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RF CAVITY BPM'S AS BEAM ANGLE AND BEAM CORRELATION MONITORS*

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Abstract

It has been shown that high performance cavity BPM's are capable of accurate beam trajectory angle and beam 'tilt', (*x-z* or *y-z* correlation) measurements [1],[2]. Such a device will be very useful for the optimization of a variety of beamlines, such as high current linacs, bunch rotators and storage rings. The signal from a non-axial trajectory or a tilted beam is in quadrature to that observed from a simple displacement of a very short bunch. Using in-phase / quadrature-phase (*I/Q*) demodulation of the cavity BPM signal, it is possible to separate position and angle/tilt. In this paper, we present results of beam angle and tilt monitor tests carried out in the KEK Accelerator Test Facility (ATF) extraction line.

INTRODUCTION

The purpose of the monitor and how it will be used in the linear collider is described in [1] and [2]. We will review only the basic signal generation here. Consider the system shown schematically in Figure 1: a beam of charge Q, composed of 2 macroparticles located at $\pm \sigma_z$, with a tilt angle θ (or projected dipole length δ), passes through a cavity BPM with frequency f and angular frequency $\omega=2\pi f$. The particles will induce voltage signals:

$$V_+(t) = -\frac{Q}{2}\theta\sigma_z \frac{d^2V}{dQdy}\sin\left(\omega\left(t+\sigma_z/c\right)\right) \qquad 1)$$

$$V_-(t) = -\frac{Q}{2}\theta\sigma_z \frac{d^2V}{dQdy}\sin\left(\omega\left(t-\sigma_z/c\right)\right) \qquad 2)$$

for the two macroparticles. The sum response is:

$$V(t) = -Q\frac{d^2V}{dQdy}\theta\frac{\omega\sigma_z^2}{c}\cos\omega t \qquad 3)$$

where we have assumed that $\omega\sigma_z/c \ll 1$. Equations 1 and 2 show that the signal is 90 degrees out of phase with the signal from a rigid offset of the beam and is proportional to the beam tilt angle.

A convenient expression is the ratio of the peak voltage, V_y, induced by a rigid offset ($y = \delta$), to the peak voltage, V_t, due to a tilted beam (total projected dipole δ).

$$V_t / V_y = \pi f \frac{\sigma_z}{c} \qquad 4)$$

Expression 4) can be thought of as the in-phase to quadrature phase ratio and it clearly shows that, if δ is non-zero, the device can also be used as bunch length monitor. If a displacement δ can be introduced and, independently, a tilt with projected dipole δ' can also be introduced, then the ratio of the response amplitudes in the I/Q plane gives the bunch length.

It is important to note that there is a similar signal induced by 'trajectory tilts' or non-axial trajectories. In that case, the length scale in equation 4) σ_z is replaced with the cavity active length.

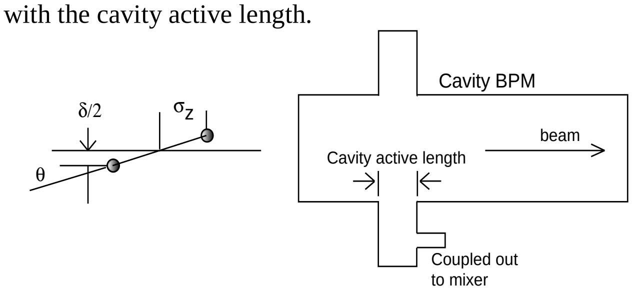

Figure 1: Schematic of the cavity BPM with an incoming 'tilted' beam.

To demonstrate the utility of a tilt monitor with resolution adequate for use in the linear collider, we installed a powered RF deflector, high performance analog and digital RF circuitry for the BPM signal processing and a set of BPM cavity movers to precisely null the BPM signal in the ATF. Both the deflection cavity and the BPM use C-band RF [3], with wavelengths of 52.5 and 46.7 mm respectively. When a 3 mA (9x 10^9 e- single bunch), intensity beam is extracted from the ATF, the bunch length σ_z = 9 mm [4]. This is large compared to the nominal LC σ_z of 110 um, so we expect the *I/Q* signals to be easier to observe.

ELECTRONICS - DESIGN

The BPM signals were mixed down to 20MHz and then recorded and analyzed using digital down conversion. A simplified block diagram is shown in figure 2. A noise measurement gave approximately 300 microvolts RMS.

Damage of the front end of the system by mis-steered beam is a serious concern for sensitive cavity BPM's. The specified damage level for the pre-amplifiers is 15dBm. For most of our test the amplifiers had an additional 20dB attenuation on their inputs. No damage was observed to the amplifiers. The maximum levels for large mis-steering were estimated to be 30-40dBm.

RF DEFLECTION CAVITY

A 5712 MHz standing wave deflection cavity was installed in the beamline upstream of the cavity BPM system. The cavity is a rectangular pillbox operating with

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an "accelerating" type mode. The beam trajectory far from the axis where the magnetic fields produce a transverse deflection. The cavity was driven by a TWT with output power of ~1 KW. The cable to the cavity had an attenuation of 3dB, for a total drive power to the cavity of ~500W peak. The RF phase was not synchronized with the beam phase. The cavity kick amplitude and trajectory transfer function to the BPM were calibrated using the BPM movers.

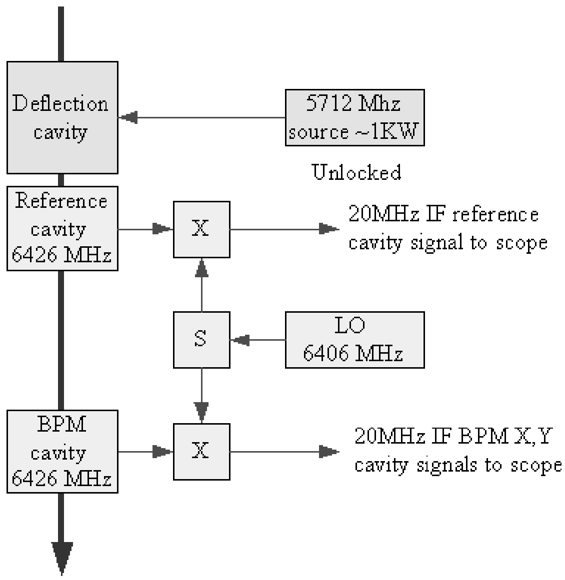

Figure 2: Block diagram of the tilt monitor beamline component layout and signal processing electronics.

DATA ANALYSIS AND CALIBRATION

The cavity and reference IF signals were fit to an assumed damped exponential of the form $V = d + Ae^{(-t/\tau)}\sin(\omega_0 t + \kappa t + \phi_0)$. The Matlab *Fminsearch* algorithm was used to fit the 5 parameters: d, τ, A, ϕ_0, and κ. An example waveform with the superimposed fit is shown in figure 3.

An analysis window that starts after the initial transient and continues for approximately τ is used. The difference between the BPM phases and the reference cavity phase is then estimated.

The resulting BPM phase and amplitude signals are converted to *I/Q* vector signals. These are normalized by the amplitude of the reference cavity signal to give normalized *I/Q* signals. The *I/Q* signals are linear combinations of the beam position and tilt signals.

The RF cavity BPM calibration was done using its *x*, *x'*,*y*, and *y'* movers. At a beam current of 5mA in the ring ($1.2x10^{10}$), the vertical sensitivity was about 30 mV/micron. A noise of 300 microvolts corresponds to a resolution of about 10 nm.

MEASUREMENTS

In order to demonstrate the effectiveness of the monitor for measuring tilts, we used the unlocked deflection cavity and observed the *I/Q* response of the cavity BPM. Figures 4 and 6 show the *I/Q* response in internal digitizer units (where the gain of *I* and *Q* channels are roughly equal) and figure 5 shows the same in calibrated units. Since the calibration of the beam tilt response cannot be independently known, the units used in the plot were derived from the trajectory tilt calibration. The 3 lines in the figures 4 - 6 show the *y* and *y'* axes from the mover based calibration, the third line is 90 degrees from the *y* calibration direction.

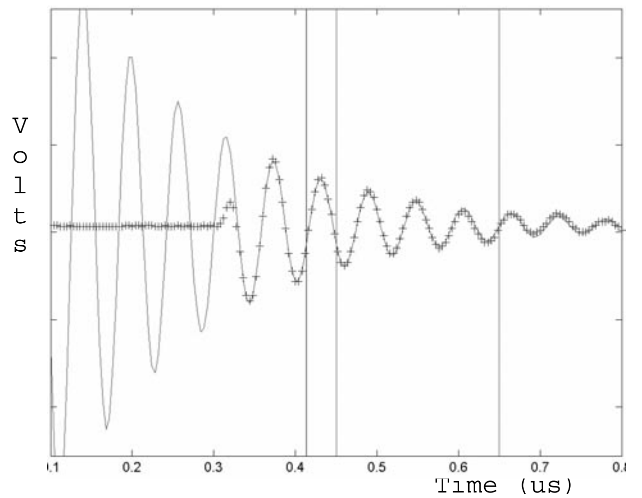

Figure 3: Example waveform with superimposed fit. The fit window is begins about 100 ns following the initial transient.

Using 4), we can estimate the bunch length from the ellipticity of the fitted curve in figure 4. Table 1 shows a comparison between the bunch length estimates from the ellipticity and those presented in [4]. The ATF beam has strong σ_z growth with current because of intra-beam scattering.

Table 1: Comparison between bunch length σ_z estimates from the cavity BPM *I/Q* ellipticity and streak camera measurements made with stored beam as the intensity and RF gap voltage (*Vg*) is varied.

Condition	ellipticity	σ_z - ellipticity	σ_z- streak camera
3.5mA	0.81	8.5 (mm)	9.0 (mm)
0.39 mA	0.64	6.9	6.3
1.7 mA	0.74	7.7	7.5
0.465 mA	0.61	6.6	6.8
0.3 mA/ *Vg* reduced 50%	0.79	8.3	8.8

SENSITIVITY TO ANGLED TRAJECTORIES AND TILTED BUNCHES

The ATF bunch is long compared to the cavity wavelength, so the assumption that $\omega\sigma_z/c$<<1 is not valid at ATF. This effect is included in the results listed in Table 1. However, for the purpose of illustration, we will use equation 4) to estimate the beam tilt sensitivity. We find that the ratio of the peak voltage, V_y, induced by a rigid offset ($y = \delta$), to the peak voltage, V_t, due to a tilted beam (total projected dipole δ') is 0.54 for σ_z =8mm, typical for the beam used in these tests. This means that if the sensitivity to a 1 micron displacement is *V*, then a beam with a total projected dipole length of 1/.54 = 1.9 um will produce the same signal *V* in quadrature to the displacement.

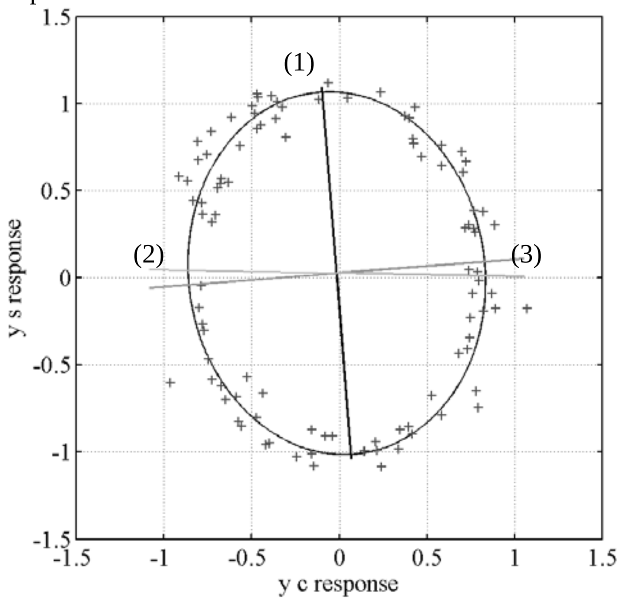

Figure 4: Cavity BPM *I/Q* signals from 100 beam pulses with the unlocked deflection cavity on. The scale is internal digitizer units. The near vertical line (1) corresponds to a pure displacement, the horizontal line (2) corresponds to an angular displacement (based on the *y'* mover) and (3) is perpendicular to (1). The fitted ellipticity is 0.8104.

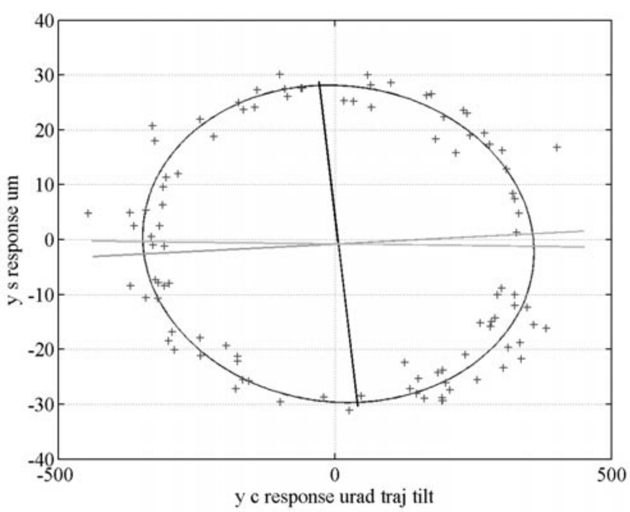

Figure 5: Scaled *I/Q* response from the cavity BPM, same data as figure 4. The horizontal scale is in units of trajectory angle (urad) and the vertical scale is in um. The small angle between the plot vertical and the actual vertical *I/Q* direction is not corrected.

CONCLUSIONS

Initial tests show a strong tilt dependent signal, as would be expected with the long ATF beam. Further tests will use a sequence of monitors in order to determine the monitor resolution. Also, the deflector cavity will be locked to the ATF RF in order to attempt to measure the actual incoming beam tilt.

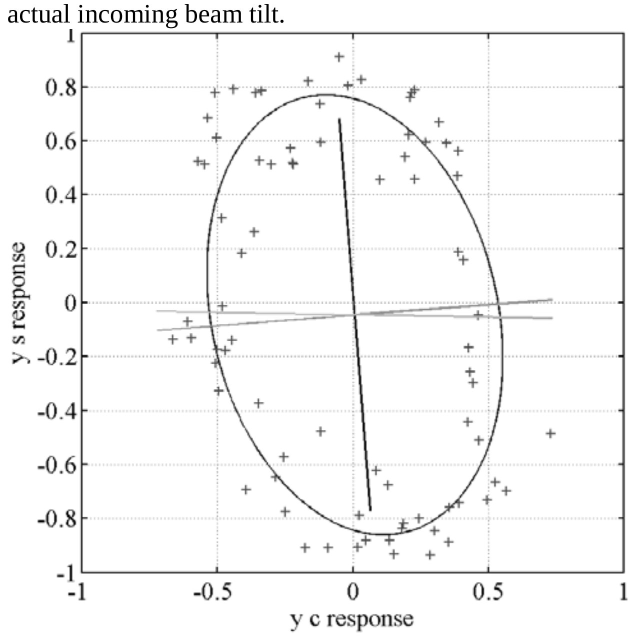

Figure 6: Cavity BPM response at lower intensity, where σ_z ~ 7 mm, showing a narrower ellipse. The figure axes units are the same as in figure 4. The fitted ellipticity is 0.6384.

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