BUNCH LENGTH MEASUREMENT WITH RF DEFLECTING CAVITY AT TSINGHUA THOMSON-SCATTERING X-RAY SOURCE *

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Abstract

An S-band RF deflecting cavity has been developed and applied for measuring the bunch length at Tsinghua Thomson-Scattering X-ray Source (TTX). This paper briefly introduces the 3-cell π-mode standing-wave deflecting cavity and reports the recent experiments of the beam diagnostics for the photo-cathode RF gun, which produces electron bunches with RMS length around 1-ps. It is also observed that the bunches are lengthened while the total charge increases, showing the strong space charge effect at a low beam energy.

INTRODUCTION

A photo-cathode RF gun has been built at Tsinghua University for the Thomson Scattering X-ray Source[1]. Preliminary experiments on this RF gun include a well-designed electron diffraction experiment[2] and a collision test of the electron pulse and the laser pulse[1]. An S-band RF deflecting cavity has been developed for bunch length measurement[3, 4].

The RF deflecting cavity gives phase-dependent transverse kick to the particles, and linearly couples the trajectory angle with the longitudinal position of a particle inside a bunch by

$$y' = \frac{keV_{\rm def}}{W}s, \quad (1)$$

where $V_{\rm def}$ is the deflecting voltage, k is the wave number, e is the charge of electron, W is the beam energy and s is the longitudinal coordinate of the particle. The reference particle of the bunch passes the deflecting cavity at "zero-phase".

Setting up a screen after a drifting space D from the deflecting cavity, the transverse beam size at the point is[5]

$$\sigma_y = \sqrt{\sigma_{y,0}^2 + \left(\frac{keV_{\rm def}D}{W}\sigma_s\right)^2}, \quad (2)$$

where $\sigma_{y,0}^2$ is the beam size on the screen without deflection, determined by the transverse emittance and the transport magnets. If two points at different longitudinal position can be separated farther than $\sigma_{y,0}$ on the screen, they can be distinguished for slice emmitance measurement. The longitudinal distance between the two points is defined as the resolution length of the measuring system[6], which can be calculated by

$$\Delta_{\rm s} = \frac{\sigma_{y,0}W}{keV_{\rm def}D}. \quad (3)$$

BUNCH LENGTH MEASUREMENT SYSTEM FOR TTX

The Tsinghua Thomson-Scattering X-ray Source (TTX) will be constructed phase by phase. The electron bunch produced by the photo-injector of the three phases are

(I) The 3.5-MeV electron bunch with length $\sigma_t \approx 3$ps
(II) The 50-MeV bunch after being accelerated, still with length $\sigma_t \approx 3$ps
(III) The 50-MeV bunch after being compressed by magnetic chicane, with $\sigma_t \approx 1$ps.

To achieve the resolution length of $\Delta_s = 0.1\sigma_s$, we had calculated the required deflecting voltage $V_{\rm def}$, shown in Table 1. The same deflecting cavity will be used throughout all the period. In the table, $R_\perp = V_{\rm def}^2/P$ is the transverse shunt impedance, while P is the input RF power. The beam energy E_0 is the kinetic energy of electrons, while for equation(2), the rest mass energy of electron, 0.511-MeV, should be included in W.

Table 1: Parameters of the bunch length measurement system for the TTX injector at different phases

	Phase-	I	II	II
E_0	(MeV)	3.5	50	50
σ_t	(ps)	3	3	1
f_0	(MHz)	2856	2856	2856
$V_{\rm def}$	(MV)	1.0	1.3	3.4
D (R_{34})	(m)	0.4	2.0	2.5
$\sigma_{y,0}$	(mm)	1.0	0.3	0.3
Δ_s	(mm)	0.10	0.10	0.03
σ_y	(mm)	10	3.1	3.1
$R_\perp$	(MΩ)	2.85	2.85	2.85
P	(MW)	0.4	0.51	4.0
$E_{\rm peak}$	(MV/m)			~ 75

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The S-band deflecting cavity

The RF deflecting cavity is a normal conducting cavity operated at the same frequency as the photo-cathode RF electron gun at 2856 MHz. Since the required deflecting voltage is low, we selected the disk-loaded structure working at the π-mode standing-wave and three cells are need with $(R/Q)_\perp = 198\Omega$. Figure 1 shows the CAD model. The peak electric field in simulation was 75 MV/m for the 3.4-MV deflecting voltage, which is achievable for well processed copper surface.

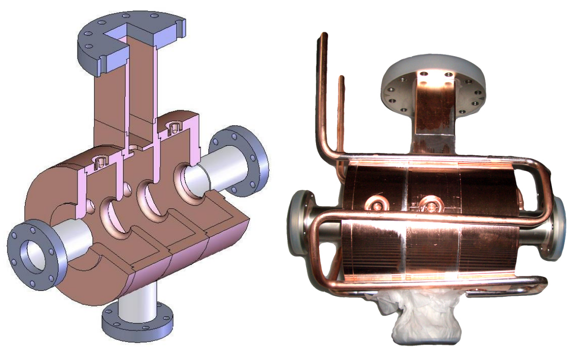

Figure 1: The CAD model and a photo of the deflecting cavity

A section of "WR-284"("BJ-32") waveguide was attached on the central cell and a coupling slot with racetrack shape (shown in figure 1) was opened as the input power coupler. The dimensions of the slot were designed by parameterized simulation to critical coupling with $Q_0 = Q_{\text{ext}}$ using time domain analysis[7]. For symmetry consideration, another slot with exactly the same size was added on the opposite side of the coupler. It will also be used as the vacuum pump port, by connecting to a pipe and flange with the same size as the beam pipe.

The cavity has been fabricated, tuned and brazed at Tsinghua University, with water pipes for control the cavity temperature directly brazed on the outside wall of the cavity. The final Q_0 after brazing is 16000.

The power feeding system

The klystron for the TTX injector provides 45-MW peak power at 2856 MHz, and the power is divided to feed two branches by an -5dB directional coupler. "A" is for the photo-cathode RF gun, while "B", followed by a phase shifter and an attenuator, is for the 3-meter traveling-wave accelerating section that will boost the beam energy to 50-MeV. However, in the first phase, a matched load is used instead of the accelerator tube. The power for the deflecting cavity was separated from the "B"-branch by the -10dB directional coupler. Fig 2 shows the scheme.

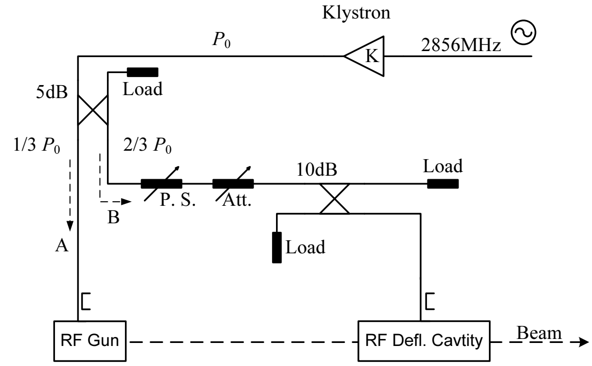

Figure 2: The power feeding scheme for TTX Phase-I

THE EXPERIMENT

The beam-line is shown in figure 3. The YAG screen is mounted in the chamber, followed by a mirror with 45° angle, which allows the camera to be set up beside the beam line. The beam profile on the screen was captured under different deflecting voltage. It is almost round with no deflecting, but vertically stretched if RF power is delivered into the cavity.

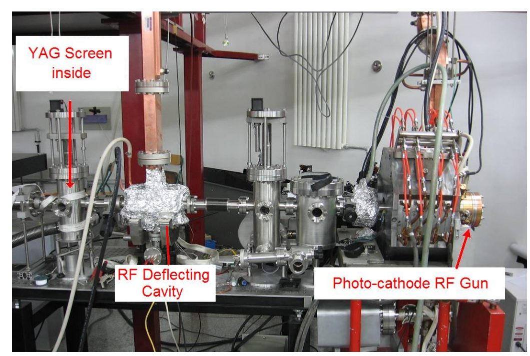

Figure 3: Snapshot of the beam-line

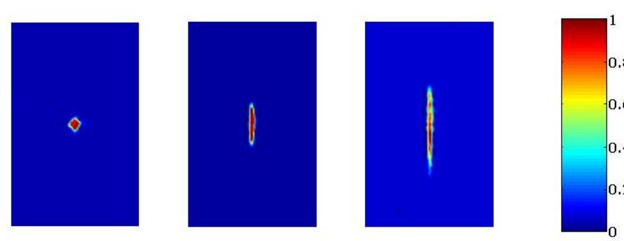

Figure 4: Beam spot with different deflection (attenuation from left: >30dB, 15dB, 7dB)

The distribution of a beam spot is plotted in Figure 5, together with the gaussian curve fitting, giving the RMS beam size as $\sigma_y = 13.8$pixels. The $S(y) = \sum_x I(x, y)$ means the summary through x direction. A pixel point in the photo represents 0.0869-mm actual size at the YAG-screen, thus we have

$$\sigma_y = 13.8 \times 0.0869\text{mm} = 1.20\text{mm} \quad (4)$$

$$\sigma_{y,0} = 2.1 \times 0.0869\text{mm} = 0.18\text{mm} \quad (5)$$

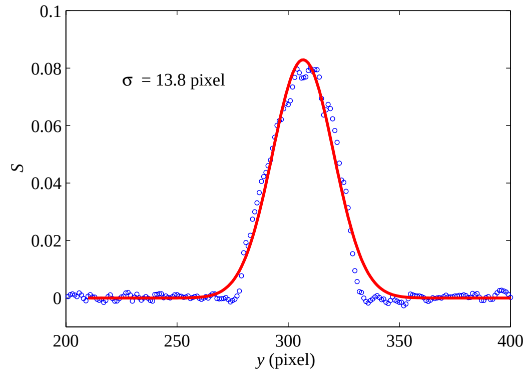

Figure 5: Gaussian fit of the bunch profile at screen

The deflecting voltage from input RF power

Equation (2) can be used to calculate the bunch length, if the deflecting voltage is obtained. The RF power generated by the klystron is 13.6 MW during the experiment, and the deflecting cavity get about 0.36 MW through the directional couplers (-5dB, -10dB), the attenuator (-2.8dB) and the long waveguide (85%). So we calculate the deflecting voltage by

$$V_{\mathrm{def}} = \sqrt{P_{\mathrm{in}} R_{\perp}} = 1.07\mathrm{MV}(\pm 0.04). \qquad (6)$$

The beam energy is 2.7$\pm$0.05MeV, which makes $W = 3.21 \pm 0.05$MeV. The distance from the deflecting cavity to the YAG screen is $D = 308.7 \pm 1$mm. Substituting these parameters into equation (2) yields

$$\sigma_s = 0.195 \pm 0.013\mathrm{mm}, \quad \sigma_t = 0.65 \pm 0.04\mathrm{ps}. \qquad (7)$$

The calibration by the phase-shifter

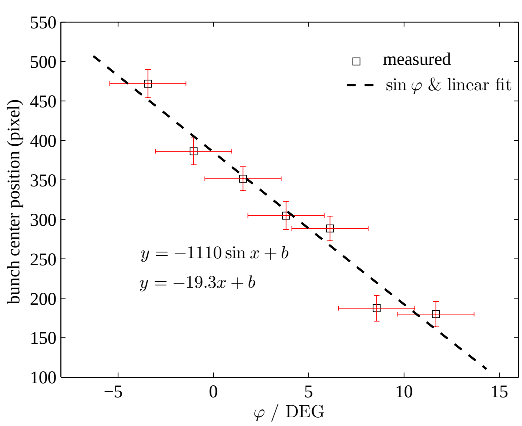

Figure 6: Beam position (vertical) with respect to the RF phase

The relationship between the bunch position and the RF phase when the bunch passes the cavity is

$$y = -\frac{eV_{\mathrm{def}}D}{W} \sin\varphi. \qquad (8)$$

If φ is small, we have "$\sin\varphi = \varphi$" and the relationship is linear. The phase shifter can be used to tune the RF phase, with the results plotted in figure 6. The slope is $\alpha = 1110^{\pm 50}$ pixel/rad, so the bunch length can be calculated by $\sigma_y/(\alpha\omega) = 0.70^{\pm 0.03}$ ps, where $\omega = 2\pi f$ is the angular frequency in $\mathrm{rad}\cdot\mathrm{s}^{-1}$.

It is also observed that the bunch position is jumping up and down on the screen, because of the time jitter. With statistics of the captured 100 bunch snapshots, we calculate the RF phase jitter of the electron bunch is about 0.9 degree RMS, or about 0.9 ps.

The bunch length v.s. the total charge

Another experiment is carried out to study the effect of the bunch charge and the result is shown in figure 7. The electric field on the cathode is approximately 50MV/m and the beam energy is 2.5MeV. The space charge effect was dominate for the bunch length. Even the total charge is as low as 10pC, the bunch length is 1ps, much larger than the input laser pulse, which is less than 150fs, RMS.

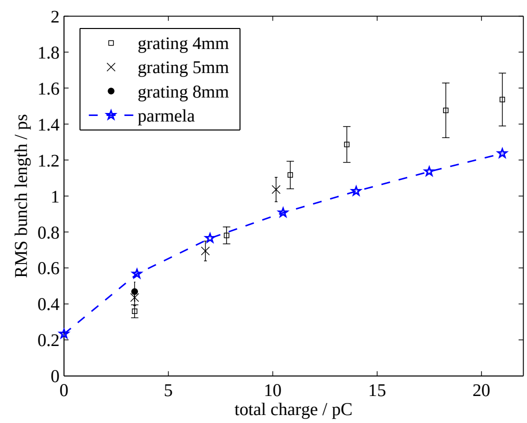

Figure 7: The bunch length with respect to the bunch charge (measured and comparison with Parmela

CONCLUSION

A 3-cell π-mode standing-wave RF deflecting cavity has been developed for the beam diagnostics of TTX injector at Tsinghua University. The bunch length of 0.7ps has been measured, with the accuracy better than 30fs. The accuracy can be improved by stabilizing the temperature of the deflecting cavity to better control the RF phase of the cavity during calibration.

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