IMPACT OF LONGITUDINALLY TILTED BEAMS ON BPM PERFORMANCE AT THE ADVANCED PHOTON SOURCE*

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Abstract

It has been shown that cavity beam position monitors (BPMs) are sensitive not only to beam centroid position but also longitudinal beam tilt [1]. Button-style BPMs also should in principle be sensitive to beam tilt that may impact their performance when used to measure the beam centroid. For the APS upgrade project, beam stability at a level better than 0.5 micron (0.1 - 200 Hz) is required. Simplified models of the button geometry are used in the calculation and simulation. For the experiment, tilt oscillations were induced by kicking the beam vertically and letting it decohere [2]. Tilt oscillations were observed using a specially instrumented set of button-type BPM pickup electrodes. Experimental results are compared with calculation and simulations to quantify the impact of beam tilt on BPM centroid resolution performance.

INTRODUCTION

In this report we calculate the expected phase sensitivity of APS storage ring (SR) rf button BPMs to beam tilts induced by kicking. We then use the calculation to analyze an experiment where the phase shift due to a tiled beam is measured using two BPM buttons and an S-band phase detector read out turn-by-turn using an FPGA. The experiment used a fast kicker to produce transient centroid oscillations in a single 1-mA bunch, which then develop into tilt oscillations [2]. Finally we estimate the expected impact of tilted beams on our existing monopulse BPM system [3].

BUTTON SIGNALS TO FIRST ORDER

Figure 1 shows the button geometry used to calculate the phase shift between two buttons for a longitudinally tilted bunch with tilt angle θ and offset δy in the vertical plane. The buttons are of diameter l, subtend an angle ϕ in the azimuthal direction, and are placed in a vacuum chamber of aperture b. The bunch has rms length $\sigma_z = \beta c \sigma_t$ and is to good approximation a Gaussian distribution in the APS SR. For vertically displaced beam, the voltage output of the buttons for cylindrical symmetry is given by [4]

$$V_{\mathrm{T,B}}(t,y) \approx \left(\frac{\phi l R}{2\pi\beta c}\right)\frac{dI_b(t)}{dt}\left\{1 \pm \kappa y\right\}, \quad (1)$$

where T and the $+$ sign and B and the $-$ sign refer to the top and bottom button, respectively; $\kappa = \frac{4\sin(\frac{\phi}{2})}{b\phi}$ is the sensitivity of each button to a beam of offset y; $I_b(t)$ is the instantaneous beam current; and R is the impedance

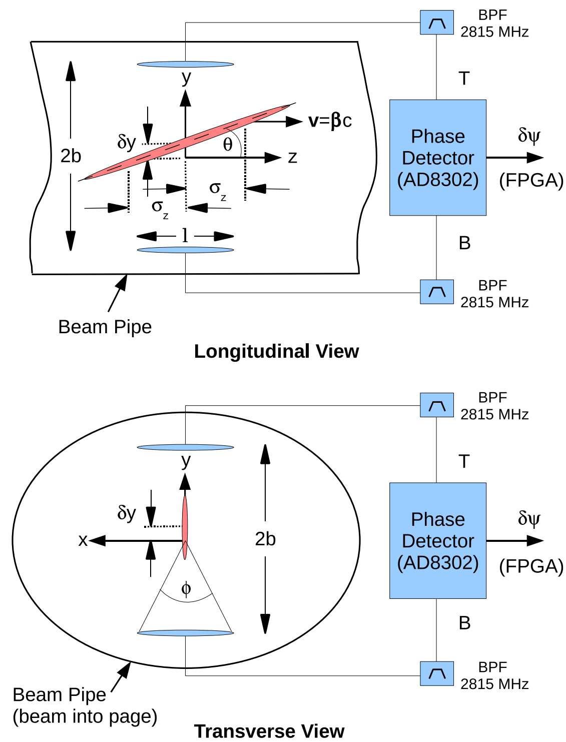

Figure 1: BPM button geometry for calculation of phase response for a vertically offset and longitudinally tilted bunch.

of the transmission line connecting the buttons to processing electronics. Equation 1 is an approximation where only first-order terms in the particle offset y are retained. Equation 1 is the starting point for analysis of the response of the buttons to tilted bunches.

One can see where the phase shift arises between button signals by considering a simple bunch model consisting of discrete point charges uniformly spaced along the tilt axis defined by θ in Figure 1. For simplicity we consider no net bunch offset ($\delta y = 0$). The point charges induce pulses of decreasing amplitude on the top button and increasing amplitude on the bottom button due to the vertical position dependence in Eq. 1. Ignoring the large offset voltage simply due to the beam charge, Fourier components for the top button signal need to combine to form a large amplitude initially, and the opposite is true for the same Fourier components for bottom button signal. It is straightforward to see qualitatively that for the Fourier component with a wavelength on the order of twice the full width bunch length a phase shift arises between top and bottom button signals for a tilted bunch. No such phase shift is present between buttons for a purely offset bunch.

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Phase Shift Due to a Tilted Bunch

The phase difference between button signals is calculated by using Eq. 1 to integrate each differential element of charge along the offset and tilted bunch to obtain the time domain signal for the bunch distribution. The button signals are then transformed to the frequency domain, and the phase difference between the top and bottom button phasors is calculated at frequency ω. The result for the button phase difference is

$$\delta\Psi(\omega) \approx \frac{2\kappa I_s(\omega)}{I_c(\omega)}\theta = 2\kappa\beta c\omega\sigma_t^2\theta, \quad (2)$$

$$I_s(\omega) \equiv \int_{-\infty}^{\infty} z \sin\left(\frac{\omega z}{\beta c}\right) f(z)dz, \quad (3)$$

$$I_c(\omega) \equiv \int_{-\infty}^{\infty} \cos\left(\frac{\omega z}{\beta c}\right) f(z)dz, \quad (4)$$

where the sine and the cosine transforms are evaluated for a Gaussian bunch distribution $f(z) = \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}}$ along the tilt axis. Equation 2 is approximate because it is derived from Eq. 1, which is only first order in y. We therefore kept only terms to first order in the tilt angle θ and offset δy in Eq. 2.

Table 1: APS SR machine and S37A:P4 "inner" BPM button parameters for large vacuum chamber buttons. Small gap chambers have b a factor of 5 lower.

Parameter	Value
b, l	18.7 mm, 12.5 mm
ϕ	$2\tan^{-1}\frac{l}{2b}$ = 0.645 rad = 36.96°
κ	1.05×10^{-4} μm^{-1}
ω	$2\pi\times$ 2815 MHz
$\sigma_t = \sigma_z/\beta c$	27 ps @ 1 mA
β	$\approx$ 1 @ 7 GeV
ν_y, ν_s, ξ	0.241, 0.008, 4.00
α_c, σ_δ	2.82e-4, 0.00096
$h, f_{rev}, \omega_{\rm rf}$	1296, 271.555 kHz, $2\pi\times$ 351.9 MHz
(Kick angle) Θ	$\approx$ 0.1 mrad
$\beta_{\rm kicker}, \beta_{\rm S37A:P4}$	5.4 m, 26.7 m

Table 1 lists the button parameters for the large vacuum chamber buttons as well as the beam parameters used in the experiment. Using the parameters in Table 1 in Eq. 2 yields $\delta\Psi^\circ \approx 4.66\times10^{-2}\,\theta(\mathrm{mrad})$ at S-band. The sensitivity to tilt increases for large frequencies and a large button sensitivity factor κ. Since κ is fixed by the geometrical factors l and b, we chose S-band as the working frequency for the experiment to maximize the sensitivity to beam tilt. For the APS SPX project where the crab cavities are expected to produce beam tilts up to 340 mrad, we expect to measure phase shifts on the order of 15.8° at S-band.

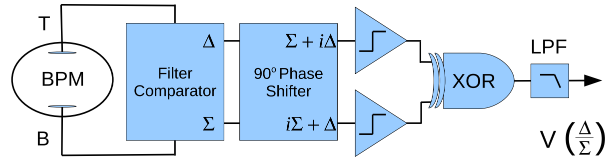

Figure 2: Monopulse button BPM signal processing schematic at 352 MHz.

Impact of Tilted Beams on the APS Monopulse BPM System

Figure 2 shows the signal flow for the APS monopulse rf BPM system [3]. The first stage filter-comparator converts the button signals to sum $\Sigma(\omega)$ and difference $\Delta(\omega)$ signals at the APS SR rf frequency of 352 MHz. These signals are then combined in a 90° combiner passed to the (amplitude) limiters where their relative phase is preserved. Finally the limited signal is passed through the XOR gate and low-pass filtered. The net effect of this circuit is to measure how much the phasors $\Sigma + i\Delta$ and $i\Sigma + \Delta$ differ from $\pi/2$ in phase from each other. The amount these phasors differ from $\pi/2$ from each other is proportional to the transverse position $\left|\frac{\Delta}{\Sigma}\right|$.

To analyze the effect of tilt on system performance, we calculate the sum and delta signals in the frequency domain by performing the calculation described in the previous section. The result is

$$\Delta(\omega) = -2\kappa I_s(\omega)\theta + 2iI_c(\omega)\kappa\delta y, \quad (5)$$

$$\Sigma(\omega) = 2iI_c(\omega), \quad (6)$$

where the sine and cosine transforms were defined in the previous section. One sees that any tilt signal shows up in quadrature to the pure offset position and sum signals. We are most interested in the performance of the circuit for measuring beam offset in the presence of large beam tilt that will be present between SPX cavities. Graphical analysis of the phasors $\Sigma + i\Delta$ and $i\Sigma + \Delta$ and using Eqs. 5 and 6 yields for the output of the circuit in figure 2

$$V\left(\frac{\Delta(\omega)}{\Sigma(\omega)}\right) \propto \delta y\left\{1 + O\left(\frac{\kappa^2 I_s^2(\omega)\theta^2}{I_c^2(\omega)}\right)\right\}. \quad (7)$$

We see from Eq. 7 that the effect of a tilted beam on the monopulse circuit is second order in the tilt angle θ. We therefore expect the circuit to be insensitive to beams with small tilt angles. Using the parameters from Table 1, the second order term in Eq. 7 has a value of about 0.03 % for the largest tilt angle expected from SPX (340 mrad) at the bending magnet source point. We see that the ability of this circuit to measure position offset of the beam is quite good even in the presence of large tilts due to the SPX cavities. We note that we must evaluate the sine and cosine transforms at the 352 MHz circuit processing frequency which makes the circuit as a whole a factor of 8^2 less sensitive to beam tilt compared to a similar circuit operating at S-band. If necessary, we expect to be able to correct position

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readings from the monopulse system using tilt information obtained from phase detectors.

BEAM TILT EXPERIMENT

We undertook an experiment to demonstrate that a phase measurement of button signals is a proxy for beam tilt. The experiment previously described generates a head-tail tilt oscillation from a betatron oscillation generated by a fast kicker. Due to the energy spread difference between the head and tail of the bunch and non-zero machine chromaticity [2], the betatron centroid oscillation turns into a tilt oscillation approximately half a synchrotron period after the kick. Table 1 lists the machine parameters used in the experiment where a single bunch of approximately 1 mA (3.6 nC) was placed in the APS SR. The experimental setup is shown schematically in Figure 1. An AD8302 phase detector was used to measure the phase shift at the S-band frequency of 2815 MHz.

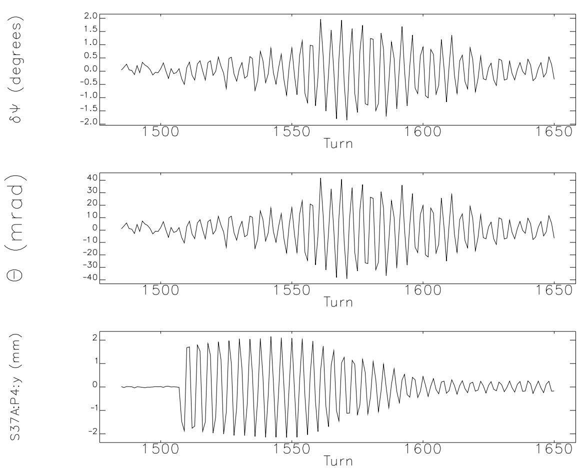

Figure 3: Measured phase shift (top plot), tilt (middle plot), and vertical beam centroid (bottom plot) measured using the S37A:P4 inner top and bottom buttons.

Figure 3 shows the measurement of the phase shift, phase shift converted to beam tilt using Eq. 2, and beam centroid position at the S37A:P4 "inner" top and bottom BPM buttons. We derived the tilt from the measured phase shift using Eq. 2 and the parameters in Table 1. We derived the beam position at the buttons by fitting a betatron oscillation to the nearest 9 BPMs turn-by-turn and normalizing the log-ratio output of the phase detector to get centroid position. One sees that the tilt oscillation builds up at approximately 60 turns or half the $\nu_s^{-1} = 125$ turn synchrotron period. The tilt signal is maximum at approximately 42 mrad. Reference [2] gives the maximum tilt amplitude for the theory in the linear regime as

$$\theta_{\rm max} = \frac{\omega_{\rm rf}\xi}{h\alpha_c c}\sqrt{\beta_{\rm kicker}\beta_{\rm S37A:P4}}\Theta = 97\,{\rm mrad}, \qquad (8)$$

where we used the parameters in Table 1 to obtain the final equality. This result is about a factor of two larger than the maximum tilt shown in Figure 3. The tilt derived in the figure was obtained using parmeters for the S37A:P4 BPM assuming it is cylindrically symmetric which is an approximation. The results of simulating the signal on a button on a small-gap chamber, reported in these proceedings [5], also exhibit differences from the analytic formula for planar geometry (similar to Eq. 1). However, the functional form given by Eq. 1 is correct and yields the correct functional form for tilt derived from phase shift. We can use an absolute measurement using a streak camera or simulation to get the correct phase-tilt calibration factor. We conclude from the experiment we can use a measurement of the phase shift between vertical buttons to measure beam tilt between SPX cavities. In fact, even though the figure shows resolution of the transient measurement is about 3 mrad, averaging the continuous wave, bandpass-filtered signal that will be present in the APS most used 24 bunch mode over a thousand turns, could provide tilt measurements down to perhaps 30 μrad up to 200 Hz BW.

CONCLUSION

In this work we demonstrated that BPM buttons can be used to measure beam tilt for the APS SR beam. We performed an experiment and verified that a measurement of button phase difference is indeed a proxy for beam tilt. We expect that for the APS SPX system, after a suitable amount of averaging, we can achieve beam tilt resolutions approaching 30 μrad. Furthermore we showed that the existing monopulse BPM system will be able to measure beam orbit offsets with very little sensitivity to beam tilt even between SPX cavities where the beam is tilted by up to 340 mrad. Finally we expect to be able to calibrate special beam tilt BPMs outfitted with phase detectors to simultaneously provide beam tilt and centroid offset for the SPX project.

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