# DESIGN OF RACETRACK CAVITY BEAM POSITION MONITOR*

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*Abstract*

A new high brightness injector is planned to be installed at HLS of NSRL. It is based on a new photocathode RF electron gun. To steer the beam along the optimal trajectory, higher precision controlling of beam position is required. The positional resolution of the BPM system designed for the new RF gun should be higher than 10μm. A new cavity BPM design is then given instead of old stripline one because of its higher positional resolution. In a normal symmetrical pill-box BPM design, machining tolerance will result in x-y coupling, which will cause cross-talk problem. A novel design is then presented here. To solve the problem before, a position cavity which has a racetrack cross section is used instead of a pill-box one. The ideal resolution of this design could be less than 4 nm.

## INTRODUCTION

The proposed high brightness injector at HLS is designed for the development of new technologies of the fourth-generation light source. The fourth-generation light sources have higher brightness, higher coherence and shorter optical pulse, so they require high quality electron bunch with high beam brightness, low emittance, low beam energy spread and high current [1]. To develop high quality electron source, it is important to improve the performance of BPM system to steer the beam along the optimal trajectory. The 4~5 MeV RF photocathode gun of the new injector in HLS is designed to produce high brightness beam with the transverse normalize emittance of 6mm-mrad for a bunch charge of 0.3 nC. The positional resolution of BPM should be less than 10μm. To meet the demand NSRL decides to use cavity BPM instead of the stripline one [2] designed for HLS LINAC before. Cavity BPM promises much higher position resolution compared to other types of BPMs [3-5]. There's no restriction on polarization direction in a perfect symmetrical pill-box design, the signals coupled out from a pair of orthogonal coupling direction will be linear independent, which means a displacement can always be expressed as Cartesian coordinates at fixed directions. When there is a random distortion, the polarization direction is then restricted and there will be cross-talk problem when the coupling directions are not same as the polarization direction, which means a beam displacement at one direction will result in signals at both two direction. Since the distortions, which caused by fabrication, welding, etc., is unpredictable, it is impossible to couple out the signals in the same direction as the polarization [3]. Therefore we use a new cavity which has predictable dissymmetry. This new cavity can be considered as a cylindrical cavity splitted and then connected by a small rectangular one.

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## RACETRACK CAVITY BPM THEORY

In the racetrack BPM design, as introduced before, a cylindrical cavity is splitted at y-direction and then connected by a rectangular cavity. Fig. 1 shows the simulation by Microwave Studio (MWS), rectangular cavities are considered as ideal waveguides. In this cavity the polarization direction can be considered as fixed and the frequencies of these two modes at fixed polarization direction are different, so the cross-talk is then minimized.

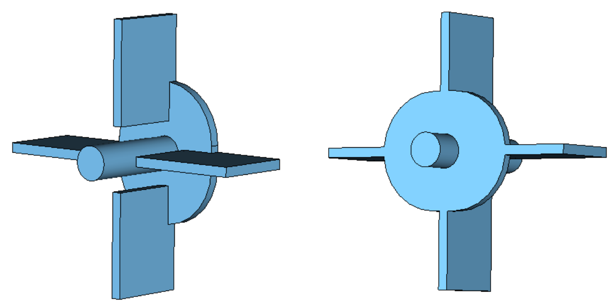

Figure 1: 3D model of racetrack BPM in MWS.

A displacement at x-direction results in a positional signal at a frequency higher than the frequency of positional signal excited by a y displacement. Fig. 2 shows the two polarization direction and how waveguides are used to couple out TM110 mode of the electromagnetic field excited by beam displacement. The monopole mode, which makes a significant contribution to inaccuracy of measurement, is also cut off [6].

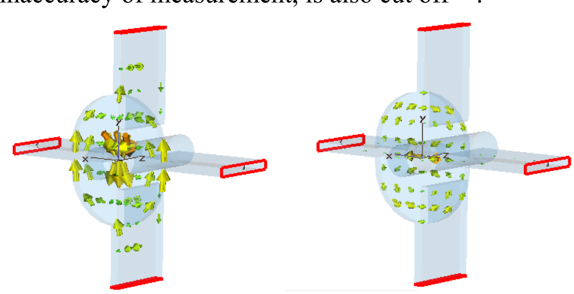

Figure 2: Two polarization direction of TM110 mode.

Figures 3 and 4 have showed the dependence of the electrical field (normalized by MWS) of TM110 modes to beam displacement. When beam displacement is in the range of ±10 mm, the electrical field can be considered as in direct proportion to beam displacement.

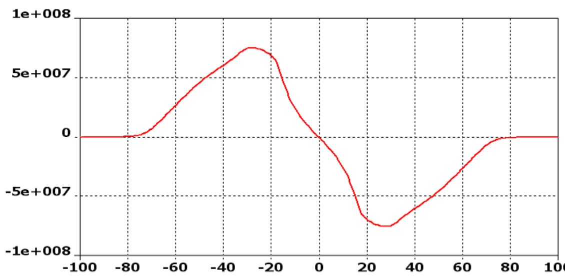


Figure 3: $E_z$ vs y coordinate, excited by y displacement.

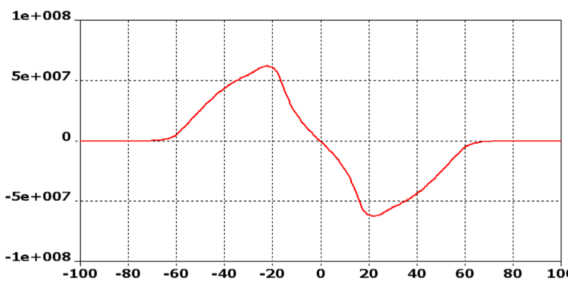


Figure 4: $E_z$ vs x coordinate, excited by x displacement.

In the linear range, the energy loss of beam satisfies:

$$E_{loss} = q^2 k_{loss} = q^2 \frac{\left|V_n\left(\vec{r}, v\right)\right|^2}{4U_n} \quad (1)$$

$$V_n\left(\vec{r}, v\right) = \int_0^l \mathrm{d}z\, \vec{E}_n\left(\vec{r}, z\right) e^{j\omega_n z / v} \quad (2)$$

Here, $\vec{E}_n$ is electric field and $U_n$ is stored energy; both of them only depend on the cavity and are normalized by MWS.

So $E_{loss} \propto r^2$, $P_L = \frac{\omega E_{loss}}{Q_L}, V = \sqrt{P_L R}$

Hence, $V_{signal} \propto r_{beam}$

TM110 mode showed in Figure 3 and 4 can be coupled out as positional signal.

## RACETRACK BPM DESIGN

Table 1 shows parameters of the racetrack BPM. Here waveguide position means the distance between the axis and the coupling slot. Rectangular cavities are considered as ideal waveguides in simulation and a waveguide end with matched feedthrough will be designed separately. The length of waveguides means the total length after installation.

The theoretical performance of the racetrack BPM is listed in Table 2.

Table 1: Prototype Parameters

| | |
|---|---|
| Racetrack Arc Radius | 60.577 mm |
| Racetrack Straight Line | 23.915 mm |
| Cavity Length | 10 mm |
| Beam Pipe Radius | 17.5 mm |
| Waveguide Longer Side a | 85 mm |
| Waveguide Shorter Side b | 10 mm |
| Waveguide Length X | 115 mm |
| Waveguide Position X | 25 mm |
| Waveguide Length Y | 107 mm |
| Waveguide Position Y | 33 mm |

Table 2: Theoretical Performance

| | |
|---|---|
| $f_{110\text{-x}}$ | 2652 MHz |
| $Q_{0,110\text{-x}}$ | 6649 |
| $\beta_{110\text{-x}}$ | 25.4 |
| $K_{\text{loss, normalized, 110-x}}$ | $6.69\times10^{14}\Omega/(m^2 s)$ |
| $f_{110\text{-y}}$ | 2448 MHz |
| $Q_{0,110\text{-y}}$ | 6460 |
| $\beta_{110\text{-x}}$ | 23.8 |
| $K_{\text{loss, normalized, 110-y}}$ | $5.17\times10^{14}\Omega/(m^2 s)$ |
| Dynamic Range | ±10 mm |

The ideal resolution $\Delta x_{ideal}$ only depends on the ideal theoretical voltage of the TM110 mode signal excited by beam displacement and thermal noise. It satisfies:

$$\Delta x_{ideal} = \frac{1}{q\sqrt{\frac{\pi}{4kT}\frac{\beta}{1+\beta}k_{loss,normalized}}} \quad (3)$$

So when quantity of electricity of bunch is 1nC and the BPM system works at room temperature, the ideal resolution will be:

$$\Delta x_{ideal,x-direction} = 2.86\text{nm}$$

$$\Delta x_{ideal,y-direction} = 3.26\text{nm}$$

### *Racetrack Arc Radius and Straight Line Length*

The cross section of the novel cavity can be considered as a circle splitted to two halves and connected by a rectangle, so the length of the rectangle is as important as the radius of circle. Fig. 5 and Fig. 6 show the dependences of frequencies of two TM110 modes to the racetrack arc radius and the straight line length. When the arc radius is greater than 50mm, the differential coefficient of TM110 frequency changes so slowly that the TM110 frequency can be considered as linear in small range. This feature and these two figures can help to give a more exact range of parameters and simplify the task.

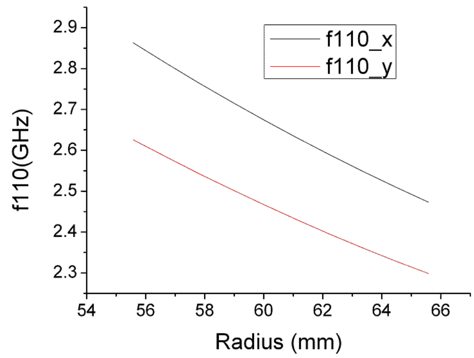


Figure 5: TM110 mode frequency vs radius.

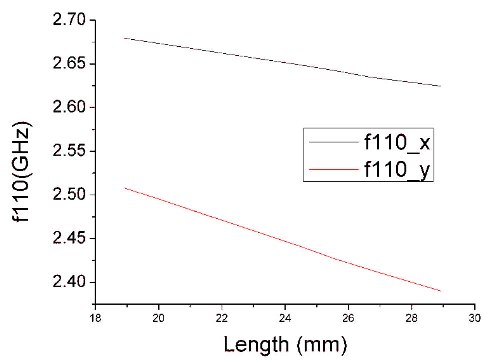


Figure 6: TM110 mode frequency vs straight line length.

### *External Q Optimization and Theoretical Resolution*

External Q is an inherent parameter of the whole pick-up station. For pick-up station with given structure ($Q_0$ and total energy loss is then fixed) and electronics with given bandwidth, signal voltage detected by electronics will be very low whether $Q_e$ is too large or too small. So there will be at least one certain external Q value that makes the electronics get the maximum signal voltage.

Assume that $V = V_0 e^{-\frac{\omega_0}{2Q_L}t} e^{j\omega_0 t}$ , and then ratio between energy in electronics and total energy loss is

$$Ratio = \frac{2}{\pi} arctg\left(\frac{\Delta F Q_L}{f_0}\right)\frac{Q_0 - Q_L}{Q_0} \quad (4)$$

So the virtual energy that the electronics get is decided by the coupling factor and bandwidth of the electronics. When the bandwidth of electronics ΔF is 10MHz, the maximum value of this ratio is 0.710 for TM110 mode excited by displacement at x-direction, and 0.716 for TM110 mode excited at y-direction.

In this paper the coupling factors are given in Table 2. So the electronics will get 46.5% of total energy stored in the mode excited by beam displacement at x-direction and 49.8% of total energy at y-direction.

After all, considering the virtual energy and noise factor of the electronics, we get

$$\Delta x_{theoretical} = \frac{\sqrt{\frac{NF}{Ratio}}}{q\sqrt{\frac{\pi}{4kT}\frac{\beta}{1+\beta}k_{loss,normalized}}} \quad (5)$$

Assume the NF of the electronics is 10; the theoretical resolution of this design will be 13.3 nm at x-direction and 14.6 nm at y-direction.

## CONCLUSION

To achieve precise controlling of beam trajectory, a novel racetrack cavity BPM design is successfully simulated. This new racetrack cavity BPM produce two positional signals that give the x and y position separately. The two signals have different frequencies so the cross-talk is minimized. A positional resolution under 20 nm can be achieved.

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