EXTRACTION SYSTEM AND BEAM QUALITIES OF THE RIKEN FULL SUPERCONDUCTING ECR ION SOURCE

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Abstract

The operation of the new superconducting ECR ion source began using two 18 GHz microwave sources and uranium beams were extracted successfully. A beam current of U^{35+} ions was 10 μA approximately. This paper describes the extraction system and discusses the qualities of the U^{35+} beams by comparing results of the emittance measurements with the tracking calculations.

INTRODUCTION

The accelerator complex of the RIKEN RI beam factory (RIBF) consists of a heavy-ion linac and four ring cyclotrons, and can accelerate all kinds of elements from hydrogen to uranium up to energy of 345 MeV/nucleon [2]. Uranium beams, especially, are valuable to generate many new isotopes, and the increase of their intensity is required strongly. So, a superconducting ECR ion source operated with a 28 GHz microwave source was constructed and was installed on the Cockcroft-Walton high voltage stage upstream of the linac. The beams from the ion source are accelerated with 127 kV and injected into the linac. This ion source generated the first plasma in May 2009 and Xe^{20+} ions were accelerated successfully with the linac in July In December 2009, uranium beams were extracted and provided for the RIBF experiments. The ion source operated with 18 GHz. A beam current of the U^{35+} was 10 μA approximately at rf power of 900 W.

THE SUPERCONDUCTING ECR ION SOURCE

The superconducting magnet of the ion source has structure that a set of sextupole coils are placed inside of six solenoid coils [3]. The magnetic field distributions of the solenoids and the sextupole are shown in Fig. 1. In the figure, the maximum field and the field in 18GHz operation are given. The sextupole coils protrude from the solenoids to reduce the magnetic force acting on the ends of the sextupole coils. Because of this, the extracted beams are influenced from the sextupole fields. Table 1 gives typical operation parameters when U^{35+} ions are provided for the RIBF. Because uranium is supplied by sputtering from metallic one, oxygen and/or argon is used as a supporting gas. The extraction voltage is 15 kV. A configuration of the extraction region is shown in Fig. 2. The extraction electrode is movable and the usual gap is 30 ~ 40 mm.

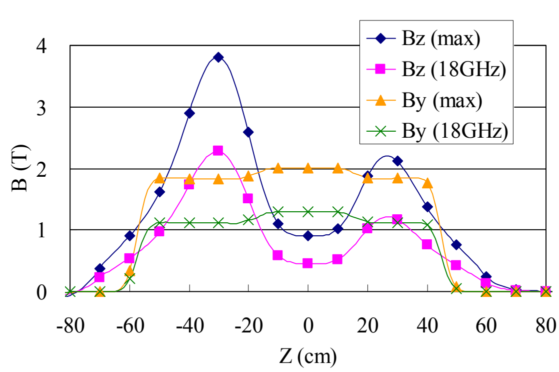

Figure 1: Axial and sextupole magnetic field distributions: Bz indicates the solenoid field along the beam axis and By sextupole field on the surface of the plasma chamber (r = 75mm).

LOW ENERGY TRANSPORT

Figure 3 shows an arrangement of the ion source and the low energy transport (LEBT) placed on the high voltage terminal. The magnetic elements of the LEBT are a solenoid, a 90-degree analyzing dipole, and two steering magnets. The design of the analyzing dipole is the same as the VENUS ion source at LBL [4]. The bending radius, pole gap and edge angle is 510 mm, 180 mm and 27.3 deg, respectively. The pole surface has a three dimensional shape and generates a sextupole field which varies in azimuth to reduce an aberration for large size beams. The beam optics is a double-focus system and the focus point is around 1.0 m downstream from the exit of the dipole.

Table 1: Typical operation parameters.

Beam	U^{35+}
Supporting gas	Oxygen / Argon
Extraction voltage	15 kV
RF source	18GHz, 500W x 2
Voltage of uraniumu rod	5 kV
Vacuum pressure	$6 \times 10^{-5} \sim 1 \times 10^{-4}$ Pa
U^{35+} Current	10 μA
Drain current	2 ~ 3 mA
Normalized beam emittance	0.05 ~ 0.14 πmmmrad

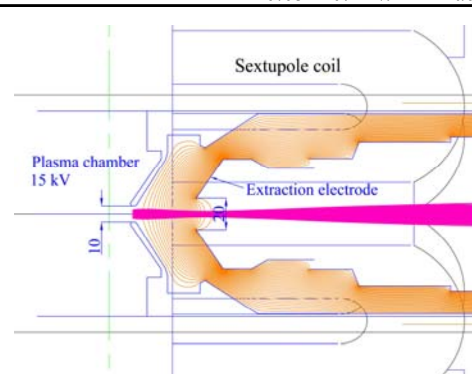

Figure 2: Configuration of the extraction area.

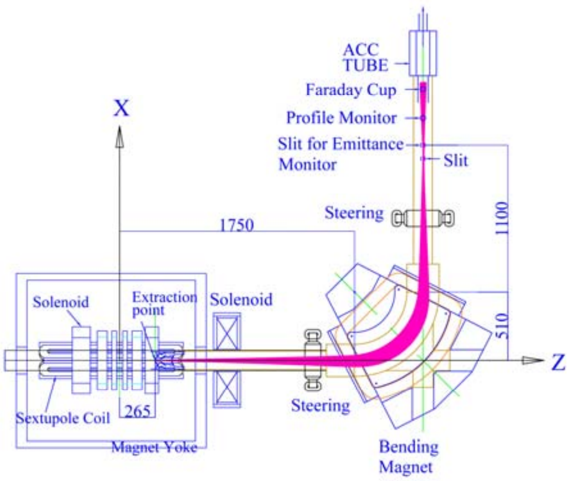

Figure 3: Configuration of the low energy transport.

The horizontal slit is located there. The scanning slit system for the emittance measurement and a beam profile monitor are placed at 1.1 m and 1.3 m downstream from the dipole exit and a Faraday cup is just before an accelerating tube.

EMITTANCE MEASUREMENT

Beam emittance is measured with the scanning slit and the beam profile monitor. A width of the slit is 0.5 mm. Figure 4 shows an instance for a U^{35+} beam with energy of 15 kV/ion. The operation parameters of the ion source are almost the same as those in Table 1 and the supporting gas is argon. The values of the rms emittance are calculated with

$$\varepsilon_{rms} = 4\sqrt{<x^2><x'^2> - <xx'>^2}$$

inside of the square frame in the figure.

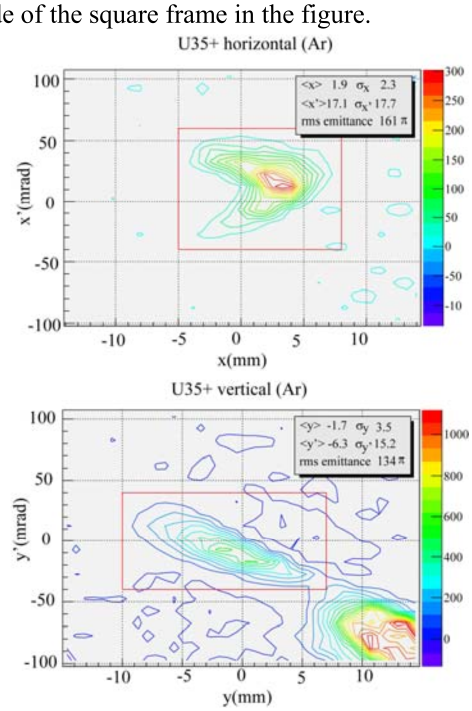

Figure 4: Measured emittance plots for U^{35+} beams.

A heap in right-down area of vertical direction is due to the beams out of the slit. In this case, the rms emittances were 161 and 134 πmmmrad in horizontal and vertical directions. On the other hand, the rms emittances were 210 and 180 πmmmrad approximately when the supporting gas is oxygen. Though U^{35+} current is 8 ~ 10 μA for both cases, the rms emittances were 30% ~ 40% small in the operation which uses argon.

BEAM TRACKING ANALYSIS

Theoretical beam emittance

The normalized beam emittance is:

$$\varepsilon_n = 2R\sqrt{\frac{kT_i}{mc^2} + \left(\frac{\varpi_L R}{2c}\right)^2} ,$$

where R is plasma outlet hole, k is Boltzmann's constant, Ti is ion temperature, ω_L is Larmor's frequency. Neglecting the first term because it is smaller than the second term due to Busch's theorem,

$$\varepsilon_n = \frac{qB}{2mc}R^2 .$$

The magnetic field is 1.15 T at the outlet hole in the 18 GHz operation, and if the outlet beam radius is 3 mm, the normalized emittance becomes 0.245 πmmmrad.

Tracking calculation without space charge effect

We performed the tracking calculations for U^{35+} ions from the outlet hole of plasma to downstream of the analyzing dipole. Calculated rms emittances are shown in Fig. 5. The initial beam radii are 3 mm, 4 mm and 5 mm, and uniform distribution was given. The plasma potential and space charge effect were not considered. The emittance values were calculated at 935 mm down stream from the outlet hole (z=120cm) and the position of the emittance slit (x=160cm). In this calculation, the influence of the sextupole field of the ion source itself was investigated. The results indicate that the rms emittances increase by the existence of the sextupole field. Especially, the emittance increases remarkably after the dipole. As mentioned above, because the measured beam

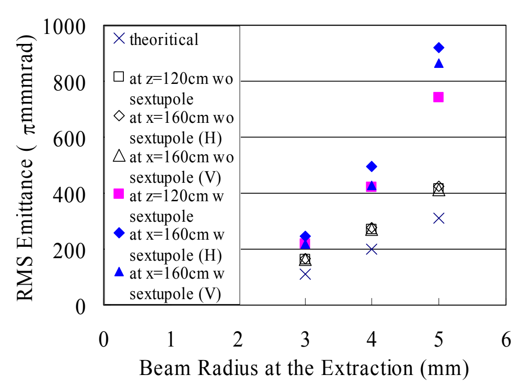

Figure 5: Rms emittances obtained by the tracking calculations without the space charge effect.

Table 2: Currents and initial beam radius in the SCALA calculations.

case index	U	Ox1	Ox2	Ox1-r5	Ar	Ar-r5
Current (μA)	U35+: 10	U35+: 10 O2+: 250 O3+: 250 O4+: 230 O5+: 170 O6+: 160	U35+: 10 O2+: 125 O3+: 125 O4+: 115 O5+: 85 O6+: 80	U35+: 10 O2+: 250 O3+: 250 O4+: 230 O5+: 170 O6+: 160	U35+: 10 Ar3+: 90 Ar4+: 105 Ar5+: 100 Ar6+: 80 Ar7+: 75 Ar8+: 110 Ar9+: 65	U35+: 10 Ar3+: 90 Ar4+: 105 Ar5+: 100 Ar6+: 80 Ar7+: 75 Ar8+: 110 Ar9+: 65
Beam radii at the extraction	3 mm	3 mm	3 mm	3 mm for U 5 mm for O	3 mm	3 mm for U 5 mm for Ar

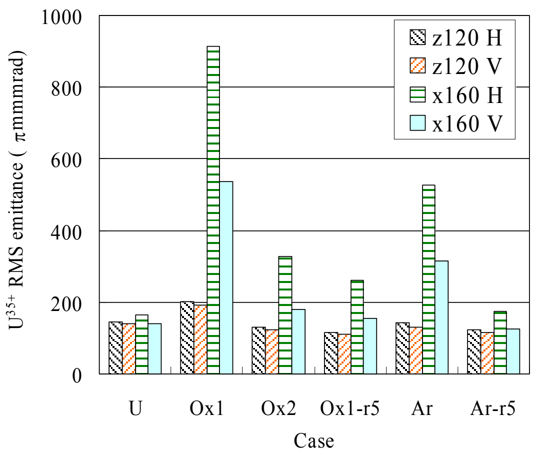

Figure 6: Rms emittances calculated by SCALA considering the space charge effect. Calculation conditions are listed in Table 2.

emittance is 150 ~ 250 πmmmrad, the initial beam radius is estimated to be smaller than 3 mm.

Tracking calculation using SCALA with space charge effect

Next, we performed the tracking calculations using 3d code SCALA [5]. This code can take the space charge effect into account and do tracking for more than one kind of ions simultaneously. The currents of each ion and the initial beam sizes are shown in Table 2. The currents given in the cases Ox1 and Ar are typical values in the real operation. The initial distribution is uniform and the plasma potential is not considered. The beam trajectories of U^{35+} ions calculated for the case Ar-r5 are shown in Fig. 3. Figure 6 shows the rms emittances at z=120cm and x=160cm for the six cases. The rms emittances of the case Ox1 and Ar increase seriously at x=160cm after the analyzing dipole, while they do not at z=120cm before the dipole. These emittances at x=160cm are much larger compared with the measured ones and this suggests that the space charge effect is too large. So, in the cases Ox1-r5 and Ar-r5, the initial beam size of the supporting ions was enlarged to 5 mm in radius. The calculated rms emittances at x=160mm in these cases are agreement with the measured values. Especially, these calculations simulate the measured results well in the followings: the horizontal emittance is larger than the vertical, the emittances of the Ar-r5 case is smaller than those of the

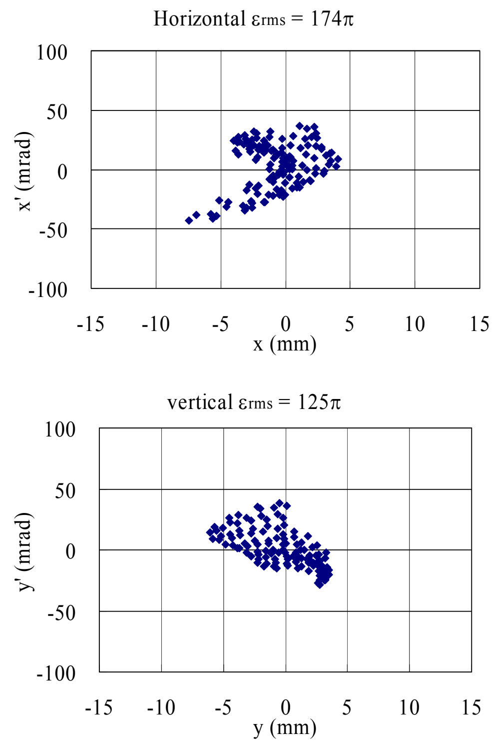

Figure 7: Emittance plots at the position of the emittance slit obtained by the SCALA calculation. Current condition is the case Ar-r5 in Table 2.

Ox1-r5 case. Figure 7 shows the calculated emittance plots at x=160cm for the case Ar-r5. Compared with the measured plots in Fig. 4, the horizontal plots resemble each other. On the other hand, vertical plots have small difference and the vertical focus point of the measured beam is located downstream by 10cm approximately.

According to these calculation results, when a beam current of U^{35+} increases by the larger rf power, it is expected that the beam emittance increases as well. Because, however, the emittance acceptance of the first-stage ring cyclotron is 0.4 πmmmrad (normalized) approximately, the beam with an emittance of larger than 180 πmmmrad at the ion source makes a loss and it may be difficult to increase the beam current provided for experimenters. Therefore it is expected that use of the oven system whose development is under progress suppresses the current of supporting gas and increase the U^{35+} currents without the emittance increase.

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