DEVELOPMENT OF CAPACITIVE LINEAR-CUT BEAM POSITION MONITOR FOR HEAVY-ION SYNCHROTRON OF KHIMA PROJECT

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Abstract

Since the beam intensity after the injection and capturing process in the KHIMA synchrotron is $\sim 7.4 \times 10^8$ particles for the carbon beams and $\sim 2.07 \times 10^{10}$ for the proton beams, the linear-cut beam position monitor is adopted to satisfy the position resolution of 100 μm and accuracy of 200 μm with the linearity within the wide range. In this paper, we show the electromagnetic design of the electrode and surroundings to satisfy the resolution of 100 μm, the criteria for mechanical aspect to satisfy the position accuracy of 200 μm, the measurement results of position accuracy and calibration by using a wire test-bench, and the beam-test results with long (~ 1.6 μs) electron beam in Pohang accelerator laboratory (PAL).

Figure 1: Layout and position of beam diagnostics in KHIMA synchrotron.

INTRODUCTION

Main purpose of the Korea Heavy Ion Medical Accelerator(KHIMA) project is to construct a proton and carbon therapy accelerator based on a synchrotron and it is currently under construction in Korea [1]. A low intensity proton and carbon beam with an energy in the range of 110 to 430 MeV/u for a carbon beam and 60 to 230 MeV for a proton, which corresponds to a water equilibrium beam range of 3.0 to 27.0 g/cm^2, is produced by the accelerator for a cancer therapy [2]. The accelerator consists of the low energy beam transport (LEBT) line, radio-frequency quadrupole (RFQ) linear accelerator (linac), interdigital H-mode drift-tube-linac (IH-DTL), medium beam transport (MEBT) line, synchrotron, and high energy beam transport (HEBT) line [3]. In the KHIMA synchrotron, a high precision beam position monitor, which has a position resolution and accuracy of 100 μm and 200 μm, respectively, is required to match and control the beam trajectory for the beam injection and closed orbit [4]. It is also used for measuring Twiss parameters, betatron tunes, and chromaticity in the synchrotron. Since the bunch length in the heavy ion synchrotron is relatively long, a few meters, and the intensity of the beam is low, a box-like device with long plates of typically 20 cm is used to enhance the signal strength and to obtain a precise linear dependence with respect to the beam displacement [5]. The number of the horizontal and vertical beam position monitors in the synchrotron are 10 and 7, respectively. The position of the monitor is determined based on the amplitude of the betatron oscillation. It is shown in Fig. 1.
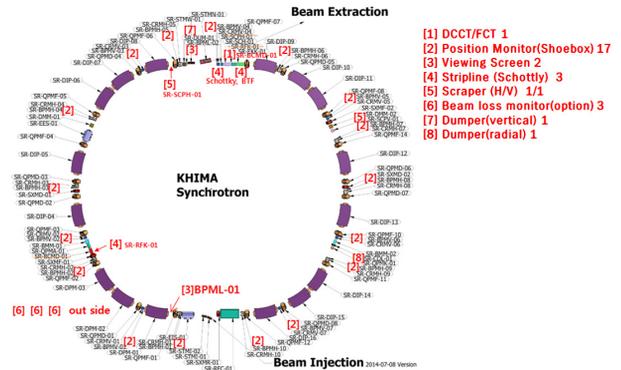
LINEAR-CUT BEAM POSITION MONITOR

The linear-cut beam position monitor consists of two electrodes with the width of 136 mm and the thickness of 2 mm, 5 mm thick body, insulator, holder and vacuum chamber. The distance between the body and electrode is maintained to be 8 mm to increase the induced signal by reducing the capacitance. The designed beam position monitor is shown in Fig. 2.

Figure 2: Linear-cut beam position monitor in KHIMA synchrotron.

The transverse and longitudinal dimensions of the beam position monitor is restricted because the beam position monitor would be installed inside the steering magnet yoke. The length of horizontal and vertical monitor are 290 mm and 244 mm, respectively. The transverse dimension of

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the electrode was kept as large as possible within a limited chamber size to increase the signal strength. Since the cross-talk between two electrodes determines mainly the position resolution of the beam position monitor, the cross-talk as function of the distance between two electrodes is investigated to optimize the distance between two electrode. The result is shown in Fig. 3.
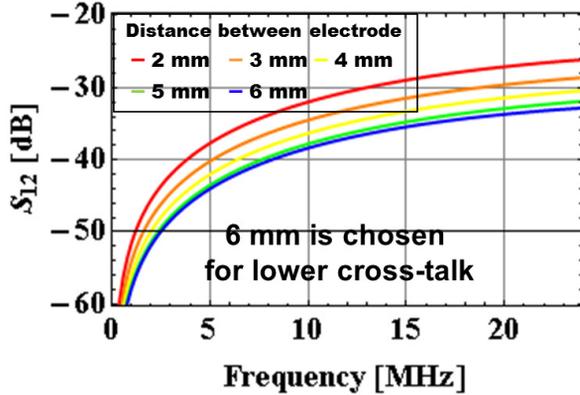

Figure 3: Cross-talk(S_{12}) as a function of the distance between two electrodes.

When the distance between the electrodes is larger than 5 mm, the cross-talk is almost saturated to be -40 dB in the operating frequency range of 0.48 to 3 MHz. The distance between the electrodes is determined to be 6 mm to achieve the cross-talk of less than -40 dB. For the cross-talk of -40 dB, the position reading error due to the cross-talk is about 2 %. The linearity of the beam position monitor is also calculated by using CST-PS that is shown in Fig. 4 [6].
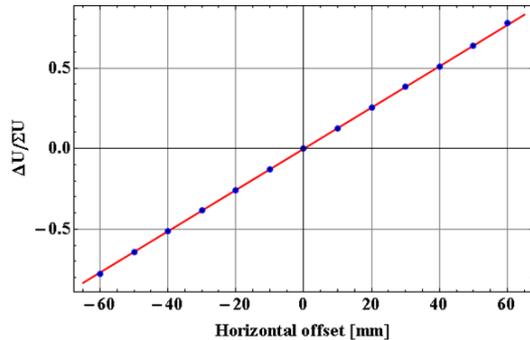

Figure 4: Linearity of the beam position monitor.

The beam position is determined by the ratio of difference and sum of the signals generated by the two electrodes that is given in Eq. 1.

$$x = a_0 \frac{\Delta U}{\Sigma U} + a_1 = a_0 \frac{U_{left} - U_{right}}{U_{left} + U_{right}} + a_1, \qquad (1)$$

where a_0 is coefficient which is proportional to the transverse dimension of the electrode, a_1 is coefficient which is related with the mechanical central position, the U_{left} and U_{right} are voltage output from the left and right electrodes,

respectively. The ideal values of a_0 and a_1 for the designed beam position monitor are 72 mm and 0 mm, respectively. Due to the internal structure, such as the insulator and surroundings, the beam position monitor, however, has the a_0 and a_1 coefficients of 78.10 mm and -72.7 μm. It is enough to satisfy the desired position accuracy of 200 μm.

CROSS-TALK MEASUREMENT AND CALIBRATION

The beam position monitor consists of two electrodes, body, insulator, holder, two feed-through and vacuum chamber. The triangular shape electrodes are made by the oxygen free copper (OFC), and the body, holder, and vacuum chamber is made by stainless steel, SUS304. The 99.6 % alumina-ceramic is chosen as the insulator material which is used to attach two electrodes inside the body with well defined distance of 8 mm. The picture of the fabricated horizontal beam position monitor is shown in Fig. 5.
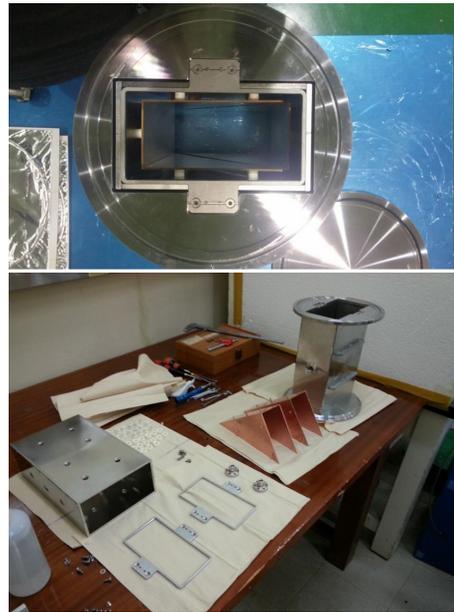

Figure 5: Picture of fabricated beam position monitor.

Based on the results of the electromagnetic and mechanical design, the beam position monitor is fabricated by the Korean company, I.T.S, and the leakage test is performed by using the helium leak detector to check the the defect during the welding process [7]. The requirement of the vacuum pressure for the beam position monitor is 10^{-9} Torr to reduce the beam loss and electron capture in the synchrotron. In order to confirm the performance of the fabricated beam position monitor, the cross-talk between two electrodes is measured by using Vector Network Analyzer. The result is shown in Fig. 6.

The measured cross-talk between two electrodes is lower than the -40 dB in the range of operation frequency, 0.48 $\sim$ 3 MHz, which is required to achieve the desired position resolution. The measurement result agrees well with the calculation result using code CST. By using the wire test
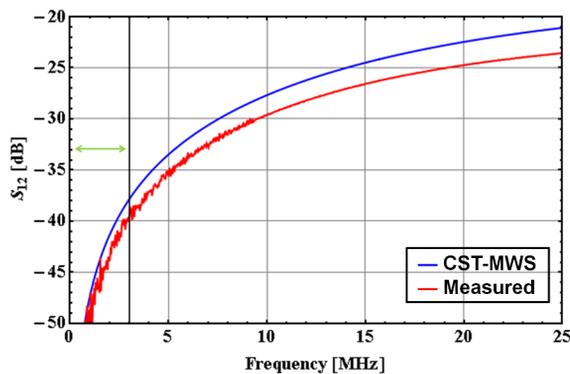
Figure 6: Measurement result of the cross-talk.

Figure 8: Calibration and linearity measurement of beam position monitor using wire test bench.

bench, which consists of the linear motor stage and well aligned and stretched wire with two feed-through on the each side, the signal response as a function of the offset was measured to confirm the linearity of the beam position monitor. The wire test bench is frequently used to confirm the frequency response and linearity of the pick-up devices from the external source. The test set-up is shown in Fig. 7.
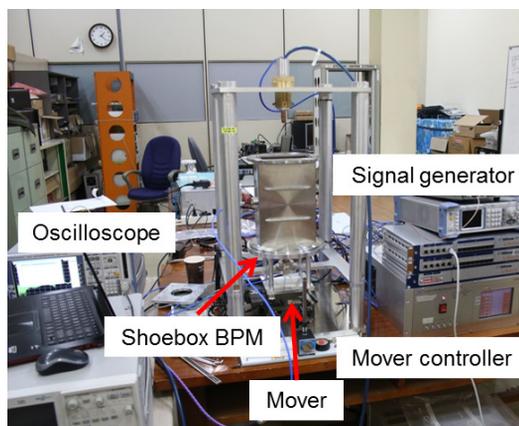

Figure 7: Picture of the test by using wire test bench.

The higher frequency noise signal is filtered by digital low-pass filter during the data processing. It suppresses all frequencies higher than the cut-off frequency and leaves smaller frequencies unchanged. The $\Delta U/\Sigma U$ as a function offset in the range of -28 mm to 28 mm is calculated to obtain the calibration coefficients, a_0 and a_1 that is shown in Fig. 8. The linearity of the beam position monitor in the range of -28 mm to 28 mm was confirmed. The calibration coefficients of a_0 and a_1 are measured to be 80.64 mm and 475 μm, respectively.

PRE-AMPLIFIER DESIGN

The pre-amplifier for amplifying the signal strength from the beam position monitor is designed. It has 1 MΩ input impedance. Two input ports are required for the pre-amplifier of the beam position monitor to calibrate the electronics on the operation. It has two individual channels because the beam position monitor has two signal ports. The bandwidth
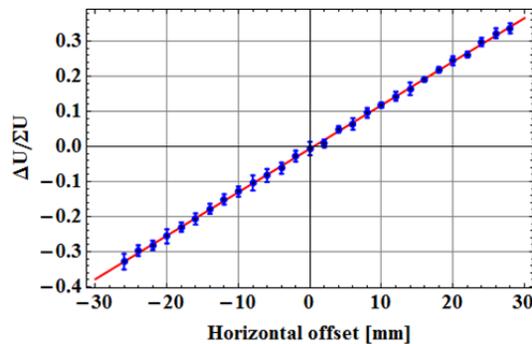
is determined to be DC ~ 50 MHz to measure the spatial structure of the beam. It was fabricated by EMWISE in Korea [8].
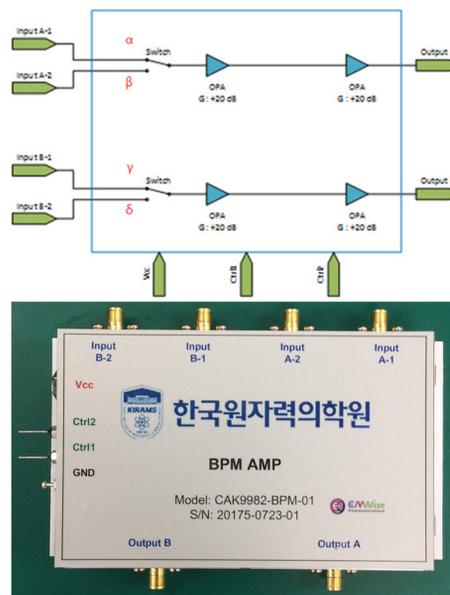

Figure 9: Schematic drawing and picture of pre-amplifier for beam position monitor.

As shown in Fig. 9, the amplifier consists of 2-port RF relay switch and two op-amplifier. The total gain is fixed to be 40 dB. The noise figure of the circuit is 9.9 dB for 10 MHz and 9.8 for 50 MHz. The gain curve as a function of the frequency is measured that is shown in Fig. 10.

MEASUREMENT WITH ELECTRON BEAM

The beam test with the long electron bunch train, ~ 1.6 μs, which corresponds to the frequency of 630 kHz, is performed to confirm the performance of the beam position monitor with pulsed beam at the test linac in the Pohang Accelerator Laboratory (PAL). Since the beam position monitor has large capacitance, ~ 120 pF, and the input impedance of the pre-amplifier is also high, 1 MΩ, the cut-off frequency is low
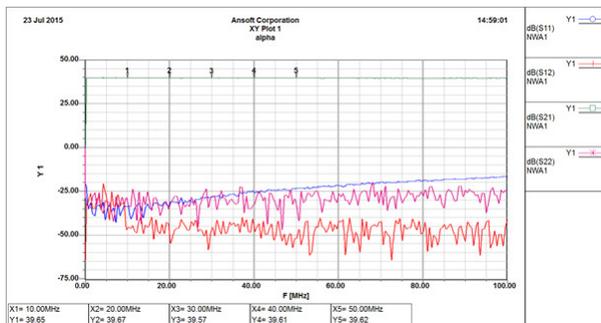
Figure 10: S-parameter of high impedance pre-amplifier for beam position monitor.

Figure 12: Measured signal as a function of horizontal offset of moving stage.

enough to collapse the effects of the micro-pulse [9]. The picture of the beam test set-up is shown in Fig. 11.

Figure 11: Picture of beam test set-up with moving stage after beam window of test linac.

Figure 13: Calibration and linearity measurement of beam position monitor using electron beam.

and a_1 are measured with electron beam to be 80.83 mm and -0.255 mm, respectively.

CONCLUSION

The length of the macro-pulse agrees well with the operation frequency although the length of the micro-pulse is very short, less than nano-second, due to the RF frequency of the S-band linac, 2.856 GHz. The energy and current of the electron beam are 60 MeV and less than 1 mA, respectively. The beam position monitor is installed on the moving stage and the high impedance amplifier is installed near the beam position monitor. The gain of the pre-amplifier is set to be 40 dB. The signal as a function of the horizontal offset of the moving stage is measured to calculate the calibration factor and to confirm the linear response of the beam position monitor. The measured signal is shown in Fig. 12

The higher frequency noise signal from the surroundings is observed and it is filtered by digital low-pass filter during the data processing. By using the filtered signal, the $\Delta U/\Sigma U$ as a function offset of the moving stage is calculated to obtain the calibration coefficients, a_0 and a_1 that is shown in Fig. 13.

The non-linear behavior is observed when the offset of the moving stage is large. It may cause due to the large beam size and halo particles at the exit of the beam window because the signal strength is decreased when the electron hit the electrode directly. The calibration coefficients of a_0
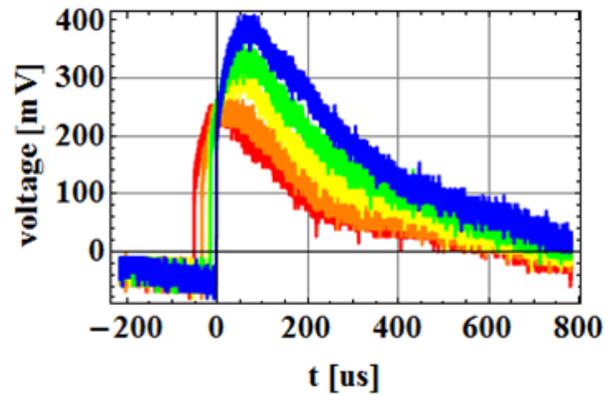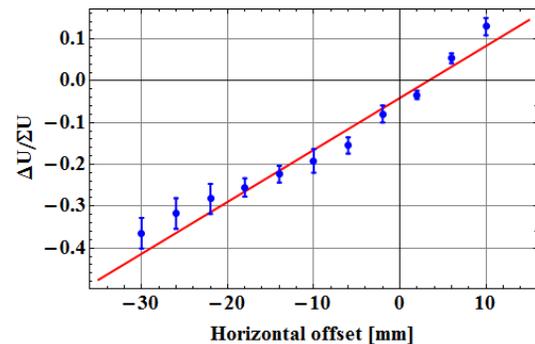
The linear-cut beam position monitor, which will be installed in the synchrotron ring of KHIMA, is under developing. The design study of the beam position monitor to achieve the desired position resolution of 100 μm and the accuracy of 200 μm was performed. And it was fabricated based on the design values and the laboratory tests, such as the vacuum leakage test by helium leak detector, the cross-talk measurement and linearity measurement using the wire test bench, were performed to confirm the performance. The measured cross-talk and calibration coefficient agree well with the designed parameter by the numerical simulation using code CST-MWS and CST-PS. The pre-amplifier with the 1MΩ input impedance is designed and fabricated. The beam test with the long electron bunch train at the test linac in PAL is performed and the measured calibration coefficients is also well agree with the result of wire test bench.

ACKNOWLEDGMENT

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