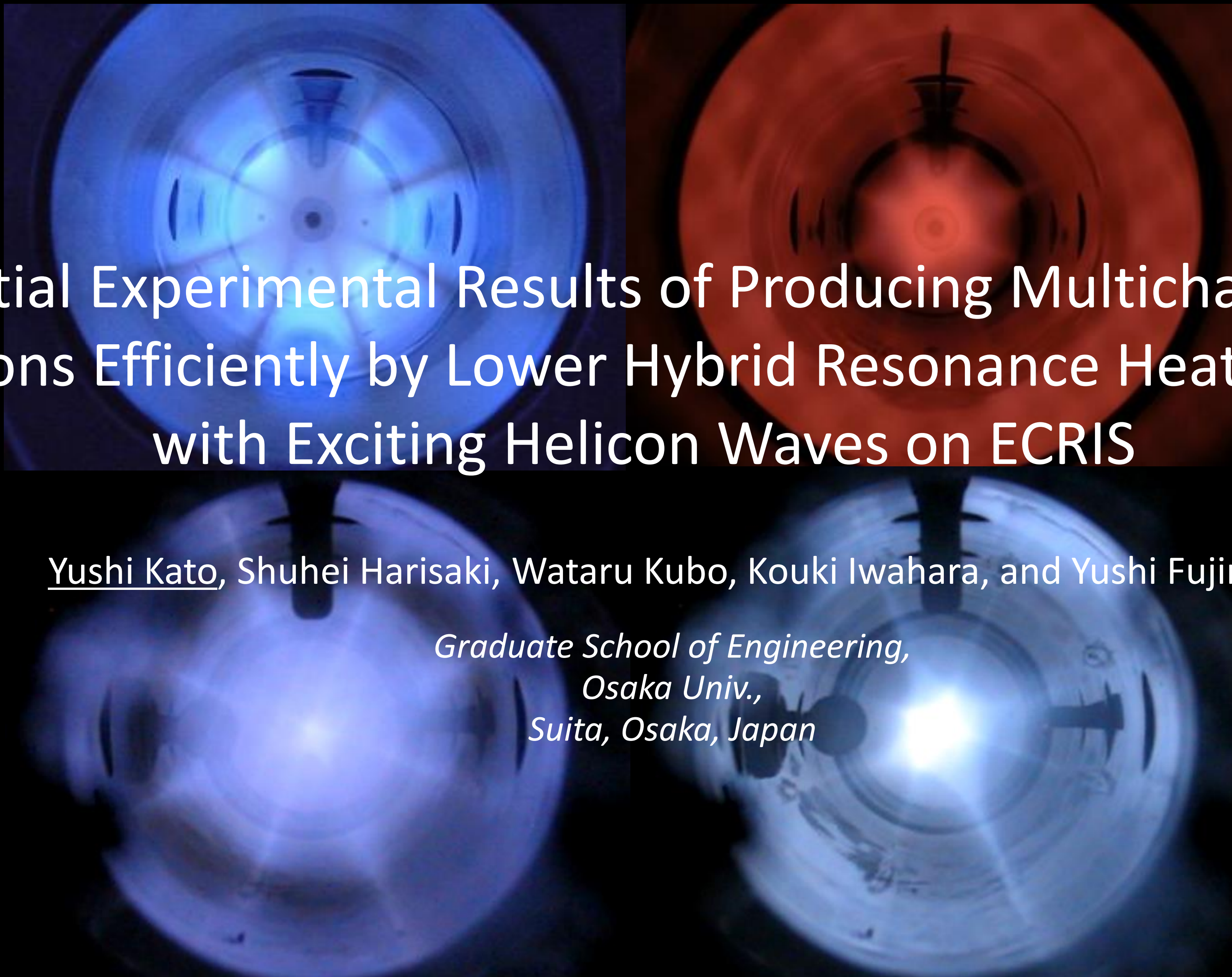


Initial Experimental Results of Producing Multicharged Ions Efficiently by Lower Hybrid Resonance Heating with Exciting Helicon Waves on ECRIS

Yushi Kato, Shuhei Harisaki, Wataru Kubo, Kouki Iwahara, and Yushi Fujimura

Graduate School of Engineering,
Osaka Univ.,
Suita, Osaka, Japan

Background and research progress

- ICIS2019: Accessibility of EM waves ⇔ in changing ***B*** config., feasibility of upper hybrid resonance (UHR)
- ICIS2021 : Accessibility ⇔ μW power & n_e dependence
- L-cutoff limitation (I_q^+ limitation) & New candidates for improving :
- *Ion cyclotron resonance* (*ICR*) & *Lower hybrid resonance* (*LHR*)

Low freq. waves

- We are embarking on new kind of experiment that is almost unprecedented on ECRIS.
  - Now, our available low frequency sources & target ion species :
    - ICR:20~50kHz (640W) for IH Fe vapor source; Xe mixed Ar.
    - LHR: 13.56MHz (1.4kW) for process plasma; H^{+}~C^{+}, $Ar^{2+\sim}$, $Xe^{3+\sim}$.

Contents (focus):

- Brief theory, The first *LHR* experimental results,
- Discussions (Summary & perspective)

Brief theoretical background I: Analysis scheme of EM waves in the ECRIS can be summarized very roughly

- Equation of motion under ***B***

- Electrons
- for fast-time varying
- (ECR&UHR)

Including ions
for slow-time varying field
(ICR&LHR)

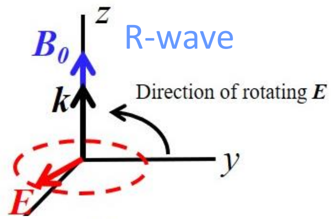
$\boldsymbol{v}_e$ $\boldsymbol{v}_i$

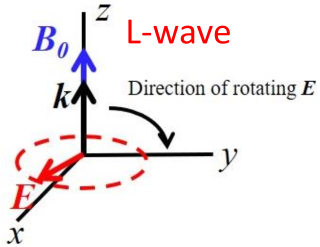
- Current density ***J***

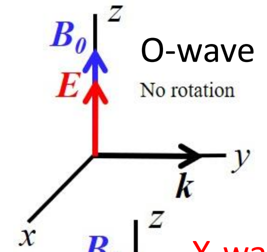
- Maxwell's curl Eqs.
- Dielectric constant $\varepsilon_0 \overline{\overline{\boldsymbol{\kappa}_{\mathrm{p}}}}$ components

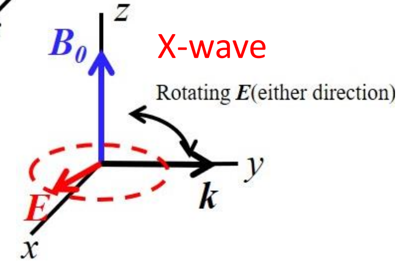
- det|left-hand side|=0

- $\widetilde{E_x}:\widetilde{E_y}:\widetilde{E_z}$ &
- Dispersion relation are decided.









- $\theta = 0$ (***B***//***k***):
- PO, R-wave(ECR), L-wave(ICR);
- R-& L- cutoffs

Summeraized to CMA daiagram

$\theta = \pi/2$(***B*** ⊥ ***k***):
O-wave(interferometer)
& X-waves(UHR&LHR)
R-& L- cutoffs

Summeraized to CMA daiagram

- Arbitrary θ & $\nabla \cdot \widetilde{\boldsymbol{E}} \approx 0$ & $\nabla \times \widetilde{\boldsymbol{E}} \approx \mathbf{0}$
- Helicon waves*

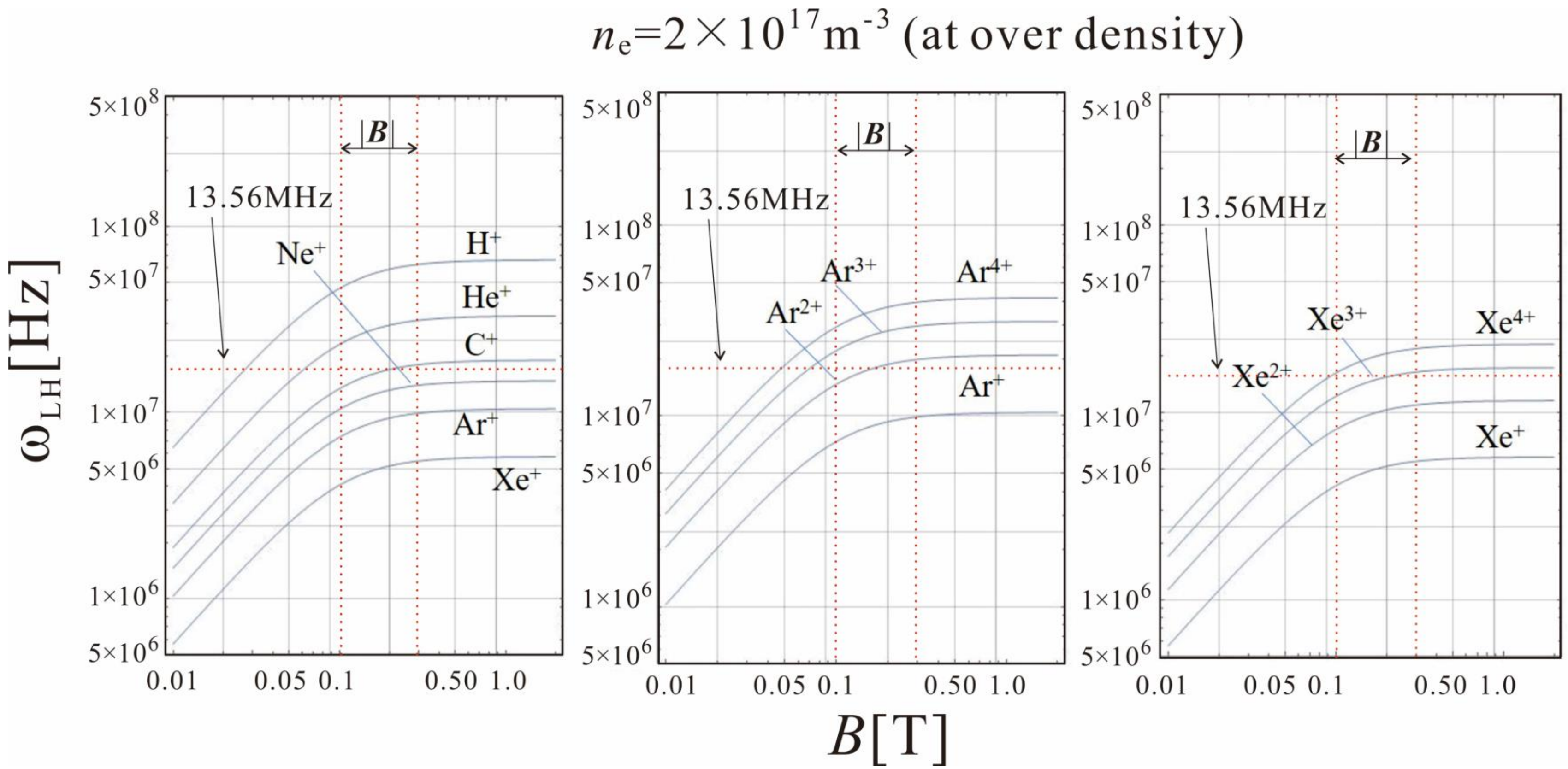
*a superimposed wave of multiple low-frequency Whistler waves propagating at a constant angle θ.

Brief theoretical background II:

- ***Dispersion relation of lower hybrid resonance (LHR):***

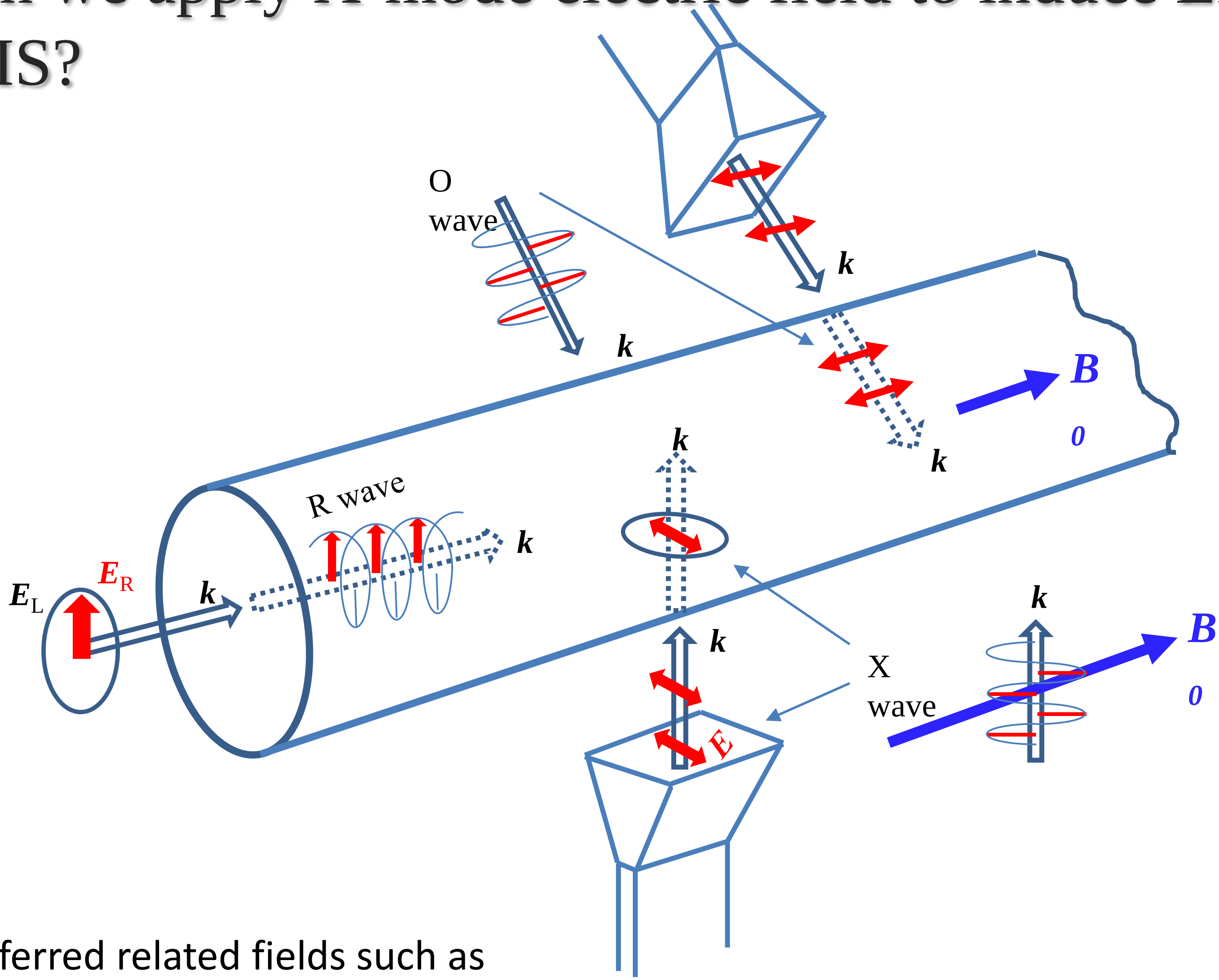
- $$\frac{1}{\omega_{LH}^2} = \frac{1}{\omega_{pi}^2} + \frac{1}{\omega_{ce}\omega_{ci}}$$

$\because \omega_{pi}^2 \gg \omega_{ci}^2$ & $\omega_{ci} \ll \omega_{LH} \ll \omega_{ce}$, $\omega_{pe} \sim \omega_{ce}$, $\omega_{pi} \sim (M/m)^{1/2}\omega_{ci}$,



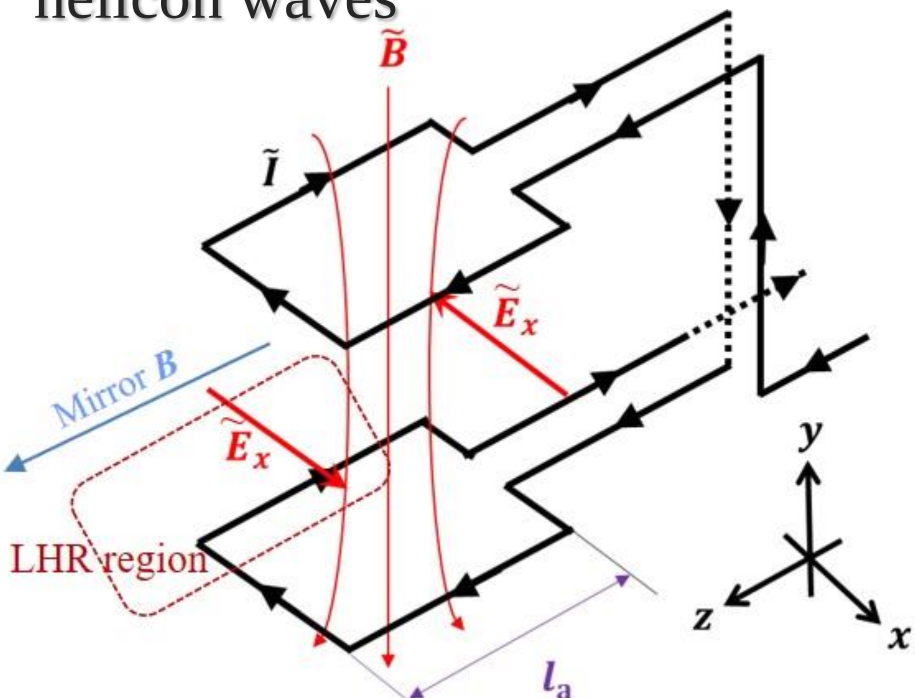
- By using available13.56 GHz RF source in the initial experiment,
- The |***B***| around our 2.45 GHz ECRIS (|$\boldsymbol{B}_{ECR}$|=0.0875G) is about 0.1-0.3 T.
- Ion species in which the LHR region exists are ones lighter than C^+, $Ar^{2+\sim}$, $Xe^{3+\sim}$.
- In our ECRIS, averaged Ar <q^+> is about 2~4, so the LHR is sufficiently possible.

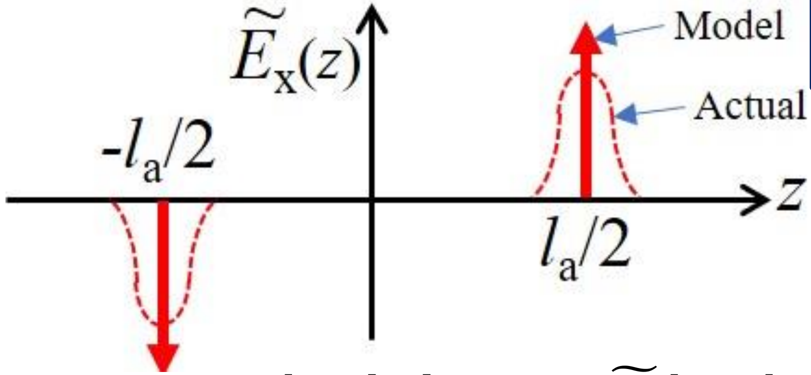
How can we apply X-mode electric field to induce LHR in ECRIS?



- We referred related fields such as
  - Fusion, process plasma, ion engine, and isotope separation, etc.
  - It is a matter of applicability to ECRIS.
- We concluded that helicon wave is the most applicable with the possibility of LHR occurrence by the X-mode electric fields.

Guiding principles of saddle-coiled antenna for LHR via exciting helicon waves





Helicon wave modes: mixtures of EM $(\nabla \cdot \boldsymbol{E} \approx 0)$ and quasi-static $(\nabla \times \boldsymbol{E} \approx 0)$ fields having form:

$$\boldsymbol{E}, \boldsymbol{H} \propto \exp i\,(\omega t - k_{/\!/}\, z - m\theta),$$

where integer m specifies azimuthal modes.

Assumption: uniform n_e and the boundary condition (Chen[9]):

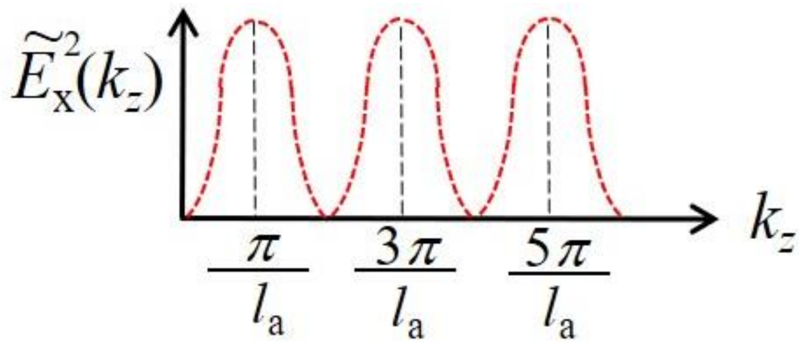
$$mkJ_m(k_\perp R) + k_{/\!/} J'_m(k_\perp R) = 0,$$

where J_m' denotes derivative of Bessel function J_m.

Here we apply a typical saddle-coiled antenna with m=1 mode excitation according to Leiberman. [7]

- Assuming the ideal antenna $\widetilde{E_x}$ has sharp δ-function peaks at both ends of the coil, we consider the following electric field:

$$\widetilde{E_x}(z) \approx \widetilde{E_{x1}}\Delta z \left[\delta\left(z + \frac{l_a}{2}\right) - \delta\left(z - \frac{l_a}{2}\right)\right]$$



- By Fourier transforming and squaring, the spatial power spectrum can be obtained as follows: $E_x^2(k_z) \approx 4\widetilde{E_{x1}}^2(\Delta z)^2 \sin^2 \frac{k_z l_a}{2}$.
- When $k_z \approx \pi/l_a$, $3\pi/l_a$, etc., and then when $\lambda_z \approx 2l_a$, $2l_a/3$, etc., the antenna is well coupled to the helicon mode, and $E_x^2(k_z)$ is maximized.

Wavelength matching condition for helicon wave excitation

(This fig. shows dispersion relations for typical densities & 13.56MHz RF freq.)

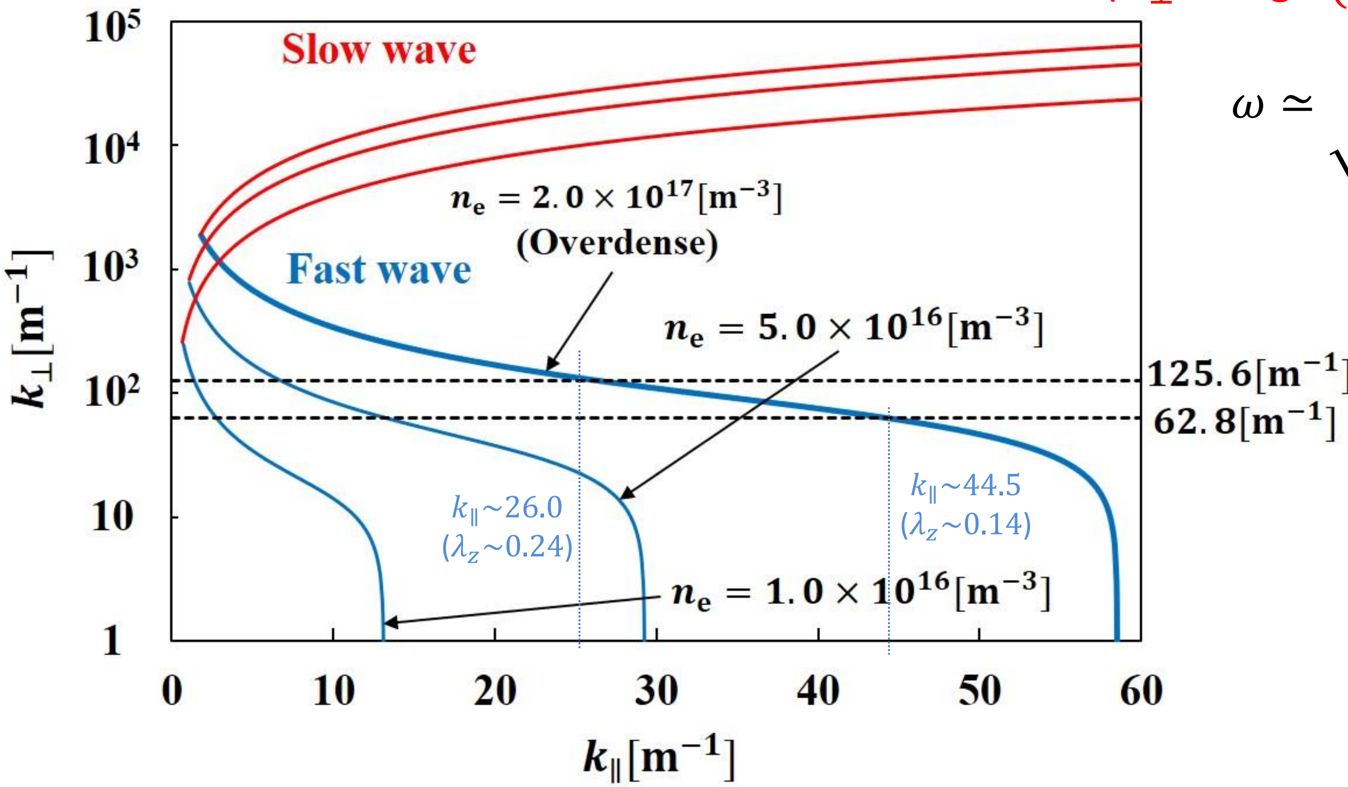
Dispersion relations of helicon modes:

Fast wave($N_\perp$: small $(k_\perp \lesssim k_{/\!/})$):

$$c^2 k_\parallel \sqrt{k_\parallel^2 + k_\perp^2} \simeq \omega\omega_{\mathrm{pe}}^2 / \omega_{\mathrm{ce}}$$

Slow wave($N_\perp$: Large $(k_\perp \gg k_{/\!/})$):

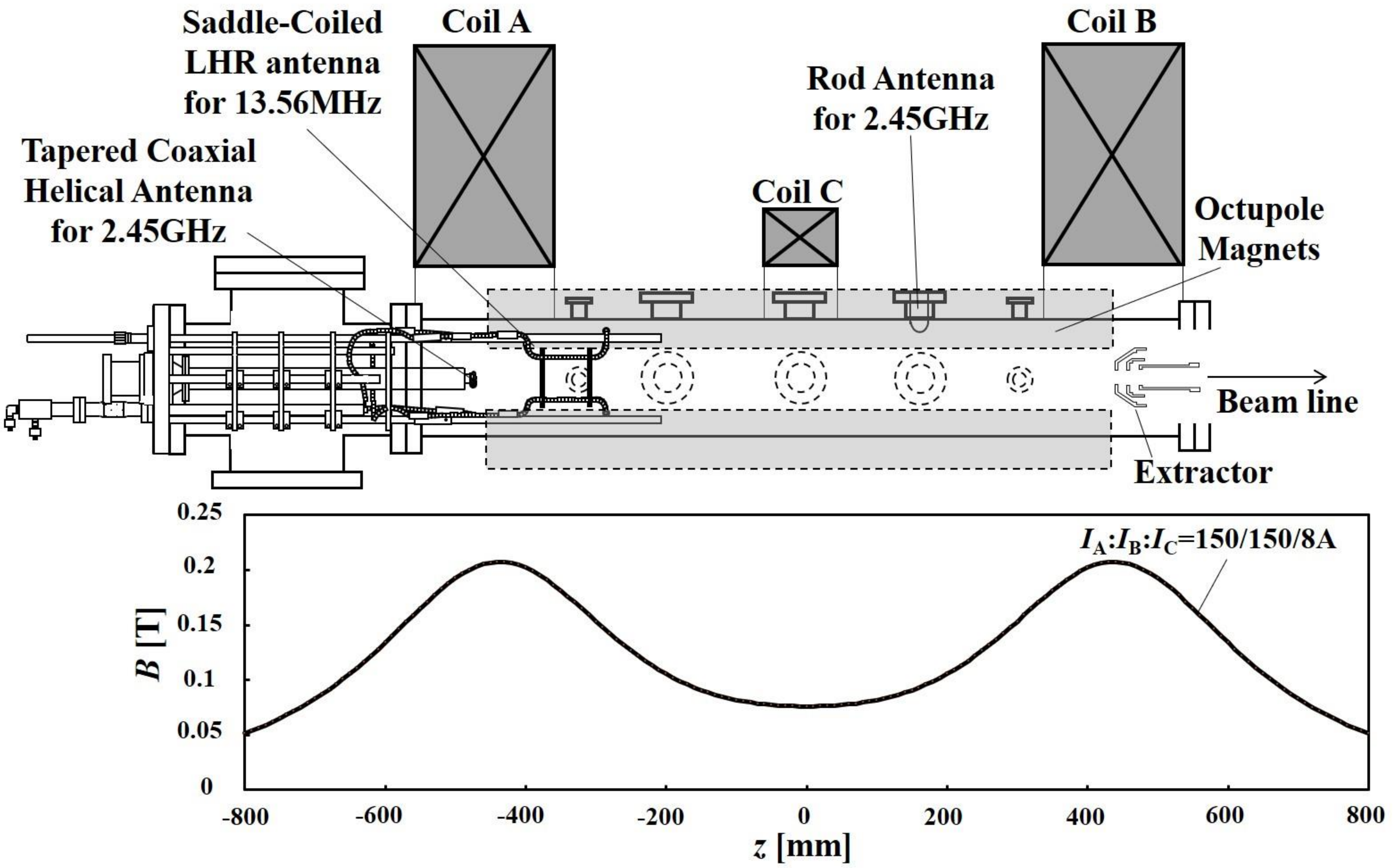
$$\omega \simeq \sqrt{\frac{\omega_{\mathrm{pe}}^2 \omega_{\mathrm{ce}}^2}{\omega_{\mathrm{pe}}^2 + \omega_{\mathrm{ce}}^2} \frac{k_\parallel}{k_\perp}}$$



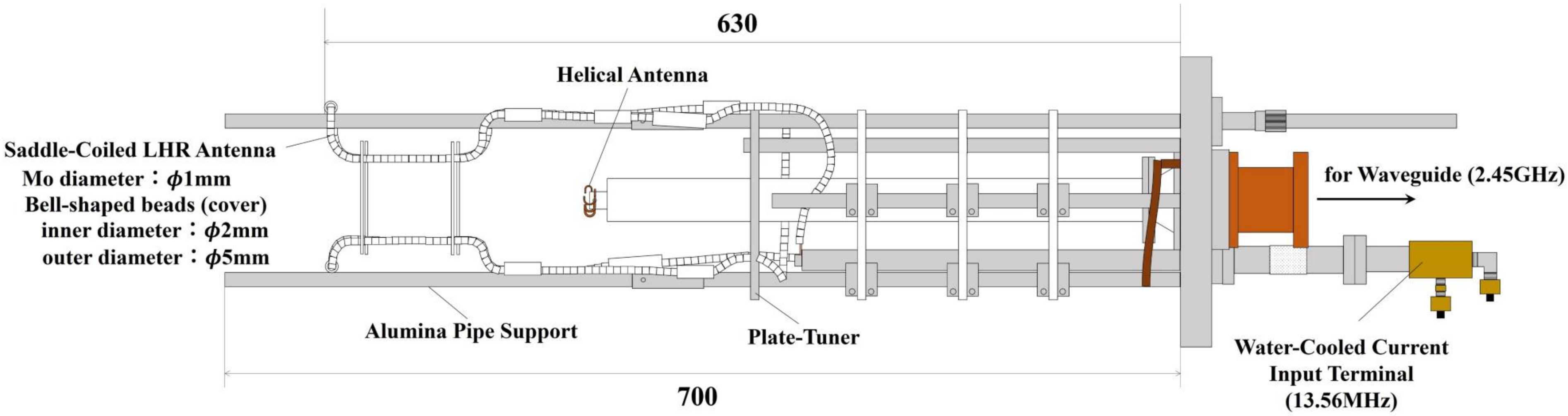
($\lambda_\perp$~0.05~0.1m ∵ Considering the plasma diameter)

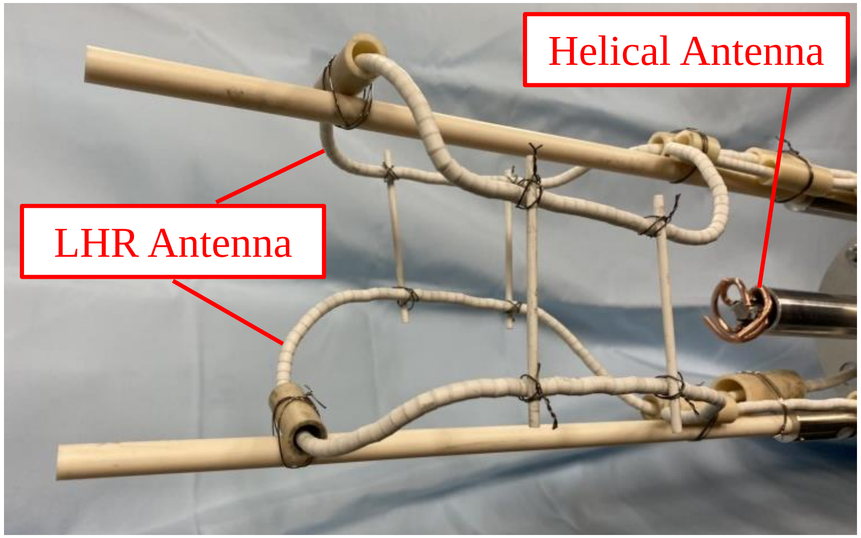
- Assuming the wavelength of the radial electric field is about $\lambda_\perp$≒**0.05~0.1m, *i.e.*, $k_\perp$≒125.6~62.8m^{-1}**, considering the plasma diameter.
- We aim to excite helicon wave at high density $\boldsymbol{n_e}$ **= 2 × 10^{17} m^{-3}** in high microwave power operation, we obtained the corresponding $\boldsymbol{k_{//}}$**≒26.0~44.5m^{-1}, and λ_z≒0.24~0.14**.
- By using $E_x^2(k_z)$ maximized conditions (**$k_z \approx \pi/l_a$, $3\pi/l_a$, etc.**, and then **$\lambda_z \approx 2l_a$, $2l_a/3$, etc.**), We determined **the axial coil length l_a = 0.12m** **and the radial length l_b = 0.1m actually**.

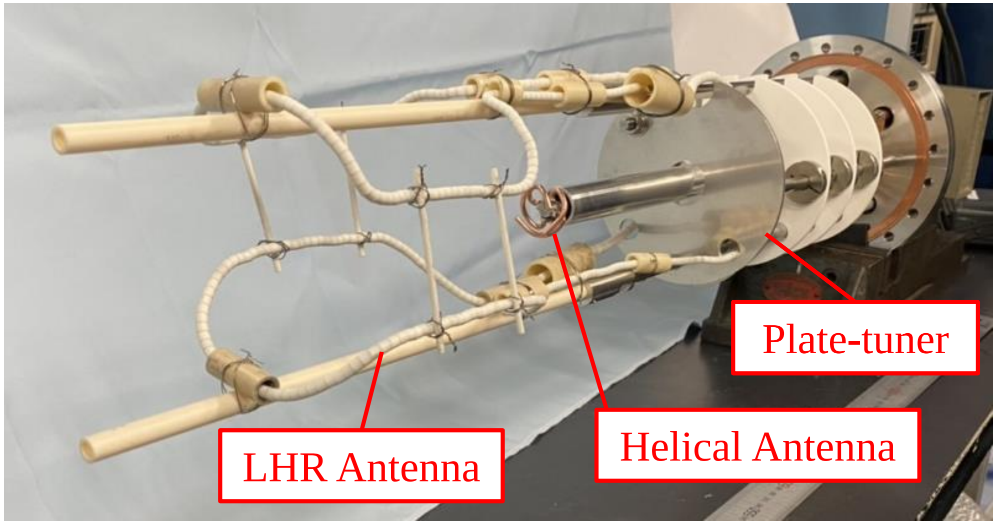
Installation of saddle-coiled LHR antenna exciting helicon waves on ECRIS



Saddle-coiled LHR antenna exciting helicon waves

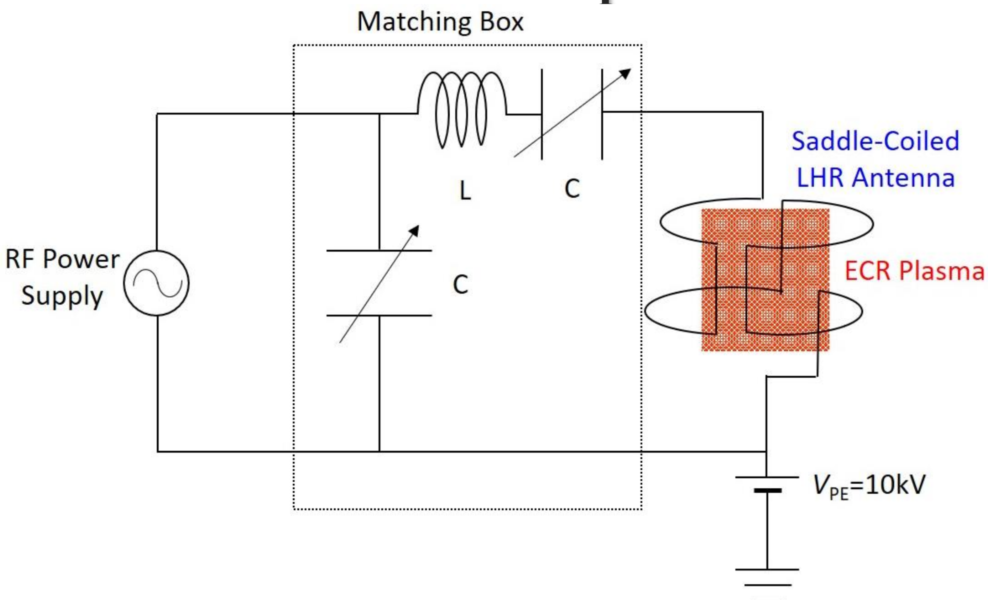


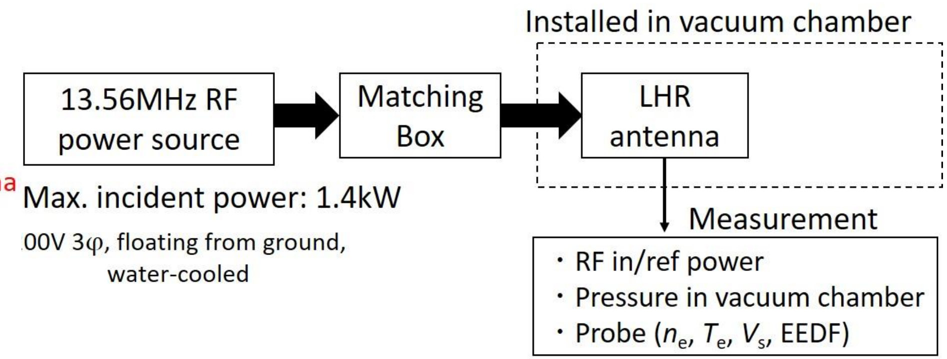




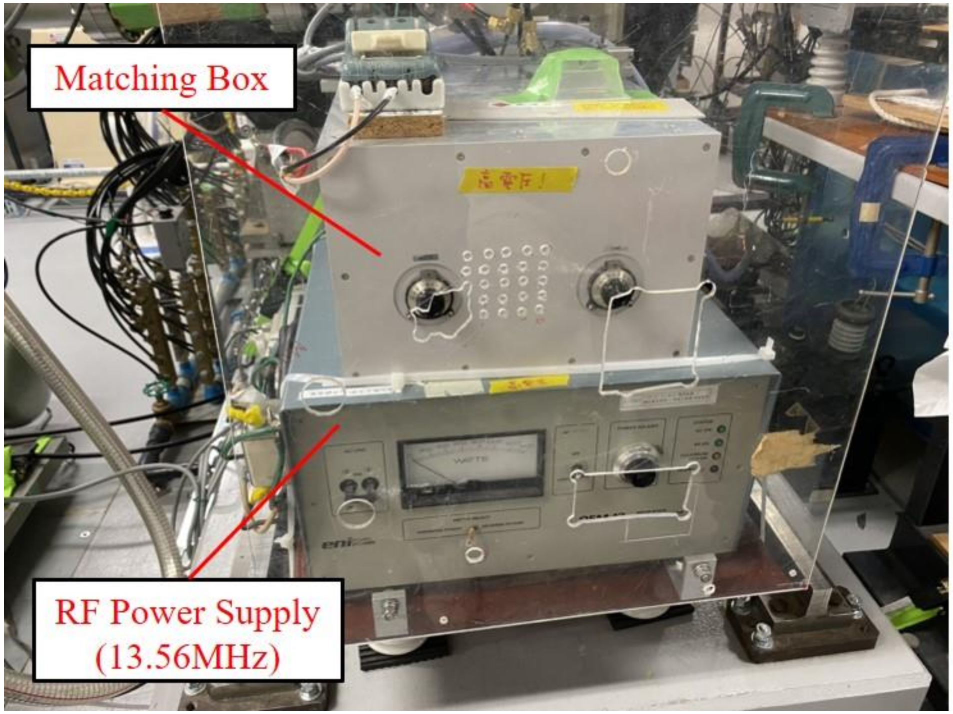
Connections of the saddle coil are made behind the plate tuner, so as not to affect the X-mode electric field as much as possible.

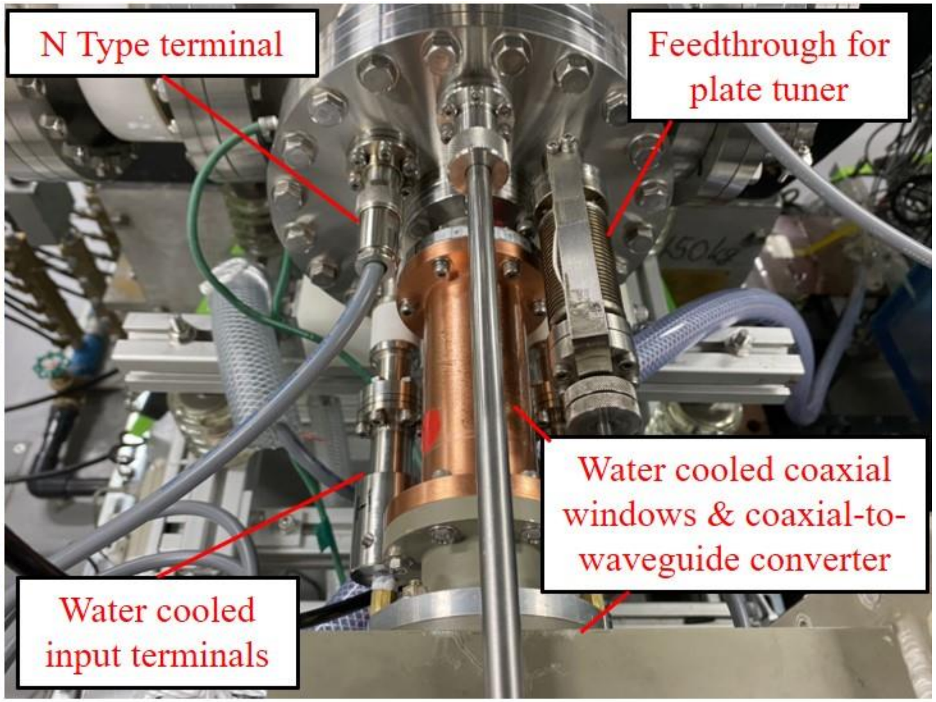
13.56MHz RF power source & matching box





We conducted the initial experiment from February to March 2021 by fabricating the RF lead-in, after initial ICR and measurement experiments to verify L-cutoff.



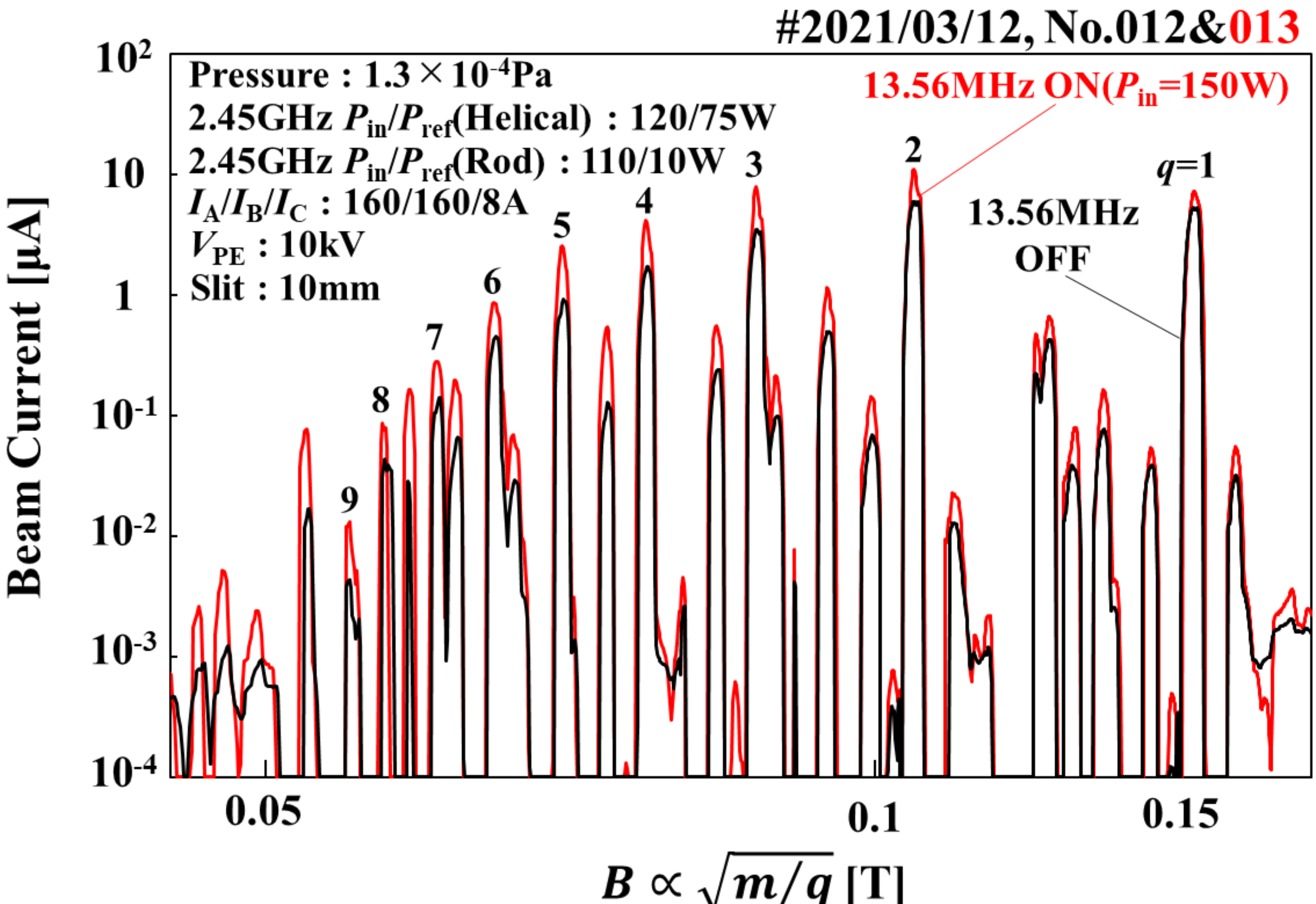


Typical CSD (in first experiment (best condition))

It indicates the effect of RF application with good reproducibility.

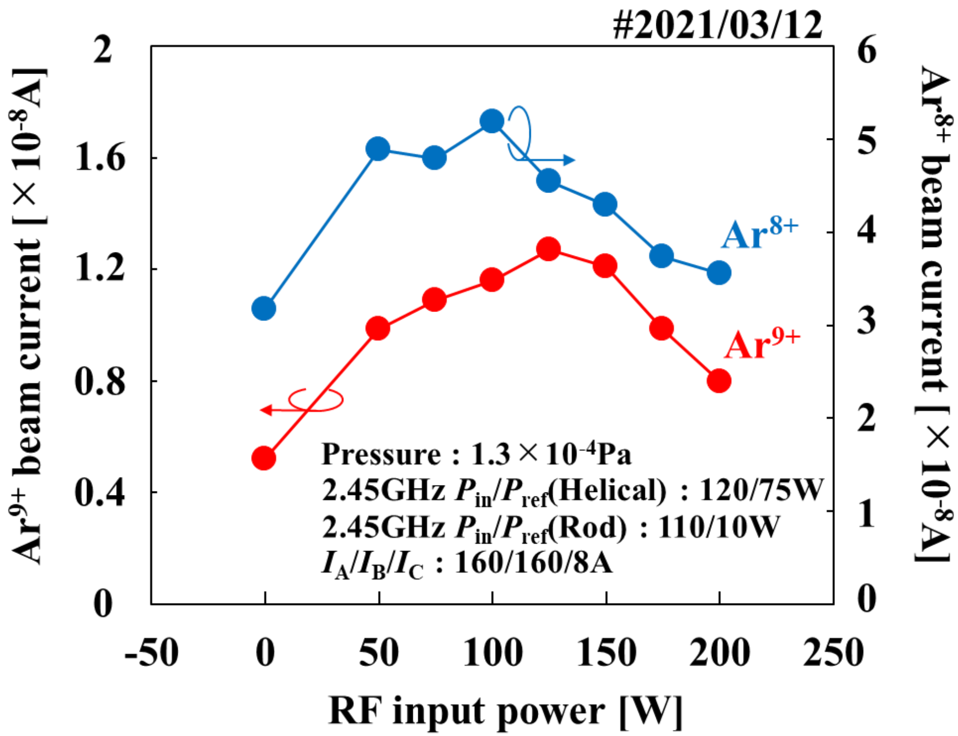
Average Charge State

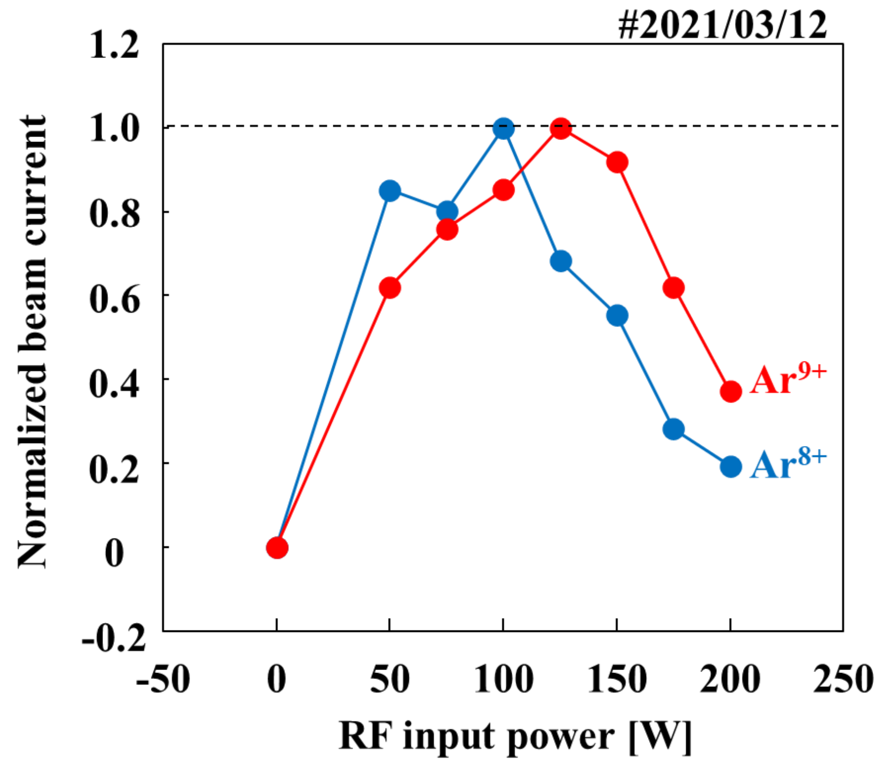
$\langle q \rangle$=1.78(13.56MHz OFF) $\langle q \rangle$=1.99(13.56MHz ON)



As we later found out from probe measurements, the n_e was quite high near the L-cutoff.
The RF application clearly increases multiply charged ion currents and shifts the average charge state to the higher side, and these results suggest an increase of the electron temperature T_e.

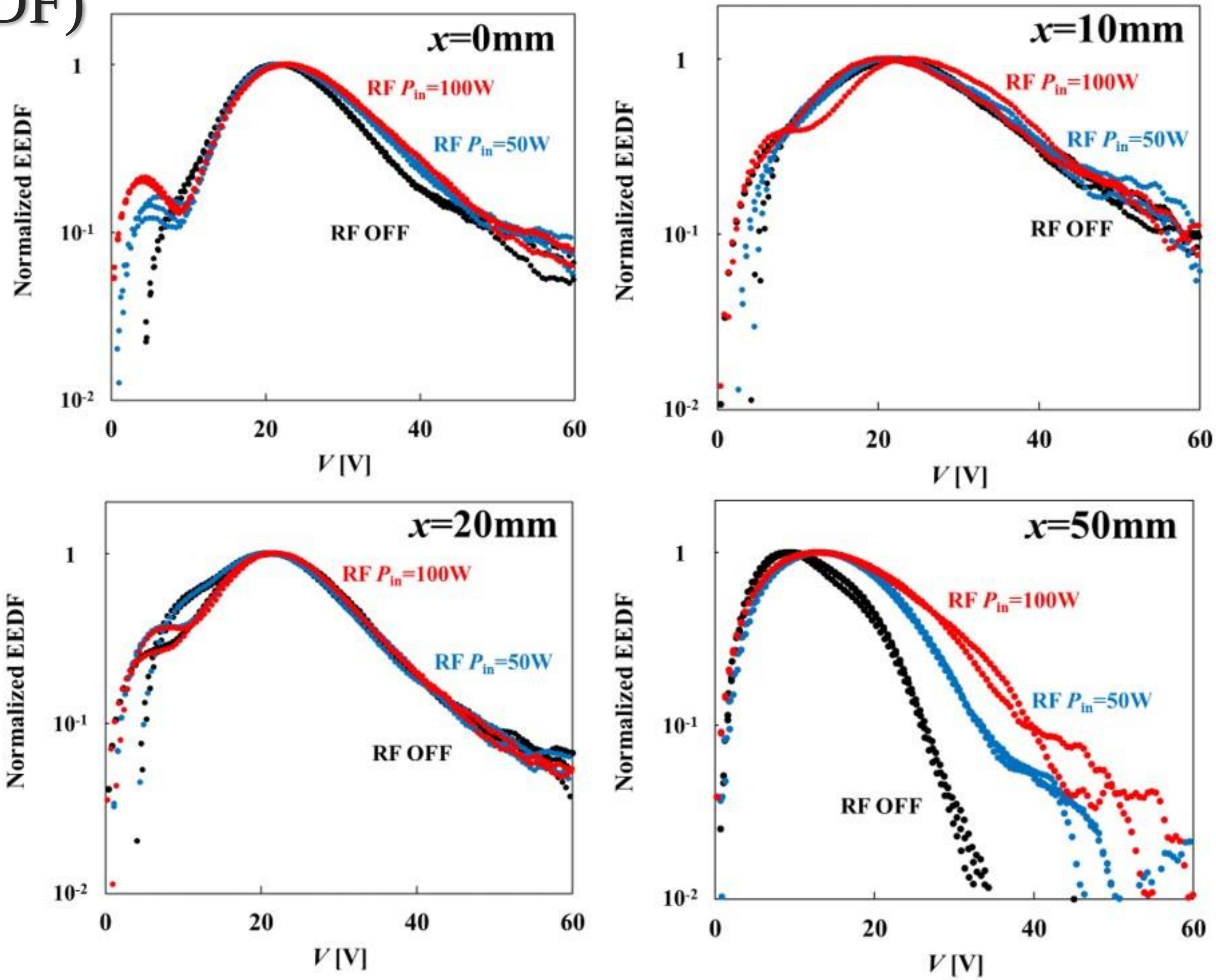
The Low Frequency RF Power Dependences of $Ar^{8+,9+}$ Currents.





From 100W to 150W, the charge state clearly shifts to the higher side.
It suggests an increase of T_e due to LHR based on helicon wave excitation.

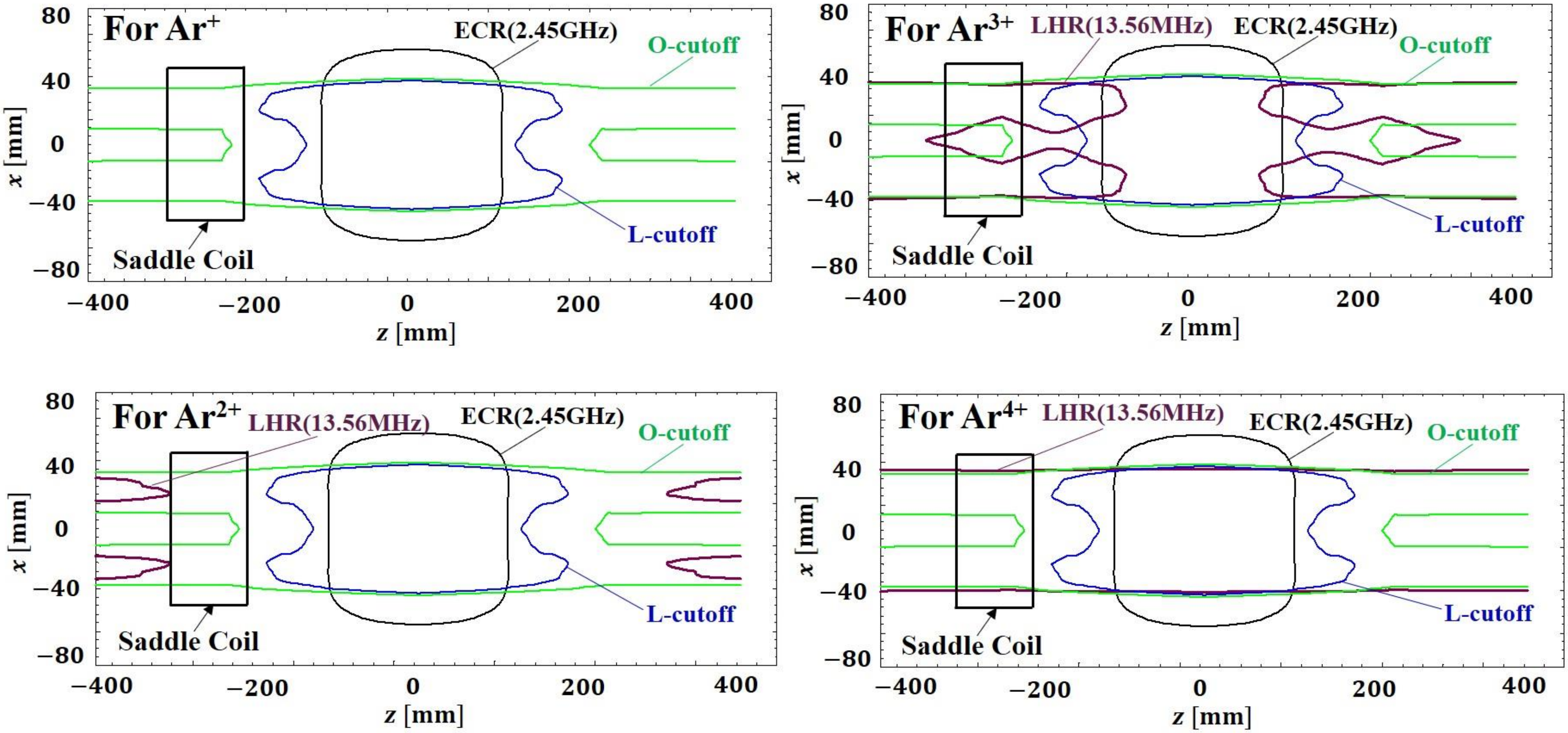
We Measured Electron Energy Distribution Function (EEDF)



A distinct shift to the higher energy side was observed in the periphery compared to that in the center. This result has a good correspondence with conventional T_e measurements. From the later accessibility considerations, it corresponds to the presence of LHR region in the periphery, suggesting the increase in T_e due to the LHR.

Accessibility Condition
(corresponding to the best condition CSD)

n_e= 2.50 × 10^{17}m^{-3} (obtained by measurements as the same conditions)



Because the average charge state is about 2+~4+,

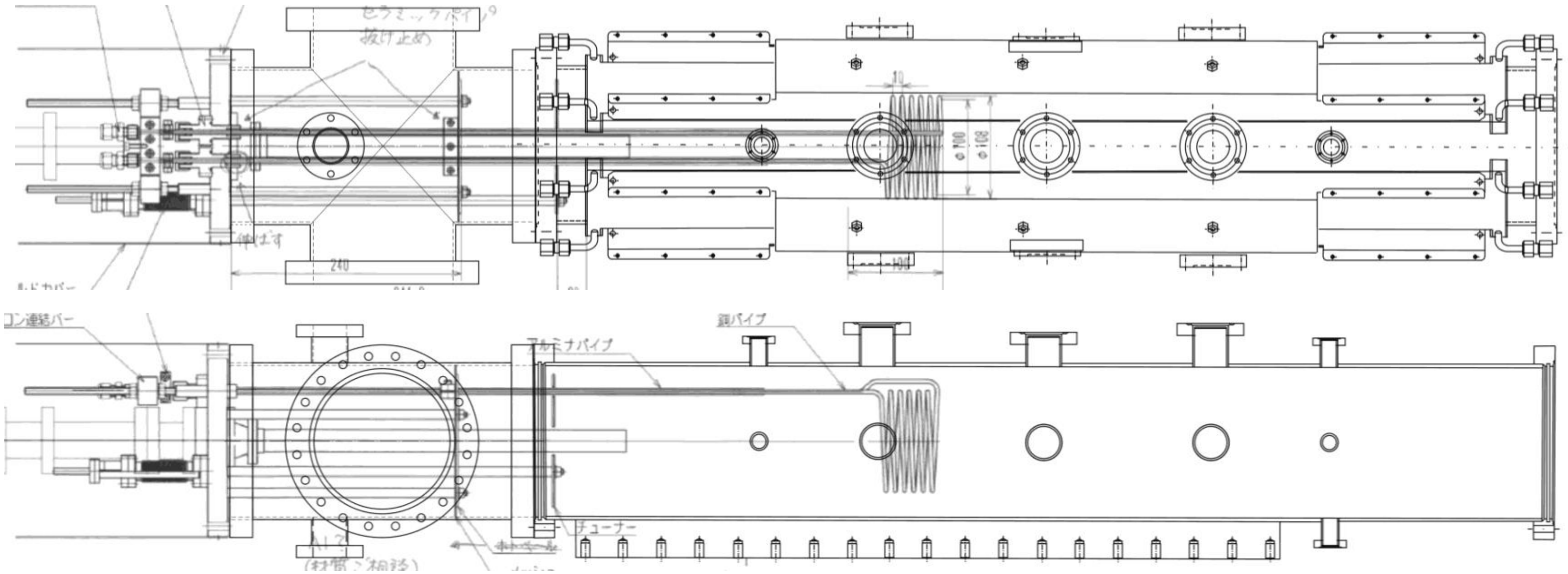
the LHR may be generated by the X-mode electric field of the helicon wave.

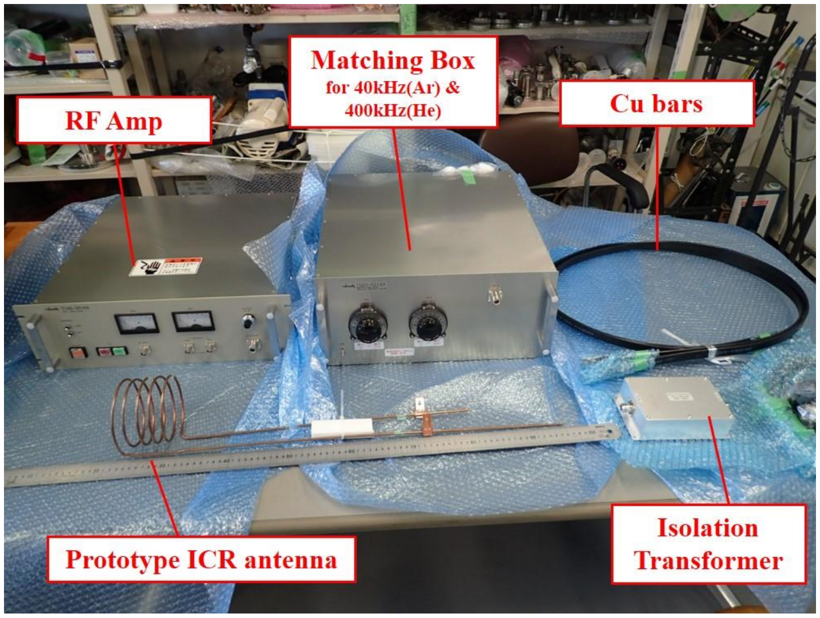
The electron heating by the LHR should be effectively contributed to produce multiply charged ions.

This result shows a good agreement with the result of EEDF and the T_e measurements.

Future perspective

- In the last summer, a Grant-in-Aid (JP) for
  Efficient multi-charged ion production by low-frequency resonance (ICR/LHR) to ECRIS
- was adopted during 2022-2026 (5 years).
- First, ICR experiment, emittance and plasma parameter measurements will be performed (2023&2024) ,
- and then LHR experiment will be started (2024&2025).
- We plan to design the power supply (20kHz-1MHz) and circularly several turned antenna for ICR.
- This ICR antenna will be water-cooled Cu pipe, insulated by ceramic spraying, and designed to be movable in its position.
- Also, the frequency for LHR will be 5MHz to 80MHz, a new antenna for LHR will be also planned to be manufactured.
- We look forward to future progress.





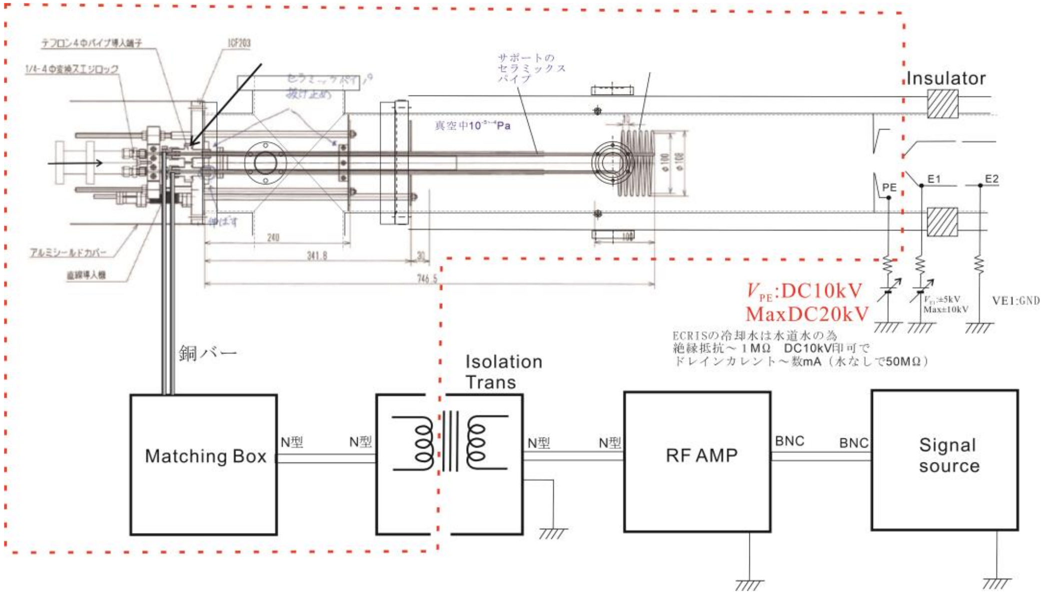


Fig. Advanced further ICR experiments on ECRIS and Preparation

Summary

- ***Background and purpose:***
- We newly propose a method to apply ICR and LHR, that are L-cutoff free, and are resonance phenomena including ions, have not been noticed in ECRIS yet. Therefore, we are embarking on a new kind of experiment that is almost unprecedented on ECRIS.
- ***Current results and future:***
- First experimental results of LHR and ICR (poster#21) under limited conditions are presenting in this conference.
- In the LHR experiment, the RF antenna was designed with the guiding principle of generating LHR due to the X-mode electric field excited by the helicon waves.
- The most important thing on the experimental results was that LHR was effective under over density cases.
- From the results of n_e, T_e, and EEDF distribution measurements, it was found that LHR was clearly effective at high n_e, and heating by LHR was confirmed.
- In addition, it was found that these have a good correspondence with the analysis results of the accessibility conditions.
- We are currently preparing to conduct new experiments using new RF antenna and sources, under new obtained budget support.

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Thank you for your attentions

If any of you are interested,
please feel free to comment, discuss,
and join us in the research.