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DEVELOPMENT TOWARDS INTENSE URANIUM ION BEAM PRODUCTION OF THE RIKEN 28 GHz SC-ECRIS

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Abstract

With the ongoing beam development for high intensity uranium beam production, we report the status and progress of the RIKEN 28-GHz Superconducting Electron Cyclotron Resonance Ion Source. The achieved beam currents for the uranium U^{35+} beam has reached up to 250 eμA as a result of optimizing the material consumption rates for high intensity beam production. The target beam intensity for U^{35+} is expected to yield 10 mA of extraction current and the analysis of beam emittance is estimated to be in the range of 0.25 π mm mrad. Furthermore, a semi-empirical method was used to examine a so-called initial emittance value and growth that correspond to space charge effects. Experiments to further investigate the initial beam emittance and the influence of space charge effects are still ongoing.

INTRODUCTION

High intensity Uranium U^{35+} ion beams are produced in the 28 GHz superconducting electron cyclotron resonance ion source (SC-ECRIS) and accelerated to high energies in the Radioactive Isotope Beam Factory (RIBF) at RIKEN [1]. With the increased demand for even higher intensity uranium beams for various nuclear physics research in RIBF, efforts have been made towards improving the performance of the SC-ECRIS. Currently, beam intensities for U^{35+} has reached up to 250 eμA beam current. This was possible through development techniques in optimizing the material consumption rates aimed at high intensity beam production [2]. Investigating the beam quality through beam emittance is the next step to confirm unforeseen issues of beam loss and aberrations along beamline components which is detrimental to the accelerator.

There have been many experimental and numerical studies on the beam emittance growth of the extracted beam from the ECRIS [3-5]. The analysis of beam emittances is complex since the ion source operational parameters, space charge effects and beamline components can easily affect the beam during transport.

The beam emittance from the ECRIS has been known to be mainly influenced by the ion temperature and the axial magnetic field at the extraction region [6]. In the case of highly charged ion production, electrons have much higher temperatures than ions and it has been a reasonable assumption that the dominant contributing factor to beam emittance is the magnetic field effect. Space charge effects on produced ion beams in the ECRIS have also been widely studied since this defocusing of the beam leads to growth in the emittance size and is found to be proportional to the beam intensity. In addition, interaction with downstream components along the beamline must also contribute to an emittance growth. In this paper, beam emittance measurement and analysis of the uranium U^{35+} beam is presented. A systematic study of different operational ECRIS parameters and its effect on the beam emittance size is examined.

URANIUM BEAM PRODUCTION

The RIKEN 28-GHz superconducting ECR ion source (SC-ECRIS) has been developed for providing high intensity heavy ion beams for the RI beam factory. Details regarding the design of the ion source has been previously reported [7]. Superconducting coil assembly with six solenoid coils and one hexapole coil allows the adjustment of the magnetic field at the B minimum to have control on the magnetic field gradient. This means it can produce a mirror magnetic field distribution from the so-called "classical B_{min}" to "Flat B_{min}" [8]. Basic specifications for the RIKEN 28-GHz ECRIS are listed in table 1.

Table 1: Specifications for the R28-GHz SC-ECRIS

Operational Frequency	28 GHz, 18GHz
Max. RF Power	10kW
Max. Magnetic Field	3.8 T
Max. Extraction	22 kV
Chamber Dimensions	Ø150 mm L525 mm
Extraction Aperture Radius	5 mm

With plans to improve the accelerator in the RIBF for studies on nuclear physics now requires output beam intensities of U^{35+} at 300 eμA from the ECRIS. Improvements on the design and performance of the high temperature oven was a crucial factor in increasing the achievable uranium beam intensities. Optimization of the material consumption rates which aimed at high intensity beam production has then allowed the beam current to reach 250 eμA.

With accumulated data sets for U^{35+} beam production, the beam intensity with respect to microwave power is shown in Fig. 1a. Assuming a linear relation between the two parameters, beam currents of 300 eμA will need ~4kW of microwave power and the corresponding extraction currents will be in the range of 10 mA as shown in Fig. 1b. From these expected beam conditions, ion source parameters should be checked thoroughly since high power operation may have some unforeseen issues in the ion source.

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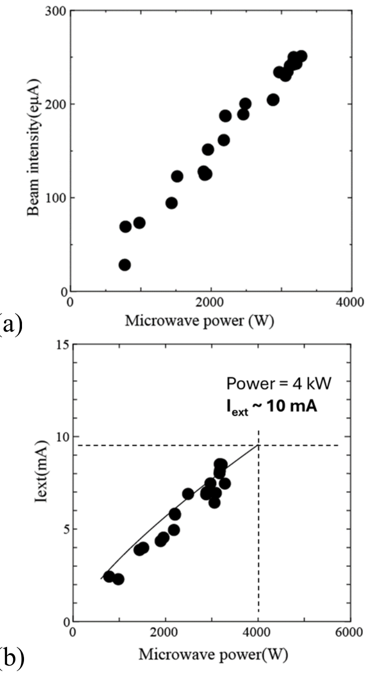
It is also important that before continuing towards operating at higher range of beam intensities, the beam quality should also be checked and confirm good beam optics to avoid any damages to the accelerator.



(a)

(b)

Figure 1: Measurements of uranium U^{35+} beam parameters with respect to microwave power: (a) beam intensity and (b) extraction current.

Measurement of Beam Emittance

The highly charged ions generated in the SC-ECRIS are extracted and then separated using a dipole analyzing magnet. Beam emittances are measured in the diagnostics chamber after mass separation. In the diagnostics chamber, a movable slit is used to scan across the beam and the emittance signals are measured from wire scanners. Other diagnostic tools such as a Faraday cup and profile monitors were used to confirm the beam parameters. The normalized root mean square emittances ε_{nrms} were calculated from the experimental measurements. In previous studies on the U^{35+} extracted beam from the SC-ECRIS, the beam focusing solenoid lens showed separate effects on the horizontal and vertical beam emittances [9]. For low solenoid coil current operation, the focusing effect is weaker and the horizontal x component was found to be around 0.1 π mm mrad larger than the vertical y component. This suggested possible beam aberration may occur along the beamline, as it passes through the dipole analyzing magnet down to the diagnostics chamber. Reduction of the beam size was possible with stronger focusing of the solenoid lens. However, strong focusing may result in a difference in the beam edge focusing angle and these uncertainties should be carefully considered in the analysis of beam emittances.

DISCUSSION

The measured beam emittance of uranium beams was analyzed with different beam conditions. One of the parameters that was observed to greatly influence the measured emittances is the extraction current. Over a range of generated beam intensities, the normalized rms y-emittance at a fixed extraction current of 5.5 mA showed small variations as shown in Fig. 2. For a 50 eμA difference in beam intensities, the obtained beam emittances did not greatly change and was constant around 0.15 π mm mrad.

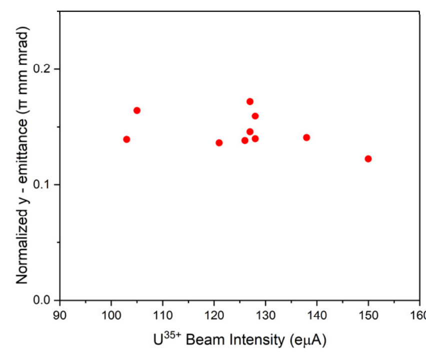


Figure 2: Normalized rms y-emittance measurements over the range of produced beam intensities for uranium U^{35+} having a fixed extraction current of 5.5 mA.

The extraction current represents the sum of all ion species present in the extracted beam. Because of this proportionality, the extraction current was used as a good indicator for estimating the total beam current of the ECRIS.

Examining the effect of the extraction ion current, the x and y normalized rms beam emittances for uranium of 35+ ion charge state with the operational microwave frequency of 28 and 18 GHz is shown in Fig. 3. As previously discussed, the x-component of the beam emittance measurement shows higher emittance values due to possible beam aberration on beamline components. From here on, we will examine only the y-component of beam emittance to avoid any uncertainties in the analysis. With the minimal influence on the beamline components, we can assume that the measured normalized beam emittance can be described by a simple equation,

$$\varepsilon = \sqrt{\varepsilon_0^2 + K(I_{ext})^2} \quad [\pi \text{ mm mrad}] \qquad (1)$$

where ε is the normalized rms beam emittance, ε_0 is an initial beam emittance in π mm mrad, K is a constant describing the beam distribution and I_{ext} is the extraction current in mA [10-11]. The term KI_{ext}^2 is assumed to be related to the effect of space charge where I_{ext} is used to indicate the total beam current. Using Eq. (1), the ε_0 can be determined with the assumption that I_{ext} approaches zero and reveals the initial value to be 0.067 π mm mrad. As shown in Fig. 4, the data measurements and calculated values for ε_0 and ε beam emittances are plotted against the extraction current.

To reach the target beam requirement for U^{35+}, it will be necessary to operate the SC-ECRIS with microwave power at ~4 kW and is expected to generate extraction currents in the range of 10 mA. Using the calculated ε, the normalized

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beam emittance at extraction current of 10 mA is estimated to reach 0.25 π mm mrad. These are the predicted beam conditions for high intensity beam operation of uranium U^{35+} at 300 eμA beam current.

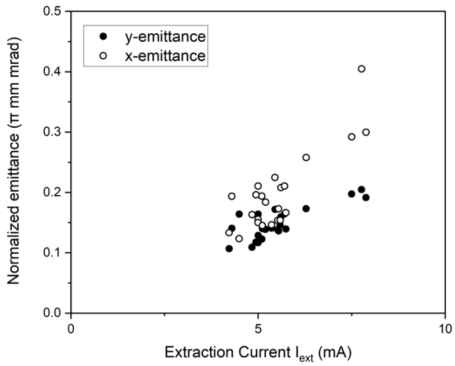

Figure 3: Normalized rms emittance measurements for uranium U^{35+} at different extraction currents.

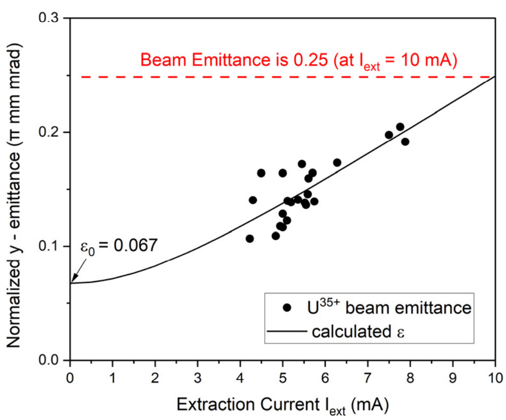

Figure 4: Normalized rms y-emittance measurements for uranium U^{35+} at different extraction currents with the calculated initial beam emittance ε_0 and emittance growth ε.

Based on the measurements, beam conditions with low total current can lead to smaller beam emittance sizes. However, achieving this condition will be challenging while having the objective of producing high beam intensities. As a next step, the optimum ECR parameters to produce high intensity beams will be investigated. A systematic study of the variable ECR parameters such as the microwave power, material consumption rates, and magnetic field strength distribution, will be performed to determine an optimization map and identify the suitable parameters for high intensity beam operation of U^{35+}.

In addition, other steps being considered are space charge compensation techniques to further lower the emittance sizes when necessary. Fundamental studies to understand the beam dynamics in the extraction region are essential and this will be used to properly formulate strategies for space charge beam compensation.

The calculated values for ε_0 represents an initial beam emittance when $I_{ext} = 0$. This may correspond to an emittance influenced by the ion source conditions. As shown in Fig. 5, the graph shows both values for ε_0 and the calculated curves for the magnetic field emittances given by the axial magnetic field strength at the extraction region. The normalized magnetic field emittance is described by the equation [12],

$$\varepsilon_{mag} = 0.032 r^2 B_0 \frac{1}{M/Q} \quad [\pi \text{ mm mrad}] \qquad (2)$$

where r is the radius of the extraction aperture in mm, B_0 is the magnetic field strength in Tesla at the extraction region, and M/Q is the dimensionless mass-charge ratio. Comparing the obtained values of ε_0 to the ε_{mag}, it is found that the experimental measurements have lower emittance sizes. One explanation may be due to the assumptions made for the ε_{mag} having a uniform distribution of the beam size which is often estimated through the diameter of the extraction electrode aperture. From the beam generation in the ECRIS, multiple ion species are co-extracted simultaneously in the extraction region which can affect the effective beam size of a single ion species examined in the beam emittance measurements. Experiments will continue to further investigate the possible beam dynamics that occur during beam extraction.

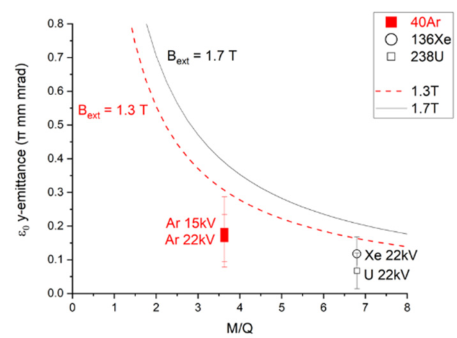

Figure 5: Calculated values for the initial beam emittance ε_0 over the range of mass-charge M/Q values.

Table 2: Parameters for the Different Ion Beams

Ion	V_{ext} (kV)	M/Q	ε_0	K
Ar^{11+}	15	3.6	0.18	3.4E-3
Ar^{11+}	22	3.6	0.16	5.1E-4
Xe^{20+}	22	6.8	0.13	6.7E-4
U^{35+}	22	6.8	0.06	5.7E-4

The calculated values for the different beam conditions are compared in Table 2. For the case of Ar^{11+} ions, experiments with different extraction voltages indicate a difference in their particle velocities. This difference is reflected on the values for the parameter K which is related to space-charge like effects, where the emittance growth is steeper for lower particle velocities. In the case for ions with the same M/Q such as Xe^{20+} and U^{35+} ions, the two beam conditions have the same extraction voltages such that the observed space-charge like effects are both similar. As I_{ext} approaches zero, the initial emittance ε_0 values which may be

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related to the ion source parameters showed a difference in the calculated values. This difference is thought to be influenced by the spatial distribution relating to the angular momentum of the ions caused by the axial magnetic fields during beam extraction. Further investigation is necessary to confirm these effects.

SUMMARY

Development of the RIKEN 28-GHz SC-ECRIS is moving towards intense uranium ion beam production aiming for the beam requirement of ~300 eμA for U^{35+}. Uranium beams up to 250 eμA has been achieved through the development of the high temperature oven to yield optimized material consumption rates for high intensity beam production. As progress moves towards more intense beams, the beam emittance growth was investigated from the experimental measurements. A semi-empirical method was tested and the using the conditions for the target beam requirement, the beam emittance at 10 mA extraction current was estimated to reach 0.25 π mm mrad. Emittance values that correspond to an initial beam emittance and emittance growth relating to space charge effects are being investigated.

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