Design of a Standing-Wave Multi-Cavity Beam-Monitor for Simultaneous Beam Position and Emittance Measurements

Jin-Soo Kim*, Roger Miller+, and Christopher Nantista+

*FAR-TECH, inc., 10350 Science Center Drive, #14-150, San Diego, CA 92121
+ Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305

Abstract. A high precision emittance measurement requires precise beam position at the measurement location. At present there is no existing technique, commercial or otherwise, for non-destructive pulse-to-pulse simultaneous beam position and emittance measurement. FAR-TECH, Inc. is currently developing a high precision cavity-based beam monitor for simultaneous beam position and emittance measurements pulse-to-pulse, without beam interception and without moving parts. The design and anlysis of a multi-cavity standing wave structure for a pulse-to-pulse emittance measurement system in which the quadrupole and the dipole standing wave modes resonate at harmonics of the beam operating frequency is presented. Considering the Next Linear Collider beams, an optimized 9-cavity standing wave system is designed for simultaneous high precision beam position and emittance measurements. It operates with the π-quadrupole mode resonating at 16th harmonic of the NLC bunch frequency, and the $3\pi/4$ dipole mode at 12th harmonic (8.568 GHz). The 9-cavity system design indicates that the two dipoles resonate almost at the same frequency 8.583 GHz and the quadrupole at 11.427 GHz according to the scattering parameter calculations. The design can be trivially scaled so that the dipole frequency is at 8.568 GHz, and the quadrupole frequency can then be tuned during fabrication to achieve the desired 11.424 GHz. The output powers from these modes are estimated for the NLC beams. An estimated rms-beam size resolution is sub micro-meters and beam positions in sub nano-meters.

INTRODUCTION

Beam position and emittance are parameters of fundamental importance for accelerator operation.[1] Beams in linear colliders require accurate measurement of these parameters. At present there is no beam instrumentation available, either commercial or research, for single-shot, non-destructive, high-precision, integrated position and emittance measurement. The significance of the integrated monitor is that for a high resolution emittance measurement it is important to obtain the beam position at the emittance measurement location.

At present there are several techniques for position and/or beam emittance measurements. A single-shot emittance measurement based on striplines has been proposed previously by Miller, *et al.* [2]. The resolution of this method, however, is quite limited. Recently, A. Jansson [3] introduced a method of measuring beam emittance using 4 loops to measure magnetic flux. This method has an advantage over

Contributed to 11th Advanced Accelerator Concepts Workshop (AAC 2004), 21-26 June 2004, Stony Brook, New York

Work supported in part by Department of Energy contract DE-AC02-76SF00515

others by not picking up monopoles but does not include resonance enhancement. More development has been made in beam position only monitors. For example, single-output S-Band cavities have been used. Hartman, *et al.*, have demonstrated 100-nm scale resolution in C-Band cavities [4] and subsequent studies by Slaton, *et al.*[5], extended this range to 25-nm, all in single-bunch mode. Recently a resonant BPM cavity was also reported [6] but this device is still at a research level. In the meantime, for the most accurate multi-bunch position measurements, recent experiments have had to rely on the thirty-year old single-output S-Band design [7]. Comparison with stripline beam position monitors has also been instructive [8].

A proven design of a high-precision pulse-to-pulse beam monitor is necessary. FAR-TECH, Inc. is developing a high precision integrated beam position-and-emittance monitor to obtain precise beam position at the emittance measurement location. This is an important advance on our recently completed Quad-Cavity project [9,10,11], which was based on a resonant cavity [12]. In addition to the following advantages of the resonant cavity approach, which have already been achieved on the previous project,

1. The resolution of the measurement was enhanced by up to $Q_e/(\pi h)$, where h is the bunch interval in rf-wave buckets
2. The measurement was non-invasive.
3. The common mode signals were suppressed via hybrid networks,

the upgrade includes several important improvements, as listed below.

4. The cavity and its network design allow for the simultaneous measurement of beam position and emittance from a single cavity.
5. For higher beam-mode coupling, the external Q was raised from 1000 to 5000 for critical coupling by adjusting the dimensions of the iris.
6. The device forms a 9-cavity standing wave structure.

For suppression of common modes in the hybrid network we employ the same method used in our recent Quad-Cavity work for a quadrupole pickup and use a similar method for the pickup of both dipoles, as sketched in Figure 1. By proper networking, the monopole, the two dipoles, and the quadrupole modes can all be separated (See the Figure caption for details).

Of the three signals, the quadrupole signal is by far the smallest. Thus, it is important to obtain maximum coupling between the beams and the quadrupole mode. Accelerator beams are nominally upright bi-Gaussian distributions in the x-y plane, that of the quadrupole magnets, and thus the focusing lattices, are aligned to the horizontal and vertical planes. To take advantage of this configuration, the cavity is rotated by 45° with respect to the beamline. The cavity has a diamond shape when looking into the beamline. The laboratory coordinates (horizontal x_L and vertical y_L are shown in Figure 1 along with the cavity coordinates *x* and *y*.

We chose a 9-cavity system. The reason behind choosing an odd number of cavities is symmetry considerations. For a standing wave structure, it is sufficient to have external coupling to only one cavity, preferably the central one. Therefore, a hybrid network need only be attached to the pickup cavity. A simple sketch of such a system is shown in Figure 2. Schematics of the cross section of a multi-cavity system are shown in Figure 2(a) and a bird's eye view of the pickup cavity with hybrid networks in Figure 2(b) including ports A and B for quadrupole pickup and ports a and b for a dipole pickup. Ports A and B are connected to series arms, while ports a and b are connected to shunt arms. The two series arms are connected to another series arm for a final subtraction (for the quadrupole pickup) and also to a hybrid off to a shunt arm (for the other dipole pickup). A 3D picture of the cavity and network system will be presented later. Additional multi-cavity systems could be attached via couplers for enhanced accuracy, if the beam parameters do not vary much over many cavity systems.

With perfect hybrid networks we should obtain perfect resolution. The limit in resolution of beam position and emittance will be due to the fabrication errors and electronic noise. The resonant frequencies can be fine tuned during the fabrication phase.

The proposed approach works for a beam in a FODO lattice where the beam is elliptical in shape. One measurement alone can provide the beam position and the quantity (rms-beam-size in x)^2 – (rms-beam-size in y)^2 . If the beams σ_x/σ_y aspect ratio is large , the difference is essentially the square of the beam size in x. Six successive beam quadrupole moment measurements, performed at different betatron phases in a linear transport system, allow us to determine the beam emittance, i.e., the beam size and shape in the beam's phase space. The beams in NLC would always be flat in the horizontal plane even when the beam is largest in y. The aspect ratio of σ_x to σ_y varies from about 100 to 4. In order to extract the vertical beam emittance or the vertical beam size in NLC we would need six full measurements which give full emittance information if no x-y beam coupling is present.

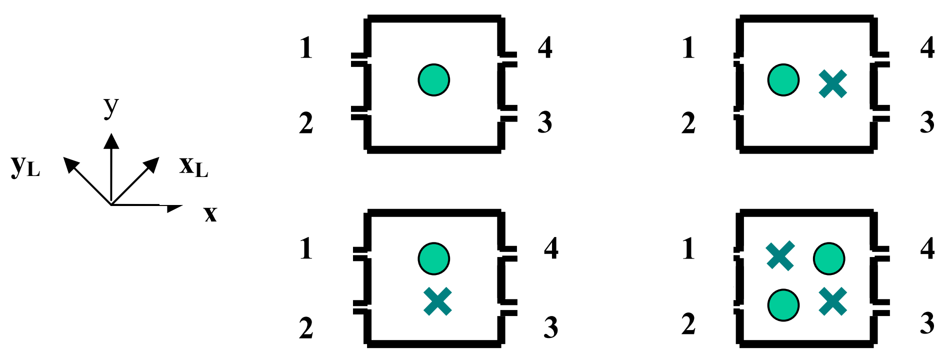


FIGURE 1: Resonance modes in rectangular cavity with irises. The monopole and the x-dipole vanish in subtraction networks performing E1-E2 and E4-E3, where E1 represent the field around iris 1. An additional subtraction network (E1-E2)-(E4-E3), rejects the other dipole, leaving only the quadrupole signals. If an additional network performs the summation, (E1-E2)+(E4-E3), we obtain only the y-dipole signal. Now if we start with summation networks, E1+E2 and E4+E3, followed by a subtraction network, we have the x-dipole signal only.

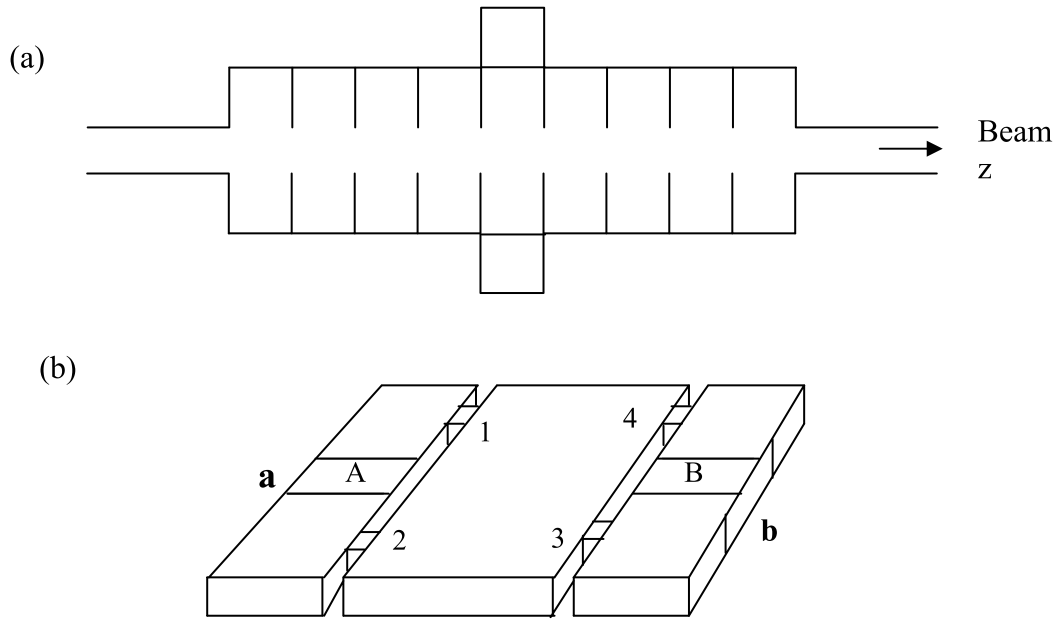


FIGURE 2: Schematic diagram of the Multiple Cavity Beam Monitor System. Shown are (a) a cross section of the 9 cavity system and (b) the bird's eye view of the pickup cavity with the hybrid networks. The quadrupole and the y-dipole signals go through ports A and B and are then separated by another hybrid tee not shown. The x-dipole signals go through ports a and b. The labeling 1-4 of the four irises matches those in Figure 1.

DESIGNS OF A STANDING-WAVE MULTI-CAVITY MONITOR

The goal is to design a cavity whose quadrupole and dipole modes resonate at harmonics of the beam operating frequency, 714 MHz. We chose the quadrupole resonant frequency at 11.424 GHz, the 16th harmonic, and the dipole frequencies at 8.568 GHz, the 12th harmonic of 714 MHz. Therefore the ratio is chosen

$$\frac{f_q}{f_d} = \frac{16}{12} = 1.33333, \quad f_q = 11.424\ GHz, \quad and \quad f_d = 8.568\ GHz. \qquad (1)$$

The resonant cavities can be stacked together. It is possible to create a good standing wave structure of up to about 10 cavities where the fields in the multi-cavities are enhanced linearly with the number of cavities.

We chose the π quadrupole Mode and 3π/4 dipole mode for the 9-cavity standing-wave structure. Due to the complexity of the 9-cavity design we first separately designed three sub-sections; standard cavities, end cavities and the pickup. In addition to maintaining the resonant frequency ratios, the iris dimensions to the waveguides are adjusted to accomplish the desired critical coupling where the external Q is the same as the wall Q. The resultant design is shown in the first two figures of Figure 3; the contours of Ez field on the z=0 plane are shown in one quadrant of the pickup cavity (Left) and a 3D view of the pickup cavity with waveguide networks (Middle). Assembling all three sections together we obtain a system shown in Figure 3 (Right).

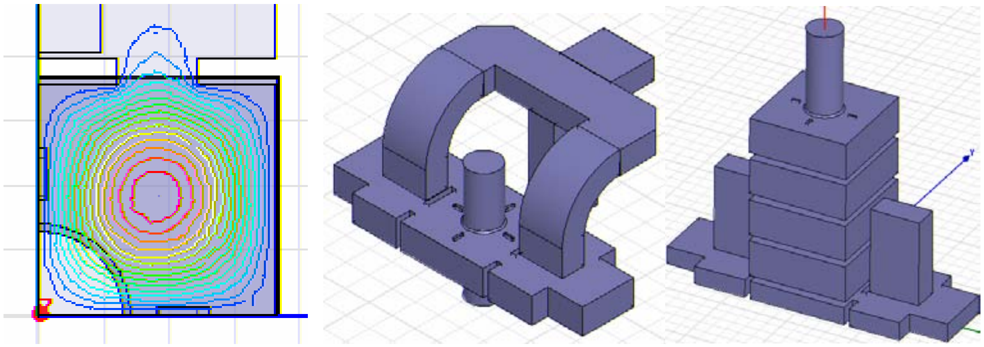
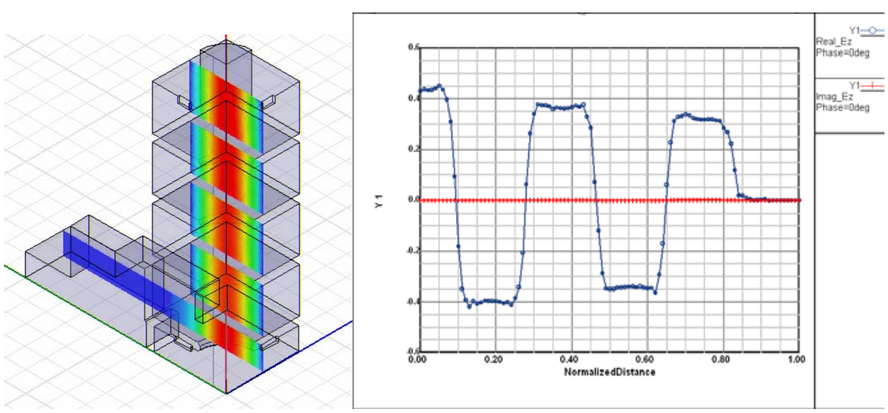


FIGURE 3*: (*Left) Quadrupole field contours in a quadrant of the pickup cavity, (Middle) 3D view of the pickup cavity with waveguide networks, and (Right) conceptual drawing of the main upper half of the 9-cavity monitor.

MULTI-CAVITY SYSTEM DESIGN ANALYSIS

Shown in Figure 4(a) is a contour plot of the quadrupole E_z field on the plane of y=Ly/4 of the cavity system with all the three sections combined. The quadrupole mode shows almost equal amplitude in all the cells. To be more quantitative, in Figure 4(b) we present the Real (E_z) in blue and Im (E_z) in red, which is zero. They are the normalized E_z values along z at x= 4mm and y=4mm for the quadrupole mode (with resonant frequency at 11.426 GHz). The E_z amplitudes are almost equal for all the cells, and show a nice π phase advance in each cell, resulting in a π-mode. A slight tuning could improve the results even more. The dimensions of the device in Figure 4(a) are around 3.6cm x 3.6 cm and the pin dimensions are around 4mm x 3mm x 1mm.



(a) (b)

FIGURE 4. : Quadrupole mode in the full 9-cavity system; (a) Color contour plot of the quadrupole E_z field on the plane of y=Ly/4. (b) Normalized E_z along z at x= 4mm and y=4mm for the quadrupole mode. Shown are the Real (E_z) in blue and Im (E_z) in red, which is zero. The E_z are almost the same for all the cells and show nice π phase advance in each cell resulting in a π-mode.

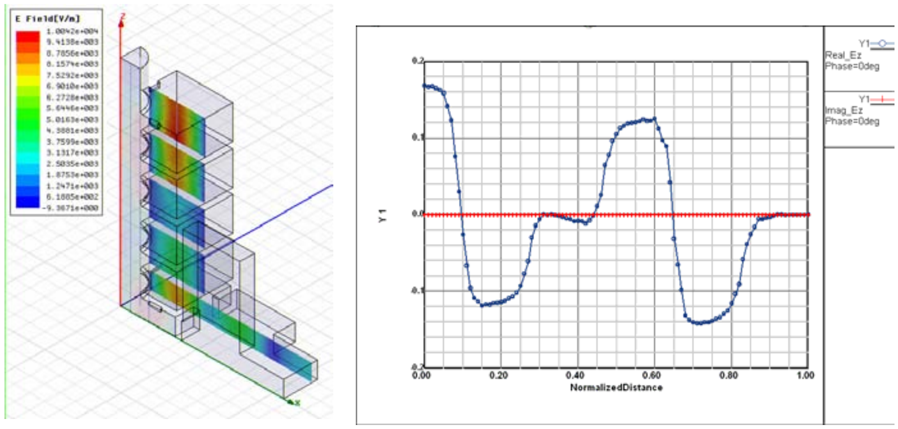


FIGURE 5. : (Left) Dipole Mode in the 9-cavity system; Contour plot of the Dipole 1 Ez fields on the plane of y=Ly/4. (Right)Normalized Ez along z at x= 4mm and y=0 for the Dipole 2 (8.5799 GHz). Shown are the Real (Ez) in blue and Im (Ez) in red, which is zero. The amplitudes show 1.5 oscillations in the half of the structure i.e. in 4-cells counting the end cell as half, thus showing a 3π/4 mode.

TUNING OF QUADRUPOLE AND DIPOLE FREQUENCIES

A variational calculation indicates that tuning pins, a center pin and two quarter-location pins, can easily adjust resonant frequencies 10-20 MHz. (See Figure 6.) Insertion of eight quarter-pin tuners of $1mm^3$ per tuner on all four side walls would increase the quadrupole frequency by 12 MHz for our cavity. This is more than we would need to tune, since the 1 mil tolerance in fabrication corresponds to about 10 MHz for our cavity geometry. Accordingly, the tuners could be moveable pins or small screws.

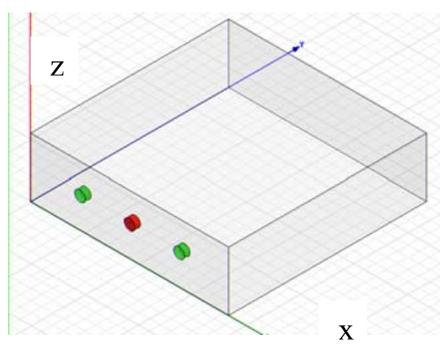


FIGURE 6*:* Tuning pins; a center pin (red) at Lx/2, and two quarter-location pins (green)

SUMMARY OF RESULTS

We have designed a 9-cavity standing wave structure for an integrated beam monitor. Special care was taken to achieve maximum power output, while reducing the common mode effects for the quadrupole and the two dipole modes. Beam analysis and engineering issues were also investigated. An esitimated rms-beam size resolution is in sub micro-meters and beam positions in sub nano-meters.

Direct application of this integrated beam monitor includes the Next Linear Collider, the Linac Coherent Light Souce, TESLA, and other linear accelertors that require high precision beam parameters. It is also directly applicable to XFEL and other free electron lasers.

ACKNOWLEDGMENTS

The authors appreciate the contribution from S. Barry, R. Jones, and A. Weidemann to this project. The work is supported by the SBIR grant # DE-FG02-03ER83658.

REFERENCES

1 M. Ross, "Frontiers of Accelerator Instrumentation", Proc. Advanced Accelerator Workshop, AIP Conf. Proc. 279 (AIP, New York, 1992) pp. 807-819.

2 R. H. Miller, J. E. Clendenin, M. B. James, J. C. Sheppard, Proc. 12th Int. Conf. on High Energy Acc. (Fermilab, Batavia, 1983) SLAC-PUB-3186.

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

4 S. C. Hartman, T. Shintake and N. Akasaka, "Nanometer resolution BPM using damped slot resonator", Proc. 1995 Particle Accelerator Conference (IEEE, New York, 1995).

5 T. Slaton, G. Mazaheri, and T. Shintake, "Development of nanometer resolution C-Band radio frequency beam position monitors in the final focus test beam", Proc. 19th Internat'l Linear Accelerator Conference (to be published) SLAC-PUB-7921. (SLAC publications are available on the web via http://www.slac.stanford.edu/find/hep.)

6 R. Johnson, Z. Li, T. Naito, J. Rifkin, S. Smith, and V. Smith, 'Cavity BPMs for the NLC', SLAC –PUB-9211, May 2002

7 R. Carr, et al., "A Precision Measurement of the Weak Mixing Angle in Møller Scattering", K.S. Kumar, coordinator, SLAC-Proposal-E-158, 1997.

8 S. Smith, P. Tenebaum, and S.H. Williams, "Performance of the beam position monitor system of the final focus test beam", Nuclear Instrum Meth. A (submitted), SLAC-PUB-7993.

9 J.S. Kim, et al, 'A Resonant Cavity for Single –Shot Emittance Measurement', Proc. PAC. 1999

10 J.S.Kim, C.D. Nantista, R.H. Miller, S. Tantawi, and A.W. Weidemann 'A Resonant Cavity for Single-Shot Emittance Measurement, PAC conference, 1999.

11 C.D. Nantista, J.S. Kim, and A.W. Weidemann, 'A Quadrupole Mode Resonant Cavity for Non-Invasive Single-Shot Emittance Measurement', Linac 2002, KyungJoo S. Korea

12 D.H. Whittum, and Y.Kolomensky, Rev. Sci. Instr. Vol. 70 (1999) p2300.