MEASUREMENT OF THREE-DIMENSIONAL DISTRIBUTION OF ELECTRON BUNCH USING RF TRANSVERSE DEFLECTOR

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Abstract

We have been studying a high quality electron beam generated by a photocathode rf gun at Waseda University. The electron beam is applied to various experiments. In those application, longitudinal parameters of the electron beam are important. For this reason, we developed the rf deflector system which has high temporal resolution and can directly convert longitudinal distribution of the beam to transverse, and performed longitudinal profile measurements of an electron beam from the rf gun. During a series of experiments using the rf deflector, we found that the bunch had a horizontal angle with respect to z axis. Thus we investigated the mechanism of bunch tilting. In addition, we reconstructed three-dimensional profiles of the bunch by computed tomography in order to consider vertical angle. In this conference, we report the principle of measurement, experimental results of the bunch tilt angle and three-dimensional measurement, and future prospects.

INTRODUCTION

Photocathode rf gun is now used as not only an injector of large accelerator system also a compact accelerator system for various applied experiments. At Waseda University, we use it to perform a pulse radiolysis experiment [1], laser Compton scattering for soft X-ray generation [2], and generation of coherent Cherenkov radiation [3]. For these applications, to clarify the precise beam parameters is important. Therefore, we have developed the rf deflector system and have performed several measurements of longitudinal parameters of electron bunch [4]. Recently, we performed bunch tilt angle measurement and three-dimensional distribution measurement using CT (Computed Tomography) technology [5]. In this paper, principles of the experiments, experimental setup, and results and discussions are described.

BUNCH TILT ANGLE MEASUREMENT

The conceptual diagram of our rf deflector system is shown in Fig.1.Inside the deflector cavity, time-dependent transverse rf magnetic field on the beam axis is procuced and the electron beam receives Lorentz force which depends on the longitudinal position inside the beam. Around zero-crossing rf phase, the displacement of the electron position on the screen monitor is proportional to that of the longitudinal electron position from the bunch centre [4]. Thus the longitudinal distribution of the bunch is converted to transverse and is projected on the screen. Assuming that the bunch distribution has a Gaussian shape, bunch length can be written as:

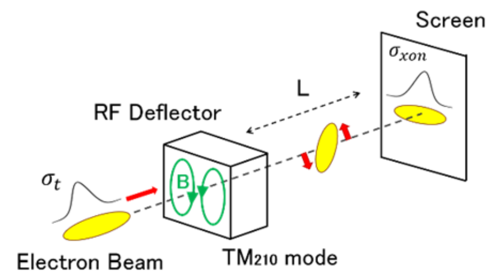

Figure 1: Conceptual diagram of the rf deflector system

$$\sigma_t = \frac{p_z c}{eV_T \omega L}\sqrt{\sigma_{xon}^2 - \sigma_{xoff}^2} \qquad (1)$$

where p_z is the longitudinal momentum of the electron, c is the velocity of light, e is the elementary charge, V_T is the deflecting voltage, ω is the angular frequency of the rf, L is the drift length from the centre of the rf deflector to the profile monitor, σ_{xon} and σ_{xoff} are the horizontal beam sizes when the rf deflector is on and off, respectively. From Eq.(1), we can obtain the equation of:

$$\sigma_{xon}^2 = \omega^2 \sigma_t^2 T^2 + \sigma_{xoff}^2 \qquad (2)$$

Here, T is defined as $T \equiv eV_T L/p_z c$ and we call it skewing strength in this paper. Skewing strength is proportional to the deflecting voltage when both the drift length and the longitudinal momentum are constant. Eq.(2) shows that the relation between the squared horizontal beam size of the bunch deflected by the rf deflector and the skewing strength should be quadratic function. When the bunch has a certain angle to the z axis, the axis of the quadratic function deviates from T= 0 as shown in Fig.2 and bunch tilt angle can be calculated as:

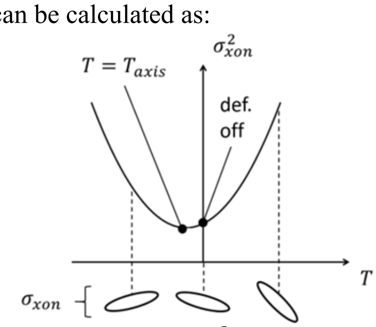

Figure 2: Relation between σ_{xon}^2 and T when the bunch has an angle.

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$$\theta_b = \tan^{-1}\left(\frac{\omega T_{axis}}{c}\right) \tag{3}$$

where T_{axis} is the value of skewing strength when the horizontal beam size is minimum.

THREE-DIMENSIONAL DISTRIBUTION MEASUREMENT

Applying CT technique, three-dimensional distribution can be reconstructed using projected profiles of the bunch which is rotated by various angles. To obtain rotated profiles, however, we have to modify deflected profiles which are projected on the screen monitor. The rotation matrix in the (z, x) plane can be written as:

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} 1/\cos\theta & 0 \\ 0 & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & -\cos\theta\sin\theta \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ T & 1 \end{pmatrix} \tag{4}$$

where θ is the rotation angle, T is the skewing strength which satisfies T=tanθ. The third matrix on the right side of Eq.(4) represents the effect of the rf deflector. Since profiles we obtain during the measurement do not have information along the z axis, the skewing and scaling along the z direction seen in the first and the second matrix on the right side have no effect on the beam profiles projected on the screen. Therefore, considering the scaling along the x direction, the projected image of the rotated bunch can be obtained by multiplying the size in the x direction of the deflected beam profile by cosθ. In this way, we can obtain the projection images of the bunch seen from various angles, and can reconstruct (z, x) cross-sections from them using CT technique. Reconstructing three-dimensional distribution of the bunch is possible by integrating all cross-sectional images along the y direction.

EXPERIMENTAL SETUP

The experimental setup for bunch tilt and three-dimensional measurement is shown in Fig.3.

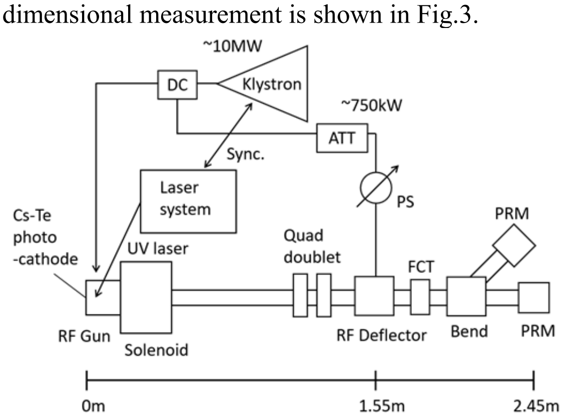

Figure 3: Experimental setup for bunch tilt and three-dimensional measurement.

We use the 1.6 cell photocathode rf gun as the accelerator system, which can provide an electron bunch with energy of maximum 5 MeV, high brightness, and low emittance (2-3π mm-mrad) [6]. The frequency of the rf is 2856 MHz (S band). The laser system for illuminating Cs-Te photocathode is composed of Nd:YLF mode-locked laser which produces a ps pulse with a repetition rate of 119MHz. The system can provide both single-pulse and multi-pulse by changing the number of picked pulses. We used single-pulse mode in this experiment. The UV pulse laser is guided into the injection port attached to the rf gun to illuminate Cs-Te photocathode. Since the laser is injected obliquely, the initial bunch generated from the photocathode has an angle to z axis, which we assume is the main cause of bunch tilting. The rf to drive the accelerator system is provided by the klystron with power of up to 10 MW. The generated rf is divided into two by the directional coupler (DC) to provide power for both the rf gun and the rf deflector. The rf power for the deflector is up to 750 kW. The power and phase of the rf for the deflector can be changed independently using the attenuator (ATT) and the phase shifter (PS), respectively. Solenoid magnet is placed right after the rf gun to compensate the emittance, followed by two quadrupole magnets which are used to focus the electron beam. The rf deflector is located 1.55 m away from Cs-Te photocathode. Fast current transformer (FCT) is used for measurement of bunch charge and beam energy is able to be measured by the bending magnet after the FCT. Beam profile images can be obtained by recording the beam profile monitor (PRM) made of Al_2O_3 using CCD camera.

RESULTS AND DISCUSSION

Bunch Tilt Angle Measurement

One of the results of bunch tilt angle measurement is shown in Fig.4.

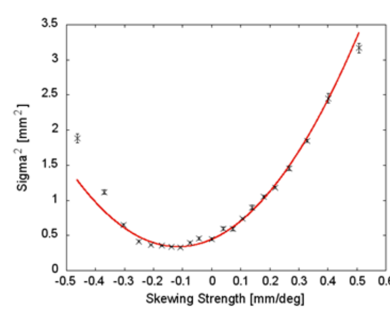

Figure 4: One of the results of bunch tilt angle measurement.

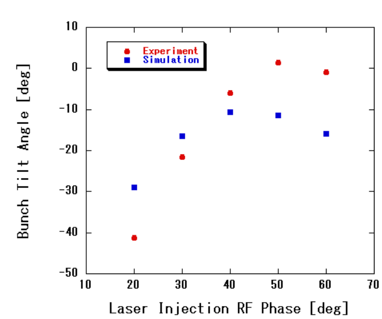

Figure 5: Bunch tilt angle as a function of rf phase.

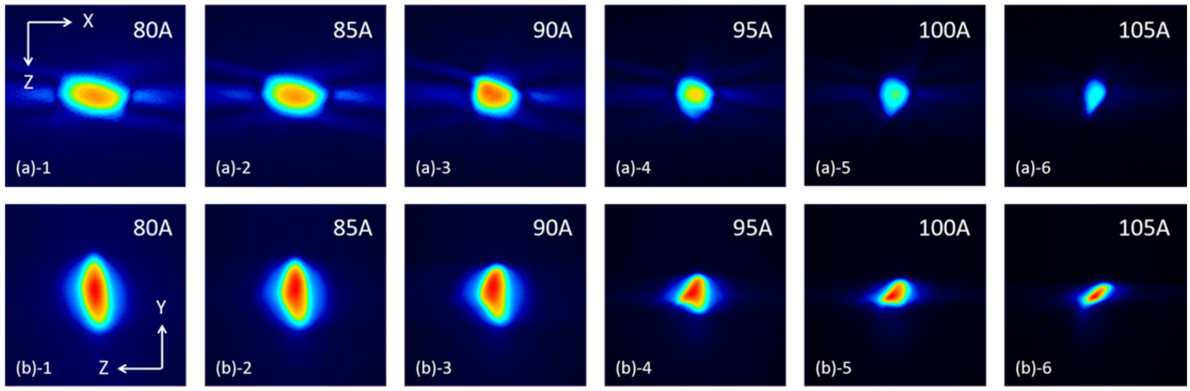

Figure 6: The result of three-dimensional measurement. (a)-1~6 are bunches seen from y direction and (b)-1~6 are those seen from x direction.

The horizontal and vertical axis represents skewing strength and squared horizontal beam size, respectively. Figure 4 shows that the relation between the squared horizontal beam size and the skewing strength is quadratic function as mentioned above. The axis of the quadratic function is off the vertical axis, which means the bunch has an angle. Using Eq.(3) allows us to calculate the angle of this bunch and we find that the angle is 21.5 deg to z axis. In this way, we have successfully measured the angle of the bunch generated by the rf gun using the rf deflector. Then we selected several accelerationg rf phases and observed how the bunch angle changed. Figure 5 shows the result of the experiment. As shown in Fig.5, the absolute values of bunch tilt angle become smaller as a function of the rf phase. At the rf phase of 20 and 30 deg, it is confirmed that initial bunch tilting caused by oblique laser incident has a significant effect on the angle of the accelerated bunch. On the other hand, at the rf phase of 40 deg or more, the absolute values of bunch angle are much smaller even though initial bunches are still tilting. We have confirmed that the energy spread of the bunch becomes larger as a function of the rf phase during several experiments so far. This leads to bunch length growth, which makes bunch angle smaller relatively. Figure 5 also shows the result of the simulation. It does not match perfectly that of the experiment. This is mainly because the actual beam line of the experiment is not aligned perfectly. Several simulations show that both position and angle misalignment of machines can tilt the bunch. So we are planning to presume the actual misalignment by matching the simulation to the experimental result.

Three-dimensional Distribution Measurement

The result of three-dimensional distribution measurement is shown in Fig.6. (a)-1~6 in Fig.6 show reconstructed images of bunches which are seen from y direction and (b)-1~6 show those seen from x direction. We succeed to reconstruct the image of the accelerated electron bunch seen from both x and y direction, which means we can observe three-dimensional distribution. We performed the experiment with several values of solenoid current from 80 A to 105 A. Transverse beam size of the bunch become smaller as a function of solenoid current because the focus strength is larger, while bunch length is constant at all value. From the viewpoint of bunch tilt angle, it is confirmed that horizontal and vertical bunch angle change simultaneously as a function of solenoid current. This shows that the bunch focus by solenoid magnet affects the bunch angle directly and both angles are mixed by its effect. This experiment has revealed that the bunch with both horizontal and vertical angle is generated by the rf gun because of oblique laser incident and solenoid effect.

SUMMARY

We have performed bunch tilt angle measurement and three-dimensional distribution measurement using rf transverse deflector. It is confirmed that the bunches with rf phase of 20 and 30 deg have large angle to z axis because of oblique laser incident, while those with the phase of 40 deg or more have smaller angle due to bunch length growth. The mismatch between the experimental result and the simulation would be caused by misalignment of the beam line. It is possible to presume the actual misalignment by matching the simulation to the experimental result. Using CT technology, we have successfully reconstructed three-dimensional bunch profiles. This experiment has shown that bunches with horizontal and vertical angle are generated due to both laser injection and solenoid effect. We are planning to apply these results to other experiments using tilted bunches.

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