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# RF deflecting cavity design for bunch length measurement of photoinjector at Tsinghua University*

SHI Jia-Ru(施嘉儒)[1)] CHEN Huai-Bi(陈怀璧) TANG Chuan-Xiang(唐传祥) HUANG Wen-Hui(黄文会) DU Ying-Chao(杜应超) ZHENG Shu-Xin(郑曙昕) REN Li(任丽)

(Department of Engineering Physics, Tsinghua University, Beijing 100084, China)

**Abstract** RF deflecting cavity can be used for bunch length measurement and is designed to diagnose the beam produced by the photocathode electron gun which was built at Tsinghua University for the Thomson scattering experiment. Detailed discussion and calculation for measuring the 3.5 MeV bunch and another with further acceleration to 50 MeV, which is under development, are presented. A standing-wave deflecting cavity working at 2856 MHz is designed and the power feeding system has been planned.

**Key words** RF deflecting cavity, bunch length measurement, photocathode electron gun

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## 1 Introduction

The photocathode RF electron gun was built at Tsinghua University to produce high quality electron beams for Thomson scattering, the scheme that uses the beam to collide with laser pulses to generate X-rays. The preliminary experiment using 5 MW klystron gives a 3.5 MeV gaussian bunch with the total charge 0.5 nC and the laser pulse has a width of $\sigma_t = 3$ ps. The emittance is 3 mm·mrad[1, 2]. Future plans include acceleration of the bunch to 50 MeV and compression of the bunch length to approximately 1 ps using magnetic chicane[3].

The length, and even the longitudinal distribution of the electron bunch, can be diagnosed by the RF deflecting cavity working at $TM_{110}$-like mode. The high frequency field in the cavity gives a phase dependent transverse kick and the longitudinal distribution of the bunch is converted to the transverse distribution on the screen after drifting a distance. This is the most direct method of measuring the bunch length and gives high resolution.

The method was first mentioned and carried out some years ago. In 1995, a rectangular cavity working at $TM_{102}$ was used to measure the bunch length at BNL. The rms bunch length was 4.7 μs[4]. At SLAC, the traveling-wave deflecting cavity (LOLA) that was designed for particle separation in the 1960s was used here and it was reported in 2000 that a bunch with the length 20 ps was measured[5, 6]. Recently, the structure was again used in LCLS[7]. INFN has designed a 9-cell S band standing-wave deflecting cavity to measure their 150 MeV bunch[8], while UCLA[9] has made an “X-Band” standing-wave structure to diagnose the beam with the energy of 15 MeV.

The photo-injector for the Thomson Scattering X-ray Source at Tsinghua University will be completed phase by phase, with different beam energies depending on the availability of the RF power source. To diagnose the beams, we have made the designs of bunch length measuring system and the RF deflecting cavity that match all the phases of the project. The same deflecting cavity will be used for the beam diagnostics of different bunch length and beam energy during the construction of the beam line and the upgrading of the klystrons and power feeding systems.

This paper presents the detailed calculation of the requirement for the three different measuring systems and the design of a 3-cell standing-wave deflecting cavity working at 2856 MHz. The deflecting structure with power input coupler design and the power supply schemes are presented.

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1) E-mail: shijiaru00@mails.tsinghua.edu.cn

## 2 Bunch length measurement using RF deflecting cavity

The RF deflecting cavity works at $TM_{110}$-like mode. It has strong transverse magnetic field on axis inside the cavity and transverse electric field near the irises and beam pipes, which may give force to a particle with speed $v=c$ and charge $q$:

$$F_y(z)=q\left[\widetilde{E}_y(z)+c\widetilde{B}_x(z)\right], \tag{1}$$

where $\widetilde{E}_y(z)$ and $\widetilde{B}_x(z)$ are the time-dependent field components at the specified direction.

In a standing-wave cavity, the electric field and the magnetic field can be described with amplitude multiplied by the time dependence factor $e^{-j(\omega t+\varphi)}$ and there is a phase difference of $\pi/2$ between them. The deflecting voltage can be written as:

$$V_y=\int_{-L/2}^{L/2}\left[E_y(z)e^{-j(\kappa z+\varphi)}-jcB_x(z)e^{-j(\kappa z+\varphi)}\right]dz, \tag{2}$$

where $\kappa=\omega/c$ is the wave number, $E_y$ and $B_x$ are the field magnitude of the component, and $\varphi$ is the RF phase when the particle passes the cavity center where $z=0$. Generally, for a cavity with a symmetry plane at $z=0$ and electric boundary condition for $E_y=0$, the particle with $\varphi=\pi/2$ gets maximum deflection and is defined as $V_{def}$:

$$V_{def} = V_y(\varphi=\pi/2)= -\int_{-L/2}^{L/2}[E_y(z)\sin\kappa z+cB_x(z)\cos\kappa z]dz. \tag{3}$$

Then the transverse deflecting voltage of a particle obtained can be simply written as:

$$V_y=V_{def}\sin\varphi\ . \tag{4}$$

Inside a bunch, the longitudinal distribution of the particles can be described using the RF phase:

$$\varphi(s)=\varphi_0-\kappa s\ , \tag{5}$$

where $\varphi_0$ is the phase of the reference particle at bunch center. By putting $\varphi_0=0$ and assuming $s\ll\lambda$, we can get

$$y'_f=-\frac{qV_{def}}{E_0}\kappa s\ . \tag{6}$$

We use thin lens approximation and the transmission matrix of the element is shown as:

$$\begin{bmatrix} y\\ y'\\ s\end{bmatrix}=\begin{bmatrix}1&0&0\\0&1&\dfrac{-\kappa qV_{def}}{E_0}\\0&0&1\end{bmatrix}\times\begin{bmatrix}y(0)\\y'(0)\\s(0)\end{bmatrix}. \tag{7}$$

Setting up a drifting space after the deflecting cavity, the obtained $y'$ will be converted to offset $y$ and the head and tail of the bunch will have a different transverse position. The transmission matrix of a drifting pipe with length $D$ in 2-D phase space is

$$R_2=\begin{bmatrix}1&D\\0&1\end{bmatrix}. \tag{8}$$

It is easy to calculate the transverse beam size at flag:

$$\sigma_y=\sqrt{\sigma_{y,0}^2+\left(\frac{\kappa qV_{def}}{E_0}\sigma_z D\right)^2}\ , \tag{9}$$

where $\sigma_{y,0}^2$ is the beam size on flag without deflecting. The first term under the square root is the transverse beam size caused by the transverse emittance while the second term is from the phase-dependent deflecting of longitudinally distributed particles.

To get high accuracy, the transverse spot size contributed by tilting the longitudinally distributed bunch should be larger than $\sigma_{y,0}$, the spot size from transverse beam emittance. While studying the resolution length of the bunch length measuring system, we follow the definition from reference[8] as:

$$L_{res}=\frac{\sigma_{y,0}E_0}{\kappa qV_{def}D}, \tag{10}$$

which means that the transverse beam size at flag has a resolution length equal to $\sigma_{y,0}$.

Table 1. Parameters of 3 different configurations.

| | | | | | |
|---|---|---|---|---|---|
| $E_0$ | 3.5 | 50 | 50 | MeV | |
| $\sigma_z$ | 1 | 1 | 0.3 | mm | ~3 ps, 1 ps |
| $\varepsilon_N$ | 3 | 3 | 3 | mm·mrad | |
| $\varepsilon$ | 0.39 | 0.03 | 0.03 | mm·mrad | $\varepsilon_N/\beta\gamma$ |
| $f_0$ | 2856 | 2856 | 2856 | MHz | |
| $V_{def}$ | 0.6 | 1.3 | 3.4 | MV | |
| $D$ | 1 | 2 | 2.5 | m | |
| $\sigma_{y,0}$ | 1.0 | 0.3 | 0.3 | mm | |
| $L_{res}$ | 0.10 | 0.10 | 0.03 | mm | |
| $\sigma_y$ | 10 | 3.1 | 3.1 | mm | |
| $R^*_\perp$ | 2.85 | 2.85 | 2.85 | MΩ | |
| $P_0$ | 0.12 | 0.51 | 4.0 | MW | |
| $E_{peak}$ | | | ~75 | MV/m | |

Using the beam parameters in the Thomson scattering system, and the requirement for resolution as $L_{res}=0.1\sigma_z$, different deflecting voltages $V_{def}$ are calculated by Eq. (10). Table 1 shows the required $V_{def}$ of the cavity for the three different configurations:

(1) 3.5 MeV bunch with $\sigma_t\approx3$ps, which we have already obtained.

(2) 50 MeV bunch after acceleration by linac (s), with bunch length $\sigma_t\approx3$ps.

(3) 50 MeV bunch after chicane, with 1/3-compressed bunch length.

Also presented in the table are the shunt impedance $R_{\perp}^{*}$, required power $P_0$, and the maximum electric field $E_{\rm peak}$ on the surface. These results are from the simulation in MAFIA E module, which will be discussed in the following section.

## 3 RF deflecting cavity design

### 3.1 Cavity geometry

The cavity shape is a regular disk-loaded structure, as shown in Fig. 1.

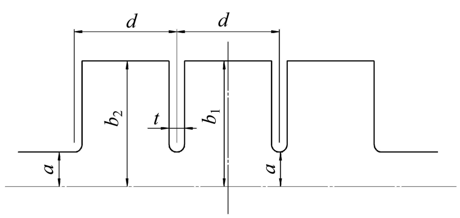


Fig. 1. 2-D geometry of the 3-cell deflecting cavity.

The MAFIA E module is used to calculate the field distribution of the eigen-modes in the cavity. $Q_0$ and shunt impedance is calculated in postprocessing. The shunt impedance is defined as

$$R_{\perp}^{*}=\frac{V_{\rm def}^{2}}{P}=\frac{\left[\left|\int_{\rm D}E_z(r=r_0){\rm e}^{-{\rm j}\kappa z}{\rm d}z\right|\right]^2}{(\kappa r_0)^2 P}, \qquad (11)$$

where $P$ is the power dissipated on the cavity wall, and $E_z(r=r_0)$ is the longitudinal electric field off-axis at $r=r_0$. Using the integral of electric field off-axis to calculate the transverse shunt impedance is derived from the Panofsky-Wenzel theorem, which gives the relationship between transverse and longitudinal voltage.

The maximum electric field on the surface should be kept below a safe threshold to avoid microwave breakdown. Though there is no theoretical value, we decide to keep it below 80 MV/m. In simulation, after the field values of the eigen-modes are exported in postprocessing, the maximum field is found and normalized by the deflecting voltage. An estimation shows that a 3-cell cavity with $E_{\rm peak}/V_{\rm def}\approx 22{\rm m}^{-1}$ may achieve the requirement.

The field balance can be tuned by changing the frequency of each individual cell. Since the frequency of the π mode is the lowest among the $TM_{110}$-like series, enlarging one cell radius will lower the frequency and yield more fields in that cell. Because of the end beam-pipe, the radii of the two end cells are larger than that of the central cell to keep the field distribution flat on all the 3 cells. Table 2 shows the parameters used in eigen-mode simulation.

Table 2. Geometry parameters of 3-cell cavity.

| | |
|---|---|
| $a$ | 17.5 mm |
| $b_1$ | 60.87 mm |
| $b_2$ | 61.61 mm |
| $d$ | 52.5 mm |
| $t$ | 10 mm |
| $x_{\rm p}$ | 37 mm |
| $r_{\rm p}$ | 8 mm |
| $(R/Q)_{\perp}^{*}$ | 198 Ω |
| $Q_0$ with coper | 17000 |
| $0.85Q_0$ | 14400 |
| $R_{\perp}^{*}$ using 85% $Q$ | 2.85 MΩ |
| $E_{\rm peak}/V_{\rm def}$ | 22 $\rm m^{-1}$ |
| $f$ of working mode/MHz | 2856.0 |
| $f$ of π/2 mode/MHz | 2874.7 |
| $f$ of 0-like mode/MHz | 2929.5 |
| $f$ of π the other polarization/MHz | 2864.0 |

### 3.2 Polarization alignment

The $TM_{110}$ is the dipole mode which has two polarizations. One is the working mode at $y$-direction, while the other is at the $x$-direction. These two modes share the same frequency if the cavity is azimuthal symmetric.

To study the degenerate modes and separate the $x$- and $y$-directions, the 2-D model of the $rz$ coordinate system is not enough and 3D models in $xyz$ are generated. We made two polarization alignment holes on each disk between the cells at $(x_{\rm p},0)$ with radii of $r_{\rm p}$ as shown in Fig. 2. The two degenerate modes have different field types at the holes: the $y$-direction working mode has a strong magnetic field along the $x$-axis and the holes will lower its frequency; the unwanted dipole mode has a strong electric field there, so the frequency is pushed up. Table 2 gives the mode frequencies of both directions of the π mode, which have been separated by 8 MHz. And the frequency of the $y$-direction of the π/2 and 0-like modes are listed as well.

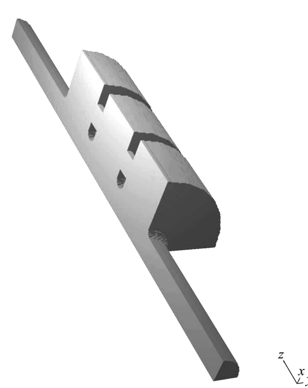


Fig. 2. 3-D MAFIA model of the 3-cell deflecting cavity with polarization holes.

### 3.3 Power input coupler design

The "BJ-32" (or "WR-284") waveguide, with a cross section of 72.04 mm × 34.14 mm, is used in the power feeding system and will be attached on the cavity with an open slot for coupling. Fig. 3 shows the schematic of the racetrack-shaped slot. Meanwhile, for symmetry consideration, a slot with the same shape is made at the opposite place for vacuum pipe. The coupling between the cavity and waveguide depends on the dimensions in the figure and the main task is to choose a geometry of the coupling slot to achieve the appropriate external quality factor $Q_{\mathrm{ext}}$.

For a standing wave structure with one input coupler, we have the requirement for critical coupling as

$$\beta_{\mathrm{in}} = \frac{Q_0}{Q_{\mathrm{ext}}} = 1 , \qquad (12)$$

where $\beta_{\mathrm{in}}$ is the coupling factor. The simulated $Q_0$ from the eigen-mode solver is $1.7 \times 10^4$. However, due to surface roughness and material defection, we usually get 85% of the theoretic $Q_0$, and it makes $Q_{\mathrm{ext}} = 1.45 \times 10^4$.

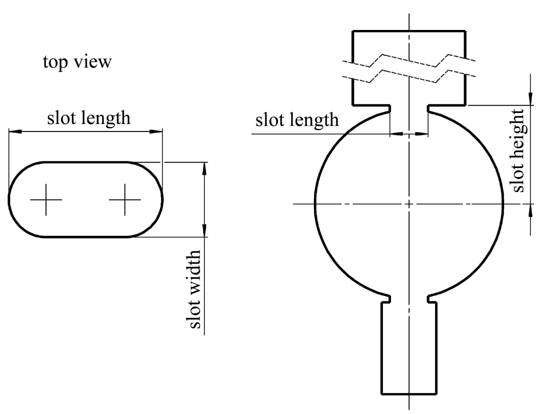


Fig. 3. Shape and dimension of the coupling slot.

The time domain solver in MAFIA T3 module can simulate the decay of RF electromagnetic field in a cavity coupled to a waveguide port and the energy decay rate can be used to calculate $Q_{\mathrm{ext}}$[10]. The most direct design procedure is to generate the whole 3-cell model and run parametric simulations, which will take a long time if we start from nothing. However, to make it easier, we begin with a smaller model of one-cell cavity coupled to the waveguide (Fig. 4).

The $Q_{\mathrm{ext}}$ requirement of a 1-cell structure can be calculated from the energy distribution in the three cells. Since the definition of $Q_{\mathrm{ext}}$ is

$$Q_{\mathrm{ext}} = \frac{\omega U}{P_{\mathrm{ext}}} , \qquad (13)$$

where $P_{\mathrm{ext}}$ is the external power dissipation, which is determined by the field pattern of the cell connected to the coupler and the geometry of the coupling slot, we estimate the external $Q$ by:

$$Q_{\mathrm{ext},1} = \frac{1}{3} Q_{\mathrm{ext}} = 4820 , \qquad (14)$$

where $Q_{\mathrm{ext},1}$ is the external quality factor of the single cell.

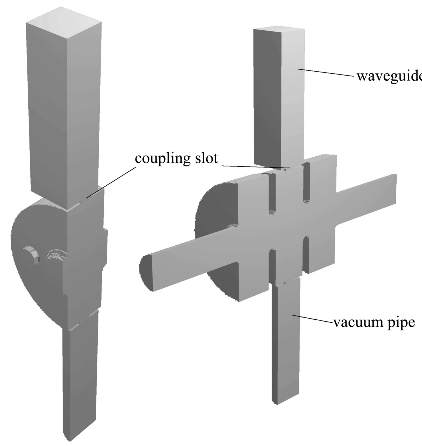


Fig. 4. 3-D MAFIA model for the coupler design of 1-cell (Left) and 3-cell (Right) structure.

In the 1-cell model, the $z$-direction boundaries, which are also the middle plane of the irises, are set as magnetic boundary to match the $\pi$ mode field distribution. A parametric sweep simulation of the slot length is made to get the required coupling, and the result shows there is an exponential relationship between the $Q_{\mathrm{ext}}$ and the length. From the curve fitting drawing, we solved the slot length to be 24.6 mm.

Also recorded are the frequencies of different lengths of the slot, showing that opening the cavity will lower the frequency, which should be tuned back to 2856 MHz by changing the radius while the slot length will be fixed for the coupling.

The 3-cell structure is then combined together to do a final run. Monitor of magnetic field on axis is set up during simulation. After $Q_{\mathrm{ext}}$ and the field flatness are verified, the last step is to tune the radii of all the three cells to get the mode frequency of 2856 MHz, which leads to the geometry parameters in Table 3. The simulated $Q_{\mathrm{ext}}$ of the total three cells is 14000, which is very close to our design goal.

Table 3. Parameters of the coupler of 3-cell cavity.

| | |
|---|---|
| $b_1$/mm | 60.38 |
| $b_2$/mm | 61.61 |
| slot length/mm | 24.6 |
| slot width/mm | 12 |
| slot height/mm | 64 |
| $Q_{\mathrm{ext},1}$ | 4800 |
| $Q_{\mathrm{ext}}$ | 14000 |

However, careful tuning during the fabrication and cold testing are still required, leaving a larger tolerance for the error of simulation. Also, tuning holes are made on the outer wall of the copper cavity for back up tuning after brazing and during operation. Fig. 5 shows the final CAD model for fabrication.

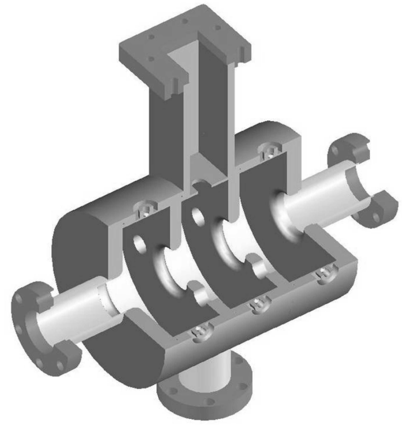

Fig. 5. CAD model for the 3-cell deflecting cavity.

## 4 Power feeding system

In Fig. 6, we present two different designs of the power feeding system for low energy and high energy configuration, focusing on the power distribution of the 5 MW klystron and the 45 MW klystron.

In the first scheme (Fig. 6(a)), most of the power is used for accelerating the electron beam in the photo-cathode RF gun to produce 3.5 MeV electron bunches. A 10 dB directional coupler separates one-tenth of the RF power from the main waveguide and is delivered to the deflecting cavity through attenuator and phase-shifter. A waveguide switch will be used to turn off the cavity and measure the spot size on the screen without deflection, $\sigma_{y,0}$.

The second one (Fig. 6(b)) uses 45 MW klystron for the injector and the 5 MW klystron for the deflecting cavity. The power of 45 MW will be divided into three parts for the photocathode RF gun and two linacs by 5 dB and 3 dB directional couplers. The deflecting cavity will receive the power from the 5 MW klystron separately, and the two klystrons will use the same low-level RF source for easier phase control.

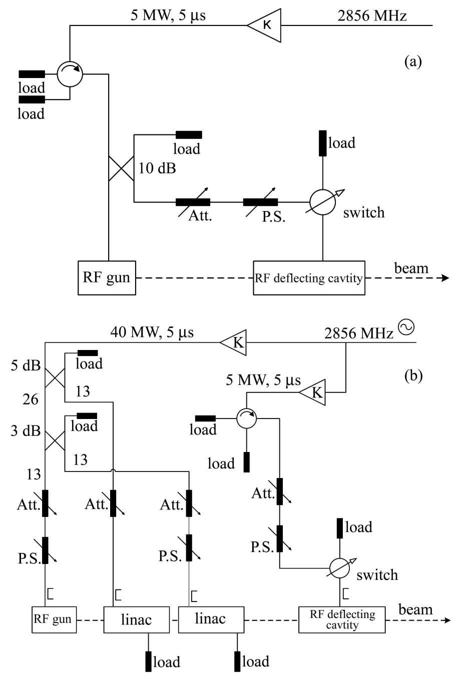


Fig. 6. (a) Power feeding system from 5 MW klystron with beam energy 3.5 MeV. (b) Power feeding system from 45 MW klystron with beam energy 50 MeV.

## 5 Conclusion

A 3-cell deflecting cavity has been designed for bunch length measurement in the Thomson Scattering X-ray Source at Tsinghua University. With one klystron giving 5 MW peak power to the RF gun and sparing 1/10 for the deflecting cavity, the designed resolution length of the measuring system is 100μm for 3.5 MeV bunch whose $\sigma_z = 1$ mm (~3 ps). After upgrading the beam line to 50 MeV and compressing the bunch length to $\sigma_z = 0.3$ mm (~1 ps), the designed resolution length is 30 μm with the 5MW klystron fully feeding the deflecting cavity.

From the coupling between the longitudinal and transverse phase space introduced by the RF deflecting cavity, it is possible to measure the slice emittance in the configuration presented here and more research will be carried out.

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