Beam Position Monitor Test Stand

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The need to produce intense X-rays in the Energy Recovery Linear Accelerator requires shorter and narrower electron beams than the Cornell Electron Storage Ring can provide. Such electron beams will demand highly accurate beam position monitors (BPMs) to enable operators to control the beam. To prepare for new BPMs, a test stand has been built to conduct experiments on new algorithms and designs. This paper discusses this test stand.

I. BACKGROUND

Beam position monitors (BPMs) are an essential instrument for all particle accelerators. Accurate measurement of particle beam positions allow operators to accurately monitor and control the accelerated beam. A beam position monitor test stand allows researchers to better understand and refine the types of BPMs in use at the Cornell Electron Storage Ring (CESR).

The Energy Recovery Linear Accelerator (ERL), a new facility still in conceptual stages, will open new frontiers in X-ray science at Cornell University. The ERL will emit radiation with higher brilliance than any light source can currently provide, this will allow researchers in fields from biology to materials science to resolve even finer structures. Furthermore, the ERL will have shorter and narrower electron beams than already possible in CESR. The control of shorter and narrower electron beams will demand better accuracy in measuring the position of the beam. Current BPM designs with improved accuracy may not be enough and entirely new designs of BPMs may be needed. This BPM test stand will help with current BPM testing and future BPM design efforts.

II. CURRENT BEAM POSTION MONITORING EFFORTS

The beam position monitor consists essentially of four electrodes attached to either side of the beam tube. The BPMs in CESR are button style electrodes; each button is a circular disk of aluminum. At CESR there are about six different designs of BPMs and a total of roughly a hundred BPMs. The placement of the buttons on the most common of the CESR BPM designs can be seen in Figure 1.

The approach used to determine the position of the electron beam is to treat the effect of the beam as a two dimensional electrostatic problem. An electron beam passing through a BPM induces a charge on the buttons, which uniquely depends on the position of the beam. Due to the lack of longitudinal variation, the electron beam appears to be essentially a line charge. Using the voltage on the buttons, one can solve for the position of the electron beam.

$$P(x,y) \rightarrow V(b_1, b_2, b_3, b_4) \tag{1}$$

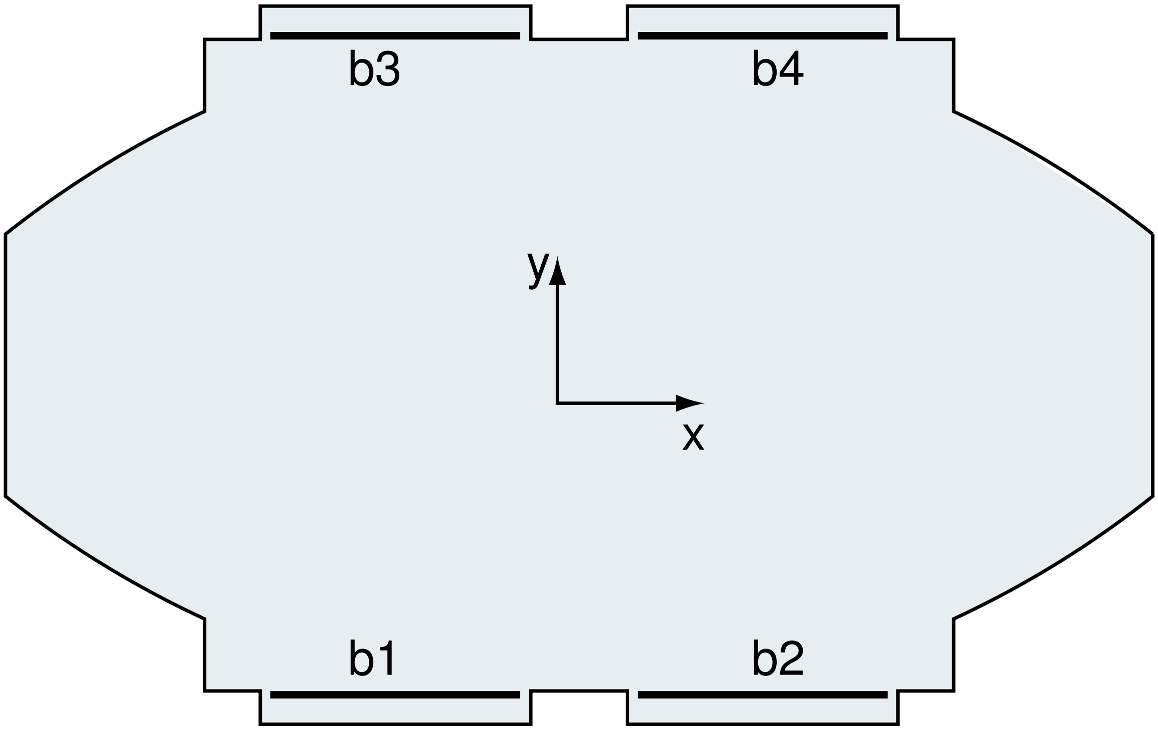


FIG. 1: Two electrodes are placed on each side of the beam tube.

In the control room of a particle accelerator, the voltages on the BPM buttons are known and the beam position is the desired variable. The challenge is to invert the function and solve for the position of the beam as a function of the voltage on the electrodes.

$$V(b_1, b_2, b_3, b_4) \to P(x, y) \tag{2}$$

A simplistic approximation involves linearization or summing over the differences.

$$x = x_0 \frac{(b_2 + b_4) - (b_1 + b_3)}{\sum_i b_i}, \tag{3}$$

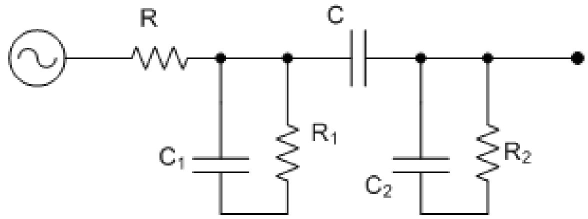
$$y = y_0 \frac{(b_3 + b_4) - (b_1 + b_2)}{\sum_i b_i}, \tag{4}$$

where x_0 and y_0 are calibration factors set by the geometry of the BPM. Though accurate when the electron beam is close to the center of the BPM, these equations are not accurate at large deviations from the center. The lack of accuracy is unfortunate because the need for the BPMs is the most acute when the electron beam is not near the center.

Rich Helms and Georg Hoffstaetter of Cornell University have developed a nonlinear model of the electron beam position which will work better for beams away from the center of BPMs [1].

III. CAPACITIVE COUPLING

The buttons on the BPMs are not perfectly aligned within the beam tube. The alignment problems can introduce inaccuracies in the calculations of electron beam position.



Capacitive coefficients are the solution; the introduction of scaling factors increases accuracy tremendously.

The capacitive coefficients can be found through analysis of the frequency response of the BPM. Using a spectrum or network analyzer, one can apply a monotonic function of frequency signal to a button and measure the response on another. The capactive coefficient may be approximated by solving for the slope of the linear region of the frequency response.

The spectrum analyzer does not provide similar results; it has a flat response.

The network analyzer, HP 3588A, has a linear response.

The general shape of the frequency response of the button should be explainable by circuit theory. The BPM may be taken as the circuit in Figure III.

The theoretical frequency response is Equation 5.

$$R(f) = \frac{Z_2 Z_4}{Z_1 Z_2 + (Z_1 + Z_2)(Z_3 + Z_4)} \tag{5}$$

where the magnitude of

$$|Z_2 Z_4| = \frac{R_1 R_2}{\sqrt{(1 + \omega^2 R_1^2 C_1^2)(1 + \omega^2 R_2^2 C_2^2)}} \tag{6}$$

Attempts to directly measure the capacitance between the buttons of the BPMs have not been successful. Using a capacitance meter produced a range of measurements from nanofarads to picofarads.

IV. NEED FOR A BEAM POSITION MONITOR TEST STAND

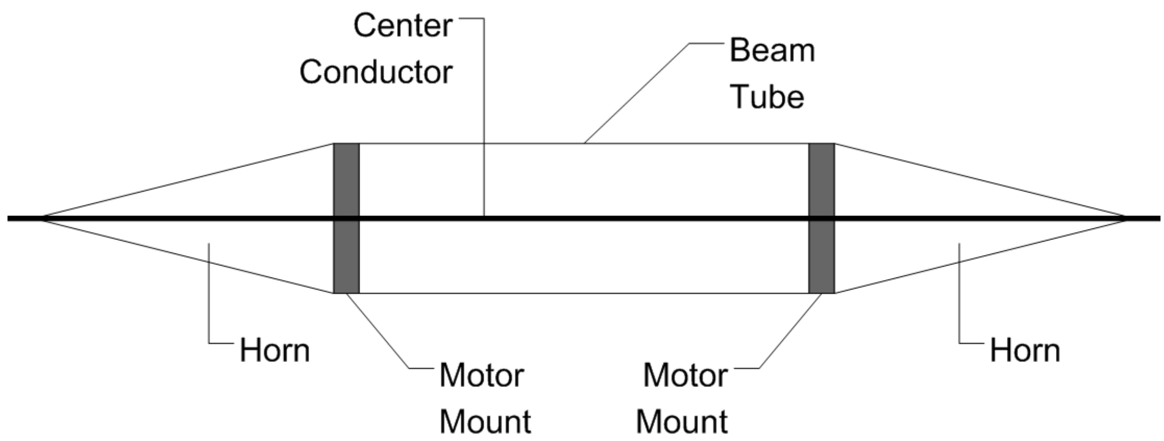
A beam position monitor test stand is needed for numerous reasons. A test stand enables experimental observations on the accuracy of the nonlinear method. The coupling between buttons can be easily measured with a test stand, as well as the electric center of a BPM.

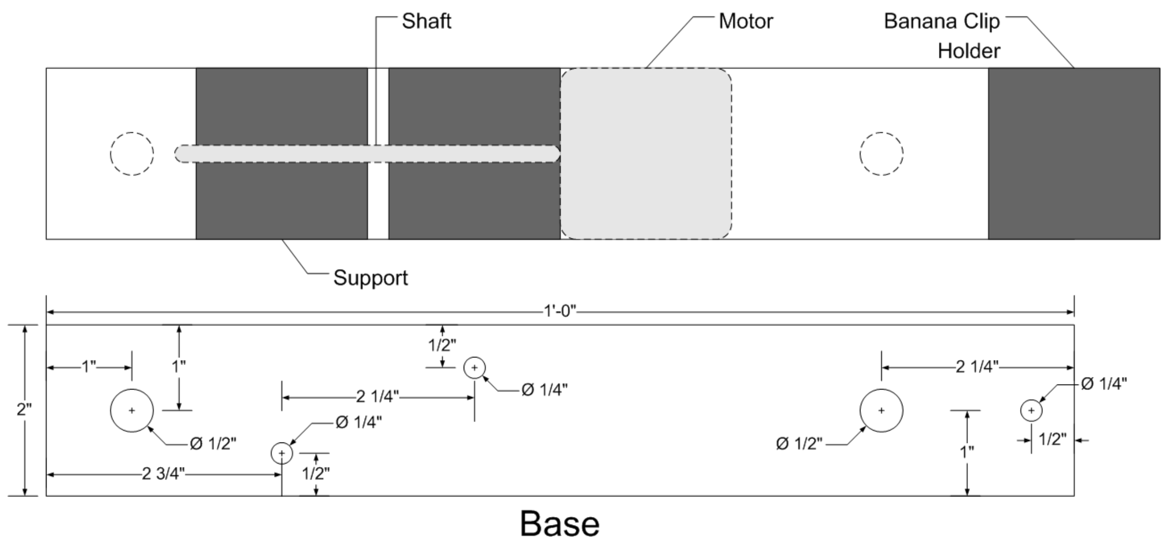
With a test stand, we can better understand current BPM designs and vaccuum chambers in CESR as well as test new designs of BPMs before installation in the ERL

V. EXPERIMENTAL SETUP

The beam position monitor test stand consists of two brass horns with a section of beam tube sandwiched between. Figure V is a schematic of the experimental setup. The electron beam is simulated by a pulse wave travelling down a center conductor that threads through the tube.

The stepper motors are supported by an aluminum structure. Figure V illustrates the supports. Each nonconducting filament is wound around a quarter inch twenty threaded



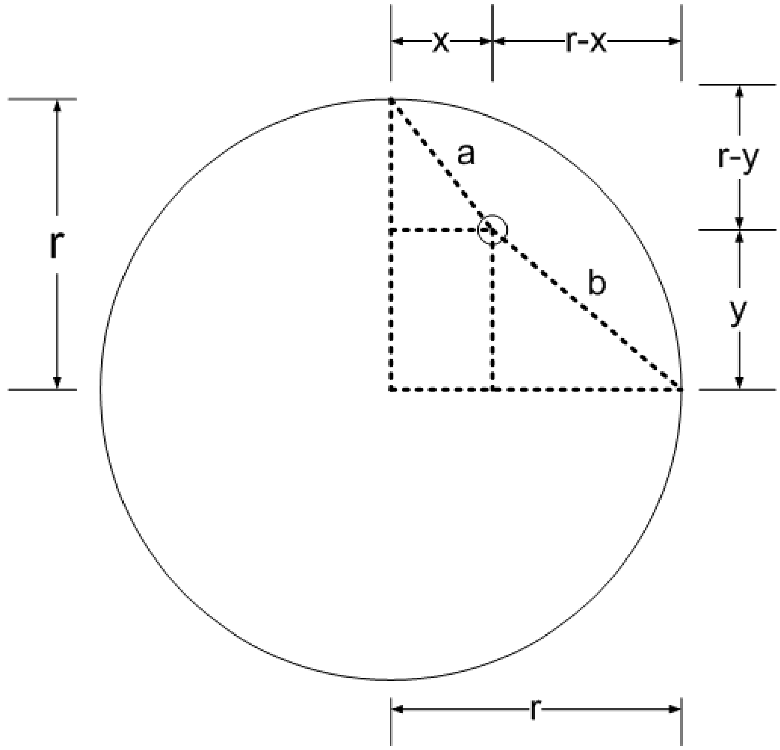


rod, which is connected to the shaft of the stepper motor. The end of both the shaft and the rod have heat shrink wrap applied; the two are attached through a quarter inch shaft connector. On the far end of the threaded rod is a shaft extender which threads through a aluminum support. The base is secured to the test stand by Unistruct.

The stepper motors are controlled by a single cable running to a serial port. The usage of multiple motors per cable necessitates the enabling of *party mode*. *Party mode* allows commands to be directed toward specific motors; motors can be independently addressed by name.

The motors are placed in the lowest resolution setting, which is four hundred steps per revolution. **MS 2**. The acceleration and velocity are capped to ten steps per second second and hundred steps per second, respectively. **A=10** and **VI=100**. The displacement of the filament per step can be determined by the diameter of the threaded rod. The diameter of the rod is 0.25 inches or 0.635 centimeters; the circumference of the rod is thus approximately 2.00 centimeters. $C = 0.635 \times \pi$. Since one revolution is 2.00 centimeters on the filament, each step is 50.0 micrometers. $2.00 \div 400 = 0.00500$.

The stepper motors may be controlled by a simple terminal interface, but a LabView program allows for easier control. A Cartesian grid is overlaid on the beam tude, dividing the tube into quadrants. The program permits a user to enter in where in the beam tube



the center conductor should go; the motors move an appropriate distance. Figure V depicts the setup of the center conductor and filaments. Where the stepper motors are mounted, the beam tube is circumscribed by an external cylinder. The cylinder allows for close to full movement of the center conductor within the beam tube. The displacement of the vertical and horizontal filament are derived as follows.

$$\Delta V = R - \sqrt{x^2 + (R - y - r)^2} \tag{7}$$

$$\Delta H = R - \sqrt{y^2 + (R - x - r)^2} \tag{8}$$

Where ΔV and ΔH are the vertical and horizontal displacement of the filament, x and y are the desired vertical and horizontal displacement, and R is the radius of the external cylinder.

The vertical motor will need to move $\Delta V \times 10^4 \div 50$ steps and the horizontal motor will need to move $\Delta H \times 10^4 \div 50$ steps, where 10^4 is the conversion factor from micrometers to centimeters and 50 is the step size in microns. A problem is the possibility that the movement of either the vertical or the horizontal filament might pull on its counterpart. Tension beyond the force from the counterweight might cause the filament to slip, destryoing efforts to calibrate the position of the center conductor. To hopefully reduce the possibility of too much tension, the number of steps each motor must make is split into ten stages. The vertical and horizontal motors take turns moving until the ten stages are complete. The need for slack is minimized.

The preliminary calculation assumes that the filament is attached directly to center conductor; unfortunately, the filament is secured to the wire by a plastic collar, complicating the calculation. The orientation of the plastic collar, though, is not significant and may be neglected; the new equations to derive the vertical and horizontal displacement are as below.

$$\Delta V = R - \sqrt{x^2 + (R - y - r)^2} \tag{9}$$

$$\Delta H = R - \sqrt{y^2 + (R - x - r)^2} \tag{10}$$

VI. RESULTS

Where $\Delta V, \Delta H, x, y$ and R are as in Equations 7 and 8, and r is the radius of plastic collar.

The true inner diameter of the threaded road is not a quarter inch either; optical survey equipment reveals that one half revolution of the motor results in a displacement of 0.898 centimenters. One full revolution is 1.796 centimeters and one step is $1.796/div500 = 0.00449$ or 44.9 microns. Therefore the vertical motor needs to move $\Delta V \times 10^4 \div 44.9$ steps and the horizontal motor needs to move $\Delta H \times 10^4 \div 44.9$ steps.

In early testing, the control of the motors works well and moves the center conductor to the appropriate place. The nonconducting filament is use currently is a nylon line. With the help of a survey specialist and the optical survey equipment, Nabil Iqbal tested the stretching of the nylon and found the tension to introduce errors on the order of twenty five percent. An attempt to position the center conductor to (1, 1) centimeters only moved the conductor to (0.8, 0.8) centimeters. Purely vertical or horizontal displacement results in lower errors; the difference is only around 0.05 centimeters since the tension is only significant in one dimension.

VII. MEASUREMENTS

After my involvment with this project, fellow researchers used the test stand to make experimental observations regarding the non-linear approach at significant deviations from the center. Jeremy Urban and Nabil Iqbal took spectra from the buttons of the BPM. A measurement was a single sweep across the horizontal plane of the BPM. To minimize the possibility of misaligment, the motors along the horizontal axis were disconnected; the opposing motors along the vertical axis had complete freedom. Another sweep was made by positioning the center conductor along a grid throughout the BPM. For this measurement, the BPM was rotated sixty degrees to maximize the area the center conductor could be positioned at. They applied a signal to the horns and measured the signal on button A, the closest button to the center conductor; the closest button is close the the peak.

Urban and Iqbal found the data to agree well with the predictions of the non-linear approach, even as far from the center as the electrodes.

VIII. FUTURE PLANS

The calculations for control of the motors may need refinement for accuracy, but the immediate next step is to move the center conductor around and read off the voltages off the BPM.

The nylon filaments will be replaced by kevlar line, which should result in less stretching on the order of seventy.

The capacitive coefficients for the BPM buttons should be accurately measured. Correct capacitances will allow for an theoretical calculation of the frequency response curve.

The BPM test stand will be used as well to accurately find the magnetic center of superconducting RF cavities. The stepper motor setup can be used to control the position of a central conductor, which when moved around the RF cavity, changes the resonant frequency in a known manner, allowing the magnetic center to be determiend.

IX. ACKNOWLEDGMENTS

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[1] Orbit and Optics Improvement by Evaluating the Nonlinear BPM Response in CESR, Richard W. Helms, and Georg H. Hoffstaetter, Submitted to Physical Review, Special Topics, 2004.