AN X-BAND CAVITY FOR A HIGH PRECISION BEAM POSITION MONITOR*

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Abstract

The next generation of accelerators will require increasingly precise control of beam position. For example designs for the next linear collider require beam-position monitors (BPMs) with 300 nm resolution. The accelerator designs also place difficult requirements on accuracy and stability. To meet these requirements a cavity BPM operating at 11.424 GHz was designed. The BPM consists of two cavities: an xy-cavity tuned to the dipole mode and a phase cavity tuned to the monopole mode. The xy-cavity uses a novel-coupling scheme that (in principal) has zero coupling to the monopole mode. This report will present the mechanical design, simulations, and test results of a prototype BPM. In addition BPM designs with even higher precision will be discussed

INTRODUCTION

Designs for the next generation of accelerators place stringent requirements on Beam Position Monitor (BPM) systems. These requirements are driven by the need to establish and maintain precise optics to prevent emittance growth. Requirements include measurement of beam position with high precision, good accuracy, and good stability. For example the Next Linear Collider (NLC) [1] will require BPMs to have precision of 300 nm, accuracy of 200 µm, and stability of 1 µm (over 24 hours).

A preliminary design of the NLC uses over 1900 BPMs placed at each quadrupole along the (X-band) main linacs. Each of these QBPMs is rigidly attached to the quadrupole and the whole assembly is mounted on precision movers. Beam based alignment will be used to determine and adjust the centers of the magnets. But this is an invasive procedure that is not compatible with production operation. Accelerator components must remain stable over long periods.

The two usual choices for BPM pickups are striplines or cavities. The mechanical complications of striplines makes insuring good stability a problem, especially when the beam tube has an internal diameter of only about 12 mm. In addition the position signal for striplines is the difference of two large numbers. This difference must be obtained with precision analog electronics or with digital electronics with a large number of effective bits.

On the other hand cavity BPMs can be machined out of a single block of metal with tolerances of about 0.5 µm. Simple pillbox cavities can be fiducialized to the outside with errors of this order. Also when the beam is centered in the cavity the position signal is zero and signal is generated only as the beam moves off axis.

For these reasons a research project on development of a cavity BPM that could meet the NLC requirements was started. This report presents results on the prototype BPM that was designed and fabricated. An initial report [2] on this prototype has been published but construction of the BPM is now complete.

DESIGN AND FABRICATION

The main linacs of the NLC operate at X-band (11.424 GHz). Although other frequencies could be selected, the cavity BPM was designed at this frequency for two reasons. First, the QBPMs are to provide a phase reference for the low-level rf control. Second, this frequency is consistent with a compact design and well established machining techniques.

A simple cylindrical cavity was designed with a thickness that would not add significant impedance to the beam. The BPM does feature a novel design for coupling the signals out [3,4]. A rectangular waveguide at right angles to the cavity intercepts the cavity only at the corner; coupling is through the magnetic field. Only the TM_{11} mode couples to the waveguide and the monopole mode (TM_{01}) does not couple. This is illustrated in Figure 1.

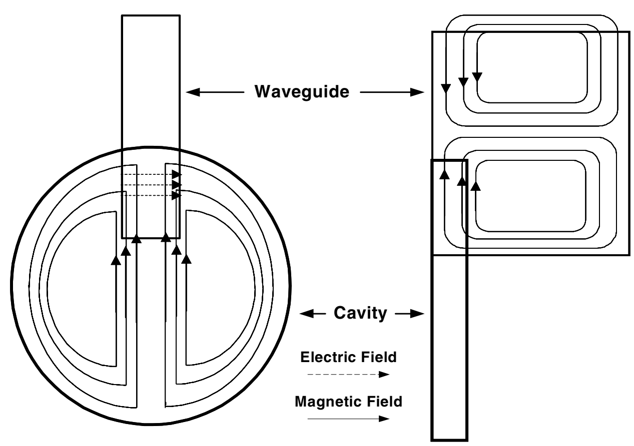

Figure 1: Coupling scheme for the cavity BPM.

Four waveguides intercept the cavity symmetrically horizontally and vertically. Signals from the vertical waveguides provide x-offsets and signals from the horizontal waveguides provide y-offsets. Extensive MAFIA simulations were performed in perfecting the design.

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Dimensions of the cavity are 29.426 mm in diameter and 3.0 mm thick. The waveguides are 18.0 mm by 3.0 mm by 30.0 mm. In addition to the xy-cavity a phase cavity was designed where the monopole mode resonates at 11.424 GHz. The cavity dimensions are 24.711 mm in diameter and 2.0 mm thick.

The body of the device is machined out of a single block of copper (OFE Class II) 43.0 mm in length, 34.0 mm in diameter, and with a 12.0 mm diameter beam tube on the axis. Copper end caps 5.0 mm thick were machined to complete the cavities. Short (16.25 mm) stainless steel beam pipes were brazed to each end of the BPM. A 3-D view of the cavity BPM without the beam pipe extensions is shown in Figure 2.

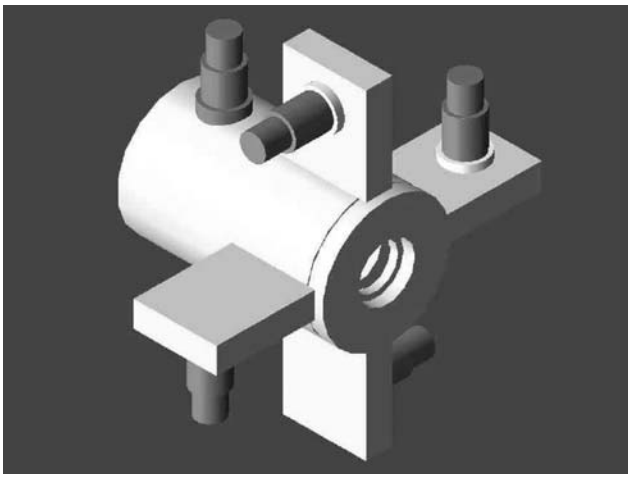

Figure 2: A 3-D view of the cavity BPM.

Waveguides are formed from two pieces of copper brazed together and brazed to the body. Electrical feedthroughs couple signals out of the waveguides serving as both a vacuum break and as pickups for converting waveguide fields to coaxial cable signals.

Tolerances for the critical dimensions of the cavity and waveguides were specified to be 1.0 µm. However the actual parts produced did not meet these tolerances. For example the diameters of the xy-cavity and phase cavity are +8 and –2 µm off their specified values. The tolerances specified are achievable and the actual parts were not bad considering that it was the first attempt.

Another problem in the construction was that following welding all the feedthroughs had vacuum leaks. It is expected that the welding heated the ceramic seals excessively. Although this BPM will not be used in a beam line, the issue must be addressed.

TEST RESULTS

In order to excite the cavity BPM a stub antenna was built. It is a small length (quarter wavelength) of the center conductor of a RG141 hard line coaxial cable. The antenna was mounted on an xy-stage. The x-stage was moved by a precision micrometer (minimum division 0.5 µm). The y-stage had much less precision (minimum division 25 µm). Measurements were made using a 20 GHz vector network analyzer.

The test setup is shown in Figure 3. The cavity BPM was mounted on a low precision xyz-stage to facilitate initial alignment.

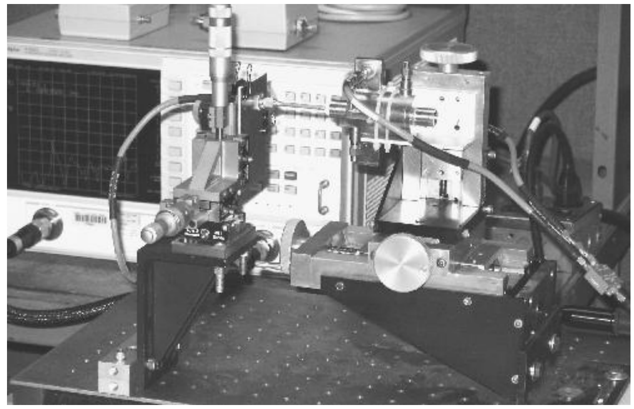

Figure 3: Cavity BPM test setup.

The frequency response (i.e. S_{21} measurements using the VNA) of the xy-cavity (top) and the phase cavity (bottom) are shown in Figure 4.

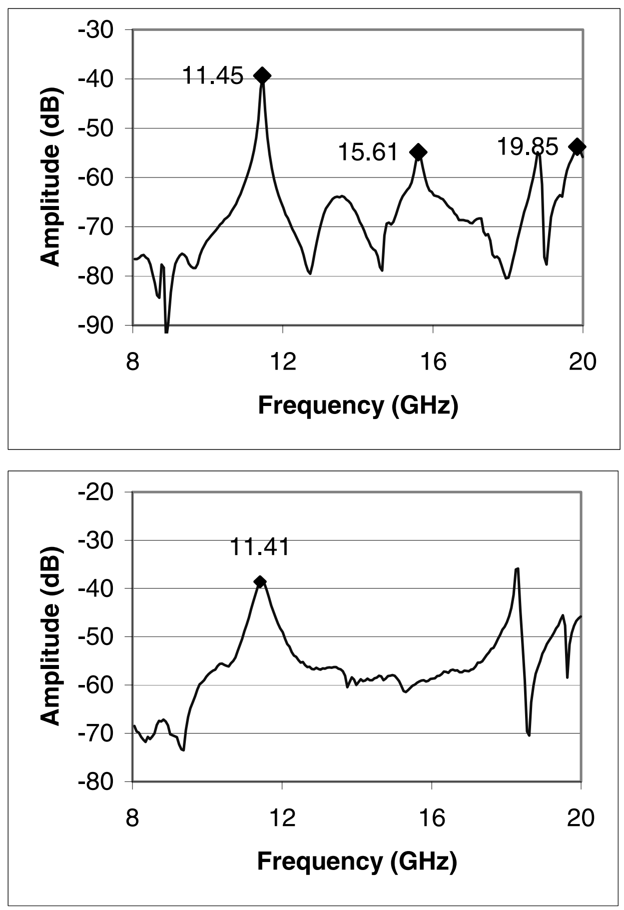

Figure 4: Frequency response of the cavity BPM.

The TM_{11} mode is at 11.45 GHz (+26 MHz off the design value). This error is not due to the error in cavity diameter. It is more likely due to lack of precision in the MAFIA calculations of the frequency shift due to the waveguides. Resonances at 15.61 GHz and 19.85 GHz are identified as the TM_{21} and TM_{31} modes. The monopole mode for the cavity is at 8.72 GHz which is below the cutoff for the waveguides, but it was previously measured using WR75 waveguide couplers. For the phase cavity the TM_{01} mode is at 11.41 GHz (-13 MHz off the design value). Coupling from port to port was also measured using the VNA. These data are summarized in Table 1.

Table 1. Cavity BPM resonant structure.

	MAFIA	Measured			
Mode	**Freq. (GHz)**	**Freq. (GHz)**	**Q**	**Coupling X-X (dB)**	**Coupling X-Y (dB)**
XY Cavity					
TM_{01}	8.72	8.55	200	-66	-60
TM_{11}	11.43	11.45	590	-6.8	-25.5
TM_{21}	15.92	15.61	~90	-13.8	-13.2
TM_{31}	20.2	19.85	~80	-8.2	-29.6
Phase Cavity					
TM_{01}	11.43	11.41	~30	NA	NA

The electrical center of the cavity BPM was compared to the mechanical center by moving the antenna from one edge of the beam tube to the other. An average of the micrometer readings at the two edges determines the mechanical center. The electrical center was determined by finding the minimum of the dipole resonance. The centers differ by about 20 µm in x and in y by less than 25 µm. The y difference is an upper limit because the y micrometer has less precision.

Measurements of resolution were made only for the x motion because of the higher precision for this motion. Initial measurements using the minimum of the dipole resonance locate the center to a few microns. As the antenna passes through zero the phase also goes through zero; however, there is an arbitrary phase in the system. This can be offset by setting the phase of the VNA. Doing so puts all the position signal in the imaginary channel of the VNA. After setting the phase offset, scans of $\pm$50 µm were made. The average rms deviation from a straight line for four scans was 200 nm. It is clear that a large part of the deviation was due to the micrometer runout. Over a restricted scan of $\pm$ 10 µm the runout was much smaller. Four scans over this range produce an average rms resolution of 100 nm. In Figure 5 plots of the response verses position are illustrated.

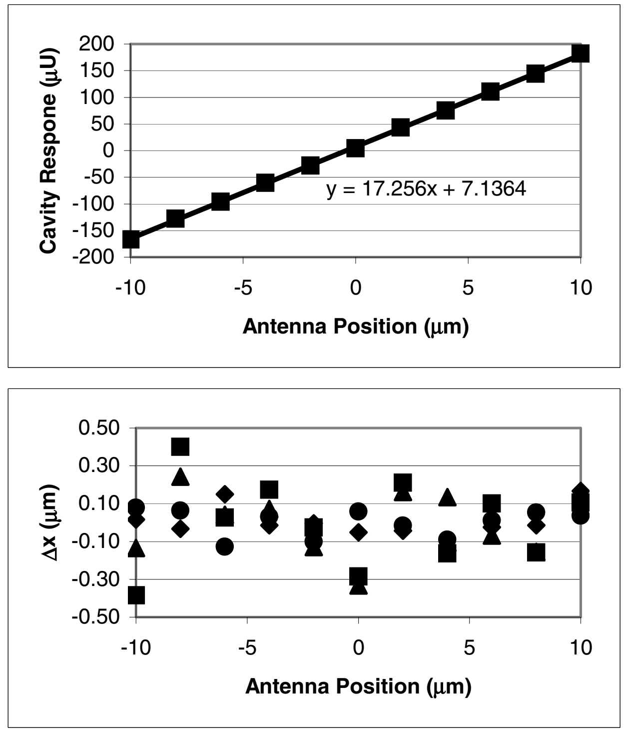

Figure 5: Top - Response of cavity BPM vs antenna position. Bottom – Difference between the calculated position and the antenna position.

CONCLUSIONS

A research program to investigate cavity BPMs has led to the successful construction of a prototype of such a BPM that would be suitable for the QBPMs of NLC. The BPM was designed for operation at 11.424 GHz and features a novel-coupling scheme that suppresses the monopole mode.

The results of tests show good suppression of the monopole mode so that there is no significant interference with measurements of the dipole mode. The most important conclusion is that the resolution has been measured to be about 100 nm. This resolution meets the NLC requirements for the QBPMs. Of course these measurements are CW not pulsed.

Plans are being made to construct additional BPMs of this type and test them in an accelerator. The resolution that can be obtained under actual beam conditions will direct the future development of these BPMs. There is interest in producing BPMs with resolution of a few nm. For cavities of this design the signal strength can be increased by simply using a larger cavity.

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