Development of an RF ion guide for trapping energetic radioactive nuclear ions

M. Wada*, Y. Ishida*, T. Nakamura*, N. Oshima*, Y. Nakai*, T.M. Kojima*, Y. Kanai*, H. Ohyama*, T. Kambara*, Y. Yamazaki*, A. Yoshida*, T. Kubo*, Y. Matsuo*, Y. Fukuyama*, K. Okada†, K. Noda**, S. Ohtani‡, H. Kawakami§ and I. Katayama§

*RIKEN, Hirosawa, Wako, Saitama 351-0198, Japan
†Department of Physics, Sophia University, Tokyo 102-8554, Japan
**National Institute for Radiological Science, Chiba 263-8555, Japan
‡Institute of Laser Science, University of Electro-Communications, Chofu 182-8585, Japan
§Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

Abstract. Although the projectile fragment separator (RIPS) at the RIKEN accelerator facility (RARF) provides wide variety of energetic radioactive beams, it is not adequate for low energy beam experiments such as precision spectroscopy of trapped ions. Aiming for an efficient deceleration and cooling of energetic radioactive ions, the development of an rf ion guide system which comprises a large He gas cell and an rf funnel structure in the cell is under progress.

A proof of the principle (pop) machine has been successfully tested on-line for collection of 70-MeV/u ^{8}Li ions. A compact gas cell of 70 cm in length and 10 cm in diameter with a He gas pressure of 30 Torr was placed after a variable wedge shaped energy degrader. The ions were stopped in the gas and were transported by a superposition of dc and rf electric field toward a small exit hole. The overall efficiency was 10^{-4} which can be separated into a gas stopping efficiency of 0.43 % and an ion-guide efficiency of 2.4 %. The former is limited by the volume of the cell and the pressure of the He gas. The latter is due to the present rf voltage limitation of 40 V. Both efficiency could be increased up to 10 % range by larger cell, higher pressure, and higher rf voltage, which would yield an expected overall efficiency of 1 %.

INTRODUCTION

At RIKEN a radioactive beam factory (RIBF) is under construction. The new facility consists of several stages of heavy ion cyclotron which provides 1-pμA, 350 MeV/u heavy ion beams, projectile fragment separators (Big RIPS) and storage rings (MUSES) [1]. The projectile fragment separator provides a wide variety of radioactive nuclear ions without any restrictions on chemical property or lifetime limit of the ions. The beam energy and quality is, however, not adequate for low-energy beam experiments, in particular for trapping experiments. Trapped unstable nuclear ions enable us to perform a variety of high precision experiments.

We will primarily apply this method to the precision spectroscopy of the hyperfine structure of various Be isotopes [2]. The hyperfine constant A shows a small but finite isotope dependence. The main part of this hyperfine anomaly stems from the finite distribution of the magnetism over the extended nucleus and is known as the Bohr-

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Weisskopf effect [3]. The effect is empirically described by

$$A = A_{\text{point}}(1 + \varepsilon_{\text{BW}}) \tag{1}$$

where A and A_{point} are the hyperfine constant for an extended and point-like nucleus, respectively, and ε_{BW} is the anomaly. Since A_{point} can not be obtained experimentally, we compare the ratio of A to the nuclear g_I-factor among the isotopes. The differential anomaly

$$^1\Delta^2 \equiv \frac{A^1/g_I^1}{A^2/g_I^2} - 1 \approx \varepsilon_{\text{BW}}^1 - \varepsilon_{\text{BW}}^2 \tag{2}$$

can then be evaluated.

We aim at the investigation of the neutron halo structure of the ^{11}Be nucleus through the measurements of the Bohr-Weisskopf effect which is sensitive to the radial distribution of the loosely bound valence neutron. A recent theoretical estimate supports the importance of the investigation of the Bohr-Weisskopf effect in connection with the nuclear structure of ^{11}Be [4]. We have been working towards the development of exact experimental techniques for this purpose [5, 6, 7].

In order to investigate the Bohr-Weisskopf effect of ^{11}Be, we must determine the hyperfine constant A and nuclear g-factor g_I for all the Be isotopes with an accuracy of at least 10^{-6}. A combined linear trap which consists of a superconducting Helmholz magnet and a linear rf trap was constructed [8] for testing a laser microwave multiple resonance method. Figure 1 shows typical microwave resonance spectra for nuclear spin flip resonance and electron spin flip resonance. We could determine the hyperfine constant A and the nuclear g_I-factor in units of the atomic g_J-factor from the two sets of resonance frequencies using the Breit-Rabi formula. We obtained a sufficiently high accuracy for the hyperfine constant A and for nuclear g_I-factor of the stable isotope ^{9}Be, 10^{-8} and 10^{-6}, respectively [9].

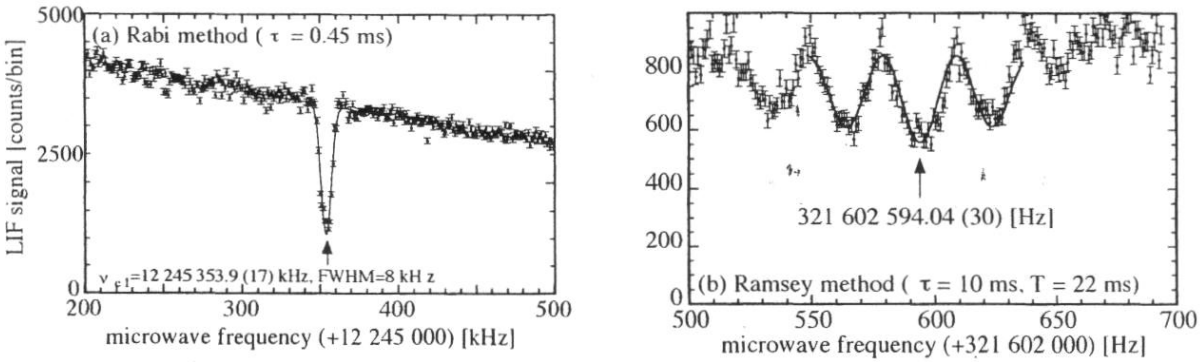

FIGURE 1. Electron spin flip resonance (left) and nuclear spin flip resonance (right) spectra of the ground state hyperfine structure of ^{9}Be$^+$ obtained by laser microwave multiple resonance spectroscopy in an external magnetic field.

In order to perform such trap experiment, a new scheme to decelerate energetic unstable nuclear ion beams and to cool them efficiently has to be developed. We have been working on the development of an rf ion guide system for this purpose.

PRINCIPLE

The rf ion guide system was proposed to obtain slow or trapped radioactive nuclear ions which are primarily produced by a projectile fragment separator. The energetic ion beams from the fragment separator are energetically degraded by passing through a degrader plate. The medium-energy ion beam thus obtained is then injected into a large He gas cell to thermalize the ions. The stopped ions have to be quickly extracted to the vacuum and transferred to the downstream instruments. A schematic diagram of the entire system is shown in Fig. 2. The ordinary ion guide system has been used for a kind of a target ion-source unit of an isotope separator on-line (IGISOL) [10]. Reaction products recoiling out from the target are mostly in singly charged state when stopped in the He gas and extracted to the vacuum. In the ordinary ion guide system, the transport of ions in the cell is carried out only by the gas flow. The use of a large cell to stop relatively high energy ion beams, however, would take much more time. Possible loss processes such as charge exchange and diffusion to the wall become effective.

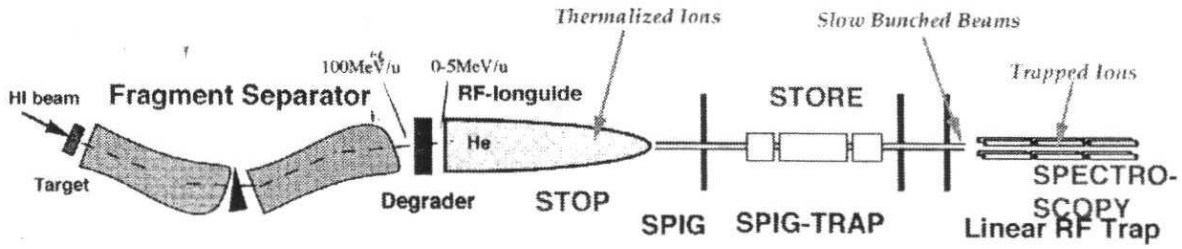

FIGURE 2. Overview of the proposed scheme

Due to the ion charge, the thermalized ions in the gas must be manipulated by an electric field. However, if a simple static electric field is applied, the ions would be lost at the cathode since the average ion motion under such high-pressure just follows the electric lines of force. There are two possible solutions to avoid the losses at the cathode electrode. One way is to apply a gas flow and the other way is to use an rf barrier field. The former is only applicable at the region very close to the exit where a significant gas flow speed is expected. In the latter, the cathode electrode is replaced by a series of lined ring electrodes on which rf voltages are applied. The electrodes produce a local rf gradient field on the surface. The average force due to the rf gradient field becomes repulsive against the electrode (Fig. 3). The fundamental principle is the same

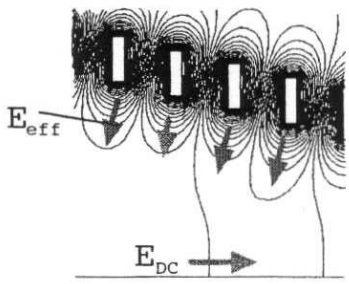

FIGURE 3. rf gradient field produced by a series of ring electrodes.

as an rf quadrupole ion trap developed by W. Paul in 1953. The first experimental test of this structure for manipulating charged micro-particles in an atmospheric pressure

air was performed by Masuda et al. in early 1970s, they called *electric field curtain* or *rf hopper* [11]. They aimed at industrial applications such as an ink-jet printer. We proposed to incorporate this rf *funnel* structure into the ion-guide gas cell to manipulate singly charged radioactive nuclear ions [12, 13].

Simulation

In order to understand the detail of the rf ion guide scheme, we performed several ways of ion motion analysis. The fundamental equation of motion is

$$m\ddot{r} = e\mathbf{E}(r,t) \tag{3}$$

where m is the mass of ion and $\mathbf{E}$ is the electric field (a function of coordinate and time). The first method is a microscopic Monte Carlo simulation which could start from this equation. The presence of a gas is taken into account by including classical potential scattering at each collision between ion and gas molecules. The scattering angle in the center of mass system is

$$\theta_{\mathrm{CM}}(b,E) = \pi - 2\int_{R_{\min}}^{\infty} \frac{b}{r^2} \frac{dr}{\sqrt{1-(b/r)^2 - V(r)/E}} \tag{4}$$

where b is the impact parameter, E the relative energy, and $R_{\min}$ the root of $1 - (b/R_{\min})^2 - V(R_{\min})/E = 0$. We have chosen a scattering potential accordingly

$$V(r) = \frac{\varepsilon}{2}\left[(1+\gamma)\left(\frac{r_m}{r}\right)^{12} - 4\gamma\left(\frac{r_m}{r}\right)^{6} - 3(1-\gamma)\left(\frac{r_m}{r}\right)^{4}\right]. \tag{5}$$

The parameters γ, ε and r_m were taken from the literature [14].

The dc and rf electric field maps were calculated independently by the POISSON [15] code, obtaining the total electric field as a function of time:

$$\mathbf{E}(r,t) = \mathbf{E}_{\mathrm{dc}}(r) + \mathbf{E}_{\mathrm{rf}}(r)\cos(\Omega t). \tag{6}$$

Typical ion trajectories are depicted in Fig. 4. The figure shows a part of the cell which is close to the exit. The electrode structure consists of a nozzle part and a large funnel part. The nozzle part is made of 70 ring electrodes with an interval of 0.3 mm. It has an aperture of 0.4 mm at the exit and an aperture of 11.2 mm at the top. The large funnel part follows at the top of the nozzle part. The interval of each electrode in this part is 0.5 mm and the aperture at the bottom is 10 mm. One trace of simulation with a 500 MHz Alpha processor required several minutes of computational time.

The microscopic simulation clearly shows the transport of ions in the rf ion guide. However, an analytical approach is more helpful to understand the various physical processes. We employed the *mobility* (μ) of ions in the gas to simulate the effect of multiple collisions as a frictional force. The equation of motion is

$$m\ddot{r} + \frac{e}{\mu}\dot{r} = e\mathbf{E}(r,t). \tag{7}$$

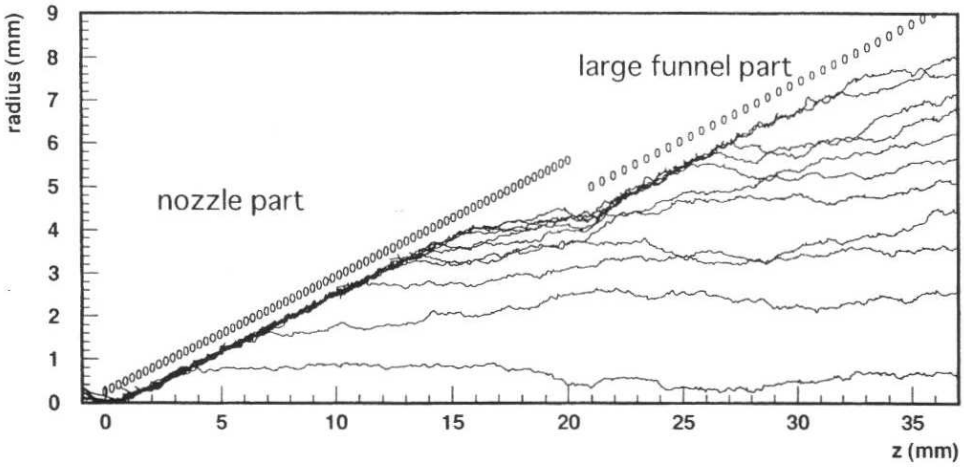

FIGURE 4. Typical ion trajectories by microscopic simulation. ^{8}Li ions in 30 Torr He gas, rf amplitude 80 V, rf frequency 10 MHz, dc gradient field 12 V/cm.

If we define the velocity relaxation time as $\tau_v = m\mu/e$, the equation becomes

$$\ddot{r} + \frac{1}{\tau_v}\dot{r} = \frac{e}{m}\left(\mathbf{E}_{dc}(r) + \mathbf{E}_{rf}(r)\cos(\Omega t)\right). \tag{8}$$

This equation permits two different ways of analysis. If we assume that the field very close to the electrode is a quadrupole field, Eq. (8) is simplified in a Mathiu equation,

$$u'' + 2pu' + (a - 2q\cos 2\tau)u = g \tag{9}$$

with the non-dimensional parameters $a = 8eV_{dc}/mr_0^2\Omega^2$ being the index of dc offset $q = 4eV_{rf}/mr_0^2\Omega^2$ being the index of rf field strength $p = e/m\mu\Omega = 1/\tau_v\Omega$ being the index of gas pressure $g = 4eE_{dc}/m\Omega^2$ being the index of external force and $\tau = \Omega t/2$. The terminal voltage of the assumed quadrupole electrode is assigned as V_{rf} and V_{dc} and the half distance of the electrode is assigned as r_0. The stability analysis of an ordinary Mathiu equation could be performed using this equation. Details of this analysis will be reported elsewhere [16].

Another way of to analyze Eq. (8) is the pseudo potential approach. The rf electric field is averaged over a cycle to deduce the strength of the effective electric field due to the rf gradient field. We omit the static field in Eq. (8) and split the motion of an ion into a slow average motion $\bar{r}$ and a small oscillation motion $\rho(t)$ as

$$r = \bar{r} + \rho(t) = \bar{r} + c\mathbf{E}_{rf}(r)\cos(\Omega t + \beta). \tag{10}$$

The coefficient c is deduced by inserting the derivative of Eq. (10) into Eq. (8), then the small oscillation is

$$\rho(t) = -\frac{e}{m\Omega}\frac{\mathbf{E}_{rf}(r)}{\sqrt{\Omega^2 + 1/\tau_v^2}}\cos(\Omega t + \beta), \quad \tan\beta = \frac{1}{\tau_v^2\Omega^2}. \tag{11}$$

The average force $\bar{F}$ due to the gradient rf electric field is

$$\bar{F}(\bar{r}) = e\langle \mathbf{E}_{\rm rf}(\bar{r})\cos\Omega t + [\nabla|_{r=\bar{r}}\mathbf{E}_{\rm rf}(r)]\rho(t)\cos\Omega t\rangle_{\rm av} = -\nabla\mathbf{E}_{\rm rf}^2(\bar{r})\frac{e^2}{4m}\frac{1}{(\Omega^2+1/\tau_{\rm v}^2)}. \quad (12)$$

Eq. (12) is simplified in two extreme cases, the vacuum limit and the high pressure limit, respectively

$$\bar{F}(\bar{r}) = \begin{cases} -\nabla\mathbf{E}_{\rm rf}^2(\bar{r})\frac{e^2}{4m\Omega^2}, & \text{for } \Omega^2\tau_{\rm v}^2 \gg 1 \quad \text{(vacuum)} \\ -\nabla\mathbf{E}_{\rm rf}^2(\bar{r})\frac{e^2}{4m}\tau_{\rm v}^2, & \text{for } \Omega^2\tau_{\rm v}^2 \ll 1 \quad \text{(high pressure).} \end{cases} \quad (13)$$

If we assume again a quadrupole field close to the electrode, the average force in high pressure limit is

$$\bar{F}_{\rm hp} = -\frac{e^2}{4m}\tau_{\rm v}^2\frac{8V_{\rm rf}^2}{r_0^3}\left(\frac{r}{r_0}\right) = -m\mu^2\frac{V_{\rm rf}^2}{r_0^3}\left(\frac{r}{r_0}\right). \quad (14)$$

If we assume the mobility being simply proportional to the reciprocal of the pressure, heavier ions in lower pressure gas are manipulated by weaker rf field. It should be noted, however, that the pseudo potential analysis does not provide any information about the stability.

EXPERIMENT

We first tested the rf ion-guide system off-line and then constructed a proof of the principle (POP) system for on-line test experiments. The on-line test was performed at the RIKEN projectile fragment separator RIPS which provides us a 70-MeV/u ^{8}Li ion beam with an intensity of $\sim 10^6$ atoms/s from a primary beam of 70-MeV/u ^{13}C and a production target of ^{9}Be. We choose ^{8}Li for the test ion beam instead of ^{11}Be, since the detection of ^{8}Li, which emits two alpha particles followed by the β-decay, is efficient and reliable.

The fragment separator consists of two dipole magnet and an energy degrader in between the two magnets. The first magnet analyzes for A/Z of the fragment ions and the second one for $\sim A^{2.5}/Z^{1.5}$, since the dependence of energy loss in the degrader is different for Z and A. The separator thus provides pure isotopic ions in many cases. Although there are many impurity ions, we used only a half part of the separator. An advantage of using the half part is that we can put our system at the momentum dispersive focal point. It allows us to use a wedge shaped energy degrader for mono-energetic deceleration. The impurity ions, on the other hand, can be eliminated by a so called range separation; heavier ions such as ^{10,11}Be stop in the degrader and lighter ions such as ^{3}H just pass through the gas cell.

Apparatus

In the off-line test [17], multiple metallic plates were used to form the rf electrodes. The distance between the electrodes was 2.5 mm. More than 50 % transmission effi-

ciency was achieved for Ta ions under the conditions of 30 Torr He pressure and an rf amplitude of 50 V. A pressure of 30 Torr was too low for practical experiments. We therefore set the target pressure 150 Torr, which corresponds to the stopping capabilities of 5 MeV/u for medium to heavy ions and 2.5 MeV/u for very light ions, if the depth of the cell is 2 m. To operate the rf ion guide mechanism under such high pressure, decreasing r_0 is the most effective way while an increase of the voltage is limited by discharge problems. According Eq. (14), a transport of Li ions in 150 Torr He gas could be realized if a higher rf amplitude ($\sim$150 V) is achieved and a fine structure electrode assembly with a distance of 0.3 mm or 0.5 mm between electrodes is fabricated. This type of electrode assembly was fabricated with a flexible printed circuit board.

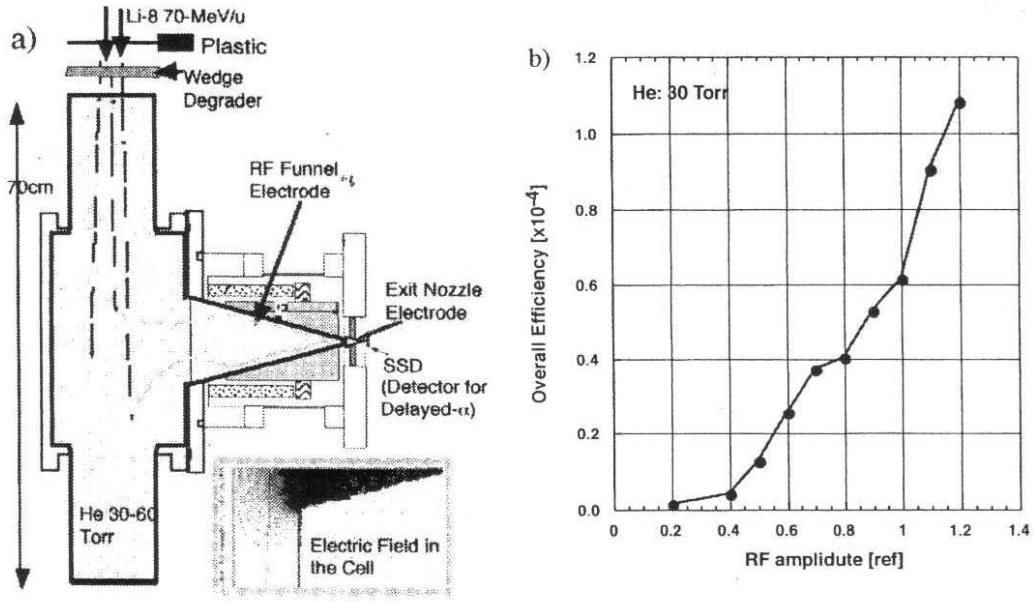

FIGURE 5. Experimental setup of the POP system (a). Overall efficiency plotted as a function of applied rf amplitude (b). Gas pressure was 30 Torr, dc field gradient 10 V/cm, rf amplitude about 40 V at ref=1.0, rf frequency 10 MHz.

A schematic diagram of the POP setup is shown in Fig. 5a. The gas cell is made of a simple vacuum duct with diameter of 10 cm and legth of 70 cm. The duct is orthogonally connected to the rf funnel structure of 10 cm aperture. The stopped ^{8}Li ions are transported by static electric field, which penetrates from the aperture, to the funnel part where the rf barrier field protects ions from the collision to the electrodes. We took the orthogonal geometry in order to avoid the direct implantation of ^{8}Li ions into the detector and also to make sure that the ions are transported by the electric field, not only from the region very close to the exit but also from the region very far from the exit.

Results and discussion

Figure 5b shows an experimental result of transporting ^{8}Li ions. We define the overall efficiency as a ratio of detected counts of delayed alpha particles from ^{8}Li to the number of ^{8}Li ions output from the RIPS. The overall efficiency was plotted as a function of the applied rf amplitude. The dc field was fixed to 10 V/cm at the center of the funnel structure electrode assembly. We could clearly see the effect of rf field applied in the ion guide gas cell and obtained a typical overall efficiency of 10^{-4} at a condition of the He gas pressure of 30 Torr and rf amplitude of 40 V. We split the efficiency into two components: First the gas stopping efficiency which indicates how much fraction of injected ^{8}Li ions can be stopped in the volume of the cell, and, second, the ion transport efficiency by the electric field. We put a collimator in front of the cell to deduce the radial acceptance of the cell which was obtained to be 28 %. Combined with a range calculation by the TRIM code [18], we obtained the stopping efficiency of 0.43 % and thus the transport efficiency of 2.4 %.

We compared the yield at different gas pressures of 30 Torr and 60 Torr. The yield at 60 Torr was lower than at 30 Torr. It is considered to be due to the fact that the rf amplitude was too low for transporting ^{8}Li ions in He gas of 60 Torr. We also tested the yield dependence on the length of the cell. The longer cell showed a higher yield than the shorter one. This indicates that even if ions are stopped in the region very far from the exit were transported by the electric field.

The overall efficiency of 10^{-4} of the present POP system was limited by the known reasons. The gas stopping efficiency could be increased up to 10 % range simply by increasing the size of cell and possibly by increasing the pressure. The ion transport efficiency could be increased also towards the 10% range by increasing the rf amplitude.

Based on the experience with the POP system we are now constructing a new system. The new gas cell is 40 cm in diameter and 2 m in length. It is capable of in-line extraction as well as orthogonal extraction. The rf system has been extensively modified. In the POP system, rf divider circuits were placed outside the cell and many long cables transported the power through a feedthrough resulting a large capacity and heat dissipation. The new rf electrode is made of a flat doughnut form plate with an outer diameter of 25 cm and an inner hole diameter of 14 mm in addition to the small funnel structure at the nozzle part. The effective aperture of 25 cm causes stronger penetration field in the whole area of the cell. The rf divider circuits are soldered on the back surface of the doughnut plate and the matching coil has a water cooling capability. This reduces the capacity as well as the required power. Typical operating parameter conditions are 10 MHz and 150 V. This can be achieved by applying an rf power of about 30 W.

CONCLUSION

We have tested the rf ion-guide system for collecting energetic radioactive beam from a projectile fragment separator. The proof of the principle model has a compact sized gas cell with a diameter of 10 cm and a length of 70 cm with an rf funnel struture of 10 cm aperture and a nozzle struture of 0.5 mm aperture: the model was shown to be effective

for collection of ^{8}Li. The overall efficiency of the compact system was 10^{-4} with a gas stopping efficiency of 0.43% and a transporting efficiency of 2.4%. Both efficiency must be improved by increasing the size of the cell and amplitude of the applied rf voltage.

We conclude that the aimed goal of an overall efficiency of 1 % should be feasible. It should be noted that the overall efficiency of an ordinary ISOL type target ion-source system rarely exceeds 1 % range for many elements, while the combination of a fragment separator and the rf ion guide system is, in principle, independent to the chemical property of the nuclides.

We plan to perform the hfs spectroscopy experiment for ^{11}Be with the new rf ion-guide system within a year. A low energy radioactive beam experimental facility based on this technique will be prepared in the RIKEN RI-beam factory.

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