IMPROVEMENT OF MASS-TO-CHARGE RATIO RESOLUTION OF THE JAEA AVF CYCLOTRON USING A BEAM CHOPPING SYSTEM

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Abstract

A mass-to-charge ratio (M/Q) resolution of the JAEA cyclotron is about 3,300 and this high-resolution enables us to quickly change the ion species by a cocktail beam acceleration technique. To further improve the M/Q resolution, a new technique is being developed by combining the cocktail beam acceleration and beam chopping techniques. The beam chopping system consists of a pre-beam kicker installed in the beam injection line and a post-beam kicker downstream of the cyclotron. This new technique is able to separate beam bunches from a pulse train of the ion beam including impurity ion species. As a result, we succeeded to completely separate the 125 MeV $^{20}Ne^{5+}$ and the 100 MeV $^{16}O^{4+}$ beams, that was quite difficult using previous techniques. The M/Q resolution of the cyclotron has been significantly improved to 25,000 at present.

INTRODUCTION

An AVF cyclotron with a K-value of 110 MeV was constructed at TIARA (Takasaki Ion accelerators for Advanced Radiation Application) facility of the Japan Atomic Energy Agency (JAEA) to provide high-energy ion beams mainly for research in biotechnology and materials science [1]. Various kinds of beam irradiation techniques such as a heavy-ion microbeam formation and a large-area uniform irradiation were developed for beam users.

A cocktail beam acceleration technique [2,3] was also developed for quick change of the ion species extracted from the cyclotron. In this technique, a cocktail of ions having almost identical mass-to-charge ratio (M/Q), produced in an ion source, is injected into the cyclotron. The cyclotron can separate an ion species from others since the cyclotron has another aspect as a high-performance mass spectrometer. Change of the ion species completes within about ten minutes by adjusting an acceleration frequency and changing a feeding gas of the ion source if necessary. However, the cocktail of ions such as $^{16}O^{4+}$ and $^{20}Ne^{5+}$ was not available since the M/Q resolution of the cyclotron was inadequate to separate them. To improve the M/Q resolution, a new technique has been developed by combining the cocktail beam acceleration and a beam chopping techniques.

In this paper, we briefly describe theories of the cocktail beam acceleration and the unique method to improve the M/Q resolution, and show some experimental results.

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COCKTAIL BEAM ACCELERATION

A radio frequency f_{RF} of an acceleration voltage generated on a pair of dee electrode is expressed as

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

where h is an acceleration harmonics defined by the ratio of f_{RF} to the orbital frequency of the ion f_{ion}, e elementary electric charge, Q charge state of the ion, u atomic mass unit, M mass of the ion in u, B magnetic field for isochronism. A beam bunch of the ion is repeatedly accelerated at a fixed phase of the rf voltage under good isochronous field, and is extracted from the cyclotron through an electrostatic deflector and a magnetic channel. When other ion species with a slight difference of the mass-to-charge ratio $\Delta(M/Q)$ is injected into the cyclotron, shift of the acceleration phase $\Delta\phi$ after N revolutions is given by

$$\Delta\phi = 2\pi hN\frac{\Delta(M/Q)}{(M/Q)}\,. \qquad (2)$$

Table 1 shows a list of ion species with the $M/Q \approx 4$, and here, we assume that $^{12}C^{3+}$, $^{16}O^{4+}$ and $^{20}Ne^{5+}$ beams are simultaneously injected into the cyclotron tuned to accelerate them up to 6.25 MeV/u. When the acceleration frequency f_{RF} is adjusted for $^{16}O^{4+}$ beam the acceleration phase of $^{20}Ne^{5+}$ advances and that of $^{12}C^{3+}$ lags gradually. The $\Delta\phi$ of $^{12}C^{3+}$ is much larger since the M/Q difference from $^{16}O^{4+}$ is about 5 times as large as that of $^{20}Ne^{5+}$, as shown in Fig. 1. The design values of the total number of revolutions are 550, 265 and 210 for the acceleration harmonics h = 1, 2 and 3, respectively. The impurity ion species cannot be extracted from the cyclotron when the energy gain of the beam bunch reaches deceleration region or decreases considerably after hundreds of revolutions. As a result, only one ion species is extracted. The ion species can be changed quickly by adjusting f_{RF} corresponding to the M/Q difference. This is the principle

Table 1: List of ion species with the $M/Q \approx 4$. Beam energy is 6.25 MeV/u for all ion species (h = 2).

Ion	M/Q	$\Delta(M/Q)/(M/Q)$	f_{RF} (MHz)
$^{4}He^{1+}$	4.00205		11.9079
		6.501×10^{-4}	
$^{12}C^{3+}$	3.99945		11.9156
		3.176×10^{-4}	
$^{16}O^{4+}$	3.99818		11.9194
		6.003×10^{-5}	
$^{20}Ne^{5+}$	3.99794		11.9201
		5.230×10^{-4}	
$^{36}Ar^{9+}$	3.99585		11.9264
		4.004×10^{-5}	
$^{40}Ar^{10+}$	3.99569		11.9268

ISBN 978-3-95450-131-1

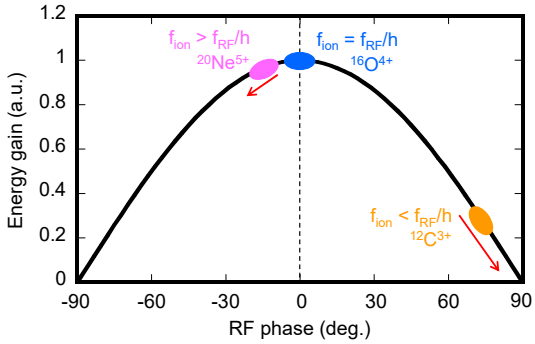

Figure 1: Correlation of the rf phase and the beam bunch for the ion species with the M/Q ≈ 4. The acceleration frequency f_{RF} is optimized for $^{16}O^{4+}$.

of the cocktail beam acceleration.

The M/Q resolution R is defined by

$$R = \left| \frac{(M/Q)}{\Delta(M/Q)} \right|, \qquad (3)$$

and the value of the cyclotron is about 3,300 [3]. Although cocktail beams such as the $M/Q \approx 2$ (26.7 MeV/u) and 5 (3.75 MeV/u) are available, the M/Q resolution is inadequate to separate the cocktail of ions such as $^{16}O^{4+}$ and $^{20}Ne^{5+}$, or $^{36}Ar^{9+}$ and $^{40}Ar^{10+}$, shown in Table 1. To separate them completely, a unique technique described in next section is being studied.

IMPROVEMENT OF M/Q RESOLUTION USING A CHOPPING SYSTEM

A beam chopping system, consisting of two types of high voltage kickers, is used to drastically increase the interval between beam pulses [4]. The first kicker (chopper 1) is installed in the beam injection line and injects a short beam pulse with repetition periods greater than 4.2 μs. The other kicker (chopper 2) downstream of the cyclotron thins out unwanted beam pulses caused by multi-turn extraction. As a result, a single-pulse of the ion beam with a repetition period over micro seconds is formed [5]. A variety of single-pulse beams are used for experiments such as pulse radiolysis and time-of-flight measurement of secondary particles.

A kicker voltage of the chopper 2 is originally sinusoidal waveform ranging from 1 to 3 MHz, and 40 kV at a maximum. The chopper 2 was temporarily modified to a pulse voltage beam kicker as shown in Fig. 2 for this study. The modified chopper 2 using a fast pulse generator (PVX-4110, Directed Energy Incorporated) is able to cut the beam bunches over a long duration compared to the original sinusoidal waveform one.

In the case of cocktail beam acceleration, as shown in Fig. 1, the energy gain of the impurity ion species gradually decreases every revolution, while the beam bunch of $^{16}O^{4+}$ whose f_{ion} equals f_{RF}/h is accelerated at a fixed rf phase. This means that more number of revolutions compared to the $^{16}O^{4+}$ is needed to reach the extraction radius for the impurity ion species. In other

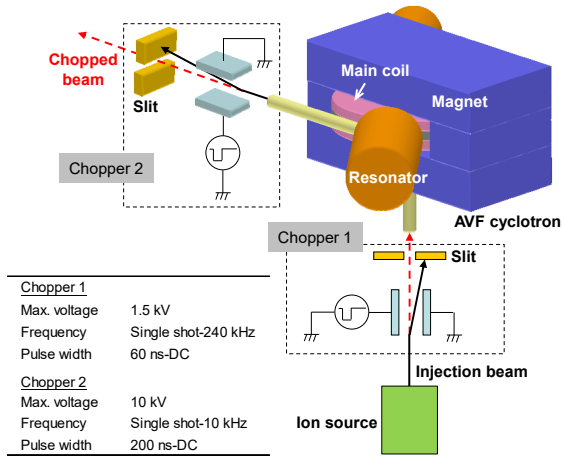

Figure 2: Layout of the cyclotron and the beam chopping system consisting of two beam kickers, installed in the beam injection line and downstream of the cyclotron, respectively.

words, the impurity ion species are extracted with delay if the cyclotron cannot remove them completely. When the chopper 1 injects a short beam pulse with about 1 cycle length (= $1/f_{RF}$), the beam pulses appear out of the cyclotron in the order of $^{16}O^{4+}$ and $^{20}Ne^{5+}$. A tiny amount of the $^{12}C^{3+}$ beam might be observed at last since the M/Q resolution of the cyclotron is close to the M/Q difference between $^{16}O^{4+}$ and $^{12}C^{3+}$. If the chopper 2 can remove the impurity ion beams by kicking them out fast, only the $^{16}O^{4+}$ beam is separated and transported to a user's target. This is the principle for improving the M/Q resolution by combining the cocktail beam acceleration and the beam chopping techniques. To realise this technique, it is indispensable to accelerate the objective ion species on the top of cosine wave where the energy gain is maximum; a method to measure and control the acceleration phase of the beam bunch is described in Ref. 6, in detail [6].

EXPERIMENTAL RESULTS

Cocktail ions listed in Table 1, excluding $^{4}He^{1+}$, were used for the experiment. The 100 MeV $^{16}O^{4+}$ (6.25 MeV/u, $h = 2$) was selected as a standard beam, and the magnetic field for isochronism and the acceleration phase were optimized using the beam. The number of revolutions was increased from the design value of 265 to about 290 by reducing the dee voltage to enlarge the phase shift $\Delta\phi$ of the impurity ion species. Only oxygen gas was fed into an electron cyclotron resonance (ECR) ion source, first.

Figure 3 shows an energy spectrum of the 100 MeV $^{16}O^{4+}$ beam measured by a solid-state detector (SSD) and a multi-channel analyser (MCA). Peaks of the 75 MeV $^{12}C^{3+}$ and the 125 MeV $^{20}Ne^{5+}$ were observed other than the main peak of 100 MeV $^{16}O^{4+}$. The amounts of contamination were estimated to be 0.06% for $^{12}C^{3+}$ and 0.2% for $^{20}Ne^{5+}$, respectively. The tiny amount of contamination was caused by residual gases in the ECR

ISBN 978-3-95450-131-1

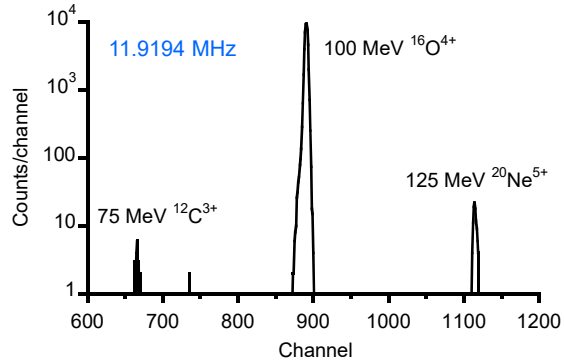

Figure 3: Energy spectrum of the 100 MeV $^{16}O^{4+}$ beam measured by using the SSD and MCA. Only oxygen gas was fed to the ECR ion source.

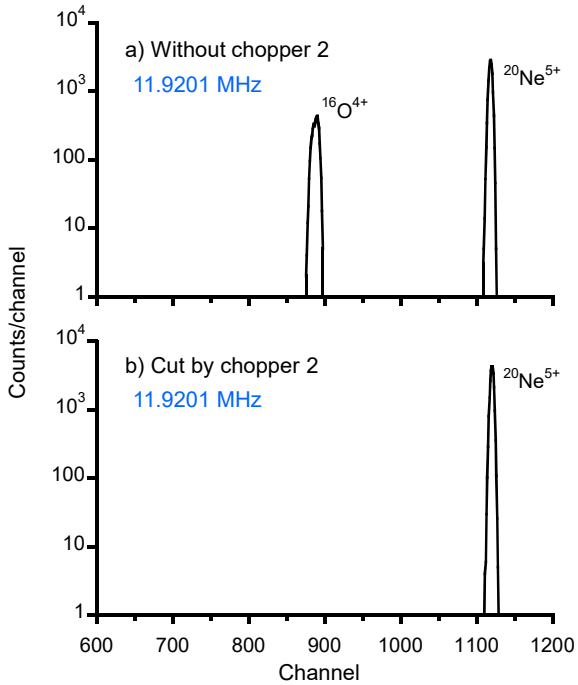

Figure 4: Energy spectra of the 125 MeV $^{20}Ne^{5+}$ beam. Only Ne gas was fed to the ion source just after generation of the $^{16}O^{4+}$ beam. a) The chopper 1 was used alone, and b) both the choppers were used to remove the 100 MeV $^{16}O^{4+}$.

ion source. Next, the feeding gas of the ion source was changed to neon. The acceleration frequency was also changed from 11.9194 to 11.9201 MHz, and the energy spectrum was immediately measured by the SSD using the chopper 1 alone for short pulse injection, as shown in Fig. 4 a). The amount of contamination by the $^{16}O^{4+}$ was estimated to be about 20%. Figure 5 shows a pulse train of the 125 MeV $^{20}Ne^{5+}$ beam, contaminated by the 100 MeV $^{16}O^{4+}$, measured by a plastic scintillator and a picosecond time analyser (9308, Ortec). The pulse train consists of the first main pulse and the other small sub-pulses. The beam bunches after the second pulse were cut

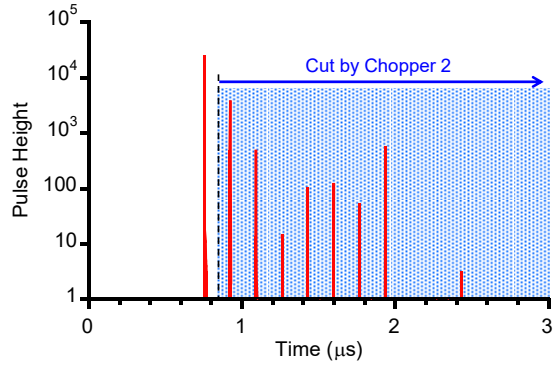

Figure 5: Pulse train of the 125 MeV $^{20}Ne^{5+}$ beam measured by a plastic scintillator. Condition of the beam tuning corresponds with that of Fig. 4 (a). The beam bunches covered by blue box were removed by the chopper 2 later, as described in the text.

by carefully adjusting the chopper 2, and the energy spectrum was measured again. The 125 MeV $^{20}Ne^{5+}$ and the 100 MeV $^{16}O^{4+}$ were completely separated as shown in Fig. 4 b). On the other hand, the $^{16}O^{4+}$ beam could not be removed for the case of bam cutting after the third pulse shown in Fig. 5. After that, the ion beam was changed to $^{16}O^{4+}$ again, and the $^{20}Ne^{5+}$ and $^{12}C^{3+}$ beams were successfully removed by the chopping system.

Finally, we tried to separate a 250 MeV $^{40}Ar^{10+}$ and a 225 MeV $^{36}Ar^{9+}$ beams. The M/Q difference of them is the smallest among the ion species shown in Table 1. The impurity $^{36}Ar^{9+}$ beam, however, could not be removed even when sub-pulses other than a first main pulse were cut by the chopper 2. In order to adequately enlarge the energy gain difference between the $^{40}Ar^{10+}$ and $^{36}Ar^{9+}$, the acceleration phase was lagged by about 25 degrees from the top of cosine wave. As a result, only the 250 MeV $^{40}Ar^{10+}$ beam was extracted by using the chopping system. The M/Q resolution of the cyclotron has been significantly improved, and is estimated to be about 25,000. The resolution will be further improved by precise control of the acceleration phase and restriction of the beam phase width.

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ISBN 978-3-95450-131-1