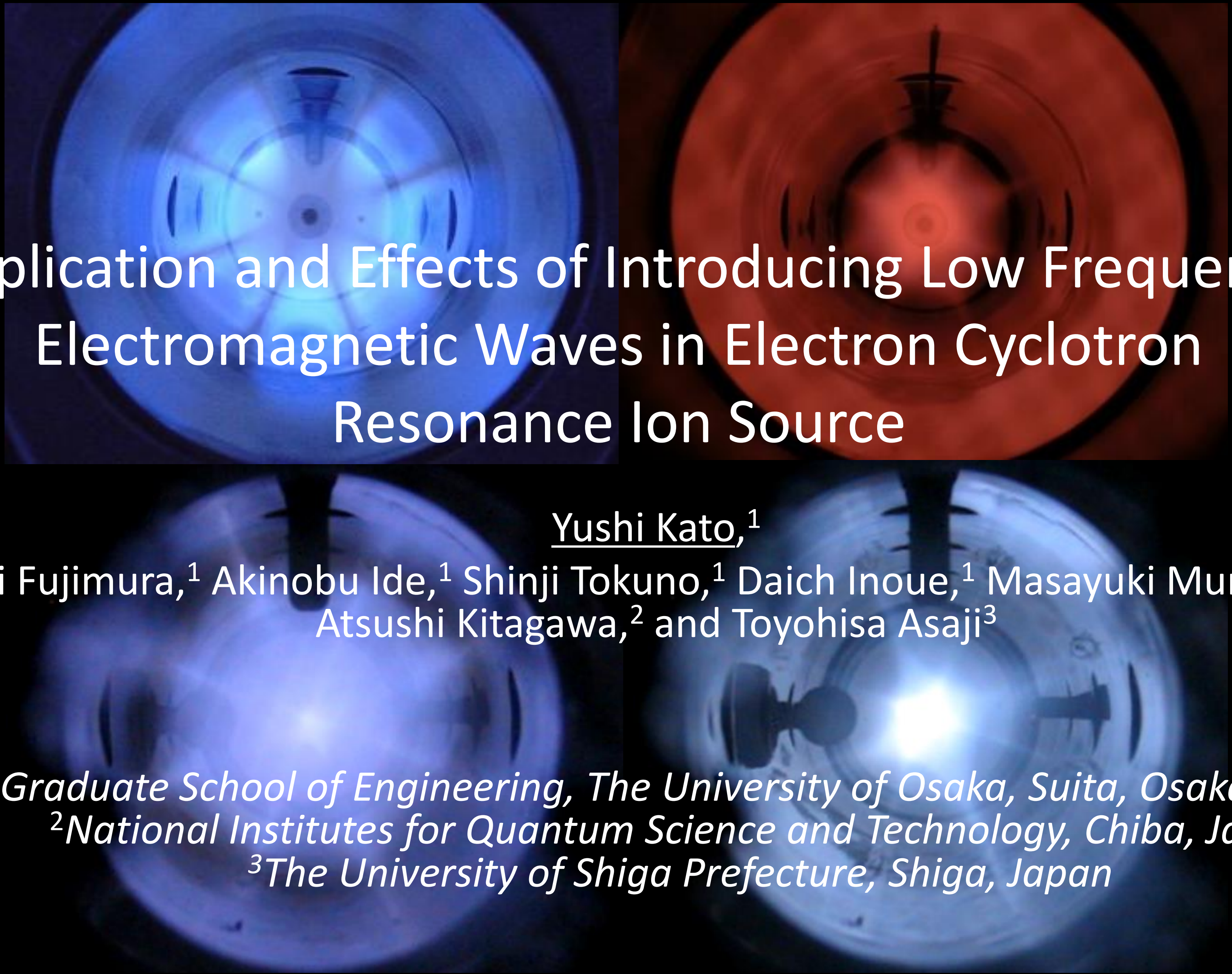

Application and Effects of Introducing Low Frequency Electromagnetic Waves in Electron Cyclotron Resonance Ion Source

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ICIS 2025 (Sept.8-12, Oxford, UK)

Background and research progress

ECRIS:
・Direct action on electron(mainstream & royal road!): included
Enhancing ECR efficiency:
High-freq. & high B, Multi-freq.ECR
Dual ECR, Helical antenna, UHR/LHR

・Direct action on ions (non-mainstream & maverick?) : included
low-z gas mixing, Low freq. waves(LHR, ICR, etc.)

- 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*)
  - We are embarking on new kind of experiment that is almost unprecedented on ECRIS.
- ICIS2023 : *Initial experimental results of ICR & LHR* on ECRIS by using available low frequency sources.

Contents (focus):

- Application and effects of introducing low frequency electromagnetic waves in ECRIS, *namely ICR selectively heating low-z ions in gas mixing*
  - Target species & freq.: He 400kHz and Ar 40kHz in Xe operationg gases.
- Plasma parameters and emittance measurements are shown with/without RF
- Preparation for LHR & application to stabilization strategies.
  - LHR: Xe and Ar plasmas.
  - Stabilization: Phase sift kHz RF application to saddle coiled antenna
- Discussions (Summary & perspective)

Motivation:collisional processes in ECRIS

Table I. Typical calculated results of ion density and mean free path.[a)]

Ar ion density n_k [10^{15} m^{-3}]					Neutral density in plasma [10^{15} m^{-3}]	Mean free path [m][b)]					
n_1	n_2	n_3	n_4	n_5	n_0	$\lambda_{\text{e-e}}$[c)]	$\lambda_{\text{e-N}}$	$\lambda_{\text{i-N}}$	$\lambda_{\text{e}-\sum k}$[d)]	$\lambda_{1-\sum k}$[e)]	$\lambda_{2-\sum k}$[e)]
17.6	10.8	3.18	0.32	0.01	42.4	2.46×10^{2}	2.26×10^{2}	3.68×10^{1}	9.74×10^{1}	3.35×10^{-2}	8.75×10^{-3}

a) Input parameters; $n_e=5\times10^{16}$ m^{-3}, $T_e=30$ eV, $n_{0\text{out}}=1.32\times10^{17}$ m^{-3} (Pressure outside plasma is 5.3×10^{-4} Pa), $T_i=0.5$ eV, $Q_1=2\times10^{18}$ m^{-3} s^{-1}, $Q_2=1\times10^{18}$ m^{-3} s^{-1}, and $V_p=10$ V.

b) Mean free path: $\lambda=v_{\text{th}}/\nu$, where v_{th} and ν denote thermal velocity and collision frequency, respectively. Subscripts e, N and i represent electron, neutral and ion species, respectively. Subscripts $\sum k$, 1 and 2 denote the summation over all ions, Ar^{1+} and Ar^{2+} species, respectively.

c) $\nu_{\text{e-e}}=3.01\times10^{-12}\dfrac{n_e \ln \Lambda_{\text{e-e}}}{T_e^{3/2}}$.

d) $\nu_{\text{e-}\sum k}=4.21\times10^{-12}\dfrac{\sum n_k Z_k^2 \ln \Lambda_{\text{e-}k}}{T_e^{3/2}}$.

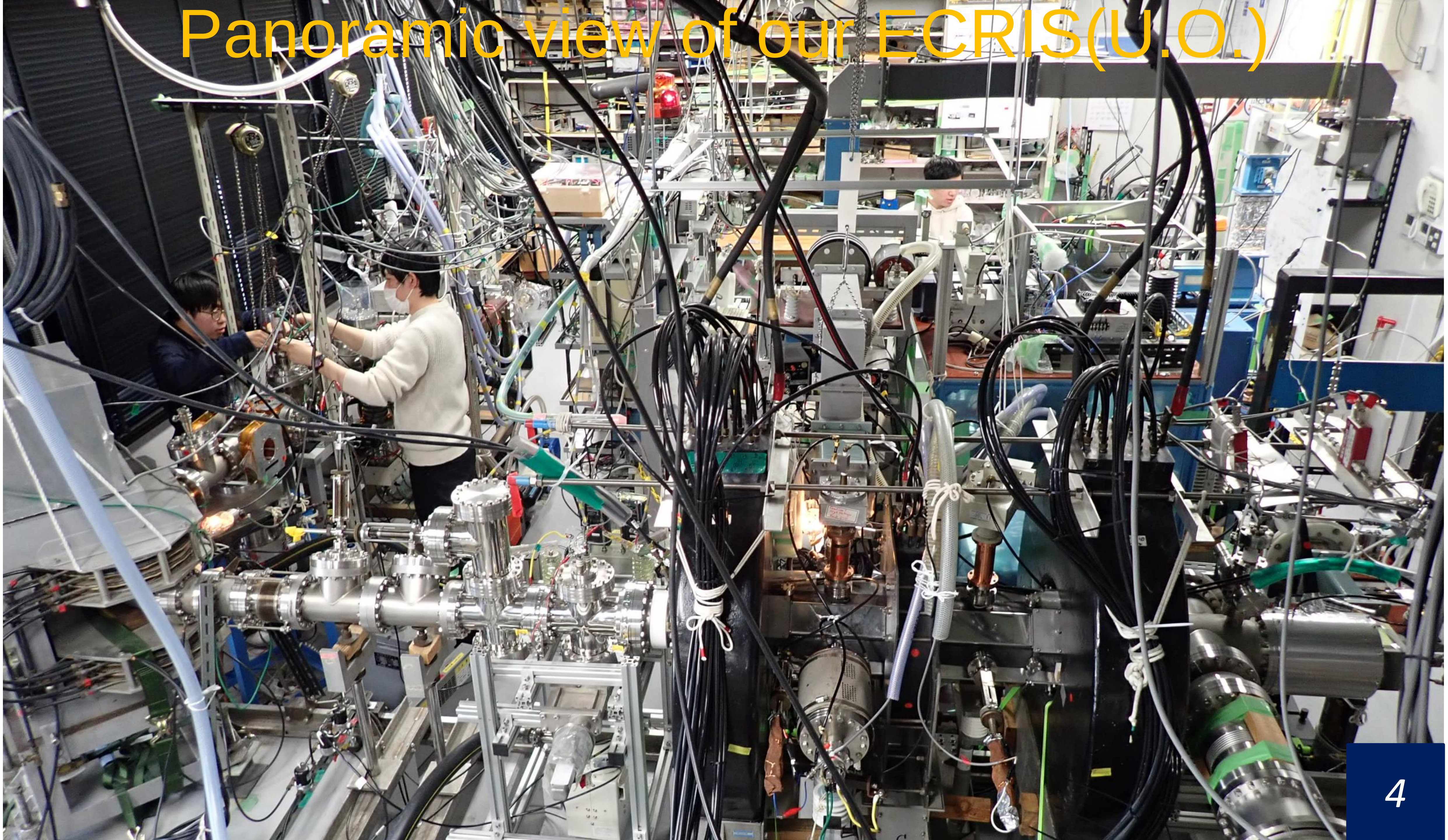
e) Equation (6). $\nu_{k-\sum k'} = 7.02\times10^{-14}\dfrac{Z_k^2 \sum n_{k'} Z_{k'}^2 ln\Lambda_{k-k'}}{A^{1/2}T_i^{3/2}}$

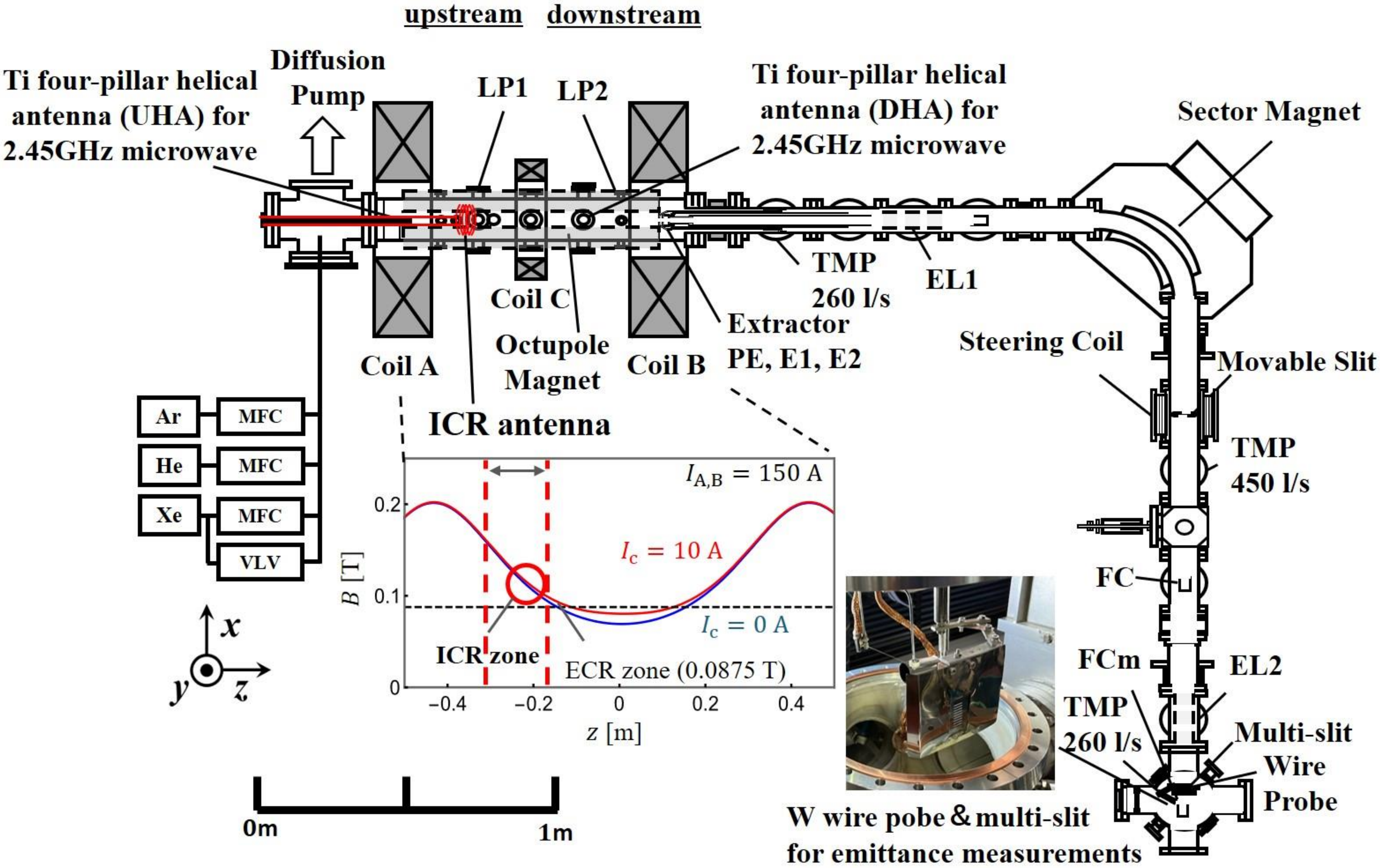
<u>Y. Kato, *et.al*, Journal of the Physical Society of Japan, Vol.64(1993)p.1221-1232</u>

Ref. :B.A. Trubnikov, `Particle interactions in fully ionized plasma`, Review of Plasma Physics I; S.I. Braginskii, `Transport processes in a plasma`, *ibid*.; L. Spitzer, Jr, `Physics of fully ionized gases`, Chap. 5

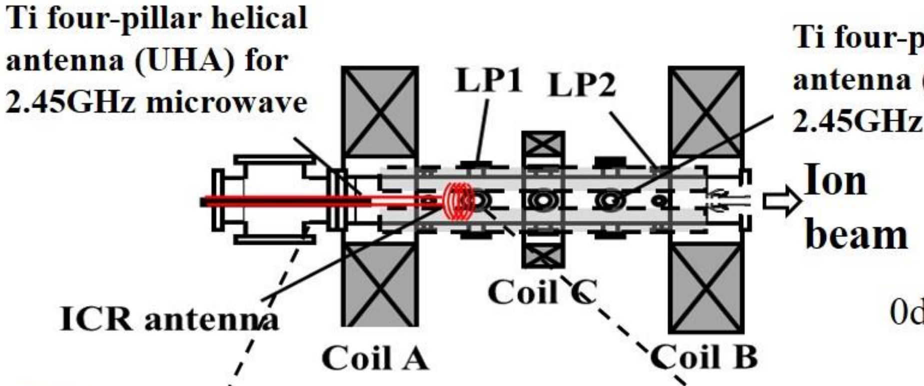
**These results means that plasma confinement is globally determined by ion diffusion, and the action of electromagnetic waves on ions affects the ion groups extremely efficiently. Then, I came up with the idea of this theme*.

Panoramic view of our ECRIS(U.O.)

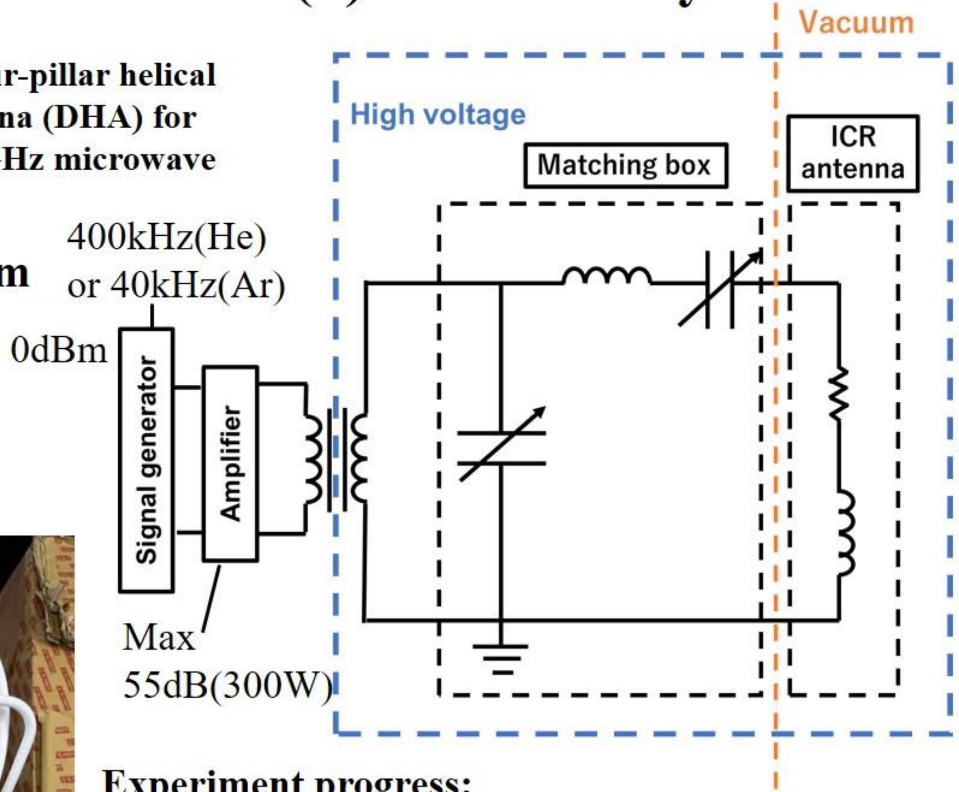



upstream
downstream
Ti four-pillar helical antenna (UHA) for 2.45GHz microwave
Diffusion Pump
LP1
LP2
Ti four-pillar helical antenna (DHA) for 2.45GHz microwave
Sector Magnet
TMP 260 l/s
EL1
Coil C
Octupole Magnet
Coil A
Coil B
Extractor PE, E1, E2
ICR antenna
Steering Coil
Movable Slit
TMP 450 l/s
Ar
He
Xe
MFC
MFC
MFC
VLV
$I_{A,B}$ = 150 A
I_c = 10 A
I_c = 0 A
B [T]
ICR zone
ECR zone (0.0875 T)
z [m]
FC
FCm
EL2
TMP 260 l/s
Multi-slit
Wire Probe
W wire pobe & multi-slit for emittance measurements
x
y
z
0m
1m

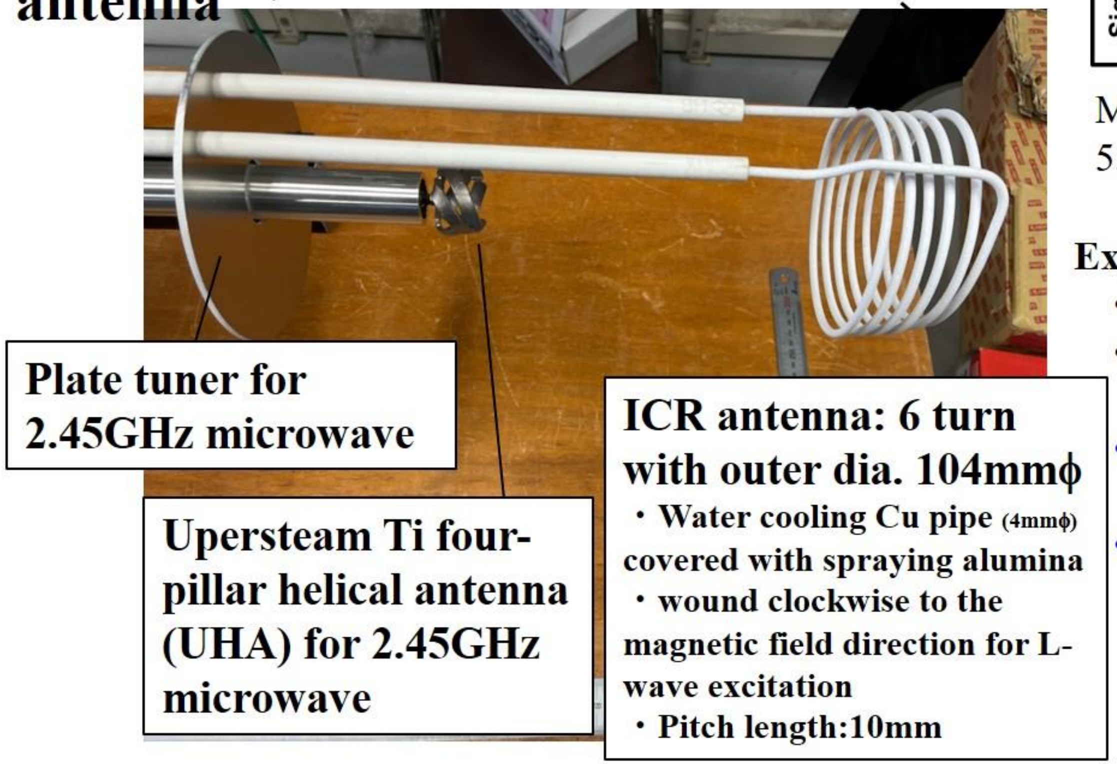
(a)2.45GHz ECRIS



(b) RF circuit system



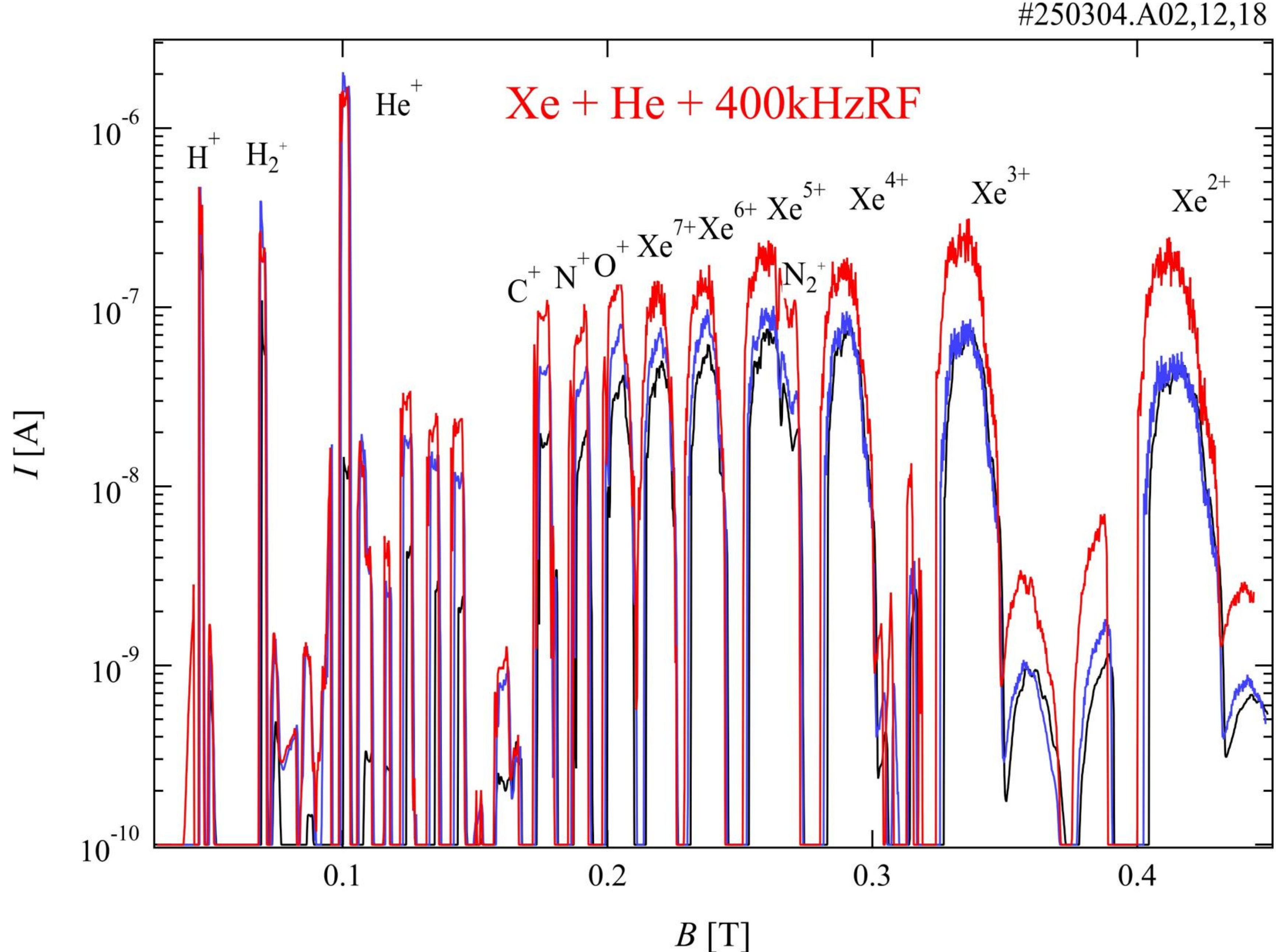
(c) ICR antenna



Experiment progress:

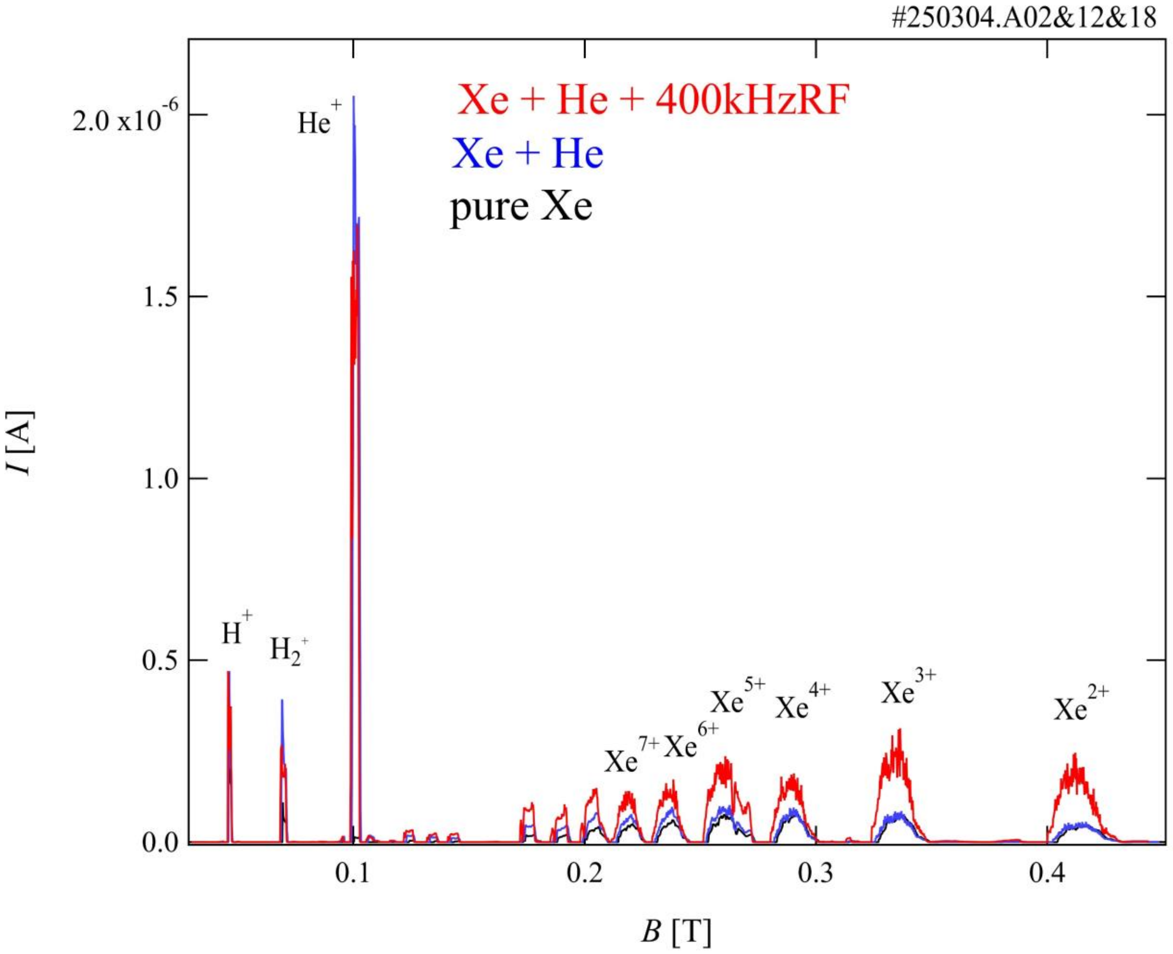
- Started in the spring 2024.
- It took a long time to deal with generation & control impurities.
- Nov.2024-Jun.2025 Xe/Ar(40kHz):
  - Effect gradually began to appear.
- Feb.2025- July 2025 Xe/He(400kHz):
  - Effect tremendous, surprisingly
  - Although impurities were also generated
  - Experintal results: good reproducibility
  - Conducting plasma parameter mesurements

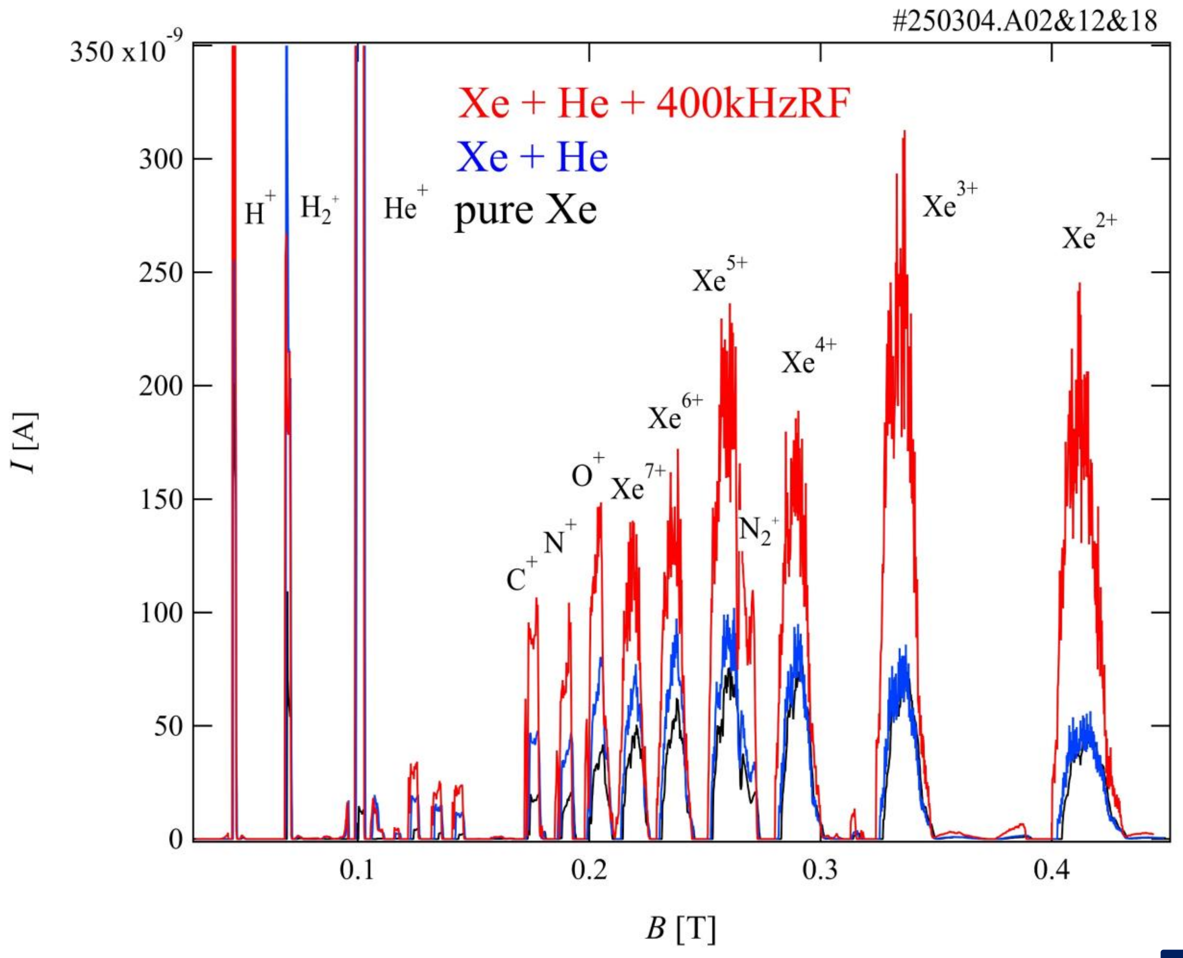
Typical CSD of pure Xe/ Xe+He/ Xe+He+400kHzRF



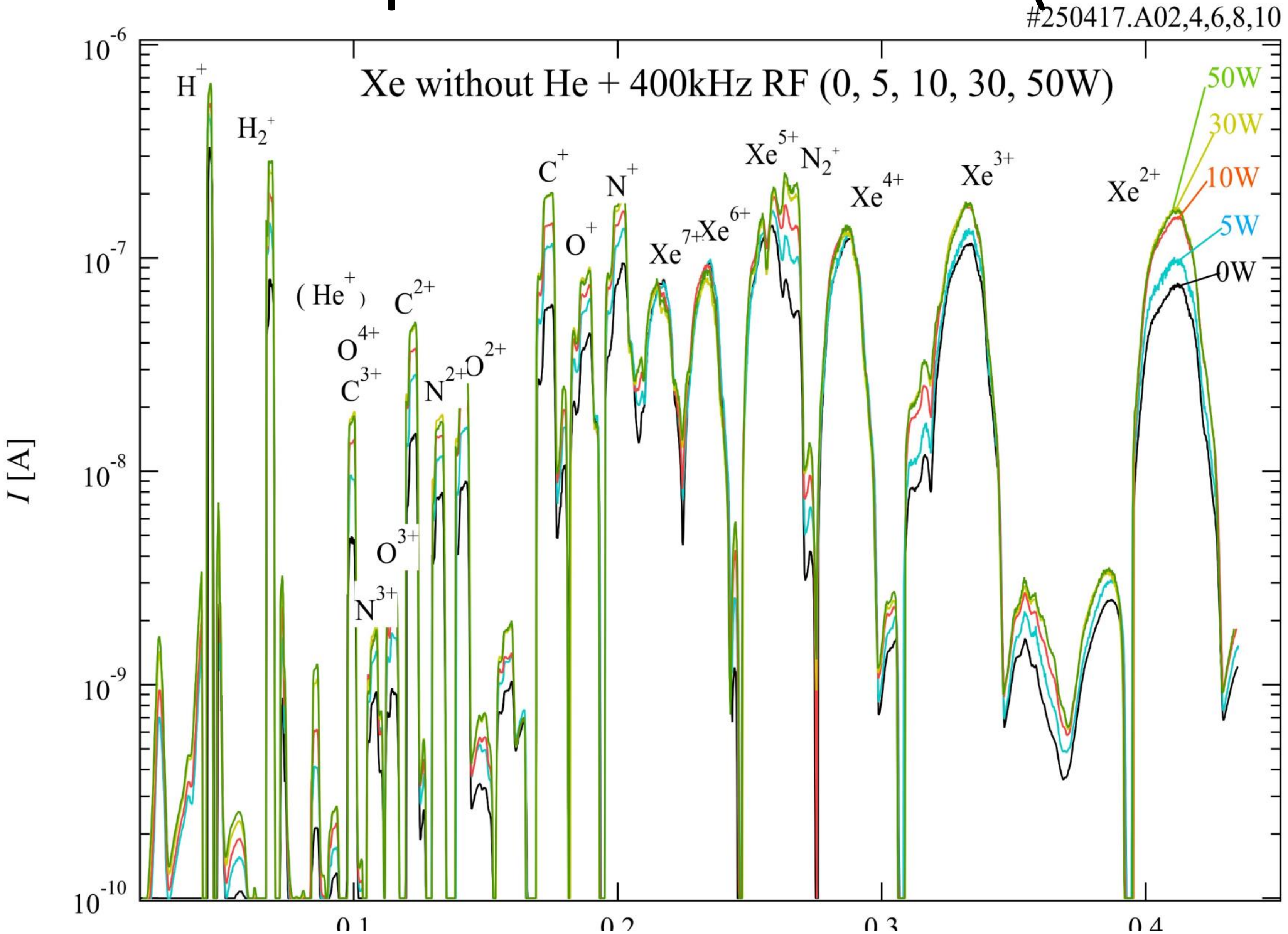
He: 0.100 SCCM
Dual μW:
160/90W (UHA), 120/95W (DHA)
400kHz 10W

Typical CSD (linear scales) of Xe & Xe/He & Xe/He with&without 400kHzRF



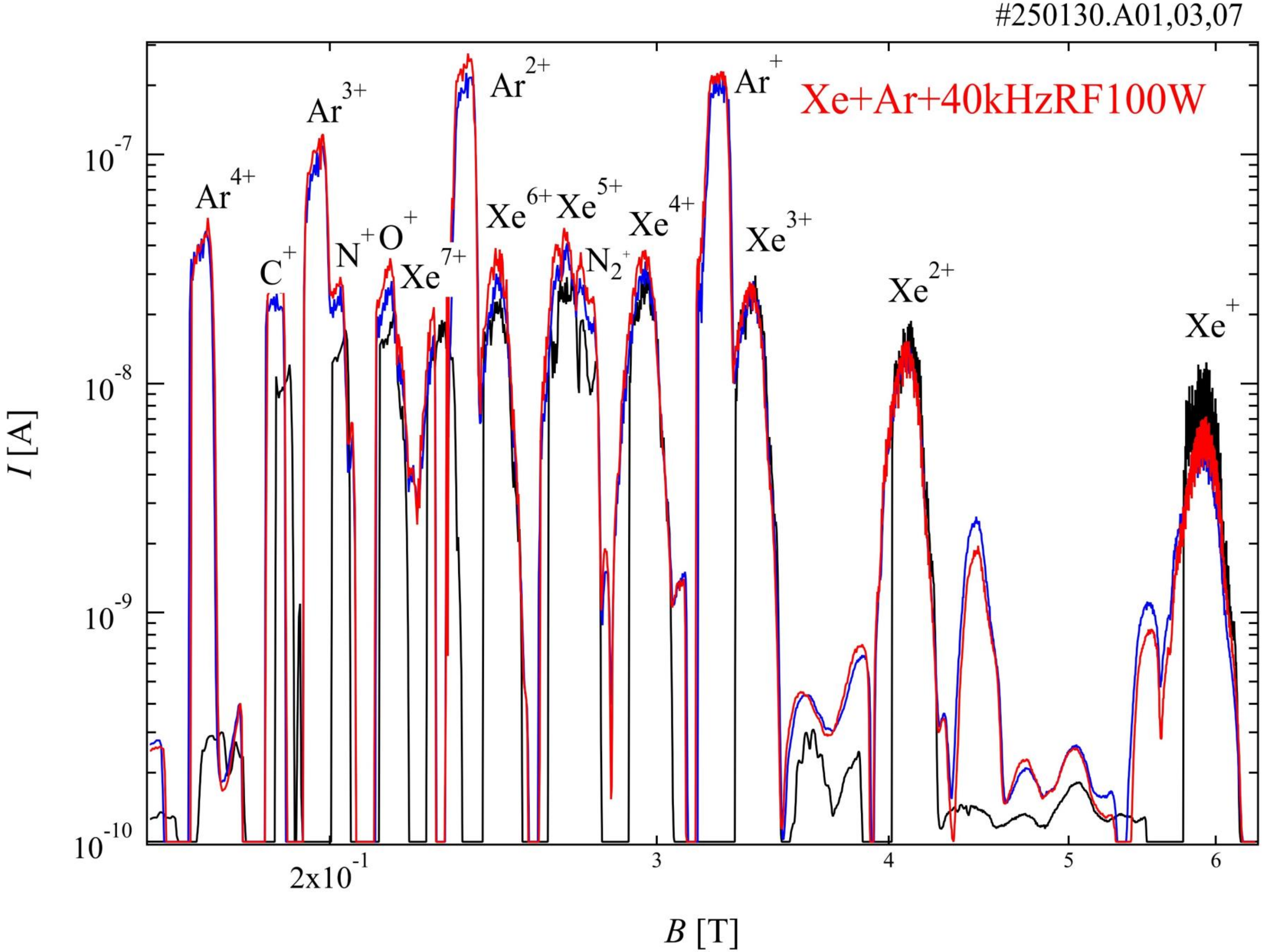


Typical CSD of pure Xe+400kHzRF (without He)

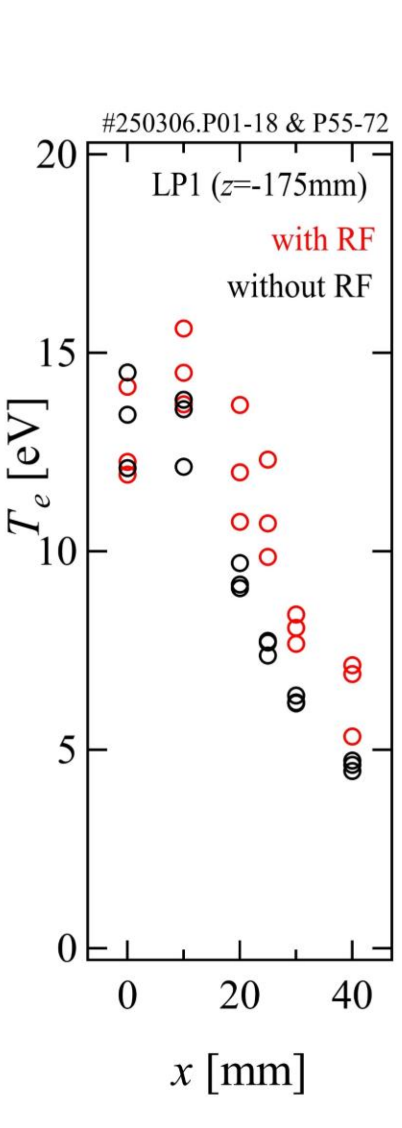


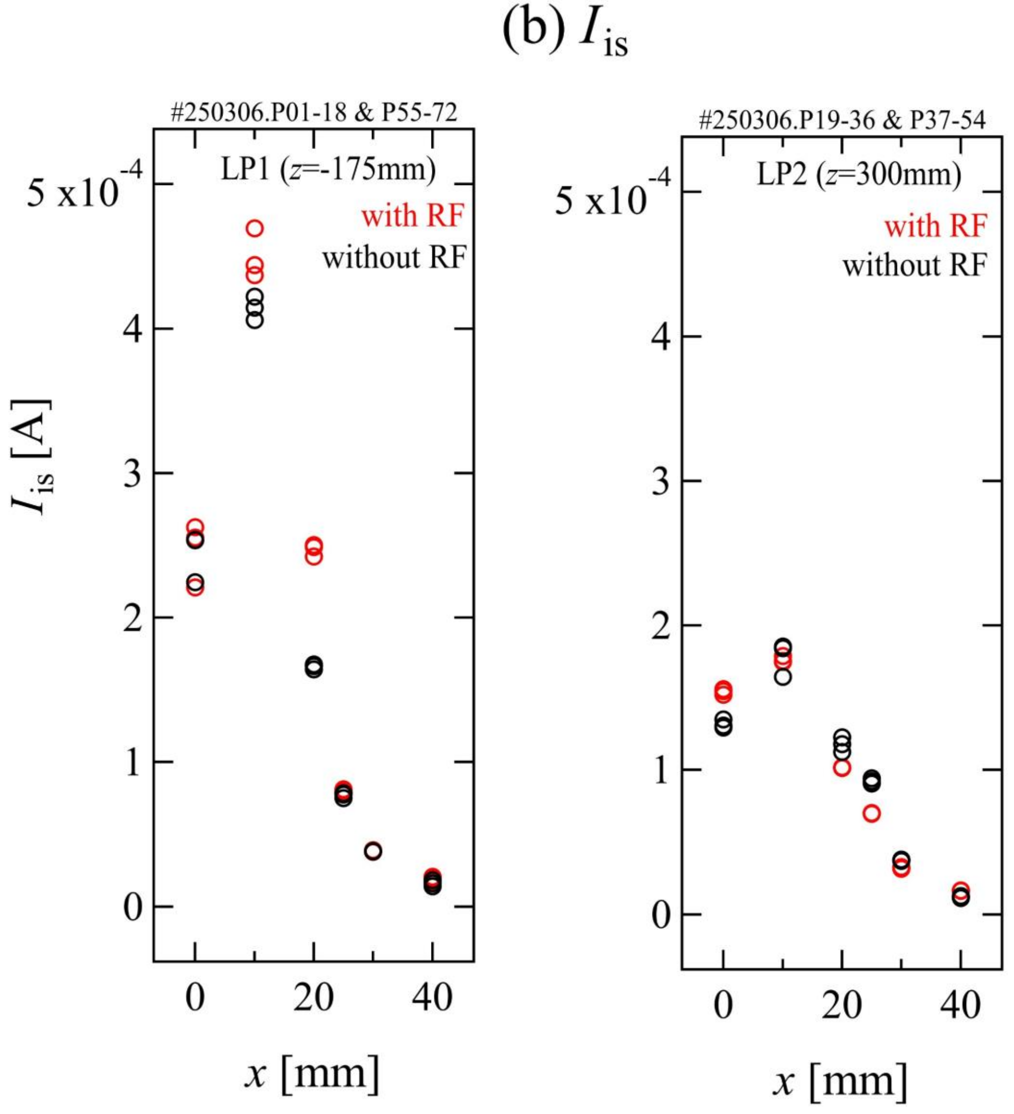
These evidences suggest that He existence is essential and promoting ion cooling by selective heating contributes to enhance confining Xe multicharged ions, and leads to increase Xe highly charge state ions.

Typical CSD of pure Xe/ Xe+Ar/ Xe+Ar+40kHzRF



Typical plasma parameters of Xe/He with RF by LP1&LP2

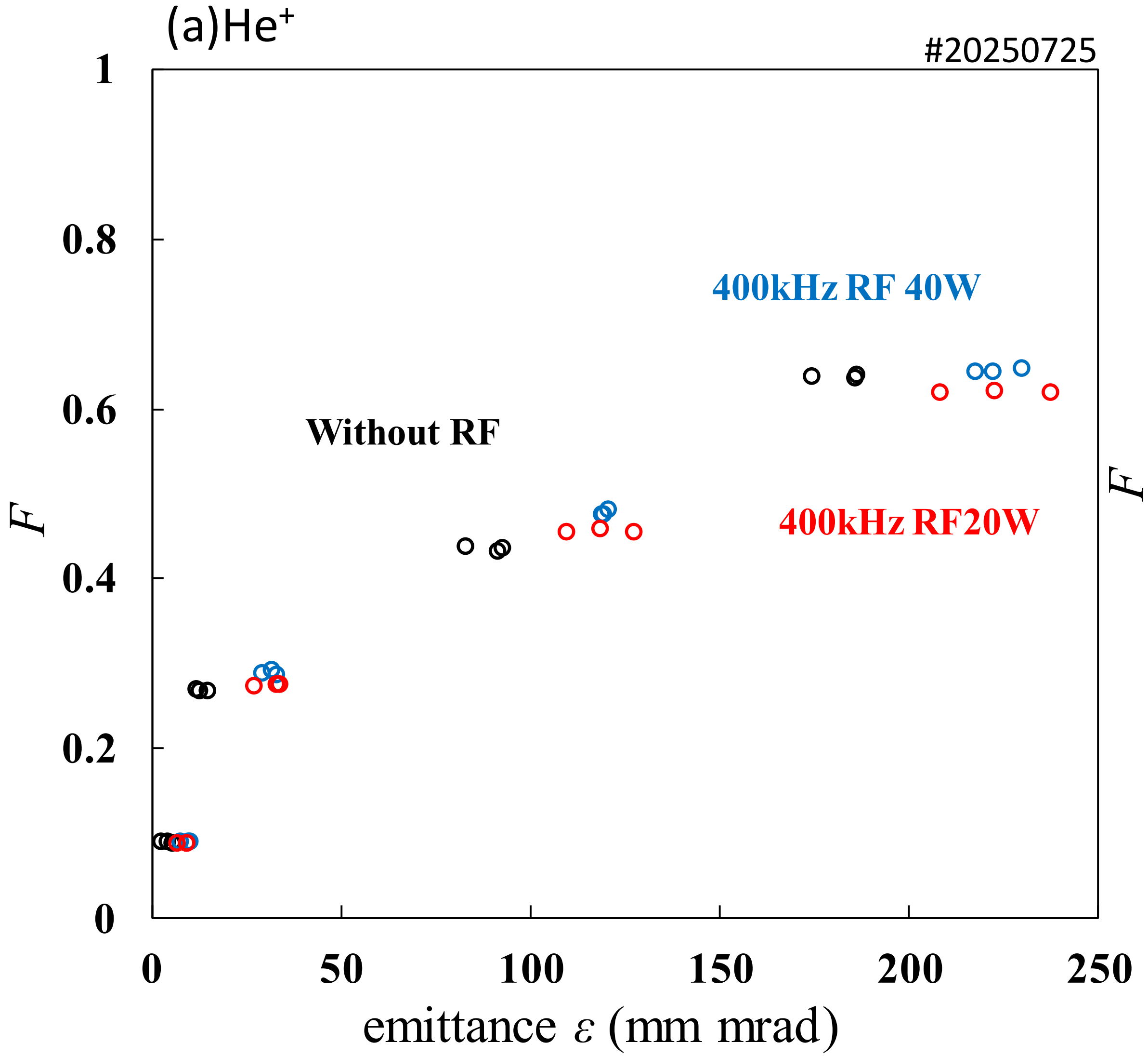


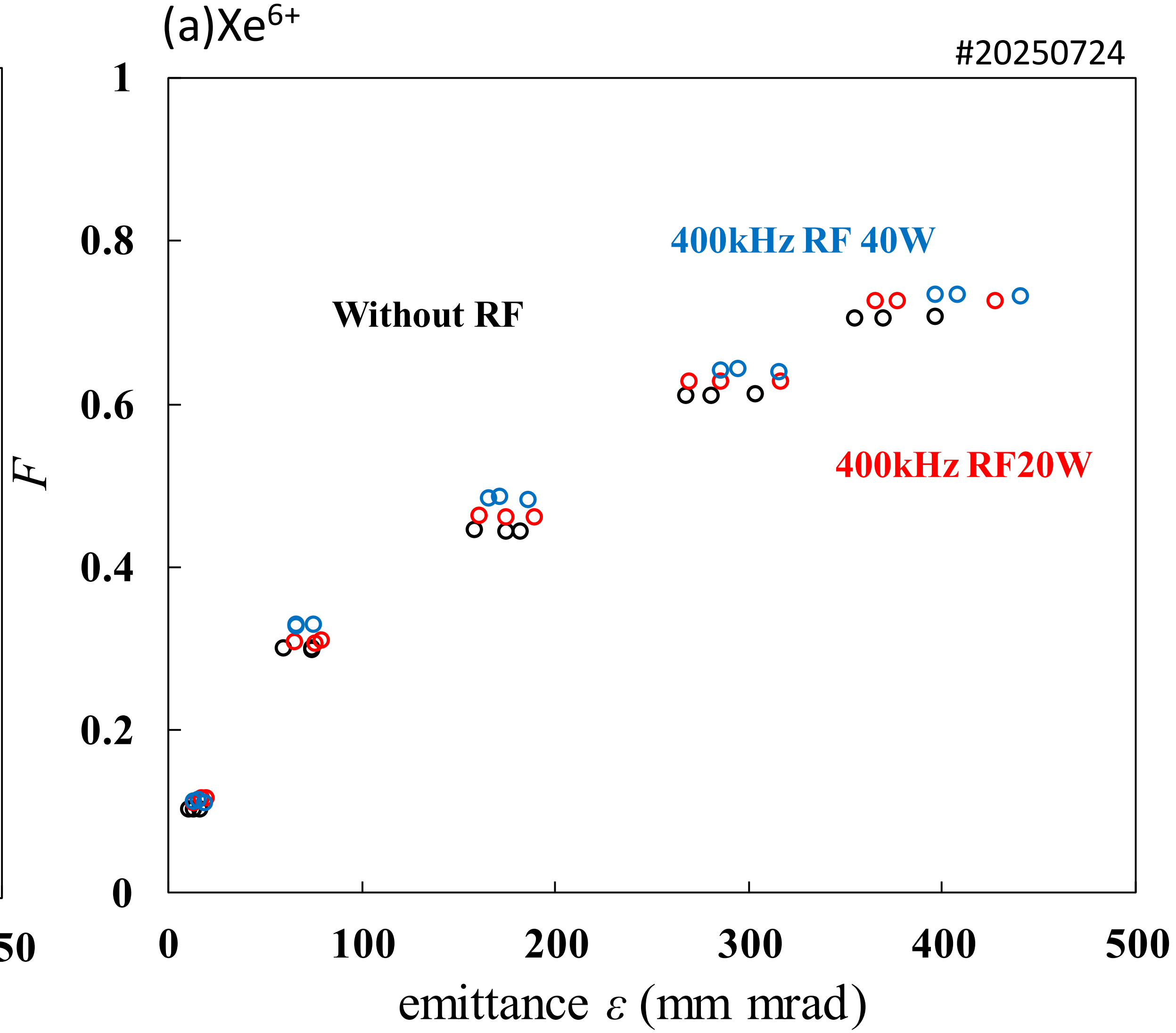


For more details, please refer to Tokuno-san's poster presentation #71 and his paper.

Enhancement of cooling effects by selective ICR heating increases confinement of Xe multiply charged ions, *and then increase confinement of electrons, resulting in heating T_e & increasing n_e.*

ε_{rms} of He^{+} & Xe^{6+} beam in Xe/He with/without RF (400 kHz)



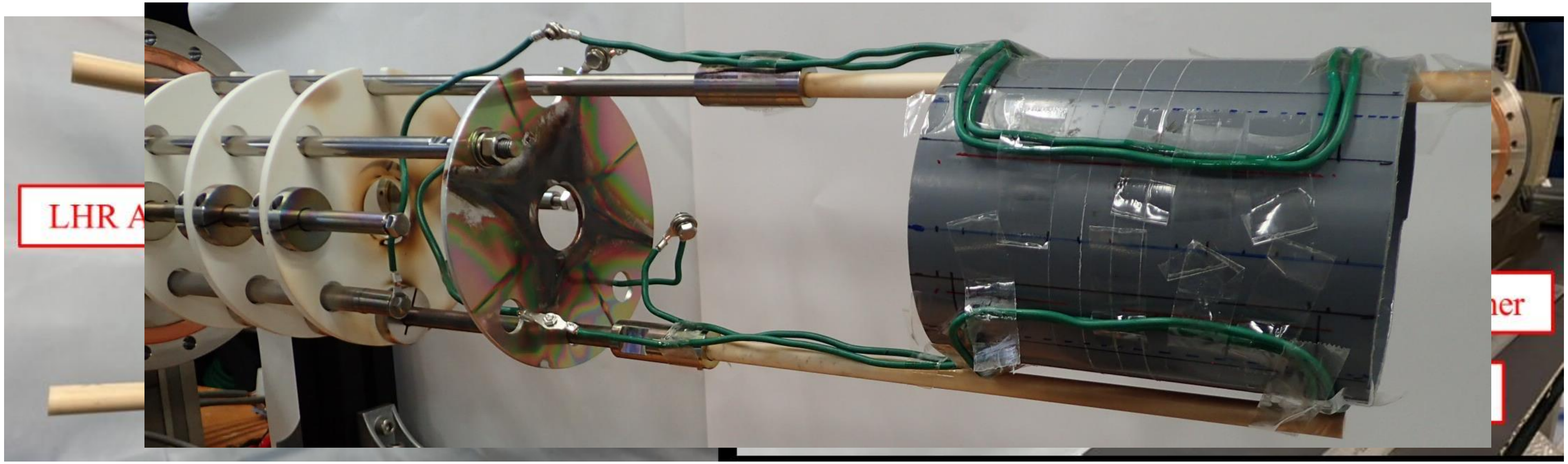


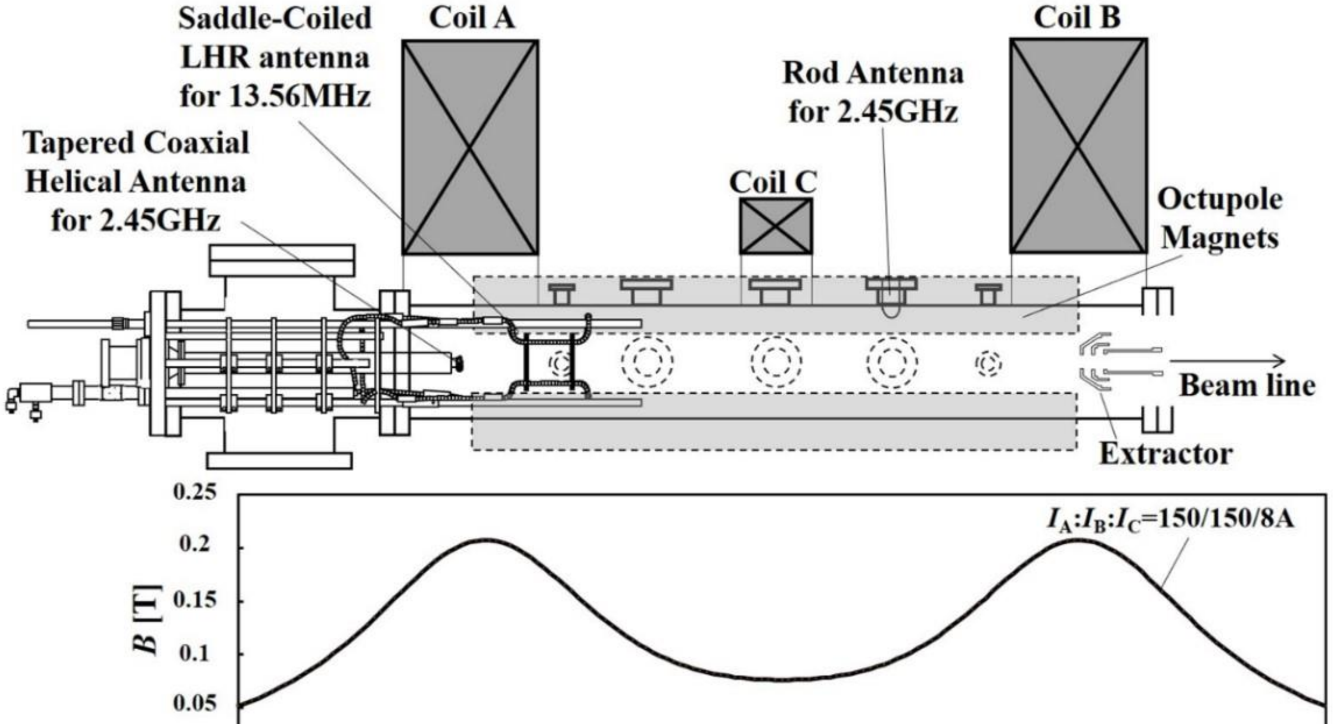
$$F = 1 - \exp(-\varepsilon/2\varepsilon_{rms})$$

Ref: A J T Holmes, 'The Physics and Technology of Ion Sources' edited by Ian G Brown, Chap.4, pp.92

For more details, please refer to Ide-san's poster presentation #75 and his paper.

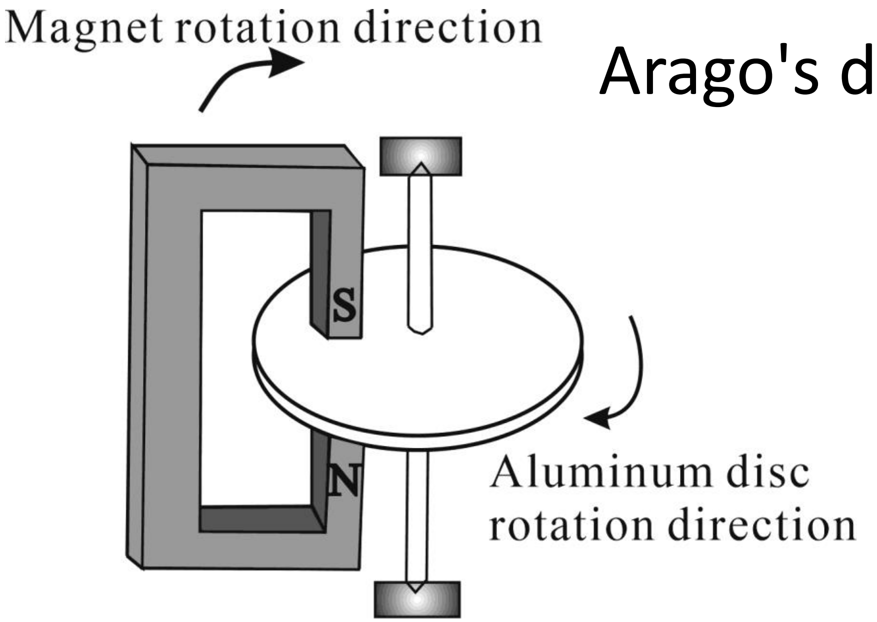
Future Perspective I: Preperation of new LHR antenna

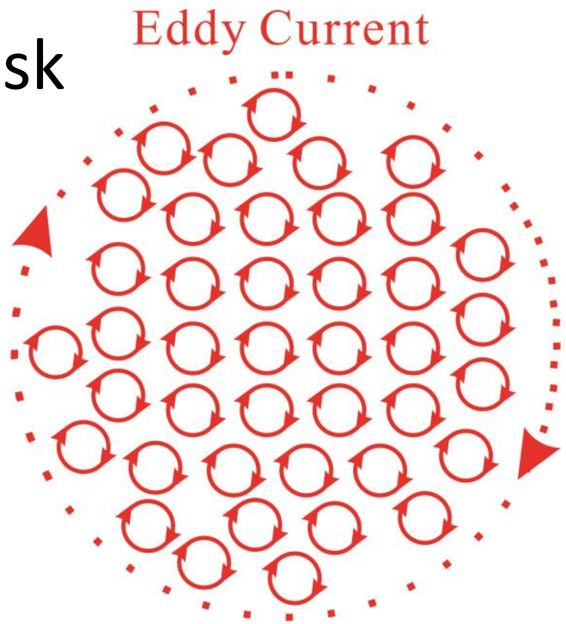


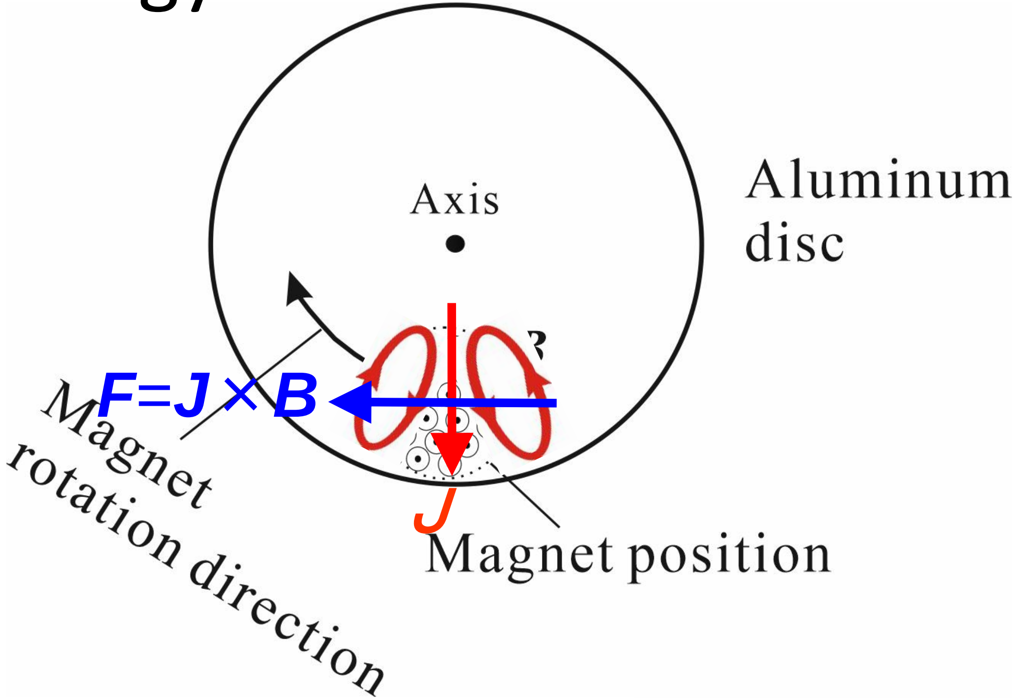


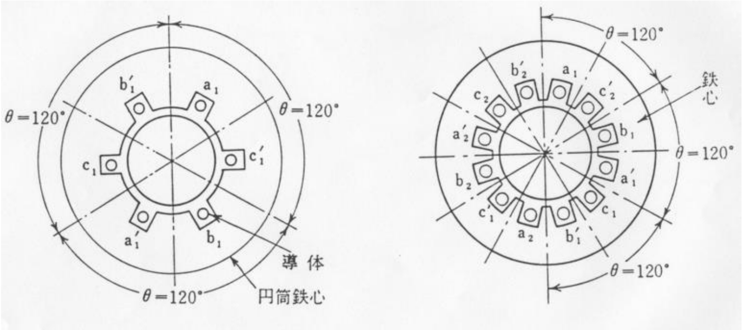
Future Perspective II: Stabilizaion strategy of Instabilities

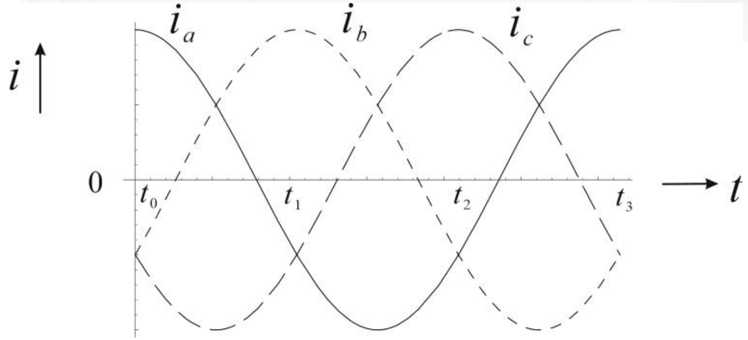
Arago's disk

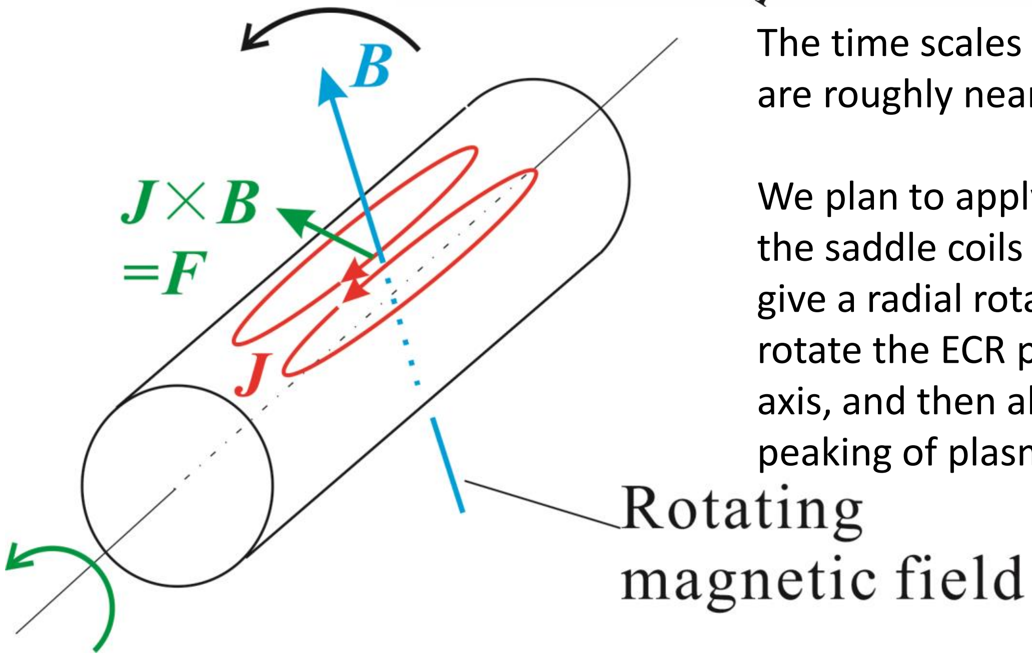








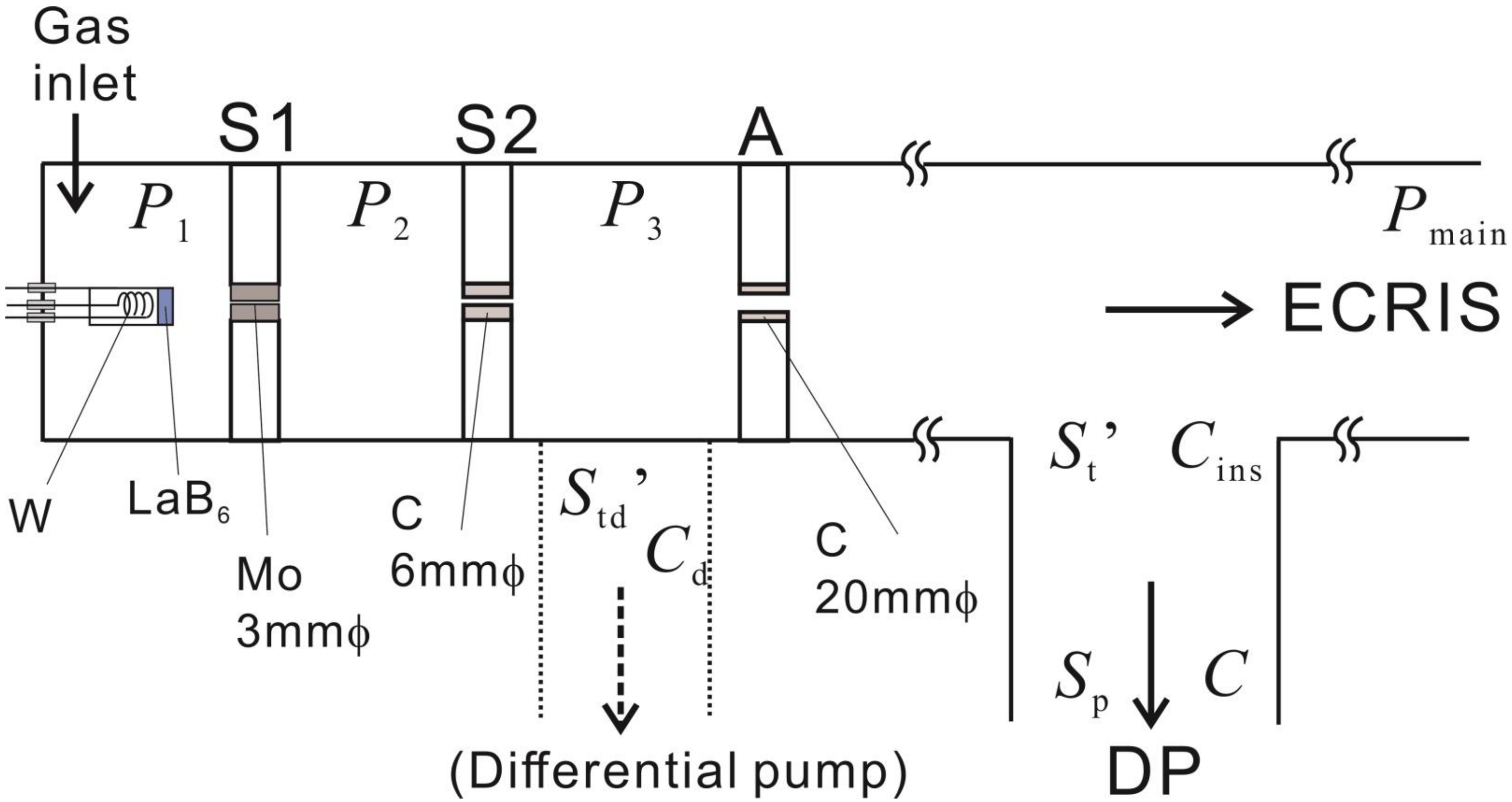


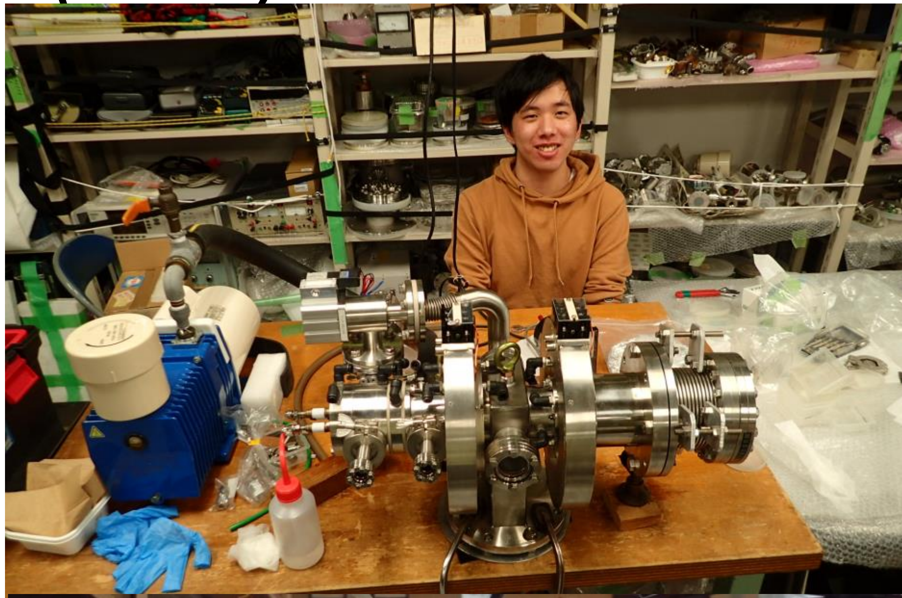


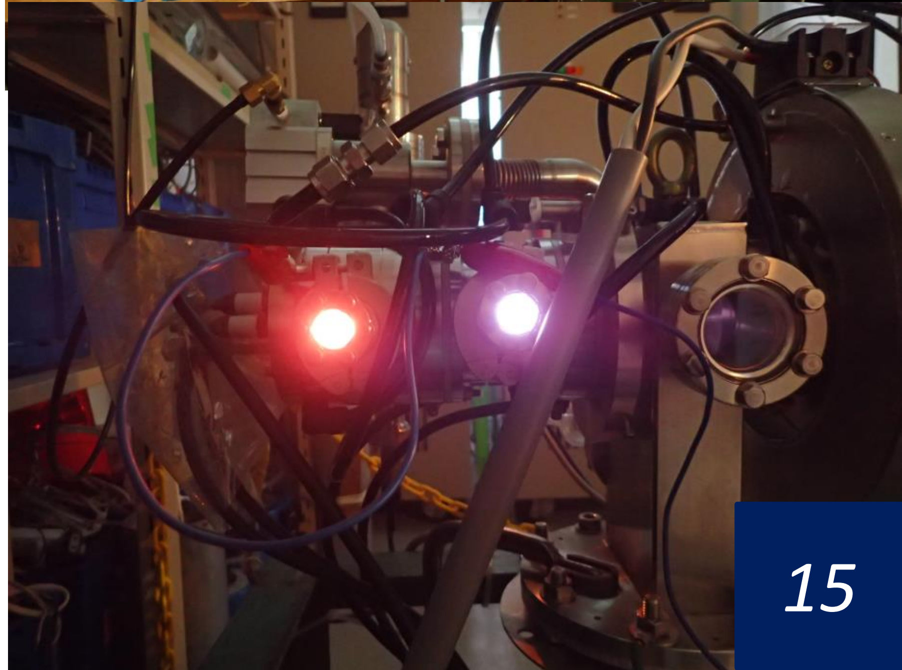
The time scales of their instabilities are roughly near our ICR experiment.

We plan to apply low-frequency RF to the saddle coils *shifted in phase*, give a radial rotating magnetic field, rotate the ECR plasma about the z-axis, and then alleviate the local peaking of plasma parameters.

Future Perspective III: Introducing electron beam/beam plasma with *Electron Beam Excited Plasma* (*EBEP*)







Specifications:

W Filament:	V_f = 35V,	I_f = 50A
plasma discharge(DC):	V_d = 120V,	I_d = 50A
Electron beam acceleration(DC):	V_a = 160V, I_a = 50A	

Episode of *Guntai-tsurugi*’

Summary

- ***Background and purpose:***
- We newly propose a method to apply low frequencies RF to ECRIS, and investigate effects of selectively ICR heating low z mixing ions.
- We first conducted an ICR experiment by enhancing ion cooling through selective heating of light element gas for Xe/He and Xe/Ar ECR plasmas.
- ***Current results and future:***
- The most important thing on the experimental results is that ICR is effective for multicharged ion production on Xe/He and Xe/Ar plasma, by enhancing the ion confinement effect.
- From the n_e and T_e measurements, it is found that ICR is clearly effective for increasing T_e, and I_{is} (n_e). It is thought that enhancing the ion confinement effect also promotes electron confinement.
- In addition, from ε_{rms} measurements, it is found that selectively heating low z ions are confirmed, and no significant changes in Xe multicharged ions.
- We are currently preparing to conduct new experiments by using a new LHR antenna and sources.
- We also plan to perform experiments to alleviate the instability caused by spatial peaking of plasma parameters due to L-cutoff by applying low-frequency RF to a pair of saddle-type antennas with different phases.
- Furthermore, we plan to inject electron beams or plasma into ECRIS using electron beam excited plasma (EBEP).

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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.