Cocktail Beam Acceleration Technique at JAERI AVF Cyclotron (I)

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Abstract

At the JAERI AVF cyclotron, an cocktail beam acceleration technique by means of changing RF frequency is used for ions with mass to charge ratios (M/Q) nearly equal to 4 and 5 in routine operation. The M/Q≅2 ions were successfully accelerated on trial recently. The M/Q resolution of the cyclotron was estimated experimentally and theoretically, and turned out to be insufficient to separate M/Q≅4 cocktail ions with small M/Q differences. In order to purify the cyclotron beam, methods of application of lower dee voltages, shift of frequency from the optimum values and injection of beams of a single ion species are examined. Radial spread of internal beam bunch caused by phase slip of particles with different M/Q value was observed using pulsed incident beams.

1 Introduction

Cocktail beam acceleration technique saves time to change ion species and energy for cyclotron beams. "Cocktail beam" is mixture of ion beams of plural species produced with an ECR ion source. Cocktail beams are injected into the cyclotron, accelerated simultaneously and extracted separately. Ion species are selected by slightly changing the RF frequency or the magnetic field. The RF frequency is changed at JAERI AVF cyclotron.

The principle and operational procedure of cocktail beam acceleration and insufficient separation of different ion species in M/Q≅4 ion acceleration were reported in detail at the last symposium in 1997 [1]. We made efforts in separating M/Q≅4 cocktail ion species and developing M/Q≅2 cocktail beam acceleration in following two years.

For the first step to separate M/Q≅4 cocktail ion species, we estimated the M/Q resolution of the cyclotron theoretically and experimentally. It turned out that the M/Q difference between M/Q≅4 ion species are comparable with or smaller than a value of separation limit defined by the M/Q resolution. In order to improve the M/Q resolution, we examined use of lower dee voltages and shift of the RF frequency from the optimum value. Another way to purify cyclotron beams is injection of beams consisting of a single ion species which are produced with an ECR ion source. Each method was effective but generally incomplete alone. By using more than one of those methods, purity of cyclotron beams significantly improved and a part of M/Q≅4 cocktail beams are supplied to research experiments.

The paper reports the estimation of the M/Q resolution, and the principle of methods to improve the M/Q resolution and the experimental results of the methods. Details of experimental data for M/Q≅2 and a modification of the ECR ion source for production of beams of a single ion species are described in a separate paper in this proceedings [2].

2 Estimation of M/Q Resolution

In order to assess the capability in separating different cocktail ions, the M/Q resolution of the cyclotron was estimated experimentally as follows. The isochronous condition for acceleration is expressed as

$$2\pi\frac{f_{RF}}{h} = \frac{eQ}{uM}B, \qquad (1)$$

where f_{RF} is the RF frequency, h the acceleration harmonics number, u the atomic unit mass and B a magnetic field of the cyclotron. If B is constant, we get the M/Q resolution R defined as

$$R \equiv \left|\frac{M/Q}{\Delta(M/Q)}\right| = \left|\frac{f_{RF}}{\Delta f_{RF}}\right| \qquad (2)$$

by differentiating Eq. (1). Thus the spread of M/Q values with which ions can be fully accelerated is evaluated from the width of the RF frequency at which an ion can be extracted from the cyclotron. Variation of beam intensity depending on the frequency shifts is shown in Fig. 1. The width of the frequency shift for the internal beam just before extraction was 8.4×10^{-4} FWHM. In this measurement, two sets of phase defining slits were placed at positions mostly away from the beam. The phase width of the internal beam was larger than 20 degrees RF. The frequency range became a half at the exit of a deflector, and further decreased to 3.0×10^{-4}

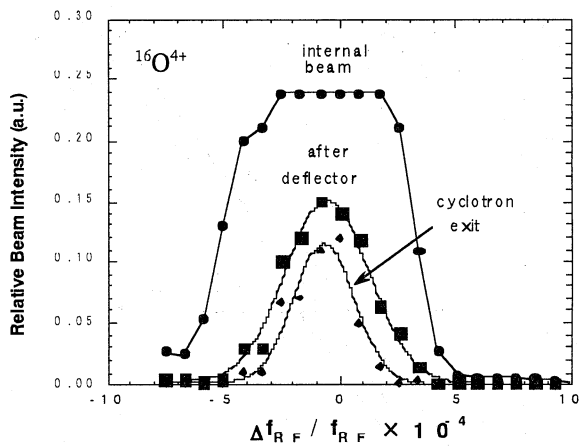

Fig. 1 Dependence of the beam intensity on the frequency shift. The frequency shift width is estimated at 8.4×10^{-4} FWHM at the entrance of the deflector, 4.2×10^{-4} FWHM at the exit of the deflector and 3.0×10^{-4} FWHM after the cyclotron exit.

FWHM after extracting from the cyclotron due to the acceptance of the extraction system. The resolution estimated from the frequency width is around 3300.

The resolution was also theoretically estimated from a frequency range in which particles can reach an extraction radius. Change in phase for the frequency shift $\Delta f_{RF}/f_{RF}$ with non-relativistic approximation is given by

$$\Delta \sin\phi = 2\pi h \frac{\Delta f_{RF}}{f_{RF}} \frac{r^2}{2} \frac{mc^2}{\Delta E} \left(\frac{2\pi f_{RF}}{hc}\right)^2, \quad (3)$$

where ϕ is a beam phase, r a radius, ΔE peak energy gain. Relation between the frequency shift and the change in phase at the extraction radius is shown in Fig. 2. The $\Delta\sin\phi$ is approximately proportional to the frequency change. The frequency range for the beam with an initial phase width of 20 degree RF is 6.8×10^{-4}. Assuming that a half width of the frequency gives FWHM, the M/Q resolution is estimated at R=2900. The resolution for the extracted beam will be higher than this, since a part of ions which reach the extraction radius do not fall in the acceptance of the extraction system [3].

The M/Q differences of $^{12}C^{3+}$ and $^{20}Ne^{5+}$ from $^{16}O^{4+}$ are 3.2×10^{-4} and 0.6×10^{-4}, respectively. They are comparable or less than 1/R of 3.0×10^{-4} (experiment) and 3.4×10^{-4} (theory). These results explain the insufficient separation of M/Q≅4 cocktail ion.

3 Improvement of M/Q Resolution

Separation of ion species in the process of the cyclotron utilizes phase-out of ions with M/Q values which do not satisfy the isochronous condition. The principle of improvement of the M/Q resolution is to amplify the small difference in isochronism by means of the large turn number. A phase slip of an ion with an M/Q difference Δ(M/Q) is given by

$$\Delta \sin\phi = 2\pi h N \frac{\Delta(M/Q)}{(M/Q)}, \quad (4)$$

where N is a number of turns, M/Q is assumed to satisfy the isochronous condition Eq. (1).

3.1 Application of Low Dee Voltages

A simple way to increase turn number is use of lower energy gain per turn or lower dee voltages. The amount of the change in phase is inversely proportional to the energy gain as explicitly given in Eq. (3).

An experiment to examine lower dee voltages was carried out using $^{12}C^{3+}$ and $^{16}O^{4+}$ cocktail beams. Pulse heights of those ions were observed with a plastic scintillator. A spectrum at dee voltages of 22.67 kV and 18.00 kV are shown in Fig. 3. The yield ratio of $^{12}C^{3+}$ to $^{16}O^{4+}$ went down to one fifth by simply changing the dee voltage. The change of the acceleration voltage was, however, not easy because optimization of several parameters was necessary to remove the different cocktail ions satisfactorily and to keep beam intensity.

3.2 RF Frequency Shift

Another way to increase the turn number is to shift the RF frequency. The calculated turn numbers of the particles reaching the extraction radius are shown in Fig. 4 as a function of the frequency. The minimum turn number is obtained at the optimum frequency for each ion species. An increment in turn number for the frequency shift of 2.5×10^{-4} (Δf_{RF} =3 kHz) is around 60.

The energy gain of particles is gradually decreasing due to drift of the beam phase caused by the frequency shift and the decreasing rate is strongly dependent on M/Q value, which causes further phase spread of a beam bunch. In addition, the energy gain of ions spreads due to the phase

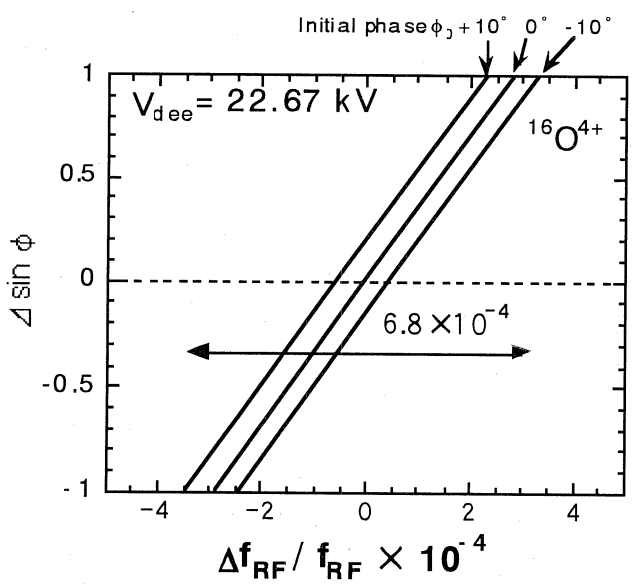

Fig. 2 Dependence of the change in phase at the extraction radius on the RF frequency shift.

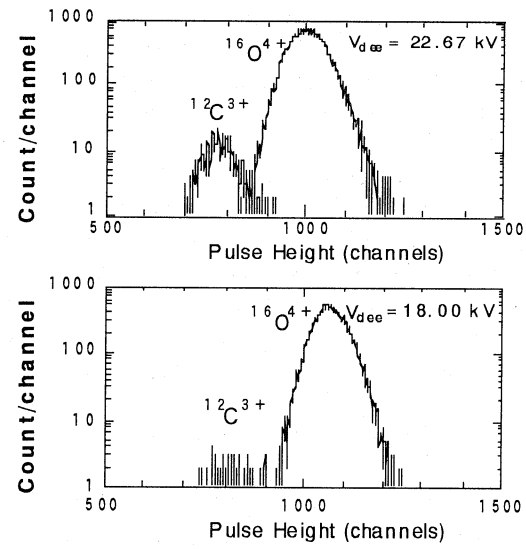

Fig. 3 Pulse height spectra of $^{12}C^{3+}$ and $^{16}O^{4+}$ cocktail beams obtained at a dee voltage of 22.67 (upper) and 18.00 kV (lower). The yield ratio of $^{12}C^{3+}$ to $^{16}O^{4+}$ is 1.6×10^{-2} at 22.67 kV and 2.9×10^{-3} at 18.00 kV.

acceptance of the cyclotron. Smaller energy gain gives slower increase of radius of ion orbit, which causes radial spread of beam bunch of cocktail beams.

The radial spread at the entrance of the deflector is larger than the aperture of the deflector. Thus the beam bunch is chopped by the deflector through a number of turns and extracted with multiple turns. Time spectra of the extracted beam at the optimum frequency for $^{12}C^{3+}$ are shown in Fig. 5. Beam was pulsed before injection using a trapezoidal voltage chopper [4] so that the multiple turns could be observed. The $^{12}C^{3+}$ ions were extracted first, and a pulse train of the $^{16}O^{4+}$ ions appeared 41 turn later. The delay of the beam pulse was consistent with the calculation result shown in Fig. 4. One can see in Fig. 5 a difference in radial beam spread between $^{12}C^{3+}$ and $^{16}O^{4+}$ caused by differences of the frequency from the optimum one for each ion. The results of this experiment clearly show beam bunch evolution both in time and radial space.

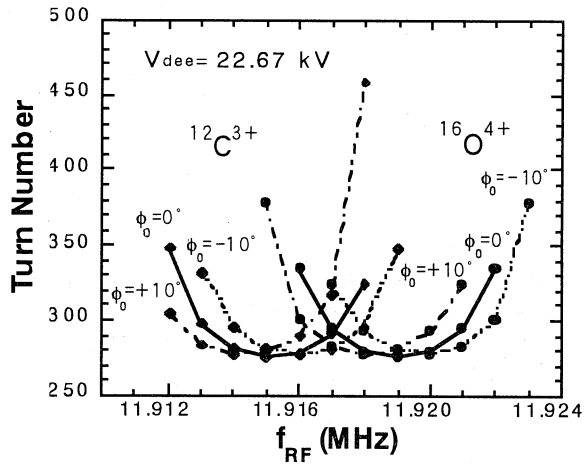

Fig. 4 Increase in turn number for the $^{12}C^{3+}$ and $^{16}O^{4+}$ cocktail beam with an initial phase width of 20 degrees caused by the frequency shift.

4 Development of M/Q≅2 Cocktail Beams

We developed cocktails of fully stripped ions of $^{4}He^{2+}$, $^{12}C^{6+}$, $^{14}N^{7+}$, $^{16}O^{8+}$, $^{20}Ne^{10+}$ and $^{36}Ar^{18+}$. There is the same difficulty in separating C and Ne from O ions as in case of M/Q≅4. The details of the experimental results are shown in Ref. 2. Energy spectra were acquired with a plastic scintillator at various RF frequencies changed step by step. When optimum dee voltages and cocktail beam injection were used, two or three species were observed at the all frequencies except for the lowest (Fig. 2 in Ref. 2). On the other hand, when lower dee voltages and injection of a single ion species were used, one peak appeared in each spectrum. Ion beam current of $^{36}Ar^{18+}$ was too low to be measured with a Faraday cup, and was estimated of the order of 0.1 epA from the count rate and the beam attenuation rate.

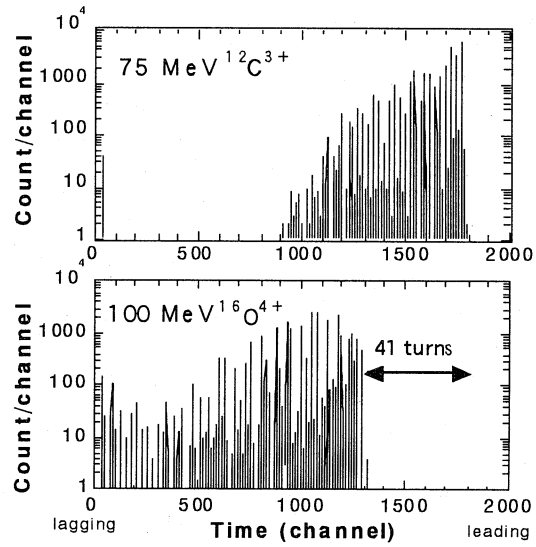

Fig. 5 Beam pulses of the $^{12}C^{3+}$ (upper) and $^{16}O^{4+}$ (lower) at the optimum frequency of 19.916 MHz measured with a plastic scintillator.

References

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