

## Development of Cocktail Beam Acceleration Technique for the JAERI AVF Cyclotron

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### Abstract

Combined with an ECR ion source, the JAERI AVF cyclotron can accelerate ion "cocktails"—mixtures of ions with nearly identical mass-to-charge ratios. In a cocktail beam acceleration procedure operators can switch from one ion to another simply by adjusting one or two parameters only. Change in ion species and/or energy is made in a matter of a few minutes, which enables users to utilize multiple ion beams of different ion species and/or energies in a single beam-time period.

### 1 Introduction

The JAERI AVF cyclotron[1] can produce various ion species in a wide range of energies. For efficient use of accelerator time, changes in ion species and/or energy should be made quickly. The time required for these changes is determined by several factors. A cyclotron magnet needs to be re-excited by a cycling excitation method to keep accurate reproduction of an isochronous field. The cycling excitation process lasts about half an hour and at least another an hour is required to obtain a stable magnetic field. In addition, at the JAERI AVF cyclotron there are about 40 parameters to be set for the ECR ion source and injection line, 70 to be set for the cyclotron and another 40 for the external beam transport. Some of these have adequate preset values but most have to be optimized for best transmission. Therefore, the tune up time from ion source to a target for a new beam is about 1 to 2 hours.

In the cocktail beam acceleration technique[2], a series of ions with almost identical mass to charge ratio ( $M/Q$ ) are injected into the cyclotron simultaneously, and each individual ion species is fully accelerated by varying an RF frequency slightly in a short period. The time-consuming magnet re-excitation process can be eliminated by the cocktail beam acceleration method.

For research in materials science and biotechnology, linear energy transfer (LET) is one of essential parameters that determines radiation effects in a material. Different LET can be brought about in a target material by changing ion species and/or energy of an incident particle. In order to meet a request of users to use different ion beams in the same beam time, cocktail beams of  $M/Q \approx 4$  and 5 have been developed.

### 2 Principle of the Cocktail Beam Acceleration

The cocktail beam acceleration is based on the principle that the ions with the same  $M/Q$  ratio can be accelerated using the same isochronous field and RF frequency. An isochronous condition of the cyclotron ac-

celeration is expressed as

$$2\pi \frac{f_{RF}}{h} = \left( \frac{Q}{M} \right) B, \quad (1)$$

where  $f_{RF}$  is the RF frequency,  $h$  the acceleration harmonics number,  $Q$  a charge of an ion,  $M$  an ion mass and  $B$  a magnetic field. "Analog beams" with essentially the same  $M/Q$  ratio are accelerated under almost identical conditions, and can be selected by making a small change in the RF frequency and/or the magnetic field equivalent to small difference of the  $M/Q$  ratio. Since the cocktail ions are identical in the magnetic rigidity of the beam constant, all the beam transport magnets to the target can be left unchanged. All other parameters of the ion source, injection, cyclotron and external beam transport systems can remain the same. Thus the cocktail beam acceleration enables very fast changes in ion species.

### 3 Procedure of the Cocktail Beam Acceleration

The technique requires an accelerator which will accelerate all ions having the same  $M/Q$  ratio and an ion source capable of producing many different ion species with identical  $M/Q$  values. An ECR ion source can produce a large number of ion species with the same  $M/Q$  because it produces ion species with a variety of charge states. The same  $M/Q$  ions, cocktail ions, cannot be separated by an analyzing magnet in an injection system. Therefore the cocktail ions are injected into the cyclotron and accelerated simultaneously.

All the cyclotron parameters are optimized for one of the cocktail ions. A set of the parameters produces a standard condition for the cocktail beam acceleration. Small difference of the  $M/Q$  ratios from the standard ion gives rise to deviation from the isochronous condition. The deviation causes a drift of a beam phase which results in a gradual decrease in energy gains. If the ions lead or lag behind the standard ion by 90 degrees in an RF phase, these ions enter a deceleration phase region and will disappear somewhere in a center region. Only the standard ion is fully accelerated and extracted from the cyclotron. Other cocktail ions can be also fully accelerated by slightly changing the magnetic field and/or an RF frequency relative to the difference of the  $M/Q$  ratios. In case the beam phase of the ions doesn't reach the critical phase before extraction, diverse ion species are extracted from the cyclotron at the same time.

### 4 Cocktail Ions with $M/Q \approx 5$

The  $M/Q \approx 5$  cocktail beam has been developed

Table 1  
 Parameters of the  $M/Q \approx 5$  cocktail.

Ion	Mass Number M	Atomic Number Z	Charge State Q	M/Q	$\Delta(M/Q)/(M/Q)$	Energy (MeV)	RF Frequency (MHz)	Stopping Power in Silicon (MeV/(mg/cm <sup>2</sup> ))
N	15	7	3	4.9995	$+9.4 \times 10^{-4}$	56	13.867	3.3
Ne	20	10	4	4.9976	$+5.6 \times 10^{-4}$	75	13.873	6.1
Ar	40	18	8	4.9948	0	150	13.881	15
Kr	84	36	17	4.9354	$-118.9 \times 10^{-4}$	323	14.047	40

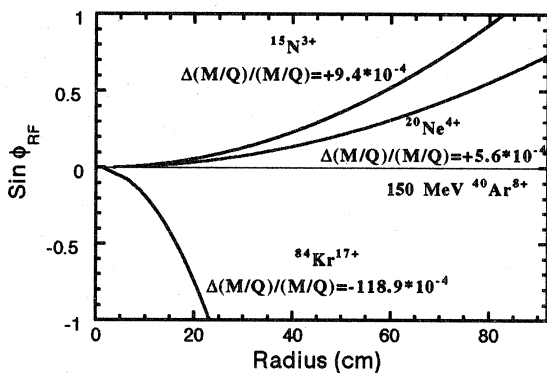


Fig. 1 Phase history of the  $M/Q \approx 5$  cocktail at the RF frequency of 13.881 MHz optimized for  $^{40}\text{Ar}^{8+}$ . Deviation of the beam phases from the isochronous condition is plotted by  $\sin \phi_{RF}$ . A lagging particle having a larger  $M/Q$  value than  $^{40}\text{Ar}^{8+}$  is drifting toward the positive direction.

using ions:  $^{15}\text{N}^{3+}$ ,  $^{20}\text{Ne}^{4+}$ ,  $^{40}\text{Ar}^{8+}$  and  $^{84}\text{Kr}^{17+}$ . Main parameters of the cocktail ions are listed in Table 1.

First an argon gas was fed to the ECR ion source together with an oxygen gas as support. Only the  $^{40}\text{Ar}^{8+}$  was injected into the cyclotron, and all the cyclotron parameters were optimized for the 150 MeV  $^{40}\text{Ar}^{8+}$  to produce a standard acceleration condition.

Next, the argon gas was replaced by a gas mixture of argon, neon and krypton to generate the  $M/Q \approx 5$  cocktail. An enriched nitrogen-15 gas was also fed to the ECR ion source by another gas supply pipeline. The cocktail of  $^{15}\text{N}^{3+}$ ,  $^{20}\text{Ne}^{4+}$ ,  $^{40}\text{Ar}^{8+}$  and  $^{84}\text{Kr}^{17+}$  were injected into the cyclotron simultaneously.

By changing the RF frequency to the optimum value for each ion species, one of the cocktail was fully accelerated and extracted from the cyclotron. The beam phases of the other ions gradually drift toward the deceleration phase region according to the difference of the  $M/Q$  values as shown in Fig. 1. Dependence of beam intensity on the RF frequency is shown in Fig. 2. The ion species were identified by a pulse height obtained with an SSD, where the energy of the cocktail ions is approximately proportional to a mass number. No intermixtures of dif-

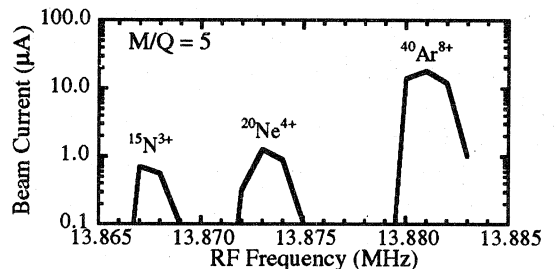


Fig. 2 Dependence of the beam intensity on the RF frequency for the  $M/Q \approx 5$  cocktail ions. The absolute values of the beam current depend on the tune of the ECR ion source.

ferent ion species were found in each independent pulse height spectrum.

Intensity of the cocktail beams depends mainly on charge state of the ions, a mixing ratio of the cocktail gas and the ECR parameters. Beam intensity of more than a hundred nA was obtained for 56 MeV  $^{15}\text{N}^{3+}$ , 75 MeV  $^{20}\text{Ne}^{4+}$  and 150 MeV  $^{40}\text{Ar}^{8+}$  beams as shown in Fig. 2. The 323 MeV  $^{84}\text{Kr}^{17+}$  beam, by contrast, had relatively low intensity of 1 nA at most. In order to obtain an intense  $^{84}\text{Kr}^{17+}$  beam, the gas mixture was replaced by a pure krypton gas, and a single  $^{84}\text{Kr}^{17+}$  ion was injected into the cyclotron. At least 10 nA  $^{84}\text{Kr}^{17+}$  beam was obtained by the single ion acceleration. However, half an hour's changing time was required for replacing the gas in the present gas supply system of the ECR ion source.

## 5 Cocktail Ions with $M/Q \approx 4$

The oxygen gas and the gas mixture of argon, neon and krypton were used to generate the  $M/Q \approx 4$  cocktail. Main parameters of the  $M/Q \approx 4$  cocktail are listed in Table 2. All the cyclotron parameters for accelerating the  $M/Q \approx 4$  cocktail ions were optimized for 100 MeV  $^{16}\text{O}^{4+}$ .

Pulse height spectra of the cocktail ions obtained at three different RF frequencies are shown in Fig. 3. Parameters except for the RF frequency were the same as the 100 MeV  $^{16}\text{O}^{4+}$ . Multiple ion species were observed in the pulse height spectra, since undesirable cocktail ions were extracted from the cyclotron before entering

Table 2  
Parameters of the  $M/Q \approx 4$  cocktail.

Ion	Mass Number M	Atomic Number Z	Charge State Q	M/Q	$\Delta(M/Q)/(M/Q)$	Energy (MeV)	RF Frequency (MHz)	Stopping Power in Silicon (MeV/(mg/cm <sup>2</sup> ))
He	4	2	1	4.0021	$+9.8 \times 10^{-4}$	25	11.908	0.2
C	12	6	3	3.9995	$+3.2 \times 10^{-4}$	75	11.916	1.8
O	16	8	4	3.9982	0	100	11.919	3
Ne	20	10	5	3.9979	$-0.6 \times 10^{-4}$	125	11.920	4.6
Ar	40	18	10	3.9957	$-6.2 \times 10^{-4}$	250	11.926	13
Kr	84	36	21	3.9952	$-7.3 \times 10^{-4}$	525	11.928	36

the deceleration phase region. The insufficient separation of the cocktail ions was due to large phase acceptance of the JAERI AVF cyclotron. Although a carbon atom was not supplied in any gases, an intense  $^{12}\text{C}^{3+}$  beam was observed. The carbon probably comes from the grease and oil in the ECR vacuum system.

In order to eliminate the undesirable cocktail ions, an acceleration voltage was lowered by 28% so that a revolution number could be increased to further the phase drift. A mixture rate of the  $^{12}\text{C}^{3+}$  and  $^{20}\text{Ne}^{5+}$  in the 100 MeV  $^{16}\text{O}^{4+}$  beam was reduced to less than  $1 \times 10^{-3}$ . In addition, several other beams were produced at low intensities which are not shown here. The metallic ions such as  $^{52}\text{Cr}^{13+}$  and  $^{56}\text{Fe}^{14+}$  were observed as impurity beams. The metals probably come from the walls of the plasma chamber in the ECR source. The metallic ion intensities are dependant on the physical size of the plasma in the second stage: the larger the plasma, the more the metallic ions are observed. This is due to the plasma contacting the stainless-steel sheathed octapoles.

### 6 Conclusion

We have developed the cocktail beam acceleration technique to offer users different ion beams in a single beam-time period. The change of ion species and/or energies is easily done in a matter of a few minutes by tuning one or two parameters only.

This technique can be also applied to diagnostics for "analog beams" with essentially the same M/Q ratio. While the ion species with almost identical M/Q ratios cannot be separated at the rigidity of the analyzing magnet, the cyclotron acts as a mass analyzer that distinguishes the ion species.

### References

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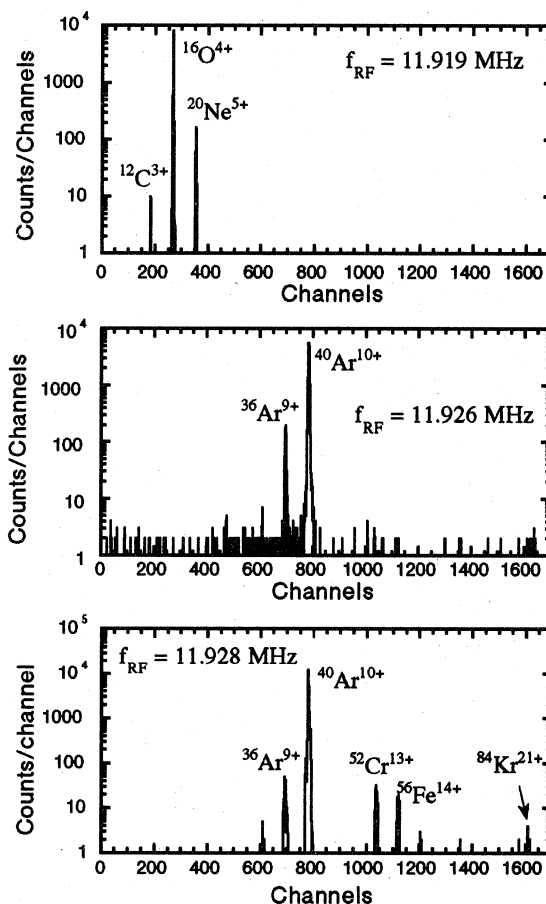


Fig. 3 Pulse height spectra of the  $M/Q \approx 4$  cocktail ions measured with a SSD. The spectra were obtained at three RF frequencies: 11.919 MHz, 11.926 MHz and 11.928 MHz.