EMITTANCE MEASUREMENTS FOR RIKEN 28 GHZ SC-ECRIS

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Abstract

In 2012, intense beams of highly charged uranium ions (180 eμA for U^{35+}, 230 eμA for U^{33+}) were extracted from RIKEN SC-ECRIS. Following this success, an intense beam of U^{35+} ions was used for the radioisotope beam factory (RIBF) experiment for a long period (about one month). It is obvious that production of high quality beams (characterized by smaller emittance and good stability etc) is also important for the RIKEN RIBF project. Therefore, in 2014, we systematically measured the emittance and beam intensity of highly charged uranium ions under varying conditions of magnetic field configuration, extracted beam intensity, beam stability etc. to obtain the optimal condition for the production of high-quality beams. In these experiments, we observed that the extent of emittance strongly depends on the magnetic field configuration, especially on B_{ext}.

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INTRODUCTION

During the last several years, we have been working on increasing the intensity of highly charged uranium (U) ion beams and we have produced intense beams (~180 eμA for U^{35+} and ~230 eμA for U^{33+}) using the sputtering method [1]. In 2013, we produced ~90 eμA of U^{35+} for long-term usage in RIKEN radioisotope beam factory (RIBF) experiments. Consequently, in the course of the last several years, the intensity of U ion beams had dramatically increased. As an external ion sources for heavy ion accelerators, it is obvious that improving the quality of the beam characteristics, such as emittance and stability, is also important. Production of intense beams from the accelerator is key in producing intense RI beams, especially in the RIKEN RIBF project. For example, the overall design power of a U ion beam (beam intensity of 1 pμA) at the energy of 345 MeV/u is 82 kW. In this case, beam loss has to be minimized to avoid damaging the accelerator. It is obvious that the emittance of highly charged U ion beams should be sufficiently smaller than the acceptance of the accelerators of the RIKEN RIBF for safety acceleration. Therefore, to minimize the extent of emittance for intense beams of U ions, we intensively studied the effect of the ion source parameters on the emittance. As described in a previous paper [2], if the magnetic field distribution affects the ion dynamics and the trajectory of the extracted beams, it may also affect the emittance of highly charged heavy ions.

In this paper, we describe the experimental results regarding the effect of various ion source parameters (drain current, position of the beam extraction electrode, and magnetic field distribution) on the emittance of highly charged U ion beams.

EMITTANCE MEASUREMENT FOR U ION BEAMS

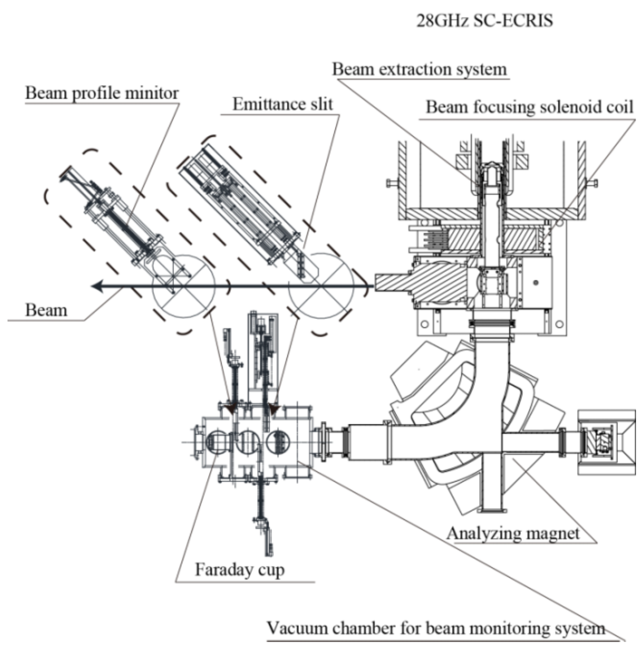

Figure 1: Schematic drawing of of the beam extraction system of the ion source and Low energy line with beam-monitoring system.

The sputtering method was used for production of highly charged U ion beams. The method is described in detail in ref. [3]. The main feature of the ion source is that it has six solenoid coils for producing the mirror magnetic field. Using this configuration, one can produce so-called "flat B_{min}" [4] and classical B_{min}. In this experiment, the extraction voltage was fixed at 22 kV.

Figure 1 shows the schematic drawing of the beam extraction system of the ion source and the low-energy beam line (analyzing magnet and beam monitoring system). Emittance was measured using the emittance monitor, which consists of a movable thin slit (emittance slit in Fig. 1) and wires (beam profile monitor in Fig. 1). We also installed the beam slit and Faraday cup in the vacuum chamber of the beam monitoring system.

The root mean square (rms) emittance is defined as

$$\varepsilon_{x-rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$
$$\varepsilon_{y-rms} = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2} \quad (1)$$

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In these equations, the averages of the phase-space coordinates of position (x, y) and divergence (x', y') are weighted by the beam intensity [5].

Effect of the Drain Current

In general, space charge strongly affects the beam trajectory and the extent of emittance. To study the effect, we measured the emittance of U^{35+} ions for various drain currents. Magnetic field distribution was the same as that in Fig. 1. Figure 2 shows the rms emittance as a function of the ion source drain current, which is proportional to the extraction current. The error bars (emittance spread) are the standard deviations. The emittance slightly increased from 0.07 to 0.08 π mm mrad as the drain current increased from ~2.5 mA to ~4.7 mA. We conclude that the space charge mostly compensates in this experiment. Furthermore, we observed the emittance spread for the same drain current as that shown in Fig. 2. This may be attributed to the plasma instabilities. Further investigation is needed to understand this phenomenon.

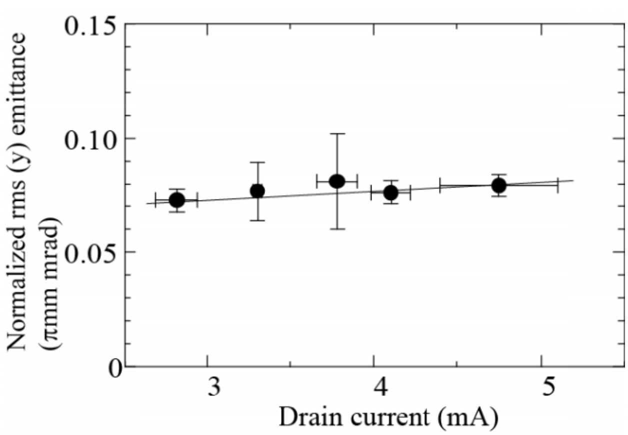

Figure 2: Normalized rms emittance as a function of drain current.

Effect of the Extraction Electrode Position

The position of the extraction electrode should affect the beam trajectory in the beam extraction region. Consequently, the emittance may depend on the electrode position. To study the effect of the electrode position on the emittance, we measured the emittance as a function of the extraction electrode position that ranged from ~25 mm to ~45 mm. Figure 3 shows the schematic of the beam extraction side. The position of the extraction electrode (L) is defined in Fig. 3. Magnetic field distribution was fixed at B_{inj}~3.1 T, B_{min}~0.65 T, B_{ext}~1.78 T and B_r~1.82 T. Figure 4 shows the normalized rms y-emittance of U^{35+} ions beam as a function of extraction electrode position (L). We observed that the effect of electrode position was very weak and the emittance slightly increased with decreasing L.

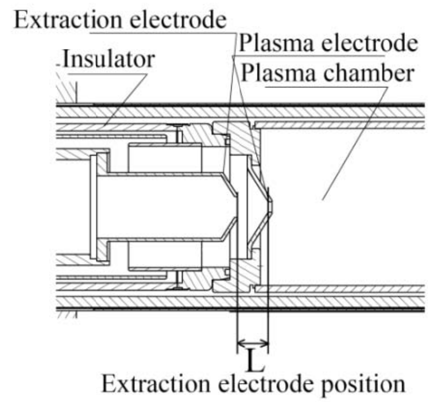

Figure 3: Schematic of the beam extraction side.

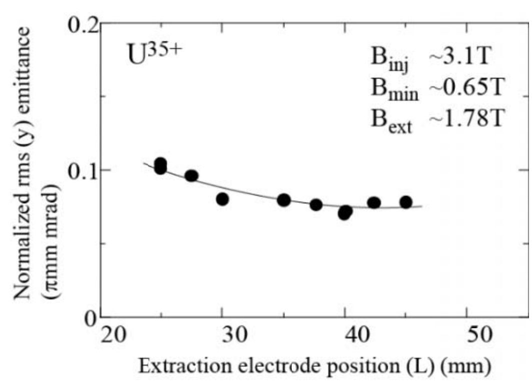

Figure 4: Rms emittance as a function of extraction electrode position (L).

Effect of the Magnetic Field Distribution

To investigate the magnetic field distribution effect, we measured the emittance for various magnetic field distributions with 18- and 28-GHz microwaves.

Figure 5 shows the magnetic field distribution for investigating the B_{ext} effect with 28GHz microwaves. The magnitude of B_{ext} was changed from ~1.8 T to ~1.4 T, while keeping the other magnetic fields strengths constant (B_{inj}~3.1 T, B_{min}~0.65 T and B_r~1.8 T). The RF power and the extraction voltage were ~1.5 kW and 22 kV, respectively. Figure 6 shows the normalized rms y-emittance as a function of B_{ext}. The emittance drastically changed from ~0.07 to ~0.17 π mm mrad as B_{ext} decreased from ~1.4 T to ~1.8 T. The beam intensity also depended on B_{ext}. It changed from ~60 eμA to 40 eμA as B_{ext} decreased from ~1.8 T to ~1.4 T.

In this figure, open circles denote the averaged emittance for various drain currents (2.5~4.5 mA), which is proportional to the extraction current. The error bars (emittance spread ~0.015 π mm mrad) are the standard deviations.

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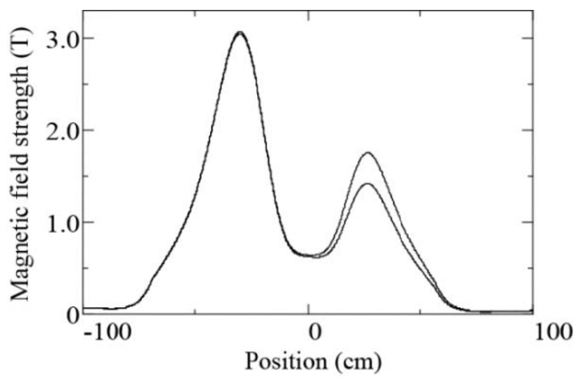

Figure 5: Magnetic field distribution for the B_{ext} effect with 28-GHz microwaves.

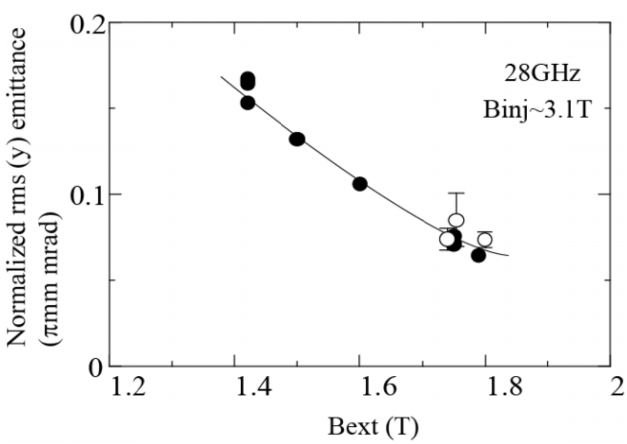

Figure 6: Normalized rms y-emittance as a function of B_{ext}.

Figure 7 shows the magnetic field distribution for investigating the B_{inj} effect. The magnitude of B_{inj} was changed from ~1.5 T to 3.1 T while keeping the other magnetic fields strengths constant (B_{ext} ~1.45 T, B_{min} ~0.65 T, B_r ~1.8 T). Figure 8 shows the results for rms y-emittance. Emittance increased from ~0.09 to ~0.17 π mm mrad as B_{inj} increased.

It should be noted that the B_{ext} in Fig. 7 was much lower than the typical magnetic field strength (so-called "high B mode operation" [6]) that is required to produce intense beams of highly charged heavy ions.

The "high B mode operation" takes B_{ext}~$2B_{ecr}$, which is higher than B_{ext}~1.45 T. In this condition, the emittance would be almost constant and independent of B_{inj}, as shown in Fig. 9. In Figure 9, the open circles are averaged emittance for B_{ext}~1.75 T. The error bars (emittance spread) are the standard deviations.

In the previous section, we presented the effect of the extraction electrode position on the emittance for the specific condition (B_{inj}~3.1 T, B_{min}~0.65 T, B_{ext}~1.78 T and B_r~1.82 T). To determine the extraction electrode position effect for additional magnetic field distributions, we measured the emittance as a function of electrode position for two conditions.

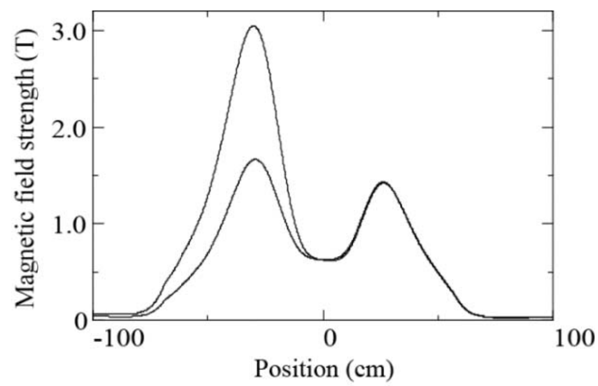

Figure 7: Magnetic field distribution for the B_{inj} effect with 28-GHz microwaves.

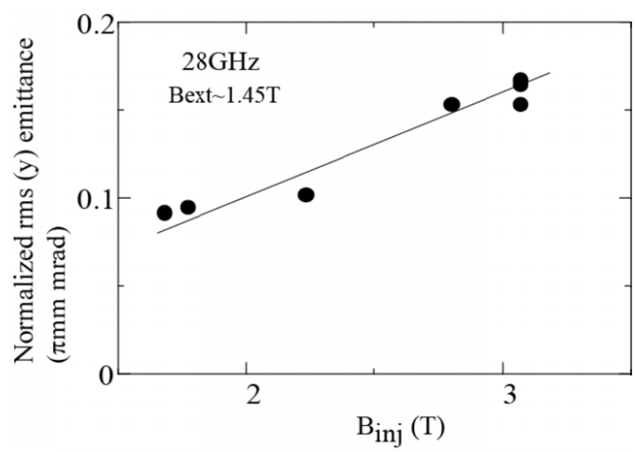

Figure 8: Magnetic field distribution for the B_{inj} effect with 28-GHz microwaves, for B_{ext}~1.45 T.

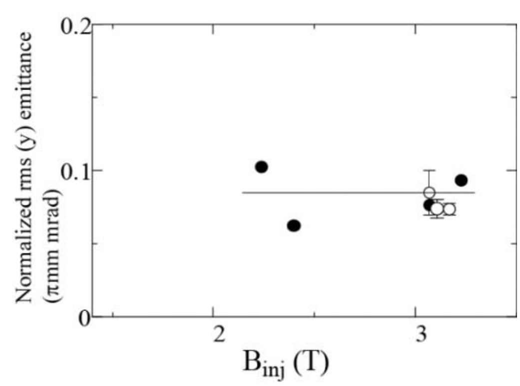

Figure 9: Magnetic field distribution for the B_{inj} effect with 28 GHz microwaves, for B_{ext}~1.75 T.

Figures 10 a) and b) show the effect of the extraction electrode position. Emittance was almost constant and ndependent of the position. Therefore, the emittance for U^{35+} ions beams might not be dependent on the extraction electrode position for the magnetic field distribution in

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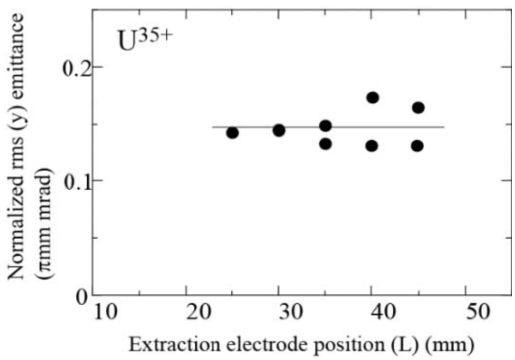
these test experiments. For these experimental results, we may conclude that ion dynamics in the plasma may be affected by B_{inj}; consequently, the emittance was changed by changing the B_{inj}.

a)



b)

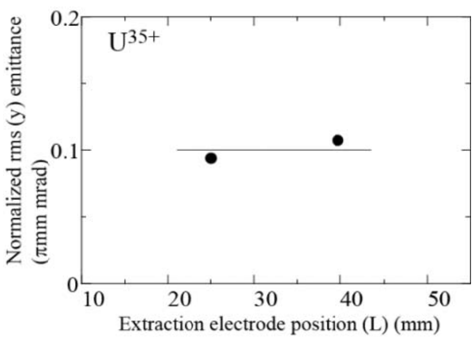


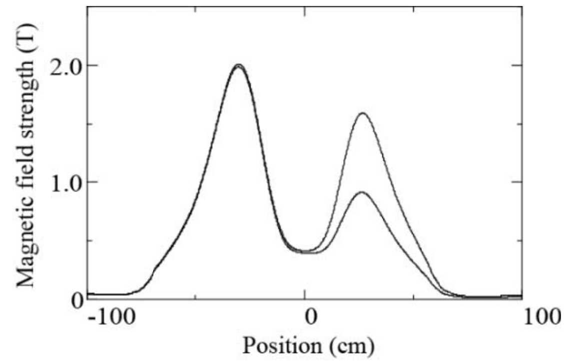
Figure 10: Normalized rms y-emittance as a function of extraction electrode position. a) B_{inj}~3.1 T, B_{min}~0.65 T, B_{ext} ~1.45 T, and B_r~ 1.8 T; b) B_{inj}~ 1.6 T, B_{min}~0.65 T, B_{ext}~1.45 T, and B_r~1.8 T.

We also observed the same phenomena for magnetic field distribution with 18-GHz microwaves. To study the B_{ext} effect, the magnitude of B_{ext} was changed from 0.9 T to 1.6 T. The RF power and extraction voltage were 500 W and 22 kV, respectively.

Figures 11 a) and b) show the magnetic field distribution for studying the effect of B_{ext} with 18-GHz microwaves and the normalized rms y-emittance as a function of B_{ext}, respectively. The emittance decreased as B_{ext} increased up to ~1.4 T and then saturated for B_{ext} above ~1.4 T. In this experiment, the minimal emittance of ~0.06 π mm mrad was obtained.

Figures 12 a) and b) show the magnetic field distribution for studying the effect of B_{inj} with 18-GHz microwaves and the normalized rms y-emittance as a function of B_{inj}, respectively. B_{ext} was fixed at 0.9 T. B_{min} values of 0.4 T and 0.5 T were chosen for this experiment. The emittance was changed from ~ 0.1 to ~0.2 π mm mrad up to 2 T, and then saturated. The maximal emittance was ~0.2 π mm mrad.

a)



b)

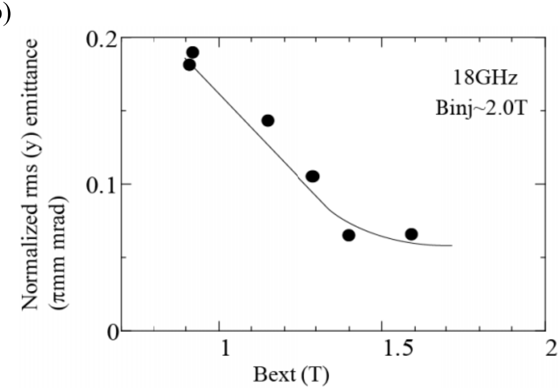
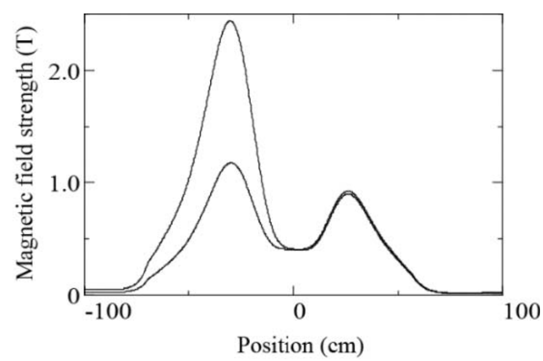


Figure 11: a) Magnetic field distribution for studying the effect of B_{ext}, b) Rms emittance as a function of extraction electrode position.

a)



b)

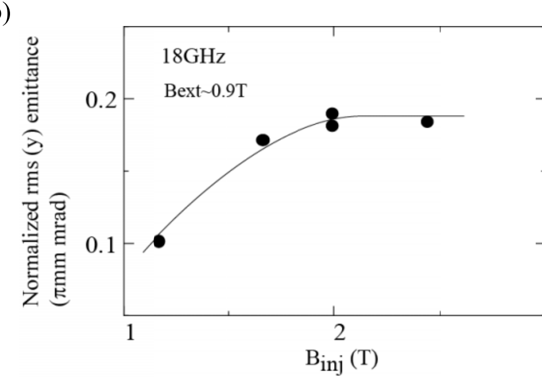


Figure 12: a) Magnetic field distribution for studying the effect of B_{inj}, b) Normalized rms emittance as a function of B_{ext}.

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For the B_{inj} effect, we observed that the emittance increased as B_{inj} increased up to 2 T, and then saturated at ~0.2 π mm mrad. This is an interesting result because the magnetic field strength at the extraction was identical for different values of B_{inj}. In addition, the emittance was not strongly affected by the extraction current. Therefore, the extraction condition should not affect the emittance. This implies that the emittance of U^{35+} ions beam was influenced by the ion dynamics in the plasma modified by the B_{inj}. Further investigation is required to understand this phenomenon.

OTHER ION SPECIES

To study the effect of magnetic field distribution on the emittance for other ion species, we measured the emittance for O, Kr, and Xe ions beams. Figure 13 shows preliminary results of the normalized rms y-emittance for Kr ions as a function of B_{ext}. The B_{inj} and B_{min} were kept at ~3.1 T and ~0.65 T, respectively. The RF power and the extraction voltage were ~1.5 KW (28 GHz) and 22 kV, respectively. It seems that the emittance slightly depended on B_{ext} for higher charge state Kr ions. Figure 14 shows the results for Xe ions. The emittance dependency was nearly the same as that for Kr ions beams. We also measured the emittance for oxygen ions. The emittance of multi-charged oxygen ions did not depend on the magnetic field distributions.

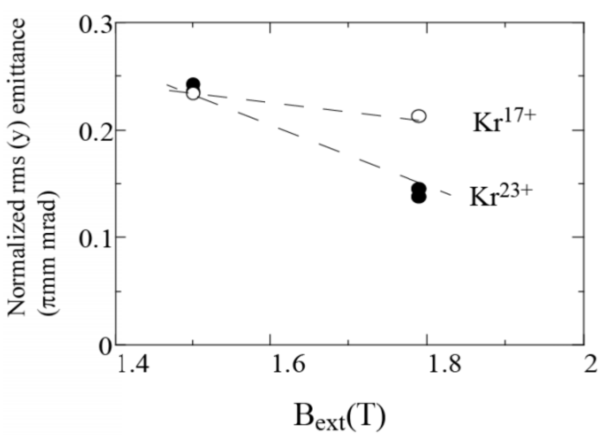

Figure 13: Normalized rms y-emittance for highly charged Kr ions as a function of B_{ext}.

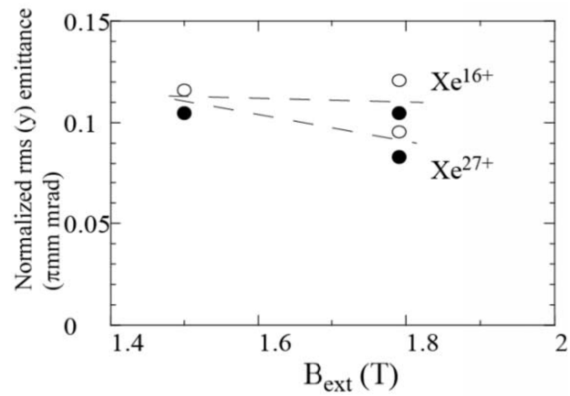

Figure 14: Normalized rms y-emittance for highly charged Xe ions as a function of B_{ext}.

CONCLUSION

We measured the emittance of U^{35+} ions for various ion source conditions. The extent of emittance was independent of the drain current and extraction electrode position. On the other hand, it strongly depended on the magnetic field distributions. The B_{inj} effect may yield some novel information, implying that the emittance of U^{35+} ions is not influenced by the extraction conditions, but rather by the ion dynamics in the plasma modified by B_{inj}. On the other hand, for less heavy ions such as Xe, Kr, and O ions, preliminary experimental results did not show any strong effects of the magnetic field distributions as in U^{35+} ion beams. The magnetic field distribution may affect only highly charged very heavy ions. Additional research is required to understand these phenomena.

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