LONGITUDINAL DIAGNOSTICS OF RF ELECTRON GUN USING A 2-CELL RF DEFLECTOR*

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Abstract

We have been studying a compact electron accelerator based on an S-band Cs-Te photocathode rf electron gun at Waseda University. We are using this high quality electron bunch for many application researches. It is necessary to measure the bunch length and temporal distribution for evaluating application researches and for improving an rf gun itself. Thus, we adopted the rf deflector system. It kicks the electron bunch with resonated rf electromagnetic field. Using this technique, the longitudinal distribution is mapped into the transverse space. The rf deflector has a 2-cell standing wave π-mode structure, operating in TM_{210} dipole mode at 2856 MHz. It provides a maximum vertical kick of 1.00MV with 750 kW input rf-power which is equivalent to the temporal resolution of around 58 fs bunch length. In this conference, we report the details of our rf deflector, the latest progress of longitudinal phase space diagnostics and future prospective.

INTRODUCTION

A photocathode rf electron gun is now widely utilized for an accelerator system in many facilities due to its controllability of initial beam profile and ability to generate low emittance beam. In Waseda University, we built a compact electron accelerator system based on an S-band Cs-Te photocathode rf electron gun. The rf gun is an improved BNL type IV 1.6 cell rf gun. It is applied to many researches, such as a pulse radiolysis experiment for tracing rapid initial chemical reactions by ionizing radiation [1], a laser Compton scattering for generating soft X-ray [2] and synchrotron radiation and transition radiation for generating coherent THz wave [3][4]. In these experiments, it is necessary to measure the bunch length and temporal distribution for evaluating temporal resolution, luminosity and coherence, respectively. The measurement of the bunch length is also helpful for studying the effect of rf acceleration. Thus, we adopt the rf deflector system.

THE METHOD OF BUNCH LENGTH MEASUREMENT USING RF DEFLECTOR

Figure 1 shows a principle of measuring the bunch length and temporal profile using an rf deflector. An rf deflector is one of rf cavities. It has been used as a strong tool for bunch length and temporal profile measurements in FELs and other facilities recently. Electromagnetic field of its own resonates in an rf deflector when rf power is supplied. In Waseda University, the rf deflector generates the electromagnetic field of the TM_{210} mode. Lorentz force gives the transverse momentum on the electron beam by the high frequency time variation of the magnetic field and the beam is “kicked” horizontally. The electric field has no effect on the beam in the rf deflector, because it doesn’t exists on the axis of the beam. Thus, the rf deflector can convert the longitudinal information of the electron beam into the transverse one. Using this technique, the temporal profile of an electron beam can be obtained directly as an image on screen.

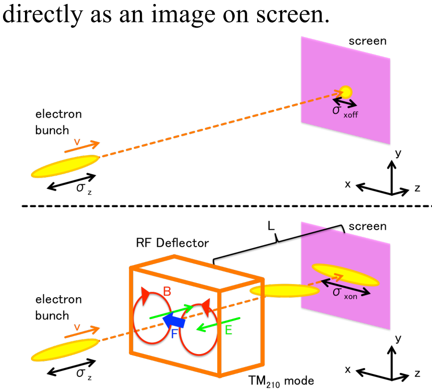

Figure 1: Bunch length measurement using an rf deflector.

Considering the transfer matrix between the rf deflector and the screen, the transverse position of each relativistic electron on the screen, Δx, as a function of longitudinal position from the bunch centroid along the bunch, Δz, is given approximately by

$$\Delta x = \frac{eV_T}{p_z c} L \sin\left(k\Delta z + \varphi\right) \cong \frac{eV_T}{p_z c} L\left[k\Delta z \cos\varphi + \sin\varphi\right] \quad (1)$$

where c is the light velocity, p_z is the longitudinal momentum, V_T is the deflecting voltage, L is the drift length between the rf deflector and the screen, k is the rf wave number, and φ is the rf phase [5]. The approximation is made that $|\Delta z| \ll 1/k$ because the longitudinal position is much shorter than the rf wavelength of 0.105 m. Operating at the zero-crossing phase like Figure 2, we can substitute φ=0 to Eq. (1),

$$\Delta x = \frac{eV_T}{p_z c} Lk\Delta z \quad (2)$$

This phase gives the best kicking effect with the horizontal beam size corresponding to the bunch length ($\sigma_x \propto c\sigma_t$).

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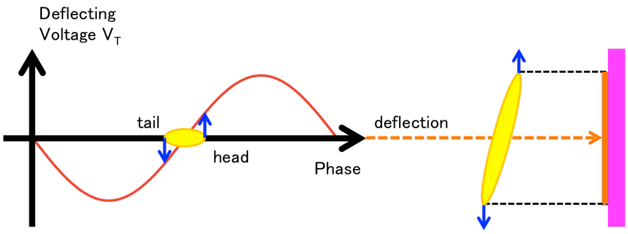

Figure 2: The schematic of rf deflection by rf zero-crossing phase.

Considering the beam size, from Eq (2), the bunch length σ_t is given by

$$\sigma_t = \frac{p_z c}{eV_T \omega L}\sqrt{\sigma_{x_{on}}^2 - \sigma_{x_{off}}^2} \tag{3}$$

and the temporal resolution σ_{t0} is given by

$$\sigma_{t_0} = \frac{p_z c}{eV_T \omega L}\sigma_{x_{off}} \tag{4}$$

where ω is the rf angular frequency, σ_{xon} and σ_{xoff} are beam sizes when the rf deflector is on and off, respectively. From Eq (4), it is clear that the temporal resolution can be better when we increase the deflecting voltage V_T, the angular frequency ω and the drift length L, and it can be worse when we increase the beam size σ_{xoff}, and the momentum p_z. ω is unique to the power supply and L is limited by the size of the facility. Thus, it is necessary to increase the deflecting voltage V_T and to decrease the beam size σ_{xoff} for better temporal resolution.

DESIGN AND MANUFACTURE OF RF DEFLECTOR [6]

We used HFSS (High Frequency Structure Simulator) for the design of the rf deflector cavity and GPT (General Particle Tracer) for the evaluation of its performance. We carried out a simulation imposing the boundary condition which generates the electromagnetic field of TM_{210} mode in the cavity. Comparing an rf deflector of a rectangular geometry with that of a pillbox geometry, magnetic field on the axis of the beam in the rectangular rf deflector was stronger than the pillbox one. From the viewpoint of the Q value, the length in the x direction should be 1.4 times longer than the length in y directions. As for the length in the z direction, we started to study the length of time which the beam in the cavity was the half cycle of the magnetic field cycle, assuming that the beam has the light velocity. To increase the Q value of the cavity, we optimized while reducing as much as possible the energy losses in the cavity wall, increasing the most magnetic field strength in the cavity by reducing the surface of the cavity with rounded corners of a rectangular rf deflector. However, it became clear that this rf deflector could not measure the bunch length of 100 fs with any design because the power supply from the Klystron is limited in our accelerator system. Therefore, to achieve much better temporal resolution, we started to design the 2-cell rf deflector. The deflecting voltage V_T of the 2-cell rf deflector is 1.41 times higher than that of 1-cell rf deflector. After all, we designed the impedance matching with the waveguide using HFSS and adjusted the length in the z direction by evaluating the deflection of an electron beam using GPT. Figure 3 shows the photograph of the rf deflector. The parameters of the manufactured rf deflector and the designed rf deflector are given in Table 1. The parameters of the manufactured rf deflector are almost as designed. Figure 4 and Figure 5 shows the result of magnetic field distribution measurement by bead perturbation method and that of rf resonant frequency measurement by reflecting method using the network analyzer respectively. The ratio of magnetic field peak in the 2-cell was almost 1:1 as designed and the electromagnetic field of π-mode is resonated around 2856 MHz. It provides the deflecting voltage of 1.00MV with 750 kW input rf power which is equivalent to the temporal resolution of around 58 fs bunch length with beam size of σ_{xoff}.

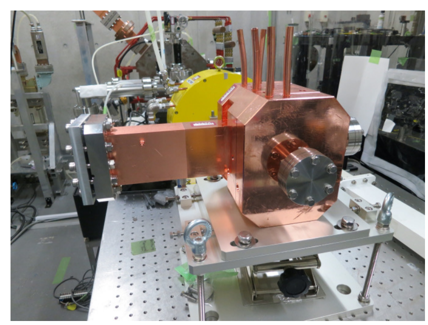

Figure 3: The photograph of the rf deflector.

Table 1: Parameters of RF Deflector

Parameters	Results	Design value
π-mode	2855.348 MHz	2855.372 MHz
0-mode	2859.874 MHz	2859.922 MHz
Δf	4.526 MHz	4.55 MHz
Q value on π-mode	16298	17282
Ratio of magnetic field	1:0.9875	1:1
Coupling constant β	0.839	1.000

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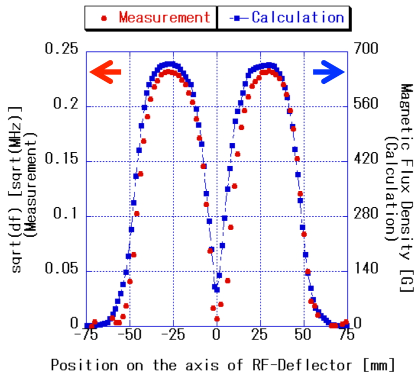

Figure 4: Result of magnetic field distribution measurement.

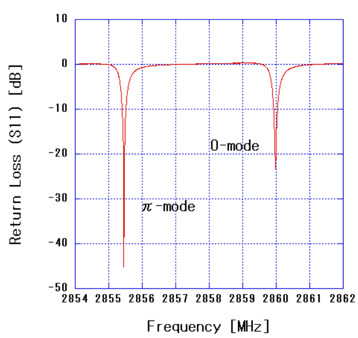

Figure 5: Result of rf resonant frequency measurement.

MEASUREMENT OF BUNCH LENGTH AND TEMPORAL PROFILE USING RF DEFLECTOR

Confirming the rf deflector was manufactured almost as designed, we installed the rf deflector in the accelerator system at Waseda University and carried out the measurement of the bunch length and temporal profile. Figure 6 shows the setup for the measurement.

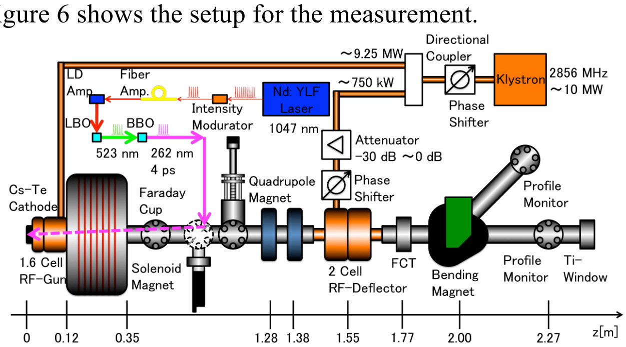

Figure 6: Setup for the bunch length measurement.

In the accelerator system, Nd: YLF laser is used as the seed laser for the rf gun. It oscillates infrared pulsed laser of which the wavelength is 1047 nm. Then the required number of pulses are picked up, amplified, and converted to ultraviolet pulses. These pulses have the pulse width of about 4 ps and the wavelength of 262 nm. They are irradiated to the Cs-Te cathode of an rf gun almost perpendicularly. The rf gun is the uppermost of the beamline and a solenoid magnet is after the rf gun to compensate the emittance increase due to space charge effect. Two quadrupole magnets to focus the beam size σ_{xoff} are 1.28 m and 1.38 m away from the cathode. The rf deflector is 1.55 m and is supplied rf power of 750 kW separated from the Klystron output of 10MW using the directional coupler. Proper amount of rf power can be supplied with the attenuator so that all of the electron beam is projected on the screen. The rf phase of the deflector is determined independently from the rf phase of the gun with the phase shifter put after the directional coupler. 2.27 m away from the cathode, the screen is installed for measuring the beam profile. Therefore, the drift length L is 0.72 m.

At the measurement of the bunch length, we first calibrated the deflecting voltage V_T. From Eq. (1), the centroid of the electron beam (Δz=0) with rf phase shift is given by

$$\Delta x = \frac{eV_T}{p_z c} L \sin\varphi \tag{5}$$

Thus, we can calculate the deflecting voltage V_T by measuring the amplitude of a sinusoidal curve which the centroid of an electron beam draws with the rf phase shift. Figure 7 shows the result of the centroid shift. The deflecting voltage is calculated to be about 0.40 MV with the rf power of 192 kW from the amplitude of 12.195 mm using Eq. (5).

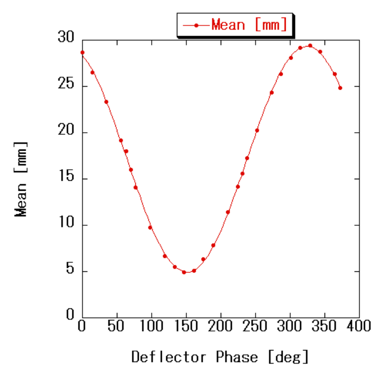

Figure 7: Deflecting voltage calibration.

Then we carried out the measurement of the bunch length and temporal profile. Figure 8 shows the typical electron beam profiles with rf deflector "off" (left) and "on" (right). The bottom line profiles show the projection to x direction. The charge of the electron beam was about 200 pC in this experiment. Temporal information is clearly projected on the screen. From the beam size σ_{xoff} =365 μm when the rf deflector was "off", and the beam size σ_{xon}=4.20 mm when the rf deflector was "on", the bunch length was calculated to be about 3.79 ps using Eq. (3). This result is consistent with the pulse width of ultraviolet laser, 4 ps, irradiated to the cathode.

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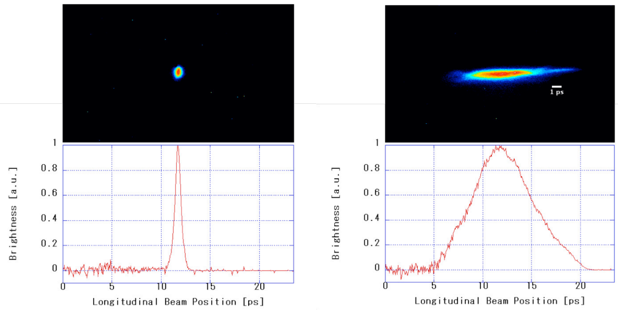

(8-a) (8-b)

Figure 8: Electron beam profiles with rf deflector "off" (8-a) and "on" (8-b). The bottom line profiles show the projection to x direction.

Changing the charge to 1 nC by controlling the intensity of ultraviolet laser, we also carried out the measurement. Figure 9 shows the result.

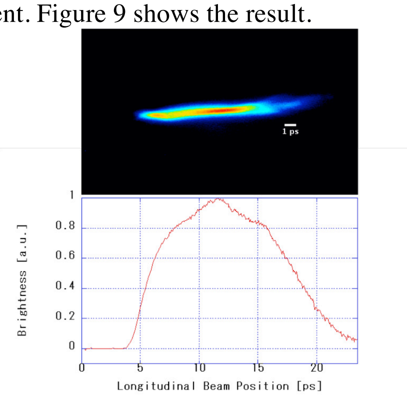

Figure 9: Electron beam profile. The bottom line profiles show the projection to x direction.

Comparing Fig. 9 with Fig. 8-a, the beam profile and the projection to x direction of both figures are different. The profile and projection in Fig. 9 are expanded due to the space charge effect with higher charge of 1 nC.

We also changed the rf phase of rf gun and carried out the bunch length measurement when the charge is 200 pC and 1 nC. Figure 10 and Figure 11 are the results of bunch length measurement when the charge is 200 pC and 1 nC respectively.

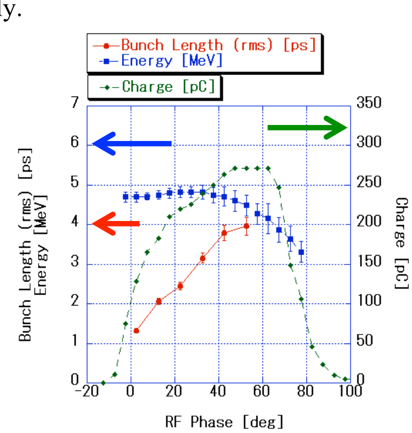

Figure 10: RF phase dependence of the bunch length, beam energy, and charge (200 pC).

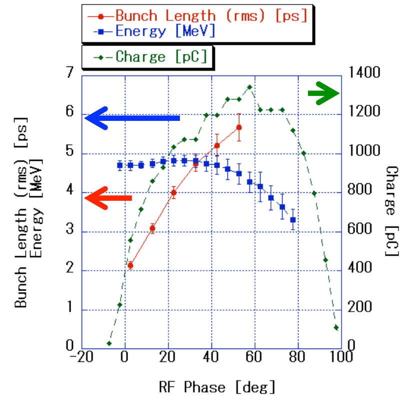

Figure 11: RF phase dependence of the bunch length, beam energy, and charge (1 nC).

Comparing Fig. 10 with Fig. 11, the bunch length increases in both figures with the increase of the rf phase. This is because the charge of electron beam increases with the increase of the rf phase. Considering the bunch length in detail, not only the absolute value but also the variation of the bunch length is larger when the charge is 1 nC due to the space charge effect.

SUMMARY AND PROSPECTS

Using the rf deflector, which we designed for our accelerator system, we succeeded in measuring the bunch length and temporal profile of an electron beam generated from the photocathode rf gun at Waseda University. For the measurement, the deflecting voltage was calculated to be about 0.40 MV with the rf power of 192 kW experimentally. The bunch length dependence on the charge of the electron beam and on the rf phase of the gun was obtained from this measurement. The charge is the key factor in the bunch length measurement. In near future, we will carry out the experiment to obtain the phase space of the electron beam using the rf deflector and a bending magnet. Through these experiments, we will examine the dynamics of the electron beam generated from the rf gun in Waseda University and utilize the rf deflector to cater to applied reseaches.

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