A QUADRUPOLE MODE RESONANT CAVITY FOR NON-DISRUPTIVE, SINGLE-SHOT EMITTANCE MEASUREMENT*

C.D. Nantista, SLAC, Stanford, CA 94309, USA, J.S. Kim, FARTECH, Inc., San Diego, CA 92122, USA, A.W. Weidemann, University of South Carolina, Columbia, SC 29208, USA.

Abstract

We describe a beamline cavity designed to detect the space charge quadrupole moment of a beam. Used in conjuction with a beam position monitor, it can provide a measurement of $\sigma_x^2 - \sigma_y^2$. In a FODO array, several such cavities installed at different phase locations in the betatron lattice can afford a means of acquiring non-disruptive, single-shot measurements of a beam's transverse emittances [1]. The device described is basically a square copper cavity oriented at 45° at a short gap in the beampipe. It is designed to resonate in its TM_{220} mode at 11.424 GHz. This allows us to excite this quadrupole mode resonantly with the bunches of the NLC Test Accelerator bunch train, enhancing our signal over other cavity modes. The signal is coupled out by four irises in the sidewalls through a waveguide network that rejects by symmetry the monopole and dipole modes. We present the rf design, cold test data, and experimental results from beam tests in the NLCTA.
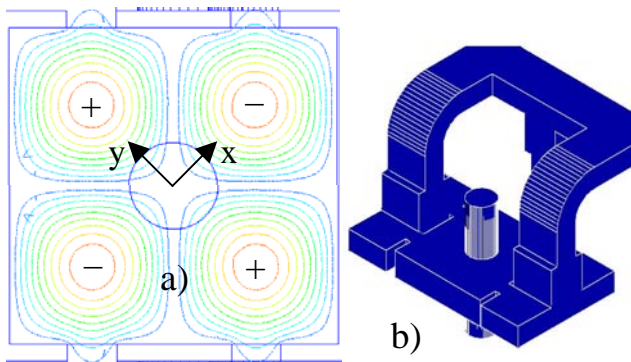

Figure 1: Quadrupole cavity a) 2-D geometry with field pattern and b) 3-D geometry with waveguide network.

1 INTRODUCTION

Emittance is an important parameter in accelerator performance. Measuring and monitoring it in a non-disruptive way, that is without intercepting the beam, can provide a valuable reduction in beam tune up time and increase in availability for linac operation. In 1983, Miller, *et al.* [1], pointed out that, in a FODO lattice, measurements of the quadrupole moment of the beam space charge at six or more strategic locations can be used, with the known TRANSPORT [2] matrices, to determine the parameters of the beam sigma matrix. From these can be calculated the transverse emittances:

$$\varepsilon_x = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}, \text{ and } \varepsilon_y = \sqrt{\sigma_{33}\sigma_{44} - \sigma_{34}^2}.$$

There are different approaches one can take to designing a quadrupole moment monitor. The above method was first tested using strip-line bpm pickups in the SLAC linac [1]. Recently, Jansson [3] has applied a monitor utilizing four magnetic pick-up loops to beam measurements in the CERN Proton Synchrotron. For a beam composed of a train of bunches, such as that f the NLC, the ideal pick-up is a quadrupole mode resonant cavity. It affords strong coupling and resonant enhancement of signal to noise.

2 CAVITY DESIGN

2.1 Main Cavity

A quadrupole monitor cavity can be designed as either a circular pillbox operating in the TM_{210} mode or a square pillbox operating in the TM_{220} mode. To couple to the quadrupole moment of an upright beam, the cavity mode's electric field must acquire the same sign with displacement in either direction along the *x*-axis and the opposite sign with displacement in either direction along the *y*-axis; i.e. it must have a $\cos 2\phi$ dependence. Thus, in operation, a square cavity must be rotated 45° with respect to the beamline coordinates (in which reference frame it might be designated a "skew"-quadrupole cavity).

Near the center of such a cavity, the longitudinal electric field, and thus the kick factor, is, to second order, proportional to $x^2 - y^2$. Convolution with an upright bi-Gaussian space charge distribution gives a cavity excitation amplitude proportional to $\bar{x}^2 - \bar{y}^2 + \sigma_x^2 - \sigma_y^2$. Thus independent bpm measurements are necessary to subtract the beam centroid position contribution to the signal and give the quadrupole moment, $\sigma_x^2 - \sigma_y^2$.

We have developed a cavity of the square type. This choice avoids degeneracy with the 45°-rotated quadrupole mode (TM_{210}^x, for the circular cavity and a combination of TM_{130} and TM_{310} for the square cavity), making that mode instead degenerate with the next higher TM mode, the second monopole mode (TM_{020} for the circular cavity and the orthogonal combination of TM_{130} and TM_{310} for the square cavity). Furthermore, the square geometry pushes the frequency of this nearest non-quadrupole mode further away. For the simple pillbox with an 11.424 GHz quadrupole mode, the spacing is 0.855 GHz for a circular cavity and 1.348 GHz for a square cavity.

For a circular cavity, coupling irises would be located at the peak magnetic field locations on the top, bottom and sides of the cavity wall. In the square TM_{220} mode, symmetry with the cavity center makes it obvious that the magnetic field must be zero in the equivalent corners. We therefore couple power out instead through two pairs of irises each located at the two field maxima along opposite walls. Since two walls are thus doubly breached and the other two uninterrupted, a perturbation is introduced to the quadrupole symmetry. To compensate for this effect and eliminate any skewing of the field pattern at the cavity center, we adjust the cavity dimensions to be actually slightly non-square (1.457"×1.417"). The coupling walls are moved inward to compensate for the fields bulging out through the irises and restore the 11.424 GHz resonance with the adjacent walls left where they'd be for an uncoupled square cavity (with beampipe). Figure 1a) shows the cavity geometry with a contour plot of the electric field strength of the quadrupole mode. The beamline coordinate axes are shown superimposed over the one-centimeter diameter beampipe. A cavity depth of 0.97 cm was chosen for good shunt impedence. Simulations of this design were presented earlier [4].
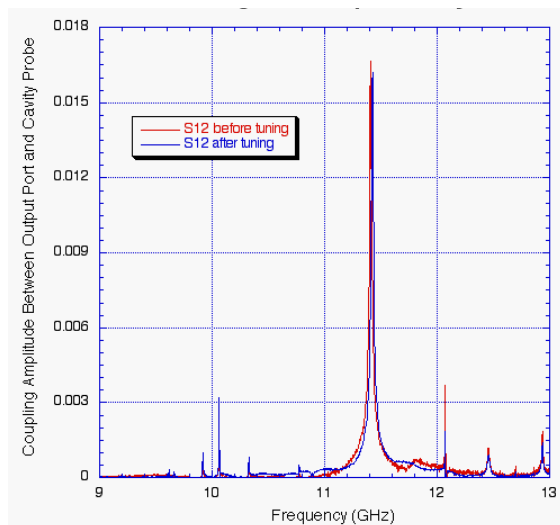

Figure 2: Cold test response of quadrupole monitor.

2.2 Coupling Network

Each pair of coupling irises opens through the side wall of a short section of WR62 waveguide. The choice of this size (0.622") provides additional mode discrimination, as in it the frequencies of the cavity monopole and dipole modes are below cutoff. Each such section is shorted at either end to provide standing wave anti-nodes centered on the irises. At the center of each section, an E-plane junction opens out from the broad wall. Rather than with a post, this junction is matched by stepping down the height of the coupled waveguide at the proper distance.

These two waveguides protruding from the plane of the cavity are then brought together through mitered H-plane bends, after curved E-plane bends included to avoid the beampipe. They meet in a third E-plane T-junction.

The signals from four irises are thus reduced to a single waveguide signal in two steps which select the odd-odd phase symmetry between irises and pairs of irises. This technique provides advantages of simplicity and (with tight machining tolerances) accuracy over electronic subtraction of four rf signals. The next cavity mode with the correct symmetry to couple through this network is TM_{240}, at a frequency up around 18 GHz.

A 3-D view of the geometry of this device is given in Figure 1b). To the single WR62 output waveguide we appended a matched taper to WR90, so that a post-matched rf vacuum window, developed for SLAC X-band klystrons, could be attached.

3 COLD TEST AND TUNING

A prototype cavity of the above design was fabricated at SLAC. Measurements were made with an HP 8510C Network Analyzer. Figure 2 shows a frequency sweep of S_{12} measured between the waveguide port and an electric probe inserted through the beampipe. There is no nearby resonance comparable to that of the quadrupole mode. Significantly, none of the few, much smaller spikes falls close to the expected frequency of the nearest other cavity modes. They are likely resonances in the waveguides or window that leak into the cavity, as is evidenced by the fact that cavity tuning doesn't budge them. Clearly mode discrimination through the symmetry-selective waveguide network suppresses the other cavity modes well, even without the benefit of resonant bunch excitation.

The cavity resonance was found to be about 15 MHz low. It was tuned up to 11.424 GHz by the following method: A bar with a threaded cup at the end was screwed onto a threaded stub of inner beampipe built into our cavity. A sliding weight was thrown a few times against a restraining nut on this bar to provide small, azimuthally symmetric shock deformations of the cavity wall. The resonance frequency was monitored until it reached the desired value. This tool was developed by Gordon Bowden for tuning accelerator coupler cells. Provision for its use was included in our design to relax machining tolerances.

4 INITIAL BEAM TEST

Our device was installed near the end of the beamline of the NLCTA. A waveguide-to-coax adaptor was attached to the WR90 port after the window. From this, low-loss heliax cable connected the cavity to the diagnostics racks outside the accelerator enclosure. The signal was fed into one channel of the low-level rf monitoring system used for high-power rf diagnostics. Here it was down-mixed with an X-band reference signal through I-Q demodulators and digitized in a 1Gsample/s digitizing scope. We could thus record high-resolution phase and amplitude signals for individual beam pulses.

Figure 3 gives a typical amplitude trace for a short beam pulse of about 15ns and 40mA. The time structure of the NLCTA beam has every rf bucket filled. Even at such a modest current and pulse length, there is plenty of

signal. From the 31ns decay time, we measure the loaded quality factor of the device to be $Q_L = \omega\tau/2 \approx 1,100$. The design was for about 800, but an imperfect window match may have increased the external Q.
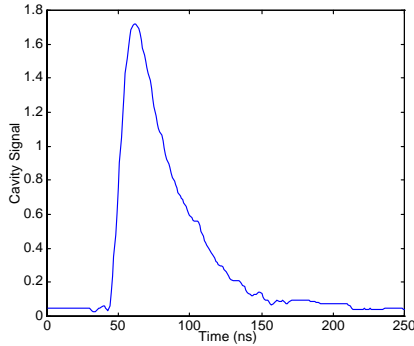

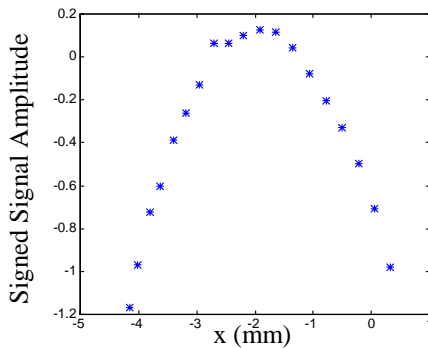Figure 3: Amplitude of response to 15ns beam pulse.

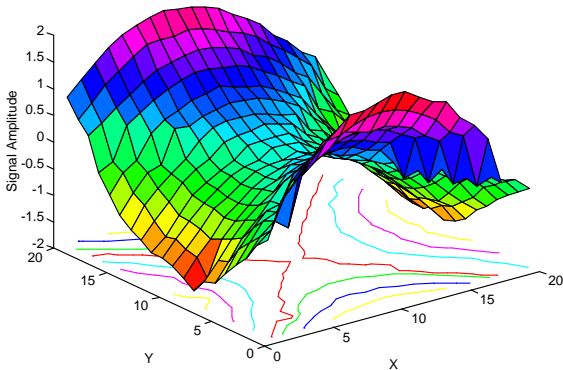Figure 4: Response as a function of beam position.

Figure 5: 2-D surface and contour plots of the cavity response as a function of beam position.

We also ran with a longer, 105ns pulse, with added attenuation. x and y correctors were used to move this beam around the cavity aperture. With a sign determined from the phase signal, the plotted signal amplitude traced out a parabola as the beam was scanned in x or y. Figure 4 is a plot of an x scan with y very close to zero. The fact that it still passes through zero twice is indicative of a non-zero beam quadrupole moment.

Figure 5 shows the variation of the cavity signal amplitude as the beam is moved over a grid. It is clearly the quadrupole mode we are exciting, as seen from the nice saddle shape. The range of the scan is approximately 5 mm in either direction. An exact calibration and measurement of the electrical center of the cavity relative to the beamline could not be obtained from this initial experiment, because the beam position at the cavity could not be precisely determined. The nearest bpm is about ten inches away, and the beam is tightly focused by an upstream quadrupole magnet. An attempt to infer the local position from the readings from two downstream bpm's using TRANSPORT matrices from the NLCTA on-line model was unsuccessful, in that it gave a y-range slightly exceeding the beampipe aperture.

5 CONCLUSIONS

A prototype cavity quadrupole moment monitor has been designed and fabricated, and its general response tested with a real beam. It performed quite well, as expected. The advantages this approach presents over other monitors were obvious. These include simplicity, tunability, and strong coupling to the beam space charge. Resonance with beam bunch frequency was utilized to enhance the quadrupole signal relative to other modes. The use of a small waveguide network to perform necessary subtractions between waves from the four cavity irises reduces the output to a single rf signal, eliminating the need for much expensive rf electronics and avoiding the source of error and noise it would present.

The cavity resonance was found to be clean, with no competing modes approaching 11.424 GHz. Displacement of the beam around the cavity center showed the clear quadrupole nature of the coupling signal. More precise characterization of our device remains to be done. Sensitivity on the millimeter scale is obvious. We see no intrinsic reason why better than 100 micron resolution should not be achievable. Calibration and operation of such a monitor is dependent on the accuracy of needed auxiliary diagnostics, namely beam position and current monitors. Combining this quadrupole cavity with a cavity bpm and monopole mode cavity such as developed by Johnson, *et al.* [5], could provide a very useful, compact, multi-function beam diagnostics structure.

6 REFERENCES

[1] R.H. Miller, et al., "Nonintercepting Emittance Monitor," 12th Int. Conf. on High Energy Accelerators, FNAL, Batavia, IL, U.S.A., August 1983; SLAC-PUB-3186.

[2] K.L. Brown, et al., SLAC-91, Rev. 2, 1977.

[3] A. Jansson, "Non-Invasive Single-Bunch Matching and Emittance Monitor," Phys.Rev.ST Accel.Beams 5:072803, 2002.

[4] J.S. Kim, et al., "A Resonant Cavity for Single-Shot Emittance Measurement," 2001 Particle Accel. Conf., Chicago, IL, U.S.A., June 2001.

[5] R. Johnson, et al., "Cavity BPMs for the NLC," 10th Beam Inst. Workshop, BNL, Upton, NY, U.S.A., May 2002; SLAC-PUB-9211.