THE DEVELOPMENT OF C-BAND CAVITY BEAM POSITION MONITOR WITH A POSITION RESOLUTION OF NANO METER

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Abstract

We developed and tested an C-band beam position monitor with position resolution of nano meter in ATF2. The C-band BPM was developed for the fast beam feedback system at the interaction point of ATF in KEK, in which C-band beam position monitor called to IPBPM (Interaction Point Beam Position Monitor). The average position resolution of the developed IPBPM was measured 10.1nm with 87% of nominal beam charge of ATF. From the measured beam position resolution, we can expect beam position resolution of around 8.8nm with nominal ATF beam charge condition. In this talk, we will describe about the development of IPBPM and the beam test results of nano meter level beam position resolution.

INTRODUCTION

The Accelerator Test Facility 2 (ATF2) at High Energy Accelerator Research Organization (KEK) is a research center for studies on issues concerning the injector, damping ring, and beam delivery system for the ILC [1]. The beam energy of ATF is 1.3 GeV and nominal beam charge is 10^{10}electrons/bunch. The aim of beam size at the IP region is 37nm vertically, which is the first goal of ATF2. The second goal of ATF2 is the achieving beam position resolution of 2nm to maintain the beam collision with nano meter scale stability at IP-region. To achieve beam position resolution of 2nm, we developed prototype Low-Q IP-BPM and tested at ATF2 extraction beam line [2]. After the prototype test, we fabricated three low-Q IPBPMs with modified design. Modified design of low-Q IP-BPM was much smaller and lighter than prototype to install at IP region [3]. The entire low-Q IP-BPM system consists of three sensor cavities (See Fig. 1) and two reference cavities. The IP-BPM resolution measurement was performed at IP region of ATF2 during beam operation.

LOW-Q IP-BPM

The low-Q IPBPM was developed for the second goal of ATF. The goal resolution of low-Q IPBPM is a challenging value of 2 nm. The low-Q IPBPM will be provide the beam position at the IP and will be used for the fast beam feedback system to stabilize the beam orbits of the following bunches. The low-Q IPBPM was used rectangular shape cavity to isolates two dipole mode polarizations and the thin cavity reduces the beam angle sensitivity to trajectory inclination. A position resolution of 8.7 nm was achieved with a high-Q BPM [4] for a beam intensity of 0.7×10^{10} e/bunch with a dynamic range of $5\mu m$. However, the high-Q IPBPM was not proper to multi-bunch beam operation due to long decay time of RF signal so that we developed a low Q-value cavity BPM to enable the bunch-by-bunch position measurement for the multi-bunch beam with bunch spacing of 154 ns. The frequency of the two dipole modes are 5.712 and 6.426 GHz for the x and y dipole modes, respectively. The cavity length in the z direction was designed to be 5.8mm for the low angle sensitivity.

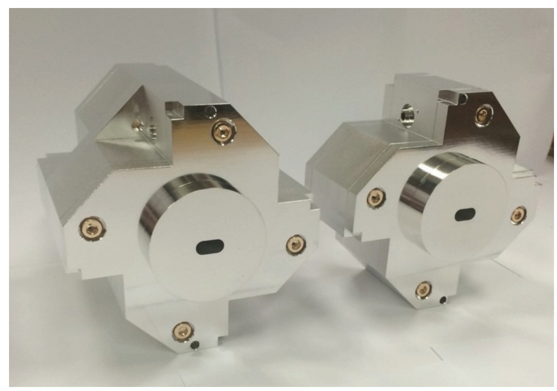

Figure 1: The fabricated low-Q IPBPM.

Table 1 shows simulated low-Q IPBPM parameters, a resonant frequency of the dipole modes f_0, the loaded quality factor Q_L, the internal quality factor Q_0, the external quality factor Q_{ext}, the coupling constant β, decay time τ and transmission parameter S21 in dB. The IPBPM design parameters are calculated by using HFSS simulation [5].

Table 1: The Design Parameters of IPBPM.

Parameter	x dipole	y dipole
f_0 [GHz]	5.7148	6.4270
Δf [MHz]	7.40	11.10
Q_L	772	579
Q_0	4021	3996
Q_{ext}	956	677
β	4.2	5.9
τ [ns]	21.51	14.34
S21 [dB]	-1.85	-1.36

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BEAM TEST SCHEME OF LOW-Q IPBPM

Most of low-Q IP-BPM system was installed inside tunnel near the IP-region of ATF. The sensor cavity BPM, reference cavity BPM, 1st stage electronics, LO signal splitter, C-band BPF, hybrid and variable attenuators(x8) are installed. At the outside of tunnel, the 2nd stage electronics and ADC are installed. More detailed scheme was shown in the Fig. 2.

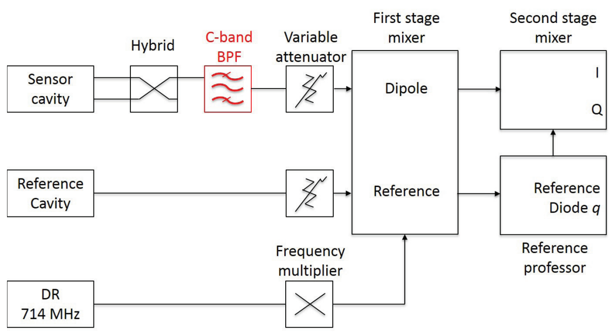

Figure 2: The beam test scheme of low-Q IPBPM entire system.

THE PRINCIPLE OF POSITION RESOLUTION MEASUREMENT

As shown in Figure 3, single BPM can be determined a beam position and two BPMs can be determined beam orbit. We can measure the beam position resolution by using three cavity BPMs. Therefore, three low-Q IPBPMs are used for the measurement of the beam position resolution. First, two BPMs are used to find the predicted position by calculating the beam orbit and then we can calculated the RMS of residual between the measured beam position and calculated predict beam position. Finally, the beam position resolution was determined by "The RMS value of the residual position at the low-Q cavity BPM" × "geometrical factor." The geometrical factor was used to correct for propagation of the error. Also, we assumed that the three cavities had the same position resolution.

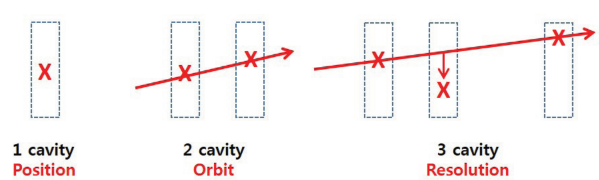

Figure 3: The principle of beam position resolution measurement of IPBPM.

The position resolution measurement consists of the following 3 steps,

- I-Q phase tuning, to distinguish the position signal as I and the other noise component as Q.
- Calibration Run, to calibrate the sensor cavity signal amplitude due to different beam position level.
- Resolution Run, to measure the RMS of the residual between measured and predicted beam position at low-Q IPBPM.

CALIBRATION RUN OF LOW-Q IPBPM

The calibration run was performed to calibrate the sensor cavity response to actual beam position. The sensor cavities of low-Q IPBPM are swept against the electron beam orbit by controlling piezo mover system and response of the output voltage of sensor cavities are monitored. Two type of piezo mover system are installed at IP region and the dynamic range of piezo mover system are 300μm for PI and 250μm for Cedrat with nano meter level accuracy.The calibration run was taking 20 data at each mover position. To calculate the calibration factor, we first calculate the normalized I' signal and Q' signal. The normalized I' signal and Q' signal are determined by following step.

- $I' = (I \times Cos\theta + Q \times Sin\theta)/(Ref.signal)$,
- $Q' = (Q \times Cos\theta - I \times Sin\theta)/(Ref.signal)$,

where the θ means the IQ rotation angle. Even though we performed IQ phase tuning to distinguish the position signal and noise component, the Q signal still include small amount of the position information. Therefore, we should calculate the IQ rotation angle to calculate actual position signal and noise component. The calibration factor was calculated by using integration method from sample number #53 to #59. The Fig. 4 shows the results of calibration run for low-Q IPBPM A case. The low-Q IPBPM calibration factors are listed in Table 2.

Table 2: The Calibration Factor of Low-Q IPBPM.

Channel of BPM	Cal factor [ADC counts/um]	Norm. cal factor [/um]
IPA YI	16599	1.0512
IPB YI	12062	0.7639
IPC YI	7810	0.4946

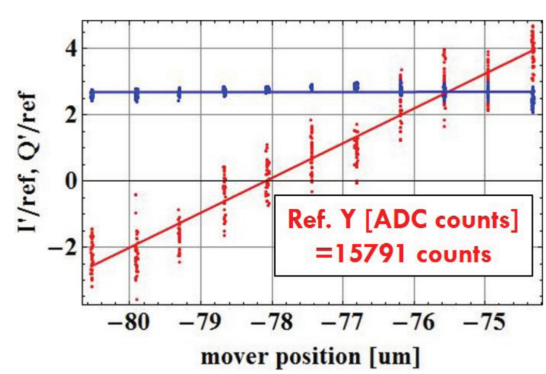

Figure 4: Low-Q IPBPM-A calibration factor. Normalized I' signal (Red) and normalized Q' signal(Blue).

RESOLUTION RUN OF LOW-Q IPBPM

The position resolution of the low-Q cavity BPM was estimated with a fixed beam offset. The electronics setup was used same configuration as in the calibration run. The main purpose of resolution run was to measure the residual, which is the difference between the measured position at one of BPM and the predicted position by using the other two BPMs. The predicted beam position was obtained from a linear regression analysis by using informations from IPBPM-B(IPB) and IPBPM-C(IPC). Those 10 parameters are,

- Vertical position signals (in phase components): IPB-YI, IPC-YI
- Vertical noise components (out of phase components): IPB-YQ, IPC-YQ
- Horizontal position signals and noise components: IPB-XI, IPC-XI, IPB-XQ, IPC-XQ
- Beam charge detected at X & Y reference cavity: Ref-X, Ref-Y

The linear regression formula by using 11 parameters was shown in below, and determined the coefficient α of each parameter.

- IPAYI' = α0+α1*IPBYI'+ α2*IPBYQ'+α3*IPCYI' + α4*IPCYQ'+ α5*RefY+α6*IPBXI'+α7*IPBXQ' +α8*IPCXI'+ α9*IPCXQ'+ α10*RefX

The residual value can be calculated as follows equation:

$$Residual = Y_{I_{meas}} - Y_{I_{predicted}}. \quad (1)$$

Figure 5 shows the result of the resolution run under 0 dB attenuation. Left top of Fig. 5 shows the measured beam position at low-Q IPBPM-A and right top of Fig. 5 shows the measured position vs predicted position of IPBPM-A. The calculated residual(left bottom) and the distribution of residual(right bottom) are shown in bottom of Fig. 5. The RMS of the residual, 330.638 ADC counts, corresponds to the position resolution.

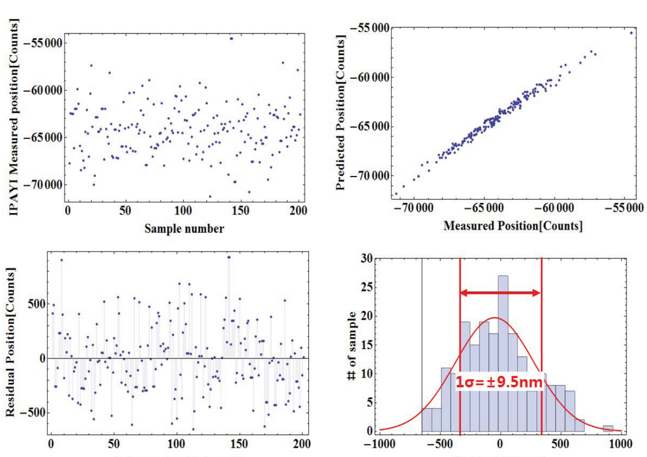

Figure 5: The measured position resolution of IPBPM-A is 9.5nm with 0.869 × 1.6nC beam charge condition.

By using the RMS of residual, we can calculate the beam position resolution as follows:

$$\text{Resolution} = \text{Geo.factor} \times \frac{\text{RMS of residual}}{\text{calibration factor}}. \quad (2)$$

The used geometrical factors for each BPM are shown in the Table 3.

Table 3: The Geometrical Factor of Low-Q IPBPM.

	IPBPM-A	IPBPM-B	IPBPM-C
Geo. factor	0.5457	0.7988	0.2531

The results of beam position resolution measurement of low-Q IPBPM are summarized in Table 4. The measured average position resolution was 10.1nm with 0.87× 10^{10} e/bunch. This measured position resolution implies that the normalized beam position resolution with nominal beam condition of ATF, which is 1.00× 10^{10} e/bunch, is expected to be 8.8nm.

Table 4: The Measured and Expected Resolution of Low-Q IPBPM.

	IPBPM-A	IPBPM-B	IPBPM-C
Meas. resol.	9.50nm	11.2nm	9.77nm
Norm. resol.	8.26nm	9.77nm	8.50nm

CONCLUSION

In this proceeding, we described the development and beam test of a low-Q IPBPM. The low-Q IPBPM was developed to provide the beam position information at the IP and will be used for the fast beam feedback system to stabilize the beam orbits of the following bunches. The measured average beam position resolution was 10.1nm for 0.87×10^{10} e/bunch and the expected resolution for nominal beam charge of 10^{10} e/bunch was 8.8nm in the vertical direction.

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