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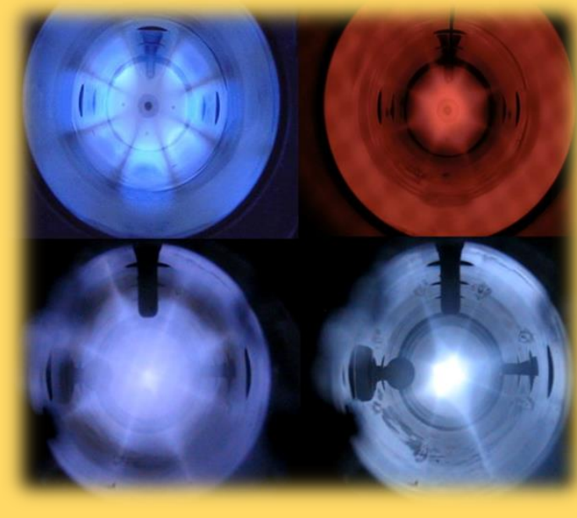
Initial Experimental Results on Ion Cyclotron Resonance Heating Selectively Mixed Low Z Ions to Enhance Production Efficiency of Multicharged Ions on ECRIS



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§ 1. Introduction

- From the viewpoint of heating by electromagnetic (EM) waves, there are two ways to break through the limit of multiply charged ion current due to this cause in ECRIS. In the high-frequency EM waves that cause ECR, one method is to induce resonance by mode conversion from EM waves with various cutoff densities, etc., to electrostatic (ES) waves with no cutoff densities. Results have already been obtained in upper hybrid resonance (UHR)[1] and dual-ECR experiments[2].
- In the high-density region, a resonance phenomenon using low-frequency EM waves (usually called Radio Frequency: RF), which does not have a similar cut-off density limit, is known as lower hybrid resonance (LHR). and ion cyclotron resonance (ICR). In the case of ion heating, it can be considered that increasing multiply-charged ion current is attained by increasing the ion cooling effect by selective heating of low-Z ions when mixing low-mass element (Z) gas, which has been done conventionally.
- In the case of ECRIS, the small size of the equipment makes it impossible to use a method that induces ICR with wave propagation from an antenna that feeds EM waves, as is done in nuclear fusion research where the size of the target plasma is large. Then we decided to take the method of directly applying an electromagnetic field with a coil.

§ 2. Theoretical Background

- ***2-1. Dispersion relations, resonances and cutoffs***
- The dispersion relation of electromagnetic (EM) waves in a homogeneously magnetized plasma with a z-axis magnetic field in a Cartesian coordinate system is given by the dielectric tensor in the cold plasma approximation including the ion contribution as follows.
- $$\overline{\overline{\epsilon_p}} = \epsilon_0 \overline{\overline{\kappa_p}} = \epsilon_0 \begin{pmatrix} \kappa_\perp & -i\kappa_\times & 0 \\ i\kappa_\times & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{/\!/} \end{pmatrix}, \qquad (1)$$
- where $\kappa_r = 1-\sum_j \frac{\omega_{pj}^2}{\omega(\omega+\epsilon_j\omega_{cj})}$, $\kappa_l = 1-\sum_j \frac{\omega_{pj}^2}{\omega(\omega-\epsilon_j\omega_{cj})}$, $\kappa_{/\!/} = 1-\sum_j \frac{\omega_{pj}^2}{\omega^2}$, $\kappa_\perp = \frac{1}{2}(\kappa_r+\kappa_l)$, $\kappa_\times = \frac{1}{2}(\kappa_r-\kappa_l)$, $\epsilon_j = \left(\frac{q_j}{|q_j|}\right)$, j =e (for electron), i(for ion), ω_{ci} (ω_{pi}) and ω_{ce}(ω_{pe}) represent the ion and electron cyclotron (plasma) frequencies, respectively, and i is the imaginary unit. $\kappa_\perp$, $\kappa_\times$, $\kappa_{/\!/}$, κ_r and κ_l are the dielectric tensor elements. Here we use an expression similar to that of Lieberman.[3] $\epsilon_0$is the permittivity in vacuum, and $\overline{\overline{\kappa_p}}$ is the relative permittivity tensor.
- When the wave vector ***k*** (magnitude |***k***|= *k*) of the electromagnetic wave propagates in the direction forming an angle of *q* with respect to the magnetic field ***B***, the dispersion relation of electromagnetic waves in magnetized plasma in cold uniform plasma is given by the following relation.
- $$(\kappa_\perp \sin^2\theta + \kappa_{/\!/}\cos^2\theta)N^4 - \{(\kappa_\perp{}^2-\kappa_\times{}^2)\sin^2\theta + \kappa_{/\!/}\kappa_\perp(1+\cos^2\theta)\}N^2 + (\kappa_\perp{}^2-\kappa_\times{}^2)\kappa_{/\!/} = 0, \quad (2)$$
- where N (=k/k_0=ck/ω, k_0 is the wavenumber in vacuum) is the refractive index.
- the magnitude of the wave vector ***k*** in directions perpendicular and parallel to the magnetic field, respectively, and *c* and *ω* represent the speed of light in vacuum and the angular frequency of the electromagnetic wave, respectively. The following relational expression is derived from Eq.(2).
  - $$\tan^2\theta = -\frac{\kappa_{/\!/}(N^2-\kappa_r)(N^2-\kappa_l)}{(N^2-\kappa_{/\!/})(\kappa_\perp N^2-\kappa_r\kappa_l)}. \qquad (3)$$
- Assuming that $\theta = 0$, the numerator on the right side of Eq. (3), the dispersion relations of right-hand circularly polarized waves (R-wave) and left-hand circularly polarized waves (L-wave) are derived as follows.
  - $$N_r^2 = \kappa_r = 1-\sum_j \frac{\omega_{pj}^2}{\omega(\omega+\epsilon_j\omega_{cj})}, \ (4) \qquad N_l^2 = \kappa_l = 1-\sum_j \frac{\omega_{pj}^2}{\omega(\omega-\epsilon_j\omega_{cj})}. \ (5)$$
- It is shown that electron cyclotron resonance (ECR) and ion cyclotron resonance (ICR) exist in the former and latter, respectively.
- Also, from $N_r^2 = 0$, $N_l^2 = 0$, there are cutoff frequencies ω_R (R-cutoff) and ω_L (L-cutoff) for each wave propagation mode, considering the contribution of only electrons for ECR-related high frequencies, it is derived as follows.
  - $$\omega_R = \frac{\omega_{ce}+\sqrt{\omega_{ce}^2+4\omega_{pe}^2}}{2}, \quad (6) \qquad \omega_L = \frac{-\omega_{ce}+\sqrt{\omega_{ce}^2+4\omega_{pe}^2}}{2}. \quad (7)$$
- Considering the density dependence of electromagnetic waves at specific frequencies from the low-density region to the high-density region in the plasma, we encounter the cutoff density limits of O-cutoff, R-cutoff, and L-cutoff, respectively. When the microwave frequency is 2.45GHz, the O-cutoff limit density is about 7.5×10^{16}m^{-3}, and the L-cutoff limit density formed near the center of the mirror in Osaka University ECRIS at the same frequency is about $2.5\text{-}3.5\times10^{17}$m^{-3}, and these values are in good agreement with the measurement results.
- [1]Kato Y, *et.al, 2020 Rev. Sci. Instrum.*, **91**, pp.013315-1-6. [2]Kubo W, *et.al.*, 2021 *Rev. Sci. Instrum.*, **92**, pp.043514-1-9.
- [3]Lieberman M A and Lichtenberg A J, Principle of Plasma Discharges and Materials Processing, 2nd Edit., A John Wiley & Son, Inc Publications, 2005, Chap.4, pp.110.

- ***2-2. Ion Cyclotron Resonance (ICR) Heating***
- Propagation of L-wave ion cyclotron waves along magnetic lines of force is necessary to induce ICR, but ECRIS is small and it is considered difficult to induce ICR based on electromagnetic wave propagation. Then we consider direct excitation of various ions of ECRIS by a coiled antenna from the strong magnetic field side near the ICR region.
- Considering the magnetic field strength of this ECRIS with a frequency of 2.45 GHz, it has a magnetic field strength near the ECR zone, and when using the existing IH power source for Fe evaporation source (frequency 50-25 kHz), it has an ICR zone for Ar ions.
- Therefore, it is possible to verify the principle by conducting experiments to increase the efficiency of multiply charged ion generation by selectively heating Ar as light Z ions with respect to Xe or Kr multiply charged ions.
- An initial experiment was conducted to verify whether the introduction of the ICR antenna has a fatal effect on the ECR plasma and the production of multiply charged ions.
- Also, if the required frequency can be arbitrarily selected and the power supply prepared, the options for heating ions will of course expand.
- In addition, when the ion heating is performed with the ICR zone in the region near the ECR zone, it becomes possible to relax the potential well generated near the ECR region by the ECR.
- From this point of view, it is also expected that the multiply charged ion current will increase.

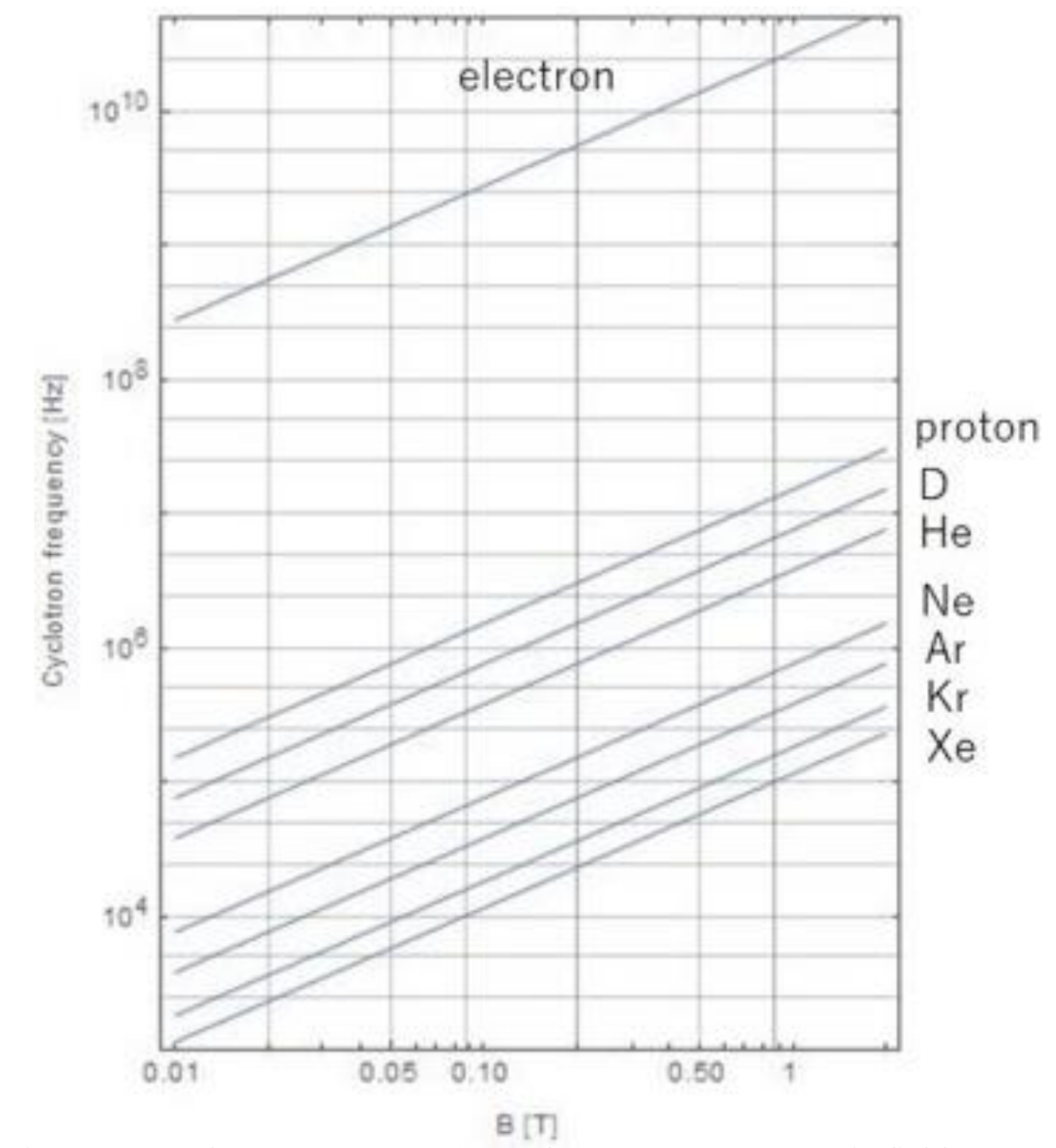


Fig. 1. Ion cyclotron resonance (ICR) frequency *v.s.* Magnetic field strength

§ 2. Preliminary Experimental Results

Typical charge state distributions (CSD's) of low-Z gas mixing (pure Xe & Xe+Ar in CW microwaves)

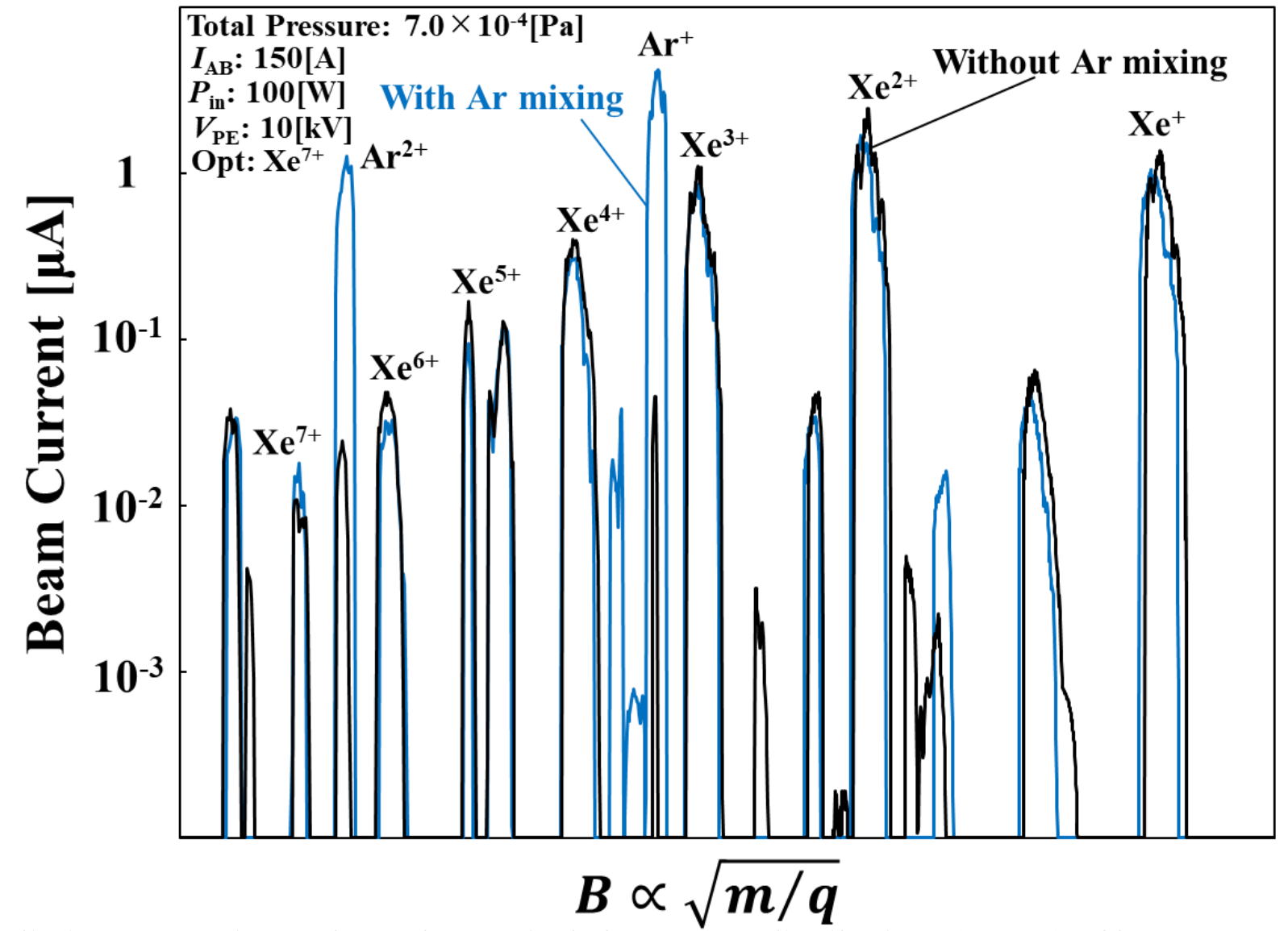


Fig. 2. Preliminary Experimental Results. Typical charge state distributions (CSD's) of low-Z gas mixing (pure Xe & Xe+Ar in CW microwaves)

Typical CSD's of CW & Pulse micorowave operation in Xe+Ar

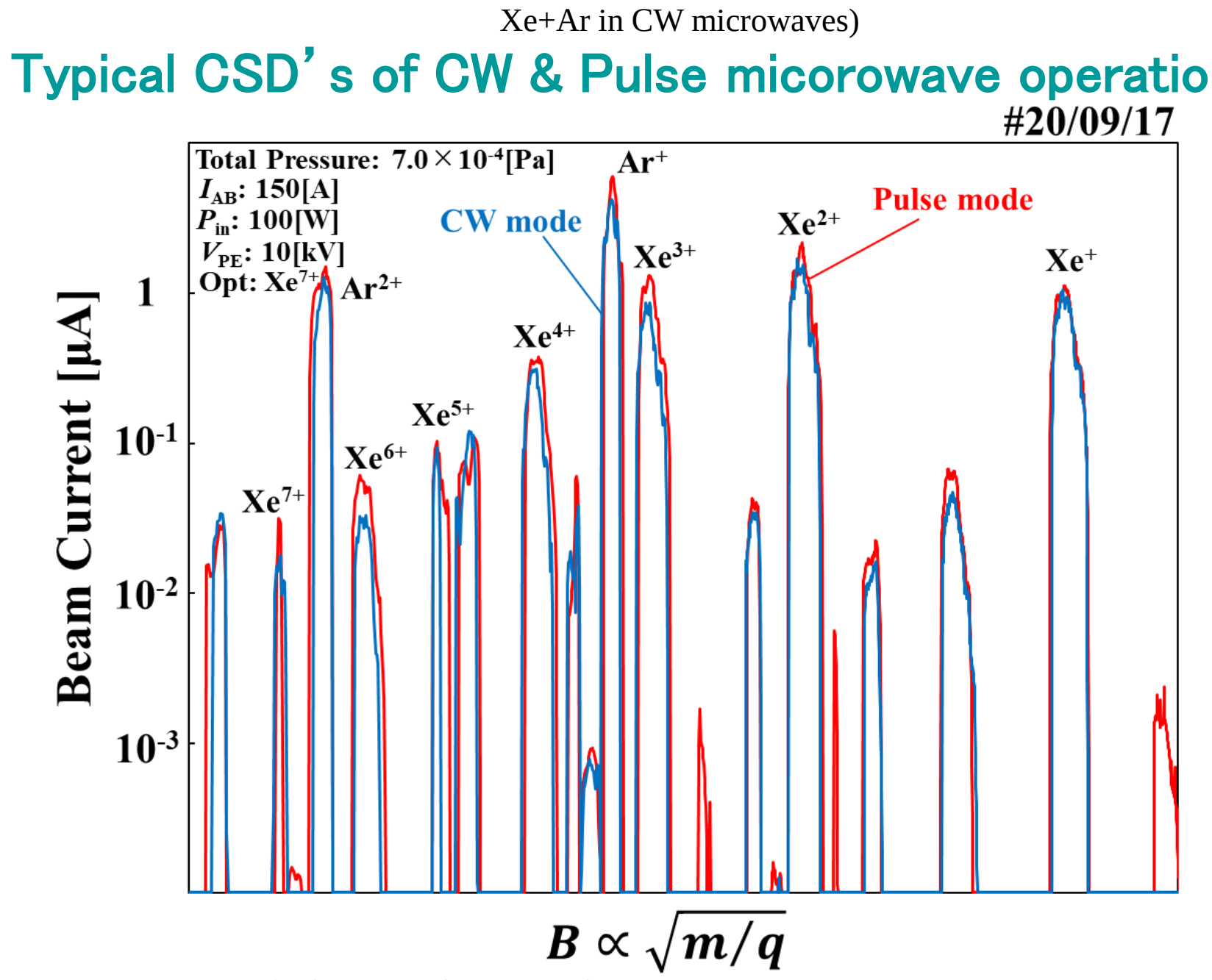


Fig. 3. Typical CSD's of CW & Pulse micorowave operation in Xe+Ar

§ 3. Experimental Setup

The ECR ion source (Osaka Univ.) with ICR antenna

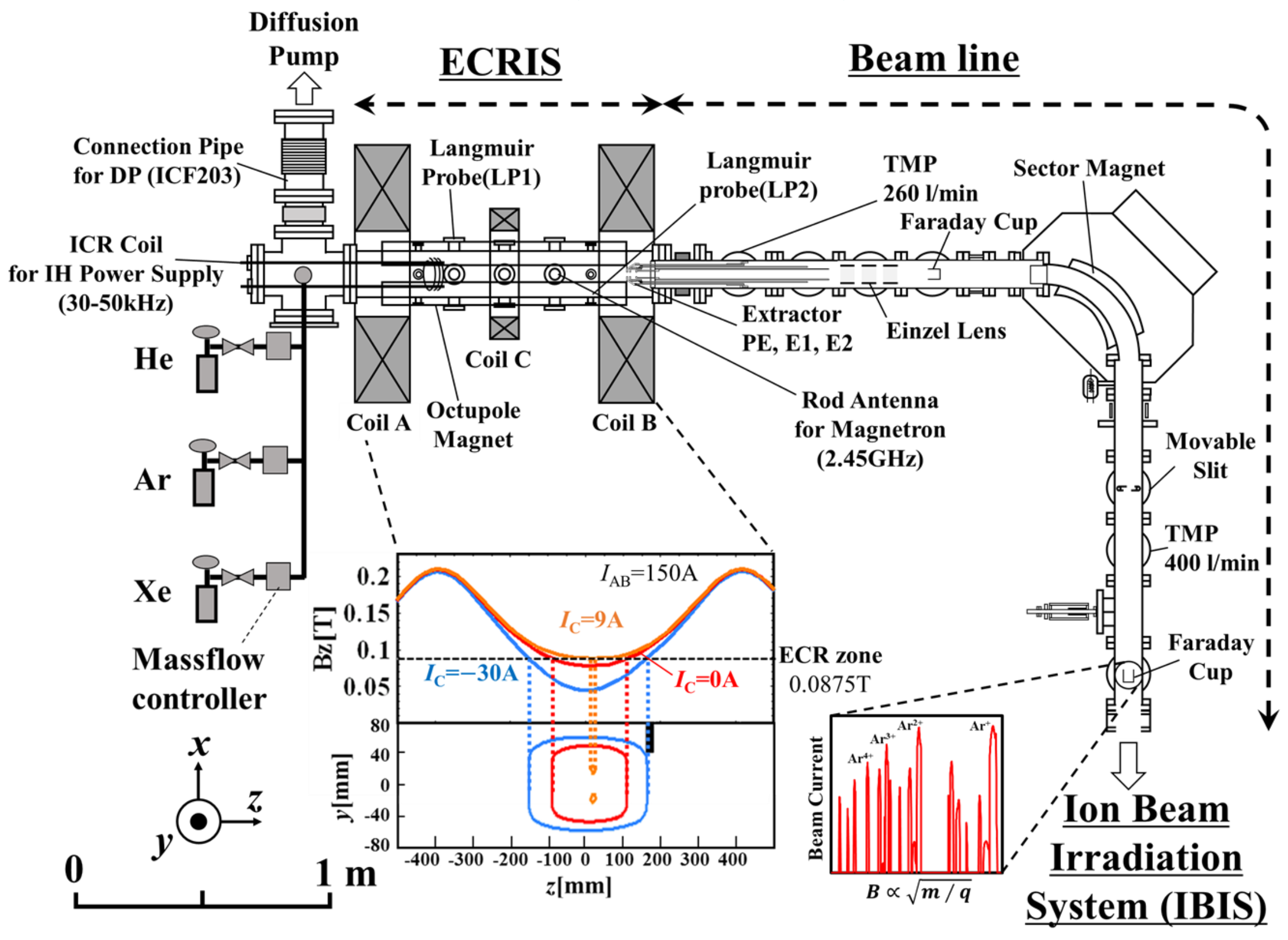


Fig. 5. The ECR ion source (Osaka Univ.) with ICR antenna for low frequency RF launching

Setting of ICR antenna to ECRIS & mirror field field

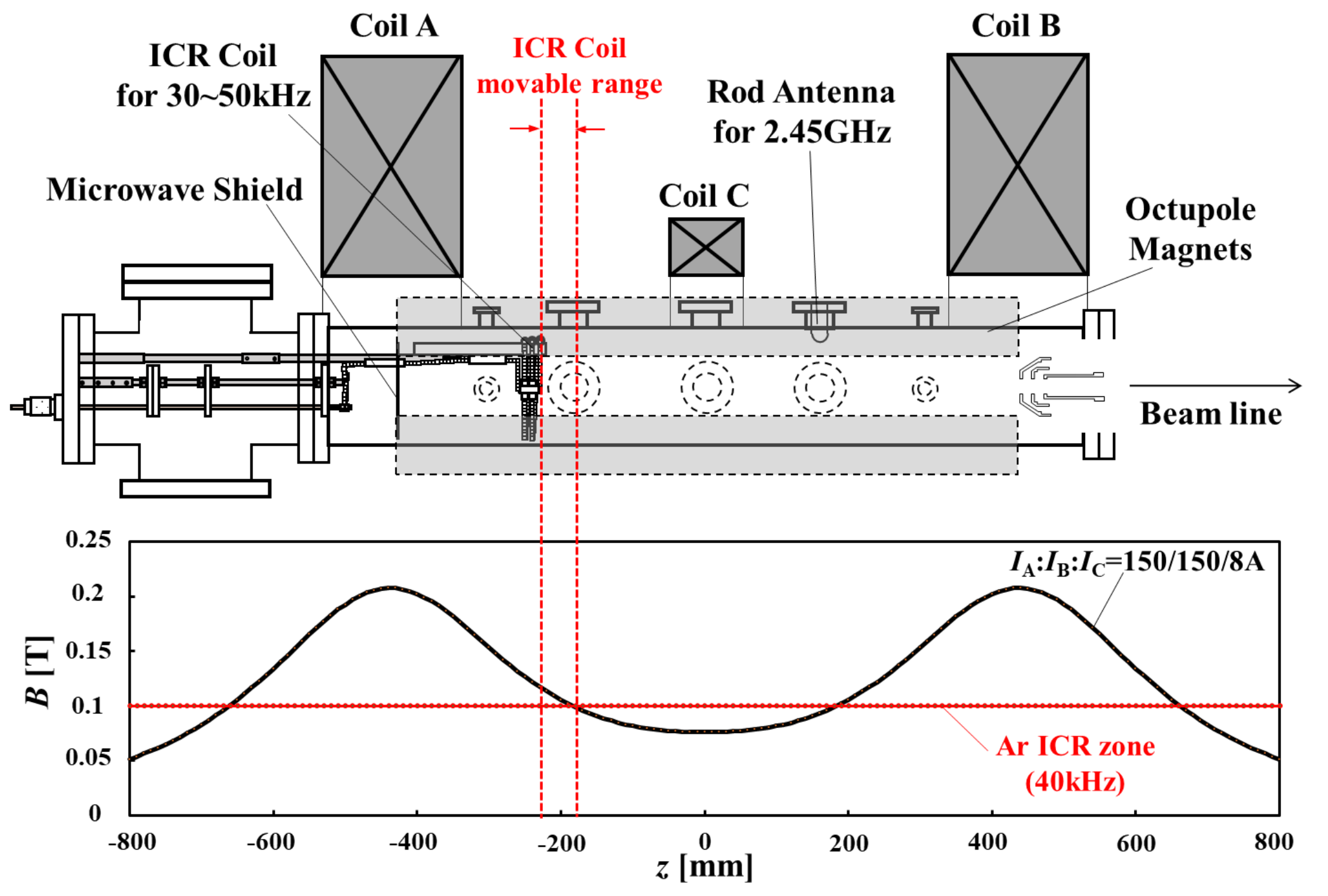


Fig. 6. Installation of ICR antenna at ECRIS (Osaka Univ.).

ICR Coil detail figure & photographs

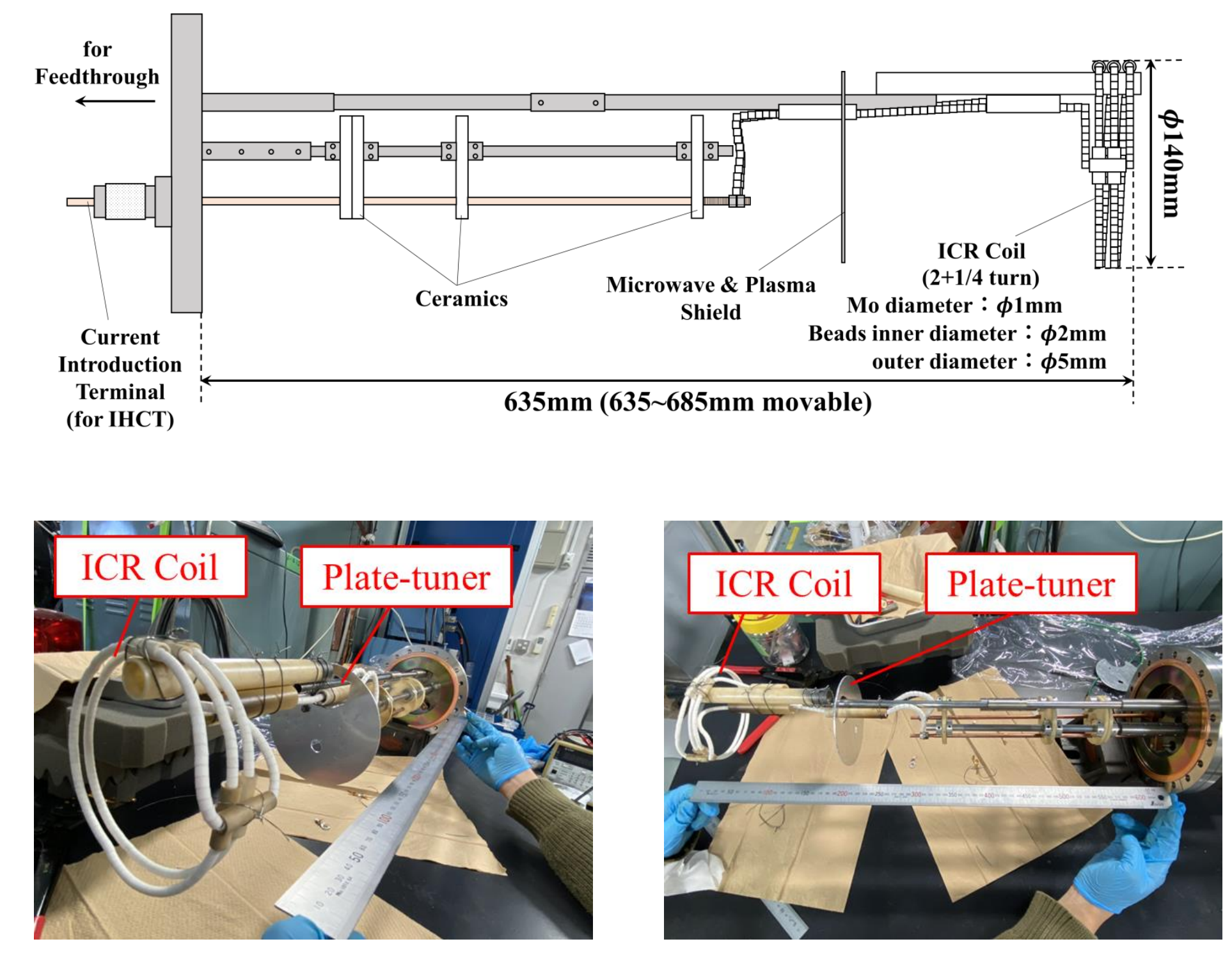


Fig. 7. ICR Coil detail figure & photographs

Low frequency RF power supply & RF introducing part into ECRIS

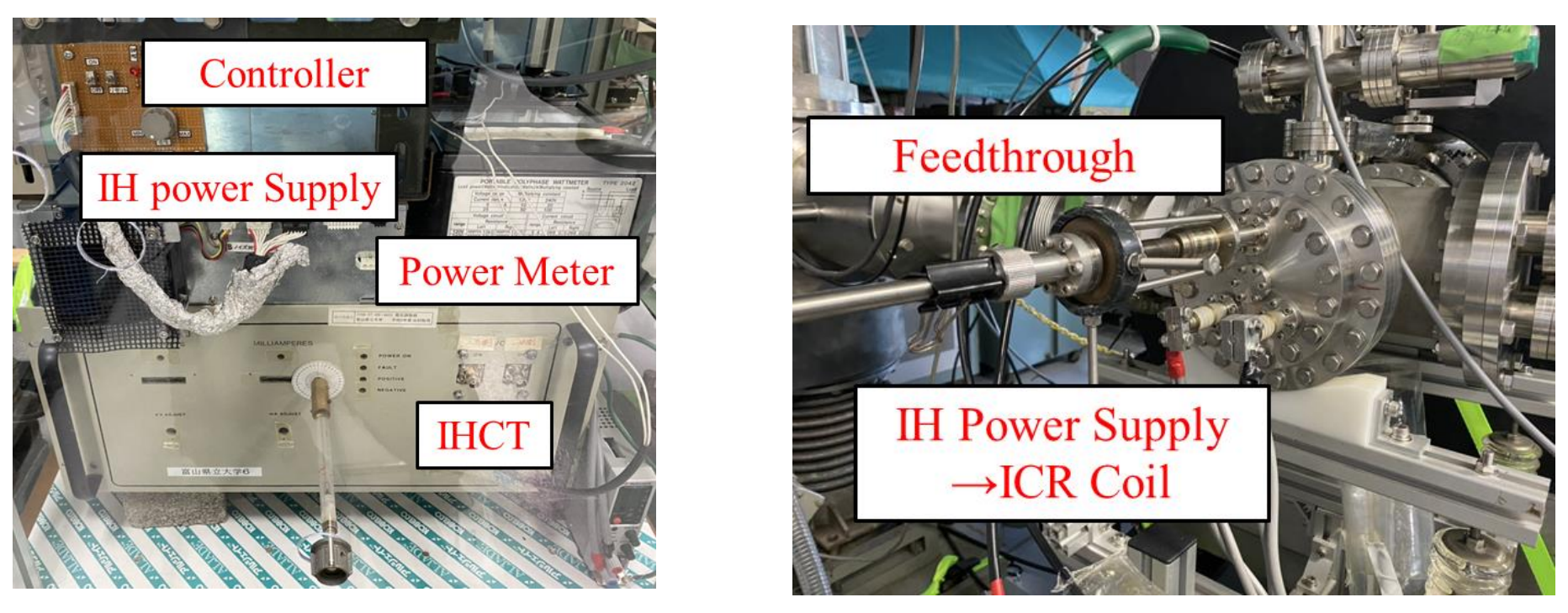


Fig. 8. Low frequency RF power supply & RF introducing part into ECRIS

Xe⁷⁺ vs pulse duration in pure Xe & Xe+Ar

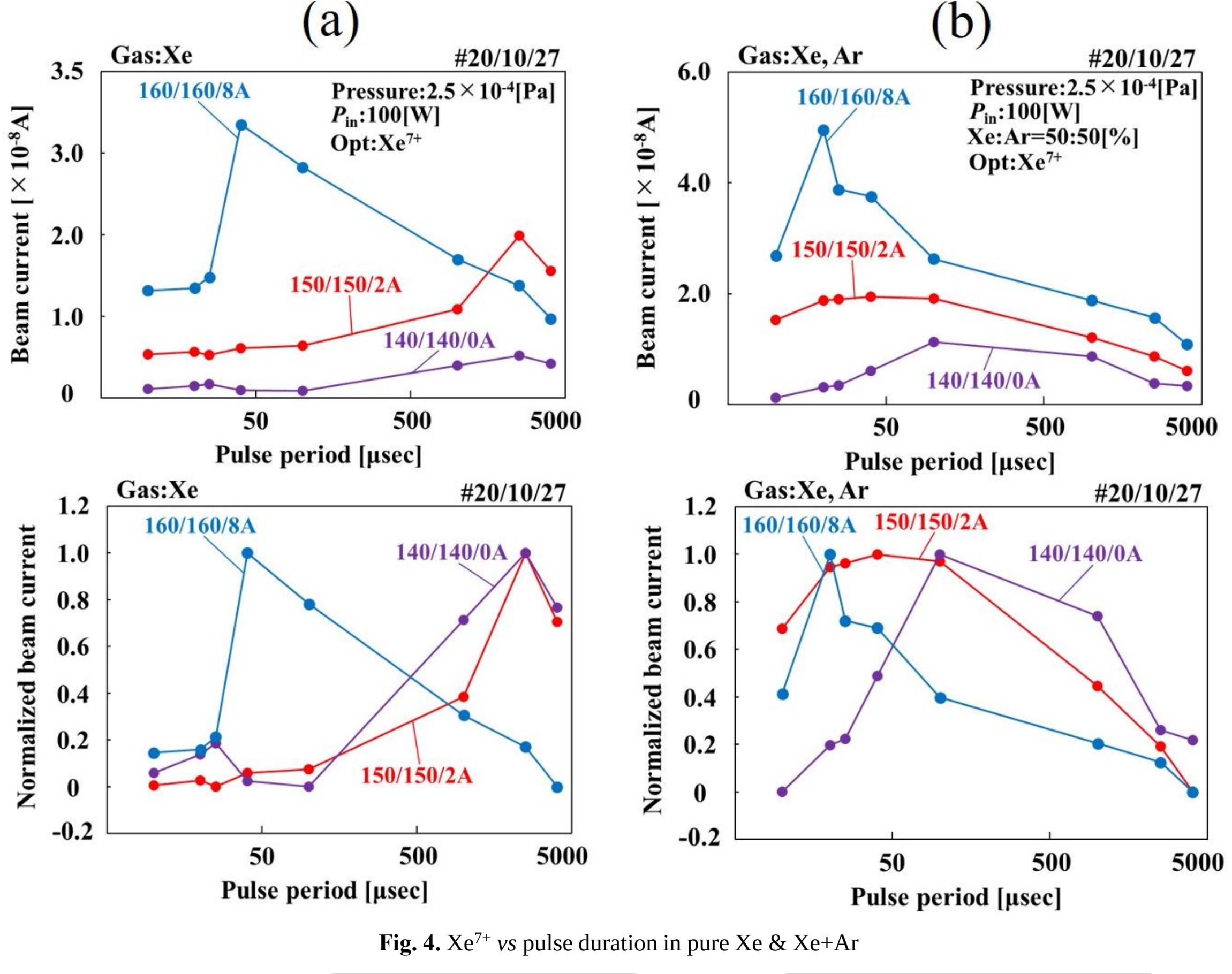
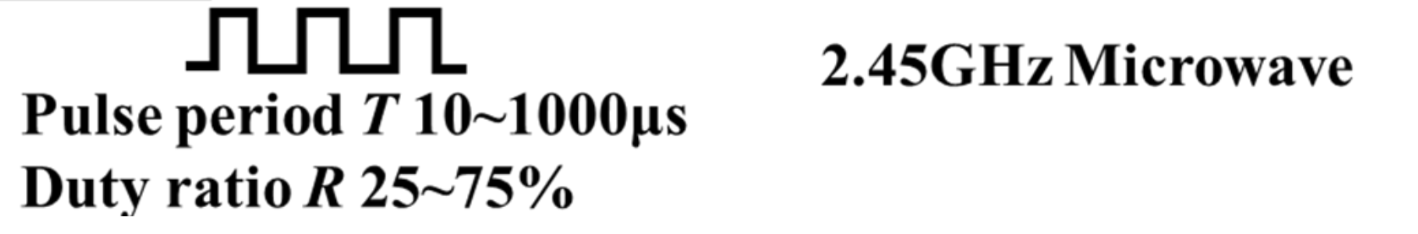


Fig. 4. Xe⁷⁺ vs pulse duration in pure Xe & Xe+Ar



FG → Magnetron → Rod Antenna

Pulse period *T* 10~1000μs
Duty ratio *R* 25~75%

2.45GHz Microwave

§ 4. Initial Experimental Results

Typical CSD's with & without low frequency RF in Xe+Ar

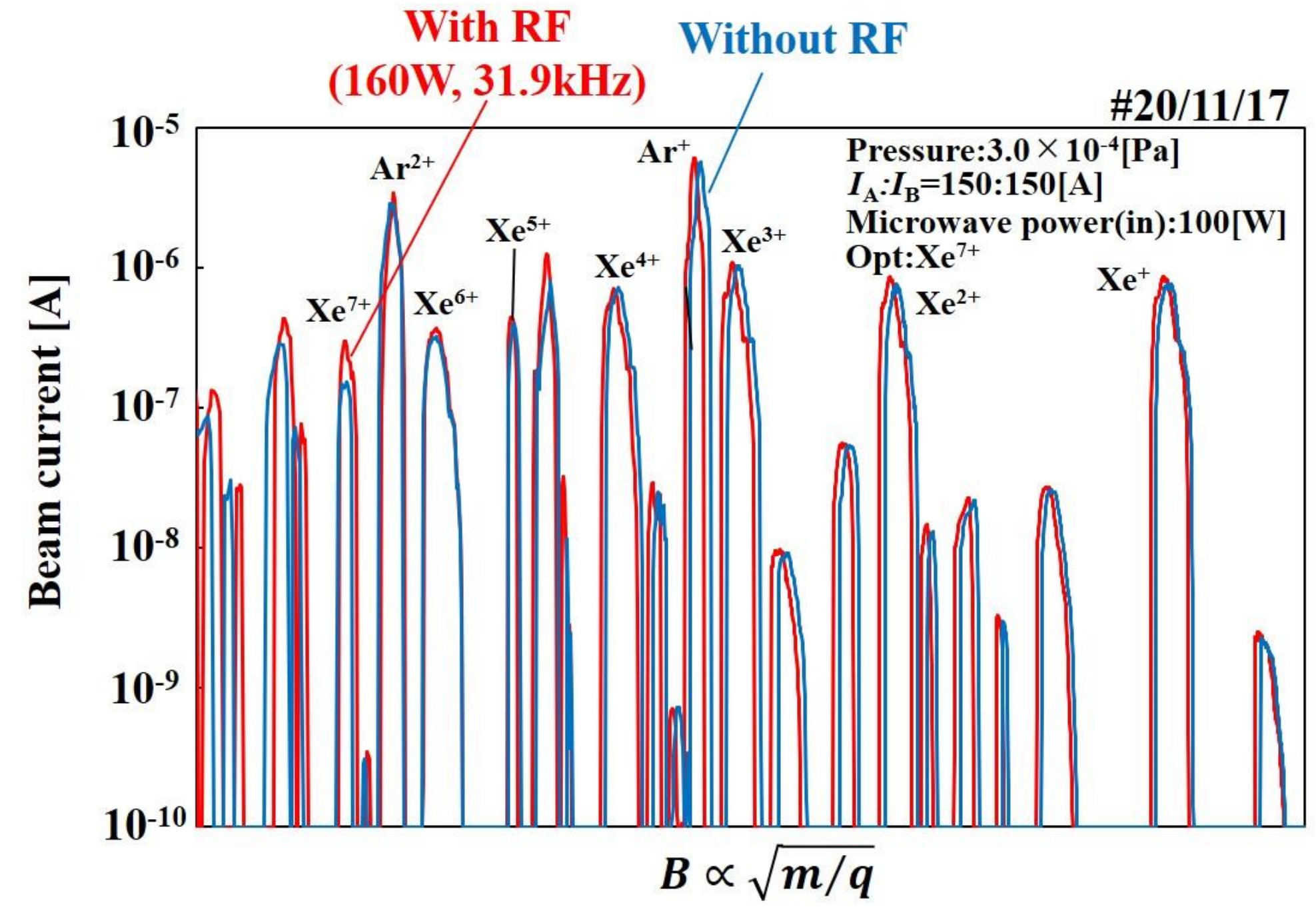


Fig. 9. Typical CSD's with & without low frequency RF in Xe+Ar

Xe⁷⁺ & ⟨*q*⟩ in case A ($I_A/I_B/I_C$=150/150/8A)

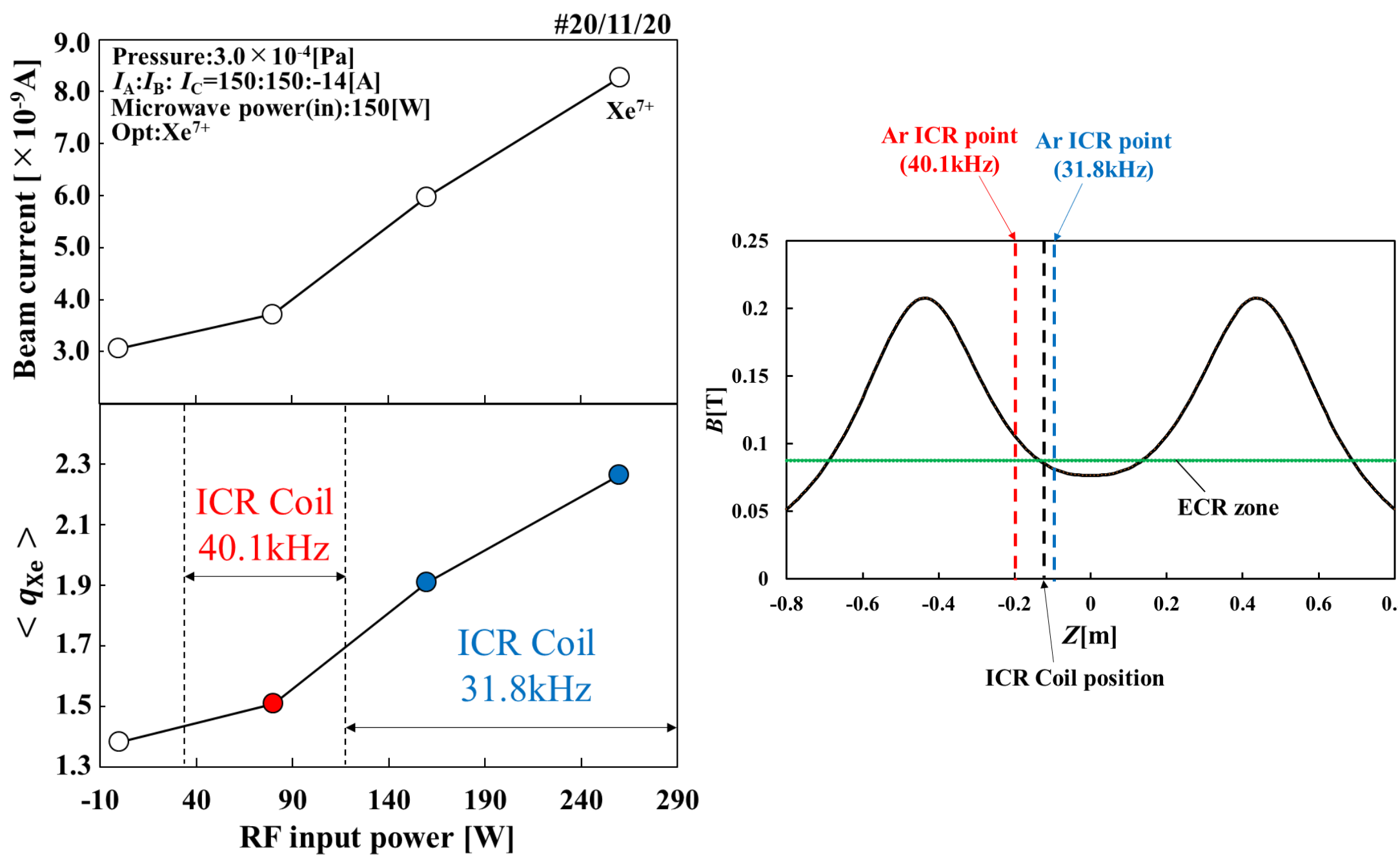


Fig. 10. Xe⁷⁺ & average charge state <*q*> in case A ($I_A/I_B/I_C$=150/150/8A)

Xe⁷⁺ & ⟨*q*⟩ in case B ($I_A/I_B/I_C$=150/150/8A)

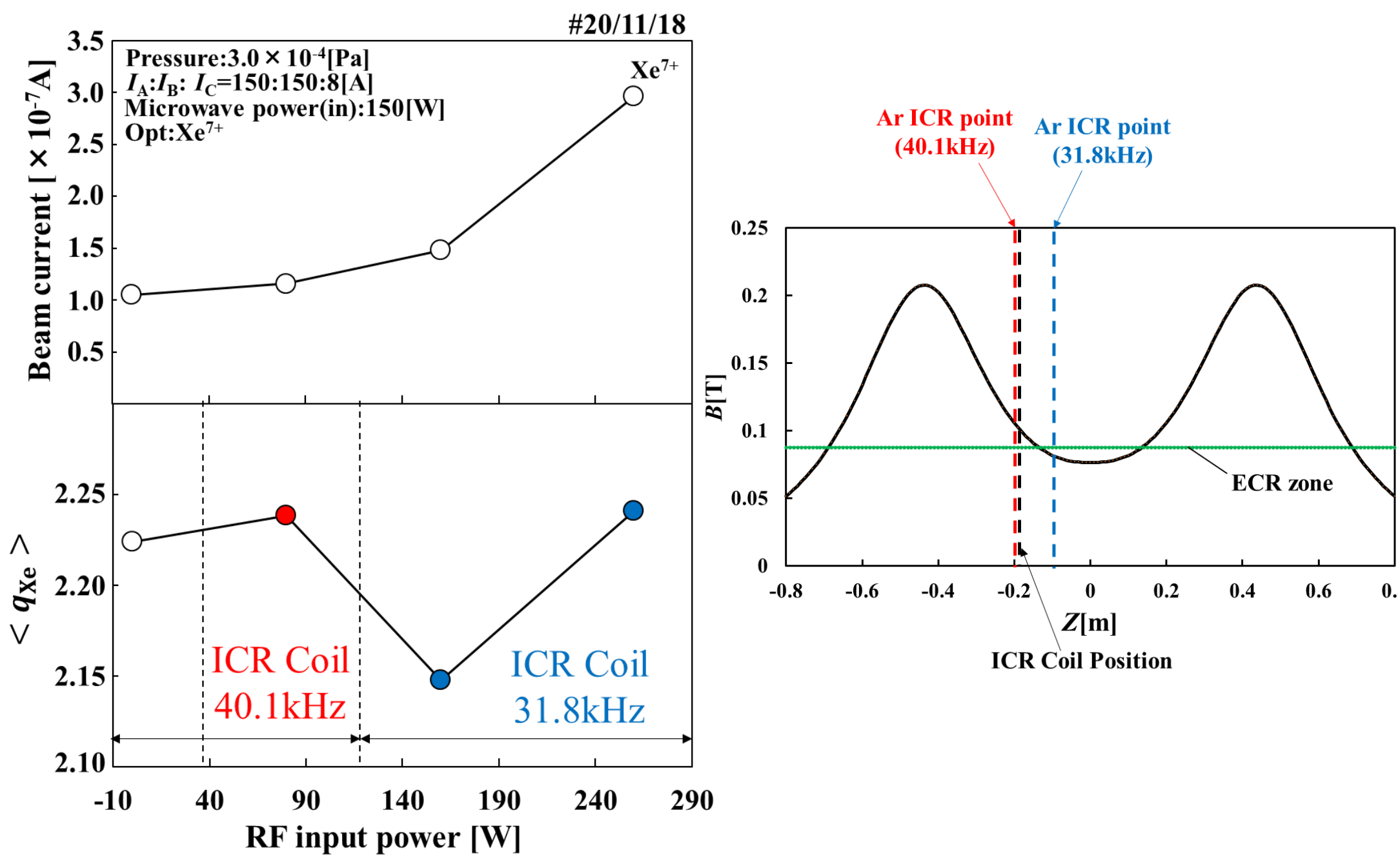


Fig. 11. Xe⁷⁺ & average charge state <*q*> in case B ($I_A/I_B/I_C$=150/150/8A)

§ 5. Advanced further ICR experiments on ECRIS and Preparation

- In the summer of 2022, a Grant-in-Aid for *efficient multi-charged ion generation by low-frequency resonance* on this ICR(2023&24) and LHR (2024&25) experiments to ECRIS was adopted, and we are currently preparing to conduct more effective experiments.
- The ICR antenna material can be water-cooled with a Cu pipe, and the surface is coated with an insulating film by thermal spraying of alumina. A dedicated water-coolable flange will be prepared for introducing the ICR antenna into the vacuum, and it will be possible to be mobile about 100 mm.
- The newly introduced RF power supply amplifies the signal source (0dBm, 1mW) with a frequency range of 20kHz to 1MHz to a maximum gain of 55dB (300W) and feeds it into ICR antenna. We prepare a matching box optimized for frequencies of 400 kHz and 40 kHz for both Xe/Ar and Ar/He, respectively. We are planning to amplify the signal from the signal source and use a special isolation transformer to the high voltage side of ECRIS.
- In particular, in the case of increasing the yield of highly charged Ar ions, a matching box is used, which is optimal at a frequency of 400 kHz for selective heating of mixed low-element He ions. Similarly, in the case of Xe multiply charged ions, the mixed low-Z-element Ar ion selective heating is set to 40 kHz as described above.
- We plan to use a 6-turn ICR antenna with a water-cooled Cu pipe insulated by ceramic spraying, based on the results of the above experiments. When this load is used, the maximum currents at 40kHz and 400kHz will be 71A and 55A, respectively, as a result of matching.

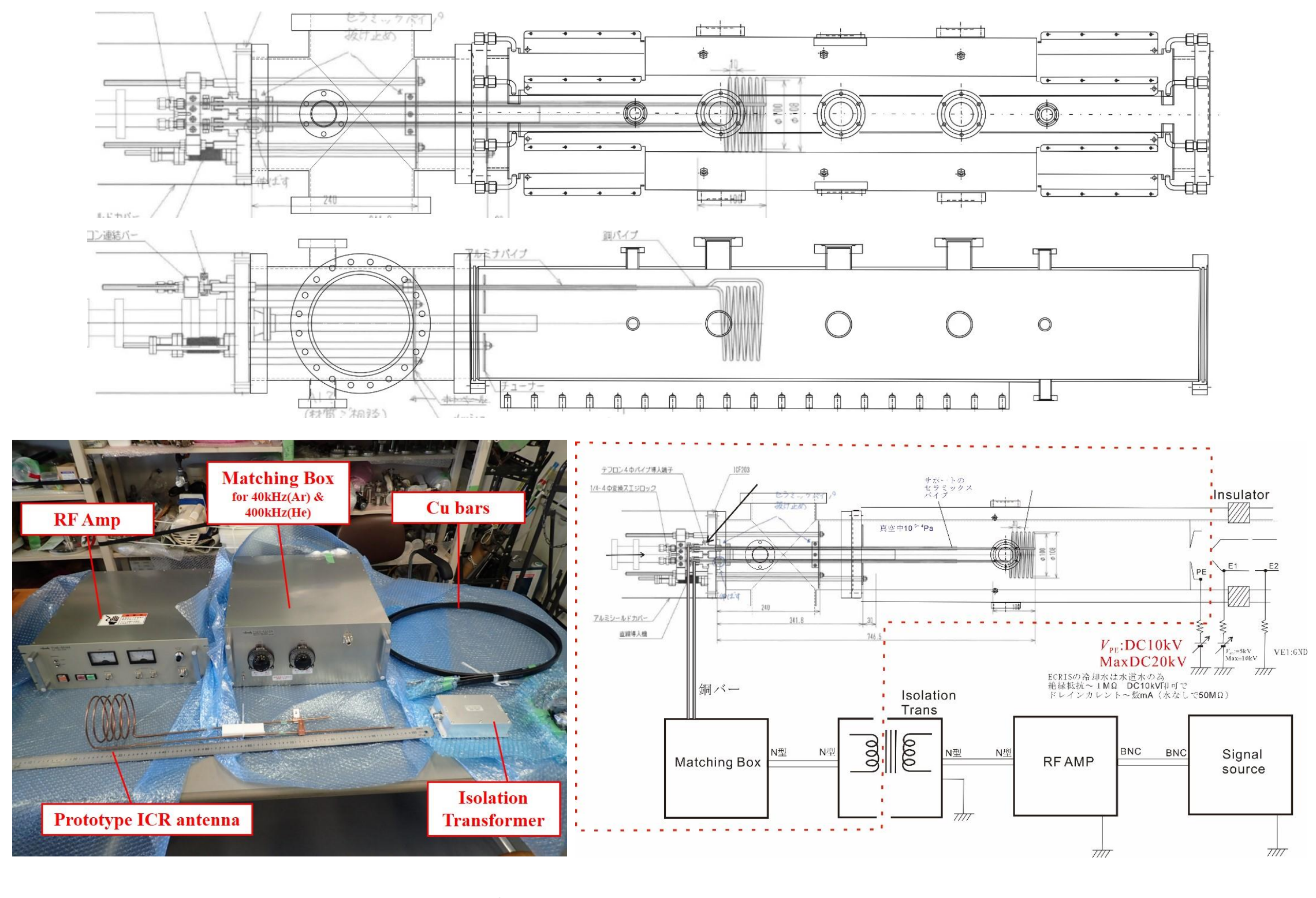


Fig. 12. Advanced further ICR experiments on ECRIS and Preparation

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