A COMPREHENSIVE STUDY OF NANOMETER RESOLUTION OF THE IPBPM AT ATF2*

Y.I. Kim†, H. Park, KNU, Daegu, Korea
S.T. Boogert, JAI at Royal Holloway
J. Frisch, D. McCormick, J. Nelson, T. Smith, G.R. White, M. Woodley, SLAC
Y. Honda, R. Sugahara, N. Terunuma, T. Tauchi, J. Urakawa, KEK

Abstract

High-resolution beam position monitors (IPBPMs) have been developed in order to measure the electron beam position at the focus point of ATF2 to a few nanometers in the vertical plane. To date, the IPBPM system has operated in test mode with a highest demonstrated resolution of 8.7 nm in the ATF extraction line during 2008. After expected noise source calculations there still remains 7.9 nm of noise of unexplained origin. We summarize the experimental work on the IPBPM system since this measurement and outline the possible origins of these sources. We then present a study plan to be performed at the ATF2 facility designed to identify and to improve the resolution performance and comment on the expected ultimate resolution of this system.

INTRODUCTION

The Accelerator Test Facility 2 (ATF2) is a test beam line for ILC final focus system in the framework of the ATF international collaboration which was constructed to extend the extraction line at ATF, located at KEK, Japan. There are two goals of the ATF2: firstly to demonstrate focusing to 37 nm vertical beam size, secondly to achieve a few nanometer level beam orbit stability at the focus point in the vertical plane [1]. High-resolution beam position monitors (IPBPMs) for the interaction point (IP) have been developed [3] in order to measure the electron beam position at the focus point of the ATF2 to a few nanometers in the vertical plane. The previous measured position resolution of IPBPMs was 8.7 nm for a 0.68 $\times 10^{10}$ e/bunch beam with a dynamic range of 5 µm [3]. The intrinsic noise of the system was estimated to be 2.6 nm at 10^{10} e/bunch. It is scaled to 3.8 nm at 0.68 $\times 10^{10}$ e/bunch which means that 7.9 nm of unknown noise remains. The origin of the unknown noise must be studied in order to improve the resolution. This paper describes the ongoing work to improve the resolution of IPBPMs.

IPBPM SYSTEM

There are three main differences of IPBPMs compared with other ATF2 cavity BPMs; rectangular cavity shape, low angle sensitivity and ultra high position sensitivity. Two cavities were fabricated together to form an IPBPM block. Since an IPBPM should be able to measure a few nanometers offset in vertical plane for the very flat beam, the IPBPM cavity was designed to be rectangular in shape to isolate the x and y dipole modes. The frequency of the two dipole modes are 6.426 and 5.712 GHz for the y and x dipole modes, respectively. The cavity length in the z direction L (6 mm) has to be small to achieve low angle sensitivity. There is expected to be large angular jitters at the IP, where the beam vertical divergence $\sigma_y^{*\prime}$ is 345 µrad. In order to measure a few nanometer beam offset an increase is needed in the cavity coupling constant β. However too large a β would easily saturate the detecting electronics and lessen dynamic range. The coupling constants β for x and y are 1.4 and 2.0, respectively.

Table 1 shows simulated parameters, resonant frequency of the dipole modes f_0, the coupling strength β, the loaded quality factor Q_L, the internal quality factor Q_0, the external quality factor Q_{ext} and decay time τ.

Table 1: Simulated Parameters of IPBPM [3]

Parameter	x dipole	y dipole
f_0 (GHz)	5.7086	6.4336
β	1.578	3.154
Q_L	2070	1207
Q_0	5337	5015
Q_{ext}	3382	1590
$(R/Q)_0$	0.549	1.598
τ (ns)	58	30

Signals from a Cavity BPM

The cavity output voltage is dependent on the beam offset [2].

$$V_x(t) = V_0 \frac{x}{x_0} e^{(-t/2\tau)} \sin(\omega t) \quad (1)$$

$$V_0 = \frac{\omega q}{2} \sqrt{\frac{Z}{Q_{ext}} (R/Q)_0} \exp^{\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right)} \quad (2)$$

where ω is the resonant angular frequency, x is the beam offset, q is the beam charge, Z is the detecting impedance, $(R/Q)_0$ is the shunt impedance at a beam offset of x_0 which is 1 mm and σ_z is the bunch length in the z direction. Using parameters from Table 1 and assuming nominal ATF2 charge of q = 1.6 nC and typical bunch length of σ_z = 8 mm, the expected sensitivities are approximately 1.63 mV/µm and 4.02 mV/µm, in x and y, respectively. They correspond to approximately −102.7 dBm and −94.9 dBm output power for 1 nm offset beam. Since the detection

* Work supported in part by Department of Energy Contract DE-AC02-76SF00515 and the World Class University (Grant No. R32-20001).
† kimyoungim@gmail.com

limit of the electronics was −95 dBm, An IPBPM is able to detect 1nm signal in vertical, and 3 nm signal in horizontal. When the beam centroid passes through the cavity along the z axis with bunch angle of α, the cavity output is given by

$$V_{\alpha}(t) \cong V_0 \frac{\sigma_z^2 \tan(\alpha)}{x_0 c} \times e^{-t/2\tau} \cos(\omega t) \tag{3}$$

When a beam passes through the center of cavity with inclined trajectory angle of θ with respect to the z axis, the cavity output is,

$$V_{\theta}(t) \cong V_0 \frac{\tan(\theta)}{L x_0} \times e^{-t/2\tau} \cos(\omega t) \cdot F(\theta)\,, \tag{4}$$

where F_{θ} is

$$F(\theta) = \frac{2c^2 \cos^2(\theta)}{\omega^2} \sin\left[\frac{\omega L}{2c\cos(\theta)}\right] - \frac{Lc\cos(\theta)}{\omega} \cos\left[\frac{\omega L}{2c\cos(\theta)}\right] \tag{5}$$

The total cavity output as a function of x, α, θ is the sum of the three contributions

$$V(t) = V_x(t) + V_{\alpha}(t) + V_{\theta}(t) \tag{6}$$

Experimental Setup

Position resolution of the BPM can be determined with at least three cavities. Two IPBPM blocks, a total of four cavities are used for this study. This section describes the electronics and mover system for these two IPBPM blocks. The signal processing is two stage, shown in Fig. 1.

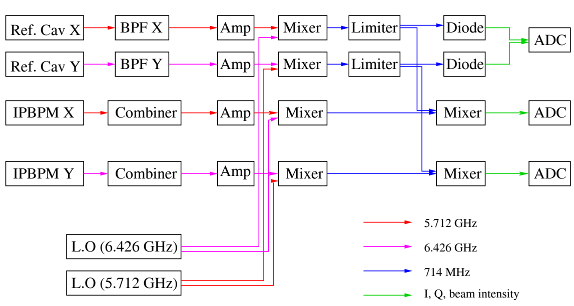

Figure 1: Block diagram of electronics.

The first stage down converts x dipole, y dipole, x reference and y reference signals to 714 MHz using synthesizer sources as local oscillators (LO) for the mixers. The down-converted reference signals are then used to drive a second stage of down-conversion of the dipole signals to baseband. It is important to down convert the IPBPM signal and reference signal with a common LO for phase detecting, to maintain a phase relation between the two signals. The total processing electronics gain is 30 dB and the minimum detectable signal is −95 dBm for x and y.

Two IPBPM blocks were mounted on a magnet mover system which was originally used for the Final Focus Test Beam experiment [4]. The mover system has three degrees of freedom, vertical, horizontal and roll. The movement range is ±1.5 mm with approximately 1 μm accuracy. The mounting frame of the IPBPM system must be rigid. The vibration of the mover system was measured using accelerometers for 5 minutes. Figure 2 shows the integrated amplitude for two accelerometers placed on top of each of the IPBPM blocks. Both BPM blocks on a mover system

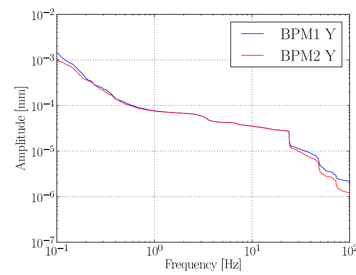

Figure 2: Integrated plot of two IPBPM blocks on the mover system, where the distance between two measurement points is about 20 cm.

are stable within 70 nm in the vertical direction at a frequency of 1.56 Hz. Above 0.5 Hz and below 10 Hz the coherence between BPM1 and BPM2 is essentially 1.0. At 1.56 Hz the coherence is 0.98 and so the expected relative motion between blocks is ~ 1.4 nm. The mover system is adequate for IPBPM resolution measurements, but care must be taken for long timescale slow drifts. The IPBPM mover system with two mounted IPBPM blocks was installed on a stable granite table, which is located in the matching section of the ATF2, as shown in Fig. 3. The granite table has been chosen for the very good coherency.

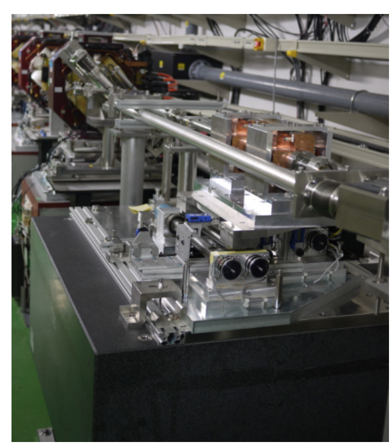

Figure 3: IPBPM system in the ATF2 beam line, located on one of two switchable beamlines, so the IPBPMs installation can be quickly removed without breaking vacuum because the small aperture could introduce wake-fields that distort the bunch shape.

SIMULATION

From Eq. 6, the BPM response should be linear in charge, position and angles assuming that offset, tilt and angles are small. Any non-linearity in the output will degrade the BPM resolution. For example, the cavity response changes with bunch length. The monopole (or common mode) mode depends mainly on charge and bunch length. If all the cavities and electronics were identical then these types of systematics effects would cancel. This is not the case as each device is slightly different.

In order to simulate all of the relevant effects which could change the BPM resolution, a complete simulation program is implementing beam optics, the BPM response and the digitization. The optics simulation is based on a python tracking code [5].

Beam orbits were generated based on ATF2 normal optics and reasonable starting beam distribution parameters. The beam position jitter was assumed to be 20% of beam size. At the IPBPM location the horizontal and the vertical jitters were 23 μm and 1 μm, respectively. The tracking code provides simulated beam positions and angles which are then used to simulate the BPM response. Cavity output can be calculated in details as follows;

- Apply cavity offsets in position and tilt
- Rotate cavity
- Simulate BPM response with Eq. 6
- Add cavity RMS voltage noise
- Simulate electronics
- Simulate digitizer

The IPBPM resolution is calculated in the following steps;

- Simulate IPBPM response (with 30 dB attenuation) to a move from -75 μm to +75 μm in x and y
- Calculate scale factor from digitizer readings to positions
- Simulate 300 machine pulses for resolution
- Apply calibration scale factors
- Calculate resolution

Three methods are used to calculate the resolution; a simple linear prediction based on the known geometry of the BPMs, a linear fit using two spectator BPMs and a model independent method based on singular value decomposition. The simple linear prediction and the linear fit results were agreed well.

The output of the simulation is shown in Fig. 4 and Fig. 5 in which th linear fit method was used. Electronics noise has not been included yet so the resolution starts from zero. Figure 4 shows the simulated vertical resolutions as a function of RMS cavity noise. The minimum detectable power against thermal noise was estimated to be – 95 dBm which is 4 μV at the input of the down-converter giving a resolution 0.5 nm. Figure 5 shows the effects varying bunch charge on vertical resolution, with a fixed cavity noise which is 20 μV. Interestingly the resolution dependence is not linear with bunch charge, this will be investigated further. For bunch charges above 0.5×10^{-9} C, the resolution is minimum. The simulation is being extended to include possible sources of non-linearity, for example bunch length variation, differences between different electronics channels, dipole frequency variation, etc. Systematics effects like local magnetic field variation, stray fields and temperature variation will also be included.

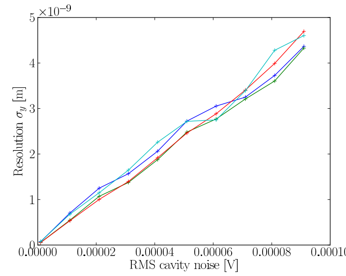

Figure 4: IPBPM simulated vertical resolutions as a function of RMS cavity noise.

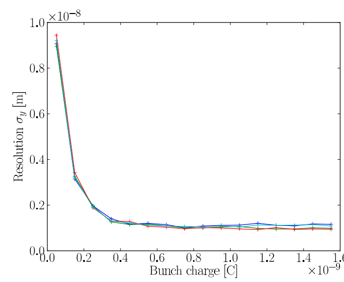

Figure 5: IPBPM simulated vertical resolution as a function of bunch charge.

CONCLUSION

We present a new experimental installation for study of high resolution BPMs. The system was installed and ready for data taking in October 2011. In order to investigate the wide range of systematic effects that could degrade BPM resolution from the thermal noise limit, a simulation of the beam, cavity response and analysis were prepared. Preliminary results from a simulation agree with the simple expectation of BPM resolution. The full range of systematic effects are to be included.

REFERENCES

[1] "ATF2 Proposal," KEK Report 2005-2.

[2] A. Lyapin, Dissertation, TU-Berlin, Berlin, (2003).

[3] Y. Inoue *et al.*, PRSTAB **11**, 062801, (2008).

[4] G. Bowden *et al.*, SLAC-PUB-95-6132, (1995).

[5] S. Molloy, IPAC-2010-TUPEC060, IPAC'10, Kyoto, Japan, (2010).