CPC(HEP & NP), 2010, **34**(3): 405–408 **Chinese Physics C** Vol. 34, No. 3, Mar., 2010

Simulation and experiments for the $Q_{\rm ext}$ of a cavity beam position monitor

LI Xiang(李享)[1,2;1)] ZHENG Shu-Xin(郑曙昕)[1,2]

[1] Department of Engineering Physics, Tsinghua University, Beijing 100084, China
[2] Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China

Abstract The external Q ($Q_{\rm ext}$) of the dipole mode is a key parameter of the Cavity Beam Position Monitor (CBPM). It determines the amplitude and length of the dipole mode signal. In this paper, $Q_{\rm ext}$ of a CBPM whose waveguides were open to the air was simulated and measured, and the results agreed with each other. Then four waveguide-to-coaxial cable adpaters were adjusted and assembled to the CBPM, and $Q_{\rm ext}$ remained unchanged. This progress provides a reliable method to evaluate $Q_{\rm ext}$ in the physics design without simulating the structurally complex adapters.

Key words CBPM, $Q_{\rm ext}$, physics design, waveguide to coaxial cable adapter

PACS 29.27.Fh, 29.27.Eg

1 Introduction

Cavity Beam Position Monitors (CBPMs) measure the transverse position of the electron beam using the cavity's dipole mode. When the beam is passing through a cylindrical cavity, the amplitude of the excited dipole mode, TM110, is linear with respect to the beam's transverse position. According to the "fundamental theorem of beam loading" [1], the amplitude of the TM110 mode output signal is represented as

$$V=\frac{q\omega}{2}\sqrt{\frac{Z}{Q_{\rm ext}}(R/Q)}\ \exp\left(-\frac{\omega^2\sigma_Z^2}{2c^2}\right),\qquad(1)$$

where (R/Q) is the shunt impedance, and σ_Z is the bunch length. Considering the signal's vibration and decay, the complete expression is

$$V=\frac{q\omega}{2}\sqrt{\frac{Z}{Q_{\rm ext}}(R/Q)}\exp\left(-\frac{\omega^2\sigma_Z^2}{2c^2}\right)\times \exp\left(-\frac{t}{2Q_{\rm L}/\omega}\right)\cos(\omega t).\qquad(2)$$

The loaded Q ($Q_{\rm L}$) in the above expression also depends on $Q_{\rm ext}$. If the coupling is strong, $Q_{\rm ext}$ is much smaller than the internal Q (Q_0), and hence $Q_{\rm L}\approx Q_{\rm ext}$. Therefore, $Q_{\rm ext}$ determines both the signal's amplitude and length, and these two parameters closely relate to the scheme of electronics. Therefore it is very important to evaluate $Q_{\rm ext}$ in physics design in order to improve the scheme of the electronics.

The Accelerator Laboratory of Tsinghua University is keeping a model CBPM. In this paper $Q_{\rm ext}$ of this model CBPM was simulated and measured, and the results agreed with each other. This progress provides a reliable method to evaluate $Q_{\rm ext}$ in the physics design of the CBPM.

2 Model CBPM structure and coupling mechanism

Figure 1 shows the picture of the model CBPM. The model CBPM is composed of a position cavity and a reference cavity. The left cavity with four waveguides is the position cavity, and its output signal is linear to the beam position. The reference cavity is beside the position cavity. Its signal is used to calculate the beam charge and serves as the phase reference.

As a model cavity, the waveguides are open to the air. But for practical CBPMs there is a waveguide-to-coaxial cable adapter on each waveguide as shown in Fig. 2. According to Ref. [2], when the beam is pass-

---

Received 27 April 2009

1) E-mail: 213h001@gmail.com

ing through the position cavity, the TM110 mode is excited and coupled into waveguides, and this is the first-stage coupling. Then the excited TE10 mode in the waveguide is coupled out by the waveguide to the coaxial cable adapter, and this is the second-stage coupling. Each stage has its β and Q and this paper deals mainly with Q_{ext}.

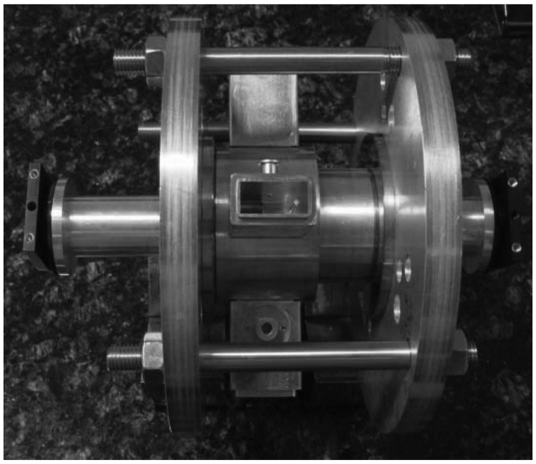


Fig. 1. Picture of the model cavity.

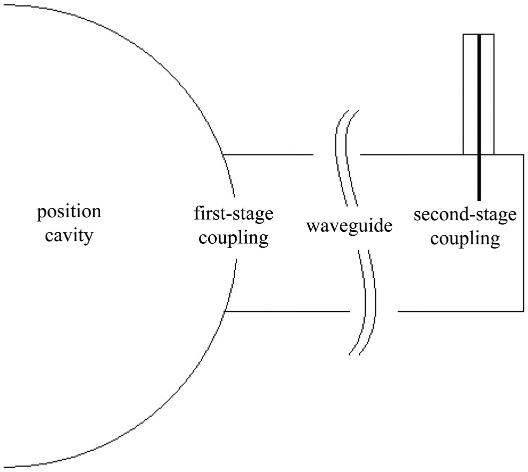


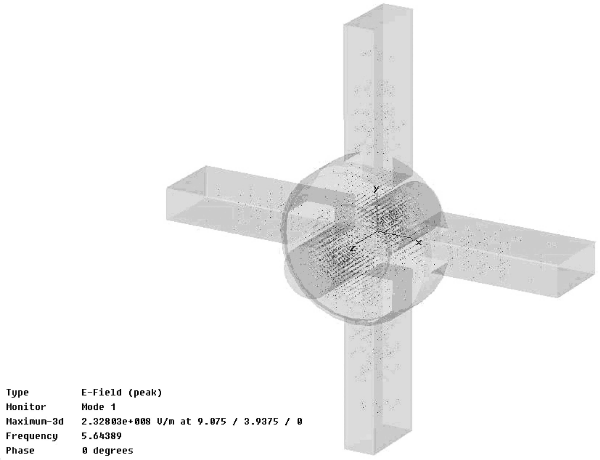
Fig. 2. Schematic diagram for two stages of coupling.

In CBPM designs people found that it was difficult to simulate the two stages of coupling together, so they did not consider the second-stage coupling in the physics design, but tried to solve it in experiments after brazing waveguides [2, 3]. In Ref. [2], the position cavity's Q_0 is about 10000, and β of the first-stage coupling is about 5. However, the total β of the two stages is only 0.75 and Q_{ext} increases from 2000 to 13000 unpredictably. Researchers from KEK-ATF simulated Q_{ext} of the two stages of coupling together, but the result did not agree with that of the two stages simulated separately[1]. Therefore they had to determine the adapter's probe length in experiments [3]. In both conditions, because Q_{ext} was unable to be evaluated in physics design, it was also difficult to make the second-stage coupling satisfactory in experiments. Moreover, if the scheme of electronics sets requirement for Q_{ext}, the above two conditions are probably unable to achieve it.

3 Simulation results of Q factors

To calculate the Q factors of the CBPM, the 3-D electromagnetic field simulation software MAFIA was used, and the modeling is presented in Fig. 1. As mentioned above, it is difficult to simulate the two stages of coupling together, so only the first-stage coupling was simulated. The reflection of each waveguide port was set to zero, so the TE10 mode was able to completely transmit outside. To calculate Q_{ext}, we used the energy decay method in the time domain [4]. The excitation source was set in parallel with the cavity's axis and 1 mm below. According to the magnetic coupling mechanism [5], most of the energy transmitted outwards from the two horizontal waveguides. The total Q_{ext} of the two horizontal ports is 978, so Q_{ext} of each port is 1956.

Eigen mode analysis was also conducted by the same software. One of the two polarizations of the electrical field is shown in Fig. 3, and the other one is perpendicular to it. The resonant frequency is 5643.9 MHz, and Q_0 is 9693.



```
Type         E-Field (peak)
Monitor      Mode 1
Maximum-3d   2.32803e+008 V/m at 9.075 / 3.9375 / 0
Frequency    5.64389
Phase        0 degrees
```

Fig. 3. Simulation result of the eigen mode analysis.

---

[1] Hitoshi Hayano. Development of a Cavity BPM in ATF. In: Workshop for the Single Pass BPM and Applications. Japan, 2005.

4 Experimental results of Q_{ext}

4.1 Experimental results of the first-stage coupling

In order to measure the first-stage coupling only, at first the waveguide-to-coaxial cable adapters were not assembled to the waveguide ports. The Q factors were measured by the transmission method. Two probes of vector network analyzer (VNA) were inserted into the position cavity from each side of the beam pipe and set below the axis of the cavity. The port numbers were defined as shown in Fig. 4.

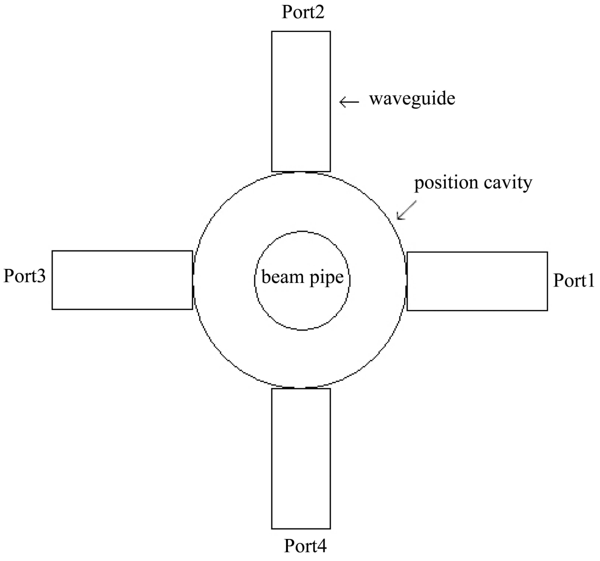


Fig. 4. Definition of the port numbers.

First Port-1 and Port-3 were horizontally placed. The two probes of the VNA were set as mentioned above to excite the TM110 mode. In order to measure Q_0, all of the waveguide ports were detuned by probes. Therefore the entire electromagnetic field energy was wasted on the inner surface of the cavity. Q_0 was calculated as

$$Q_0=\frac{f_0}{\Delta f}, \tag{3}$$

where f_0 is the resonant frequency and Δf is the frequency difference between two 3 dB points.

Then Q_{L} was measured. In order to let the energy transmit outwards without reflection, all ports were connected with matching-loads. The expression for Q_{L} is similar to (3). As mentioned in Section 2, the two probes of VNA were placed below the axis, so most of the TM110 mode energy was transmitted outwards from the two horizontal ports. Therefore we defined Q_{L} as $Q_{\mathrm{L},13}$, and from $Q_{\mathrm{L},13}$ and Q_0 we got $Q_{\mathrm{ext},13}$.

$$Q_{\mathrm{ext},13}=\frac{1}{\left(\frac{1}{Q_{\mathrm{L},13}}-\frac{1}{Q_0}\right)}. \tag{4}$$

Afterwards, the cavity was rotated by 90 degrees so that Port-2 and Port-4 became horizontal. The above steps were repeated and we got $Q_{\mathrm{L},24}$ and Q_0, and hence $Q_{\mathrm{ext},24}$. All the experimental results are summarized in Table 1.

Table 1. Results of the first-stage coupling.

	f_0/MHz	Q_{L}	Q_0	dual-port Q_{ext}
Port-1,3	5691.2	998	9485	1116
Port-2,4	5691.0	1084	9687	1221
simulation	5643.9	–	9693	978

Experimental and simulation results of Q_{ext} agree well with each other.

4.2 Experimental results of Q_{ext} after assembling the waveguide to coaxial cable adapters

4.2.1 Adjustment of the SMA waveguide to coaxial cable adapters

The waveguides on position cavity are "BJ-84", and the BJ-84 SMA adapters' working frequency is above 8 GHz. However, the CBPM's working frequency is designed to be 5.712 GHz, so the adapters' standing wave ratio (SWR) at this frequency cannot meet the requirement. Therefore we first adjusted the adapters' SWR before experiments. The goal was to have $\rho<1.25$ in the frequency range from 5.6 GHz to 5.8 GHz, and the moving-load method [6] was used to measure the adapters' SWR. The adjustment result of Adapter-1 at 5.6 GHz is shown in Fig. 5.

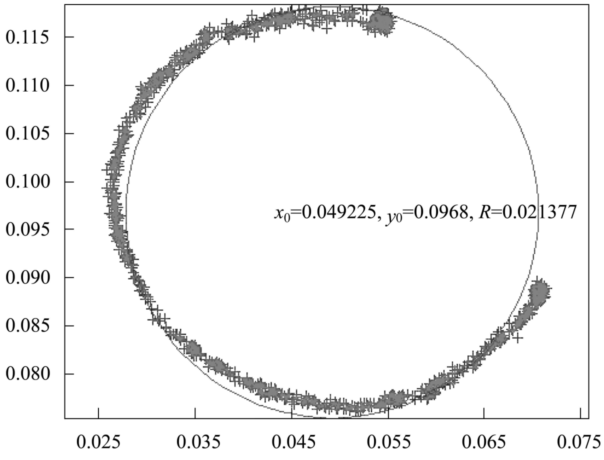


Fig. 5. Measurement result of Adapter-1 at 5.6 GHz (in Smith Chart).

The points were fitted to a circle, and the radius was the adapter's reflection. The SWR of Adapter-1 at 5.6 GHz is 1.19. The same steps were repeated to the other three adapters and finally we made them meet the requirement of SWR.

4.2.2 Experimental results of the two stages of coupling

After assembling the adapters to the waveguide ports, the experimental steps described in Section 4.1 were repeated. The changes in experiments were that when measuring Q_L, all adapters were terminated by 50Ω loads. The experimental results are summarized in Table 2.

Table 2. Results of the two stages of coupling after assembling adapters.

	f_0/MHz	Q_L	Q_0	dual-port Q_{ext}
Adapter-1,3	5691.3	923	9933	1018
Adapter-2,4	5691.1	960	10000	1062
simulation	5643.9	–	9693	978

It can be seen that Q_{ext} remains unchanged after assembling the adapters.

4.2.3 Experimental results of Q_{ext} by the reflection method and transmission method

The reflection method was also used to measure Q [2]. When measuring each adapter's reflection, the other three were terminated by 50 Ω loads. The experimental results are summarized in Table 3.

Q_{ext} remains unchanged as in Table 1 and Table 2. Q_0 of each condition shows some differences. It is perhaps due to the different wastages in each adapter.

Then Q_{ext} was measured by the transmission method, but the two probes of VNA were connected to two opposite adapters. Q_{ext} was calculated from the transmission parameter as mentioned in Ref. [7]. The experimental results are summarized in Table 4.

Table 3. Results of the reflection method.

	f_0/MHz	Q_L	Q_0	Single-port Q_{ext}
Adapter-1	5691.5	799	8380	1860
Adapter-3	5691.5	838	8786	1765
Adapter-2	5691.4	828	9167	1843
Adapter-4	5691.5	842	9324	1830
Simulation	5643.9	–	9693	1956

Table 4. Results of the transmission method.

	f_0/MHz	Q_L	Q_0	Single-port Q_{ext}
S31	5691.6	928	7831	2106
S13	5691.6	928	8536	2083
S42	5691.4	952	8169	2154
S24	5691.4	943	8014	2137
Simulation	5643.9	–	9693	1956

The results also agree with the former ones. Notice that Single-port Q_{ext} in the above table is not for a certain adapter, but the average of Adapter-1 and 3, or Adapter-2 and 4.

5 Conclusions

In this paper Q_{ext} of a model CBPM was simulated and measured, and the results agreed well with each other. Then four waveguide to coaxial cable adapters were assembled and Q_{ext} remained unchanged. Therefore we provide a reliable method to evaluate Q_{ext} in physics design without simulating the structurally complex adapters, and as long as the reflection of each adapter is small enough, it will not affect the CBPM's Q_{ext}.

References

1 Yoichi Inoue, Hitoshi Hayano, Yosuke Honda et al. Physical Review Special Topics – Accelerators and Beams, 2008, **11**: 062801

2 CHU Jian-Hua. Development of a C-Band Cavity BPM and RF Electronics. Doctoral Thesis. Shanghai: Shanghai Institute of Applied Physics, 2008 (in Chinese)

3 Liapine A. For the Reference – BPMs and BPM Designs We Have Now. http://www-project.slac.stanford.edu/lc/local/nanoBPM/documents/bpm designs we have.ppt

4 SHI Jia-Ru, CHEN Huai-Bi, ZHENG Shu-Xin et al. Comparison of Measured and Calculated Coupling between a Waveguide and an RF Cavity Using CST Microwave Studio. Proceedings of EPAC 2006. Edinburg: 2006. 1328–1330

5 LI Zeng-Hai, Ronald Johnson, Stephen Smith et al. Cavity BPM with Dipole Mode Selective Coupler. http://accelconf.web.cern.ch/AccelConf/p03/PAPERS/ROAB004.PDF

6 YAO Chong-Guo. Electrical Linear Accelerator. Beijing: Science Press, 1986. 572–587 (in Chinese)

7 GU Mao-Zhang, ZHANG Ke-Qian. Microwave Technology. Beijing: Tsinghua University Press, 1989. 310–314 (in Chinese)