第18卷 第9期
2006年9月

强 激 光 与 粒 子 束
HIGH POWER LASER AND PARTICLE BEAMS

Vol. 18, No. 9
Sep., 2006

Article ID: 1001-4322(2006)09-1564-05

Cavity BPM design for PKU-FEL injector*

XU Wen-can, ZHUANG Jie-jia, ZHAO Kui, ZHU Feng,
ZHANG Bao-cheng, QUAN Sheng-wen, LU Xiang-yang, HAO Jian-kui,
WANG Li-fang, WANG Fang, LIU Zhen-chao

(*Institute of Heavy Ion Physics, Peking University, Beijing* 100871, *China*)

Abstract: A cavity beam position monitor (BPM) is designed for the injector of PKU-FEL Facility. The designed frequency of the dipole mode TM_{110} is 1.3 GHz, which is equal to the frequency of the main accelerator in PKU-FEL Facility. The cross-talk problem is solved by introducing two rectangular recesses into the cavity. The position resolution of the cavity BPM is about 10 μm, the dynamic range is more than 30 mm and the time response is bunch to bunch, which are sufficient for the PKU-FEL injector. Compared with the bunch power, the power dissipation of the main resonant modes excited by e-bunches can be neglected.

Key words: Cavity BPM; Position resolution; Time response; Power dissipation

CLC number: O572.211; O572.212 **Document code:** A

The basic idea of cavity BPM[1] was first proposed and built in SLAC in 1960's. The TM_{120} mode resonates 2856 MHz in a rectangular cavity was used to detect x or y position according to cavity orientation. A cylindrical cavity of TM_{010} mode was used to measure the beam current intensity and provide the phase reference. Since then, various configurations of BPM cavities were developed in many laboratories and widely used to monitor the beam trajectory, mostly in linear accelerators. Recently, the resolution of cavity BPMs reaches to tens of nm, which is nearly to its limit. The basic idea of cavity BPM is the linear dependence of the bunch displacement on E-field of dipole mode[2]. A bunch excites electro-magnetic field oscillation in the cavity when passing through a BPM cavity. The dipole modes are excited if the beam is off axis or non-zero trajectory angle. The bigger the offset of the beam is, the stronger the dipole modes is. Therefore the position of the beam can be got from the signal picking up dipole modes with antennas.

In this paper, a BPM cavity is designed for the injector of PKU-FEL Facility[3]. The BPM cavity is a cylindrical cavity with two stamp-eroded rectangular cavities to fix the polarized orientations of the dipole mode. The position resolution and time response of the BPM cavity are calculated according to the parameters of the injector.

1 Design and characteristics of BPM cavity

The TM_{110} mode in the cylindrical cavity is used to get the position information of bunches. The frequency of TM_{110} mode is about 1.3 GHz with a radius of 140.5 mm. The 60 mm cavity length is chosen for common mode rejection[4]. In reality, cavity distortions may be caused by fabrication, welding, etc, which are usually out of control. The polarized orientation is basically unpredictable which is called cross talk[5]. To solve this problem, two stamped-eroded rectangular recesses are introdued into the cavity. Figure 1 shows the design and dimensions of the BPM cavity.

Table 1 lists the selected parameters of the BPM cavity for the injector of PKU-FEL Facility. The magnitude of each rectangular recess $\Delta V(x, y, z)$ is 20 mm×64 mm×12mm, which will produce 10.75 MHz difference between the x and y orientations of TM_{110}-like mode by cavity wall perturbation. Hence, the fabrication tolerance is about 0.5 mm for the cavity radius.

* **Received date** 2006-04-25; **Revised date** 2006-07-10
Foundation item Supported by National Basic Research Project (No. 2002CB713602).
Biography Xu Wencan(1982—), Male, Doctoral Student; wencanXu@pku.edu.cn。

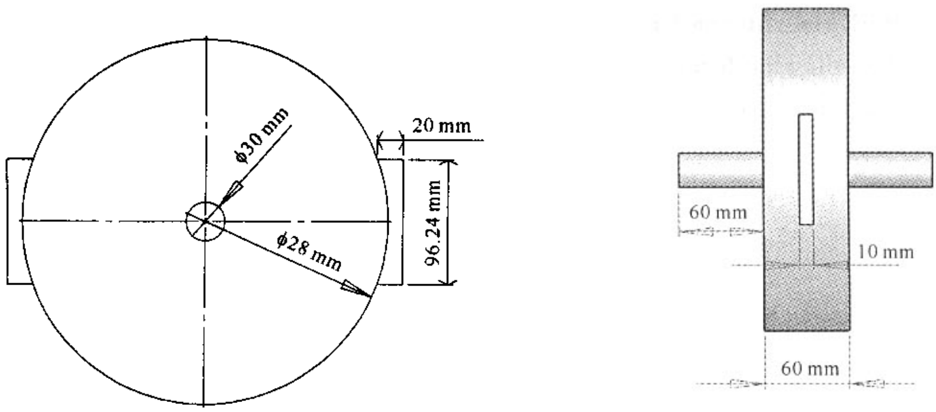

Fig. 1 Structure of the BPM cavity

Table 1 Cavity parameters of real design

cavity radius b/mm	cavity length L/mm	beam pipe radius /mm	beam pipe length /mm	$\Delta V(x,y,z)$	Δf/MHz	tolerance ΔR/mm
140.5	60	15	60	20 mm × 64 mm × 12 mm	10.75	0.5

The characteristic parameters of BPM cavity are calculated by 3D computer code. Table 2 shows the results of the main resonant modes in the BPM cavity. The results are based on copper with 5.8×10^7 s/m conductivity. The results show that the frequency difference between $TM_{110(x)}$ and $TM_{110(y)}$ direction is about 11.4 MHz, which accords with the perturbation method well.

Table 2 Simulation results

mode	frequency/GHz	Q_0	R/Q
TM_{010}	0.814 151	$1.774\ 1\times10^4$	138.043
$TM_{110(x)}$	1.285 42	$2.157\ 8\times10^4$	0.051 714 2
$TM_{110(y)}$	1.296 83	$2.261\ 3\times10^4$	0.053 019 7
TM_{020}	1.869 80	$2.991\ 7\times10^4$	78.981 5

Usually, the linear character of a detector is one of the most important qualities. The coupled voltage of dipole mode is

$$V_{110,\mathrm{out}}(\delta x) = \pi f_{110}\sqrt{Z\left(\frac{1}{Q_L}-\frac{1}{Q_0}\right)\left(\frac{R_{\mathrm{shunt}}}{Q_0}\right)_{110}}\,q \tag{1}$$

where, $(R_{\mathrm{shunt}}/Q)_{110} = V(\delta x) * V^*(\delta x)/4\pi f_{110}$ is the value of shunt impedance over Q of TM_{110}-mode depending on the bunch offset δx. Q_0 and Q_L are unload and load quality factors of the cavity, respectively. Z is the impedance of the coupling which is 50 Ω usually. q is the charge of the bunches. Figure 2 shows the linear relationship between the voltage and bunch offset. It shows that the linear range is about 35 mm for the cavity BPM, which means that the measurement is exact whenever the offset of the bunch is smaller than 30 mm.

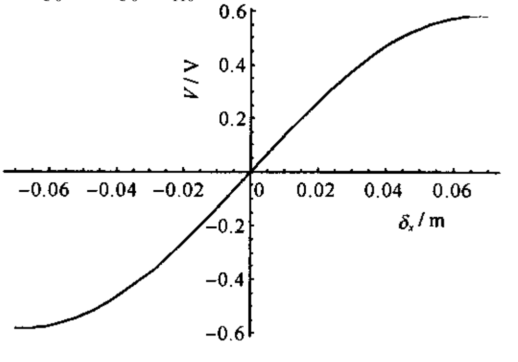

Fig. 2 Voltage of TM_{110}-mode depending on the offset

2 Design of the antenna for the BPM cavity

The BPM cavity is to be connected with outer circuits for feeding or coupling out signals. The connection can be realized by electronic coupling with pin-antennas, magnetic coupling with loops or electro-magnetic coupling with aperture. The pin-antenna coupling is chosen for easily testing the Q_0 and Q_L after the fabrication of the cavity. With the antenna length, diameter and its position at the cavity, the coupling factor β can be calculated by the following formulas when cavity is coupled into the 50 Ω line.

For the TM_{0n0} monopole modes, the coupling factor is

$$\beta_{0n0} = \frac{P_c}{P_{in}} = \frac{100\pi\omega_{0n0}^2\varepsilon_0\mu_0\delta_{0n0}\int_p^{p+l+d/2} J_0(rk_{0n0})\, r\mathrm{d}r}{bJ_1^2(bk_{0n0})(L+b)} \tag{2}$$

and the coupling factor of the TM_{110} dipole modes is

$$\beta_{110} = \frac{P_c}{P_{in}} = \frac{0.25^2 \times 25\sigma\delta_{110}k_{110}^2}{\pi}\,\frac{\left[\int_p^{p+l+d/2} J_1(rk_{110})\,\mathrm{d}r\right]^2}{\frac{bL}{2}J_1'^2(bk_{110}) + \int_0^b J_1'^2(rk_{110})\, r\mathrm{d}r + \frac{1}{k_{110}}\int_0^b \frac{J_1'^2(rk_{110})}{r}\mathrm{d}r} \tag{3}$$

where, $\delta_{mnp} = 1/\sqrt{\pi f_{mnp}\mu_0\sigma}$ is the skin depth, which depends on the frequency and the material. The p, l and d are the position, length and diameter of the antenna respectively (see figure 3).

To reduce the frequency perturbation due to coupling antennas, the pin antenna radial location is $p = 0.080$ m, which is farther away from the axis of the BPM than the maximum point of the electrical field of the mode TM_{110}. With the pin-antenna length $l = 0.007$ m and diameter $d = 0.002$ m, the pin-antenna coupling factors are shown in table 3.

Table 3 Pin-antenna coupling factors

	β ($p = 0.080$, $d = 0.002$, $l = 0.007$)
TM_{010}	68.753 400
$TM_{110(x)}$	2.251 212
$TM_{110(y)}$	2.263 050
TM_{020}	17.617 400

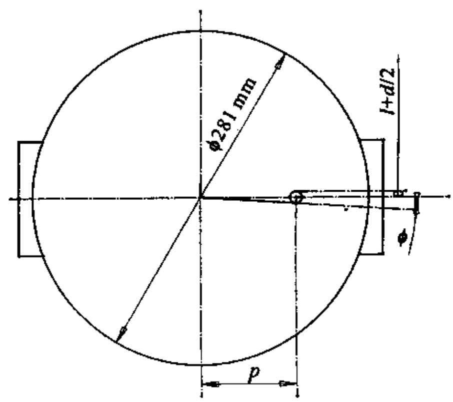

Fig. 3 Top view of the cavity with pin-antenna

3 Estimation of position resolution of the BPM cavity

Generally, the signal coupled out by pin-antenna can be formalized as[6]

$$V_{out} = V_{110,out}(\delta x) + V_{110,out}(x') + V_{010,out} + V_{020,out} + V_N + V_{jitter} \tag{4}$$

where, $V_{110,out}(\delta x)$ is the signal of TM_{110} modes excited by beam off axis; $V_{110,out}(x')$ is the signal of TM_{110} modes excited by non-zero trajectory angle; $V_{010,out}$, $V_{020,out}$ are the signals of common modes produced by beam itself and the leakage through beam pipe; V_N is the thermal noise in the detector circuit; V_{jitter} is the signal from the beam jitter or circuit jitter.

The cavity length is very short and $V_{110,out}(x')$ can be neglected. V_{jitter} can also be neglected if the measurement is bunch by bunch. Then, equation (4) can be rewritten as

$$V_{out} = a\cdot\delta x + b + V_N \tag{5}$$

where $a\cdot\delta x = V_{110,out}(\delta x)$ and $b = V_{010,out} + V_{020,out}$, a and b are constant values for a given bunch. So, the minimum displacement can be detected when

$$a\cdot\delta x \geqslant V_N \tag{6}$$

The constant a can be calculated using equation (1) with the data listed in table 2 and table 3.

$$\begin{aligned} V_{110,out}(x) &= 6.632\,65x \\ V_{110,out}(y) &= 6.635\,97y \end{aligned} \tag{7}$$

As the circuit is chosen, the noise factor (F_N) is about 7.5, the band pass (W_B) is about 100 MHz and the impedance (Z) of the circuit is 50 Ω. Assuming the temperature is 300 K, the thermal noise can be calculated by

$$V_N = F_N\sqrt{4k_bTW_BZ} = 0.068\,24 \text{ mV} \tag{8}$$

where, $k_b = 1.38 \times 10^{-23}$ J/K is the Boltzmann coefficient.

The resolution can be calculated by equations (7) and (8).

$$\begin{aligned} V_{110,\text{out-}x} &= 0.068\ 24\ \text{mV} \\ V_{110,\text{out-}y} &= 0.068\ 24\ \text{mV} \end{aligned} \tag{9}$$

Equation (9) shows that the resolution value of the cavity BPM is about 10 μm in x and y direction.

4 Estimation of time response

Approximating the frequency of TM_{110} mode to 1.3 GHz, the damping time of TM_{110} mode is

$$\tau = \frac{1}{\pi W_B} = \frac{Q_L}{\pi f_{110}} = 3.18\ \text{ns} \tag{10}$$

The time space between bunches is $t_b = 12.3$ ns and the repeat rate of the laser is 81.25 MHz. Damping time of TM_{110} mode is smaller than the bunches space, so the cavity BPM is bunch to bunch measurement.

5 Estimation of power dissipation

Passing through the BPM cavity, the bunches excite electro-magnetic modes. The electro-magnetic energy W dissipates on the walls. The electro-magnetic energy stored in the cavity can be computed by[7]

$$W_{\text{mnp}} = \frac{\omega_{\text{mnp}}}{4}\frac{R}{Q}q^2 \tag{11}$$

where W_{mnp} is the stored energy in the TM_{mnp} mode. PKU-FEL Facility works in 5 ms ,10 Hz repeat rate macro-pulse. In a macro-pulse, there are 406250 micro-pulses with 81.25 MHz laser repeat rate. The charge of each bunch is about 100 pC. Using the data from table 3, the total energy of main modes loss on the walls from a micro-pulse is

$$W_{\text{total}} = W_{010} + W_{020} + W_{110,x} + W_{110,y} = 4.087\ 22 \times 10^{-9}\ \text{J} \tag{12}$$

The total power which dissipates on walls from a macro-pulse can be calculated

$$P = 16.604\ 3\ \text{mW} \tag{13}$$

The equations (12) and (13) show that the power loss from bunches is very little compared to the 5 MeV at the downstream of the injector . It is safe to neglect the power dissipation effect on bunches caused by the BPM cavity.

6 Conclusion

The design of a cavity BPM for the injector of PKU-FEL Facility has been described. The frequency of TM_{110} dipole mode is chosen as 1.3 GHz, which is the same as the frequency of the main accelerator in PKU-FEL Facility. Two stamped-eroded rectangulars are recessed into the cavity to solve the cross-talk problem. The common mode is rejected by choosing the magnitude of the cavity carefully.

The main properties of the cavity BPM are presented. The linear range of the cavity BPM is about 40 mm. The position resolution is about 10 μm and the measurement could be bunch to bunch. The effect of the cavity on the bunches is so little that it can be neglected. The designed cavity is qualified for the beam position monitor in the injector of PKU-FEL Facility.

References:

[1] Farkas Z D, Martin H L, Miller R H, et al. Precision energy measurement technique[R]. SLAC-PUB-1970.

[2] Shintake T. Development of the nanometer resolution RF-BPMs[C]//Proc of HEACC '98. Dubuna, 1998.

[3] Wang G M, Zhao K, Lu X Y, et al. Experimental progress of DC-SC photoinjector at Peking University[C]//the 27th International Free Electron Laser Conference. USA,SLAC, 2005.

[4] Schnell W. Common-mode rejection in resonant microwave position monitors for linear colliders[R]. CERN-LEP-RF/88-41, CLIC Note 70, 1988.

[5] Sargsyan V. Cross-talk problem in pill box cavity[R]. DESY-TESLA-2003-01, 2003.

[6] Liapine A. Cavity beam position monitor for the TESLA energy spectrometer[C]//Proceedings DIPAC 2003, Mainz, Germany, 2003.

[7] Padamsee H, Knobloch J, Hays T. RF superconductivity for accelerator[M]. New York: Wiley Interscience Publication, 1998.

用于 PKU-FEL 注入器的腔式 BPM 的设计

徐文灿， 庄杰佳， 赵 夔， 朱 凤， 张保澄， 全胜文，
鲁向阳， 郝建奎， 王丽芳， 王 芳， 刘振超
（北京大学 重离子物理研究所，北京 100871）

摘 要： 设计了用于 PKU-FEL 注入器的腔式位置诊断装置。该 BPM 腔采用的偶极模 TM_{110} 模的频率与 PKU-FEL 主加速器的基模频率一致，都是 1.3 GHz 通过在圆形腔上镶入两个完全一致的矩形腔解决了腔式 BPM 的 Cross-Talk 问题。根据 PKU-FEL 的设计要求，所设计的 BPM 腔的最小位置响应约 10 μm，动态范围大于 30 mm，时间响应小于束团间距。还估算了该 BPM 腔引起的束团功率损耗。结果表明，BPM 腔引起的束团功率损耗是可以忽略的。

关键词： 腔式 BPM； 位置分辨； 时间响应； 功率损耗