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 \( \theta \) (or projected dipole length \( \delta \)), passes through a cavity BPM with frequency \( f \) and angular frequency \( \omega = 2\pi f \). The particles will induce voltage signals:

\[
V_x(t) = -\frac{Q}{2} \theta \sigma_z \frac{d^2V}{dQdy} \sin(\omega(t + \sigma_z/c))
\]

\[
V_y(t) = -\frac{Q}{2} \theta \sigma_z \frac{d^2V}{dQdy} \sin(\omega(t - \sigma_z/c))
\]

for the two macroparticles. The sum response is:

\[
V(t) = -\frac{Q}{2} \frac{d^2V}{dQdy} \frac{\omega \sigma_z^2}{c} \cos \omega t
\]

where we have assumed that \( \omega \sigma_z/c < 1 \). 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, \( V_x \), induced by a rigid offset \( y = \delta \), to the peak voltage, \( V_y \), due to a tilted beam (total projected dipole \( \delta \)).

\[
\frac{V_x}{V_y} = \pi f \frac{\sigma_z}{c}
\]

Expression 4) can be thought of as the in-phase to quadrature phase ratio and it clearly shows that, if \( \delta \) is non-zero, the device can also be used as bunch length monitor. If a displacement \( \delta \) can be introduced and, independently, a tilt with projected dipole \( \delta \) 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) \( \sigma_z \) is replaced with the cavity active length.

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...
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.  

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.

**DATA ANALYSIS AND CALIBRATION**

The cavity and reference IF signals were fit to an assumed damped exponential of the form:

\[ V = d + A e^{(-\omega t)} \sin(\phi_0 + \kappa t + \phi_b) \]

The Matlab `Fminsearch` algorithm was used to fit the 5 parameters: d, \( \tau \), A, \( \phi_b \), and \( \kappa \). 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 \( \tau \) 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 (1.2x10^16), 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 3 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.

**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, \( V_p \), induced by a rigid offset \( (y = \delta) \), to the peak voltage, \( V_t \), due to a tilted
beam (total projected dipole $\delta'$) is 0.54 for $\sigma_z = 8\text{mm}$, 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 $1/0.54 = 1.9\text{um}$ will produce the same signal $V$ in quadrature to the displacement.

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.

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REFERENCES

[1] W. Wuensch, “Measurements for Adjusting BNS Damping in CLIC”, CLIC – 244, 17.08.94