**TITLE:** Beam Test of the ILC Main-Linac Beam Position Monitor at KEK-ATF

**AUTHORS:**
Sun Young Ryu, Jung Keun Ahn  
Department of Physics, Pusan National University, Korea  
Hitoshi Hayano  
Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Japan  
(August 20, 2008)

**SYNOPSIS:**

A 2.04GHz cavity-type beam position monitor (BPM) was developed for the future International Linear Collider (ILC). BPMs of the ILC will measure beam positions with the resolution of a few hundreds nm. The cavity BPM is required to have a low Q-value for fast signal damping to avoid interference with succeeding bunch and to have high signal-to-noise ratio for high resolution position measurement. The cavity BPM was designed to pick up the second dipole TM120 mode effectively through four symmetrically arranged waveguides. The HFSS simulation shows that the resonant frequency is 2.043 GHz and the Q-value is 1382. RF properties of the cavity BPM model was tested at KEK-ATF. The resonant frequency was measured to be 2.0438GHz and its bandwidth 8.4MHz. The coupling constant $\beta$ was found to be improve to 1.96 which is 11 times as high as that of the first prototype. The performance of the cavity BPM was tested using electron beam at the KEK-ATF. The cavity BPM housed in a vacuum chamber was installed in the straight section at the end of the linear accelerator. Two stripline BPMs were placed at upstream and downstream of the cavity BPM as references. The differential signals from hybrid circuits were amplified and fed into 2.04GHz band-pass filters. The beam sweep-scan results proved a good spatial resolution of the level of sub-microns with the hybrid and amplifier circuits.
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Abstract
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I. INTRODUCTION

A 2.04GHz cavity-type beam position monitor (BPM) was developed for the future International Linear Collider (ILC). 616 cavity-type cold-BPMs of the ILC are required to measure beam positions with the resolution of a few hundreds nm for a single pass and bunch-by-bunch. A good fiducialization with respect to a magnetic center is also required. Cavity-type BPM is a good candidate to satisfy such requirements. The BPM should accommodate a large-aperture beam pipe with a diameter of 78mm with having a good common-mode rejection ability for high-accuracy position measurement. The inner surface of the BPM should be washable by high-pressure rinsing. The cavity BPM is required to have a low Q-value for fast signal damping to avoid interference with succeeding bunch and to have high signal-to-noise ratio for high resolution position measurement. It is also required to have a good reproducibility and a long-term stability under cryomodule cool-down circumference.

Saclay group has been developing on a re-entrant cavity BPM, which reads a dipole-mode signal from the coaxial cavity. One the other hand, FNAL group has been developing a TM\textsubscript{110} cavity BPM coupled to waveguides with ceramic window slots. Our Design is based on using TM\textsubscript{120} signal of the cavity coupled to waveguides. The resonant frequency of TM\textsubscript{120} mode is well beyond the cutoff frequency of pickup waveguides which should be small enough to make the whole volume of the BPM accomodate in the main-linac cryomodule. The cavity BPM was designed carefully to pick up the second dipole TM\textsubscript{120} mode effectively through four symmetrically arranged waveguides.

In this report, we present a development of the new cavity BPM running with a resonant TM\textsubscript{120} mode, its performance results and the beam test at the KEK-ATF.
II. DESIGN OF THE CAVITY BPM

When an electron beam bunch passes through the cavity, the field of the bunch excites eigenmodes of the electromagnetic field in the cavity. The signal voltage of our BPM is determined by beam energy loss to a second dipole mode (TM120) and by an external coupling of the waveguide.

For a pill-box cavity with a radius of \( b \) and a length of \( L \) in Figure 1, a longitudinal electric field \( E_z \) in the \( \text{TM}_{120} \) mode can be given by

\[
E_z = E_0 \cos \phi J_1(xk_{120})e^{i\omega t}, \quad k_{120} = \frac{\omega}{c} = \frac{7.016}{b}
\]

and its electric potential \( V_z \) can be then written as

\[
V(x) = \int_0^L E_0 \cos \phi J_1(xk_{120})e^{i\omega t} dz = E_0 J_1(xk_{120}) \frac{\sin \frac{\omega L}{2c}}{\frac{\omega L}{2c}} e^{i\frac{\omega L}{2c}} = E_0 J_1(xk_{120}) LT e^{i\frac{\omega L}{2c}},
\]

where \( t = \frac{z}{c}, \phi = 0 \) and \( T \) is called a time transit factor (TTF) represented by \( T = \frac{\sin \frac{\omega L}{2c}}{\frac{\omega L}{2c}} \).

The energy \( U \) stored in the cavity can be given by

\[
U = \frac{1}{2} \epsilon_0 \int |E_z|^2 dV = \frac{1}{4} E_0^2 \epsilon_0 \pi L b^2 J_0^2(bk_{120}).
\]

FIG. 1: Pill-box cavity with radius of \( b \) and length of \( L \)

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\]

where \( t = \frac{z}{c}, \phi = 0 \) and \( T \) is called a time transit factor (TTF) represented by \( T = \frac{\sin \frac{\omega L}{2c}}{\frac{\omega L}{2c}} \).

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\]
The ratio of a shunt impedance \( R_{sh} \) to an unloaded quality factor \( Q_0 \), called as a normalized shunt impedance \( R/Q \), is given by

\[
\frac{R}{Q} = \frac{|V|^2}{\omega U} = \frac{E_0^2 J_1^2(x k_{120}) L^2 T^2}{\frac{1}{4} \omega E_0^2 \epsilon_0 \pi b^2 J_0^2(b k_{120})} = \frac{4 J_1^2(x k_{120}) L T^2}{\omega \epsilon_0 \pi b^2 J_0^2(b k_{120})} \approx 27.1 (\omega/c)^3 LT^2 x^2
\]

where \( J_1(x) \approx \frac{1}{2} x \) at \( x \ll 1 \), and \( J_0(b k_{120}) = J_0(7.016) = 0.30012 \). For dipole modes such as TM_{110} and TM_{120}, it is to convenient to define a shunt impedance \([R/Q]_0\) which corresponds to a beam passing through the cavity on a trajectory offset from the electrical center by an amount \( x_0 \). The \( R/Q \) is then represented as a function of beam position \( x_0 \), \( x \) from the electric center,

\[
\frac{R}{Q} = \left[ \frac{R}{Q} \right]_0 \frac{x^2}{x_0^2}
\]

and \([R/Q]_0 = 27.1 (\omega/c)^3 LT^2 x_0^2\) for the TM_{120} mode. The energy \( U \) is represented as a function of electric charge \( q' \) by \( U = q' V/2 \),

\[
U = V^2 \frac{Q}{R \omega} = \left( \frac{2U}{q'} \right)^2 \frac{Q}{R \omega},
\]

thereby \( U \) is given by

\[
U = \frac{\omega}{4} \frac{R}{Q} q'^2 = \frac{\omega}{4} \left[ \frac{R}{Q} \right]_0 \frac{x^2}{x_0^2} q'^2
\]  

(1)

If a bunch length distribution is Gaussian with a spread of \( \sigma_z \), the electric charge \( q' \) is given by

\[
q' = \frac{q}{\sqrt{2\pi}\sigma_z} \int_{-\infty}^{\infty} \exp \left( -\frac{z^2}{2\sigma_z^2} \right) \cos \left( \frac{\omega z}{c} \right) dz
\]

\[
= q \exp \left( -\frac{\omega^2 \sigma_z^2}{2c^2} \right)
\]

thus the stored energy can be calculated as

\[
U = \frac{\omega}{4} \left[ \frac{R}{Q} \right]_0 \frac{x^2}{x_0^2} q'^2 \exp \left( -\frac{\omega^2 \sigma_z^2}{c^2} \right)
\]  

(2)
The external quality factor of the cavity represents the coupling strength between the cavity and the output network, and is given by

$$Q_{\text{ext}} = \frac{\omega U}{P_{\text{out}}} = \frac{Q_0}{\beta},$$  \hspace{1cm} (3)

where beta is called a coupling constant. The larger beta is, the better coupling is accomplished. Thus, the output power from the cavity after the excitation is given by

$$P_{\text{out}} = \frac{\omega^2}{4Q_{\text{ext}}} \left[ \frac{R}{Q} \right] \frac{x^2}{x_0^2} q^2 \exp \left( -\frac{\omega^2 \sigma_z^2}{c^2} \right),$$  \hspace{1cm} (4)

and the output voltage $V_{\text{out}}$ with impedance $Z$ is

$$V_{\text{out}} = \frac{\omega}{2} \sqrt{\frac{Z}{Q_{\text{ext}}}} \left[ \frac{R}{Q} \right] \frac{x^2}{x_0^2} q \frac{x}{x_0} \exp \left( -\frac{\omega^2 \sigma_z^2}{2c^2} \right) e^{-\frac{t}{\tau}} \sin \left( \omega t + \phi \right),$$  \hspace{1cm} (5)

where $\tau = \frac{Q_L}{\omega} = \frac{Q_L}{2\pi f}$. Figure 2 shows a the time evolution of simulated $V_{\text{out}}$ with an electric charge of $3.2\,\text{nC} \left( 2 \times 10^{10} \text{electrons/bunch} \right)$, bunch size($\sigma_z$) of $300\,\mu\text{m}$ and damping time $\tau=49\,\text{ns}$.  

![Diagram of time evolution of $V_{\text{out}}$](image)
The cavity BPM was designed to pick up the second dipole TM_{120} mode effectively through four symmetrically arranged waveguides. A design configuration of the cavity structure is shown in Figure 3. A coupling-slot configuration of the cavity BPM is enlarged to show the detailed structure in Figure 4.

![Design configuration of the cavity BPM](image)

**FIG. 3**: Design configuration of the cavity BPM

![Coupling slot configuration of the cavity BPM](image)

**FIG. 4**: Coupling slot configuration of the cavity BPM

Resonant frequencies for TM_{010}, TM_{110}, TM_{020}, and TM_{120} modes are found to be 0.77, 1.04, 1.83 and 2.04GHz, respectively, in the HFSS simulation. Figure 5 displays electric field strengths for each eigenmode of the cavity BPM in the HFSS simulation.
Figure 6 shows a distribution of electric field for the cavity BPM, whereas Figure 7 shows magnetic field lines in a driven mode. Table 1 represents rf parameters in terms of antenna depth in the waveguide, which reflects how effectively pick up the field in each depth. The antennas were set in the depth of 9mm.
FIG. 7: Magnetic field lines for the cavity BPM in a driven mode

<table>
<thead>
<tr>
<th>Antenna depth</th>
<th>7.4mm</th>
<th>8mm</th>
<th>8.5mm</th>
<th>9mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$</td>
<td>2.0434GHz</td>
<td>2.0414GHz</td>
<td>2.039GHz</td>
<td>2.036GHz</td>
</tr>
<tr>
<td>$2\Delta f$</td>
<td>3.4MHz</td>
<td>4.8MHz</td>
<td>5.9MHz</td>
<td>8MHz</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>601</td>
<td>425.29</td>
<td>345.59</td>
<td>254.5</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.3</td>
<td>2.2</td>
<td>3</td>
<td>4.2</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>1382.3</td>
<td>1357.5</td>
<td>1386.5</td>
<td>1323.4</td>
</tr>
</tbody>
</table>

TABLE I: RF parameters in terms of antenna depth in the waveguide
III. RF TEST OF THE CAVITY BPM

Figure 8 shows a photograph of the prototype cavity BPM. It was made of stainless steel (SUS) with bolted connection, which make it possible to modify each part of the cavity BPM for better performance. To tighten the bolted connection a 50μm step structure was applied on the surface of the bolted connection. Coupling slots are open on the endplate of the pillbox cavity with a length of 70mm, and are extended to the beam pipe surface with a length of 38.5mm, as shown in Fig. 4. There is a small opening to the beam pipe at the corner of the waveguide. It enables us to make a high-pressure rinsing of the BPM. The depths of pick-up antennas are adjustable for fine coupling. The antennas are connected to the SMA connector mount directly by soldering.

![Figure 8: Photograph of prototype the cavity BPM.](image)

Figure 9 shows the waveguide port assignment for S-parameter measurements. The port 1 and 3 are attached to the vertical waveguides, detect horizontal beam position. The port 2 and 4 are attached to the horizontal waveguides for vertical beam position. Figure 10 shows broadband $S_{11}$ reflection and $S_{21}$ transmission parameters for the cavity BPM. Dotted boxes indicate S-parameters near the resonant frequency of 2.04GHz which are our interest BPM mode.

Figure 11 shows S parameters for the expanded area of the resonant frequency of the
cavity BPM. RF measurement results are summarized in Table II. Unloaded Q-value ($Q_0$) is given by $Q_0 = (1 + \beta)Q_L$, where $\beta$ is a coupling constant given by the sum of $\beta_{01}$ and $\beta_{02}$.

Decay constant $\tau$ is given by $\tau = \frac{Q_L}{2\pi f_0}$ in ns, where $Q_L$ is a loaded Q-value. The coupling constant $\beta_0$ is given by $\beta_0 = (1 - |\Gamma_i|)/(1 + |\Gamma_i|)$, where $\Gamma_i$ is the ratio of the output voltage to the input voltage. S parameter is defined as $S = 20\log_{10} \Gamma$.

Table III shows isolation and transmission parameters measured in the rf test. Such high isolation parameters ranging from -41.8dB to -37.3dB imply that signals from the orthogonal waveguides are well isolated from the readout waveguides.

The resonant frequency of the cavity was found to be 2.043GHz in a rf measurement,
which is the same as the design value as listed in Table I. A loaded Q value ($Q_L$) was measured to be 273.07, which is consistent with the design value. However, we found that a unloaded Q factor ($Q_0$) of the rf measurement was different from the design value, which could be mainly due to a leakage of electromagnetic field through the cavity surface and also through the boundaries tightened by screwing. A small discrepancy between the measured $S$ parameters for port 1 to 3 and port 2 to 4 could be attributed to a different response of pick-up antennas. The overall characteristics of the cavity BPM turns out to be then consistent with that of the design. Decay time $\tau$ runs with a coupling parameter $\beta$, and the
<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>$f_0$ (GHz)</th>
<th>S11 (dB)</th>
<th>S22 (dB)</th>
<th>S21 (dB)</th>
<th>$2\Delta f$ (MHz)</th>
<th>$Q_L$</th>
<th>$Q_0$</th>
<th>$\beta$</th>
<th>$\tau$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2.0438</td>
<td>−9.84</td>
<td>−9.082</td>
<td>−3.978</td>
<td>7.48</td>
<td>273.07</td>
<td>808.28</td>
<td>1.96</td>
<td>21.26</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2.0427</td>
<td>−7.4891</td>
<td>−7.6372</td>
<td>−5.11</td>
<td>8.4</td>
<td>241.56</td>
<td>574.91</td>
<td>1.38</td>
<td>18.8</td>
</tr>
</tbody>
</table>

TABLE II: RF test results of the cavity BPM

<table>
<thead>
<tr>
<th>Port</th>
<th>Slot</th>
<th>Isolation (dB)</th>
<th>Transmission (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>−41.849</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>−39.71</td>
<td>−3.978</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>−39.71</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>−41.846</td>
<td>−5.11</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>−37.304</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE III: Measured values of isolation and transmission parameters

S/N ratio depends on $\beta$, which is given by $S/N = V_{out}/\sqrt{4k_BT(2\Delta f)Z}$. Figure 12 represents evolution of $\tau$ and S/N ratio as a function of the measured $\beta$.

![FIG. 12: S/N ratio and damping time as a function of the coupling constant $\beta$](image)

In Eq. 1 the amplitude of $V_{out}$ represents a linearity of the BPM signals with respect to the beam position. An antenna scan is required to determine an electrical center of the
cavity BPM. Figure 13 shows a schematic view for the antenna-scan setup. A scan antenna is connected to the port 1 of a network analyzer (NA), which generates electromagnetic field to the cavity BPM. On the other hand, a pick-up antenna is connected to the port 2 of NA from a waveguide. The scan antenna is placed on the x-y mover that is controlled by a PC through GP-IB interface. The pick-up antenna reads the 2.043GHz signals from the cavity BPM.

**FIG. 13: Setup of the antenna scan**

Figure 14 shows the electronic diagram for monopole rejection. Measured $S_{21}$ parameters are displayed in Figure 15.

**FIG. 14: A monopole-mode rejection system.**
The voltage at an electrical center was measured to be 0.0252 mV with a monopole-mode rejection. The center position was slightly off by 0.084mm, and $S_{21}$ parameter was found to be -78.819dB. Figure 16 shows output voltage distribution for x scan with a monopole-mode rejection.

The output voltage from the cavity BPM turns out to have a linear response to the position x, and the electrical center is clearly seen, as shown in Figure 16.
FIG. 16: Output voltage for x scan with a monopole-mode rejection
IV. BEAM TEST OF THE CAVITY BPM AT THE ATF

A. Setup for the Beam Test

We have performed a beam test of the cavity BPM at the ATF with three shifts in May, 2008. First two 4-hour shifts were devoted for preparation, and the last 8-hour shift for the beam test. The cavity BPM was installed in the straight section at the end of the linear accelerator, as shown in Figure 17.

Two stripline reference BPMs are placed approximately 3.5 m upstream and 2.7 m downstream of the cavity BPM. The first stripline BPM was placed just downstream of the quadrupole magnet located at the straight beam line after the bending magnet of the beam transport to ATF damping ring. A set of corrector dipole magnets was used to change a beam orbit for x and y sweep scans. The cavity BPM was housed by a vacuum chamber sitting on a movable support structure.

One of signals out of the two vertical waveguides was extracted to the outside of the accelerator tunnel, and fed into a 2.043GHz band-pass filter, and then sent to a low-frequency (LF) amplifier through the detecting diodes. The amplified signal was finally fed into an ADC running on CAMAC bus after passing through a low-pass filter (LPF). The other

FIG. 17: Schematic view of the cavity BPM housed by a vacuum chamber and its location at the ATF.
vertical signal was extracted similarly, and amplified by a radio-frequency (RF) amplifier before a 1.83GHz band-pass filter for monitoring beam intensity with a monopole-mode signal. The beam which we used to this experiment was $1 \times 10^{10}$ electrons/bunch intensity of single bunch with 1.5Hz repetition. The beam size was monitored and adjusted by using the profile monitor in front of the cavity BPM. It was about 1mm r.m.s. radius with round shape.

The left hand side of Figure 20 displays a raw signal from the waveguide, which was read by a 3GHz bandwidth oscilloscope, whereas a right hand side of the figure shows a fast Fourier-transformed (FFT) result, where many peaks appear at various frequencies. We can see the clear main peak at 2.04GHz with neighboring peaks, which will cause common mode mixture into the position signal. Figure 21 shows a raw signal (left) and its FFT result with a 2.043GHz band-pass filter, the bandwidth of which was 20MHz. Only the 2.04GHz peak appears in the FFT spectrum, however small fraction of common mode mixture appears as the tail of the slope.

Figure 22 shows a diagram of readout electronics with hybrid circuits. Raw signals were
fed into hybrid circuits. Differential signals ($\Delta$) from two pairs of the waveguides were sent to rf amplifiers and 2.043GHz band-pass filter. On the other hand, the sum signal ($\Sigma$) from a pair of the waveguides was filtered by a 1.83GHz band-pass filter after amplification, which was used to monitor a monopole-mode intensity referred as a beam intensity. ADCs are a charge integration type with 200ns gate signal which is supplied from the ATF timing system and synchronized to beam coming time. The ADC read-out is controlled by the ATF BPM reader software to synchronized with whole BPM read-out to capture the single
beam pass orbit. We used this ATF BPM reader and data logging system for the selected BPM read-outs.

B. Experimental Results

We measured ADC signals from the cavity BPM as a function of the beam position along the x and y directions by changing currents on a pair of corrector dipole magnets. The ADC read-outs depend not only on the beam position off the center of the cavity BPM but
also on the beam intensity. We then monitored beam intensity with an integrating current transformer (ICT). For each beam scan ADC values were normalized with respect to the value of ICT in order to avoid beam intensity dependence of dipole signal intensity.

Figure 23 shows beam scan results along the x and y positions without a hybrid circuit. The vertical waveguide signal (left) from channel 2 was obtained by the x scan. Its pedestal spread with beam off as for overall noise was found to be 3.5 ADC counts, and the dipole slope for beam position change was obtained as 5.26 counts/µm by fitting it with a straight line. The spatial resolution of the cavity BPM is then given by the ratio of the pedestal spread to the slope parameter: 3.5/5.26 = 0.6µm. The beam position at the cavity BPM was obtained by an interpolation of the positions from two stripline BPMs. The y beam scan result (right) from channel 1 shows a slope parameter of 5.26 counts/µm from the straight-line fit and a pedestal spread of 3.0 counts. The spatial resolution can then be obtained as 0.5µm.

Figure 24 shows a strength change of the monopole-mode signal without a hybrid circuit for x beam scan and y beam scan. It is likely showing that a monopole isolation was not perfect in the y beam scan result. Such a large position dependence implies that there could
exist a significant contribution from dipole modes.

Figure 26 shows beam scan results with a hybrid circuit. In this measurement the signal was not amplified with a rf amplifier before the hybrid circuit. The horizontal waveguide signal (left) from channel 1 was obtained in the y beam scan. Its pedestal spread was found to be 6.1 counts, and the dipole signal slope was obtained as 7.2 counts/µm from a straight-line fit. The spatial resolution of the cavity BPM is then given by the ratio of the pedestal spread to the slope parameter: 6.1/7.2 = 0.85µm. The x scan result (right) from channel 2 shows a slope parameter of 6.2 counts/µm and a pedestal spread of 9.9 counts. The spatial resolution can then be obtained as 1.5µm.

Figure 27 shows monopole signals of the beam scan with hybrid circuits. It is likely to look flat compared to the results without hybrid circuits. It shows the hybrid relaxed a conflict of dipole mode.

Figure 28 shows a pedestal distribution of the ADC signals amplified by rf amplifiers.

Figure 29 shows beam scan results with a hybrid circuit and a rf amplifier. The horizontal waveguide signal (left) from channel 1 was obtained in the y beam scan. Its pedestal spread was found to be 11.9 counts, and the slope was obtained as 28.4 counts/µm from a straight
The spatial resolution of the cavity BPM is then given by the ratio of the pedestal spread to the slope parameter: \(11.9/28.4 = 0.42\mu m\). The x beam scan result (right) from channel 2 shows a slope parameter of 37.6 counts/\(\mu m\) and a pedestal spread of 12.4 counts. The spatial resolution can then be obtained as 0.33\(\mu m\). With the rf amplified signals a spatial resolution is much improved with large slope parameters. However, it turns out that the accuracy for finding the electrical center is not good enough because of a non-linear response of the BPM near its center. Further consideration should include more effective common-mode rejection, a correction for possible tilts of the BPM with respect to the beam axis, and a precise calibration of the reference stripline BPMs. Figure 30 shows beam scan results in terms of the beam intensity which is measured to be 0.2, 0.7 and \(1.0 \times 10^{10}\) electrons/bunch of the ICT, respectively. Right plot represents a slope parameter in ADC counts/\(\mu m\) as a function of the beam intensity by ICT.

We have moved the support structure for the cavity BPM in a vertical direction by 1mm in order to calibrate stripline BPM response. However, the shift of the vertical position signals from the cavity BPM was found to be only about 0.65mm as shown in Figure 31. The calibration factor is then given by the ratio of the shift of the position signals from
FIG. 26: Beam scan results with a hybrid circuit.

the stripline BPM to a mechanical shift of cavity BPM : 0.65mm/1mm. Spatial resolutions weighted by a calibration factor are summarized in Table IV

<table>
<thead>
<tr>
<th>Resolution(µm)</th>
<th>Without hybrid and amp</th>
<th>With hybrid</th>
<th>With hybrid and amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>No calibration factor</td>
<td>0.6µm</td>
<td>0.85µm</td>
<td>0.33µm</td>
</tr>
<tr>
<td>Calibration factor-weighted</td>
<td>0.9µm</td>
<td>1.4µm</td>
<td>0.5µm</td>
</tr>
</tbody>
</table>

TABLE IV: Summary of spatial resolutions according to circuit elements and calibration-factor weighting.
FIG. 27: Beam scan results on the monopole signal with a hybrid circuit.

FIG. 28: Pedestal distribution of the ADCs for beam off with a rf amplifiers.
FIG. 29: beam scan with rf amplifiers

FIG. 30: Beam scan results in terms of the beam intensity change.
(a) Horizontal waveguide signal for y beam scan before moving the cavity BPM

(b) Horizontal waveguide signal for y beam scan after moving the cavity BPM to up 1mm

FIG. 31: Beam scan results with a mechanical movement of the cavity BPM


V. SUMMARY

A 2.04GHz cavity-type BPM was developed for the future project International Linear Collider (ILC). The cavity BPM is required to have a resolution of a few hundreds nm, a low Q-value for fast signal damping to avoid interference with succeeding bunch and to have high signal-to-noise ratio for high resolution position measurement. The cavity BPM was designed to pick up the second dipole TM120 mode effectively through four symmetrically arranged waveguides. The HFSS shows that the resonant frequency is 2.043 GHz and the Q-value is 1382. RF properties of the fabricated BPM model was tested and measured to be 2.0438GHz and its bandwidth 8.4MHz. The coupling constant $\beta$ was found to be improved to 1.96. The performance of the cavity BPM was tested using electron beam at the KEK-ATF. The BPM model was housed in a vacuum chamber and installed in the end of the ATF linear accelerator together with two stripline BPMs. The differential signals from the hybrid circuits were amplified and fed into 2.04GHz band-pass filters. The extracted signal was well damped after 300ns from the beam passing. The beam sweep-scan results proved a good spatial resolution of 0.5 $\mu$m for x with the hybrid and amplifier circuits. However, it turns out that the accuracy for finding the electrical center is not good enough because of a non-linear response of the BPM near its center. Further consideration on more effective common-mode rejection is need.

APPENDIX A: DRAWINGS OF THE CAVITY BPM

FIG. 32: Drawing of scan antenna
FIG. 33: Drawing of cavity and beam pipe
FIG. 34: Drawing of cavity and beam pipe
FIG. 35: Drawing of waveguide
FIG. 36: Drawing of vacuum chamber