ELECTROMAGNETIC DESIGN OF THE RF CAVITY BEAM POSITION MONITOR FOR THE LCLS*

G. Waldschmidt#, R. Lill, L. Morrison, ANL, Argonne, IL 60439, U.S.A.

Abstract

A high-resolution X-band cavity BPM has been developed for the LCLS. A dipole mode cavity and a monopole mode reference cavity have been designed in order to achieve micron-level accuracy of the beam position. The rf properties of the BPM as well as beam interaction with the cavities will be discussed including output power and tuning. In addition, methods will be presented for improving the isolation of the output ports to differentiate between horizontal / vertical beam motion and to reject extraneous modes from affecting the output signal. The predicted simulation results will be compared to data collected from low-power experimental tests.

INTRODUCTION

Cavity beam position monitors have been designed and constructed for the LCLS in order to achieve micron-level resolution of the beam offset [1]. Cavity BPM's typically consist of two cavities, a monopole mode reference cavity to measure bunch charge and a dipole mode XY cavity to measure beam offset. Since the monopole mode is invariant to the beam offset for small offsets, the reference cavity measures the charge of the passing bunch by extracting the amplitude of the fundamental monopole mode signal.

The XY cavity determines beam offset by using the cavity TM_{110} dipole modes. The dipole mode field strength is linearly dependent upon the radial distance from the center of the cavity with no electric field component directly on-axis. As a result, the beam position is simply calculated from the amplitude of the output signal calibrated to the bunch charge determined by the reference monopole cavity. The direction of the beam offset can be determined, in part, from the phase of the output signal since the modal pattern of the dipole modes consists of counter-parallel electric fields above and below the cavity axis.

The beam interaction with the monopole mode of the XY cavity is many orders of magnitude larger as compared with the dipole mode for small beam offsets. As a result, in order to prevent contamination of the output signal, the monopole mode must be extracted from the output signal or simply rejected. One method is to separate the monopole mode from the dipole mode using the common and differential branches of a magic-tee. Another method is to use selective mode coupling to preferentially couple to the dipole mode.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
# waldschm@aps.anl.gov

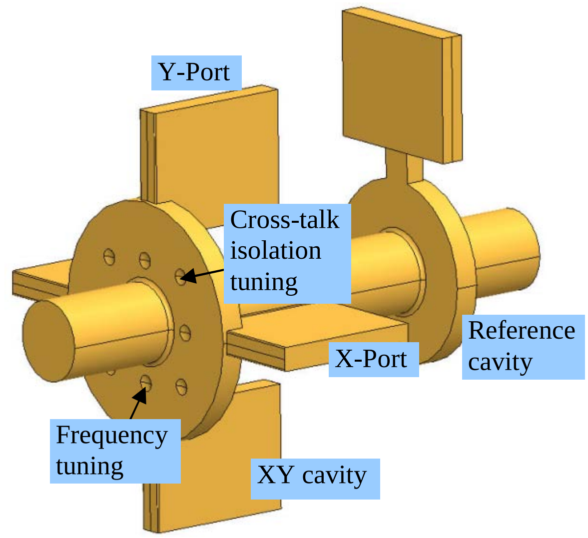

Figure 1: Cavity BPM consisting of the XY and monopole cavities with coupling waveguides and tuning areas.

CONFIGURATION

The layout of the cavity BPM operating at 11.384 GHz is shown in Fig. 1. The output waveguides in the XY cavity are designed to reject the fundamental mode resonance of the cavity at 8.31 GHz while coupling to the dipole mode using selective coupling [2]. The dipole mode is magnetically coupled to the TE_{10} waveguide mode. Each orientation of the dipole mode couples independently into either the pair of X- or Y-ports of the waveguide. In a fashion similar to the monopole mode rejection, the other orientation of the dipole mode is rejected from one of the two pairs of output waveguide. Selective coupling, therefore, reduces the contamination of the output signal, improves the resolution, and avoids the complexity of canceling the monopole mode contribution.

In both cavities, the output waveguides extend for 1 meter before they are terminated with a coaxial transformer feeding the BPM electronics. As a result, additional fundamental mode rejection could easily be achieved by adjusting the cutoff frequency of the XY cavity output waveguide above the fundamental frequency. However, a bandpass filter is used in the electronics to provide 60-dB attenuation at 8.3 GHz and additionally attenuates higher frequency components.

Isolation between the monopole cavity and the XY cavity is achieved using a conservative 36-mm cavity-to-cavity separation. Given the 5-mm beampipe radius, a field decay of 130 dB of the monopole mode is achieved.

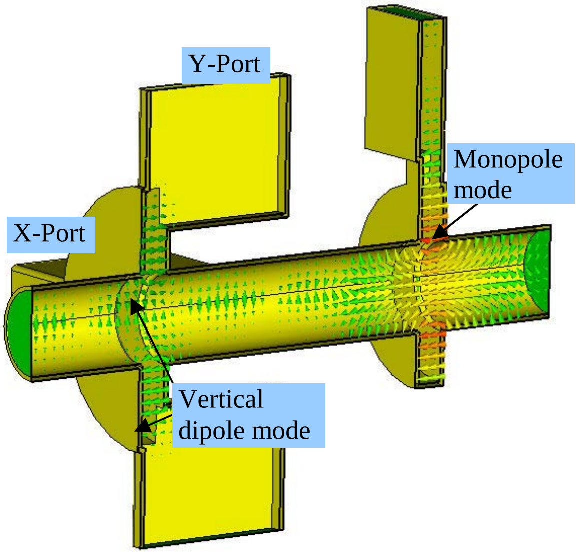

Figure 2: Electric field vectors at 11.384 GHz produced by the wakefield of a 1-nC, 300-fs Gaussian bunch with 1-mm vertical offset.

Isolation at the operating frequency is governed by the decay of the fields due to the evanescence in the beampipe, copper losses, and the poor coupling of the TM beampipe mode to the cavity dipole mode. As a result, negligible energy transfer between the cavities has been measured.

DESIGN

The upper limit of the external coupling of the waveguides to the cavities is determined by the peak power and voltage handling capability of the receiver electronics. For the XY cavity, the output power is calculated as

$$P_{Dipole} = \frac{\omega_o q^2 k_{loss} \exp(-\frac{\omega\sigma}{c})^2}{Q_{ext}} \frac{\Delta x^2}{r_{fix}^{\ 2}} \quad ,$$

where σ is the beam sigma, Δx is the assumed radial offset of the beam, and k_{loss} is the typical monopole mode loss factor evaluated at radial distance r_{fix}. The exponential form factor is included in order to account for the reduced energy transfer from the beam to the cavity due to the finite Gaussian profile of the beam. The output power for the monopole cavity is similarly calculated with the exception that the loss factor is calculated on-axis and Δx and r_{fix} are excluded.

Frequency tuning of the cavities is performed using four tuning areas in the end caps located along the vertical and horizontal axes see Fig. 1. Since this is a high electric field area, the frequency decreases as the tuning pin is inserted. Optional radial tuning areas on the perimeter of the cavity have been used, but their effectiveness and usability are suspect due to the limited 3-mm cavity gap.

Cross-talk between the vertical and horizontal dipole modes of the XY cavity is defined as the parasitic excitation of the orthogonal dipole modal orientation due to beam excitation of the other dipole mode. As a result, there is a perceived offset of the beam that does not exist, thereby limiting the fundamental resolution of the BPM. Since a loss of symmetry would adversely affect the cross-talk, four output waveguides were used in the XY cavity, although two are terminated in a matched load and do not contribute to the BPM signal analysis.

However, since the output waveguide and manufacturing imperfections disrupt the symmetry [2], power is leaked into the other orientation. To help compensate for cross-talk contamination, isolation tuning pins were designed at 45^o angles from the vertical at 90^o intervals. They are introduced in order to reorient the dipole mode such that the modes are symmetric about the vertical and horizontal planes. An inadvertent effect of the cross-talk pins is the frequency adjustment similar to the frequency tuning pins. However, the sensitivity of the frequency tuning decreases as the radial distance increases, so the cross-talk isolation pins are located further from the cavity axis.

SIMULATION RESULTS

Microwave Studio [3] was used to simulate the BPM cavities in order to generate the appropriate frequency tunability, peak power and voltage output, cross-talk optimization, and beam interaction, see Fig. 2. Table 1 lists the final simulation results for the two cavity geometries. The Q was designed to be large enough, by using a 3.0-mm gap, in order to simplify the data acquisition without creating a large impedance bump for the beam. The output voltage and power were chosen to be low to protect the front end of the electronics. The frequency tuning range of each cavity is estimated to be greater than 20 MHz depending on the depth of the deformation applied at the tuning areas. Cross-talk isolation was better than the design goal of 20 dB in simulated results after deliberate imperfections were created and then compensated using the cross-talk isolation pins.

Low-power testing of prototype cavities has borne out these results [4] and has achieved frequency tuning and

Table 1: Cavity Parameters

	XY Cavity	**Monopole Cavity**
f (GHz)	11.384	11.384
r_{cav} (mm)	14.89	11.48
D_{gap} (mm)	3.0	3.0
Q_l	3549	3695
β	0.128	0.0048
R/Q	2.28*	56.5
P_{peak} (W)	0.093	0.094
V_{peak} (V)+	2.16	2.16

*1.0-mm off-axis; +Voltage at coax output

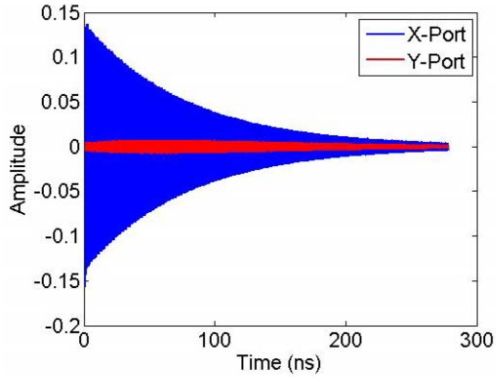

Figure 3: Time-domain output signal from the X-port and Y-port of the XY cavity for a 1-nC beam vertically offset by 1.0- mm.

isolation improvements equal to, and in some cases, in excess of simulation results.

Wakefield Simulations

A simulation of a long-range, 300-meter wakefield was performed to evaluate the dipole mode coupling and the monopole mode rejection. Figure 2, shows the resultant electric field vectors at the operating frequency from a 1.0-nC beam vertically offset by 1mm using the Particle Studio module in Microwave Studio. Note the large difference in the excitation magnitude of the monopole mode in the reference cavity compared with the dipole mode in the XY cavity. Monopole mode rejection in the XY cavity was evaluated in order to help ensure successful operation of the BPM.

Figure 3 shows the cross-talk isolation in the time-domain of the output signals at the X- and Y-port. Given a vertical beam offset, the Y-port excitation is purely parasitic. Figure 4 shows the frequency spectrum of the same output signal. The output in the X-port is approximately 20 dB greater than at the Y-port at 11.384 GHz. The effectiveness of the selective coupling can be seen from Figs. 4 and 5. As seen in Fig. 5, the beam impedance of the XY cavity only (without any contribution from the reference cavity) shows that the monopole mode of the XY cavity at 8.31 GHz has an impedance that is at least an order of magnitude larger than for the dipole mode. However, the output X-port frequency spectrum in Fig. 4 shows that selective coupling has reduced the monopole mode by an order of magnitude relative to the dipole mode. Further elimination of the monopole mode is performed by filtering in the electronics.

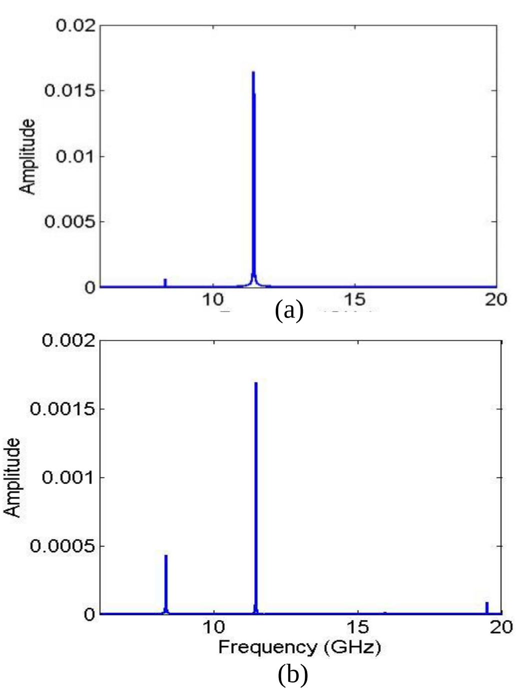

Figure 4: Frequency spectrum of the output signal of the XY cavity at the (a) X-port and (b) Y-port

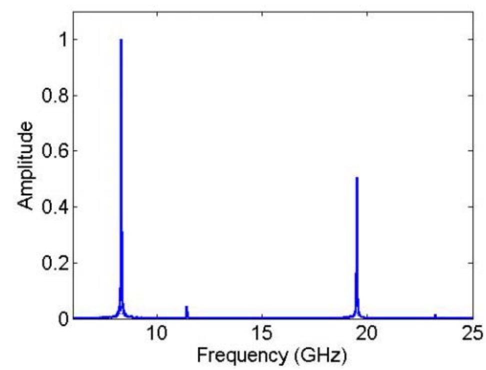

Figure 5: Normalized impedance spectrum of the XY cavity only given a 1mm vertical beam offset

CONCLUSION

The electromagnetic design of the cavity BPM, including the XY and the reference cavities, is expected to meet the specifications required for the LCLS. The XY, dipole-mode cavity was successfully designed using selective mode coupling to reject the large monopole mode contribution. Static tuning of tens of MHz as well as dipole-mode cross-talk tunability has been implemented into the design. Improved cross-talk performance as well as additional enhanced monopole mode rejection was discussed.

REFERENCES

[1] R. Lill et al., "Linac Coherent Light Source Undulator RF BPM System," FEL06, Berlin 2006: http:www.jacow.org.

[2] Z. Li et al., "Cavity BPM with Dipole-Mode-Selective Coupler," PAC03, Portland, OR 2006: http:www.jacow.org.

[3] Microwave Studio, v. 2006B, Computer Simulation Technology, Wellesley Hills, MA.

[4] B. Lill, et al., "Design and Performance of the LCLS Cavity BPM System," these proceedings.

1-4244-0917-9/07/$25.00 ©2007 IEEE