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# DEVELOPMENT OF A STRIPLINE-TYPE POSITION MONITOR FOR THE KEK ELECTRON/POSITRON LINAC

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## ABSTRACT

A stripline-type beam-position monitor (BPM) is under development at the KEK electron/positron linac. This monitor will be installed so as to easily handle the orbit of a high-current electron beam ($\approx$10 nC/pulse) generating a positron beam in the B-factory. The prototype BPM was tested at a bench and in the linac using a single-bunch electron beam. In this report some basic characteristics and the experimental results are presented.

## INTRODUCTION

The KEK electron/positron linac is being upgraded for the B-factory project.[1] The linac is required to accelerate a high-current primary electron beam of single bunch to generate a high-current positron beam. It is important to easily handle orbits of the high-current electron beam so as to suppress any beam blowup generated by a large transverse wake-field.[2] A prototype BPM using stripline pickups has been under development since 1992, and was tested at a bench using a wire current and in an experiment using a single-bunch electron beam (E=35MeV, I=0.27 nC/bunch) at the NERL linac[3] of the University of Tokyo.

## BEAM-POSITION MONITOR

### STRUCTURE OF BPM

The prototype BPM is shown in Fig.1. It is a conventional stripline-type monitor made from stainless steel (SUS 304) with $\pi/2$ rotational symmetry. The total length (250 mm), electrode length (130 mm) and electrode inner radius (20 mm) were chosen so as to be installed into the present beam line of the KEK linac. The inner radius of the vacuum pipe is 28.5 mm in order to a compose 50$\Omega$ transmission line. The total length is variable within ±15 mm by a bellows connected to one side of the BPM. Each electrode is supported by 50 $\Omega$ SMA vacuum feedthroughs at one end of the pipe. The four other ends of the electrodes are short-circuited to the pipe. The opening angle of the electrode viewed from the central axis was chosen to be 60 degrees (Fig. 2).

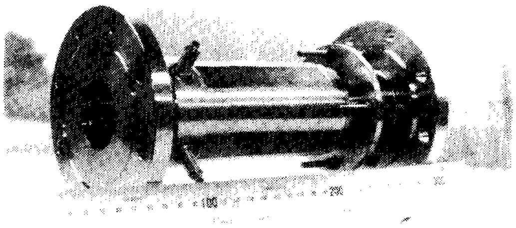

Fig.1. Stripline-type BPM.

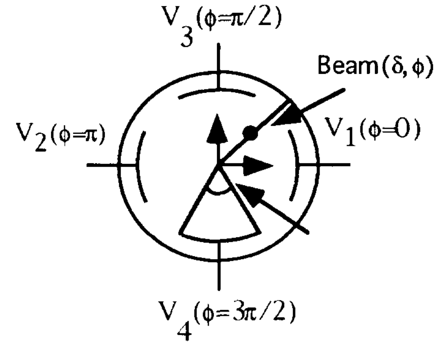

Fig.2. Cross section of the stripline BPM.

## POSITION CALCULATION

The beam position can be calculated by the $\Delta/\Sigma$ ratio (difference/sum) of signals coming from two pairs of the electrodes facing each other (see Fig.2):

$$x = S_b \frac{V_1 - V_2}{V_1 + V_2}, \quad y = S_b \frac{V_3 - V_4}{V_3 + V_4}, \tag{1}$$

where $S_b$ is a coupling factor which is calculated on the basis of the geometrical configurations between the beam and electrodes. If the BPM has $\pi/2$ rotational symmetry, the coupling factor is the same in the x and y directions.

The distribution of the induced charge inside the BPM by a line-charge at polar coordinates $(\delta\ ,\theta)$ is given by

$$q = \frac{a}{2\pi R} F(\delta,\theta,\phi)\lambda, \tag{2}$$

where

$$F(\delta,\theta,\phi) = \frac{R^2 - \delta^2}{R^2 + \delta^2 - 2R\delta\cos(\phi - \theta)}. \tag{3}$$

Here, a is the electrode area, R the inner radius of the BPM, $\lambda$ the line-charge density and $\phi$ the azimuthal angle coordinate of the electrode at the BPM wall. The function $F(\delta,\theta,\phi)$ contains beam displacement-dependent terms (see Fig.2). If the BPM has $\pi/2$ rotational symmetry and the electrode width is sufficiently narrow so that the field is constant over the electrode surface, the beam displacement can be calculated using eqs.(1) and (3):

$$x = \delta\cos\theta = S_b \frac{F(\delta,\theta,0) - F(\delta,\theta,\pi)}{F(\delta,\theta,0) + F(\delta,\theta,\pi)} \tag{4}$$

and

$$y=\delta\sin\theta=S_b\frac{F(\delta,\theta,\pi/2)-F(\delta,\theta,3\pi/2)}{F(\delta,\theta,\pi/2)+F(\delta,\theta,3\pi/2)}. \qquad (5)$$

By using eqs.(3), (4) and (5) we obtain

$$S_b=\frac{R^2+\delta^2}{2R}. \qquad (6)$$

When the BPM has broad electrodes, the coupling factor can be calculated by integrating the induced charge over the surface of the electrode in order to calculate the pickup voltage:

$$S_b=\delta\cos\theta\times \left[\frac{\int_{-\Delta\phi}^{\Delta\phi}F(\delta,\theta,\phi)d\phi-\int_{-\Delta\phi}^{\Delta\phi}F(\delta,\theta,\phi+\pi)d\phi}{\int_{-\Delta\phi}^{\Delta\phi}F(\delta,\theta,\phi)d\phi+\int_{-\Delta\phi}^{\Delta\phi}F(\delta,\theta,\phi+\pi)d\phi}\right]^{-1}. \qquad (7)$$

If the beam displacement ($\delta$) approaches zero, $S_b$ obeys the following formula:[4]

$$\lim_{\delta\to 0} S_b=\frac{R}{2}\frac{\Delta\phi}{\sin\Delta\phi}. \qquad (8)$$

## SPECTRUM CALCULATION

The frequency spectrum can be calculated by using a lumped circuit model[5] based on a standard transmission-line analysis. The BPM equivalent circuit is shown in Fig.3.

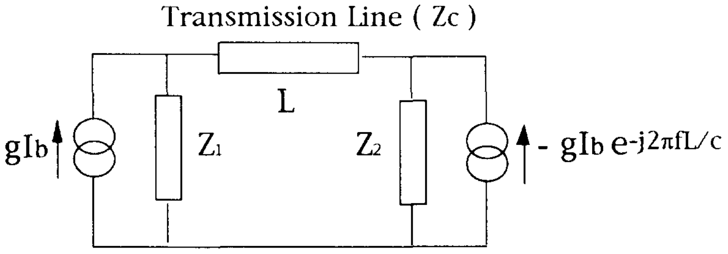

Fig.3. Equivalent circuit of the BPM. Zc and L show the characteristic impedance and the length of the transmission line respectvely, $Z_1$ and $Z_2$ terminated impedances, g the coupling factor and Ib the beam current.

The prototype BPM was constructed under the conditions that $Z_c=Z_1$ (=50 Ω) and $Z_2=0$ (short-circuited line) to give the frequency spectrum by

$$F(f) \propto Z_1|\sin(2\pi fL/c)|I_b, \qquad (9)$$

where f is the frequency, $I_b$ the beam current, L the stripline length and c the velocity of light. The frequency spectrum shows a notch-like structure of a sinusoidal function where the maximum sensitive points are obtained at $2\pi fL/c=(2n-1)\pi/2$ (n:integer). In this BPM the first maximum point is given at f=576.9 MHz.

# EXPERIMENTS

## TEST BENCH

Figure 4 shows a picture of the test bench. Broadband transformers to match the cable impedance to the characteristic impedance of the beam pipe are attached to both ends of the BPM. A thin current-carrying wire (2.3 mmϕ) was stretched through the center of the monitor to simulate the beam. Leaving the wire and the matching sections fixed, the relative position between the monitor and the wire can be changed by moving the monitor with a precision micro-adjustable stage, controlled by a personal computer.

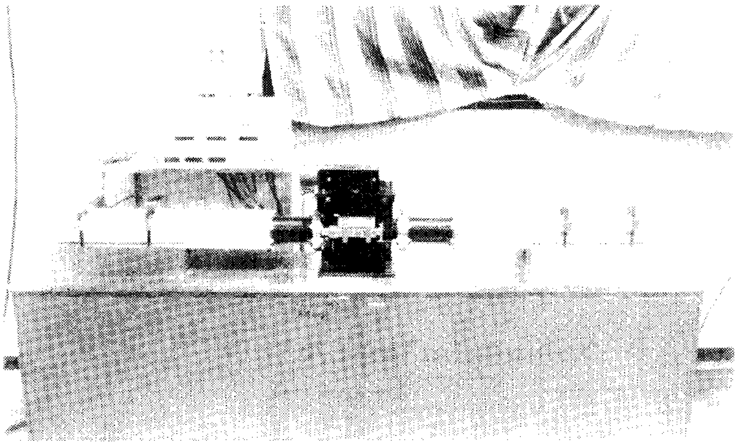

Fig. 4. Test Bench.

The four signals of the BPM are outputted through 50Ω SMA feedthroughs connected to the pickups and are transmitted to the electric circuit by coaxial cables. Figure 5 shows a block diagram of the electric circuit. Its main parts comprise bandpass filters (BPFs) with a center frequency of 250 MHz and a 5 MHz bandwidth, 60 dB amplifiers and synchronous RF-receivers.

The impulse response of the BPF generates a pulse of a 250 MHz RF-burst which is 200 ns wide. This signal is split in two by a power divider (P/D): 1) to a 60 dB amplifier and 2) to a power combiner (P/C). The latter is fed to a limiting amplifier (L/A) to provide a 250 MHz reference. The former is demodulated by a double-balanced mixer (DBM) and the timing requirement is adjusted by a delay line. The limiting amplifier comprises 5-cascaded RF circuits integrated in a chip. The DBM output signal is fed to a low-pass filter (LPF) providing amplitude information of the 250 MHz signal. A sample and hold unit are triggered to store the peak value and a CAMAC-ADC module digitizes the peak voltage. The beam-position calculation is made in real time by a personal computer.

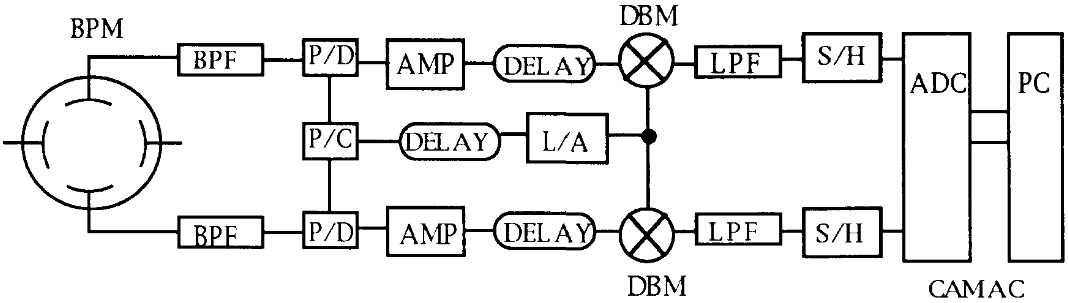

Fig.5. Block diagram of the electric circuit.

## BENCH TEST RESULTS

Figure 6 shows the $\Delta/\Sigma$ curve measured by moving the monitor along the horizontal direction. These experimental data points coincide approximately with the theoretical curve derived from eqs.(3) and (4) after correcting the pedestals of the ADC as well as the gain variation of the amplifiers.

Figure 7 shows the difference between the actual displacement and its derived value by the least-square fit of a third-order curve over a ±8 mm region. As the result shows, a position resolution of about 0.18 mm was obtained in the central ±3 mm region. Figure 8 shows the variation of the horizontal position resolution at the BPM center and the reduced chi-square value obtained by changing a test current from 0.1 to 2.1 amperes. The reduced chi-square values were calculated by a least-square fit of a two-dimensional (horizontal and vertical directions) third-order curve over a ±8 mm region and give a precision of the calibration in the region. These two curves show that the available current in this circuit with 0.2 mm resolution at the center and with a minimum reduced chi-square is from 0.2 A through 1 A. This range is limited in the low-current region (< 0.1 A) by the S/N ratio, and in the high-current region (> 1 A) by the nonlinearity of the 60 dB amplifiers.

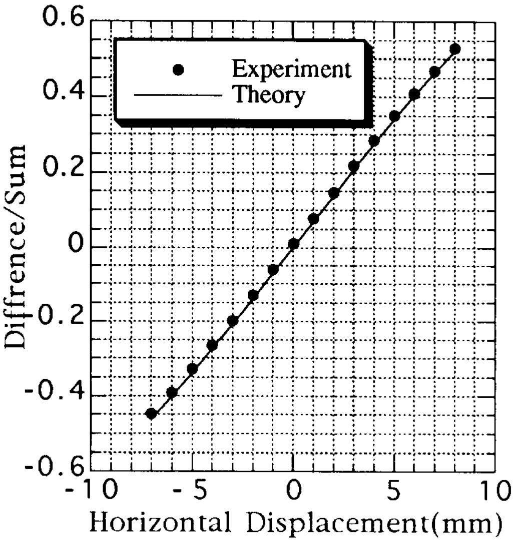

Fig.6. Difference/Sum curve obtained at a current of 0.21 A. The solid line shows the theoretical curve.

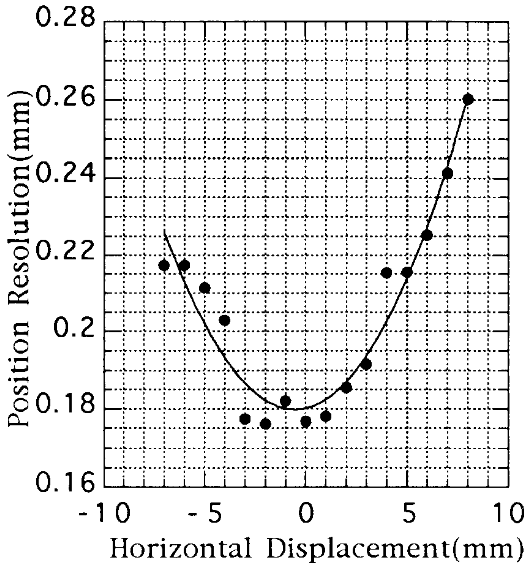

Fig.7. Horizontal position resolution obtained at a current of 0.21 A. The solid line is an eye guide.

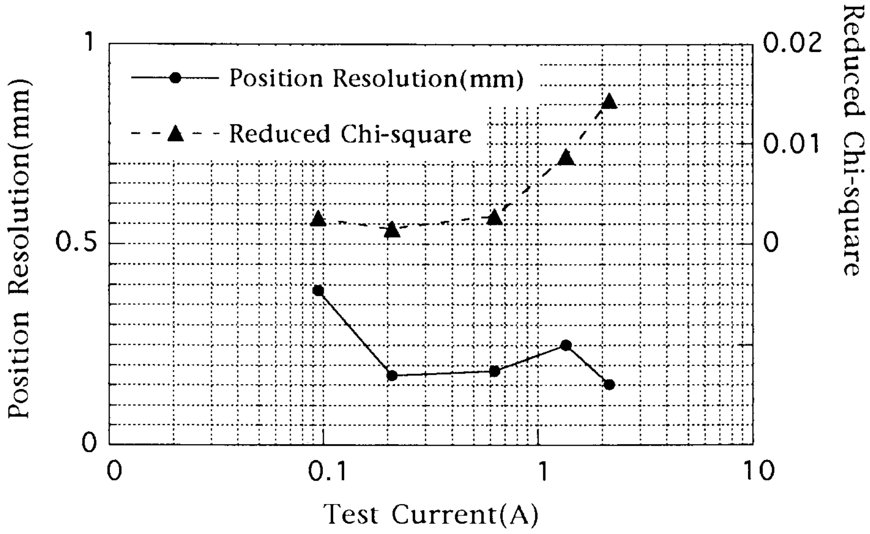

Fig.8. Variation of the horizontal position resolution at the BPM center and the reduced chi-square value by changing a test current. The reduced chi-square values were calculated by a least-square fit of a two-dimensional third-order curve over ± 8 mm region. The solid and dashed curves are eye guides.

## BEAM TEST RESULTS

An actual beam experiment[6] of the BPM was carried out by using a single-bunch electron beam (E=35 MeV, I=0.27 nC/bunch, FWHM≈10 ps) from the NERL linac. After a thin vacuum window at the end of the linac, the BPM was placed on a precision micro-adjustable stage in order to change the position of the BPM relative to the beam. The pickup signals were transmitted by using 15 m-long coaxial cables (RG 223/U) and observed by an analog oscilloscope (Tektronix 7104, BW 1GHz) and a digital sampling scope (HP 54124T, BW 50 GHz). A spectrum analyzer (ADVANTEST R4131D) was also used.

A typical waveform measured by the digital sampling oscilloscope is shown in Fig.9. The pulse height from each pickup was measured by scanning manually the micro-adjustable stage in the vertical and horizontal directions. The horizontal measurements are shown in Fig.10. Here, the output pulse height is defined as being the height of the first negative peak measured by the 1 GHz oscilloscope. The data points show the measurement at a beam current of 0.27 nC/pulse. The solid lines are the theoretical curves derived from eq.(3). The measurement includes about a 10% error due to the oscilloscope amplifier gain difference and the absolute position error relative to the beam. The absolute center positions were obtained by minimizing a chi-square value calculated using theory (the sensitivity curves) and all of the data points. Figure 11 shows a $\Delta/\Sigma$ curve measured by moving the BPM in the horizontal direction. The coupling factor ($S_b$) at the center position is 13.9 mm, derived from the slope of the $\Delta/\Sigma$ curve. The agreement between theory and the experiment is good within the errors. Figure 12 shows the frequency spectrum of the pickup measured by the spectrum analyzer. This shows half-sine forms with some dips which depend on the length of the stripline. The first dip is at 1.17 GHz and the second one at 2.35 GHz. These frequencies agree well with the theoretical values.

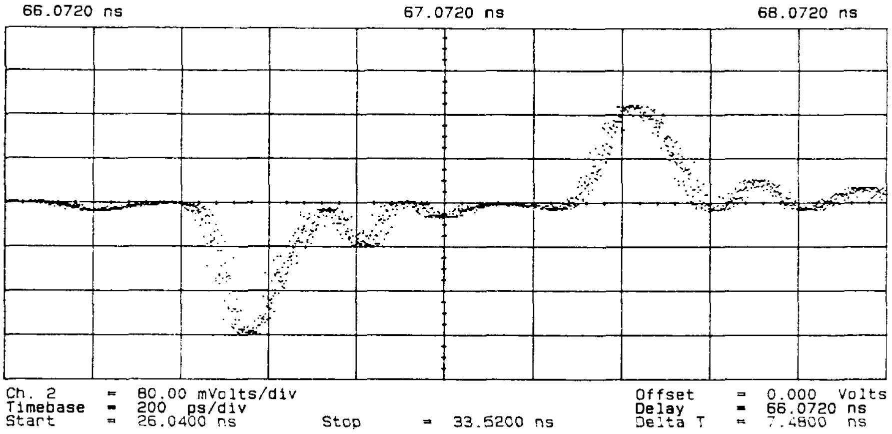

Fig.9. Pickup pulse measured by the digital sampling oscilloscope.

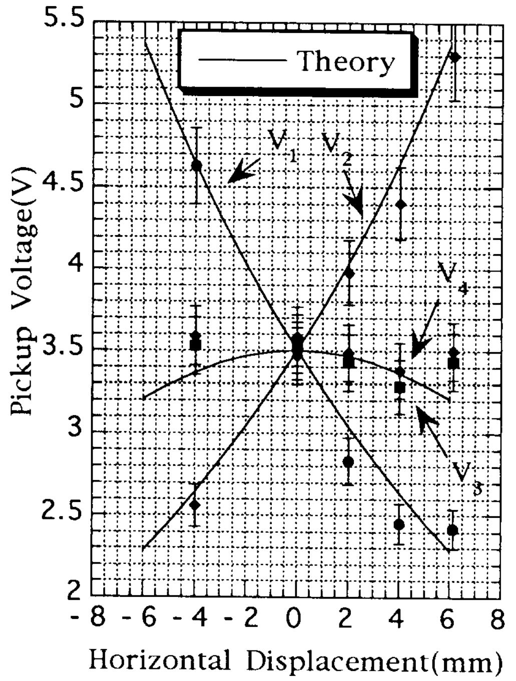

Fig.10. Pickup voltages as a function of the horizontal displacement.

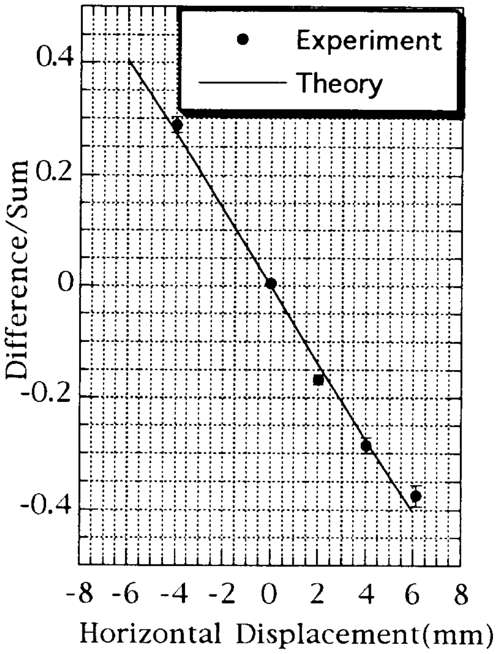

Fig.11. A difference/sum as a function of the horizontal displacement.

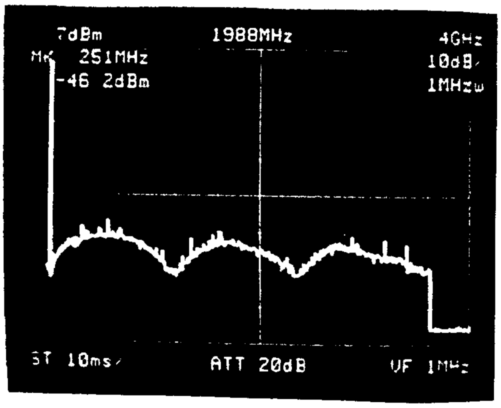

Fig.12. Frequency spectrum of the pickup pulse.

# SUMMARY

Several characteristics of a prototype BPM using stripline pickups were measured at a bench and a linac. In the bench test position resolution of the BPM was about 0.18 mm over a ±3 mm region from the center position. The available input range in the low-current region is mainly limited by the noise level of the limiting amplifier and in the high-current region, by the nonlinearities of the 60 dB amplifiers. The prototype was also tested for a single-bunch electron beam, where the frequency spectrum as well as other basic characteristics are in good agreement with theory.

# ACKNOWLEDGMENT

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