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INTERFEROMETRIC MEASUREMENT OF BUNCH LENGTH OF A 3 MeV PICOCOULOMB ELECTRON BEAM*

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Abstract

We report the bunch length measurement of low-energy 3 MeV electron beams in picosecond regime with the charge from 1.0 to 14 pC. It is the first time that we demonstrate single-cycle nano-joule coherent terahertz (THz) radiation from 3 MeV electron beam can be measured *via* a far-infrared Michelson interferometer using a QOD. At this low energy range, when charge is about 1 pC, the signal from the conventional helium-cooled silicon composite bolometer is too low. Compared to the bunch length measurement *via* the ultrafast-laser-pump and electron-beam-probe in the timescale 10^{-14} to 10^{-12} s which is determined by the phase-transition dynamics in solids, the advantages are: there are no needs of pump laser and probe sample, greatly simplifying the experiment; the timing jitter between laser and electron beams contributes no error to the bunch length measurement; furthermore, the method can be extended to sub-picosecond regime enabling bunch length measurement in a much broader timescale 10^{-14} to 10^{-11} s for low-energy electron beams. In the current experiment the bunch length is limited to 1 ps only because the setup of driving laser to cathode with a large 70° incident angle, effectively lengthening the laser pulse to ≥1 ps.

INTRODUCTION

In recent years, there has been a growing interest in developing a single-shot mega-electron-volt ultrafast-electron-diffraction (UED) system. UED takes advantage of the strong interaction between electrons and matter and minimizes space charge problems [1-6]. Much finer structural details can be resolved compared to X-rays due to the 1000-fold shorter wavelength of electrons. Single-shot UED enables us to see how atoms in molecules move and allows us to make molecular movies of ultrafast chemical reactions. 3 MeV electron bunches with charges up to 14 pC ($0.9\cdot10^8$ electrons) focused to 75 µm beam size using a broadly tunable transverse focusing system have been demonstrated at Brookhaven National Laboratory (BNL) [7]. This tunable system used electromagnetic quadrupole lenses to significantly improve ultrafast electron diffraction and imaging instrumentation, achieving an electron beam intensity several orders of magnitude higher than current technology (~10^4-10^5 electrons) [8-12].

To characterize the brightness of an electron beam in 6D phase space, we need a complete set of diagnostics tools measuring the transverse beam size and divergence, longitudinal bunch length and energy spread. The space charge effects lead to the bunch lengthening with the charge. Therefore, bunch length measurement is critical to understand the space charge effect.

MEASUREMENT TECHNIQUE

Several techniques have been developed to measure the bunch length of low-energy and low-charge electron beams. Recently, bunch length measurements using the ultrafast-laser-pump and electron-beam-probe in the timescale of 10^{-14} to 10^{-12} s have been reported [8,13,14]. We measured the bunch length of a 3 MeV picocoulomb electron beam using a far-infrared Michelson interferometer and a QOD [15]. The signal-to-noise ratio (SNR) of the QOD in the THz frequency range is thirty-times higher compared to the conventional bolometer. The measured bunch length in recent experiment is in the range of a few picoseconds.

The advantages of using the interferometer compared to the pump and probe method are:

- The experimental setup is greatly simplified because there is no need for a pump laser and a probe sample.
- The timing jitter between the laser and electron beams contributes no error to the bunch length measurement.
- The method can be easily extended to sub-picosecond regime enabling the bunch length measurement in a much broader timescale from 10^{-14} to 10^{-11} s for low-energy low-charge electron beams.

The electron bunch length in our experiment was larger than 1 ps due to the effective length of the laser pulse. The incident angle of the drive laser pulse is 70° to the photocathode causing different parts of the wave-front to arrive at the photocathode at different times. This makes the electron bunch longer than the laser pulse. This effect can be corrected by compensation optics which have not been implemented at the Accelerator Test Facility II (ATF-II) at BNL. The electron bunch length can be varied by changing the laser spot size on the photocathode. Details will be described later in the paper.

EXPERIMENTAL RESULTS

The bunch length measurement presented in this paper was developed at the ATF-II at BNL. The schematic diagram is shown in Fig. 1. A frequency tripled Ti:sapphire laser pulse at 265 nm is sent to the copper photocathode to produce photoelectrons. The electron beam interacting with an aluminum (Al) target shown in Fig. 1 generates a single-cycle sub-nanojoule coherent THz pulse. The charge of a 3 MeV electron beam can be varied from 1 to 14 pC by changing

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the drive laser energy. The THz pulse is extracted from the accelerator vacuum pipe through a 35-mm diameter high density polyethylene window with the transmission >90% in the THz frequency range [16]. The divergent THz radiation is collimated by a parabolic mirror with f = 152 cm into a parallel beam entering the far-infrared Michelson interferometer. In the interferometer, the THz pulse is split into two pulses by a 50/50 beam splitter (BS), and one pulse is delayed by a variable interval τ with respect to the other. The two pulses are then recombined and detected by the QOD. Only half of the incident energy goes into the QOD, while the other half is lost. If the path-length difference is greater than the bunch length, the detected intensity is constant, called the baseline. If the path-length difference is less than the bunch length, the intensity varies about the baseline. The detected intensity as a function of the delay τ is defined as the interferogram. The width of the peak in the interferogram can be used to estimate the bunch length [17-21]. For a Gaussian beam, the bunch length σ_t is determined by (interferogram FWHM)/$\sqrt{2\pi}$.

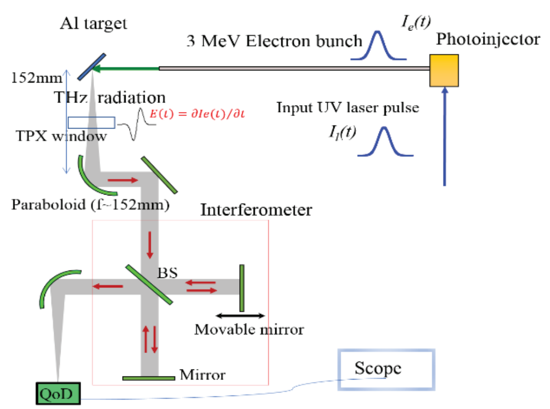

Figure 1: Schematic of the bunch length measurement setup. TPX represents high density polyethylene.

We numerically studied whether the QOD frequency response distorted the interferogram. The QOD response is shown as red curves in the right column of Fig. 2. We compared the calculated interferograms with two different bunch lengths, corresponding to the minimum 1.8 ps (top row) and maximum 4.5 ps (bottom row) of measured bunch lengths. At every bunch length, the interferograms were calculated in two different conditions, the QOD frequency response (blue curves in the left column) and the response of a bolometer in the THz frequency range (red curves in the left column). The interferograms shown in Fig. 2 indicate that the QOD response does not influence the bunch length measurement result.

For 10 pC, the signal at the peak of the interferogram measured by the QOD was 500 mV and the signal measured by the bolometer was 15 mV. The noise level for both detectors was about 5 mV. The bolometer doesn't have an adequate SNR to measure the interferogram. Usually SNR > 5 is needed.

We measured the bunch length at two different laser sizes Σ_x on the photocathode, 707 μm and 289 μm in full width half maximum (FWHM). The formula $\Sigma_{t,laser} = \Sigma_x \cdot \sin\theta / c$ is used to estimate the effective laser pulse length of 2.21 ps (Fig. 3) and 0.902 ps (Fig. 4) respectively. The effective laser pulse length is dominated by the lengthening effect for a very short laser pulse of 100 fs. $\theta (= 70°)$ is the incident angle of the drive laser pulse to the cathode. c is the speed of light. The minimum bunch length of 1.8 ps was obtained with a laser spot size of 707 μm on the cathode and a charge of 1 pC. The interferogram and its Fourier transform are shown in Fig. 3(a) and 3(d). Fig. 3(b) and 3(c) show the corresponding interferograms of 2 pC and 14 pC charges respectively. Their Fourier spectra are shown in Fig. 3(e) and 3(f). The case with a laser spot size of 289 μm is shown in Fig. 4.

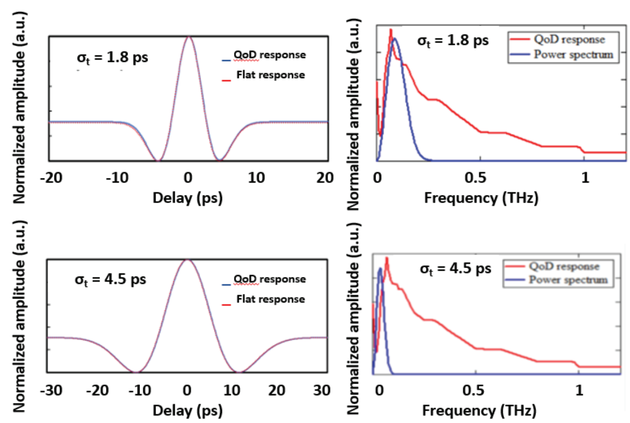

Figure 2: Simulated interferograms (left column) and their Fourier spectra (blue curves in the right column) at two different bunch lengths: 1.8 ps (top row) and 4.5 ps (bottom row). For each bunch length, the interferograms with the QOD response (blue) and with the response of a bolometer (red) are plotted. The QOD frequency response is plotted as blue curves in the right column.

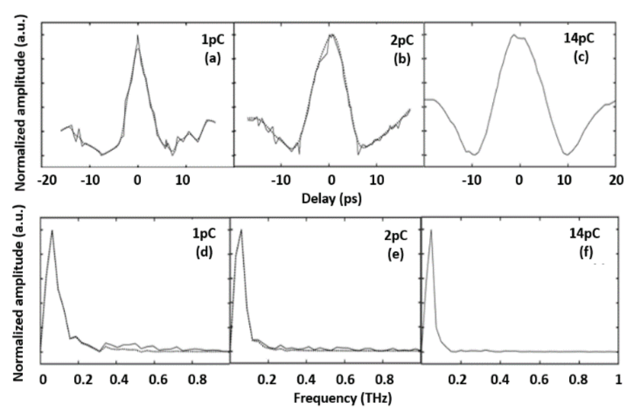

Figure 3: In the case with a laser size of 707 μm on the cathode, the measured field autocorrelation of THz radiation for the charge 1pC (a), 2pC (b), 14pC (c), and their corresponding Fourier spectra of 1pC (d), 2pC (e), 14pC (f).

To study the space-charge effect, we chose the highest charge (14 pC) at the effective laser pulse length of 2.21 ps compared to 7.6 pC at the effective laser pulse length of 0.902 ps. The measured bunch lengths were similar 4.3 ps

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and 4.5 ps [22]. The final bunch length of a high charge electron beam is primarily determined by the space charge effect. Increasing the laser spot size on the cathode reduces the charge density and mitigates the space charge effects. We observed less bunch lengthening in the 707 µm laser size case with the effective laser pulse length of 2.21 ps. Detail studies of the electron beam dynamics are beyond the scope of our paper.

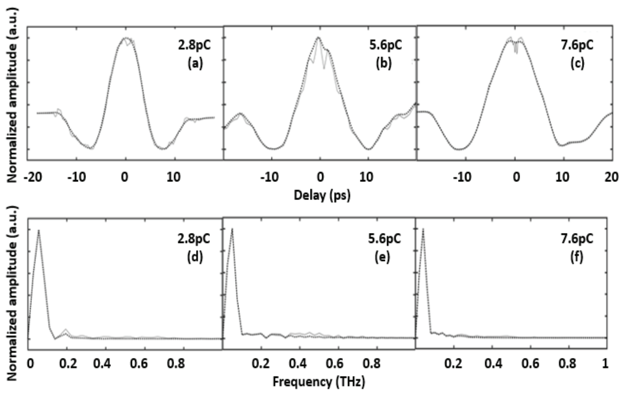

Figure 4: In the case with a laser size of 289 µm, the measured field autocorrelation of THz radiation for the charge 2.8pC (a), 5.6pC (b), 7.6pC (c), and their corresponding Fourier spectra of 2.8pC (d), 5.6pC (e), 7.6pC (f).

Spectral widths in FWHM and spectral peak positions of the Fourier transform of calculated and measured interferograms agree reasonably well. The bunch lengths of the electron beams at two different laser sizes on the cathode 707 µm (blue) and 289 µm (red) as a function of the charge are plotted in Fig. 5.

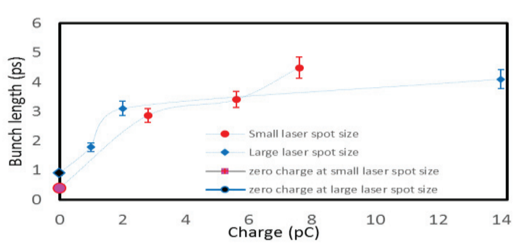

Figure 5: The bunch lengths of electron beams at two different laser sizes on the cathode 707µm (blue) and 289µm (red).

CONCLUSION

This experiment demonstrated for the first time the bunch length measurement of a 3 MeV electron beam with a charge of from 1 to 14 pC using the interferometric method. The picosecond bunch length (1.8 to 4.5 ps) is limited by the current cathode drive laser setup. A room-temperature QOD is critical for success. Not only does the QOD have more than 30 times higher SNR in the THz frequency range, more importantly, it doesn't require any liquid-helium cooling like a bolometer, greatly simplifying the experiment. Compared to the bunch length measurement by the ultrafast-laser-pump and electron-beam-probe, the advantages of using interferometer are: the experimental setup is simple; no measurement error caused by the timing jitter between laser and the electron beams; the method can be easily extended to sub- to tens- picosecond range. In the future, a single-shot bunch length measurement is possible with modifications to the interferometer and the use of a 1D array of QODs [23].

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