DEVELOPMENT OF HIGH PRECISION CAPACITIVE BEAM PHASE PROBE FOR KHIMA PROJECT

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Abstract

In the medium energy beam transport (MEBT) line of KHIMA project, a high precision beam phase probe monitor is required for a precise tuning of RF phase and amplitude of RFQ and IH-DTL. It is also used for measuring a kinetic energy of ion beam by time-of-flight (TOF) method using two phase probes. In this paper, we show the electromagnetic design of the high precision phase probe to satisfy the phase resolution of 1 ° (@ 200 MHz), the test result with a wire test bench to estimate a signal strength and phase accuracy, the design of the 0.2 2.0 GHz broad-band electronics for amplifying the signal strength, and the results of beam energy and RF frequency measurement using a proton beam from the cyclotron in KIRAMS.

INTRODUCTION

The Korea Heavy Ion Medical Accelerator (KHIMA) project is launched to construct a heavy-ion therapy machine using carbon and proton beams. It will provide a carbon beam up to 430 MeV/u and proton beam up to 230 MeV which correspond to a water equilibrium range of 3.0 to 27.0 g/cm^2 [1]. The machine consists of an injector included an electron cyclotron resonance ion source (ECR-IS), low energy beam transport(LEBT) line, RFQ and IH-DTL linacs, and medium beam transport (MEBT) line, synchrotron, and high energy beam transport (LEBT) line. The carbon and H_3^+ beam produced by the ECR-IS with the energy of 8 keV/u and the $^{12}C^{4+}$ and H_3^+ beams were separated from the unnecessary beams by using an analyzing dipole magnet and it is transported through the low energy beam transport (LEBT) line. The low energy beam, 8 keV/u, is accelerated up to 7 MeV/u by the RFQ and IH-DTL [2].

By a carbon foil with a thickness of 100 μg/cm^2 in the MEBT line, the $^{12}C^{4+}$ beam is fully stripped and H_3^+ beam is changed to proton beam and injected to the synchrotron. The $^{12}C^{6+}$ and proton beams is accelerated up to 430 MeV/u and 230 MeV, respectively. A high precision beam phase probe monitor is required in the MEBT line of the KHIMA project for a precise tuning of RF phase and amplitude of the RFQ and IH-DTL to achieve the designed performance and high injection efficiency by adjusting longitudinal beam parameters such as a beam energy and bunch length at the exit of the IH-DTL, and to monitor the status of the carbon foil by measuring the variation of the kinetic energy of ion beam by time-of-flight (TOF) method using two phase probes.

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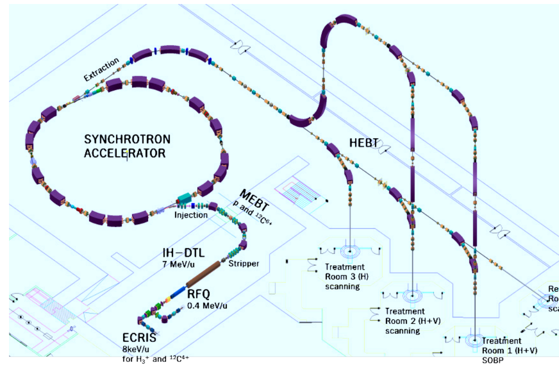

Figure 1: Layout of KHIMA accelerator.

CAPACITIVE PHASE PROBE DESIGN

In the MEBT line, two phase probes are installed to measure the kinetic energy of the ion beams from IH-DTL and to adjust the RF phase and amplitude of IH-DTL by measuring the length of micro-pulses. Since the stripping foil is installed between two phase probes, the status of the stripping foil can be confirmed by the beam energy measurement because the energy loss due to the straggling effects, ~ 16 keV/u, is vanished when the foil is broken. In order to achieve the energy resolution of 10 keV/u, the phase resolution of the phase probe monitor should to be 1° at 200 MHz. Since the beam current is low, ~ 0.1 mA for carbon beam, the capacitive type phase probe monitor is chosen to get the longitudinal distribution without the signal distortion and to get the relatively strong signal. The capacitive pick-up is a stripline bent around the beam pipe axis and then the impedance matching is significant to reduce the ringing effect due to the reflection by the impedance mis-matching. The impedance of the stripline is given by [3]

$$Z_0(l) = \frac{87}{\sqrt{\epsilon_r + 1.4}} \ln\left(\frac{5.98h}{0.8l + d}\right), \quad (1)$$

where ϵ_r is the relative permittivity, h is the distance between the pick-up ring and surroundings, and d and l are the thickness and length of the pick-up ring. In order to determine the length of the pick-up ring, the impedance as a function of the length when the distance between the inner and outer conductor(h) and the thickness (d) are 14 mm and 3 mm, respectively, that is shown in Fig. 2.

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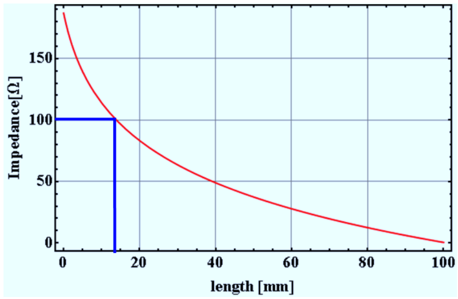

Figure 2: Impedance as a function of length of pick-up ring.

Based on the impedance calculation, the length of the pick-up ring is 14 mm because the impedance of the pick-up ring with surroundings should be matched to be 100 Ω due to the two pathes of the signal. The pick-up ring with the inner diameter of 40 mm and thickness of 3 mm is installed at the center of the double sided CF flange and 1.5 mm thick metal plates are provided on each side to protect the effect by hitting the beam on the pick-up ring. The PEEK (Polyether ether ketone) is used as the insulator material between the pick-up ring and metal plates. The inner diameter of the pick-up ring is determined to be a factor of 2 larger than the full beam size at the installation position to ensure stable operation. The designed capacitive phase probe is shown in Fig. 3.

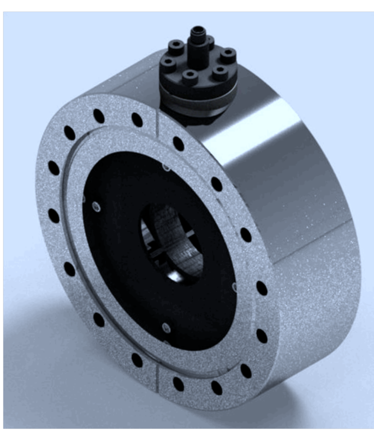
Figure 3: Capacitive phase probe.

Since the distance between the pick-up ring and feed-through, which is required to pick the induced signal at the pick-up ring, is long, about 40 mm, the outer conductor is applied to reduce the signal decay during the signal propagation along the long connector and to prevent the noise signal from surroundings [4]. The inner radius of the outer conductor is determined to match the impedance of 50 Ω based on impedance formula for the coaxial transmission line, $Z = 377\Omega/2\pi \ln(r_o/r_i)$, where r_o is the inner radius of outer conductor and r_i is the outer radius of the inner conductor. The detail structure for the coaxial transmission line is shown in Fig. 4.

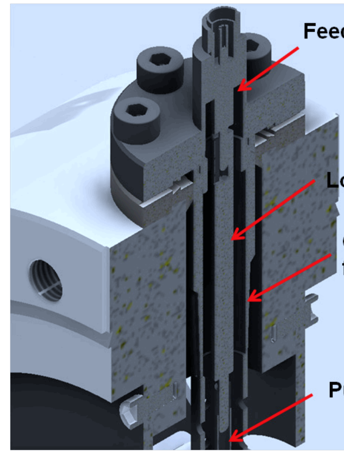

Figure 4: Structure of coaxial transmission line.

In order to determine the proper gain of the pre-amplifier, which is installed near the detector for amplifying the signal, the induced voltage signal from the capacitive phase probe is calculated. The induced voltage signal across the resistor, R, is given by [4]

$$U(t) = R\frac{A}{\beta c 2\pi a}\frac{dI_{beam}}{dt}10^{g/20}, \quad (2)$$

where R is the resistor, A is the area of the pick-up, $\beta = v/c$, a is the radius of pick-up, and g is the gain of an amplifier. Based on the beam parameters, the expected voltage signal with the 60 dB gain pre-amplifier is calculated that is shown in Fig. 5.

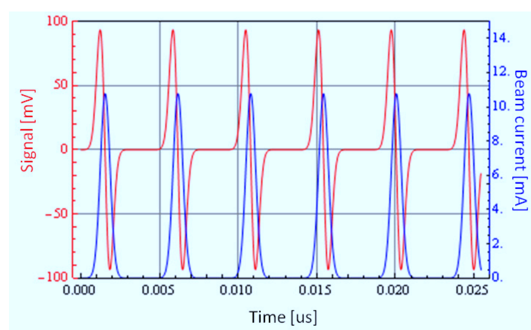

Figure 5: Expected beam current and resulting voltage signal with 60 dB gain pre-amplifier.

From the calculation result as shown in Fig. 5, the maximum gain of the pre-amplifier is determined to 60 dB with 20 dB gain step, minimum gain of 0 dB, and the input power of -50 to 0 dBm. In order to measure the longitudinal distribution of the ion beam by using the phase probe, the time response of the phase probe is significant because the capacitive phase probe has the cutoff frequency due to the structural capacitance and resistance [5]. The half value of time difference between the peak to peak voltage of the induced signal($\Delta t_{P2P}/2$) as a function of the bunch length for a Gaussian distribution is calculated by using CST-PS [6].

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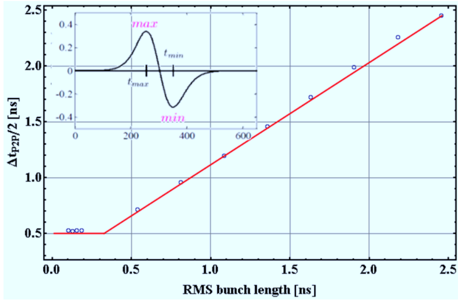

Figure 6: Half value of time difference between peak to peak voltage of induced signal($\Delta t_{P2P}/2$) as a function of rms bunch length for a 7 MeV/u beam.

As shown in Fig. 6, the designed capacitive phase probe has the linear response on a time domain down to RMS bunch length of 0.33 ns, which corresponds to the phase spread of 24° at 200 MHz.

MEASUREMENTS ON WIRE TEST BENCH

The test of the phase probe is performed for measuring the phase resolution of the capacitive phase probe and confirming and the effectiveness of the outer conductor, which is installed to increase the pick-up signal by reducing the propagation loss, using the wire test bench which consists of the linear motor stage and well aligned and stretched wire with two feed-through on the each side. The wire test bench is frequently used to confirm the frequency response and linearity of the pick-up devices from the external signal source. The picture of the test set-up is shown in Fig. 7.

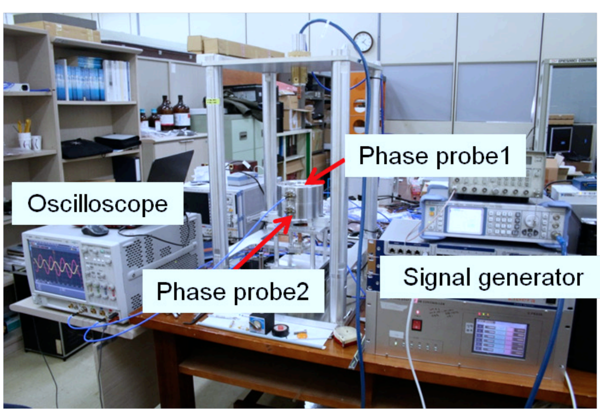

Figure 7: Picture of measurement by using wire test bench.

A 1GHz signal from an RF signal generator is excited on the wire and the induced signal at the phase probe is measured with and without the outer conductor and compared to confirm the effectiveness of the outer conductor. The results are shown in Fig. 8.

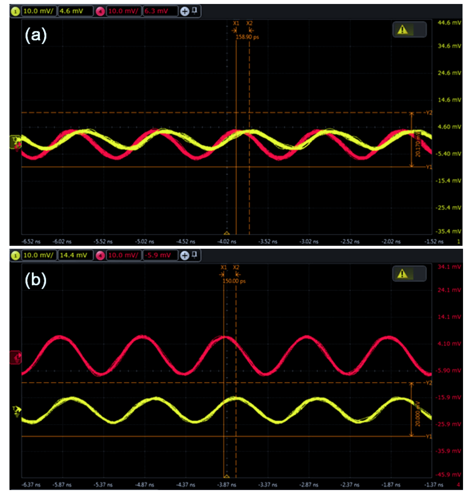

Figure 8: Measured 1GHz signal from two phase probes (a) without outer conductor, (b) with outer conductor.

As shown in Fig. 8, the strength of the pick-up signal is increased about 20 % when the outer conductor is installed.

In order to confirm the phase resolution of the phase probe, two phase probes were mounted on the wire bench with the distance of 50 mm and the signal from the pick-up is measured by using a high sampling speed oscilloscope when the external signal with the frequency of 2 GHz and current of 0.138 mA is excited on the wire. The expected time difference between two phase probes is 167 ps due to the distance of 50 mm. The measured signal and the time difference between two phase probes are shown in Fig. 9.

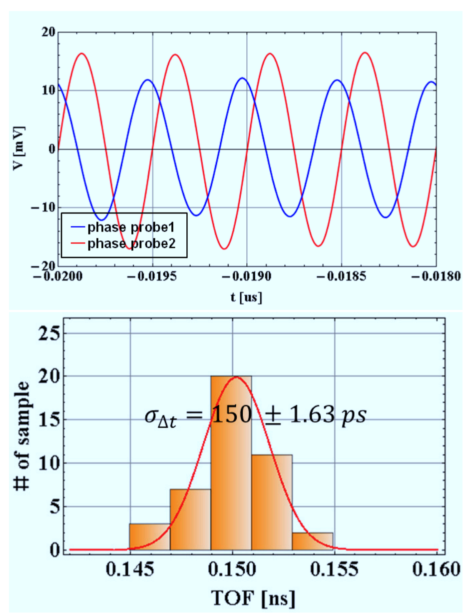

Figure 9: Measured signal (top) and time difference between two phase probes (bottom).

As shown in Fig. 9, the signal from the first phase probe (phase probe1), which is closed to the signal source, is fasten than the signal from the second phase probe(phase probe2). Based on the calculation of the zero-crossing point

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of the each signal, the measured time difference between two phase probes is calculated that is to be 150 ± 1.63 ps. The difference between the expected and the measured value is 17 ps. It corresponds to the phase of 1.2 ° at 200 MHz.

PRE-AMPLIFIER DESIGN

Based on the calculation and measurement result on wire test bench, the pre-amplifier for amplifying the signal strength from the capacitive beam phase probe is designed. The pre-amplifier for the phase probe is required to have more than three input ports, which is used to the signal from the phase probe, calibration signal, and termination to prevent the damage due to the high power from IH-DTL, respectively, and it has two output port for providing the phase signal to de-buncher in the MEBT line. It was fabricated by EMWISE in Korea [7].

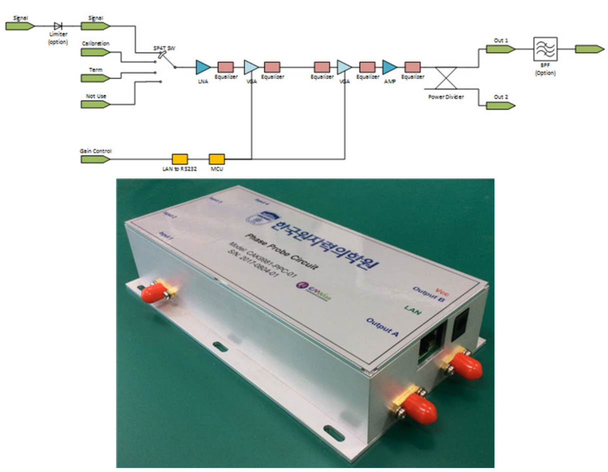

Figure 10: Schematic drawing and picture of pre-amplifier.

As shown in Fig. 10, the amplifier has 4-port RF relay switch, low-noise amplifier (LNA), two variable gain amplifier (VGA), and power divider. The total gain is to be 60 dB with 20 dB step. The gain level and the switch for the selection of input port was controlled via the Ethernet connection. The noise figure of the circuit is 3.69 dB for 500 MHz and 3.93 for 1 GHz. In order to measure the longitudinal distribution of the beam, the wide-bandwidth, 0.2 ~ 2.0 GHz, is required. Then the gain curve as a function of the frequency with 0, 20, 40 , and 60 dB gain is measured. As shown in Fig. 11, the gain flatness in the range of 0.2 GHz to 1.6 GHz is ± 2 dB.

MEASUREMENTS WITH PROTON BEAM

The time-of-flight(TOF) experiment with the proton beam from the MC-50 cyclotron in KIRAMS is performed to confirm the performance of the phase probe. The extraction energy, average beam current, and RF frequency of MC-50 cyclotron are 30 MeV, 1 uA, and 20.28 MHz, respectively. Then the relative velocity of the beam, $\beta = v/c$, is 0.247. Two phase probes are installed at the extraction

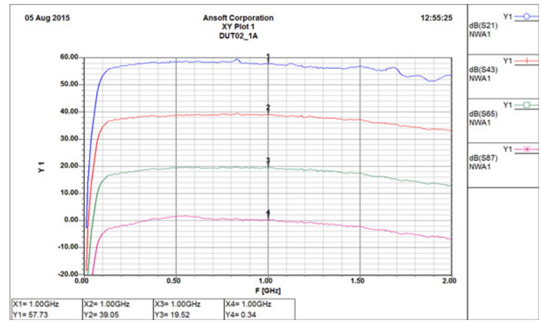

Figure 11: Gain curve as a function of frequency with 0, 20, 40, and 60 dB gain.

line without vacuum condition and the distance between two phase probes is 452 mm. The experimental set-up is shown in Fig. 12.

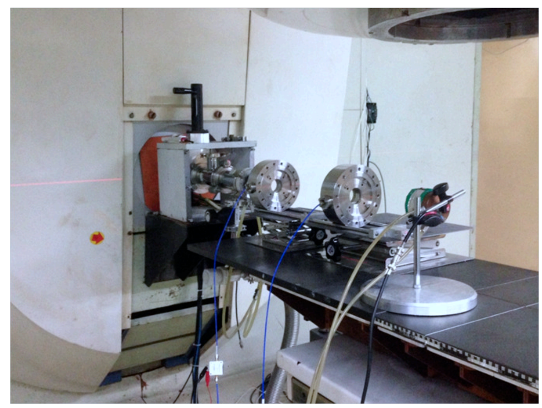

Figure 12: Experimental set-up for TOF measurement with proton beam at KIRAMS.

The signal is amplified by the pre-amplifier with 16.8 dB gain and the bandwidth of 0.1 ~ 1000 MHz and the data acquisition is done by the 2.5GS/s sampling speed digital oscilloscope, DPO4054B. The measurement result is shown in Fig. 13.

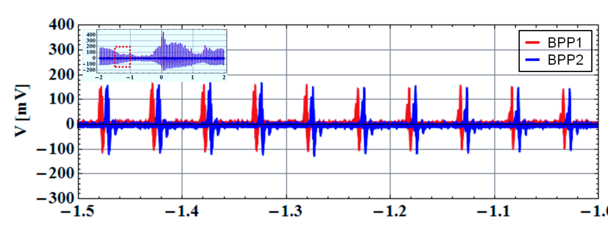

Figure 13: Measured signals from two phase probes.

From the measurement result, the repetition rate of the each signal, T_0, is calculated to confirm the RF frequency,f_{RF}, of the cyclotron because the repetition rate of the beam is well matched to the RF frequency, $f_{RF} = 1/T_0$. The measurement result of the repetition rate of the pulse is shown in Fig. 14.

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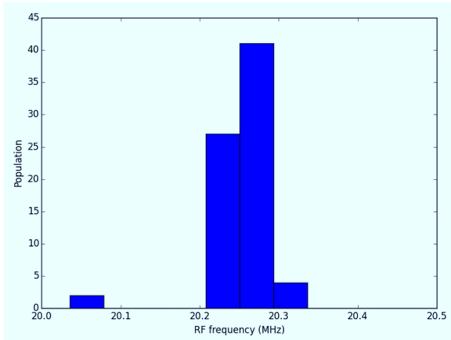

Figure 14: Histogram of the repetition rate of the pulse from the phase probe.

As shown in Fig. 14, the reciprocal of the repetition rate of the pulse, $1/T_0$, is well correspond to the RF frequency, f_{RF}, of the cavity in the cyclotron. The kinetic energy of the beam is defined by measuring the time difference between the zero-crossing points of the signal from each phase probe. The result is shown in Fig. 15.

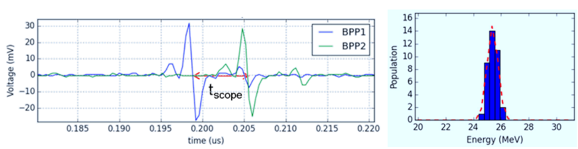

Figure 15: Result of kinetic energy measurement by TOF experiement.

The measured energy is 25.38 ± 0.39 MeV. It is smaller than the extraction energy due to the energy loss in the aluminum window and air.

CONCLUSION

The electromagnetic and mechanical design of the capacitive beam phase probe is performed to achieve the high phase precision, 1° at 200 MHz for identifying the status of the stripping foil and measuring the kinetic energy and the longitudinal distribution of the beam from the IH-DTL in KHIMA project. The time response and expected signal strength of the phase probe is also estimate to determine the proper gain and bandwidth of the pre-amplifier. The pre-amplifier was fabricated and the noise figure, gain flatness, and gain step is measured. The performance of the phase probe is confirmed by measuring the signal response on the wire test bench and TOF experiment with the proton beam.

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