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# RF deflecting cavity for bunch length measurement in Tsinghua Thomson scattering X-ray source*

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**Abstract** An RF deflecting cavity used for bunch length measurement has been designed and fabricated at Tsinghua University for the Thomson Scattering X-Ray Source. The cavity is a 2856 MHz, $\pi$-mode, 3-cell standing-wave cavity, to diagnose the 3.5 MeV beam produced by photocathode electron gun. With a larger power source, the same cavity will again be used to measure the accelerated beam with energy of 50 MeV before colliding with the laser pulse.

The RF design using MAFIA for both the cavity shape and the power coupler is reviewed, followed by presenting the fabrication procedure and bench measurement results of two cavities.

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

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## 1 Introduction

The preliminary experiment of the photocathode RF electron gun that was designed to produce high quality electron beams for Thomson scattering at Tsinghua University obtained a 3.5 MeV gaussian bunch with the total charge of 0.5 nC[1, 2]. The laser pulse width was $\sigma_{\rm t} = 3$ ps and the peak power from the klystron was 5 MW. Future plan of the photo-injector is to accelerate the bunch to 50 MeV and compress the bunch length to approximately 1 ps using magnetic chicane[3].

A bunch length measuring system based on RF deflecting cavity has been designed to diagnose the bunches of different energies during the phases for constructing the beam line. The RF deflecting cavity in the system is a 3-cell disk-loaded standing-wave cavity working in $\pi$-mode at the frequency of 2856 MHz[4].

With oxygen-free copper, the structure has been fabricated, tuned and brazed step by step. This paper starts with reviewing the bunch length measuring system and the RF cavity design. Then the detailed fabrication procedure and the results of tuning the frequency and coupling of the cavity with microwave measurement are presented.

## 2 Cavity design consideration

Based on the phase-dependent transverse kick provided by the RF deflecting cavity, the longitudinal distribution of a bunch can be calculated from the beam spot on the screen after the bunch was tilted and drifted a certain space. Earlier research indicated that 0.6 MV deflecting voltage was required for the 3.5 MeV beam.

The input power, separated from the main klystron for the electron gun in the first phase, is 0.1 MW to produce the deflecting voltage for the low energy beam. It will later be upgraded to 4 MW for the 50 MeV beam.

The cavity is a three-cell disk-loaded structure.

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Both MAFIA 2-D and 3-D modules were used to simulate the cavity. The transverse $(R/Q)_\perp$ and the peak field were monitored in the post-processer of the code. The dimensions are listed in Table 1, where $a$ is the iris radius, equal to that of the beam pipe, $b_1$ and $b_2$ are the radii of central cell and end cells, $d=\lambda/2$ is the cell length and $t$ is the thickness of the disks between adjacent cells.

A section of "BJ-32"("WR-284") waveguide was attached on the central cell and a coupling slot with race-track shape (shown in Fig. 1) was opened as the input power coupler. The dimensions of the slot were also designed by parameterized simulation to critical coupling with $Q_0 = Q_{\rm ext}$ using time domain analysis[5]. 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 dimensions are listed in Table 1, where $l_{\rm s}$, $w_{\rm s}$ and $h_{\rm s}$ are the length, width and height of the coupling slot.

Table 1 also shows the simulation result of $(R/Q)^*_\perp$, $Q_0$ and so on. It can be calculated from the value of $E_{\rm peak}/V_{\rm def}$ that the peak electric field will be around 80 MV/m for the 3.4 MV deflecting voltage.

Table 1. Dimensions and parameters of the 3-cell cavity.

| geometry dimensions in mm | | | |
|---|---|---|---|
| $a$ | 17.50 | $b_1$ | 60.38 |
| $b_2$ | 61.61 | $d$ | 52.50 |
| $t$ | 10.00 | | |
| $l_{\rm s}$ | 24.60 | $w_{\rm s}$ | 12.00 |
| $h_{\rm s}$ | 64.00 | | |
| $f$ | 2856.0 | MHz | |
| $(R/Q)^*_\perp$ | 198 | $\Omega$ | |
| $Q_0$ with coper | 17000 | | |
| $0.85Q_0$ | 14400 | | |
| $R^*_\perp$ using 85% $Q$ | 2.85 | M$\Omega$ | |
| $E_{\rm peak}/V_{\rm def}$ | 22 | $\rm m^{-1}$ | |

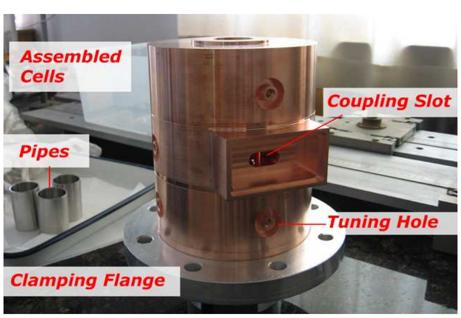


Fig. 1. Cavity in assembling showing the coupling slot.

## 3 Cavity fabrication

The fabrication starts from solid cylinders of oxygen free electric (OFE) copper with a lathe and a milling machine. After two cycles of cutting and anneal, the cells are assembled for the microwave measurement before final brazing. The first structure on the bench has a 0.20 mm smaller diameter than the final simulation, for the unknown error of the meshing in the code.

### 3.1 Bench testing

The microwave measurement was set up with an vector network analyzer (VNA), with a short plane in the waveguide used for calibration (shown in Fig. 2). The frequencies and the two quality factors, $Q_0$ and $Q_{\rm ext}$, are obtained from the reflection $(S_{11})$ curve.

The cavity was designed to work under 44℃ in vacuum, but measurements were carried out at room temperature with air, therefore, the linear expansion coefficient of copper, $\alpha$, and the relative permittivity of air, $\varepsilon_{\rm r}$, were used to estimate the operating frequency by

$$f(t_0)\approx f(t_1)\sqrt{\varepsilon_{\rm r}}\,[1-\alpha(t_0-t_1)], \tag{1}$$

where $t_0$ is the operation temperature, 44℃ and $t_1$ is the environment temperature of microwave measurement.

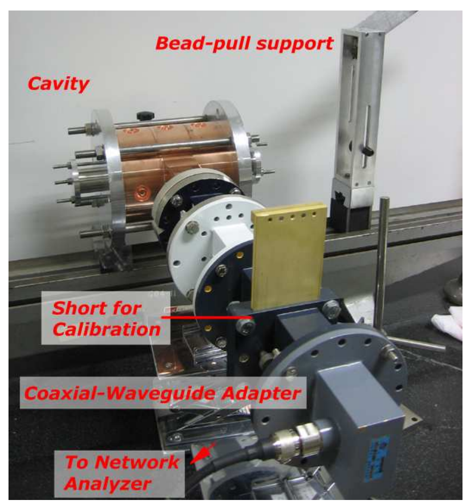


Fig. 2. Assembled cavity in microwave measurement.

### 3.2 Tuning the frequency and coupling

We have fabricated two cavities, and the history of the microwave properties can be found in Table 2. Since we left the cavity radii of 0.10 mm, the first frequency was higher than the target frequency as expected. This would be tuned by re-cutting the radii on the lathe.

The ratio of $\Delta f/\Delta 2b$ was $-21.3$ MHz/mm in simulation, while the values in the tuning process listed in Table 2 are $-20\pm2$ MHz/mm in the second step of Cavity-I and $-20.5\pm1.0$ MHz/mm in the first step of Cavity-II. Meanwhile, the frequency is also shifted by the increased opening of the slot for coupling tuning and simulation gives $\Delta f/\Delta l_s \approx -0.5$ MHz/mm. Depending on these slopes, the prediction of the frequency change by re-cutting the cells, noted as $(\Delta f)_p$ in the table, was quite successful.

The deformation during brazing will give a frequency shift which is hard to be predicted precisely, but in our experiences of the disk-loaded accelerating structures, it would be around 200 kHz. This was proved in this deflecting structure. The uncertainty of this shift would be tuned back by the tuners on the outer wall of the cavity shown in Fig. 1.

The $Q_{ext}$ was 14400 in CST time domain simulation, but we get high values up to 20000 in the first measurement for the two cavities. This is mainly because of the simulation error[5] and should be tuned by enlarging the slot. Another reason is that the decreased radius makes a larger distance from the cavity to the waveguide, and thus reduces the coupling. It is found that the $Q_{ext}$ decreased when the radii were cut for frequency tuning.

Table 2. History of the $Q$ factor and frequency.

| cavity-I | $f$/MHz | $Q_0$ | $Q_{ext}$ | $\Delta 2b$/mm | $\Delta l_s$/mm | $\Delta f$/MHz | $(\Delta f)_p$/MHz |
|---|---|---|---|---|---|---|---|
| first cut | 2862.559 | 15453 | 22809 | | | | |
| 1st step | 2857.409 | 15812 | 18118 | 0.22±0.01 | 1.0±0.04 | −5.150 | −5.2±0.2 |
| 2nd step | 2855.807 | 13333 | 15373 | 0.08±0.01 | | −1.602 | −1.7±0.2 |
| brazing | 2856.012 | 15975 | 15420 | | | | |
| cavity-II | $f$/MHz | $Q_0$ | $Q_{ext}$ | $\Delta 2b$/mm | $\Delta l_s$/mm | $\Delta f$/MHz | $(\Delta f)_p$/MHz |
| first cut | 2862.370 | 14381 | 20281 | | | | |
| 1st step | 2858.675 | 13049 | 18267 | 0.18±0.01 | | −3.695 | −3.8±0.2 |
| 2nd step | 2855.664 | 14036 | 14057 | 0.12±0.01 | 0.4±0.04 | −3.011 | −2.8±0.2 |
| brazing | 2855.975 | 16476 | 15116 | | | | |

Before being brazed, the cavities were clamped by the flanges and the obtained $Q_0$'s were around 14000, which was expected due to the bad RF contact between the cells. While the RF contact becomes better after brazing, the tested $Q_0$'s increased and almost reached the simulation value with ideal material and surface finish. This means that the expected 85% of the simulation value was too low.

But fortunately, the tolerance of the coupling is much looser than the frequency. Assuming we get the standing wave ratio $\rho=1.2$, the reflection coefficient at working frequency will be

$$|\Gamma|=\frac{1.2-1}{1.2+1}\approx 0.1\,, \tag{2}$$

so only 1% of the incident power will be reflected at steady state. We decided to tune the coupling factor to the target as

$$0.85<\beta<1.2\,, \tag{3}$$

where $\beta=Q_0/Q_{ext}$ is the coupling factor. The final results of the two cavities are 1.04 and 1.09.

Totally, the amount of re-cutting the diameter of two cavities were both 0.3 mm, but larger than the residual 0.2 mm compared with simulation. The slot lengths of them have a difference of 0.6 mm, but with close $Q_{ext}$. An explanation is the different field distributions of these two cavities, which were obtained by the "bead-pull" method and are shown in Fig. 3. Since the coupler is connected to the central cell, the more field in that cell yields the stronger coupling.

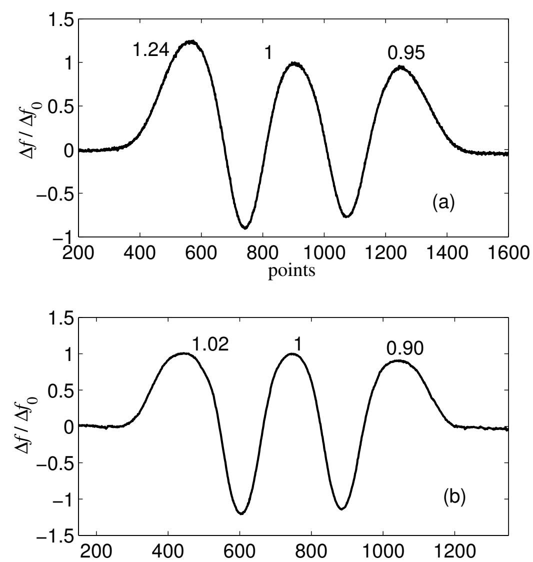


Fig. 3. On-axis field distribution of Cavity-I (a) and Cavity-II (b) measured by "bead-pull" method.

## 4 Conclusion

A 3-cell S-band deflecting cavity for bunch length measurement in Tsinghua Thomson Scattering X-ray Source is designed and fabricated. With carefully tuning the radii of the cells and the size of the coupling slot, we obtained the working frequency and the almost critical coupling.

The frequency prediction from the simulation tools was quit close to the experiment especially for the tuning slope. However, a 2 MHz frequency error at $S$-band (0.1 mm error of diameter) and $\sim 20\%$ error of the $Q_{\rm ext}$ still need to be improved.


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