Bunch length measurement using a traveling wave RF deflector*

ZHANG Jing-Ru(张敬如)[1,2] DAI Jian-Ping(戴建枰)[1;1)] GU Qiang(顾强)[3] PEI Guo-Xi(裴国玺)[1]
ZHAO Ming-Hua(赵明华)[3] ZHONG Shao-Peng(钟少鹏)[3] WANG Xing-Tao(王兴涛)[3]
CHEN Yong-Zhong(陈永忠)[3] HOU Mi(侯汨)[1]

[1] Institute of High Energy Physics, CAS, Beijing 100049, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China

Abstract RF deflectors can be used for bunch length measurement with high resolution. This paper describes a completed S-band traveling wave RF deflector and the bunch length measurement of the electron beam produced by the photocathode RF gun of the Shanghai DUV-FEL facility. This is the first time that such a transverse RF deflector has been developed and used to measure the bunch length of picosecond order in China. The deflector's VSWR is 1.06, the whole attenuation 0.5 dB, and the bandwidth 4.77 MHz for VSWR less than 1.1. With a laser pulse width of 8.5 ps, beam energy of 4.2 MeV, and bunch charge of 0.64 nC, the bunch lengths for different RF input power into the deflector were measured, and an averaged rms bunch length of 5.25 ps was obtained. A YAG crystal is used as a screen downstream of the deflector, with the calibrated value of 1 pix = 136 μm.

Key words RF deflector, bunch length, RF gun, HEM_{11} mode

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1 Introduction

The development of future free electron lasers and linear colliders requires high brightness electron beams with bunch lengths on the order of ps or sub-ps. Reliable measurement of such a short bunch is not a trivial problem. There are several ways to measure such short bunch lengths, such as the electro optic technique [1], zero-phase crossing measurement [2], coherent radiation from a short bunch [3], the RF deflector method [4] and so on. Among them, the RF deflector method is quite promising, shown by the demonstrated results at SLAC [4] and DESY [5]. It is an advanced, reliable and economical method.

In order to handle the RF deflector method and measure the bunch length of Shanghai Deep Ultra-Violet FEL (SDUV-FEL), a short traveling wave RF deflector was developed and used to measure the bunch length of the photocathode RF gun of SDUV-FEL as a first step.

2 RF deflector

A short traveling wave RF deflector was designed and fabricated [6]. The transverse RF deflector is of an iris-loaded waveguide structure. The deflecting mode is TM_{11}-like or HEM_{11} mode. It operates at 2856 MHz because high power klystrons and other equipment are readily available in our lab. A $2\pi/3$ phase shift per cell has been chosen. It works in backward-wave type mode. Two additional holes are provided to stabilize the mode and to prevent mode rotations.

The main parameters of the deflector are reported in Table 1, while Fig. 1 shows a picture of the completed deflector. The VSWR of the deflector is 1.06. The whole attenuation is 0.5 dB from input to output. The bandwidth is 4.77 MHz when VSWR is less than 1.1.

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1) E-mail: jpdai@ihep.ac.cn

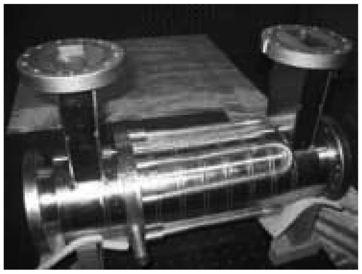

Fig. 1. The completed deflector.

Table 1. The main parameters of the deflector.

type of structure	constant impedance structure
mode type	HEM_{11} (hybrid mode)
frequency	2856 MHz
number of cell	8cells+2couplers
phase shift/cell	$2\pi/3$ (120°)
cell length	35 mm
wavelength	105 mm
relative group velocity	−0.0189
transverse shunt impedance	~10 Mohm/m

3 Experimental setup

3.1 Power feeding system

There is only one 25 MW klystron to provide the power. A 3 dB directional coupler is used to divide the power into the photocathode RF electron gun and the deflector. Fig. 2 shows a sketch of the power feeding system. The RF gun needs to feed more than 10 MW, so the power to the deflector will also be more than 10 MW. Yet the input power needed for the deflector is less than 1 MW, therefore a high power attenuator is installed in the deflector branch. In order to change the phase of the input power to the deflector, a high power phase shifter is installed downstream of the attenuator. A 50 dB directional coupler is installed downstream of the phase shifter in order to monitor the RF power level and phase into the deflector.

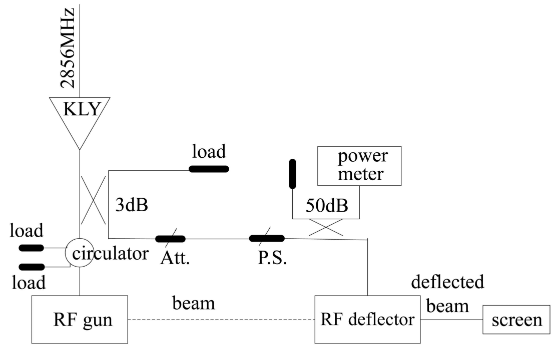

Fig. 2. A sketch of the power feed system.

3.2 Measurement system

The system consists of the photocathode RF gun and some beam diagnostic elements, as shown in Fig. 3. The RF can could produce a high brightness electron beam with an rms bunch length of about 4–6 ps. At 2.7 meters from the gun exit, the deflector is installed. The YAG screen is 0.984 meters away from the center of the deflector.

The photocathode RF gun consists of a 1.6-cell cavity with a Cu incorporated metallic cathode, operating at the S band (2856 MHz). It generates a 4.2 MeV electron beam with a charge of 0.64 nC. The laser pulse has a width of 8.5 ps. The emittance is about 4 mm·mrad.

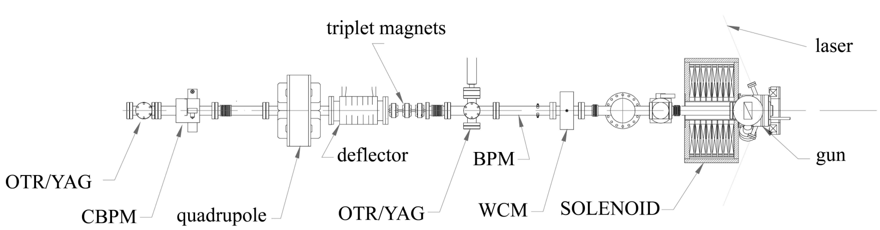

Fig. 3. Layout of the bunch length measurement setup.

4 Bunch length measurement principle

Figure 4 shows the principle of bunch length measurement [7]. Assume that two electrons e1 and e2 enter the cavity on axis of the vacuum chamber one after another. The RF phases experienced by the particles are different from each other. With a velocity v_c and a longitudinal distance d_{long}, the phase difference $\Delta\varphi$ according to the RF frequency f amounts to

$$\Delta\varphi = 2\pi \cdot \frac{d_{\text{long}}}{c} \cdot f\,, \qquad (1)$$

After the electrons leave the cavity, the motion is straight. They strike on the screen with a vertical distance $d_{\rm ver}$ and produce radiation. That is imaged with a profile downstream. If the particles are located within the linear range of the sine, the vertical distance on the screen is proportional to their longitudinal distance in their motion.

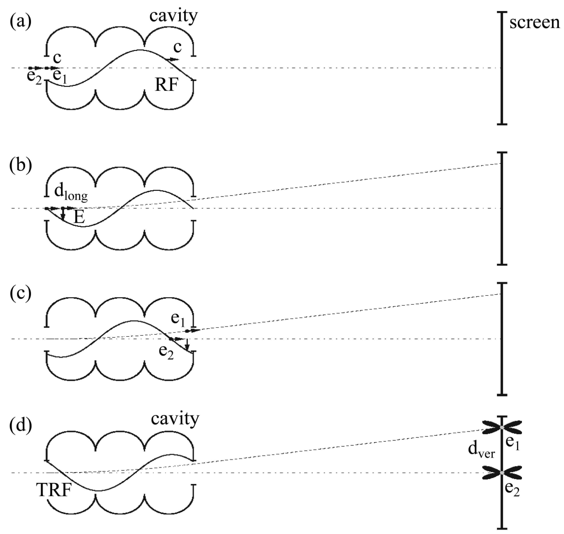

Fig. 4. Bunch length measurement principle.

The measured intensity distribution is a convolution of the streaked longitudinal and vertical beam distribution. Assuming a Gaussian beam distribution in both the y and z directions, where y and z are the vertical and longitudinal coordinates respectively, the measured beam size $\sigma_{\rm meas}$ can be expressed as

$$\sigma^2_{\rm meas}=\sigma^2_{\rm hor}+\sigma^2_{\rm long}, \quad (2)$$

where $\sigma_{\rm hor}$ is the horizontal beam size without deflection. $\sigma_{\rm long}$ is the longitudinal beam size on the screen.

5 Measurement procedure

5.1 System calibration

Because the deflecting direction is vertical, we use triplet magnets to focus the vertical beam size small, as shown in Fig. 5(a). The data are the means of 10 images which are then Gauss fitted, shown in Fig. 5(b). The maximum value of the graph is the centroid position of the bunch. The optical system is calibrated, and we get 1 pix = 136 μm.

The zero crossing was confirmed by the down stream profile. The input power was fixed and the phase changed by 180°. We can see the beam spot from down to up, and the mean place is considered as the zero crossing.

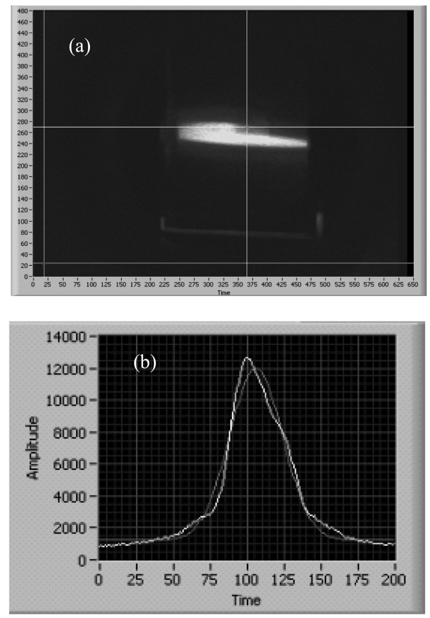

Fig. 5. The compressed bunch and Gauss fitting graph.

5.2 The transverse bunch size

When the gun works, we cannot stop the input power to the deflector. In order to obtain the transverse beam size, we tune the attenuator value to the maximum and change the phase shifter till the bunch is on the RF crest (phase is 90° or −90°). This size is used as the vertical beam size of the deflecting direction. Its rms value is 0.64 mm.

5.3 The reference longitudinal resolution

From Fig. 6, we can see that the longitudinal beam size is not only kicked but also enlarged. In order to evaluate better the scaling factor between the bunch longitudinal length and its vertical dimension on the screen, the deflector deviation is calibrated by measuring the beam center position vs. the varying deflector phase. From the curve slope the scaling

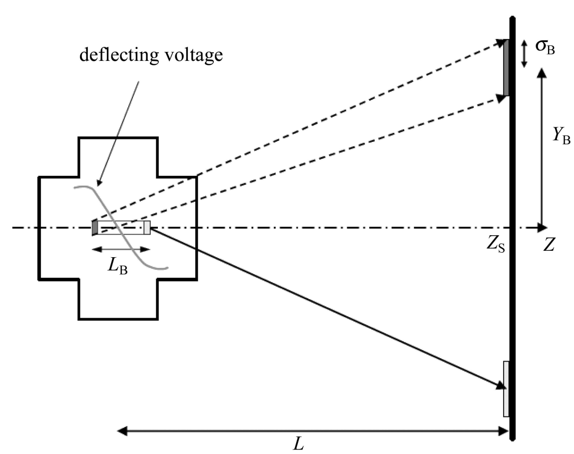

Fig. 6. The enlarged longitudinal bunch length.

factor between the longitudinal and the vertical dimensions is obtained.

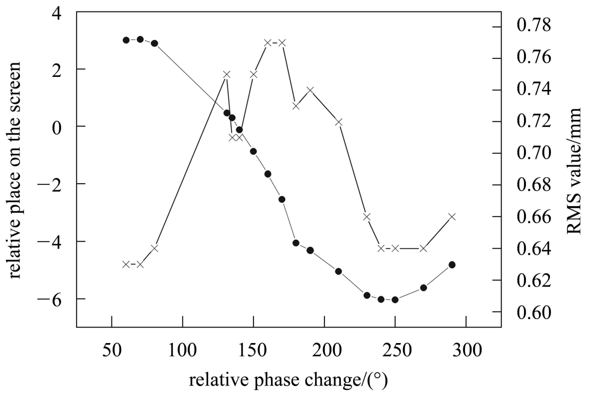

Fig. 7. Centroid positions and beam sizes for different RF phases.

We choose the input power of 9.16 kW as a reference power. This is the biggest input power to the deflector which does not make the beam image out of the profile when the phase is changed in the range of 180°. As the phase shifter is changed by 180°, we can see that the change of the centroid position of the beam on the profile is like a sine graph. Fig. 7 shows the centroid position and the corresponding measured beam size on the screen when we change the phase shifter more than 180°. At this power, the longitudinal resolution is 4°/mm, the measured beam size at zero crossing on the screen is 1.26 mm. So the bunch length is 4.22 ps (rms).

5.4 Measurement result

Figure 8 gives the beam spot at zero crossing at different input powers.

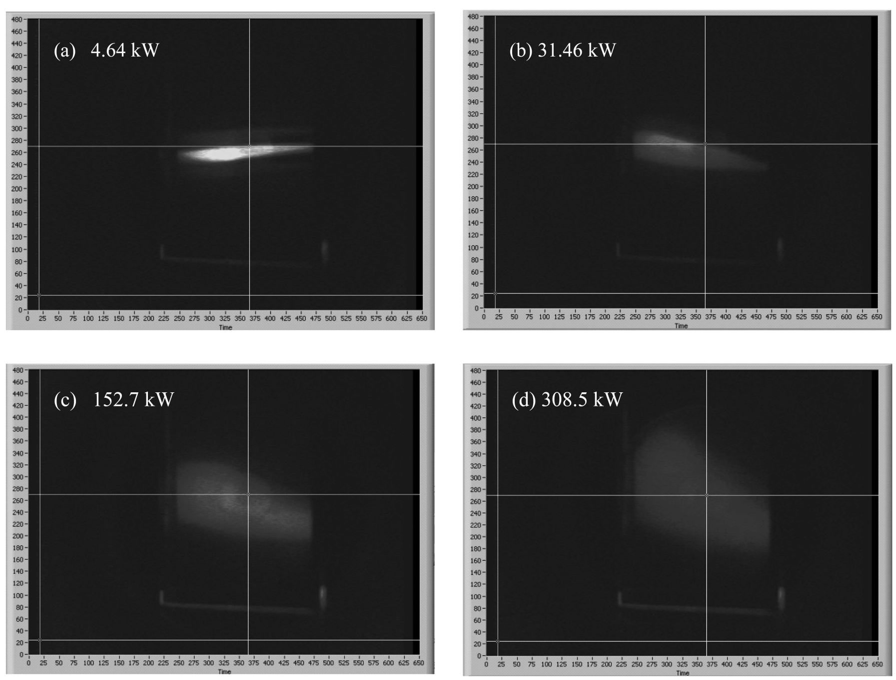

Fig. 8. Beam spots for different input powers.

We know that the acceleration of a charged particle within an electric field is proportional to the voltage square v^2. The corresponding power P is proportional to v^2. Thus the resolution r at an arbitrary power P is calculated by

$$r = r_{\rm ref} \cdot \sqrt{\frac{P_{\rm ref}}{P}}\,, \tag{3}$$

where $r_{\rm ref}$ is the reference longitudinal resolution corresponding to the reference input power $P_{\rm ref}$. From this relationship, we get the bunch length at different input powers. See Fig. 9. Finally we get the mean value of the bunch length 5.25 ps (rms).

For our system, the transverse bunch length is 0.64 mm. So the maximum beam size at the YAG stream of the streaked longitudinal bunch length is 0.64 mm. Our permitted maximum input power is 308.5 kW for the test system. At this power, the longitudinal resolution is 0.69°/mm. So the whole system's resolution of the bunch length is 0.43 ps (rms).

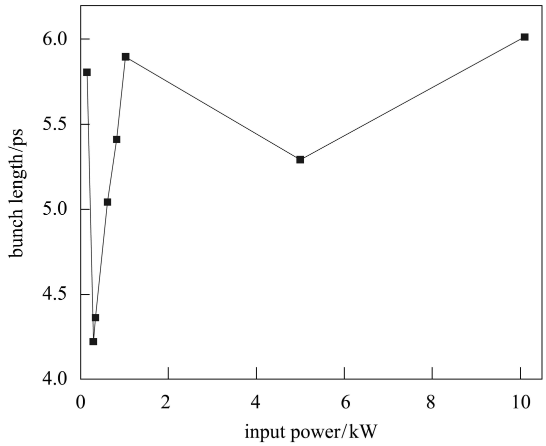

Fig. 9. Bunch lengths for different input powers.

6 Conclusions

A transverse RF deflector was fabricated and tested. The bunch length was measured and reasonable results were obtained. More work will be done at the Shanghai DUV FEL facility using this deflector and to prepare for a reliable bunch length monitor in the future.

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