RF Phase Studies of Internal and External Beams for JAERI AVF Cyclotron

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Abstract

Beam phases have been corrected by using a phase probe to accomplish isochronous conditions. Phase deviation has been reduced within ±5° after a few times iterative corrections. Phase history of the internal beam has been obtained from beam current distributions for different frequency shifts. Phase band width corresponds to around 57° RF for 10 MeV H^+ and 41° RF for 50 MeV $^4He^{2+}$. Time spectrum of the external beam pulses has been measured with a plastic scintillator. The pulse width for 10 MeV H^+ corresponds to 7.3° and 18° FWHM of RF phase with and without cuts made by the phase slits, respectively.

I. INTRODUCTION

The JAERI AVF cyclotron[1] is a variable-energy, multi-particle cyclotron designed to accelerate ions in a wide range of energy: 5 to 90 MeV for protons and 2.5×M to 110×Q^2/M MeV for heavy ions, where M is a mass number and Q a charge state. Harmonic numbers of 1, 2 and 3 are available for ions with mass to charge ratio up to 6.5. The extensive beam-development work is required for accelerating various kinds of ions in a wide energy range necessary for research[2] in materials science and biotechnology.

One of the important attributes of the internal beam is the RF phase of the beam in the acceleration process. The beam phase depends on the field deviation from isochronous conditions. The RF phase of the beam is quite sensitive to field perturbation because the turn number amounts to 550 for a harmonic number of 1, 265 for 2 and 210 for 3, which are determined by a constant orbit method. The RF phase acceptance is determined by two sets of phase defining slits installed in the central region[3]. Extraction efficiency can be improved by reduction in transmission of RF phase with internal cuts. The width of the external beam pulse depends on the phase width of the internal beam and energy spread. In this work the beam studies are focused on the beam phase behavior in the cyclotron.

II. CORRECTION OF BEAM PHASE

The phase probe consists of ten pairs of rectangular pickup electrodes placed in a radial direction. Each electrode with the gap of 30 mm is radially 58 mm long, and azimuthally 40 mm wide for the inner threes, 60 mm for the middle fours and 93 mm for the outer threes. The variation of the signal cable length is within 4 mm, so that the error of the phase measurement due to the variation is negligible. The pickup signal from the electrode detected by a digital storage oscilloscope is shown in Fig. 1. The signal contains RF noise with large amplitude. Relative beam phases are measured exactly by detecting the point where the signal wave intersects the noise wave.

Initial main coil and circular trim coil currents for generating the isochronous field are calculated by an optimization code based on measured field maps. After fine adjustment of the base field and the central bump field, phase deviations of the beam are converged within 30°. The measured beam phases are used for trim-coil-current correction, made by a least-square fitting program, to minimize the field deviation from the isochronous field. The phase deviation can be finally reduced within ±5° after a few times iterative corrections.

The isochronism of the internal beam is cross-checked by the phase drifts for positive and negative frequency shifts of $\Delta f/f=2.4\times10^{-4}$ equivalent to the same amount of a base field change ΔB/B. Phase drifts for 50 MeV $^4He^{2+}$ is shown in Fig. 2. The amount of the phase drifts for the positive frequency shift is the same as that for the negative one. The measured beam phases are consistent with the calculated ones. The field deviation from the isochronous condition is estimated to be within 1 gauss.

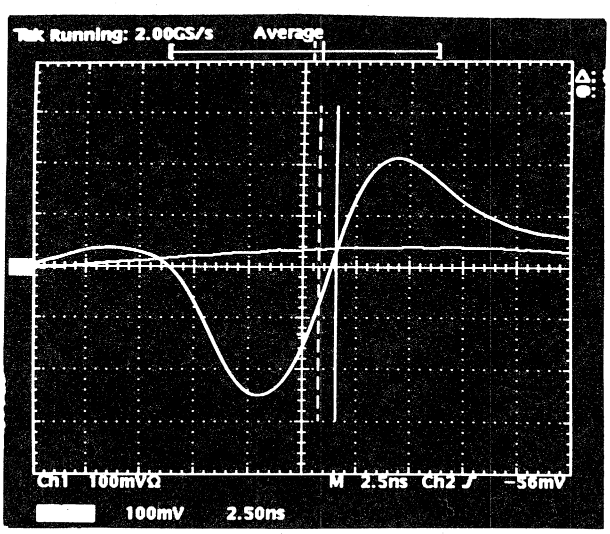

Fig. 1 Pickup signal from the phase probe electrode for 10 MeV H^+ beam.

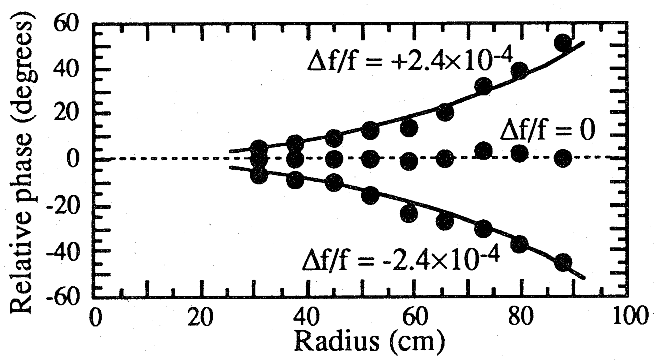

Fig. 2 Phase drifts for 50 MeV $^4He^{2+}$ due to the positive and negative frequency changes of $\Delta f/f=\pm2.4\times10^{-4}$. Measured and calculated phases are indicated by circles and solid lines, respectively.

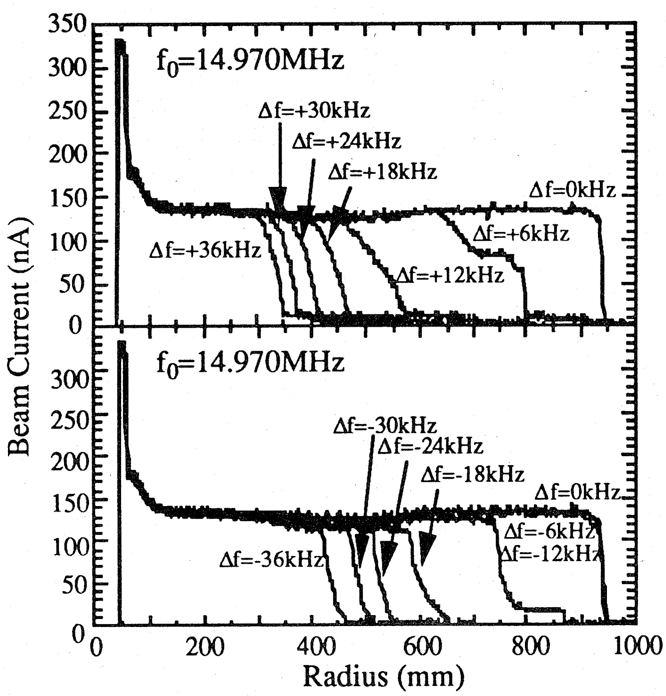

Fig. 3 Beam current versus radius for 10 MeV H^+ beam. The upper and lower distributions are obtained for the positive and negative frequency shifts at an interval of $\Delta f/f=4\times10^{-4}$.

III. PHASE DISTRIBUTION OF INTERNAL BEAM

The phases measured with the phase probe correspond to radially averaged ones because the pickup signals are produced by the particles passing through the electrode covering the radial length of 58 mm. The phase behavior of the internal beam is deduced from records of beam current versus radius (I vs. R) at several radio frequencies above and below the optimum frequency by using the method described by Smith and Garren[4]. An additional amount in phase for the frequency shift Δf/f with non-relativistic approximation is given by

$$\Delta \sin\phi_{RF} = 2\pi\, h \frac{\Delta f_{RF}}{f_{RF}} \frac{r^2}{2} \frac{mc^2}{\Delta E} \left(\frac{2\pi f_{RF}}{hc}\right)^2 ,$$

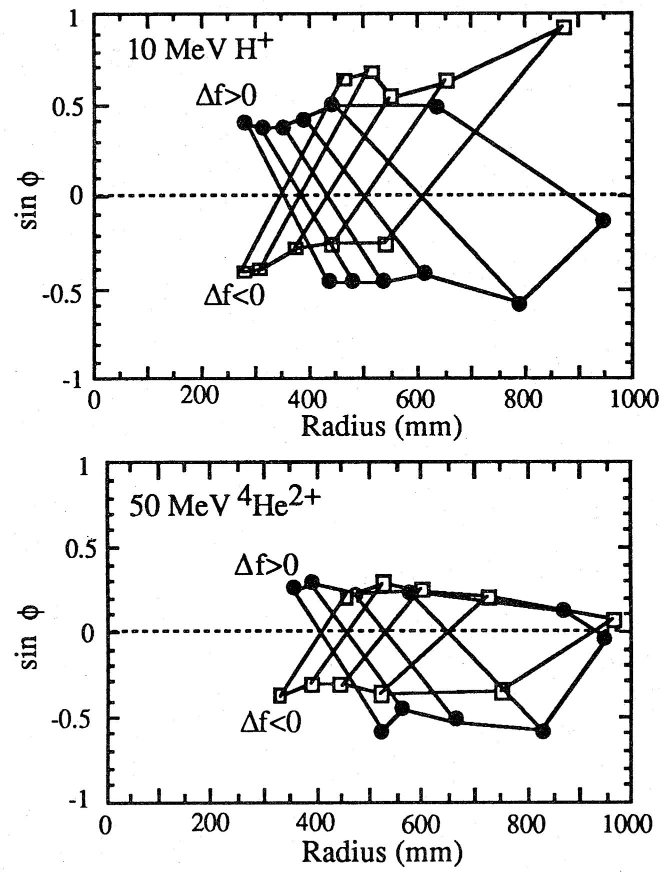

Fig. 4 Phases of the 10 MeV H^+ and 50 MeV $^4He^{2+}$ beams. The circles and squares indicate the phase bands deduced from the I vs. R curves for the positive and negative frequency shifts, respectively.

where h is the harmonic number, r the radius, mc^2 the mass and ΔE the peak energy gain per turn.

Beam current distributions of 10 MeV H^+ for different frequency shifts measured with a radial main probe are shown in Fig. 3. The frequency is shifted at an interval of $\Delta f/f = 4\times10^{-4}$. The phase plots for 10 MeV H^+ and 50 MeV $^4He^{2+}$ beams are shown in Fig. 4. The phase slits are inserted into the beam of the first turn to cut the beam phase. The cut for the 10 MeV H^+ beam is different from that for the 50 MeV $^4He^{2+}$ beam. In case of 10 MeV H^+ the phase band for a series of negative frequency changes is shifted by $\sin\phi=0.2$ from that for a series of positive ones. The cause of the difference is under investigation. The internal phase width corresponds to around 57° for 10 MeV H^+ and 41° for 50 MeV $^4He^{2+}$. The deduced phase widths are wide in spite of the phase cuts. The defining effect of the phase slits appears to be incomplete. Figure 3 shows that the I vs. R curves for the positive frequency shifts have a long tail just before vanishing. A small amount of beam still remains in the lead phase region. The phase history of the 50 MeV $^4He^{2+}$ beam is shown in Fig. 5. The change of phases obtained from the I vs. R curve is consistent with that of the measured ones with the phase probe.

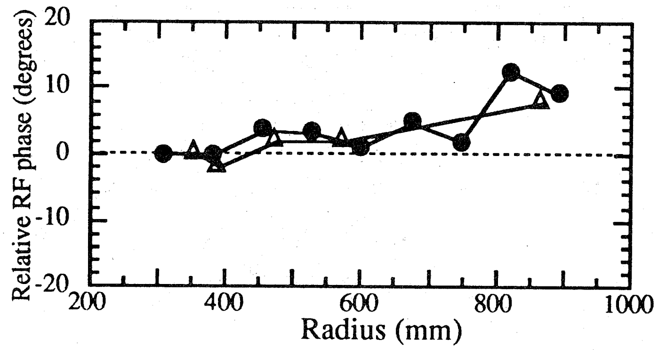

Fig. 5 Phase histories of the 50 MeV $^4He^{2+}$ beam. Phases measured with the phase probe are indicated by circles. The lag boundary of the phase band deduced from the I vs. R curves are indicated by triangles.

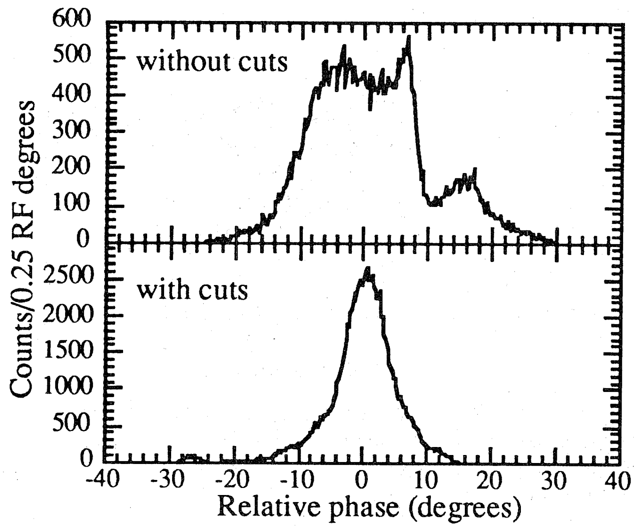

Fig. 6 Time structure of the external 10 MeV H^+ beam pulse. The upper and lower spectrum show the time structure without and with cuts made by the phase slits, respectively. Phases are relative, and the zeros are not absolute.

IV. Time Structure of External Beam

The time structure of the external beam pulse has been measured with a plastic scintillator at the end of the beam line. The plastic scintillator with a diameter of 5 cm is 10 cm long, and around 41 m distant from the deflector. The beam particles passing through a vacuum partition foil of 50 μm thick titanium are detected directly by the plastic scintillator in the air. The beam intensities can be reduced down to a factor of at least 10^{-10} with three sets of beam attenuators[5] installed in the injection line. The incidence time of the beam particles relative to a stop signal generated by the RF pickup has been measured with a good resolution below 0.5 ns FWHM. The time spectrum has been obtained for the events selected by a gate on pulse height.

The time structure of an extracted 10 MeV H^+ beam by preliminary analysis is shown in Fig. 6. Assuming that the time structure is independent on the reduction rate of the beam attenuator, and that accidental noise events are negligible compared with the incident ions, full widths of the time distribution with and without phase cuts are around 5.6 ns and 8.8 ns corresponding to 30° and 47° of RF phase, respectively. FWHM is 7.3° for the cut beam and 18° for the uncut beam. The measured width of the uncut beam is narrower than that of the internal beam with cuts obtained from the phase plots. Assuming that the uncut distribution consists of three components, time widths of the components are much narrower. The beam phase is assumed to be reduced by a certain amount in the extraction region of the cyclotron because the efficiency of extraction from the deflector to the first Faraday cup is around 60 %. The pulse width of the external beam depends upon the phase width of the internal beam, the spatial beam cut in the extraction region and the energy spread of the beam particles. Flight path length is around 41 m from the entrance of the deflector to the plastic scintillator. If the 10 MeV H^+ beam has an energy spread of $\Delta E/E=1\times10^{-3}$, the width of the time distribution additionally extends to 0.5 ns equivalent to a RF phase of 2.6°. The effect of the energy spread cannot be evaluated in the present spectrum because the energy resolution of the plastic scintillator is not good. Precise analysis for the time structure of the external beam pulses is required.

V. Conclusion

Isochronism of the internal beam has been checked by phase measurement with little variation of RF frequency. It is estimated that the isochronous field is generated within 1 gauss. The phase distribution of the internal beam has been investigated by analyzing the beam current versus radius measurement. The phase band width is around 57° RF for 10 MeV H^+ and 41° RF for 50 MeV $^4He^{2+}$. The time structure of the external beam pulses has been obtained by measuring beam particles with a plastic scintillator. The pulse width for 10 MeV H^+ corresponds to 7.3° and 18° FWHM of RF phase with and without cuts made by the phase slits, respectively.

VI. References

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