PHOTO-ELECTRON BEAM LONGITUDINAL PHASE SPACE TOMOGRAPHY STUDIES AT THE ATF

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Abstract

The longitudinal phase space distribution of electron beam plays critical role in ultra-short electron bunch production, coherent radiation, free electron laser (FEL) and many other applications. Photocathode RF gun is capable of controlling not only the transverse emittance of electron beam, but also longitudinal emittance. The longitudinal phase space distribution of photoelectron beam was investigated at the Brookhaven Accelerating Test Facility (BNL-ATF) using tomography technique [1]. The longitudinal phase space distribution is reconstructed by measuring the energy spectrums of the beam for different RF phases. We will first briefly describe the principle of tomography technique and the ATF experiment set-up. The longitudinal emittance as function of RF gun phase was measured first time. The longitudinal emittance growth caused by the space charge effect was observed.

1 INTRODUCTION

The ultra-short electron bunch is required in linear collider, single-pass X-ray FEL, second-generation laser accelerator and many other applications. Producing and measuring the short electron bunch is one of the most active areas in beam physic R&D [2]. The experimental results of the longitudinal emittance characterization of femto-seconds long photo-electron beam is presented in this report.

After almost 20 years R&D, photocathode RF gun has emerged as the only technology now capable of producing high-brightness electron beam to drive future X-ray FEL and second-generation laser accelerators. Experimental characterization of the transverse phase space of electron beam was performed in many places, but few experiments were done to study the longitudinal phase distribution of photo-electron beam. Experimental characterization of photo-electron beam is critical to further reduce the transverse emittance of the photo-electron beam, and in understanding the coupling between the transverse emittance and longitudinal emittance. Further more, longitudinal emittance determines the shortest bunch length could be compressed down to. Longitudinal phase distribution also plays an important role in all coherent radiation generation experiments, such as FEL, and reducing emittance growth caused by the coherent radiation during the bunch compression [3,4]. The longitudinal tomography technique developed at Stanford Picosecond FEL Center [1] is one of the tools for longitudinal phase space characterization. We implemented this technique at the Brookhaven Accelerator Test Facility (ATF) to study the photo-electron beam longitudinal phase space. We have first time measured the photo-electron beam longitudinal emittance as a function of the RF gun phase. The longitudinal emittance growth caused by the space charge effect was observed.

2 PRINCIPLE OF LONGITUDINAL TOMOGRAPHY

The tomography technique is widely used in the medical imaging community for diagnostics, brain function studies and many other applications. Similar technique was employed for both transverse [5] and longitudinal [1] phase space characterization of electron beam. The two-dimensional image can be reconstructed from its one-dimensional projections (Figure 1) using tomographic technique. For electron beam phase reconstruction, the projections of the phase space in physical space are measured as the phase space is being rotated. For transverse phase tomography, the electron beam profiles are measured as the phase space being rotated by quadrupole magnets.

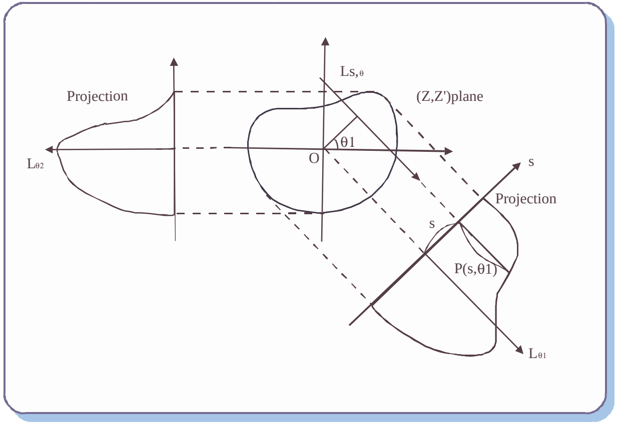

Figure 1 Principle of tomographic imaging

For the longitudinal phase space tomography, the physical space projections being measured are the electron beam energy spectrum. A magnetic dispersion section, an off-phase accelerating structure, or its combination could be used to rotate the electron beam in longitudinal phase space. The temporal distribution in phase space is stretched in the dispersion section; and the off-phase accelerator section modulates energy distribution within the bunch. As an electron bunch goes through a dispersion section and an off-phase accelerator (Figure 2), the longitudinal coordinates (z_0, E_0) of electrons within the electron bunch are transformed in the following way [1]:

$$\begin{pmatrix} z \\ E \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ k & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & l_z \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ E_0 \end{pmatrix} = \begin{pmatrix} z_0 + l_z E_0 \\ k z_0 + E_0 (l_z k + 1) \end{pmatrix} \qquad (1)$$

where k is RF slope which depend on accelerating phase and l_z is the first order longitudinal dispersion factor in the dispersion section. The energy spectra of the electron beam are measured by a spectrometer as the longitudinal phase space being rotated.

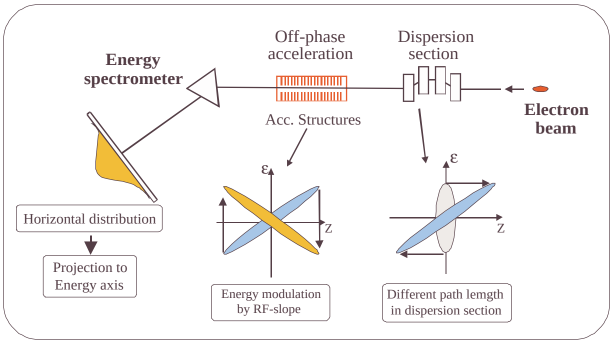

Figure 2 Transformation of longitudinal phase space distribution using the dispersion section and the off-phase accelerating structure.

3 LONGITUDINAL TOMOGRAPHY STUDIES AT BNL-ATF

3.1 Experimental Set-up

The ATF is a laser linac user facility dedicated for beam physics R&D. Characterization of the photo-electron beam longitudinal emittance is important not only for high-brightness beam dynamics, also critical for producing electron beam with bunch length less than 20 fs (FWHM) for laser accelerator injection [2]. Figure 3 shows the layout of the ATF accelerator system. It is composed of a S-band photocathode RF gun, two 3-m long accelerating structures, and beam transport lines (H-line, F-line). Using the calibrated mechanical phase shifter, accelerating phases of two sections of the linac can be controlled independently. By varying the RF phase of the second section of the linac, electron beam energy within the bunch was modulated. The energy spectrum was measured with a phosphor screen based beam profile monitor (BPM) which located at the dispersion part of the F-line.

The experimental set up at the ATF limited the longitudinal phase space rotation less than 180°. There is no dispersion section for the stretching of temporal profile at the off-phase accelerator upstream. The limited energy acceptance of the spectrometer and equal acceleration gradients between two sections of the linac further limited the RF phase range of the off-phase acceleration. Taking advantage of the bunch length variation with RF gun phase, we were able to carry out the experiment by operating the RF gun at lower phase. The RF gun operating at the lower RF phase can produce sub-pico-second long electron beam [6], which allowed relative large RF phase range of off-phase acceleration.

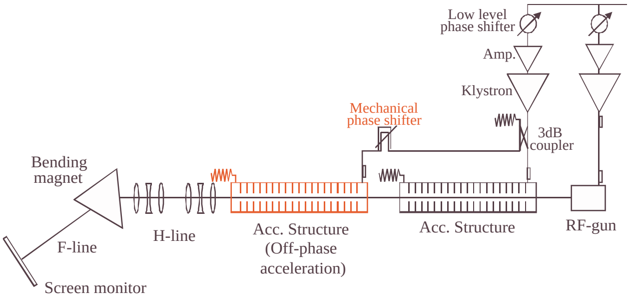

Figure 3 Layout of BNL-ATF beam line

3.2 Data Acquisition and Analysis

Longitudinal tomography study was implemented using commercial software MATHCAD. The communication established between the ATF accelerator control system and MATHCAD [7] allows directly access the database of the ATF control system from MATHCAD.

We have developed a beam optics which minimized the β-function where the beam profile was measured. To reduce the wake-field contribution to the energy spectrum of the beam, the photo-electron beam charge was limited to less then 0.5 nC.

The longitudinal tomographic measurements were carried out in according to the following steps:

1. Measure the photo-electron beam charge as the function of the RF gun phase to establish the absolute laser phase.
2. The second accelerator’s phase was set and read-backed. Beam energy was calculated from the RF phases and amplitude.
3. Set-current of quadrupole magnets and dipole magnet was according to the estimated beam energy to keep the beam line optics constant.
4. Save parameters (RF phases, magnet currents) and the beam image as bit-map files.
5. The energy spectrum was obtained from beam profile image, and the rotation angle in phase space was calculated from beam line optics. The phase space distribution was reconstructed from the measured energy spectrum using tomographic technique.

3.3 Experimental Results and Discussion

Figure 4 shows a set of measured beam profiles at the energy spectrometer. For this measurement, we typically changed the phase of second section of the linac from 5 to 160 degrees (90 degrees is the RF crest), this range of RF phase corresponds to 110 degrees rotating angle in longitudinal phase space. From Figure 4, minimum energy spread was realized at 80 degrees RF phase. It means that energy of bunch head is higher than bunch tail.

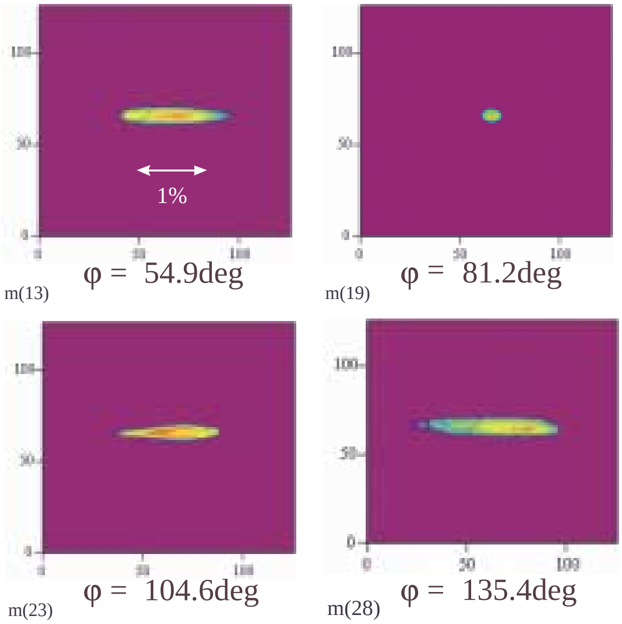

Figure 4 Beam profile at the energy spectrometer in different phase where the dispersion function is 0.3 m.

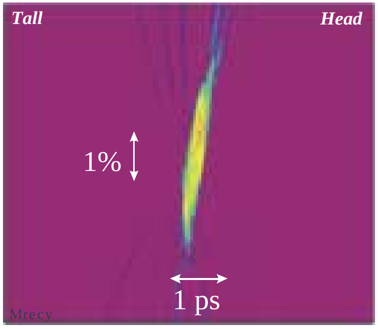

Figure 5 Reconstructed image of electron beam density-distribution in longitudinal phase space at right upstream of first accelerator.

The longitudinal emittance variation caused by the space-charge effect and the RF-gun phase was investigated using the tomographic technique. We varied the energy of the RF gun driving laser to change the photo-electron charge from 50 pC to 250 pC at the constant RF-gun phase. Figure 6 shows the relation between bunch charge and longitudinal emittance, where the longitudinal emittance was calculated according to the following equation,

$$\varepsilon = \sqrt{\left\langle (z-\langle z\rangle)^2\right\rangle \left\langle (pz-\langle pz\rangle)^2\right\rangle - \left(\langle z\cdot pz\rangle - \langle z\rangle\langle pz\rangle\right)^2}. \quad (2)$$

Figure 6 shows that, the longitudinal emittance is roughly linear proportional to the photo-electron charge.

In another study, we measured the longitudinal emittance as a function of the RF-gun phase. When the RF gun phase is varied, the charge also changes due to the Shottkey effect. To keep the constant charge, we controlled the irradiate laser energy. During this measurement, the photo-electron charge was about 70 pC. Figure 7 shows relation between the longitudinal emittance and the RF-gun phase. The longitudinal emittance of the photocathode RF gun due to the RF effect is [8],

$$\varepsilon_z^{RF} \propto \sigma_z^{\,3}\cdot\cos(\phi) \qquad (3)$$

where σ is electron beam bunch length, and ϕ is the RF gun phase. Fig.7 show reasonable agreement with our results because space-charge effect is negligible. We also observed the linear relation between the bunch length and RF gun phase as reported in Ref. [6,9].

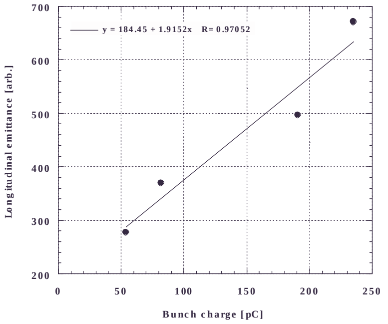

Figure 6 Bunch charge vs longitudinal emittance

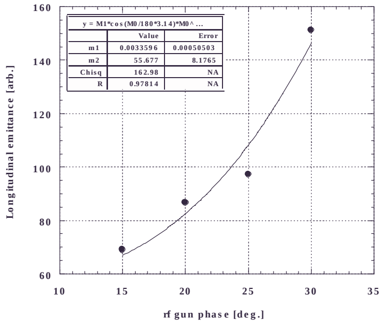

Figure 7 RF gun phase vs longitudinal emittance

4 ACKNOWLEDGMENTS

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