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RESEARCH ARTICLE | OCTOBER 10 1994

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AIP Conference Proceedings 319, 334–342 (1994)
https://doi.org/10.1063/1.46984

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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 in order to easily handle the orbit of a high-current electron beam (≈10 nC/pulse) generating a positron beam in the B-factory. The prototype BPM was tested at a test bench and then in the linac using a single-bunch electron beam. In this report some basic characteristics and the experimental results of the BPM are presented.

INTRODUCTION

The KEK electron/positron linac is being upgraded for the B-factory project[1]. For the B-factory, the linac is required to accelerate a high-current primary electron beam for generating 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. In this report the experimental results of the BPM are presented based on a bench test and an experiment using of a single-bunch electron beam (E=35MeV, I=0.27 nC/bunch) at the NERL linac[3] of the University of Tokyo.

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BEAM-POSITION MONITOR

STRUCTURE OF BPM

The picture of 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 that it could 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 compose 50Ω transmission line. The total length is variable within ±15 mm by bellows connected to one side of the BPM. Each electrode is supported by 50Ω SMA vacuum feedthroughs at one end side of the pipe. The four other sides of the electrodes are short-circuited to the pipe. The opening angle of the electrode viewed from the center position of the BPM was chosen to be 60 degrees.

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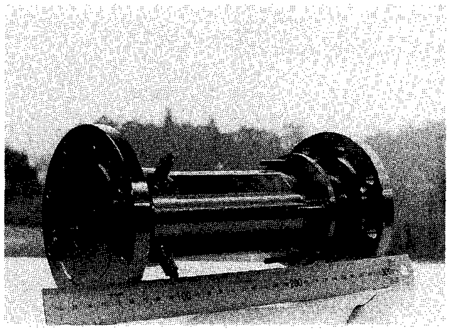

Fig.1. Picture of the stripline-type BPM.

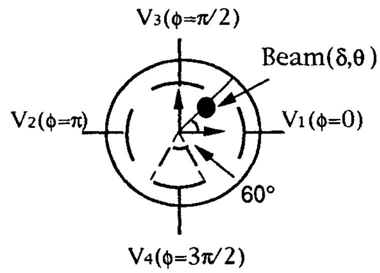

Fig.2. Cross section of the stripline BPM.

SENSITIVITY OF THE BEAM PICKUP

The beam position in the BPM can be calculated by the Δ/Σ 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 conversion 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 conversion 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 (δ, θ) is

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

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, λ the charge density of the beam and ϕ the azimuthal angle coordinates 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 very narrow, the beam displacement can be calculated using eqs.(1) and (2):

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

and

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

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

$$S_b = \frac{R^2+\delta^2}{2R}. \tag{6}$$

When the BPM has broad electrodes, the conversion factor can be calculated by integrating the induced charge over the surface of the electrode in order to calculate the pickup voltage[4] :

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

If the beam displacement δ approaches zero, S_b obeys the following formula[4] :

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

SPECTRUM CALCULATION

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

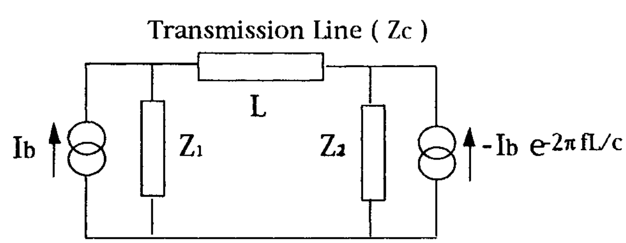

Fig.3. Equivalent circuit of the BPM. Zc and L show the characteristic impedance and the length of the transmission line respectvely, Z_1 and Z_2 terminated impedances, and Ib the beam current.

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The prototype BPM was constructed in the conditions of Z_c=Z_1 (=50 Ω) and Z_2=0 (short-circuited line). In this condition the frequency amplitude is given by

$$F(f) \propto Z_1 |\sin(2\pi f L/c)| I_b, \tag{9}$$

where f is the frequency of the pickup pulse, 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. 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. The BPM is installed at the center of the bench connected to a computer-controlled precision micro-adjustable stage. The broad matching transformers are connected to both sides of the BPM. These matching sections are needed to match the cable impedance to the characteristic impedance of the beam tube. A thin current-carrying wire (2.3 mmϕ) is stretched through the center of the monitor to simulate the beam. The position of the wire relative to the monitor was changed by fixing both the wire and the matching sections and by moving the monitor with a precision micro-adjustable stage controlled by a personal computer.

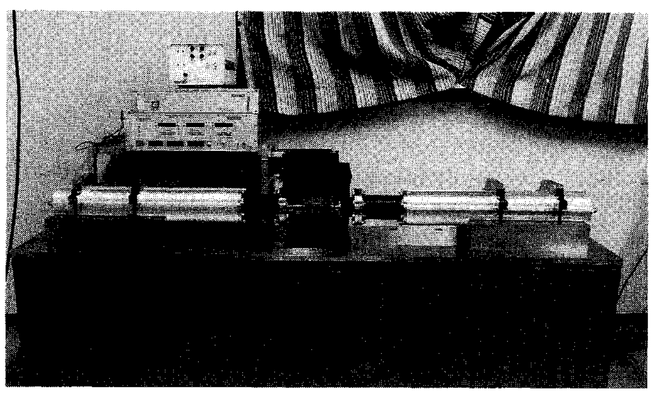

Fig. 4. Test Bench.

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. The main parts of this circuit comprise bandpass filters (BPFs) of 250 MHz in the center frequency and 5 MHz in band width, 60-dB amplifiers and synchronous RF-receivers. The RF signals from the pickups first pass

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matched bandpass filters (250±2.5 MHz), which respond to a single-bunch signal with a 250 MHz RF-burst that is about 200 ns wide. The RF-burst signals are transmitted to the 60-dB amplifier and are detected by the synchronous RF-receivers. On the other hand, the pickup signals divided by power dividers (P/D) are transmitted to a hard limiter comprising 5-cascaded RF limiter-amplifier integrated circuits. The 250 MHz-signals can be demodulated by a homodyne mixer (DBM), which provides an amplitude-envelope of the 250 MHz signal at the output of the low-pass filter. Then, the signals are sampled and held by the S/H-modules, which detects the gated peak of a pulse. The output signals of the S/H-modules are fed directly to the CAMAC ADC module, which digitizes a peak voltage, and are read out in real time by a personal computer which calculates the beam position.

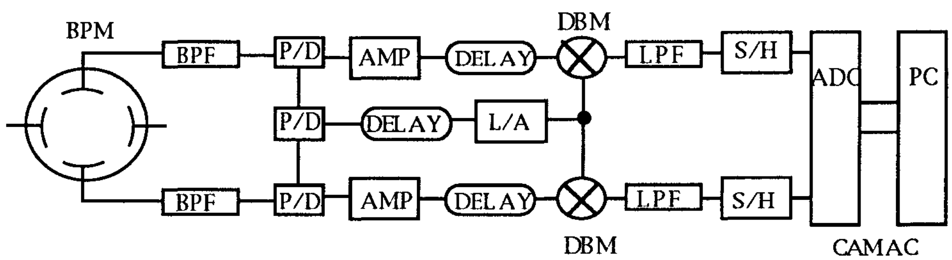

Fig.5. Block diagram of the electric circuit.

BENCH TEST RESULTS

Figure 6 shows the sensitivity curve for the outputs of the pickups 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 for the pedestals of the ADC modules as well as the gain variation of the amplifiers to the pulse height. Figure 7 shows the difference between the data and the values reconstructed 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 at the central region. Figure 8 shows variation of the horizontal position resolution at the BPM center and the reduced chi-square values 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 (the horizontal and vertical directions) third-order curve over a ±8 mm region. The flat regions of these curves give an available dynamic range of the electric circuits. The dynamic range was spread over a factor of about 10. In the present status of the circuits the position resolution is limited in a low current region (< 0.1 A) by the S/N ratio, and in a high current region (> 1 A) by the noise level of the hard limiter and the nonlinearity of the 60-dB amplifiers.

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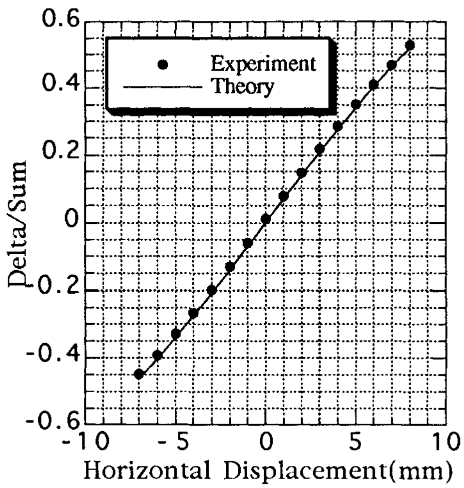

Fig.6. Delta/Sum curve obtained at a current of 0.21 A. The solid line shows the theoretical curve.

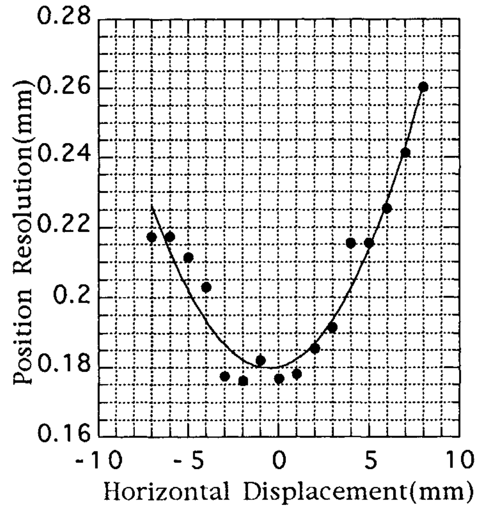

Fig.7. Horizontal position resolution obtained at a current of 0.21 A. The solid line shows an eye's guide.

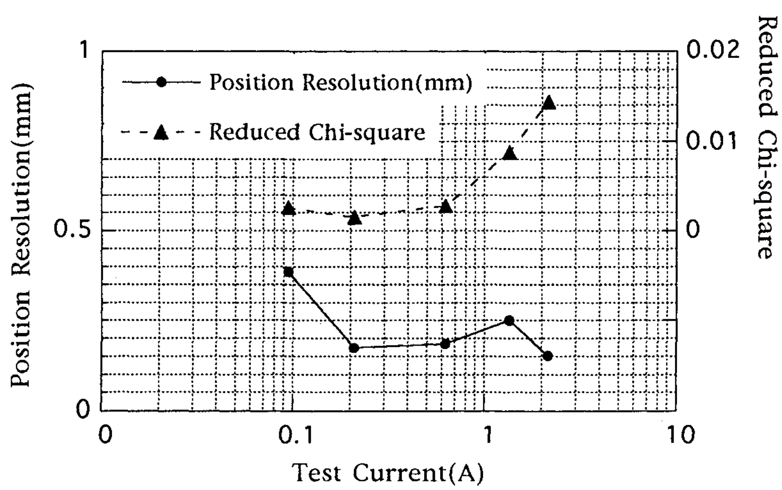

Fig.8. Variation of the horizontal position resolution at the BPM center and the reduced chi-square values by changing a test current. The reduced chi-square values were calculated by a least-square fit of a two dimensional third-order curve over ± 8 mm region. The solid and dashed curves show eye's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

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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 the exit of the linac the stripline-type BPM was set in air on a precision micro-adjustable stage in order to change the position of the BPM relative to the beam in the horizontal and vertical directions manually. The BPM pickup signals were sent to the measurement room using 15 m long coaxial cables (RG 223/U) and observed by an analog oscilloscope (Tektronix model 7104, BW=1GHz) and a digital sampling scope (HP 54120B, BW=50 GHz). A frequency spectrum was also measured using a spectrum analyzer (ADVANTEST R4131D).

A typical waveform measured by the digital sampling oscilloscope is shown in Fig.9. The pulse height from each pickup was measured with changing the position of the BPM in the vertical and horizontal directions by moving the micro-adjustable stage manually. The sensitivity curves of the pickups 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 eqs.(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 the theory (the sensitivity curves) and all the data points. Figure 11 shows a Δ/Σ curve measured by moving the BPM in the horizontal direction. The conversion factor (S_b) at the center position is 13.9 mm derived from the slope of the Δ/Σ curve. The agreement between theory and the experiment is good within the errors. Figure 12 shows a frequency spectrum of the pickup pulse measured by the spectrum analyzer. The spectrum 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.

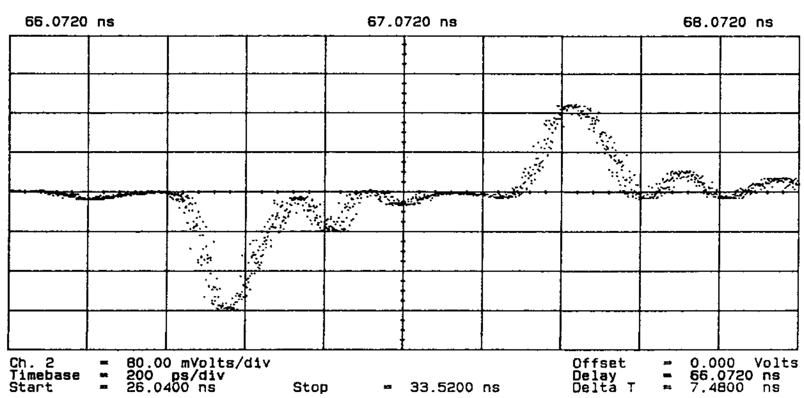

Fig.9. Pickup pulse measured by the digital sampling oscilloscope.

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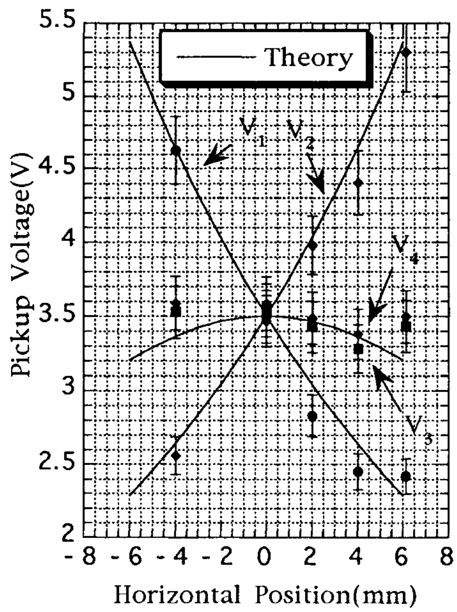

Fig.10. Sensitivity curves of the pickups by moving the BPM in the horizontal direction.

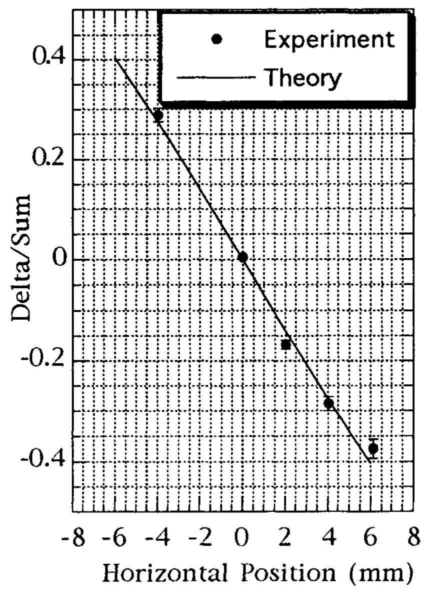

Fig.11. A Delta/Sum curve measured by moving the BPM in the horizontal direction.

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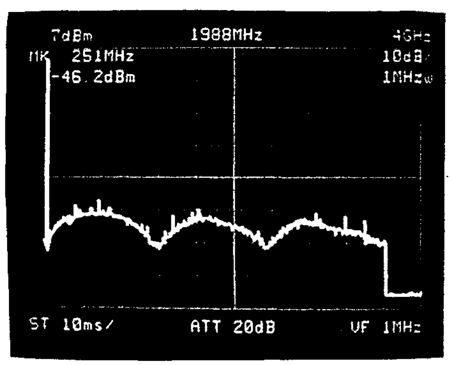

Fig.12. Frequency spectrum of the pickup pulse.

SUMMARY

A BPM using stripline pickups was developed in order to improve the beam operation of the electron/positron beams at the KEK 2.5-GeV linac. Particularly, during beam injection into the B-factory the BPM must be used in order to detect beam instability due to wake-field effects caused by any beam displacement from the central orbit. In this bench test the position resolution of the BPM was about 0.18 mm over a ± 3 mm region from the central position. The resolution is mainly attributed to the noise level of the hard limiter in the electric circuit. The dynamic range to the beam current was obtained to be spread over a factor of about 10.

The prototype BPM was also tested for a single-bunch electron beam. The frequency spectrum response as well as other basic characteristics are in good agreement with theory.

ACKNOWLEDGMENT

The authors wish to thank T. Kozawa, T. Ueda and T. Kobayashi in the University of Tokyo, who helped the preparation of the beam experiment and operated the linac.

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