MEASUREMENT, SIMULATION, AND SUPPRESSION OF APS STORAGE RING VACUUM CHAMBER TE MODES IMPACTING VERTICAL BPM READINGS *

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Abstract

The Advanced Photon Source (APS) storage ring rf beam position monitors (BPMs) are impacted by the presence of beam-excited transverse electric (TE) modes. These modes are excited in large-aperture vacuum chambers and become trapped between the bellow end flanges. The TE modes are vertically oriented and are superimposed on the TEM beam position signals, corrupting the BPM measurements. Erroneous step changes in beam position measurements and systematic intensity dependence in the vertical plane have been traced to these modes, placing a fundamental limitation on vertical beam position stabilization. Experiments were conducted suppressing these modes on a test vacuum chamber. These experiments were simulated with Mafia [1] and Microwave Studio [2], confirming experimental results. We will describe the measurements, simulations, and prototype test results.

INTRODUCTION

As the Advanced Photon Source (APS) prepares for a large-scale upgrade, many of the fundamental limitations on beam stability are being studied. The APS storage ring vacuum chambers presently suffer from transverse electric (TE) longitudinal resonances trapped in the beam vacuum chamber. These TE-like modes are excited in the large-aperture sections of the vacuum chambers and become trapped between the bellow end flanges. The modes are vertically oriented and are superimposed on the beam position signals. These modes were identified and reported in 1998 when a network analyzer was used to measure the transmission of rf power from one beam position monitor (BPM) to an adjacent BPM on the same vacuum chamber section [3].

VACUUM CHAMBER DESCRIPTION

The Advanced Photon Source (APS) storage ring has 40 sectors each having 5 sections of vacuum chambers for a total of 200 individual sections. There are 80 curved and 120 straight sections of vacuum chambers that make up the 1104-meter-diameter APS storage ring. The storage ring vacuum chamber geometry shown in figure 1 has an oval beam chamber (left), connected to the antechamber by a small gap in the area between the two sections. The 0.426-inch gap section between the beam and antechamber sections shown in figure 1 introduces large capacitive loading that effectively lowers the cut-off frequency for TE01-like modes of the chamber.

The wavelength in a hollow waveguide satisfies the relationship:

$$F = \frac{c\sqrt{\left(1+\left(\lambda_g/\lambda_c\right)^2\right)}}{\lambda_g}.$$

Where c is the speed of light in free space, λ_c is the cut-off wavelength, and λ_g is waveguide wavelength. Using chamber length L = 4.81 m and λ_g = 2L/N (N=1, 2, 3….), the resonance frequencies can be estimated. The first resonance is the one closest to the cutoff frequency of the waveguide. The waveguide wavelengths for these lower-order modes are much longer than free space wavelengths.

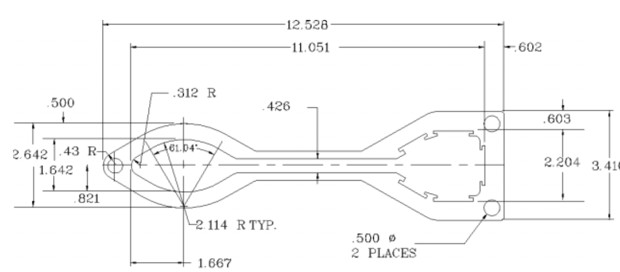

Figure 1: Storage ring vacuum chamber cross section (dimensions shown are inches).

MEASUREMENTS

Figure 2 illustrates the measurements that led to the discovery that these TE-like modes were corrupting

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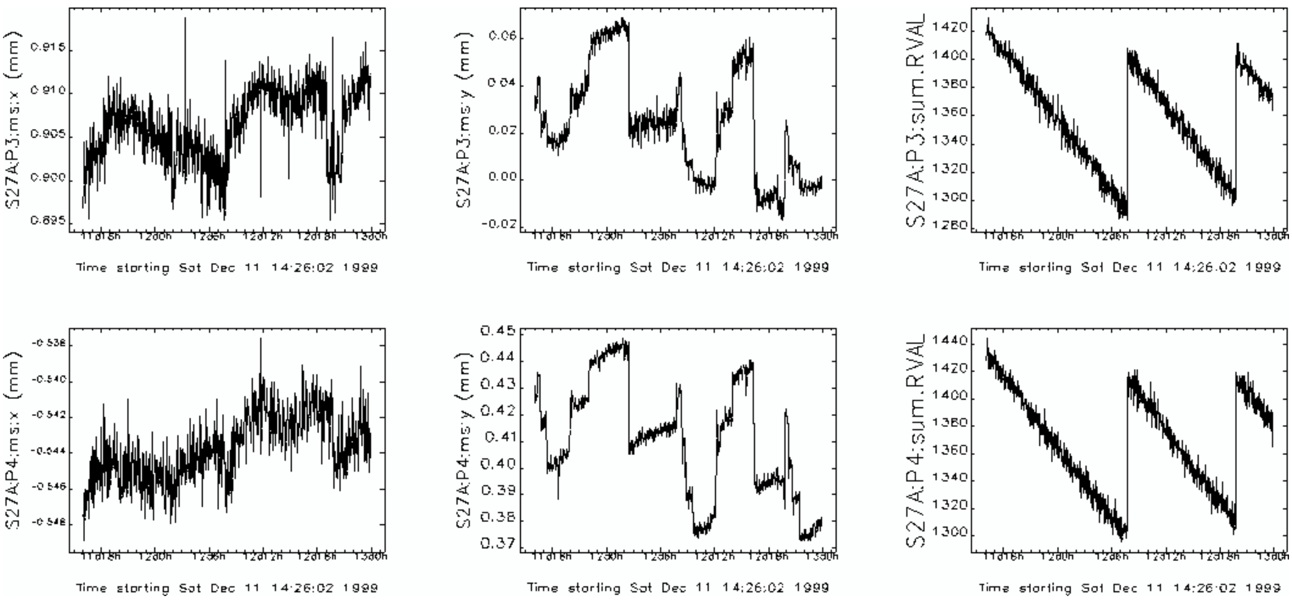

Figure 2: Systematic error measurements that led to the discovery of these TE-like modes. Horizontal position, far left plots; vertical position, center plots; and beam current, far right plots.

vertical BPM readings. The curved chamber (section 2) in sector 27 has two BPMs, S27:AP3 and S27:AP4 that are strongly effected by this mode. The beam current is represented in the far right plots labeled "sum RVAL," which is the sum of four button electrodes. As the beam decays as a function of time, the vertical position shown in the center plots exhibits a step-like function in two different positions along a single section of the curved vacuum chamber. At the same beam charge, the horizontal position does not show the step-like position change. The vertically orientated TE-like modes depend on the stored current and change as the current decays. This might be explained by source points of the TE mode, being heated and cooled as the beam intensity decays.

The electronics were closely examined and the chamber physically monitored for evidence of these step changes. The conclusion of this examination showed no signs of problems that could explain the step-like systematic errors. This led to the measurements of the BPM coupling from the upstream BPM to the downstream BPM on the same section of vacuum chamber. A network analyzer was used to make this transmission measurement and confirmed there was a weak coupling one from one button BPM to the downstream button BPM.

Early investigations to solve this problem included the use of lossy ceramics and shorting plungers to damp or otherwise modify the modes [3]. These ideas were never implemented since they required breaking vacuum for each of the 200 vacuum chambers affected. The solution to date has been to rely on rf BPMs attached to the insertion device vacuum chambers which do not have this problem. In addition, bending magnet and insertion device photon BPMS are used for vertical DC orbit correction.

RF Bench Measurements

The APS upgrade will include an extensive effort to improve beam stability. This opportunity has enabled us to revisit many of the fundamental limitations on beam stability. An R&D effort started last fall to study and write a proposal to reduce or eliminated this rogue TE mode. A spare curved vacuum chamber was set up on the bench and historic measurements of the chamber resonances were revisited. The first measurement was a simple transmission measurement from one button to a downstream button. This was similar to the measurement that was made in the discovery phase on this problem. The coupling is weak from button to button, but there is evidence that the vacuum chamber is not in cut-off at the BPM center frequency of 351.927 MHz. The next set of measurements was made using an electric field probe launch. The electric field probe launches a vertically polarized signal from one end of the chamber to a downstream BPM button used to receive the signal. Figure 3 shows the result of a measurement of microwave transmission using this arrangement. The cut-off frequency measured is about 331 MHz and the first resonance is 335.5 MHz. Table 1 shows the measured resonant peaks and the calculated eigenmodes [1] for a simplified geometry of the chamber.

Table 1: Measured and Calculated Resonances

Eigen mode Mode number	Measured (MHz)	Calculated (MHz)
1	335.5	330.2
2	341.0	336.5
3	345.5	346.8
4	356.4	360.7
5	369.4	377.8
6	384.6	384.6

These data demonstrate that the resonances fall in the operating band of the BPMs: 351.927 MHz with a 10 MHz, -3 dB bandwidth. The TE modes are vertically oriented, corrupting only the vertical BPM measurements. These data were compared with historical data taken for the chamber measured showing similar results. The measurements were also made using a magnetic field probe to launch a signal into the antechamber and showed similar results.

Mode Suppression Measurements

A new approach that effectively alters the geometry of the vacuum chamber by periodically shorting the high field region in the small gap was tested. The vacuum chamber was probed to determine if the cut-off frequency could be increased by shorting the small gap areas closest to antechamber, where getter vacuum pumping strips are mounted. The basic idea is to short the small gap region closest to the antechamber to avoid intercepting stray x-rays and increase the cut-off frequency. To demonstrate that the cut-off frequency could be shifted to a frequency higher than the BPM processing frequency, low-resistance shorting material was installed in the gap at 3 locations. The shorts were inserted about halfway into the small gap region in three different locations through antechamber pumping ports at about quarter length intervals. Figure 4 shows the results when the 10 mm gap is shorted. The resonances that were previously measured in figure 3 were greatly reduced or eliminated. This was encouraging and prompted a full investigation of ray tracing through each of the chambers to determine the optimal placement of shorts inserted into the small gap.

MODE SUPPRESSION REQUIREMENTS

The most critical requirement for implementing the mode suppressor is that the shorting device does not intercept the x-ray beam. To determine this, careful ray tracing plots have been generated for each chamber under worst-case steering conditions. The arrangement used for the data in figure 4 violates this requirement and could not be implemented because the short would intercept the x-rays.

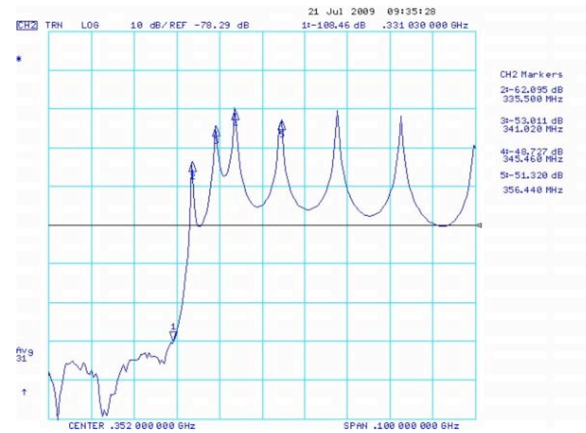

Figure 3: Vacuum chamber rf transmission as built.

Figure 4: Vacuum chamber rf transmission with three shorts installed in gap area.

The short or snubber circuit must provide low resistivity at UHF frequencies and provide reliable and complete grounding of high-field areas. The installation must be accomplished by access of the vacuum flanges on each end of the chamber. It should be installed similar to the getter strips, which slide in tracks along the antechamber shown in figure 1. There are a total of five tracks in the antechamber, but only two are presently being used. This facilitates the use of the inside tracks closest to the small gap. It is critical that the installation of these snubber circuits does not damage the chamber.

SIMULATIONS

Simulations have been conducted on a simplified straight section model of vacuum chamber with Mafia [1] and Microwave Studio [2]. The source was modeled as a vertical 50 ohm S-parameter discrete port, which produces a TE mode signal at the upstream port. The receiver probes were located close to the downstream end of the chamber. Shown in figure 5 are simulation results with longitudinal magnetic field Hz vs. frequency. First a transient progress was simulated in a 158-inch straight smooth vacuum chamber without shorting snubbers. Then a series of 3, 6, 9 and 12 rf shorts were added in the small gap one inch from the antechamber. The short height was 10-mm which is the same as the small gap between the beam and the antechamber. The first short shown in figure 6 is located 6 inches from the source. The following two snubbers are 12 inches apart. Each new sequence adds 3 addition shorts separated by 12 inches. Figure 5 shows the simulation results without short and with 3, 6, 9, 12 shorts starting from the upstream port. Similar to the bench measurements in figures 3 and 4, the resonances without shorts were suppressed over 50 dB when the small gap was shorted by different numbers of shorts. The more shorts, the greater the resonances were reduced and the higher the cut-off frequency was shifted.

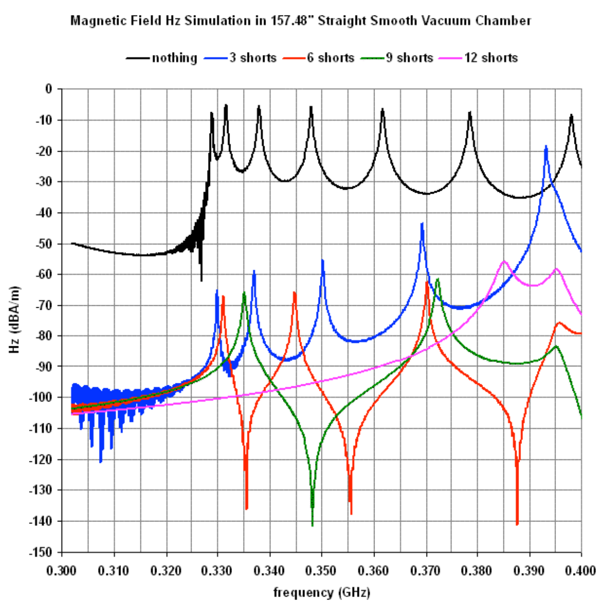

Figure 5: Simulation results without short and with 3, 6, 9, 12 shorts installed in the gap area.

MODE SUPPRESSION PROTOTYPE SNUBBER

The snubber prototypes feature an off-the-shelf longitudinal grounding strip to short the top to bottom of the chamber in the small gap region shown in figure 6. The grounding strip is designed to provide a low impedance path from the top to bottom of the small gap and can be readily inserted into the vacuum chamber. The material is beryllium copper giving it excellent spring features and resistance to compression set. The grounding strips are mounted in stainless steel carriers that can be linked together as shown in figure 7. Installation is similar to that of installing the vacuum chamber getter strips.

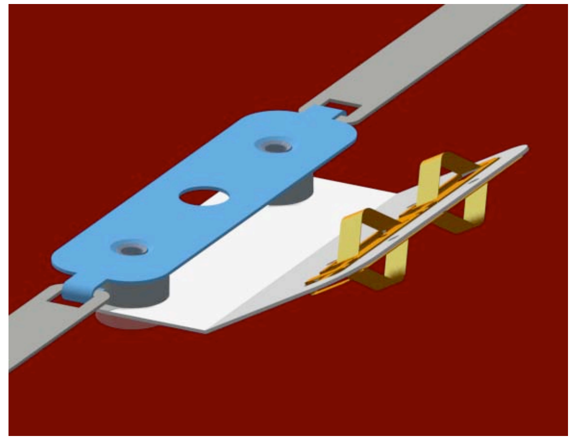

Figure 6: Snubber prototype

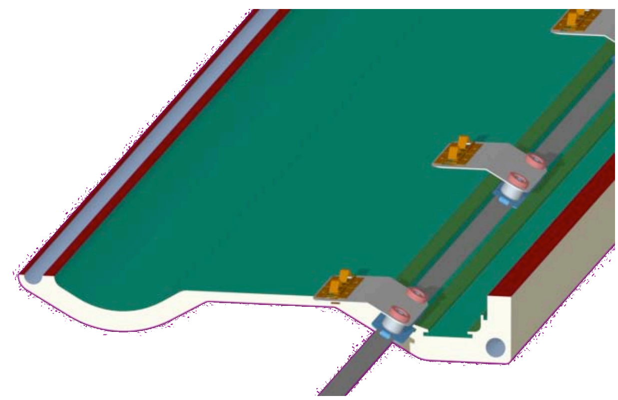

Figure 7: Storage ring vacuum chamber cross section with snubbers installed.

PROTOTYPE SNUBBER SIMULATION

Only eight snubbers can be used on the curved vacuum chamber to avoid x-ray interception. For the convenience of simulation, a straight simplified chamber geometry was assumed. A diagonal 50Ω S-parameter discrete port worked as a source at the upstream port. The adjacent two snubbers were 15.6 inches apart, and the first one started at 6.4 inches away from the upstream port. A vertical cylinder through the chamber was considered, but the x-ray absorber and rf screens installed in this cylinder were ignored. The probes were located at the downstream BPM's position. The simulated structure is shown in figure 8. Figure 9 shows the simulated results for the simplified straight chamber and the measured results in the APS curved chamber without snubbers. The simulated and measured resonances were similar, especially at the ring RF frequency of 351.93 MHz. The difference between the simulation and measurement may come from the simplification of the chamber and snubbers.

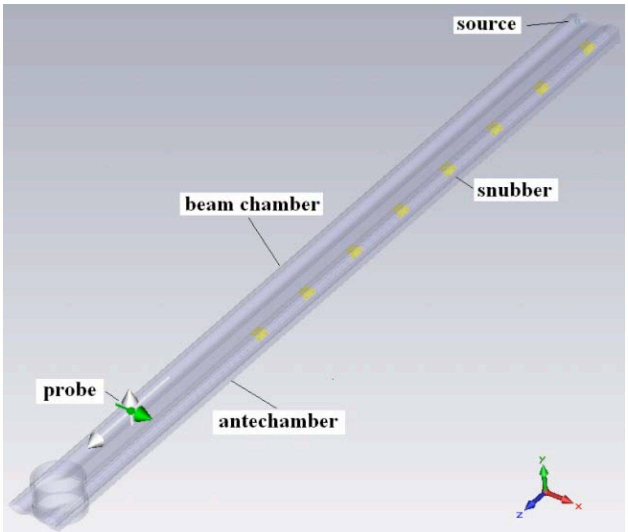

Figure 8: Straight APS vacuum chamber without x-ray absorber and rf screens.

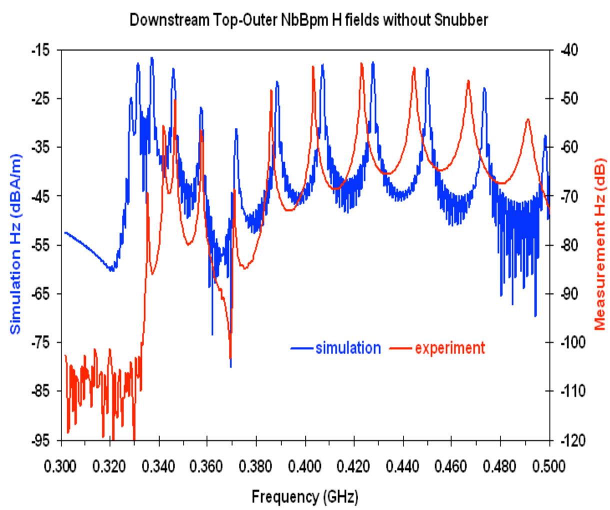

Figure 9: Comparison of the simulated and measured results without snubbers.

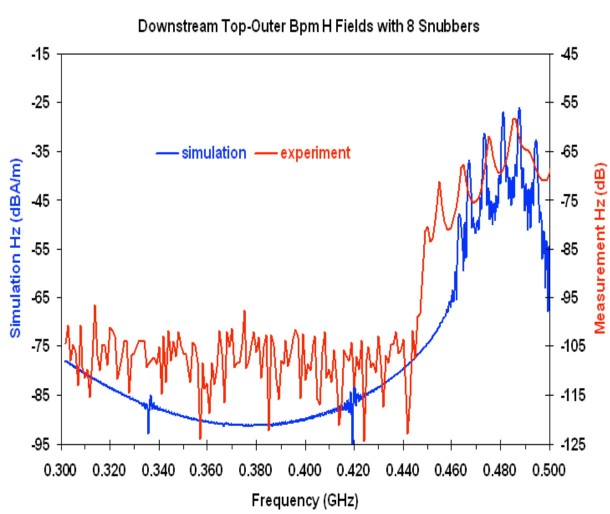

Figure 10 shows the simulated results in a straight simplified chamber and the measured results in the APS curved chamber with 8 snubbers installed. The cut-off frequencies were shifted much higher than the ring rf frequency of 351.93 MHz in both simulation and measurement.

CONCLUSION

The snubber design will reduce or eliminate the trapped TE mode resonances in the APS storage ring vacuum chambers. This solution will work for all but two of the nine BPMs. The two curved vacuum chambers present a new challenge. The ray-tracing studies indicate that the x-ray stay-clear area of the two downstream BPMs would inhibit installation of the snubbers. The snubbers as designed cannot be subjected to high-power x-rays. Additional measurements and simulations to suppress the sources from the downstream port, such as the crotch absorber, have to be considered. This effort could involve a more robust snubber design or a stick absorber that is water cooled for these two BPMs.

Figure 10: Comparison of the simulated and measured results in with 8 snubbers.

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[3] Y. Kang, G. Decker, and J. Song, "Damping Spurious Harmonic Resonances in the APS Storage Ring Beam Chamber," PAC '99, New York, NY March 1999, THP61, p. 3092 (1999); http://www.JACoW.org