometer viewer. A high energy electron is on the right. Top: linac phase is 24°. Middle: linac phase is on the crest. Bottom: linac phase is −24°.

The typical measured profiles are shown in Fig. 2. This clearly shows that the transverse beam size with the linac phase on crest is much smaller than that with the linac phase at $+\phi_0$ or $-\phi_0$. This means that the transverse beam size due to transverse emittance and intrinsic spread can be ignored, and this is consistent with the assumptions.

We first measured the lengths of electron beams with different laser injected phase. The bunch charge is controlled to less than 3 pC in the measurements to eliminate the space charge effect. Fig. 3 presents the measurement results. The phase convention in Fig. 3 is zero degree corresponding to zero field, and the electron acceleration increases with the phase. Fig. 3 shows that the bunch is compressed in the gun, since the electron at the bunch tail is accelerated with higher RF field and becomes relativistic in a shorter time than that at the bunch head. We are also able to observe less electron beam bunch compression with higher laser injected phase since the RF field deviation between the bunch head and tail is smaller with higher launch phase. The simulation result is also shown in Fig. 3, and it agrees well with the measurement result. The slight deviations may be due to the different parameters for the measurement and the simulation, such as the pulse duration of the drive laser, the field gradient in the gun and linac, and the uncertainty for linac phase determination. Another possibility is an imbalance in the RF fields between the half and full cells. All effects are being investigated.

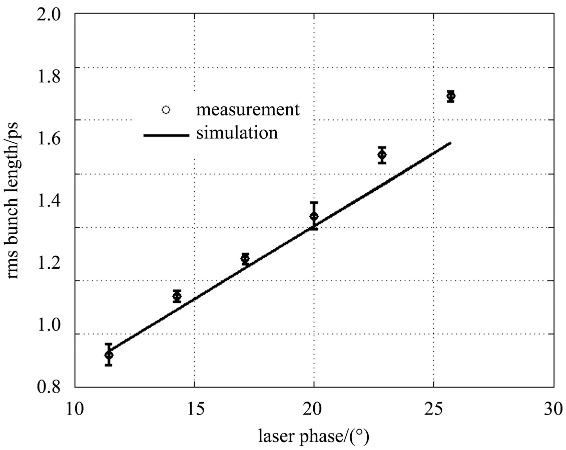

Fig. 3. The bunch length versus the laser incident phase, where the circles are from measurement, and the line curve is from simulation. The zero phase corresponds to the zero RF field.

Figure 4 shows the dependence of the bunch length on the bunch charge. The bunch length is seen to grow linearly with charge. The strong growth is due to the strong longitudinal space charge force. The space charge force increases the electron energy at the bunch head and decreases the electron energy at the tail. Such energy modulation induces a slight speed difference between the head and the tail, and elongates the bunch length while the beam is transported in the beam line. This elongation is approximately proportional to $1/\gamma^5$, where γ is the beam energy at the gun exit, and the elongation can be effectively suppressed by increasing the peak RF field in the gun to improve the beam energy.

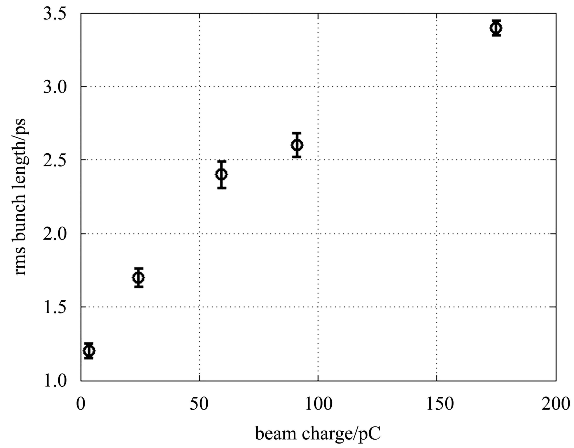

Fig. 4. The bunch length versus the beam charge. The bunch shows the compression below and the elongation above 60 pC. The laser is injected at 20°.

4 Conclusion

In summary, the bunch length at the linac entrance is measured with the spectrometer in the beam line. The measurement results are in agreement with the simulations and consistent with the deflecting cavity measurements. This provides a simple and easy way to determine the longitudinal bunch distribution and bunch length with common devices, and has played a crucial role at TTX in beam diagnosis.

Obvious compression at low laser injection phase is observed while the space charge effect can be eliminated. This can be used to generate ultra-short electron bunches (less than 100 fs), which are necessary for ultra-fast electron diffraction, ultra-short X-ray sources, and so on. The elongation by the strong longitudinal space charge effect is also observed when the bunch charge increases. The gun peak acceleration field should be increased up to 100 MV/m to weaken the elongation, when a large charge bunch is necessary.

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