RESONANT-CAVITY DIAGNOSTICS FOR AN EMITTANCE EXCHANGE EXPERIMENT*

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Abstract

The emittance exchange experiment planned at the Argonne Wakefield Accelerator facility will rely on a set of cavity based beam diagnostics in order to map the transport matrix through the beamline. These will include cavity beam profile monitor (BPM) and time-of-flight diagnostics, as well as beam quadrupole measurement (BQM) cavity to diagnose the x-y coupling. The measurement system will be designed to fit within compact space requirements, while also maintaining a sufficient clear aperture and sensitivity. The RF design of the system, as well as RF cold-test data for the BPM cavities, is presented.

INTRODUCTION

The Argonne Wakefield Accelerator (AWA) group has proposed an emittance exchange experiment (EEX) [1] towards solving the beam quality problem based on the observation that some accelerator applications can benefit from an optimization of the beam partition within 6D phase space. The focus is on the many accelerator applications that can benefit from an increase in the transverse (longitudinal) plane but can withstand relaxed requirements in the longitudinal (transverse) plane.

Emittance exchange between the two transverse dimensions has been demonstrated in an experiment [2] performed at Fermilab. The emittance exchange between the two transverse directions is performed by starting with a beam having a non-zero angular momentum due to being produced in a solenoidal magnetic field. The beam distribution is then manipulated with three skew quadrupole magnets, which have the effect of canceling the initial angular momentum, and producing a beam with an asymmetric emittance. The proposed AWA experiment, shown schematically in Figure 1, further manipulates the beam to provide transverse to longitudinal emittance exchange. First, a dogleg with two bend magnets correlates x and z dimensions and adds dispersion. Then, a TM_{110} RF cavity fed by external RF power is then able to further manipulate that correlation by introducing an energy loss or gain that linearly depends on the x dimension. Finally, a second dogleg, identical to the first, removes the dispersion, and thus completes the process of emittance exchange between the transverse and longitudinal directions. Thus, by controlling both emittance exchange steps, a beam can be prepared with virtually any desired ratio of the three emittances.

We discuss cavity based diagnostics suitable for measuring the transport matrix of the transverse to longitudinal portion of the EEX beamline.

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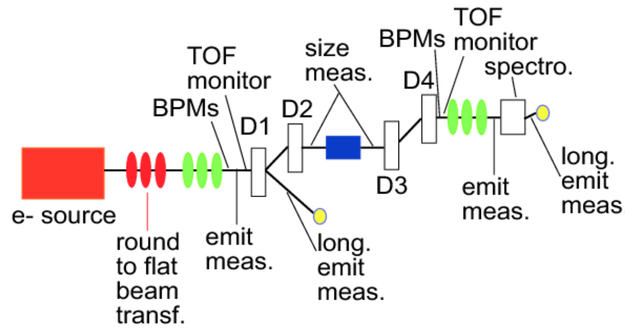

Figure 1: AWA proposed beamline with emittance exchange optics in both the x-y and x-z planes. Time of flight (TOF) and BPM locations are indicated.

BPM DESIGN

The design of the BPM cavities was driven by requirements of a minimal spatial footprint, a partially reentrant geometry to optimize shunt impedance, and an large beam aperture in order to be useful for the AWA experiment.

At a given cavity frequency, the longitudinal size of the cavity is minimized by using degenerate dipole modes, as well as using the same cavity to support the monopole mode to obtain a phase reference. Such a design often uses four waveguides to couple to the cavity mode

In some projects, especially those that require cleaning procedures to be compatible with superconducting RF structures, the waveguides are fully connected to the cavity. This generally requires very tight mechanical tolerances for the transverse placement of the waveguides in order to avoid breaking the four-fold symmetry of the structure and introduce cross-coupling between the x and y ports. However, when the cavity is made partially reentrant, we find that the coupling of those slots is insufficient and an alternative coupling slot geometry was introduced that meets our sensitivity requirements. A partially reentrant cavity saves space because it can have a smaller outer radius, and usually offers an improvement in shunt impedance for the dipole mode. A model showing the basic geometry of the BPM cavity is shown in Figure 2.

Capacitively-loaded waveguides

A further way to save space is to use capacitively-loaded waveguides for the coupling ports. If these waveguides are oriented with the long dimension (the H-plane) perpendicular the z-axis, it can save a modest, but significant, amount of space.

Two output port design

Most BPMs designed to use degenerate dipole modes use four output ports. This requires an additional hybrid coupler outside the vacuum system in order to combine the power from the two ports for each of the TM_{110} polarizations. Simply removing two of the waveguides breaks the four-fold symmetry of the cavity system and

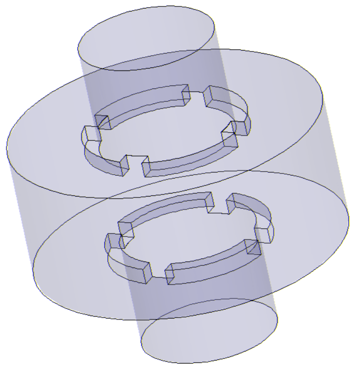

Figure 2: HFSS model of the BPM cavity without coupling slots and waveguides.

introduces cross-coupling between the two output ports. It was determined that if the uncoupled slots were connected to a small "void", it resulted in acceptable cross-coupling characteristics. The monopole frequency was 2350 MHz and the dipole frequency was 3250 MHz for the final design.

Simulations of the full cavity geometry were performed, but the reentrant nature of the BPM cell led to inadequate meshing which gives spurious cross-coupling readings. A geometry using four standard waveguides gave cross-plane coupling at the -30 dB level, while the capacitively loaded waveguides had a cross-plane coupling of -25 dB. This does not necessarily mean that the capacitively loaded waveguides case is worse, as the result value may have been biased by the fact that the waveguides themselves required more mesh points.

Shunt impedance and resolution

The shunt impedance of the dipole mode is 170 kΩ at a 5 mm offset. Assuming low-noise amplifiers having a 1.1 dB noise figure, the theoretical resolution of the device for a 100 pC beam is 1 µm. This is more than enough to satisfy the base requirements of the emittance exchange experiment.

BEAM QUADRUPOLE MEASUREMENT (BQM) DESIGN

The purpose of the quadrupole cavity is to measure any residual x-y coupling that may exist within the beam. In either of the two possible beam input cases, round-beam or flat-beam, there is an assumption that motion in the x and y directions are uncoupled. When placed in a normal orientation, the quadrupole cavity measures the second order moment ($\langle x^2-y^2 \rangle$). When placed in a 45° skew orientation the cavity measures the correlated second order moment ($\langle xy \rangle$). By placing a skew quadrupole cavity either before or after the longitudinal-transverse portion of the emittance exchange beamline a non-destructive measurement of the correlation between the x and y directions can be directly performed.

In order to achieve the 3250 MHz resonance frequency target, the quad cavity outer diameter was 4.5", which is slightly larger than the dipole cavities. The cavity uses a patented four internal post design to improve the shunt impedance of the quadrupole mode. The HFSS model for the cavity is shown in Figure 3.

The waveguide system for this cavity needs to selectively couple out the quadrupole mode and reject the monopole and both polarizations of dipole mode. In Figure 3, each waveguide couples to the quadrupole mode and one of the dipole modes. The remaining dipole mode can be suppressed with a hybrid coupler placed outside of the vacuum environment. This subtraction is done outside of the vacuum to limit the physical size of the cavity and to use a similar waveguide and vacuum feedthrough design as is used in the BPM cavities.

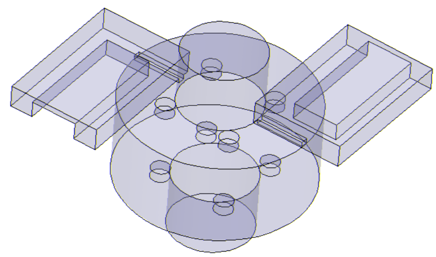

Figure 3: HFSS model of a quadrupole moment cavity with internal posts to increase the mode shunt impedance and slot-coupled capacitively-loaded waveguides.

The resolution of the present cavity can be compared to that of previous FAR-TECH projects at X-band. The X-band 2-cell BQM cavities we have made have a theoretical resolution down to 5 microns for 50 MHz of noise bandwidth at 290K. The cavity output power scales as $f^{3.5}$, which predicts a resolution of 18 microns for the proposed cavity. Low-noise amplifiers around 3 GHz have better noise factors than those at X-band. The filter bandwidth might also be reduced, provided that the filter phase response is reasonably linear over a Q-width around the center frequency. This level of resolution is thought to be sufficient to accurately measure the beam residual x-y coupling for the Argonne Emittance Exchange Experiment.

COLD TEST

A cold-test model of the BPM cavity geometry was fabricated out of copper and aluminum, and tested using an Agilent 8720ES network analyzer. The hardware used for the test is shown in Figure 4. The cavity itself was constructed of copper. The end pieces had a reentrant ridge with slots to provide proper mode alignment as can be seen on the simulation model in Figure 2 The rectangular copper piece had the coupling slots, waveguides and voids machined on the "outer" edge. The waveguide and voids were terminated with an aluminum plate that contained couplers that matched to the APC-7 couplers of the network analyzer. The non-brazed cavity was bolted together with threaded rod.

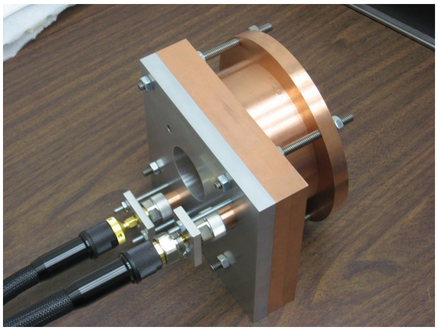

Figure 4: BPM cold test hardware.

The measured frequency of both of the dipole modes was 3248.92 MHz. To the accuracy measured, the modes always had the same frequency. The nominal cross coupling (S_{12}) between the output ports was -29.8 dB when tightly clamped.

This hardware differs from what is actually planned for the EEX experiment at Argonne by the direct coupling to the APC-7 ports of the network analyzer. The real BPM cavity would need a set of vacuum feedthroughs. The SMA feedthroughs that we have used in the past couple to a coaxial transmission line of very similar dimensions as the APC-7 standard, and we would in principle only need to match to the unique characteristics of the SMA connector itself. The SMA feedthrough has a reflection coefficient S11 of around 0.2, which is easy to match to by slightly altering the geometry of the coaxial line in the waveguide coupler.

TRANSPORT MATRIX MEASUREMENT

Measure x and x′

The BPMs labeled "BPM1" and "BPM2" in the top picture of Figure 5 are used to measure the position and angle of the beam as it enters the first dogleg of the EEX beamline. Similarly, BPMs "BPM3" and "BPM4" would measure the position and angle of the beam after it exits the EEX beamline. Either initial BPM could define the initial longitudinal position corresponding to the start of the portion over which the transport matrix is to be measured.

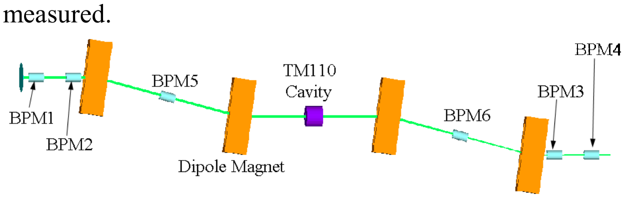

Figure 5: Layout of the EEX lattice showing the BPM placement.

Measure Energy Offset δ

If a single BPM is placed between the first and second dipole magnets of each dogleg, then the deflection at the BPM depends on δ due to dispersion. By measuring the beam angle outside the dogleg and the offset at a position with known (or calibrated) dispersion, δ can be determined.

TOF and initial longitudinal offset z

Measuring the longitudinal spatial offset from the beam center (either as time, τ, or in space, z) is significantly different than measuring the time-of-flight (TOF) between two distinct positions (or more correctly, measuring differences in the TOF between the current shot and some reference shot). TOF has a complication in that it measures the difference between the initial and final longitudinal spatial offsets. With careful timing of the injection phase relative to the TM110 cavity it is possible to know the initial longitudinal offset, but given the timing jitter common to a photoinjector this initial offset cannot be set externally with sufficient accuracy and must be measured. Thus, by combining a measured the initial longitudinal offset (relative to the cavity) and the TOF, the final longitudinal offset can be determined.

The TOF can be measured by determining the phase difference between the signal in an upstream BPM with one of the downstream BPMs. To measure the initial longitudinal position, the phase between the upstream BPM can be compared with the TM_{110} cavity though appropriate electronics.

Estimated Beam Coordinate Errors

An estimate of the measurement error of each of the coordinates based on the analysis of the appropriate BPM signal is summarized in Table 1 for various assumptions on BPM position accuracies. These estimates assume the layout from Figure 5 and are based on a spacing between the BPMs used to measure angle of 400 mm, and the energy diagnosing BPM positioned 475 mm from the dipole at a position with 132 mm of dispersion. These fixed numbers were assumed to be exactly known. It should also be noted that these number are ideal best case scenario where no real world issues such as calibration, and both collective and nonlinear effects have been included.

Table 1: Estimates of the uncertainties associated with measuring the beam phase space coordinates

Device Resolution Parameters	
BPM position resolution [μm]	1
Phase resolution for initial long. offset [°]	0.1
TOF phase resolution [°]	0.05
Measured Value Resolution	
Beam position error [μm]	1
Beam angle error [μrad]	3.5
Initial beam long. offset error [mm]	0.073
TOF error [ps]	0.06
Beam energy offset error [%]	0.0017

REFERENCES

[1] Y.-E. Sun, *et. al.*, Proc. of PAC07 p. 3441.
[2] P. Piot, Y.-E. Sun, and K.-J. Kim, Phys. Rev. ST AB **9**, 031001 (2007).