Cutoff limitation of left-hand polarization wave and candidates for further enhanced producing multicharged ions on ECRIS

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Focus: μW power & n_e ⇔ Accessibility of waves
(*B* config.(Last conf.))

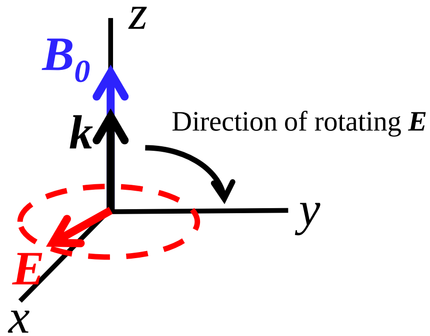
Contents: Brief theory, Experimental results,
Discussions (L-cutoff, I_{q+}) & New canditates, Summary & perspective

Brief theoretical background

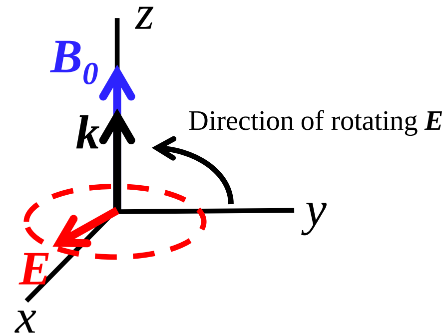
The four principle wave modes:

L, R, O, X waves

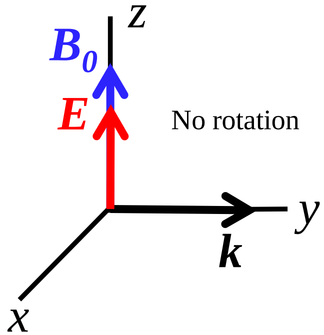
- Left-hand circularly polarized wave (L)
- (θ=0)



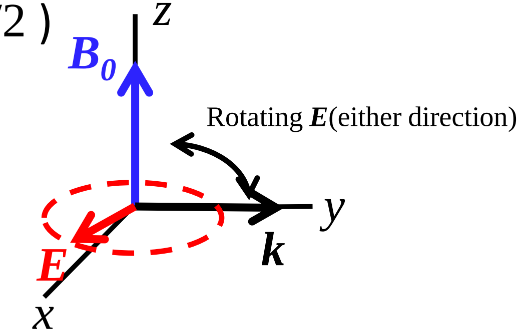
- Right-hand circularly polarized wave (R)
- (θ=0)



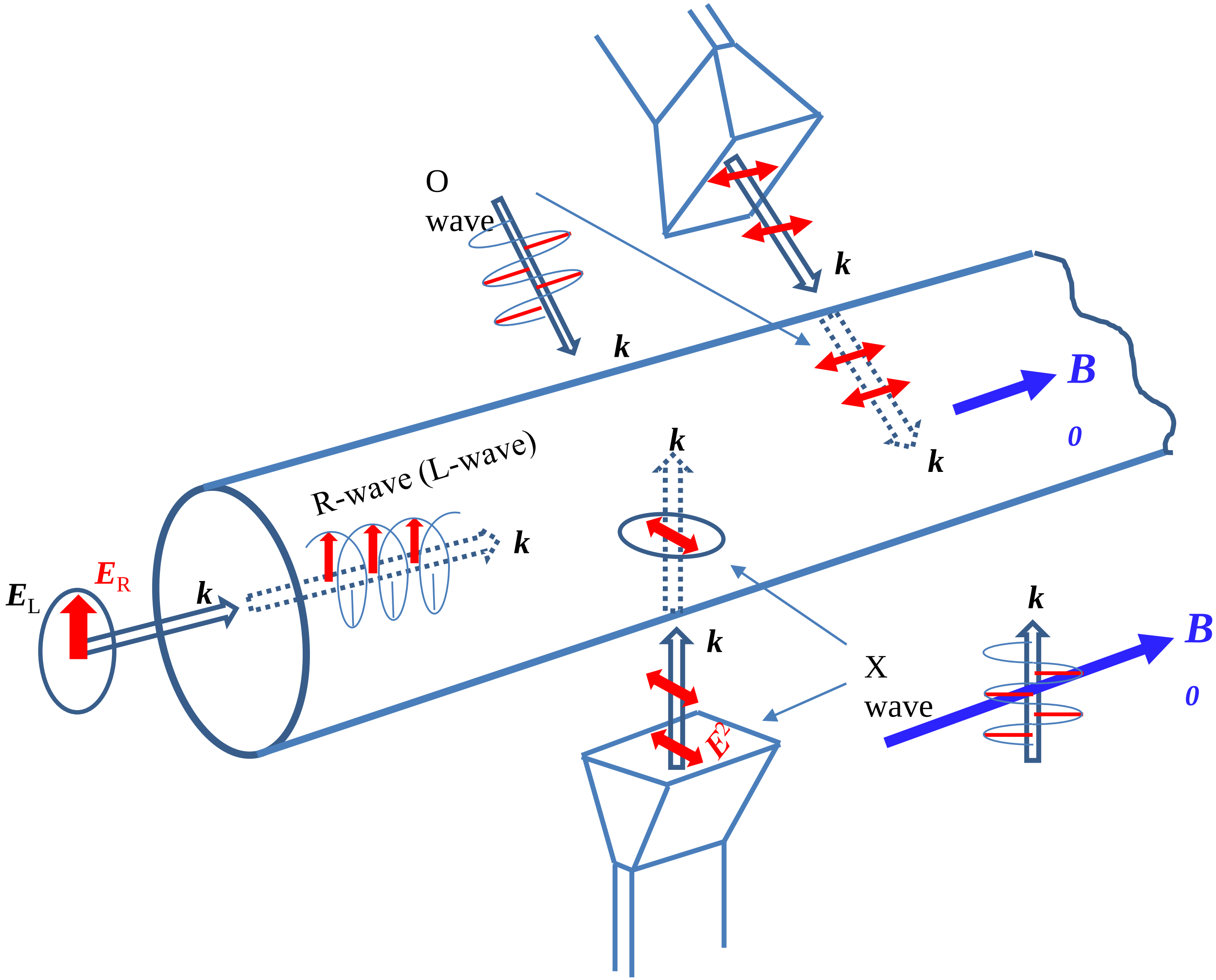
- Ordinary wave (O)
- (θ=π/2)



- Extraordinary wave (X)
- (θ=π/2)



Waves launched towards a magnetoplasma



Brief theoretical background

- In the electromagnetic waves propagating along the magnetic field lines, there exist right-hand polarization wave (R-wave) and left-hand polarization wave (L-wave). There are cutoff frequencies ω_r (R-cutoff) and ω_l (L-cutoff) for each wave propagation mode, and they are derived as follows:

$$\omega_{\mathrm{r}} = \frac{\omega_{\mathrm{ce}} + \sqrt{\omega_{\mathrm{ce}}^2 + 4\omega_{\mathrm{pe}}^2}}{2} \quad , \quad \omega_{\mathrm{l}} = \frac{-\omega_{\mathrm{ce}} + \sqrt{\omega_{\mathrm{ce}}^2 + 4\omega_{\mathrm{pe}}^2}}{2} \; .$$

- Resonance phenomena related to X-wave include high-frequency hybrid resonance (UHR) and low-frequency hybrid resonance (LHR) as follows:

$$\omega_{\mathrm{UH}}^2 = \omega_{\mathrm{ce}}^2 + \omega_{\mathrm{pe}}^2 \; , \qquad \frac{1}{\omega_{\mathrm{LH}}^2} = \frac{1}{\omega_{\mathrm{pi}}^2} + \frac{1}{\omega_{\mathrm{ce}}\omega_{\mathrm{ci}}} \; ,$$

where, $\omega_{\mathrm{ce(ci)}}$ and $\omega_{\mathrm{pe(pi)}}$ indicate the electron (ion) cyclotron frequency and the electron (ion) plasma frequency, $\omega_{\mathrm{ce}} = \frac{eB}{m_e}$, $\omega_{\mathrm{ci}} = \frac{qeB}{M}$, $\omega_{\mathrm{pe}} = \left(\frac{en}{\varepsilon_0 m_e}\right)^{1/2}$, and $\omega_{\mathrm{pi}} = \left(\frac{q^2 e^2 n}{\varepsilon_0 M}\right)^{1/2}$.

- In the wave propagation of the frequency ω microwaves in the magnetized ECRIS plasma, when O-cutoff density is n_c and the magnetic field strength corresponding ECR is B_{ECR}, R-, L-, and UH-cutoff densities n_{cr}, n_{cl}, and n_{cu} are expressed by the following equations:

$$n_{\mathrm{cr}} = n_c\left(1 - \frac{B}{B_{ECR}}\right) (*) \; , \qquad n_{\mathrm{cl}} = n_c\left(1 + \frac{B}{B_{ECR}}\right) , \qquad n_{\mathrm{cu}} = n_c\left(1 - \left(\frac{B}{B_{ECR}}\right)^2\right) .$$

(*) for R-wave coming from $B/B_{\mathrm{ECR}} < 1$)

Experimental apparatus

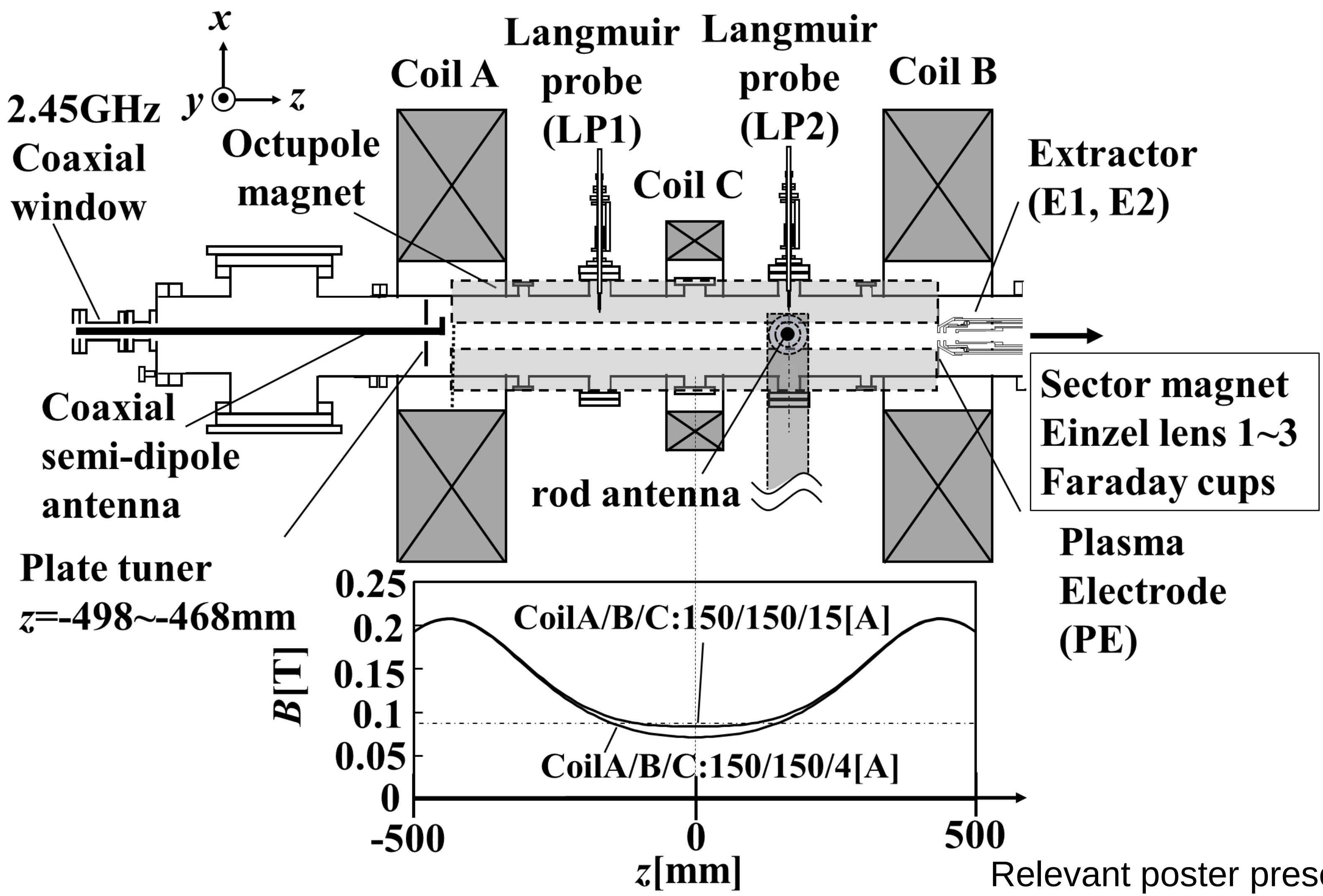


Figure 1. Top view of ECRIS(Osaka Univ.)

Relevant poster presentation:

- Sato-san(ThuP101)
- Owada-san(ThuP103)
- Tsuda-san(ThuP117)

Tapered coaxial semi-dipole & rod antenna

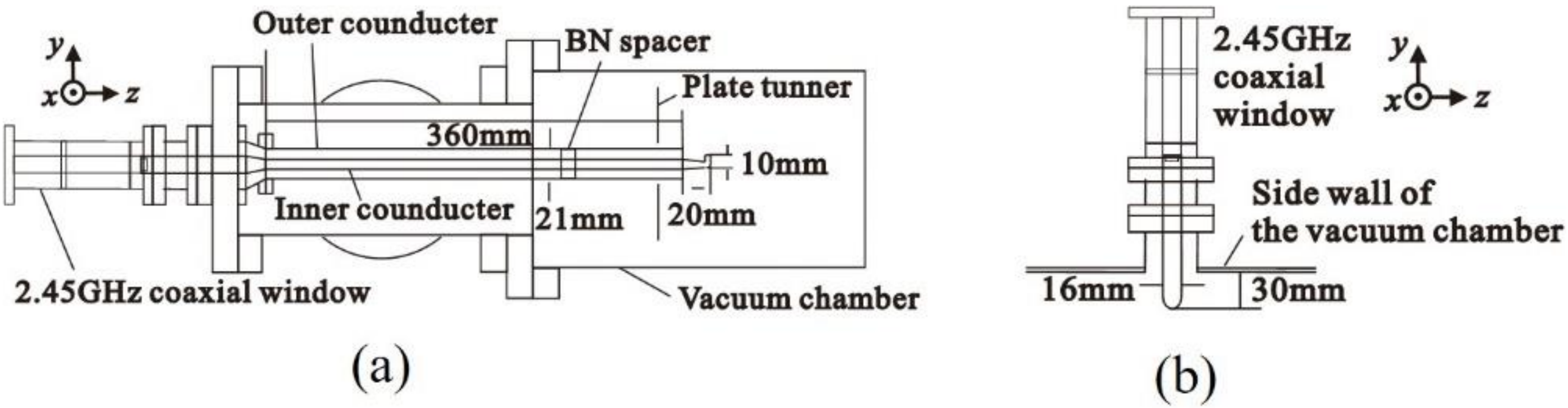


Figure 2. Schematic drawing of microwave feedings by coaxial semi-dipole (a) and Ti rod antennas (b).

Langmuir probe (LP1&2(x-directions), LP3(z-direction))

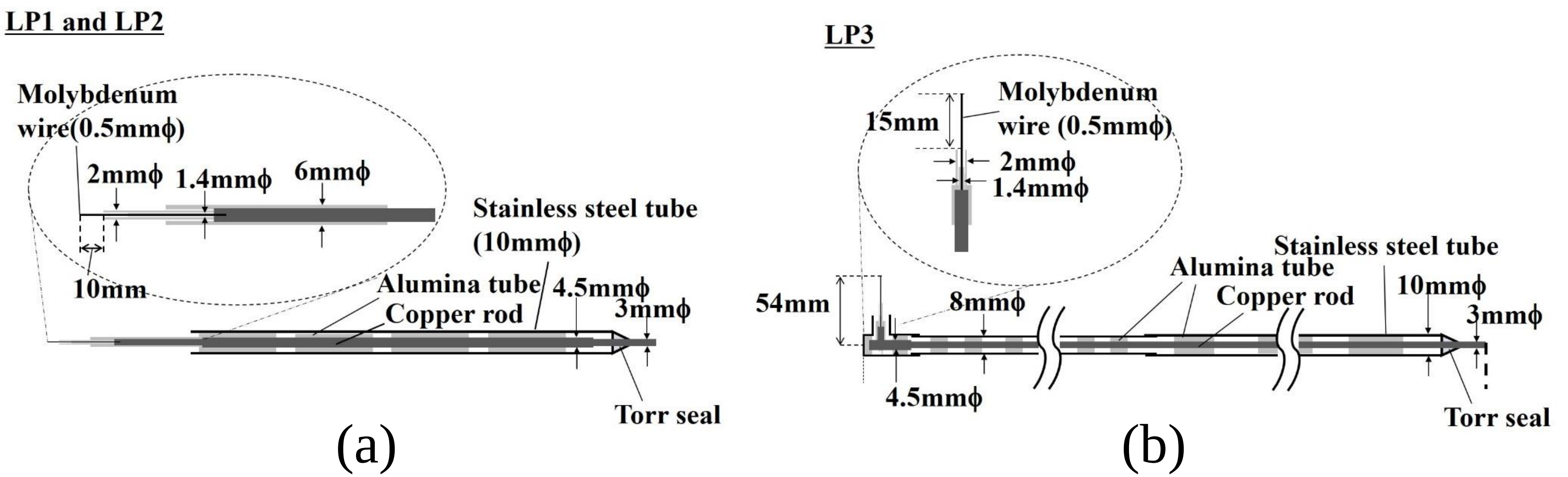


Figure 3. Schematic drawing of probes LP1, LP2(a) and LP3(b).

Axial distribution measurement of plasma parameters in ECRIS by LP3 (z-direction)

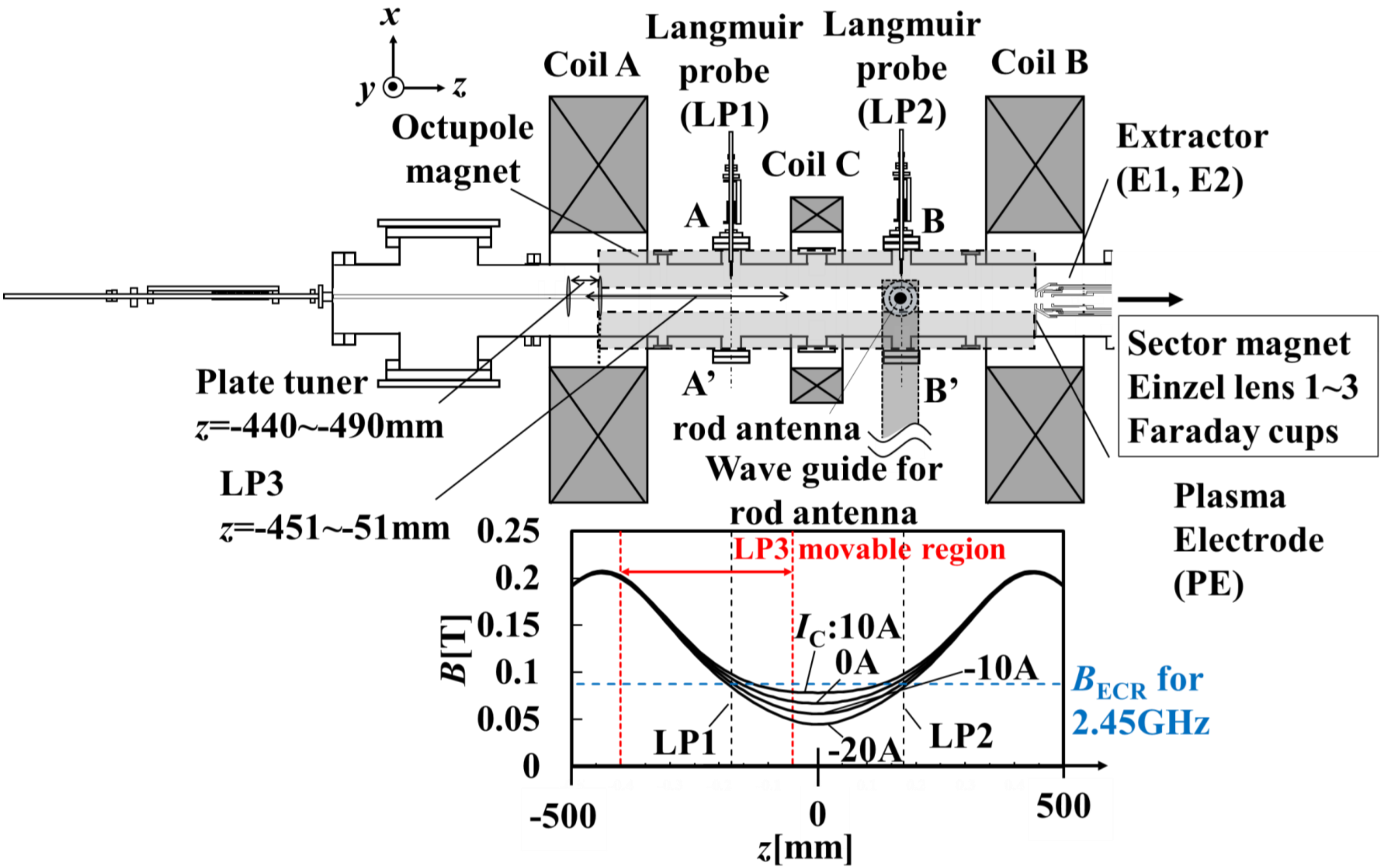


Figure 4. Top view of ECRIS(Osaka Univ.) with LP1, LP2 and LP3.

Axial distribution measurements of plasma parameters in ECRIS by LP3 (z-direction)

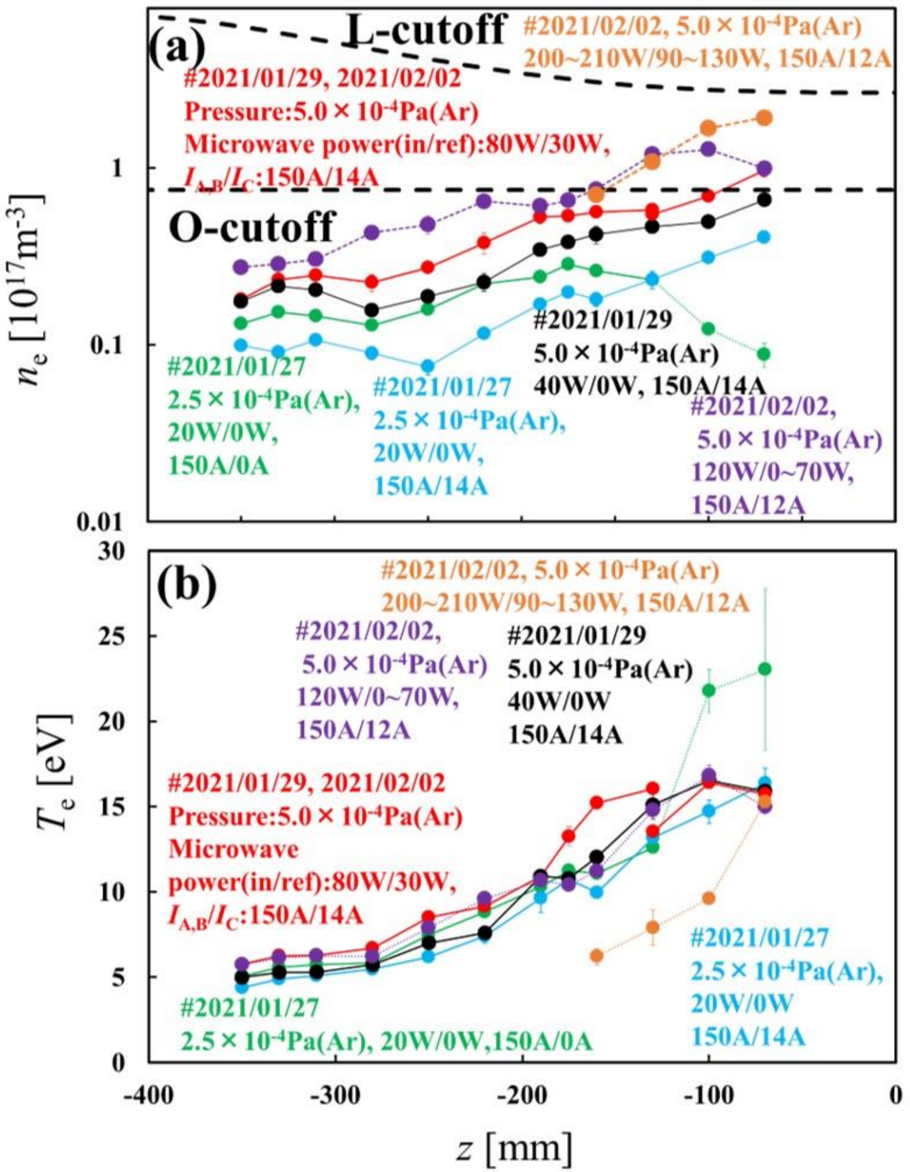


Figure 5. Measured axial (z) profiles of n_e(a) and T_e(b).

Scaling axial n_e distribution on microwave powers

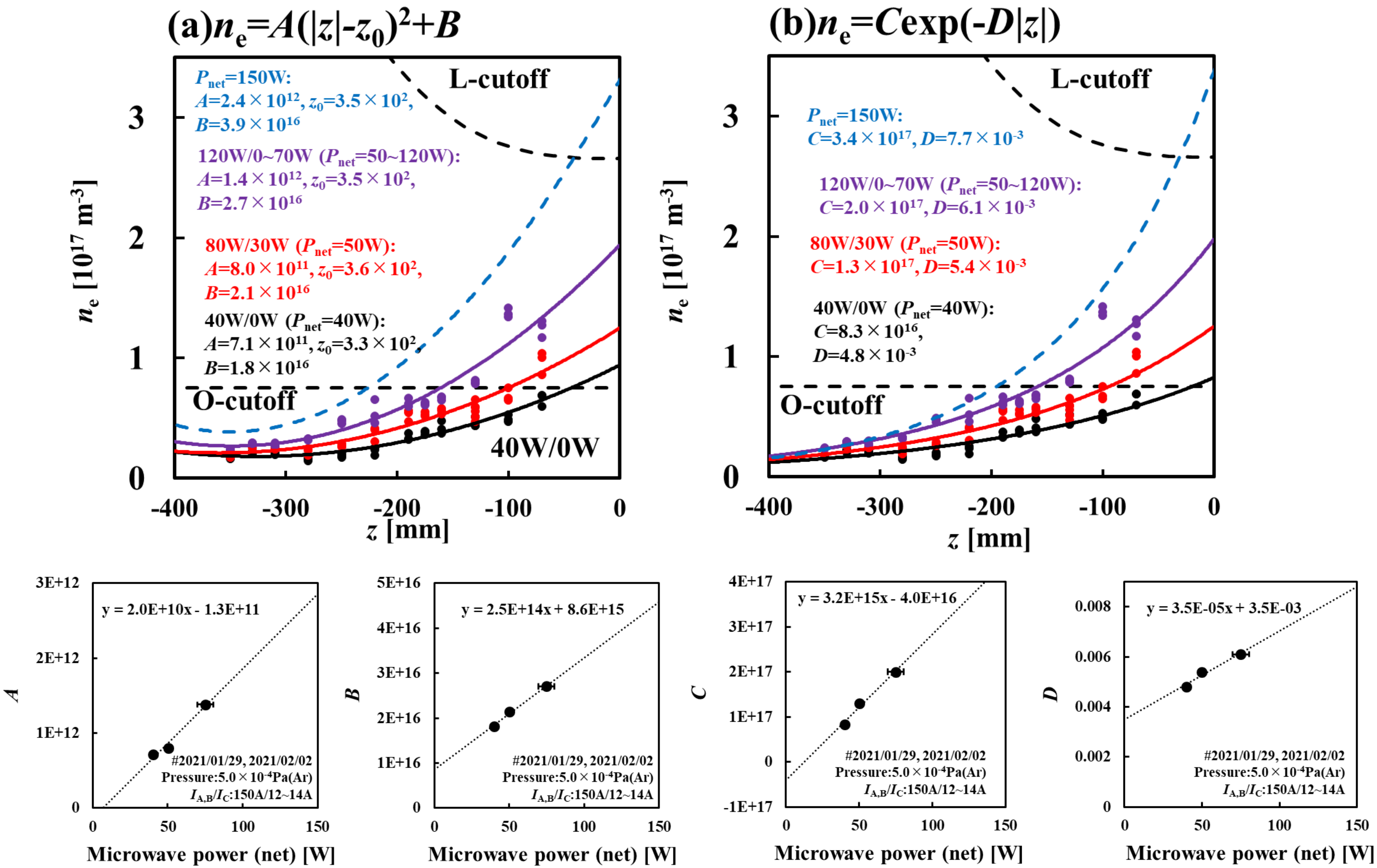


Figure 7. The fitting axial (z) n_e profiles to the functions of square (a) and exponential (b), and obtained fitting-parameters in each below, and scaling on the net microwave powers.

Typical radial n_e profile

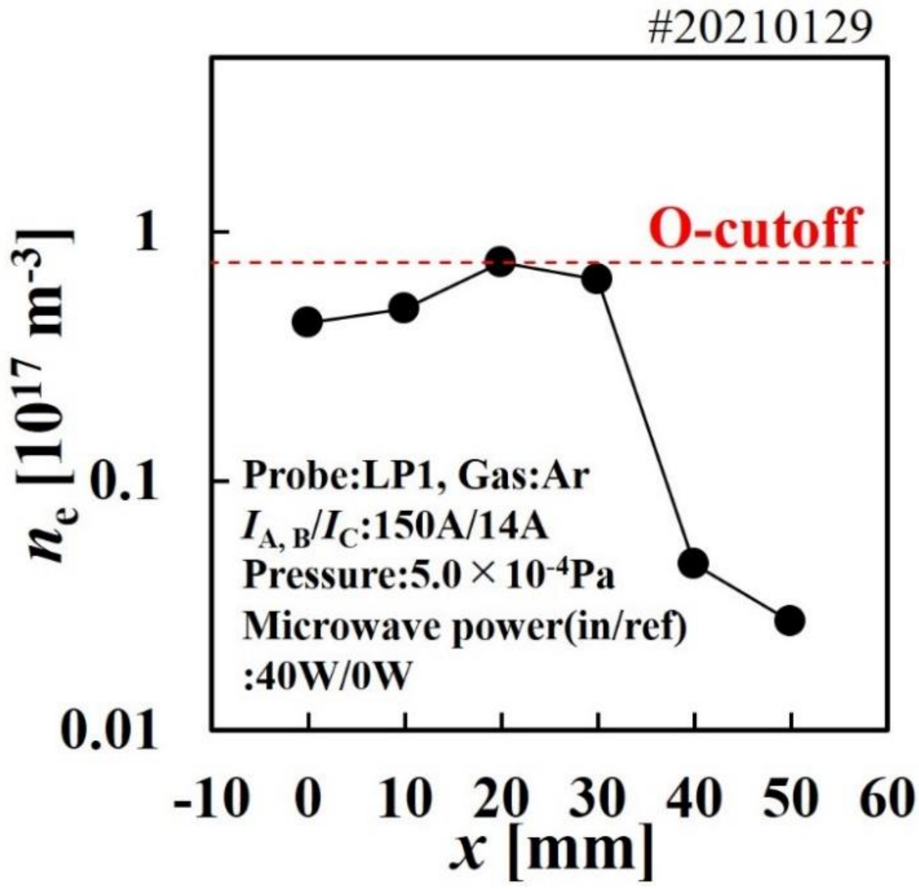


Figure 8. Typical measured radial profiles of n_e.

Appearance/ disappearance of resonances & cutoffs according to microwave powers & n_e

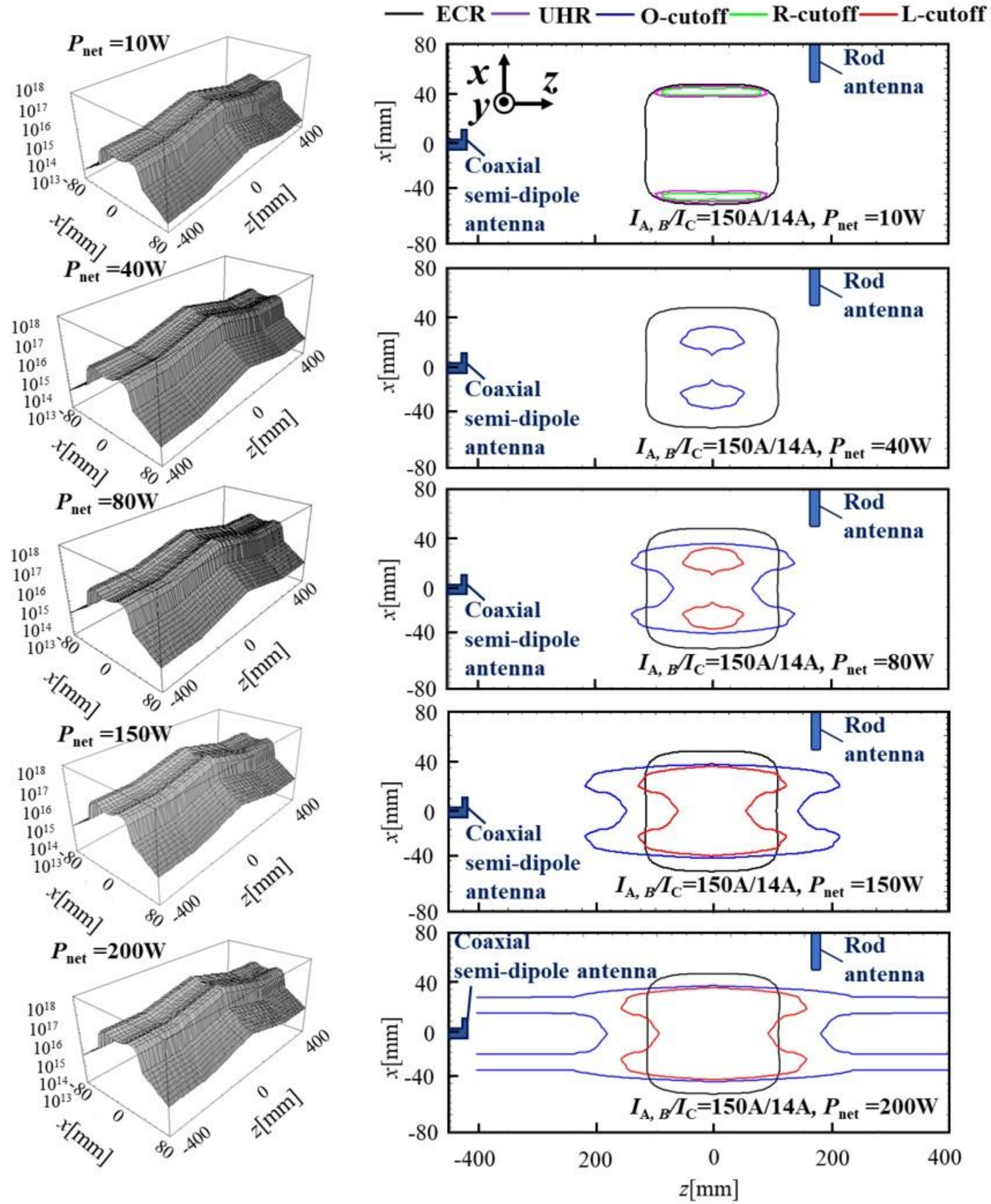


Figure 8. The *x*-*z* profiles of n_e (left side) and the contour plots of the corresponding various resonances and cutoff (right side) on various microwave powers.

Accessibility condition on real space & CMA diagram

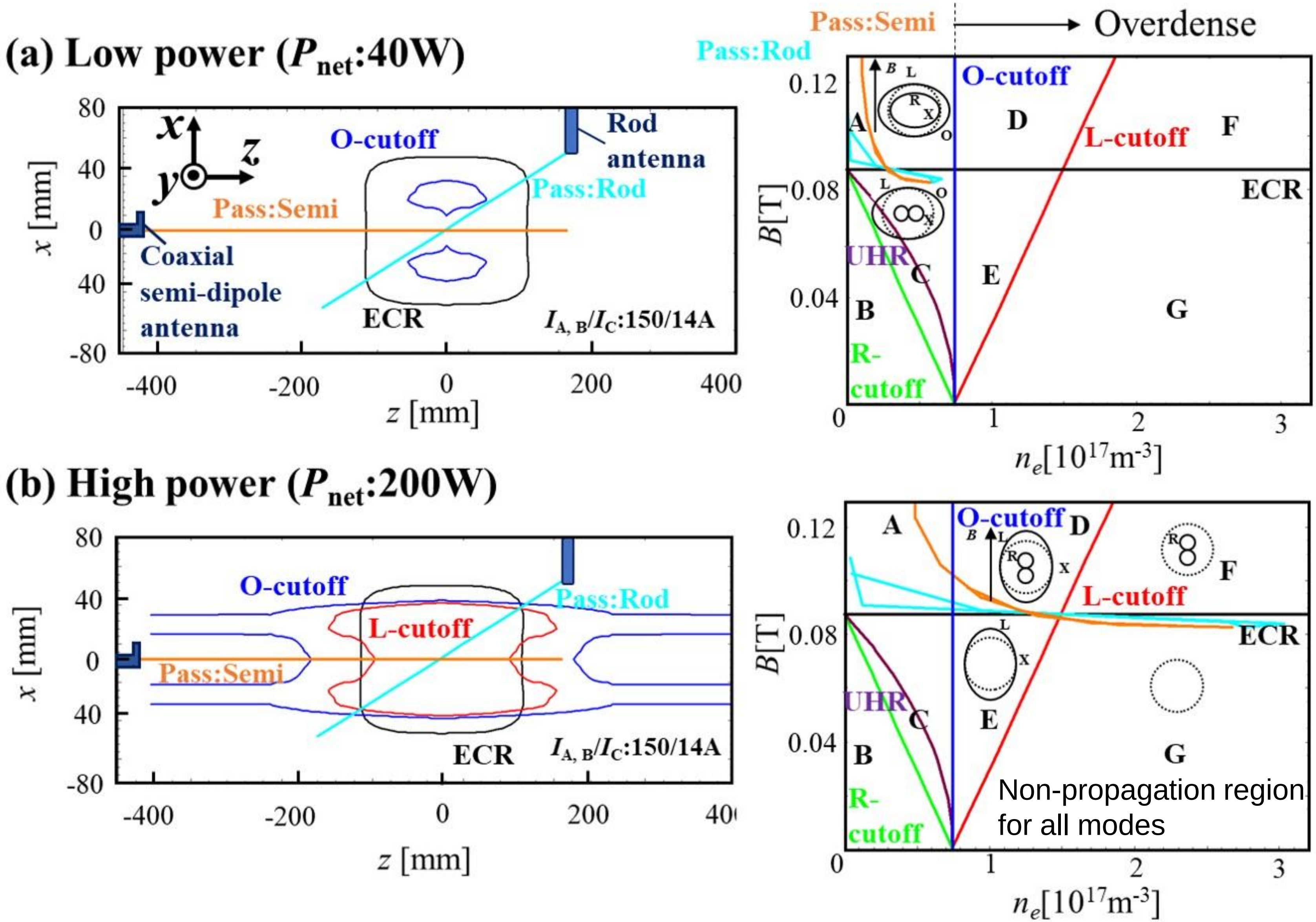
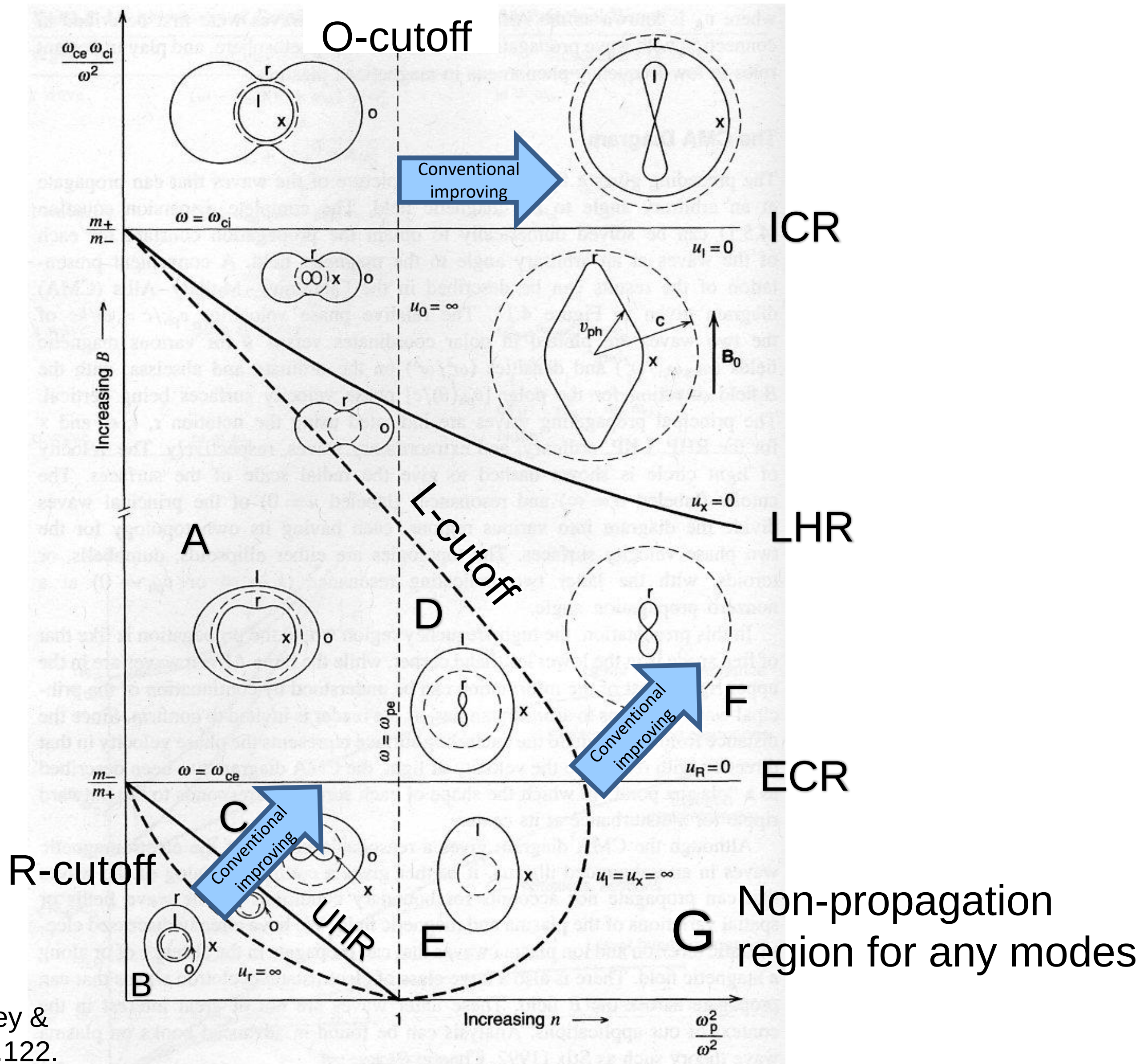


Figure 9. The accessibility condition in the real space of ECRIS (left figure) and in CMA diagram (right figures) at the microwave power 40 W (a) and 200 W (b), respectively.

Avoiding the existence of the "G region": What should we do?



Quarted from Lieberman A M and Lichtenberg J A 2005 Principle of Plasma Discharges and Materials Processing, 2nd Edit., A John Wiley & Son, Inc Publications, Chap.4, pp.122.

New candidates for further enhanced producing multicharged ions on ECRIS

- Advanced high-frequency resonance via conversion from electromagnetic to electrostatic waves:
  - Upper hybrid resonance (UHR) heating
- Applications of new low-frequency resonances without density limit:
  - Lower hybrid resonance (LHR) heating
  - Ion cyclotron resonance (ICR) heating
- New microwave feeding methods:
  - For example: Dual-ECR heating (bidirectional)

Dual-ECR heating Exp.

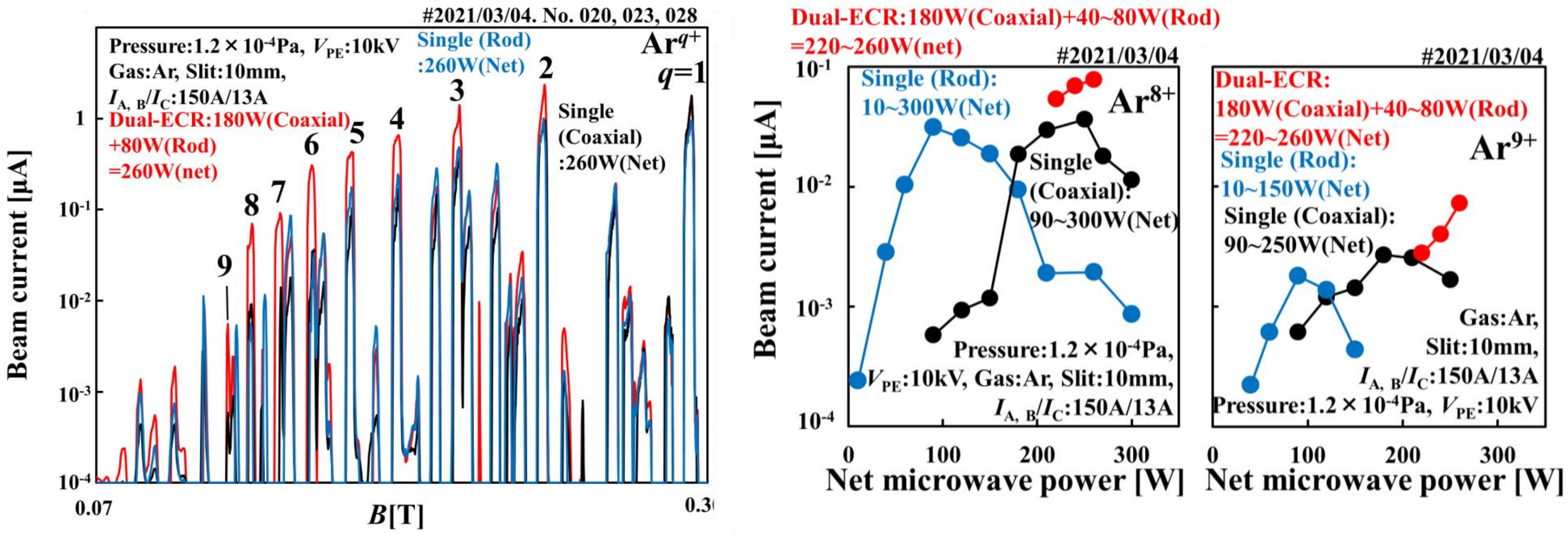


Figure 11. The CSD extracted ion currents (a) and dependences of Ar^{8+} and Ar^{9+} currents in the single microwave feeding (blue lines) and Dual-ECR heating (red lines).

Ref: [7] Kubo W, Harisaki S, Owada I, Sato K, Tsuda K and Kato Y 2021 *Rev. Sci. Instrum.* 92 pp.043514-1-9.(on line publication: 2021.4.2, https://doi.org/10.1063/5.0035631)

Summary & Future perspective

- The experimental dependence of the n_e on the microwave power are shown in ECRIS, and the accessibility conditions are discussed.
- As a result, it was shown that O- and L-cutoff densities are formed due to the increase by the incident microwave power, and the electromagnetic wave propagation is covered by the non-propagation G region.
- It is possible that this basically determines the saturation and limit value of the multicharged ion current with respect to the microwave power.
- As breakthrough candidates, in addition to increasing conventionally microwave frequency and accompanying magnetic field strength, we have proposed new power feeding methods such as Dual-ECR heating and UHR, and have already started and presented some of the results.
- Furthermore, we newly proposed a method to apply ICR and LHR, that are L-cutoff free and are resonance phenomena including ions, have not been noticed in ECRIS.
- We are currently preparing to conduct experiments along to these guidelines.

Thank you for your attentions

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