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Technical notes

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 Radio Frequency Quadrupole (RFQ) accelerator and IH-DTL linac. It is also used for measuring a kinetic energy of ion beam by time-of-flight (TOF) method using two phase probes. The capacitive beam phase probe has been developed. The electromagnetic design of the high precision phase probe was performed to satisfy the phase resolution of 1° (@200 MHz). It was confirmed by the test result using a wire test bench. The measured phase accuracy of the fabricated phase probe is 1.19 ps. The pre-amplifier electronics with the 0.125 ~ 1.61 GHz broad-band was designed and fabricated for amplifying the signal strength. The results of RF frequency and beam energy measurement using a proton beam from the cyclotron in KIRAMS is presented.

1. 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 3.0–27.0 g/cm^2 [1]. The machine consists of an injector included two electron cyclotron resonance ion sources (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 in the LEBT line and it is transported to the entrance of RFQ accelerator through the LEBT line. The low energy beam, 8 keV/u, is accelerated up to 7 MeV/u by the RFQ and IH-DTL linacs. The $^{12}C^{4+}$ beam is fully stripped and $H_3{}^+$ beam is changed to proton beam by using a carbon foil with a thickness of 100 μg/cm^2 in the MEBT line of KHIMA. The stripped beam is injected to the synchrotron through the MEBT line. The $^{12}C^{6+}$ and proton beams are accelerated up to 430 MeV/u and 230 MeV, respectively. The accelerated ion beam is extracted by the slow extraction method using third-order resonance with the RF knock-out method [2]. A beam phase probe monitor is required in the MEBT line of the KHIMA for a precise RF phase and amplitude tuning of the RFQ and IH-DTL linacs to achieve the designed performance and high injection efficiency by adjusting longitudinal beam parameters such as a kinetic energy, energy spread and bunch length at the exit of the IH-DTL. It is also used to monitor the failure of the carbon foil by measuring the kinetic energy of ion beam by time-of-flight (TOF) method using two phase probes. The stripping foil is installed between two phase probes. The phase resolution of phase probe monitor should be smaller than 1° at 200 MHz for monitoring the status of the stripper foil because the energy loss due to the straggling effects in the stripper foil is about ~16 keV/u [3]. When the stripper foil is broken, the kinetic energy of the ion beam measured by TOF method using two phase probes is changed. The phase resolution of the phase probe monitor should to be 1° at 200 MHz to achieve the energy resolution of 10 keV/u (Fig. 1).

2. Capacitive phase probe monitor design

Since the beam current is low, ~0.1 mA for carbon beam and beam energy is 7 MeV/u at the MEBT line, the capacitive type phase probe monitor was chosen to get the longitudinal distribution without the signal distortion and to get the relatively strong signal. The ratio of signals strength between capacitive and inductive type monitor can be estimated dependent on the β value, $V_{cap}/V_{ind} \sim 0.133/\beta$ [4]. The capacitive pick-up was 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 [4]

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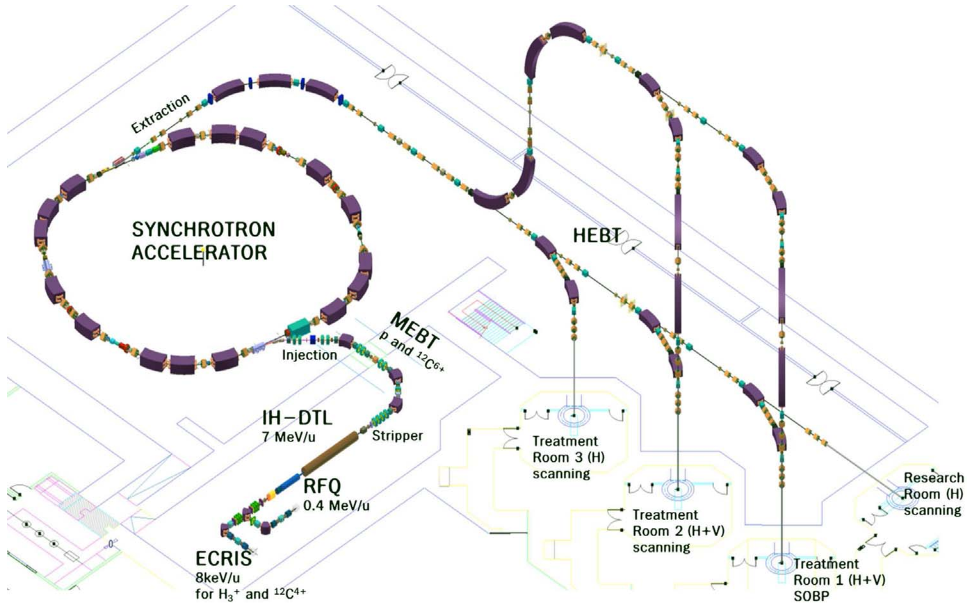

Fig. 1. Layout of KHIMA accelerator.

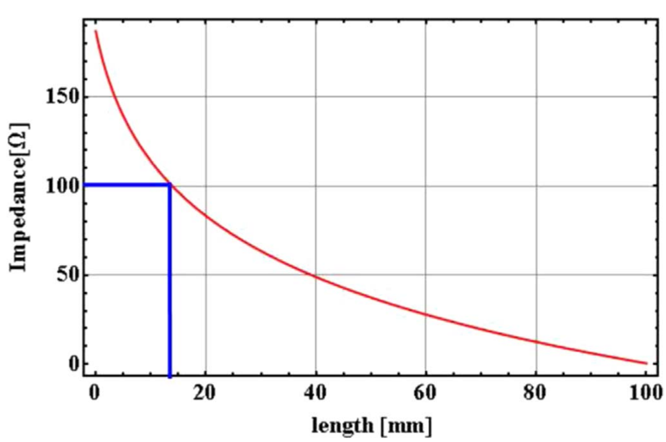

Fig. 2. Impedance as a function of length of pick-up ring. Length of the pick-up ring is decided to 14 mm for impedance matching.

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

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.

Based on the impedance calculation result, the length of the pick-up ring was determined to be 14 mm because the impedance of the pick-up ring with surroundings should be matched to be 100 Ω due to the two paths of the signal. The pick-up ring with the inner diameter of 40 mm and thickness of 3 mm was installed at the center of the double sided 6 in. CF flange and 1.5 mm thick metal plates were provided on each side to protect the noise signal by hitting the beam to the pick-up ring directly. The PEEK (Polyether ether ketone) was used as the insulator material between the pick-up ring and metal plates. The inner diameter of the pick-up ring was 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.

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, more than 40 mm, the outer conductor was applied to reduce the signal decay during the signal propagation along the long connector and to prevent the noise signal from surroundings [5]. The inner radius of the outer conductor was determined to match the impedance of 50 Ω according to 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. In our case, the outer radius of inner conductor and inner radius of outer conductor are 2 mm and 4.6 mm, respectively. The detail structure for the coaxial transmission line is shown in Fig. 4.

When the longitudinal distribution of the ion beam is measured by using phase probe, the time response of it is limited by the cut-off frequency due to the structural capacitance and resistance [6,7]. 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 distributed beam was calculated by using CST-PS [8].

As shown in Fig. 5, 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.

3. Measurements on wire test bench

The test of the phase probe was 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. 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, 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. 6.

A 1 GHz signal from an RF signal generator was excited on the wire and the induced signals at the phase probe with and without the outer conductor were measured and compared each other to confirm the effectiveness of the outer conductor.