FURTHER IMPROVEMENT OF PERFORMANCE OF RIKEN 28GHZ SC-ECRIS AND SEARCH FOR THE OPTIMUM STRUCTURE OF ECR ION SOURCES

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1.Introduction

RIKEN SC-ECRIS

2. Effect of Magnetic field distribution

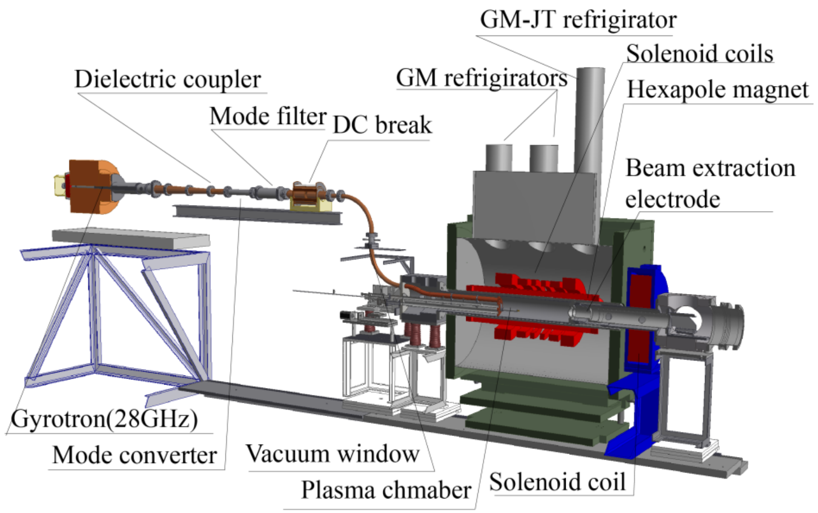
Microwave absorption

Magnetic mirror

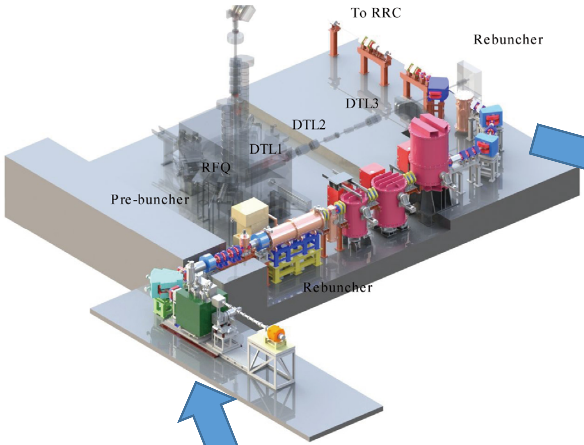
3. Sputtering method

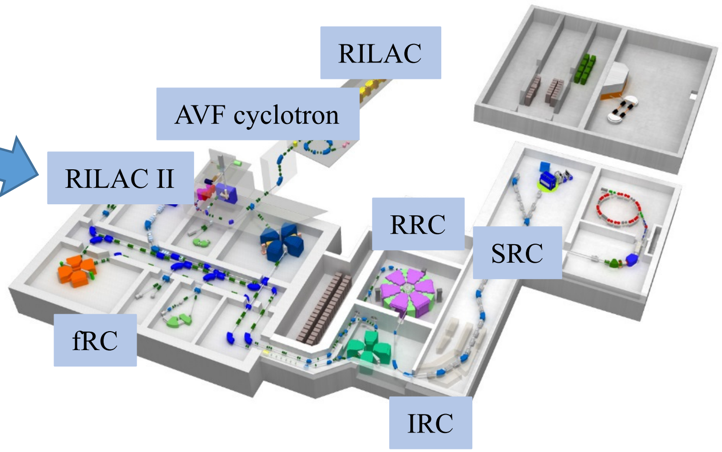
consumption rate

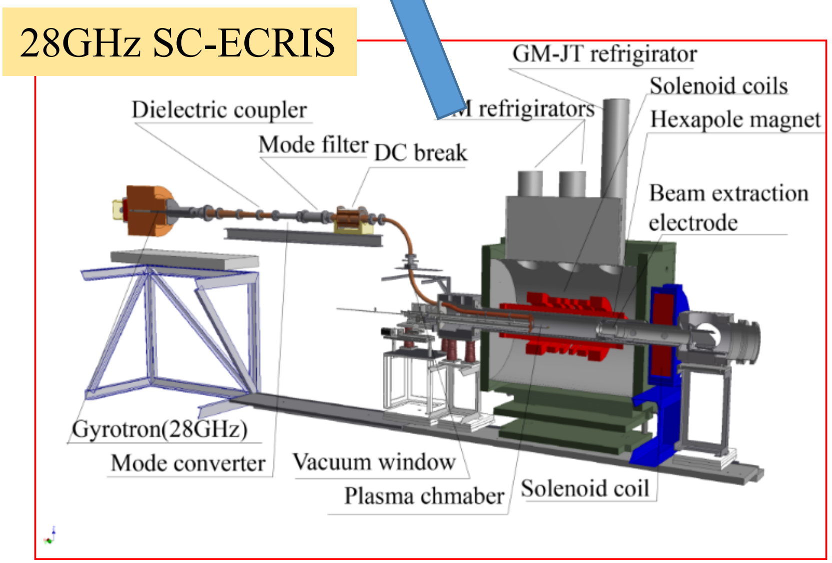
4. Optimum structure of ECR ion source

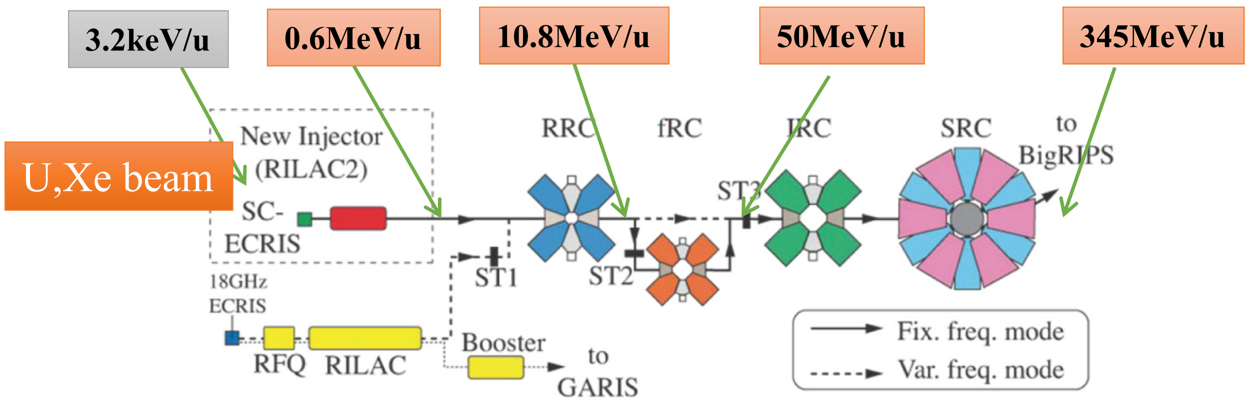


RIKEN 28GHz SC-ECRIS I

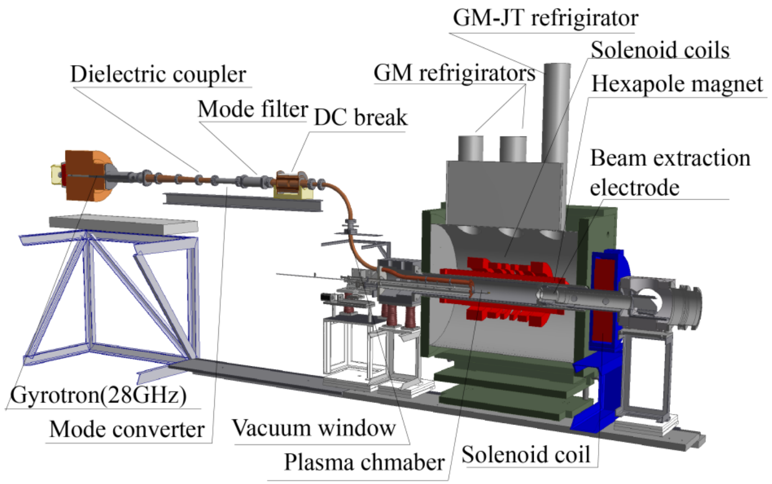








RIKEN 28GHz SC-ECRIS II

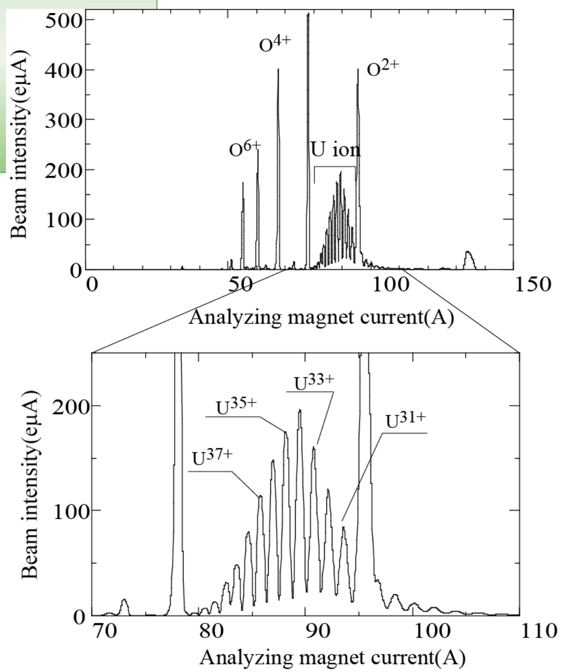


B_{inj}	~3.8T
B_{min}	<1T
B_{ext}	~2.2T
B_r	~2.2T
Microwave	28GHz, 18GHz
RF power	<10kW
Chamber dia.	15cm
length	50cm
Cooling power (4.2k)	~8W

The RIKEN SC-ECRIS can be operated at flexible axial field distributions with six solenoid coils

It is possible to change the gradient of the magnetic field strength and the surface size of the ECR zone.

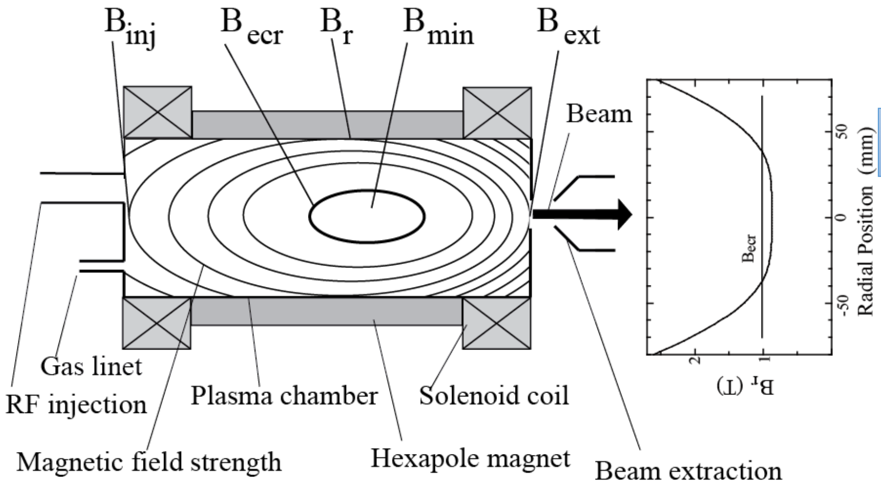
The RIKEN 28GHz SC ECRIS produced ~200eμA of U^{35+}, with the sputtering method at the injected RF power of ~2.6kW (28GHz).

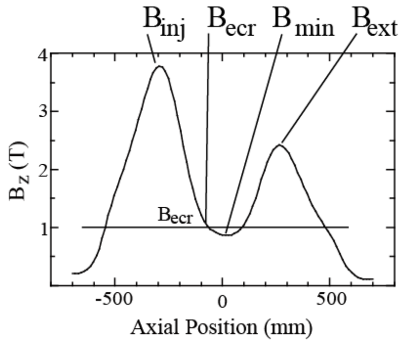


T. Nakagawa et al, Rev. Sci. Instrum.81 (2010) 02A320.
G. D. Alton and D. N. Smithe, Rev. Sci. Instrum. **65**, 775 (1994).

Key parameter of ECRIS

Key parameters of ECR ion source





ECR ion source

Magnetic mirror machine

Magnetic field distribution
B_{inj}, B_{ext}, B_{min}, B_r

Mirror ratio
B_{inj}/B_{min}……

Microwave power absorption
B_{min}

Microwave power and frequency

Gas pressure

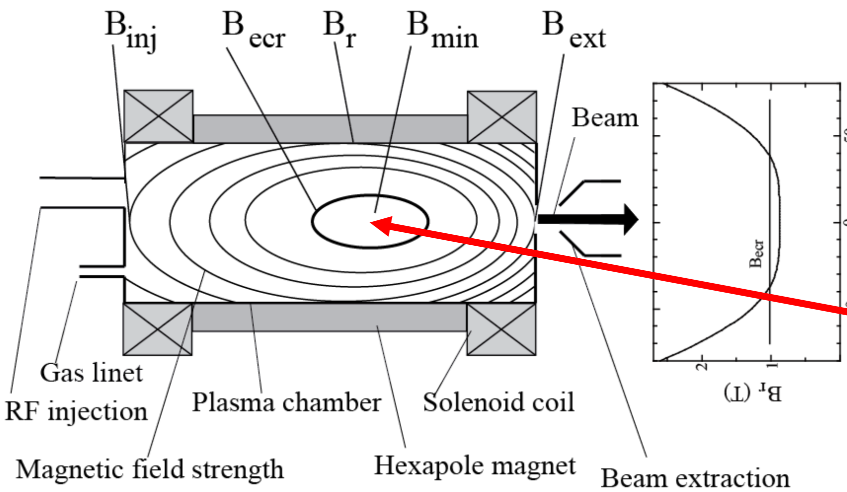
Geometrical effect
chamber size
chamber shape

High B and new formula

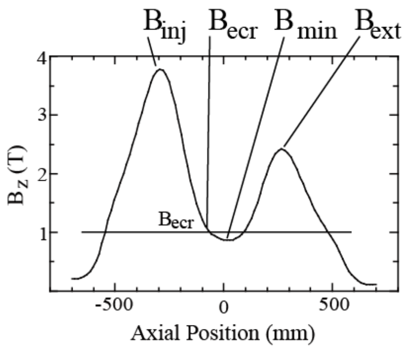
S. Gammino, G. Civola, L. Celona, M. Castro, F. Chines, and S. Marletta, Rev. Sci. Instrum. **70**, 3577 (1999).

D. Hitz, A. Girard, G. Melin, S. Gammino, G. Ciavola, and L. Celona, Rev. Sci. Instrum. **73**, 509 (2002).

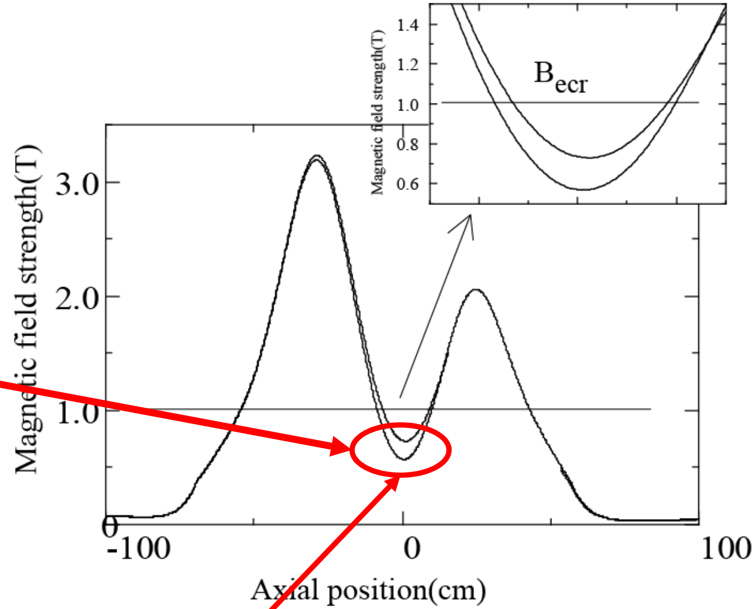
B_{min} effect



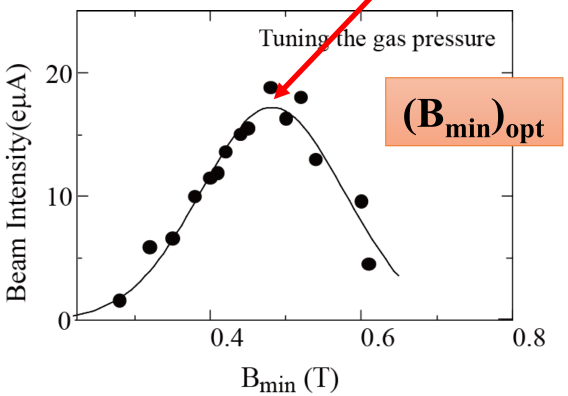
B inj
B ecr
B r
B min
B ext
Beam
Gas linet
RF injection
Plasma chamber
Solenoid coil
Magnetic field strength
Hexapole magnet
Beam extraction
Becr
Radial Position (mm)
Br (T)



Binj Becr Bmin Bext
Bz (T)
Becr
-500 0 500
Axial Position (mm)

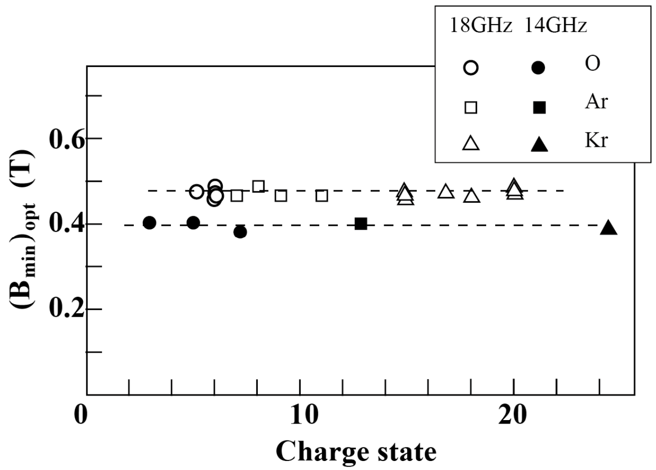


Magnetic field strength(T)
Becr
Axial position(cm)
-100 0 100



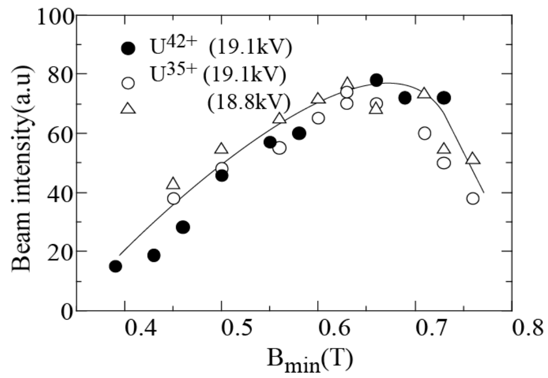
Tuning the gas pressure
(Bmin)opt
Beam Intensity(eμA)
Bmin (T)

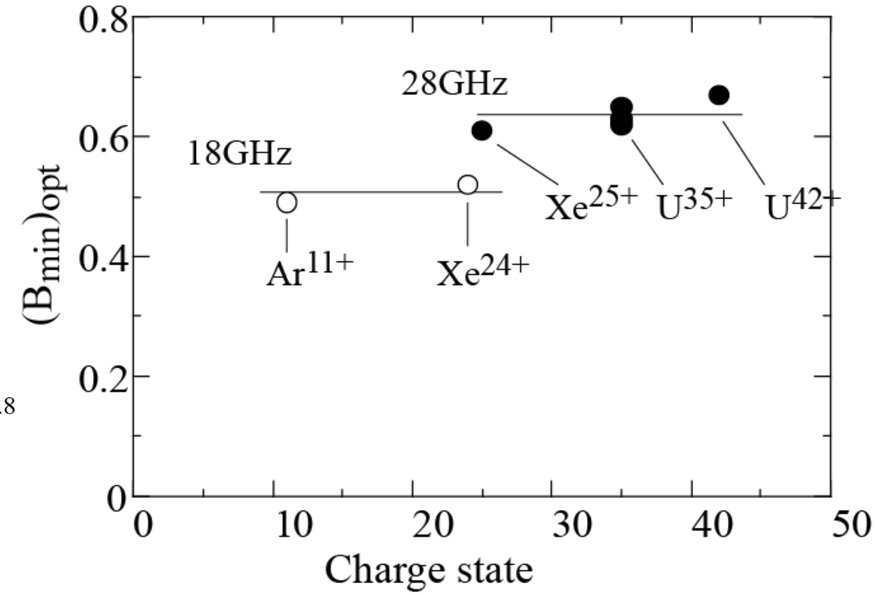
B_{min} *effect*



Liquid He free SC-ECRIS (14, 18GHz)

28GHz SC-ECRIS



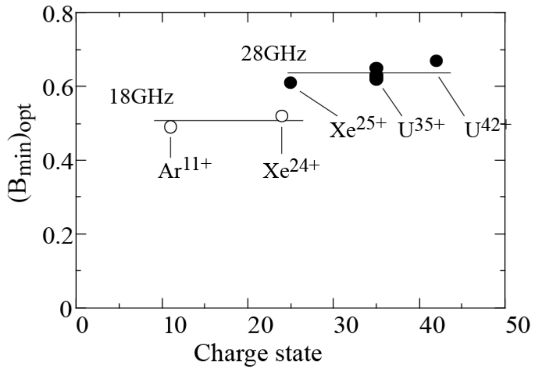


RIKEN 28GHz SC-ECRIS (18, 28GHz)

It is well known that the optimum value of the minimum mirror magnetic field strength $(B_{min})_{opt}$ maximizes the beam intensities of highly charged heavy ions; for electron cyclotron resonance (ECR) ion sources with 14 GHz and 18 GHz microwave operation, $(B_{min})_{opt}$ was determined to be about 80% of the magnetic field strength at the ECR point (B_{ecr}). For 28GHz, $(B_{min})_{opt}$ was ~0.65T (65% of B_{ecr})

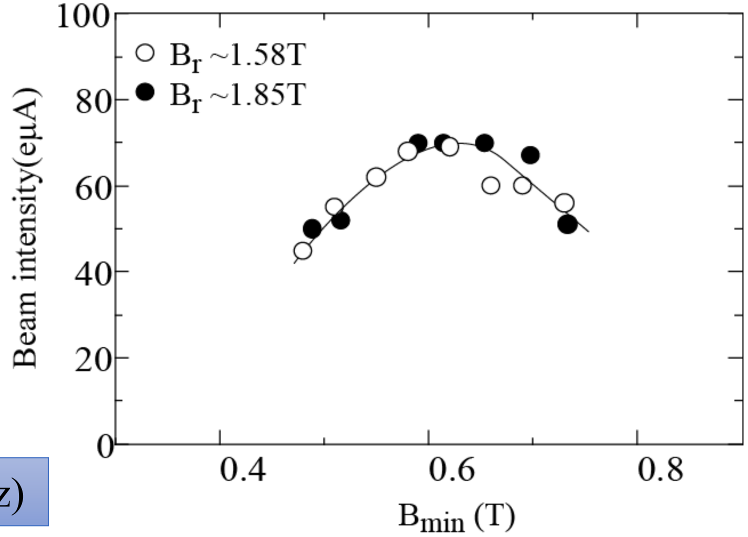
B_{min} effect (different B_{ext}, B_r)

B_{ext}~1.75T

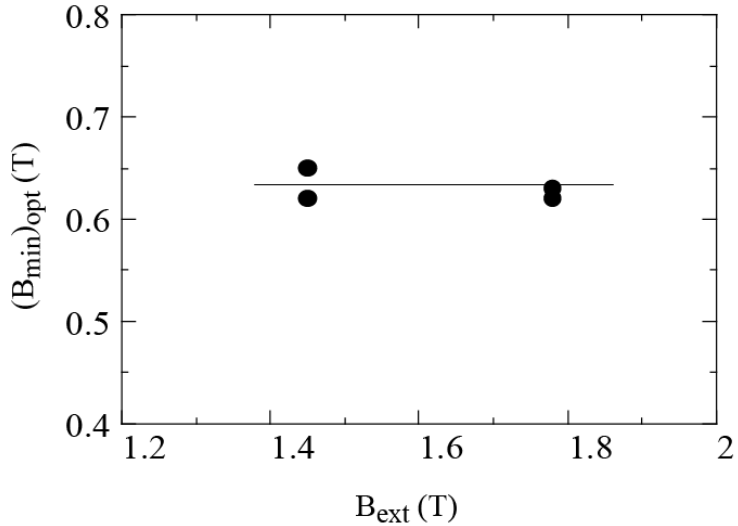


B_{inj}~3.1T, B_{ext}~1.75T, B_r~1.8T(28GHz)

Br effect (B_{ext}~1.45T)

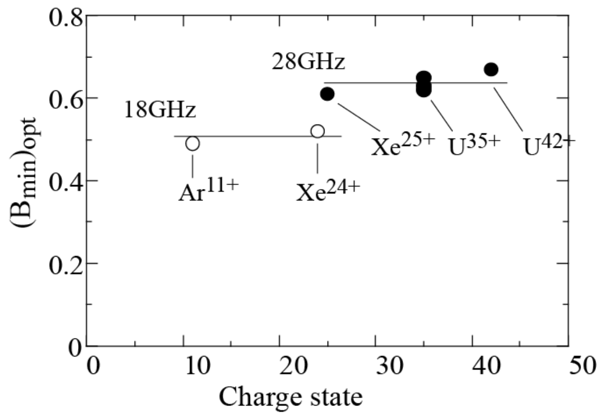


Bext effect (B_r~1.8T)



For the 28 GHz microwaves, the optimum value of B_{min} to maximize the beam intensity (($B_{min})_{opt}$) was ~0.65 T for the production of the U ion beam. To investigate the effectiveness of this tendency in a wider parameter range, we measured $(B_{min})_{opt}$ for different values of B_{ext} and B_r. Figure shows the beam intensity of U^{35+} ions as a function of B_{min} for B_r ~ 1.58 T, and B_r ~ 1.85 T. The beam intensity increased with increasing B_{min} and decreased for B_{min} values above ~0.65 T. Figure shows the results as a function of B_{ext}. Roughly speaking, we observed that $(B_{min})_{opt}$ is not dependent on the B_r and B_{ext} in the range measured in this experiment.

B_{min} effect (frequency)



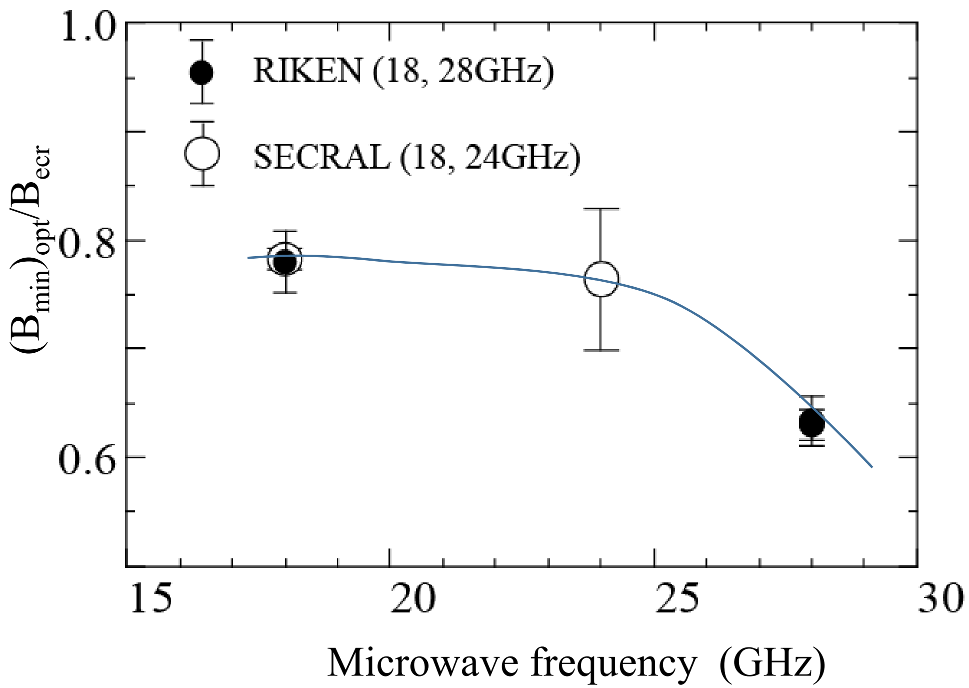


Figure shows $(B_{min})_{opt}$ for several microwave frequency (18~28GHz). Open circles shows the results of SECRAL.(RSI 81 02A202(2010), ECRIS2010) Closed circles show the results of RIKEN SC-ECRIS. (Bmin)opt gradually decreases with increasing the microwave frequency

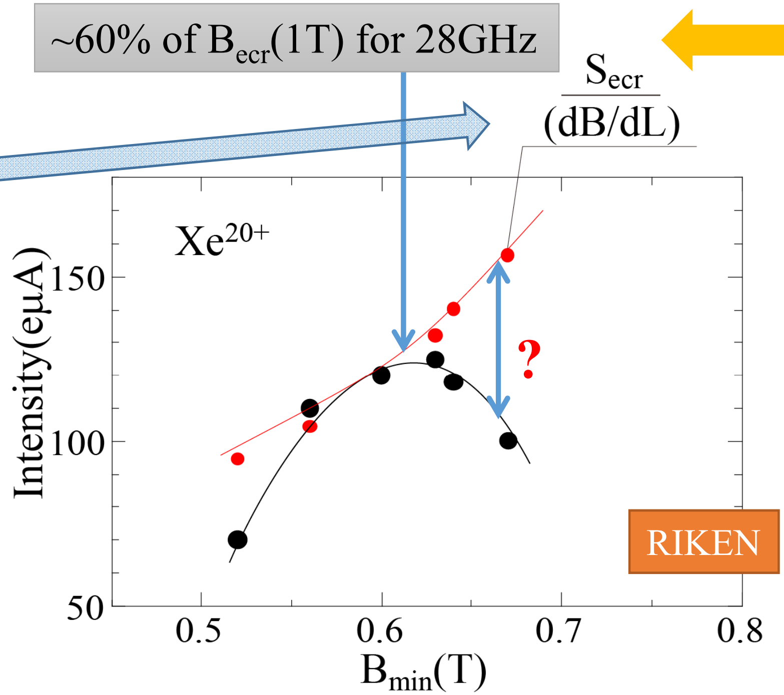
B_{min} (mechanism)

Power absorption at ECR zone

$$W_{power} = \left(\frac{\pi n e^2 E^2}{m\omega \left(\frac{dB}{dZ} \right)} \right) S_{ecr}$$

Secr: surface size of ECR zone

(dB/dZ): magnetic field gradient



Plasma instability

$$\frac{dE_\mu}{dt} \approx \langle \gamma - \delta \rangle E_\mu$$

$$\gamma_w \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle} - 1 \right) e^{-\xi \frac{B^2}{\langle E_\parallel \rangle N_{e,cold}}}$$

$$\gamma_x \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\parallel \rangle^2}{\langle E_\perp \rangle m_e c^2} \right),$$

$$\delta_w \approx \frac{\omega}{\omega_{ce}} \nu_e + \frac{v_g |\ln R|}{L}$$

$$\delta_x \approx \nu_e + \frac{v_g |\ln R|}{L},$$

O. Tarvainen et al, Plasma Sci. tech. 23(2014)025020

Red line shows the calculated result of the RF absorption of plasma. The absorption power increases with increasing the B_{min}(gentler field gradient. However the beam intensity becomes maximum at Bmin~0.65T. One of the possible explanation is that it may be due to the plasma instabilities. It is strongly dependent on the number of hot electrons, electron temperature, etc as shown in the formula

B_{min} (mechanism)

Plasma instability

$$\frac{dE_\mu}{dt} \approx \langle \gamma - \delta \rangle E_\mu$$

$$\gamma_w \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle} - 1 \right) e^{-\xi \frac{B^2}{\langle E_\parallel \rangle N_{e,cold}}}$$

$$\gamma_x \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\parallel \rangle^2}{\langle E_\perp \rangle m_e c^2} \right),$$

$$\delta_w \approx \frac{\omega}{\omega_{ce}} \nu_e + \frac{v_g |\ln R|}{L}$$

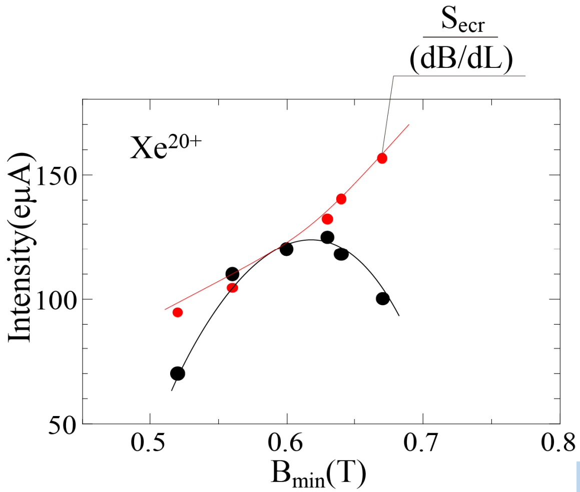
$$\delta_x \approx \nu_e + \frac{v_g |\ln R|}{L},$$

Key parameters

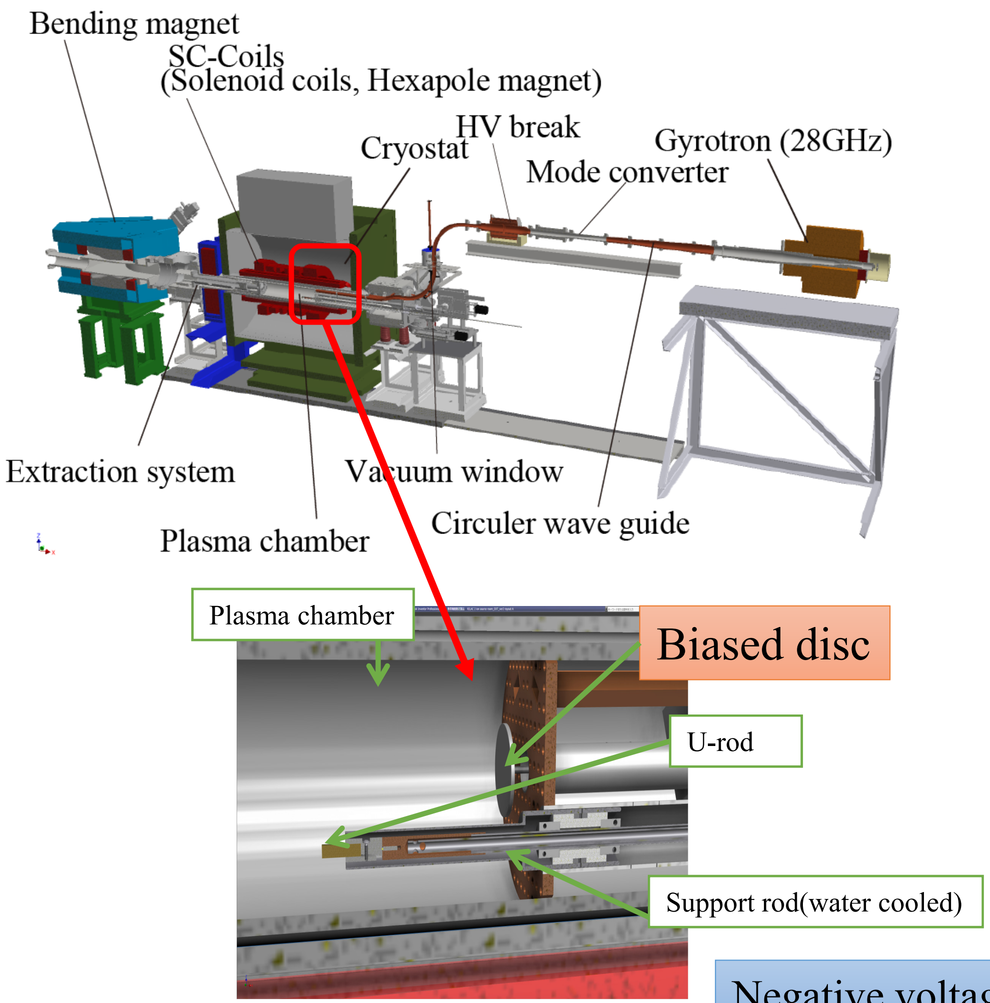
$$\frac{N_{e-hot}}{N_{e-cold}}$$

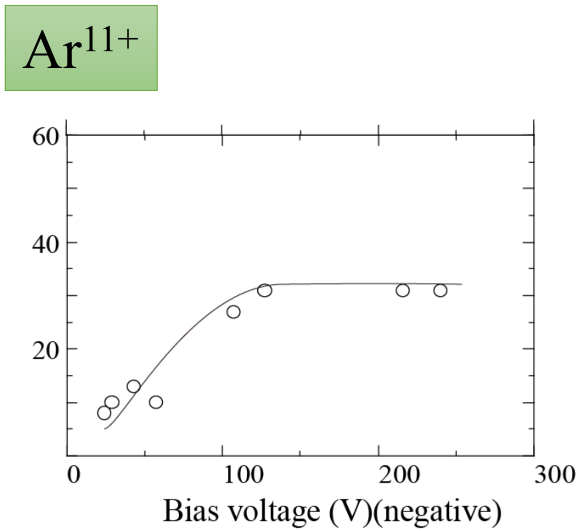
Electron injection (biased disc)

$$\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle}$$



B_{min} *(mechanism) Biased disc (electron donor)*





Negative voltage is supplied to the metal disc

B_{min} (mechanism) Biased disc (electron donor)

Plasma instability

$$\frac{dE_\mu}{dt} \approx \langle \gamma - \delta \rangle E_\mu$$

$$\gamma_w \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle} - 1 \right) e^{-\xi \frac{B^2}{\langle E_\parallel \rangle N_{e,cold}}}$$

$$\gamma_x \propto \omega_{ce} \frac{N_{e,hot}}{N_{e,cold}} \left(\frac{\langle E_\parallel \rangle^2}{\langle E_\perp \rangle m_e c^2} \right),$$

$$\delta_w \approx \frac{\omega}{\omega_{ce}} \nu_e + \frac{v_g |\ln R|}{L}$$

$$\delta_x \approx \nu_e + \frac{v_g |\ln R|}{L},$$

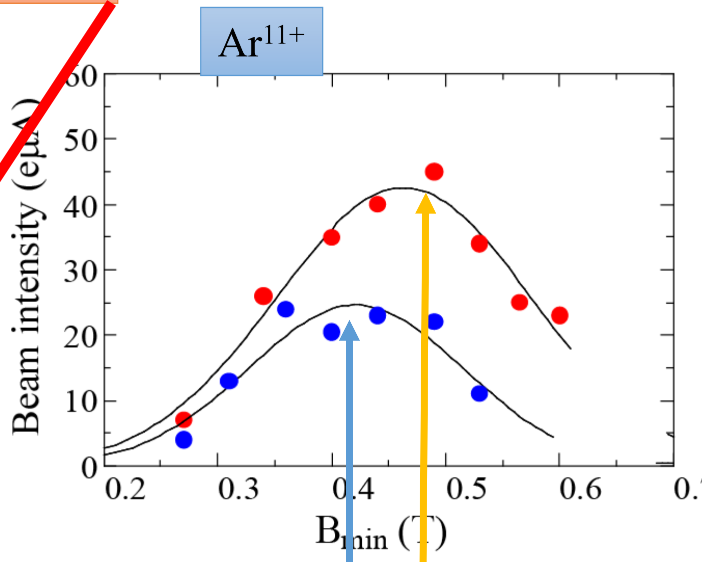
Biased disc (Electron donor)

Key parameters

$$\frac{N_{e-hot}}{N_{e-cold}}$$

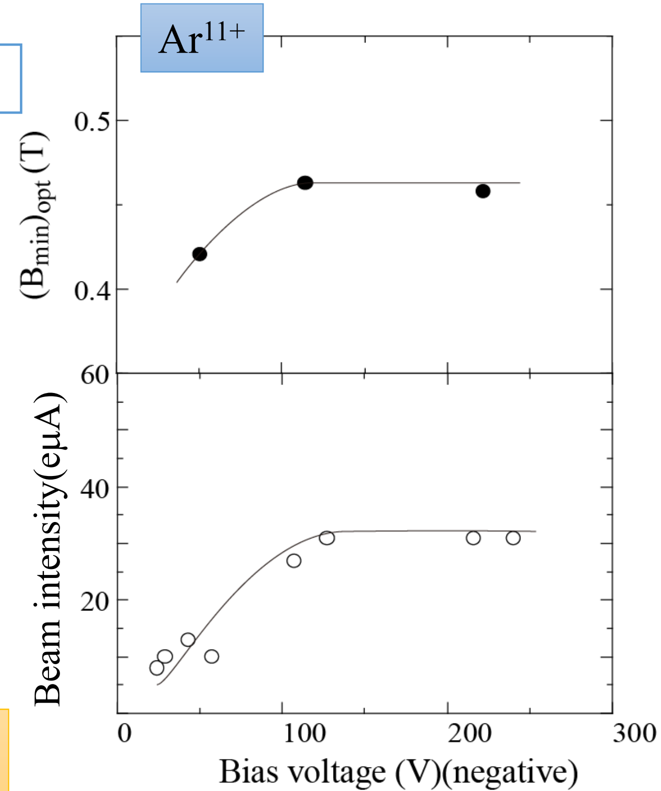
$$\frac{\langle E_\perp \rangle}{\langle E_\parallel \rangle}$$

Liquid He free SC-ECRIS(18GHz)

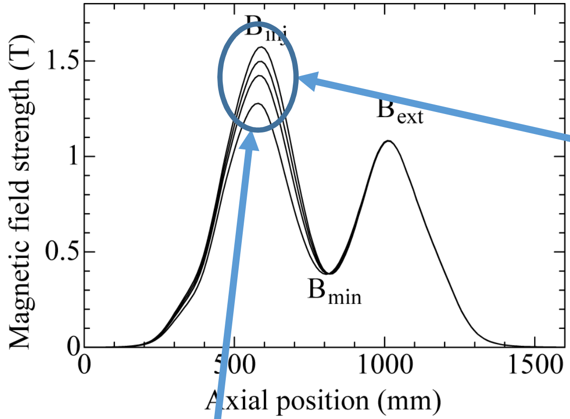


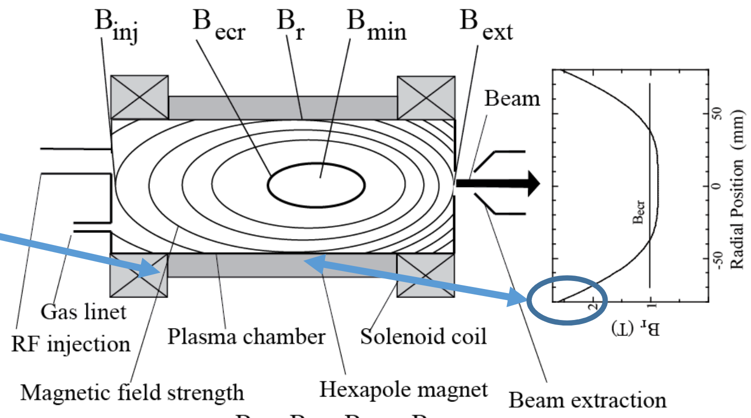
Bias voltage -55V $(B_{min})_{opt}$ ~0.42T

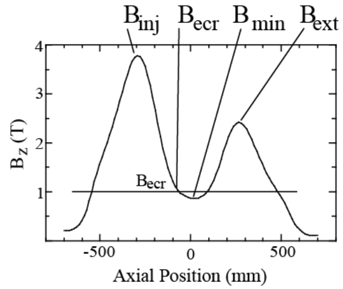
Bias voltage -114V $(B_{min})_{opt}$ ~0.46T

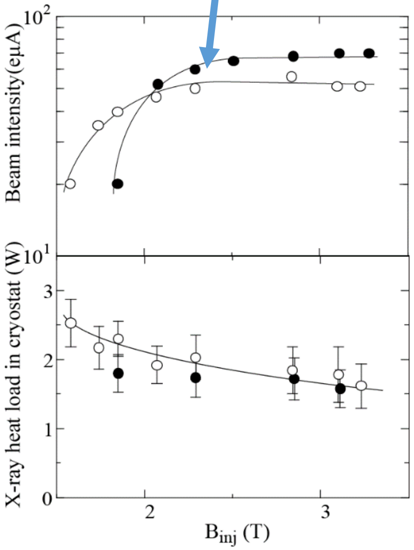


Magnetic mirror (B_r/B_{min}, B_{inj}/B_{min}, B_{ext}/B_{min})



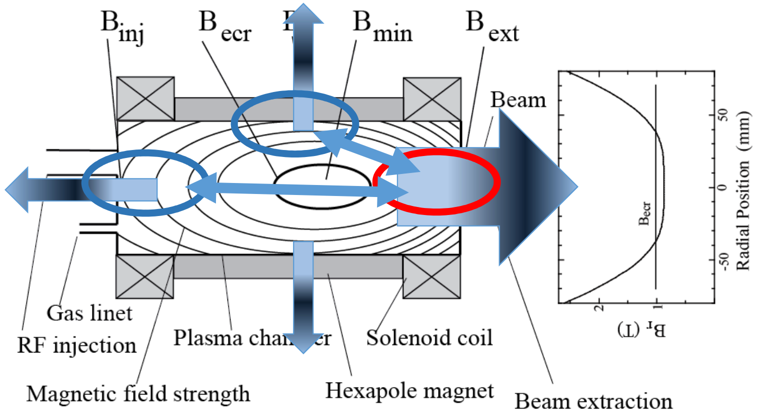


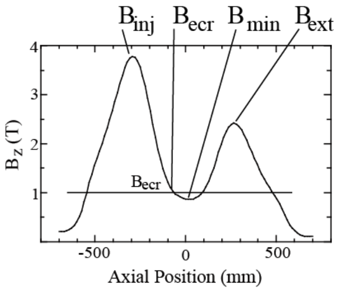


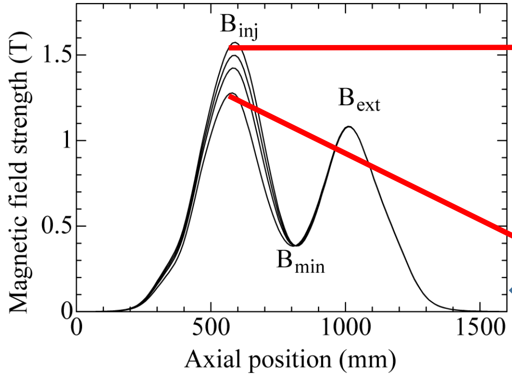


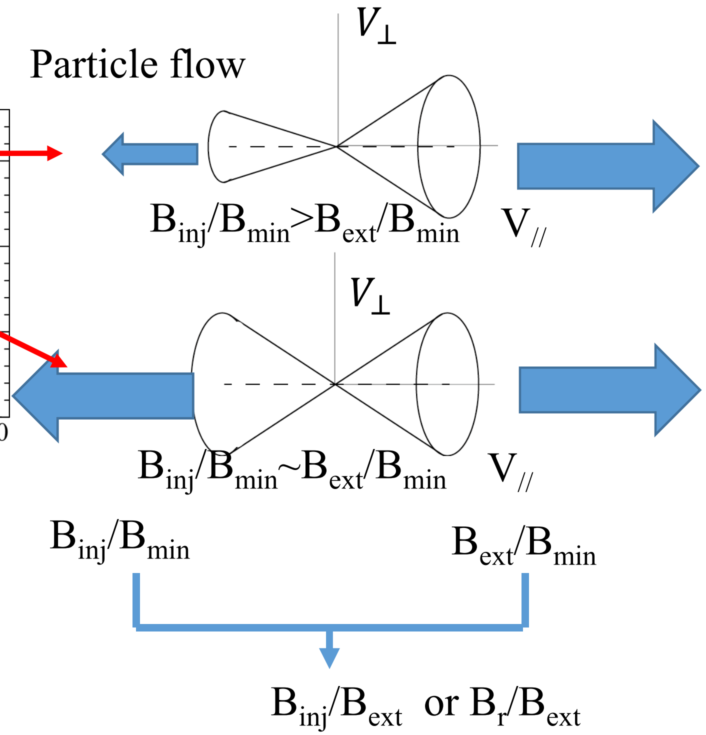
It is obvious that B_{inj}, B_{ext} and B_r work as a part of the magnetic mirror to confine the plasma. In the mid 1990s, so-called "High B" mode, which basically gives high magnetic mirror ratio to confine the plasma, was proposed to increase the beam intensity of highly charged heavy ions Many laboratories adopted this empirical formula to design the ECR ion source.Using it, they successfully increased beam intensity of highly charged heavy ions.

Magnetic mirror (B_r/B_{min}, B_{inj}/B_{min}, B_{ext}/B_{min})

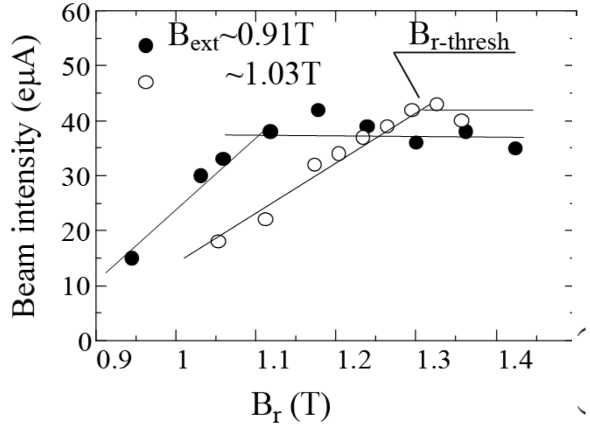


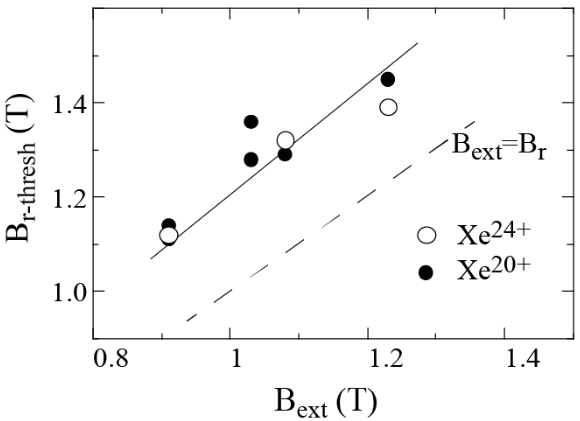


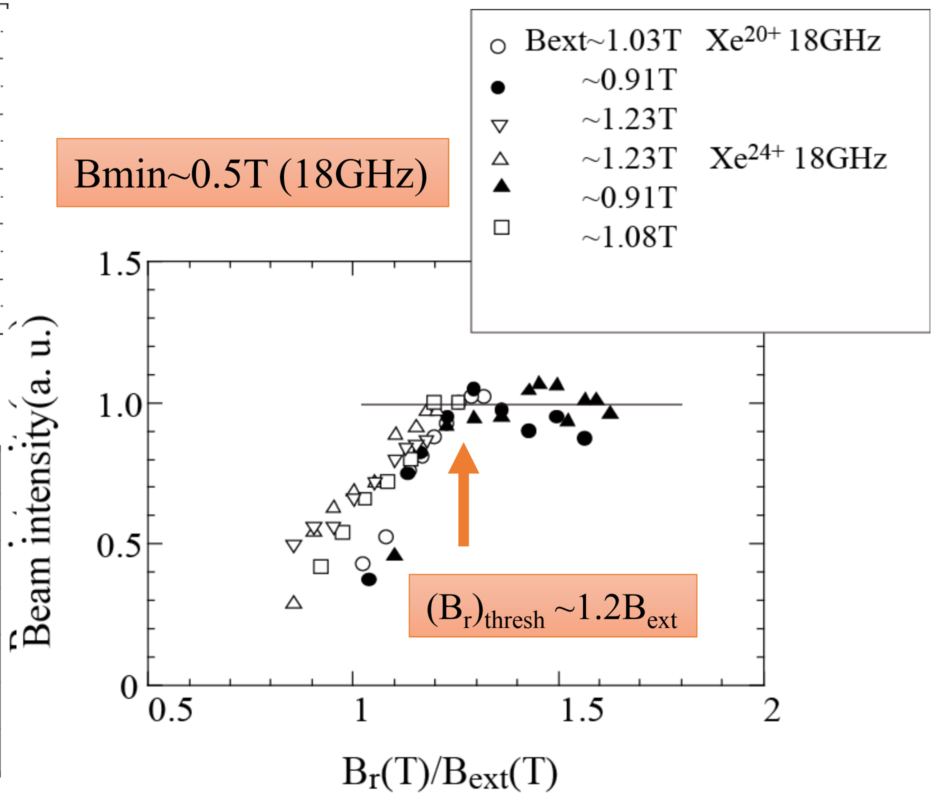




Magnetic mirror (B_r)







The beam intensity increases with increasing the B_r and saturated at certain B_r. The saturation point increases with increasing B_{ext}. Figure shows the bema intensity as a function of B_r/B_{ext}. Very roughly speaking, the beam intensity is saturated at B_r/B_{ext}~1.2

To investigate this effect for 28GHz operation, we measured the U^{35+} ion beam as a function of Br. To measure it in a wide range, B_{ext} was fixed to 1.42T. The beam intensity increased with increasing Br and saturated at Br~1.2Bext, which is same tendency for 18GHz operation.

Magnetic mirror (B_r)

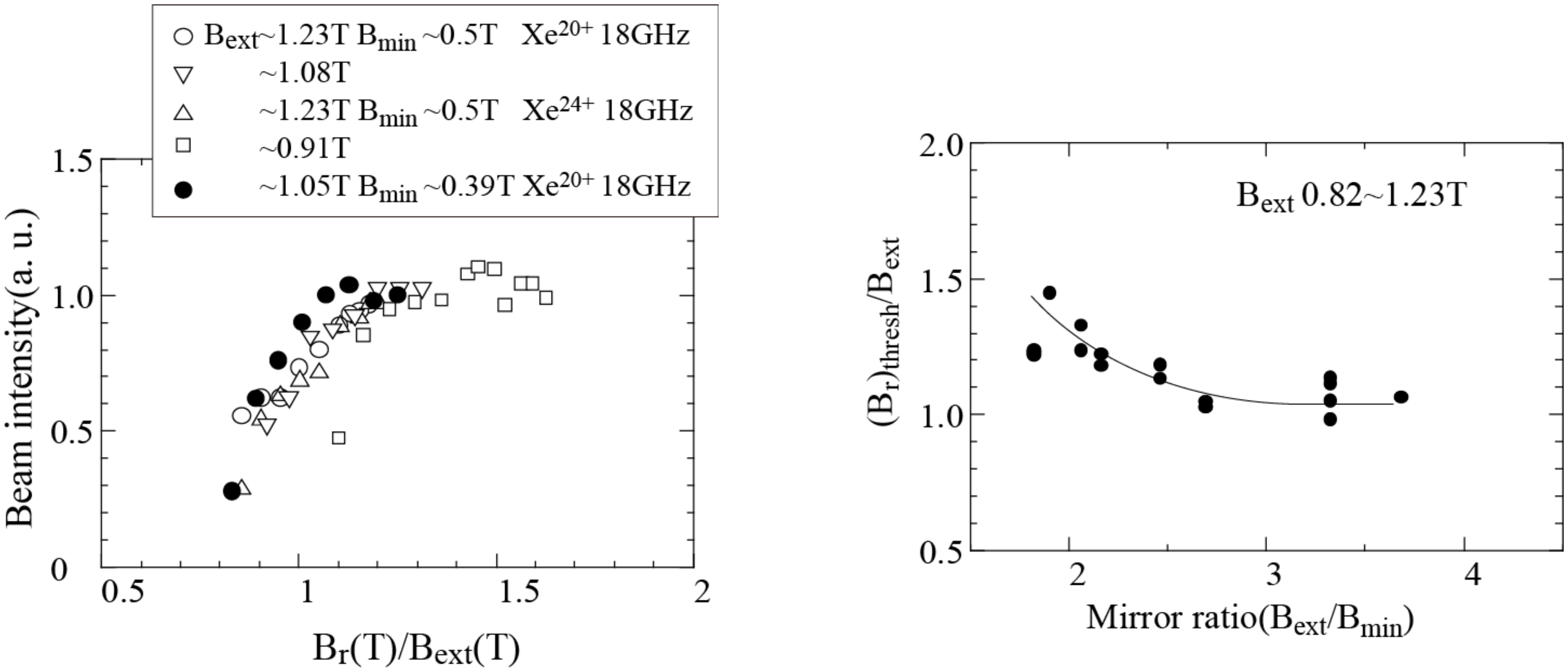
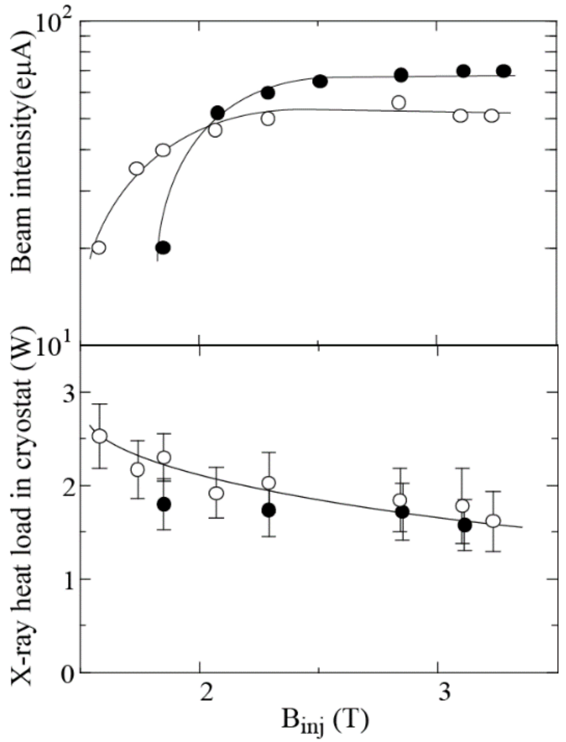


Figure shows a part of the experimental results, with the beam intensity as a function of B_r/B_{ext} at different B_{min} (0.5 T and 0.39 T). It appears that $B_{r\text{-}thresh}$ slightly depends on $B_{min,}$ and a lower B_{min} value may give a lower value of $B_{r\text{-}thresh}$, which is ~1.1B_{ext} for B_{min} ~ 0.39 T. As shows figure (right), $(B_r)_{thresh}/B_{ext}$ is slightly dependent on the mirror ratio (B_{ext}/B_{min})

Magnetic mirror (B_{inj})



U35+

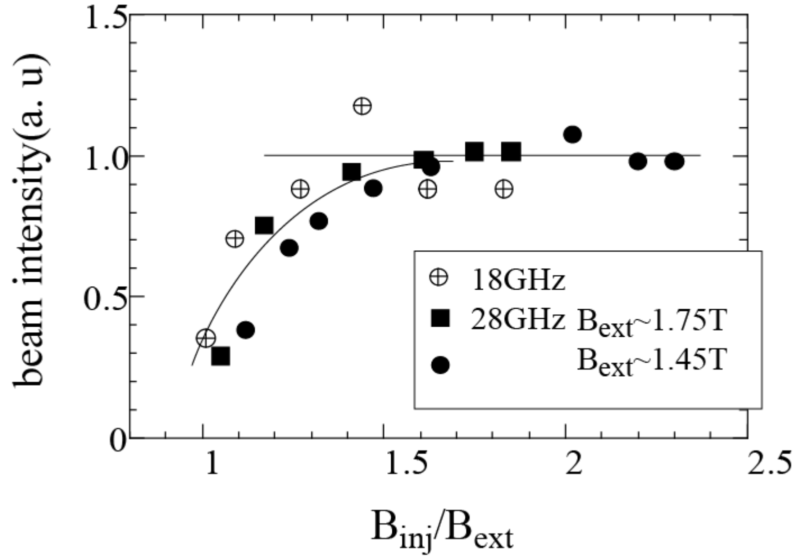
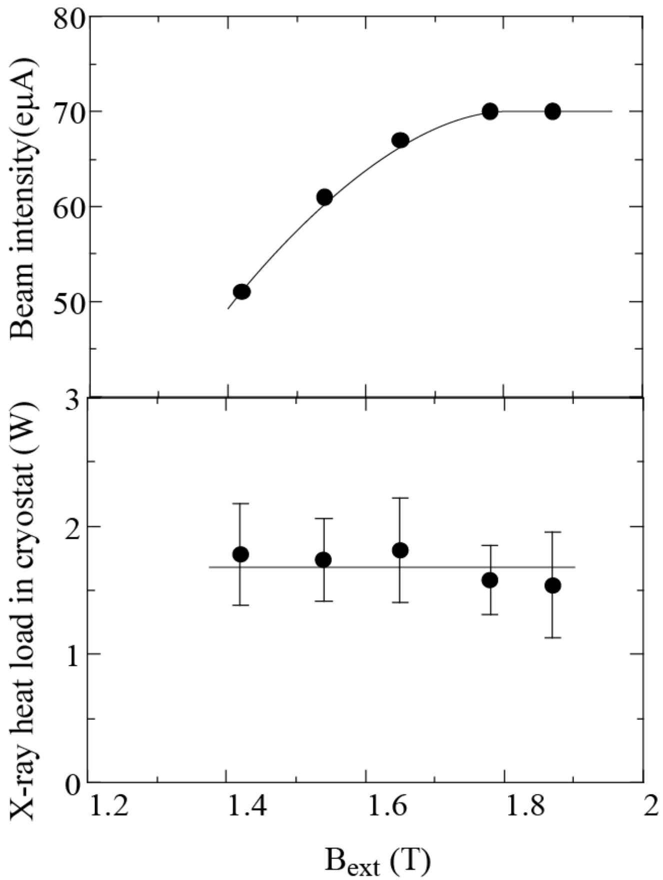


Figure shows the U^{35+} beam intensity as a function of B_{inj}/B_{ext}, where the beam intensity was normalized by setting its value for $B_{inj} > 1.6B_{ext}$ equal to 1 eμA. It is evident that the beam intensity is saturated at $B_{inj} \approx 1.6B_{ext}$. In addition, the results of using 18 GHz microwaves are also shown in this figure, and the beam intensity appears saturated at almost the same point. At lower B_{inj}/B_{ext} (~1), the loss cone size on the B_{inj} side is almost equal to that on the B_{ext} side. Therefore, the plasma confinement and ion flow are comparable on both sides. As B_{inj} increases, the loss cone on the B_{inj} side becomes smaller. At higher B_{inj}/B_{ext} (>1.6), B_{ext} may govern the plasma confinement, because the loss cone on the B_{inj} side is smaller than that on the B_{ext} side. For these reasons, the beam intensity becomes saturated.

Magnetic mirror (B_{ext})

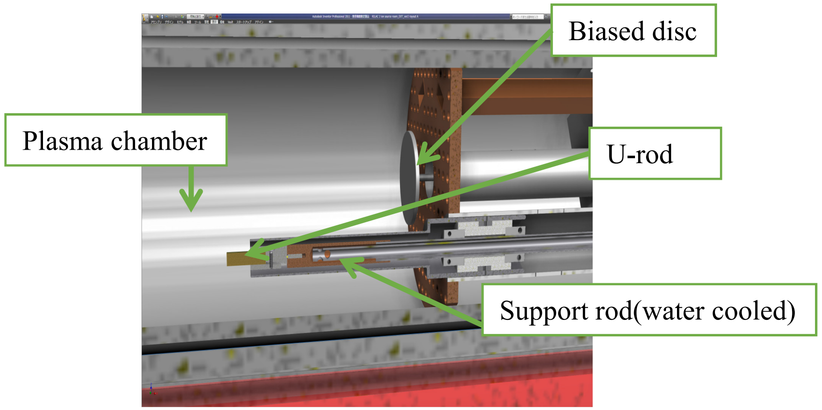
U^{35+}(28GHz)

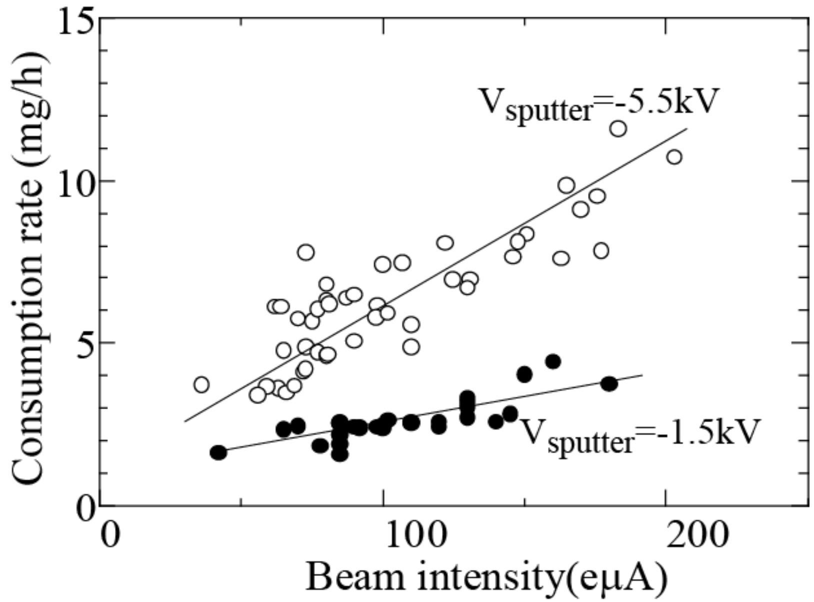


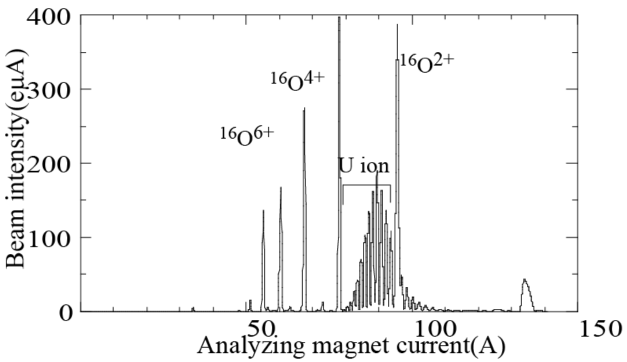
When setting the optimum value of B_{inj} and B_r, the beam intensity is strongly dependent on the B_{ext}.

The beam intensity U^{35+} (28GHz) increased with increasing B_{ext}

U production (sputtering method)

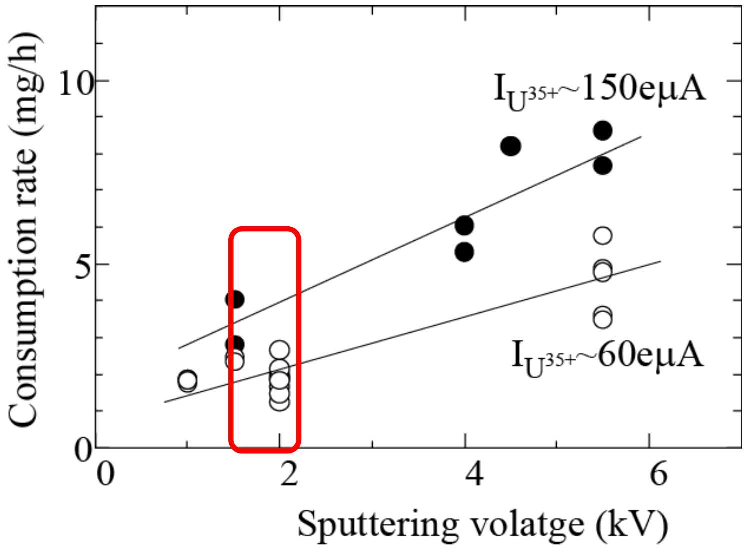






To obtain the consumption rate, we performed long-term measurements of the total amount of material consumption and total sputtering current, at fixed sputtering voltage. For example, we obtained the consumption rate of ~1 mg/h for 1 mA of sputtering current (ion current + current due to the secondary electron emission) at the sputtering voltage of -2 kV. Consumption rate strongly depended on the sputtering voltage and was proportional to the sputtering current at fixed sputtering voltage.

U production (sputtering method)



Even though the consumption rate is lower at lower sputtering voltages, we obtained the same beam intensity. In the theoretical sputtering calculations, the average energy of particles scattered from the target material decreases with decreasing incident ion energy. One possible interpretation of these results is that particles with lower energies (or lower velocities) may be more easily captured by the plasma; consequently, the number of U ions in the plasma may increase with decreasing voltage, even though the number of sputtered particles is lower at lower sputtering voltages.

Energy of sputtered particle

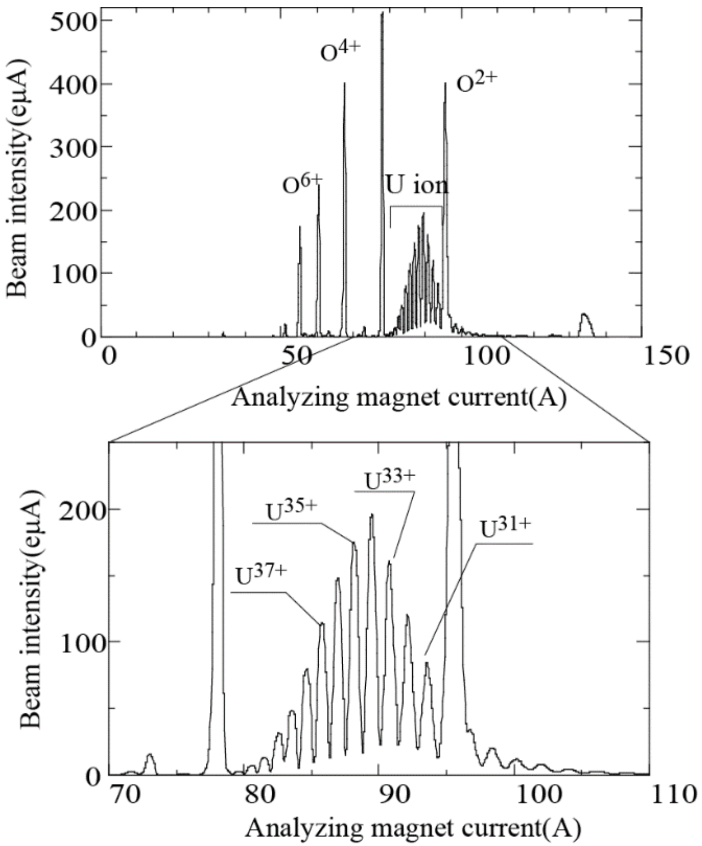
$$f(E) \propto E\frac{1-\sqrt{(E_b+E)/\Lambda E_1}}{(E+E_b)^3}$$

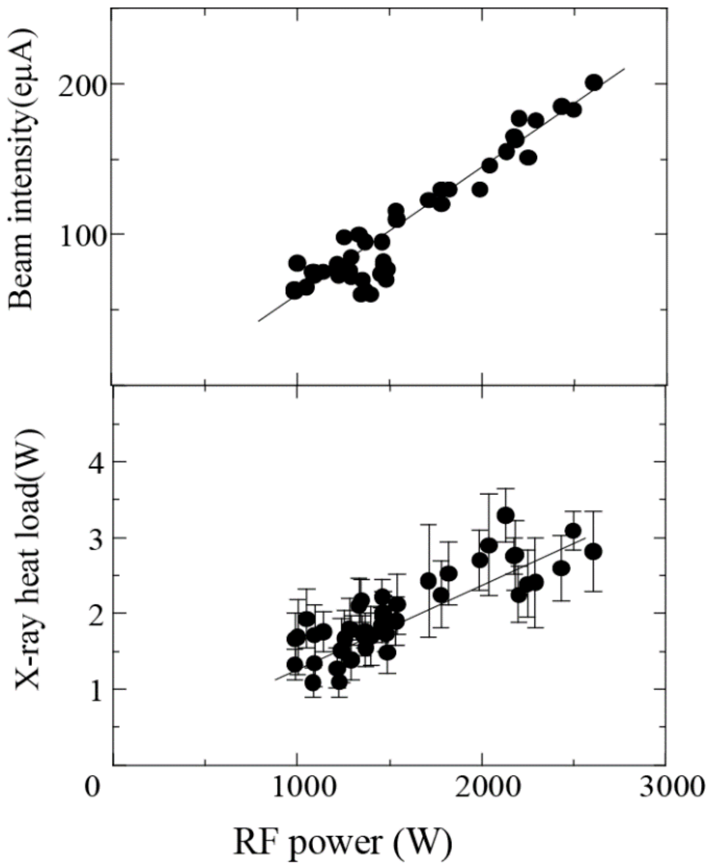
E_b: binding energy
E_1: incident energy of ions

Energy of sputtered particles decrease with decreasing the incident energy of the ions

M. W. Thompson, Philos. Mag. **18**, 377 (1968).

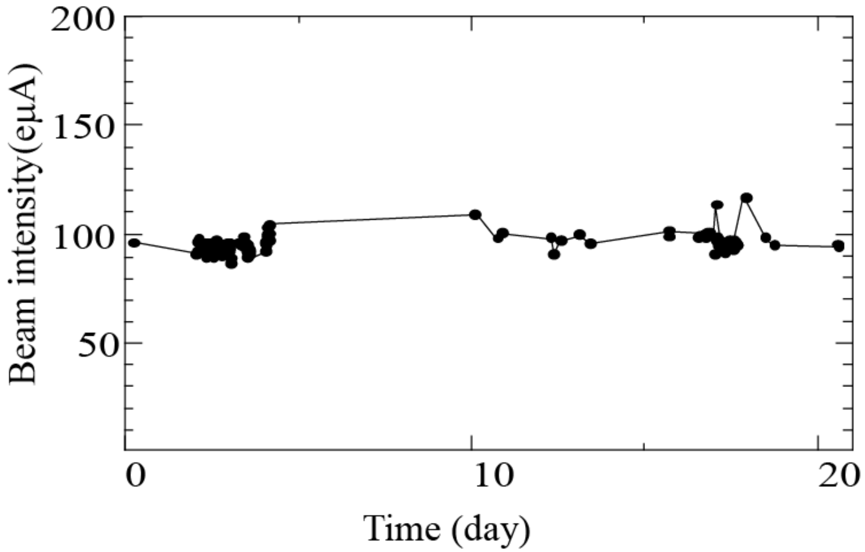
U production

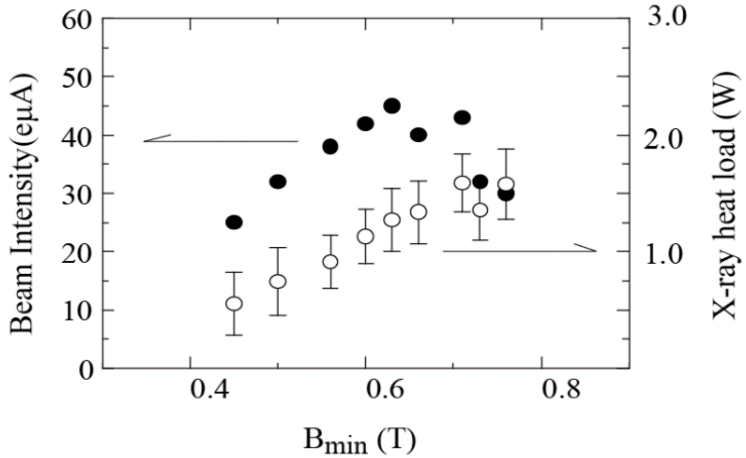


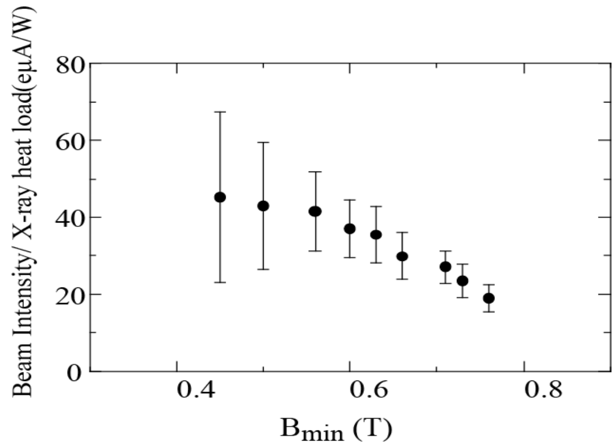


201eμA(~2.6kW)

B_{inj}	~3.11T,
B_{min}	~0.62T
B_{ext}	~1.78T
B_r	~1.87T
RF	18+28GHz
V_{ext}	~22kV
$W_{X\text{-}ray}$	~2.8W

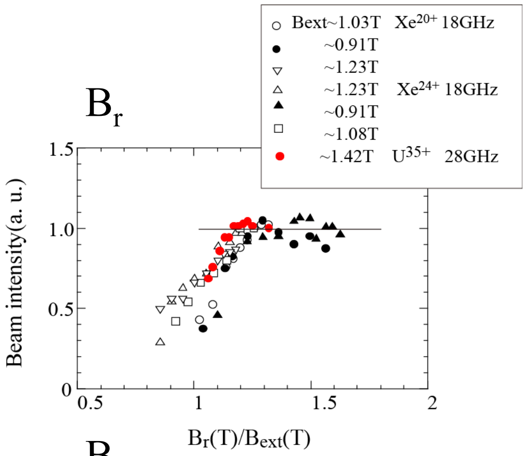


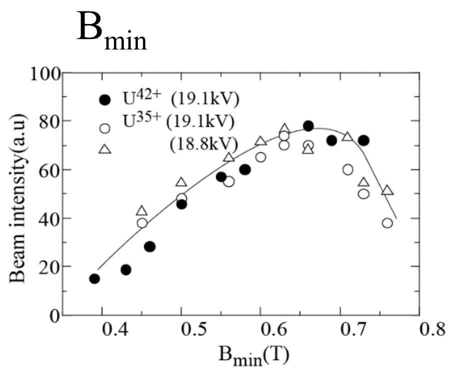


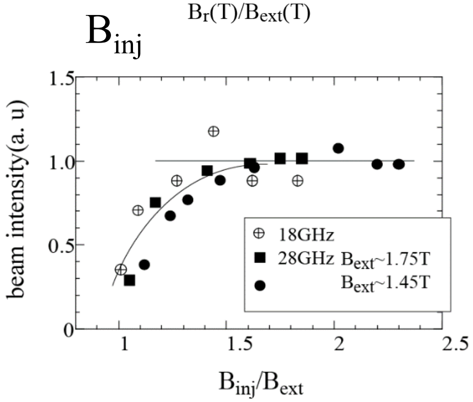


We observed a strong X-ray heat load in the cryostat (~2.8 W), which increases linearly with increasing RF power. To increase the beam intensity further, more RF power is required. Therefore, we need to minimize the heat load for the safe operation of the ion source. The beam intensity and X-ray heat load decreased with decreasing B_{min}. Figure shows the beam intensity divided by the X-ray heat load ($I_{U35+}/W_{X\text{-}ray}$) as a function of B_{min} at a fixed RF power (~1.0 kW). $I_{U35+}/W_{X\text{-}ray}$ gradually increased with decreasing B_{min}. This suggested that to minimize the X-ray heat load while maintaining the beam intensity, it is better to use a low B_{min}. However, we require more power to produce the same beam intensity

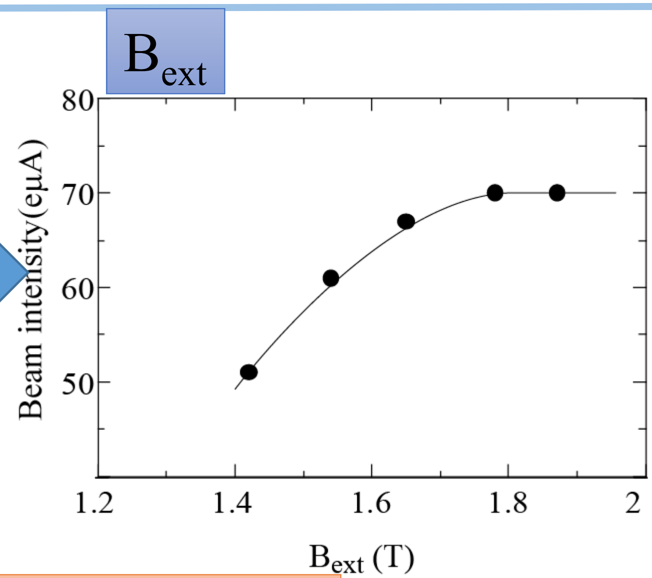
Summary







B_{inj} $>1.6B_{ext}$
B_r $>1.2B_{ext}$
B_{min} $\sim 0.8B_{ecr}$ (18GHz)
$\sim 0.65B_{ecr}$(28GHz)



Neutral atom injection (Metal)

+