RECENT PROGRESS ON HIGHLY CHARGED ION BEAM PRODUCTION FROM THE RIKEN 18 GHz ECRIS

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Abstract

Production of light to medium highly charged ions is one of the main responsibilities of the RIKEN 18 GHz Electron Cyclotron Resonance Ion Source (R-18 GHz ECRIS) in the Radioactive Isotope Beam Facility (RIBF). As part of an ongoing systematic study on the operational ion source parameters, experimental results on the mean charge state of ^{129}Xe and ^{40}Ar ion beams are reported. The chamber gas pressure dependence and effect of gas mixing on the mean charge ion states in the ECRIS is investigated. Increasing chamber gas pressures leads to lower mean charge states and careful tuning is needed to adjust towards high charge state ions. Experiments on the gas mixing technique show high ^{16}O:^{129}Xe mixing ratio yield high mean charge states reaching up to $^{129}Xe^{29+}$. Further investigation using different ECR conditions are still ongoing. In addition, a pepper pot emittance monitor was newly installed in the R-18 GHz ECRIS diagnostics beamline and preliminary measurements of the beam emittance are currently being examined.

INTRODUCTION

The R-18 GHz ECRIS has been continuously developed to provide various light to medium highly charged beams such as $^{40}Ar^{11+}$ and $^{129}Xe^{25+}$. Realizing the suitable conditions to produce highly charged ions together with achieving the desired ion beam currents require careful tuning of the key ECR parameters. Research and development activities have focused on increasing the achieved beam intensities through the plasma electrode position, tuning the magnetic field confinement, and other empirical techniques such as the positioning and voltage potential of bias probes [1-2]. Another important objective of the research is the optimization of ECR parameters towards high charged ion production. With inter-related parameters changing simultaneously for different conditions, a systematic study is necessary to understand how each affects the produced ion charge states.

In an ECR plasma, ions are produced through a step-by-step ionization process through the electron cyclotron resonance phenomenon. To produce highly charged ions, it is important to achieve certain conditions of the ECR parameters. First, it would require high electron temperatures T_e, having enough energy to ionize the neutral atoms by electron impact, continuously, further ionizing up to multiple-charge states. In addition, other key conditions require high electron density n_e and long ion confinement time τ_i to allow longer duration for impact ionization to eventually realize even higher charge states. This relationship between ECR parameters (T_e, n_e, τ_i) and the produced ion charge states is best described by the Golovanivsky diagram as a simplified criterion for multiple charge state ion production [3].

As the ECR parameters (T_e, n_e, τ_i) vary with respect to the conditions set by the ion source, the distribution of the ion charge states also changes accordingly. Through studying the evolution of the produced ion charges and the ion mean charge state, information on the ECR plasma conditions can be indirectly examined. This indicator will be used in the systematic study on the effects of different ion source parameters.

The experimental results of the chamber gas pressure and input RF power dependence on the ion mean charge state are summarized in this paper. The first part of the experiment investigates the effects of chamber gas pressure and the input RF power on the mean charge state for test ions of ^{40}Ar and ^{129}Xe. Next, is examining how the mean charge state is affected with the addition of a mixing gas in the ECR plasma. Future research plans of the R-18 GHz ECRIS is reported along with a newly installed beam emittance monitoring system. Preliminary measurements on the various extracted ion beams from the ECRIS are ongoing.

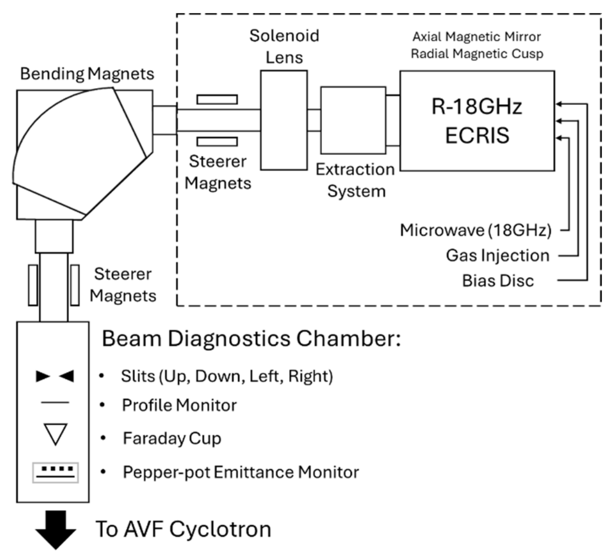

Figure 1: Simplified diagram of the R-18 GHz ECRIS and the low energy beam transport line.

RIKEN 18-GHz ECRIS

The R-18 GHz ECRIS is a ~1 L volume hybrid-type having two sets of solenoid coils for the axial mirror magnetic field and 36-segments of Nd-Fe-B permanent magnets for the radial magnetic field configuration. Detailed descriptions are provided in the following references [4]. A TWT amplifier is used to inject 18 GHz microwaves of up to 600 W to the cylindrical plasma

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chamber of inner diameter ϕ 72 mm and length 250 mm. Some specifications are described in Table 1.

A simplified diagram (Fig. 1) shows the R-18 GHz ECRIS and the low energy beam transport line. A primary and secondary gas line is connected to the gas injection side of the plasma chamber. The chamber gas pressure measurements were made at the first stage chamber outside the central ECR plasma region. For gas mixing experiments, calibration for ^{129}Xe and ^{16}O gas pressures are measured before plasma operation. The experiments were performed with mirror magnetic fields optimized to yield maximum beam intensities for the test ions, $^{40}Ar^{11+}$ and $^{129}Xe^{25+}$. The charge state distribution for different chamber gas pressures and input RF power were measured.

Also shown in the downstream region of the beam transport line is the beam diagnostics chamber which beam profile and current measurement are performed.

Mean Ion Charge State

Experiments using the R-18 GHz ECRIS with different ion source conditions were performed looking at the charge state distribution through the calculated mean ion charge state. The ion mean charge state is described as,

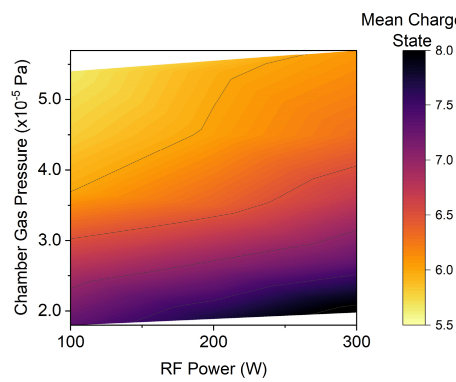
$$\langle q \rangle = \frac{\sum_{i=1}^{n} q_i \cdot I_{q_i}}{\sum_{i=1}^{n} I_{q_i}}$$

where q_i is the charge state, I_{q_i} is the beam current of q_i. This average ion charge calculated from the charge state distribution is a useful indicator as it reflects the degree of ionization brought by conditions set by the ECR parameters.

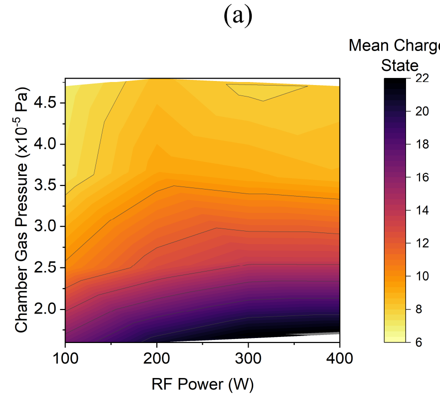
For ECRIS conditions with the 18 GHz RF frequency, magnetic field configuration, chamber volume and extraction settings, experiments were conducted for ^{40}Ar and ^{129}Xe ions and a 2D contour map (Fig. 2) to show the dependence of chamber gas pressures and input RF power to the corresponding mean charge states. In the case of ^{40}Ar ions, chamber gas pressures of around 5.0x10^{-5} Pa have lower mean charge states of 5.5 which slightly increased to 6.0 as the RF power ranged from 100 to 300 W. With low chamber gas pressures below 2.0x10^{-5} Pa, the mean charge state was now higher at 7 and increased to 8 as the RF power was increased. At 300 W RF power condition, trace current signals of high ion charge state $^{40}Ar^{14+}$ were measured.

For the case of ^{129}Xe ions, a similar behaviour to the experiment with ^{40}Ar is observed for the chamber gas pressure and input RF power dependence on the mean charge state. High chamber gas pressures of above 4.5x10^{-5} Pa had mean charge states ranging from 7 which increased up to 8 as the input RF power was increased from 100 to 400 W. Operating at low chamber gas pressures would yield mean charge states of 16 at 100 W RF power and then increases up to 22 at 400 W RF power. The observed maximum ion charge state in the charge state spectrum was $^{129}Xe^{30+}$ having minimal current signals of ~0.5 μA.

Other studies on the effect of RF power have been observed to increase the extracted beam intensities from the ECRIS [5]. The input RF power increases proportionally to the absorbed RF power for electron heating in the ECR. This in turn impacts the optimum T_e as well as the achieved beam intensities in the charge state distribution. However, the absorbed RF power is also influenced by the neutral density or translated in the form of chamber gas pressures. The gas pressure, which relates to the neutral and electron densities, affects the ionization conditions in the ECR plasma. By examining the evolution of the mean charge state in different ion source conditions, changes to the ECR plasma conditions could be indirectly monitored. Considering the relationship of the key ECR plasma parameters (T_e and $n_e\tau_i$) and the degree of ionization, the mean charge state contour map can be correlated to the basic criterion for multi-charged ions in the ECRIS. For ^{40}Ar and ^{129}Xe, depending on the desired ion species for production, the ion source parameters should be carefully tuned accordingly, especially when optimizing for high beam intensity production.



(a)



(b)

Figure 2: 2D contour plots of the calculated mean charge states for (a) ^{40}Ar ions and (b) ^{129}Xe ions, showing the dependence on chamber gas pressures and the input RF power.

Effect of Gas Mixing

One of the empirical techniques to increase the beam intensity of highly charged ions is the gas mixing method.

Through the addition of a mixing gas with lighter atomic mass, it has been observed that the charge state distribution leans towards higher charge state ions [6]. Since the addition of a mixing gas increases the overall chamber gas, these were considered during the investigation of the effect of gas mixing.

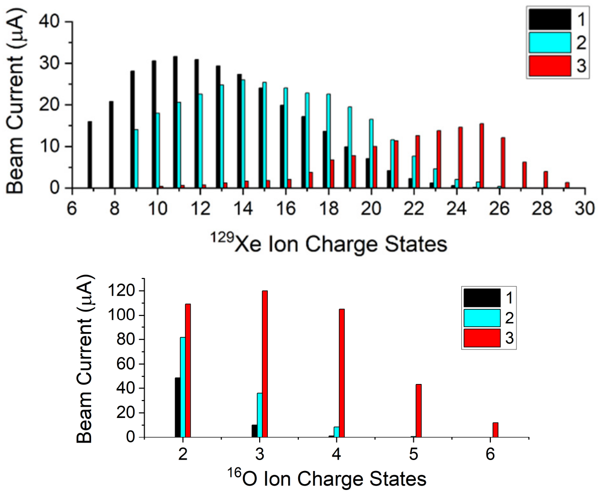


Figure 3: Beam current measurements across the charge state distribution of ^{129}Xe ions (top) and the corresponding mixing gas ^{16}O ion charge state distribution (bottom).

Beam current measurements (Fig. 3) were performed across the charge state spectrum of ^{129}Xe ions produced with a 400 W input RF power. The measurements were made with gas pressure conditions of pure ^{129}Xe at 7.1x10^{-5} Pa, and two gas mixed conditions with ^{16}O, and these are described in Table. 1. All three conditions have similar overall chamber gas pressure conditions and with only different proportions of ^{129}Xe and ^{16}O. From the beam measurements, it can be clearly observed that for only pure ^{129}Xe gas condition, the lower charge state ions around ^{129}Xe^{11+} dominate the distribution. With the addition of ^{16}O gas, the proportion of the ^{129}Xe gas slowly becomes smaller showing less extracted beam intensities and stronger ^{16}O ion signals. However, the results show that larger amounts of ^{16}O increases the probabilities for high charge state ion production.

Table 1: Chamber Gas Pressure Conditions for ^{129}Xe and ^{16}O During the Gas Mixing Experiment

Expt	^{129}Xe gas pressure (Pa)	^{16}O gas pressure (Pa)
1	7.1 x 10^{-5}	
2	5.5 x 10^{-5}	5.7 x 10^{-5}
3	3.4 x 10^{-5}	6.5 x 10^{-5}

Measuring over a range of gas proportions of ^{129}Xe and ^{16}O, the 2D contour plot for the calculated mean charge state (Fig. 4) clearly shows the region for high charge state ion production for larger amounts of ^{16}O. Decreasing the amount of ^{129}Xe and introducing more ^{16}O can lead to even higher ion charge states, the measured beam intensities is expected to decrease accordingly. Careful considerations in using larger input RF power can help compensate for the smaller beam intensities but additional experiments are needed to confirm the limits of these parameters.

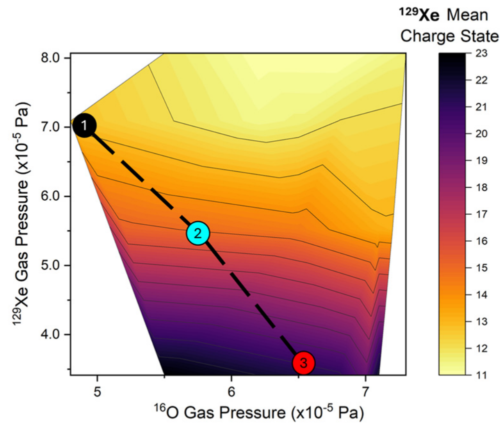


Figure 4: 2D contour plot of the calculated mean charge state of ^{129}Xe for the range of ^{129}Xe and mixing gas ^{16}O gas pressures with details described in Table 1.

Beam Diagnostics for R-18GHz ECRIS

With the development of a pepper-pot emittance monitor (Fig. 5) that allows the 4D beam emittance measurement [7], this system has been recently procured and installed in the beam diagnostics chamber of the R-18 GHz ECRIS low energy beam transport beamline. Experiments on beam emittance growth factors, space charge compensation and evaluating the beam optics of the low energy beam transport line are being planned. Currently, preliminary measurements are currently being performed using various ion beam species of ^{40}Ar and ^{84}Kr. In the case of He^{2+} and H^{+} ions, beam measurements show large beam sizes, and the measurement method are being adjusted to ensure accuracy when considering lighter ions.

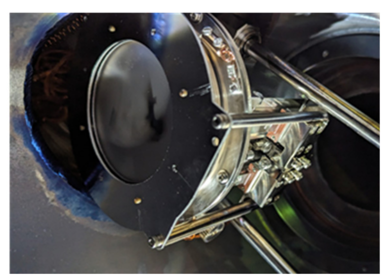


Figure 5: Image of the pepper-pot emittance monitor installed inside the beam diagnostic chamber of R-18 GHz ECRIS.

CONCLUSION

The status of current research activities in the RIKEN 18 GHz have been reported. The mean charge state in the ECRIS was calculated for different ion source parameters (gas pressure and input RF power) to investigate the suitable conditions for high charge state ion production. Low chamber gas pressures and high input RF power show an increase in the mean charge state of the ECR plasma. Experiments on ^{129}Xe and the effect of gas mixing ions showed production of high charge state ions of up to 29+ for conditions with smaller portions of ^{129}Xe and larger amount of mixing gas. The experimental results show the effectivity in increasing the population of high charge state ions. This systematic study of ion source parameters are important to further optimize the operational conditions for high charge state ion production and should be continued further when considering the conditions for higher beam intensities.

REFERENCES

[1] T. Nakagawa *et al*., "Production of multi-charged ions in the RIKEN 18 GHz ECRIS", Nucl. Instrum. Methods B, vol 226, p. 392 – 400, 2004.

[2] Y. Higurashi *et al*., "Optimization of magnetic field configuration for the production of Ar ions from RIKEN 18 GHz ECR ion source", Nucl. Instrum. Methods A, vol 510, p. 206-210, 2003.

[3] R. Geller, ECR Ion source and ECR Plasma, IOP, Bristol, 1996.

[4] T. Nakagawa and Y. Yano, "Recent Performance of Japanese electron cyclotron resonance ion sources", Rev. Sci. Instrum. vol 71, p. 637-642, 2000.

[5] D. Hitz, Advances in imaging and electron physics, 144 (2006).

[6] M. Mack *et al*., Proc. of the 7th Int. Workshop on ECR Ion Sources, (Julich) p. 152, 1987.

[7] T. Nagatomo *et al*., "Development of a pepper-pot emittance meter for diagnostics of low-energy multiply charged heavy ion beams extracted from an ECR ion source", Rev. Sci. Instrum. 87, 02B920 (2016).