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CAVITY BPM WITH DIPOLE-MODE-SELECTIVE COUPLER*

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Abstract

In this paper, we present a novel position sensitive signal pickup scheme for a cavity BPM. The scheme utilizes the H-plane of the waveguide to couple magnetically to the side of the cavity, which results in a selective coupling to the dipole mode and a total rejection of the monopole mode. This scheme greatly simplifies the BPM geometry and relaxes machining tolerances. We will present detailed numerical studies on such a cavity BPM, analyze its resolution limit and tolerance requirements for a nanometer resolution. Finally present the measurement results of a X-band prototype.

1 INTRODUCTION

Requirements on the Beam-Position Monitor (BPM) system for the proposed Next Linear Collider [1] are very stringent, especially on position stability. In order to meet these requirements it was decided that cavity BPMs [2,3,4,5] were the best choice. In a conventional cavity BPM design, pickups couple to both TM_{11} (position sensitive) and TM_{01} (only charge sensitive) modes. Since for small beam offsets, the TM_{01} signal is many orders of magnitude larger than the TM_{11} signal, one cannot use directly the signal from one pickup to determine the beam position. The common practice is to eliminate the TM_{01} common mode using a magic-T like subtraction/addition device, which subtracts the signal of the TM_{01} mode and combines the TM_{11} signal from two pickups placed symmetrically on the cavity. This complicates the BPM system and subjects it to tight tolerances. To eliminate these complications, we propose a novel design for a cavity BPM that uses the H-plane of the waveguide to couple magnetically to the side of the cavity. This coupling scheme selectively couples the waveguide only to dipole modes. The suppression of the TM_{01} and other monopole modes greatly simplifies the geometry. The signal from the waveguide can then be directly used to obtain beam position. This coupling scheme also provides looser tolerances. In this paper, we will present the detailed numerical analysis on such a cavity BPM design and analyze tolerance requirements to reach nanometer resolution using such a cavity BPM. The numerical studies will assume X-band frequency. In the calculations to follow, we assume a $1nC$ bunch charge, which is close to the NLC beam parameter.

2 COUPLING MECHANISM

One of the major concerns in a cavity BPM is the contamination of the TM_{01} (monopole) mode. Though resonant at a much lower frequency, the tail amplitude of the TM_{01} spectrum at the TM_{11} frequency can be many orders of magnitude higher than the TM_{11} mode when excited by a beam with a small offset. Because of the distinguishable mode patterns of the TM_{01} and TM_{11} modes, it is possible to design the coupling waveguide to couple selectively to the TM_{11} mode but not the TM_{01} mode [6]. A schematic of such a coupling scheme is shown in Fig.1, where the waveguide is coupled to the cavity TM_{11} mode magnetically through the radial magnetic field. The waveguide mode does not have azimuthal magnetic fields in the coupling slot, hence there is no coupling to the cavity TM_{01} mode. Four waveguides (flags), with two in the vertical plane that pickup the x-displacement and two in the horizontal plane that pickup the y-displacement are needed to keep the BPM symmetric to eliminate x-y coupling and the common mode leakage. It is important for the waveguides not to cut through the beam pipe in order to provide clean signals at the ports.

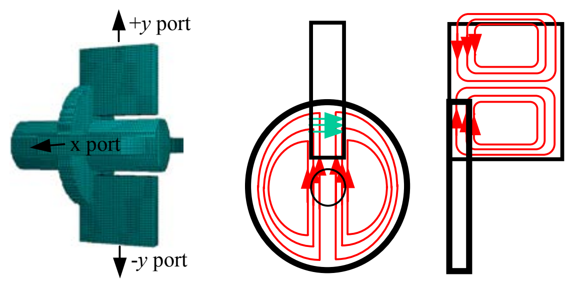

Figure 1 Cavity BPM with dipole mode selective coupler.

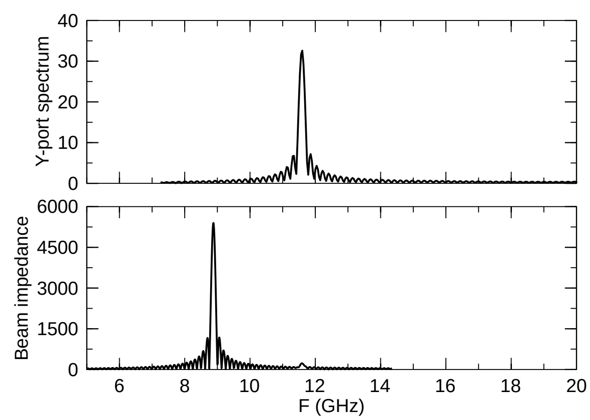

Figure 2 The y-port signal spectrum for a beam offset in the x-plane. The coupler only couples to the TM_{11} mode, rejects the monopole mode.

The MAFIA simulation of the BPM with the beam offset in the x-plane is shown in Fig. 2. The y-port spectrum

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shows a clean TM_{11} signal at around 11.4*GHz* and a total rejection of the TM_{01} mode at around 9*GHz*.

3 BPM RESOLUTION

Without the contamination of the common mode, the intrinsic BPM resolution is limited by the signal to thermal noise ratio of the system. The signal voltage of the BPM is determined by the energy loss of the beam to the TM_{11} mode and the external coupling of the waveguide. The beam loss parameters, defined by the energy loss $\Delta U=q^2x^2k_{11}$ ($k_{11}=V^2/4Ur^2$) and $\Delta U=q^2k_{01}$ ($k_{01}=V^2/4U$) for TM_{11} and TM_{01} modes respectively are shown in Fig. 3. The energy lost to the TM_{01} mode produce undesirable wakefields and should be minimized in the design. The sensitivity curves suggest it desirable to use small beam pipe radius, if possible, to enhance the dipole coupling.

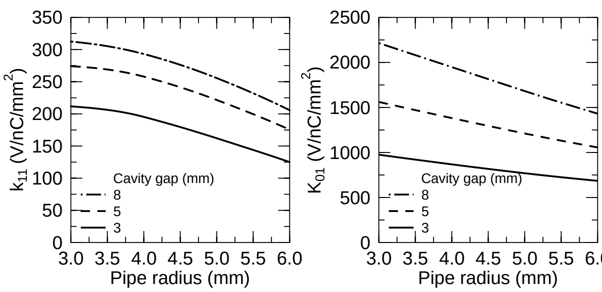


Figure 3 Loss factor of TM_{11} and TM_{01} modes versus beam pipe size and cavity gap.

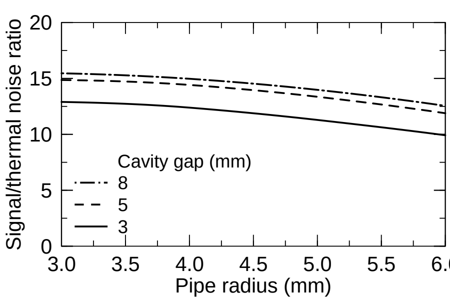


Figure 4 Signal to thermal noise ratio for 1*nm* offset. The inverse of this ratio is the resolution of the BPM.

For a given coupling coefficient β ($=Q_0/Q_{ext}$), the signal voltage on a $Z0=50\Omega$ coax matched to the waveguide can be calculated as

$$V(q,x)=\sqrt{q^2Z_0\frac{\beta}{1+\beta}\frac{\omega_0 k_{loss}x^2}{Q_L}} \qquad (1.1)$$

The thermal noise voltage of the BPM is given by

$$V=\sqrt{Z_0kT\Delta F} \qquad (1.2)$$

where k ($1.38\times10^{-23}J/K$) is the Boltzmann's constant, T the temperature in Kelvin, and ΔF the bandwidth in *Hz*. At room temperature, the noise voltage is about $0.45\mu V/(MHz)^{1/2}$. The signal/noise ratio shown in Fig. 4 for a 1*nm* beam offset indicates that the intrinsic resolution of the cavity BPM is about 0.1*nm* at room temperature. It is worthwhile to mention that the signal-to-noise ratio does not depend on the bandwidth of the system, as seen from above equations. The signal voltage shown in Fig. 4 was obtained assuming β=1. However, one can gain up to 3*dB* more signal power by over coupling.

4 BPM BANDWIDTH

The external Q of the dipole mode for such a coupling scheme is sensitive to the depth (r-location of the waveguide) of the coupling slot and insensitive to the beam pipe size and the cavity gap as shown in Fig. 5. While the wall loss Q is about 4000 for a 3*mm* cavity gap at X-band, external Q can vary within a wide range by changing the slot depth, adding flexibility for the design to meet different coupling β requirements. A design for a broadband cavity BPM, with an external Q well bellow 100, can be realized with this scheme.

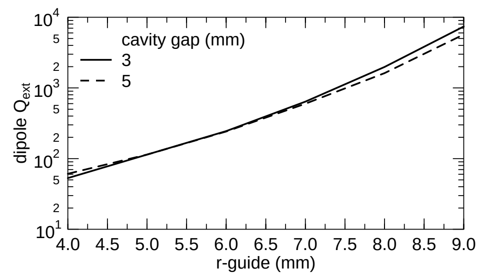


Figure 5 External Q of dipole mode as functions of waveguide r-location and cavity gap

5 TOLERANCE

The requirement on the cavity frequency is stringent since we need to measure both phase and amplitude. The sensitivity to the major cavity parameter "b" is about 0.7$MHz/\mu m$. The cavity maybe made tunable to relax machining tolerance. But it is important to maintain the cavity symmetry to minimize common mode leakage and x-y coupling.

Machining errors on coupling slots may induce leakage of the common mode (TM_{01}) to the pickup port as well as cross coupling between the two x-y polarizations. While the x-y coupling can be removed numerically, the tail of the TM_{01} at the dipole frequency may deteriorate the BPM resolution. We consider three misalignments as shown in Fig. 6, and study the impact on the BPM resolution.

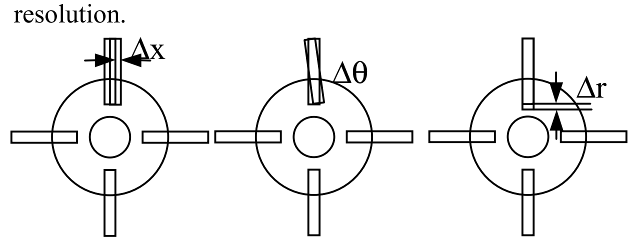


Figure 6 Three types of misalignments in slots.

1 x/y misalignment

Both the x-offset and the $\Delta\theta$-tilt result in non-zero projection of the azimuthal magnetic field of the TM_{01}

mode along side the slot opening, causing coupling of the TM_{01} mode to the waveguide. Here we use the *x*-offset as an example to study this effect.

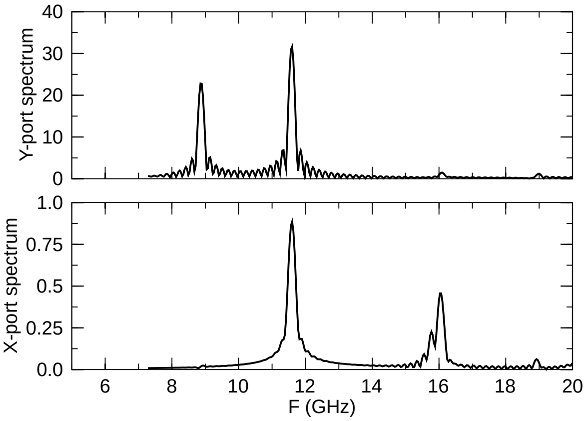


Figure 7 Spectra of the *x/y*-port signals with *y*-coupler misaligned in the *x*-direction by 0.5*mm*.

Figure 7 shows the *x/y* signal for the case of *y*-coupler shifted in *x*-direction by 0.5*mm* with a beam off axis in the *x*-plane. The peak at 9*GHz* in the *y*-port shows the TM_{01} mode leakage, and *x*-port signal at 11.4*GHz* shows *x-y* coupling. To estimate accurately the TM_{01} contamination at the TM_{11} frequency, we calculate the external *Q* and use Eq. (1.1) and the resonant curve to obtain the tail amplitude of the TM_{01} mode at the dipole frequency.

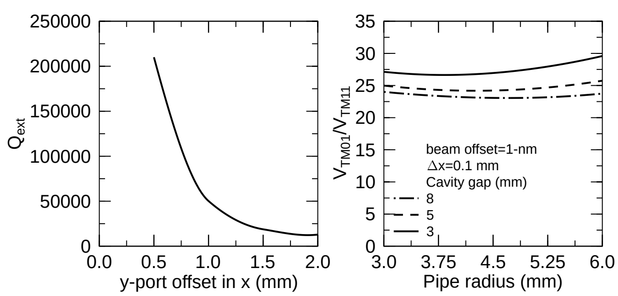


Figure 8 Left) Q_{ext} of TM_{01} mode due to misalignment of *y*-port; Right: monopole/dipole voltage ratio for 1*nm* beam offset and 100μm *y*-port misalignment.

The Q_{ext} of the TM_{01} mode due to the *x*-misalignment of the *y*-port is roughly proportional to $1/\Delta x^2$ as shown in Fig. 8. The monopole to dipole signal ratio for 100μm misalignment and 1nm beam offset is about 25. One can achieve resolution near the thermal noise limit of about 0.1*nm* with modern electronics.

2 Radial misalignment

Since the slots are parallel to the current of the TM_{01} mode, the perturbation on the TM_{01} due to the *r*-misalignment is small. Though simulation with a beam shows some TM_{01} leakage in the *x*-port, Fig. 9, the external *Q* of such a leakage is too high to be calculated correctly. The tolerance on the *r*-misalignment is significantly looser than the *x/y* misalignment.

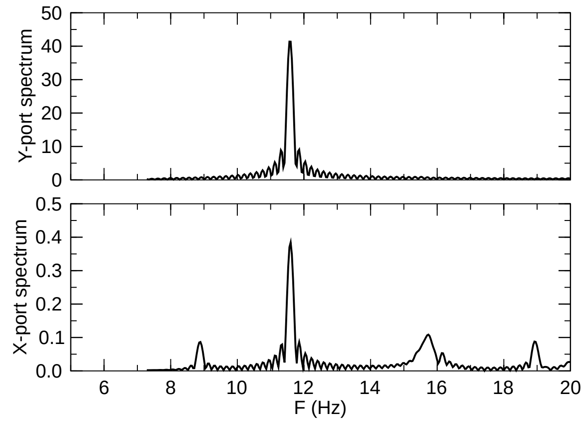
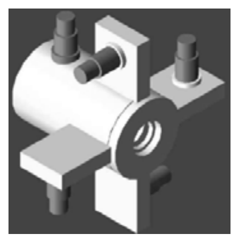


Figure 9 Spectra from *y* and *x* ports with *y*-port misaligned in *r* by –0.5*mm*

6 PROTOTYPE FOR THE NLC

A prototype X-band cavity BPM for the NLC was designed and cold tested. A picture of the cold test model and the cavity BPM parameters are shown in Fig. 10. A resolution better than 100*nm* has been obtained. Detailed cold test setup and test results can be found in ref. [7,8].



Cavity gap	3*mm*
Beam pipe radius	6*mm*
Waveguide	3x18mm^2
r of coupling-slot	8*mm*
rms resolution	100*nm*

Figure 10 Cold test model of the NLC cavity BPM.

CONCLUSION

The selective coupling scheme presented in this paper can reject the common TM_{01} mode effectively and provide clean signal for position measurement. It has advantages of simplicity of geometry. Nanometer resolution can be achieved with relatively loose tolerance requirements. The coupling scheme is flexible in achieving low and high external *Q*s. The cavity BPM can be designed for both narrow and broadband applications.

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