Dynamic responses of negative ion meniscus to externally applied RF field

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Contents

Negative ion meniscus

Negative ion meniscus is

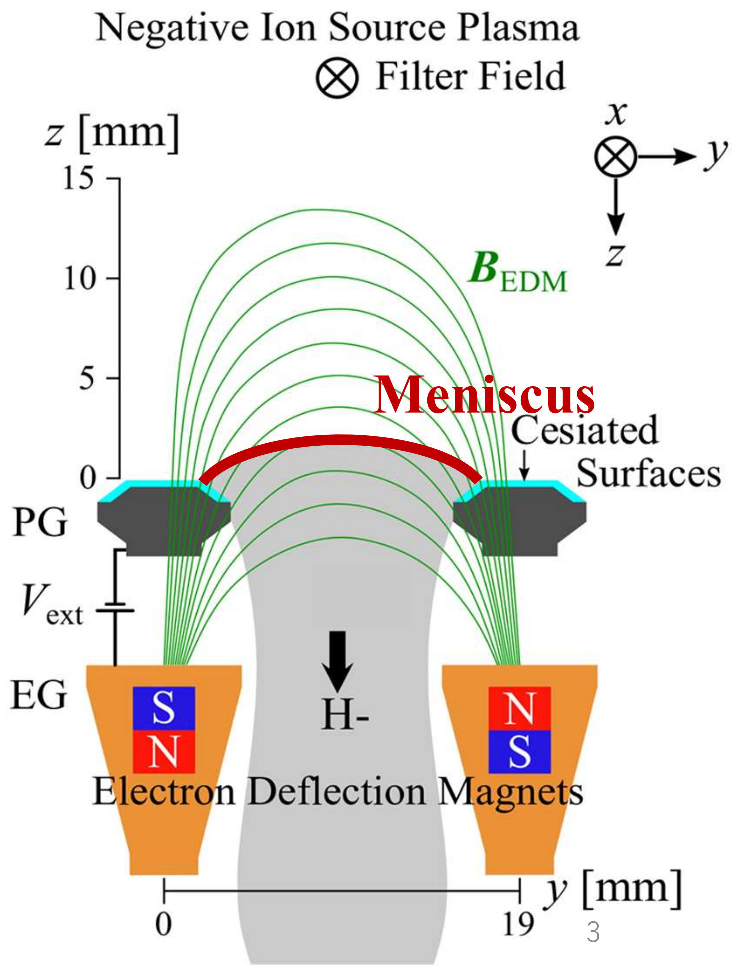
- first electrostatic lens
- essential to the negative ion beam focusing
- still open issue

Cf. Bohm sheath model for conventional plasma

K. Nagaoka, NIBS2020, K. Miyamoto, NIBS2022

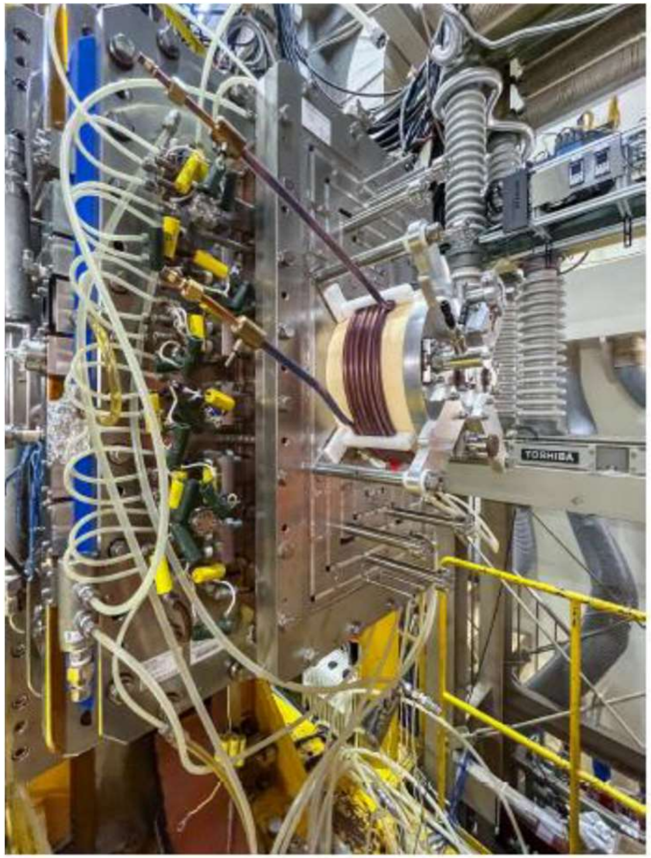
Negative ion beam extraction boundary is complexed,

- existence of magnetic field
- closely located negative ion production surface



Beam divergence is an argent issue

K. Tsumori NIBS2022, P. Veltri NIBS2022



The beam divergence requirement for ITER is 7mrad

- **RF source ~ 12 mrad >7 mrad**
- **Arc source =4 – 7 mrad**

But, no significant difference (1.0-1.4 deg.) appears in the case of Positive IS

The explanation of the different divergence between RF- and Arc-sources are required

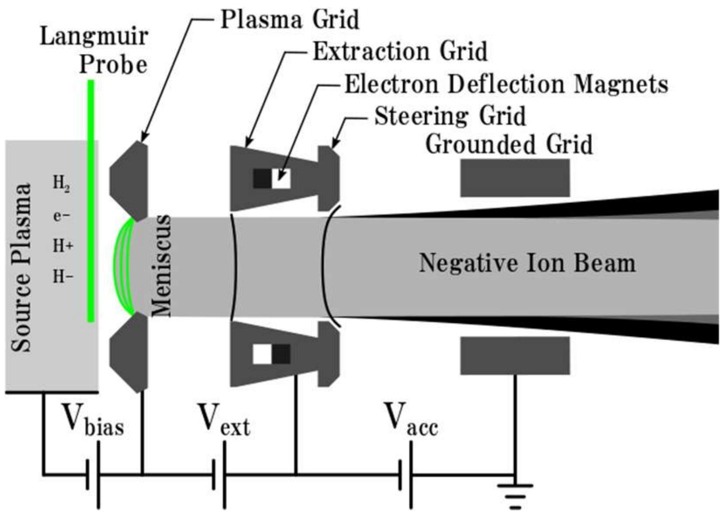
Our group (NIFS) collaborates with IO and IPP to investigate beam focusing with hybrid source

Direct comparison of beam focusing properties between RF- and Arc-sources **with the same accelerator and the same diagnostics is coming soon**, then
=> Understanding of the meniscus physics becomes more important

Two Approaches to the meniscus physics

Goal of this study is
"**experimental characterization of negative ion meniscus**"
with beam measurement and dedicated analyses

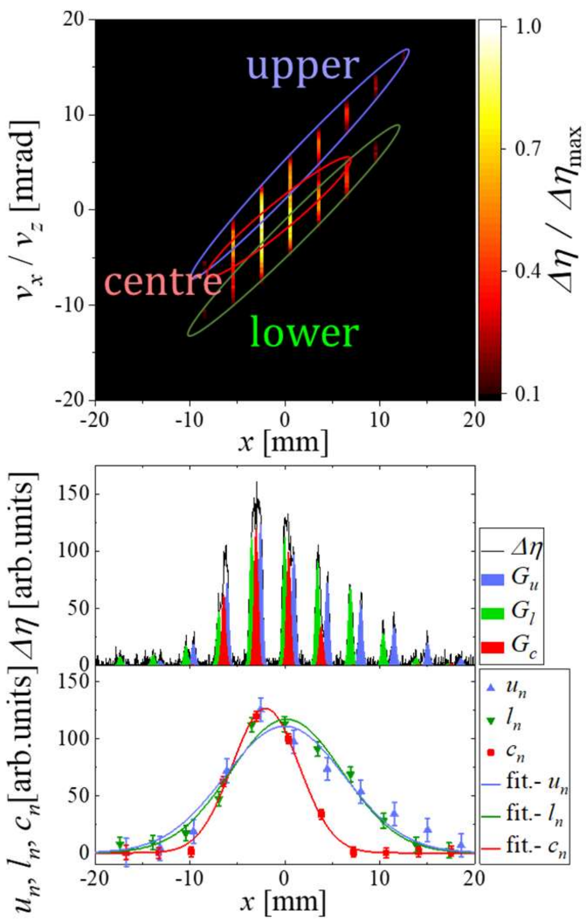
E. Rattanawongnara, NIBS2022



1) **Phase space structure measurement**
   - **shape of meniscus**
   - **beam profile at meniscus**
2) **Responses to the perturbations**
   - **shape of meniscus**
   - **key parameters for meniscus formation**

Phase space structure measurement

Y. Haba, New J. Phys. 2020,

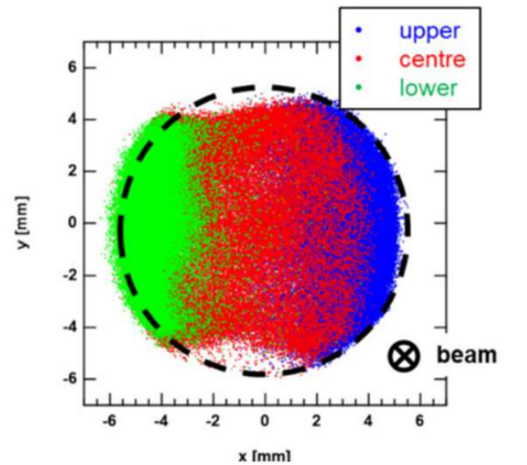


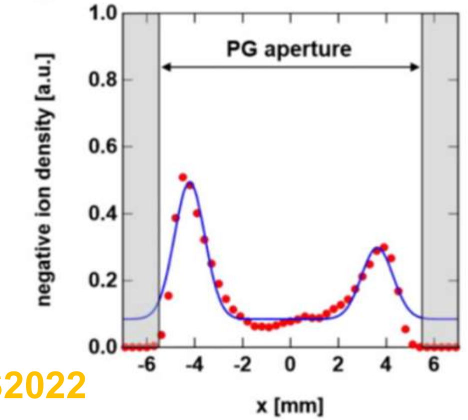
In y direction,
the single Gaussian beam was identified

In x direction (perpendicular to Electron Deflection Magnetic field),
the three components of Gaussian beam were identified

The inversely calculated beam trajectory revealed **the three components come from three different locations at meniscus**. **The non-uniformity of negative ion current density at the meniscus** was also identified.

M. Kisaki, Nucl. Fusion 2022

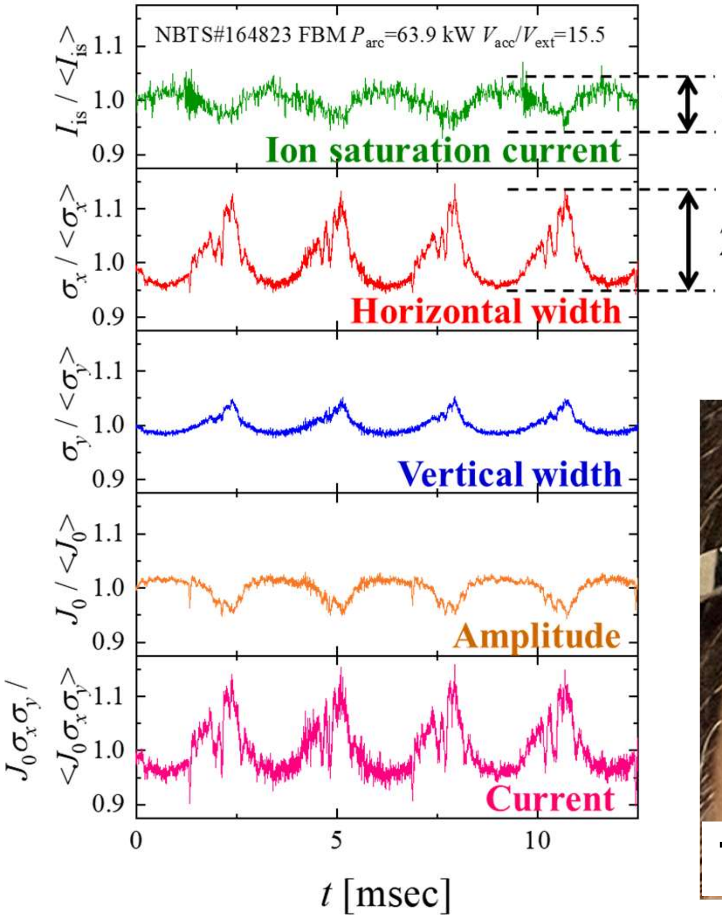


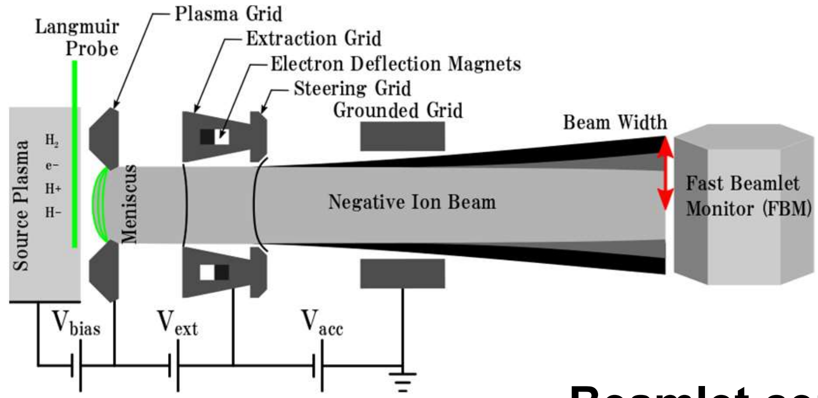


K. Miyamoto NIBS2022, G. Fubiani, NIBS2022

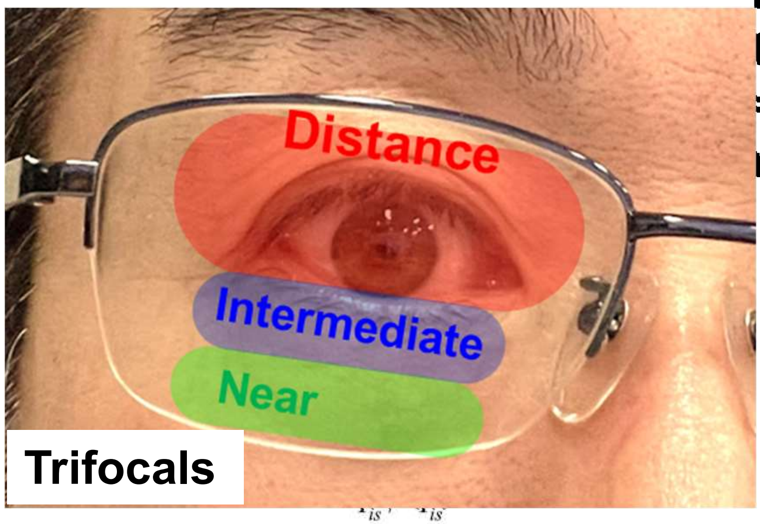
Responses to the perturbations

Y. Haba, Jpn. J. Appl. Phys. 2020

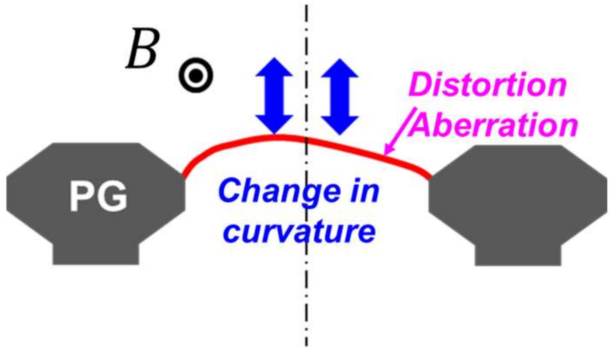




Bias power supply caused switching noise.
The responses of beamlet was observed **32ch Faraday cup (up to 25MHz)**



Beamlet center also responds to the perturbation
=> *Distortion aberration* of meniscus shape



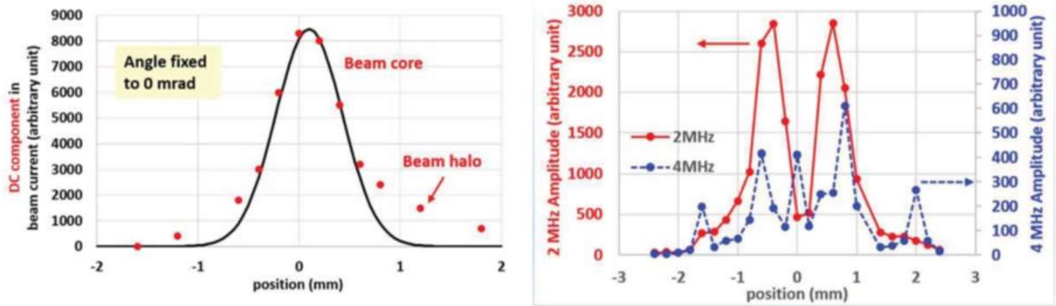
Responses to the RF field

Meniscus responses to the externally applied RF field is discussed based on the single beamlet dynamics

The main difference from the J-PARC source experiment is the plasma production.

In our experiment, Arc source + RF field (as a perturbation)
=> Plasma production effects could be minimized.

T. Shibata, AIP Conf. proc. 2021
M. Wada, NIBS2022



(a) (b)

The beam oscillation at the plasma production RF frequency and at the second harmonics

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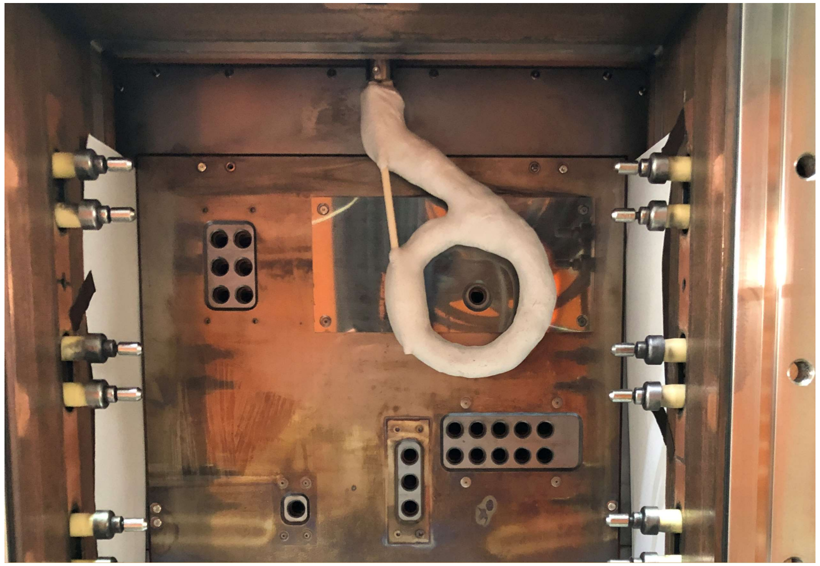
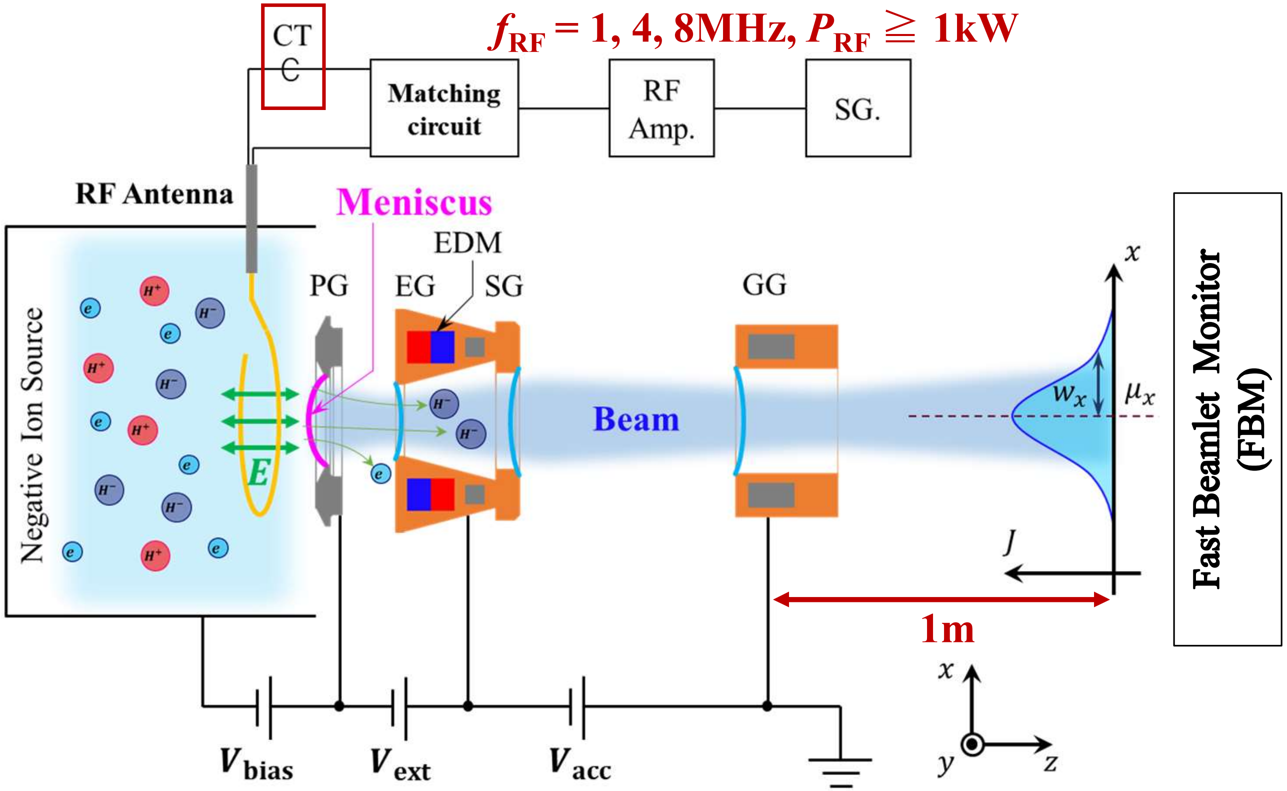
Overview of the Experimental Setup

RF Antenna

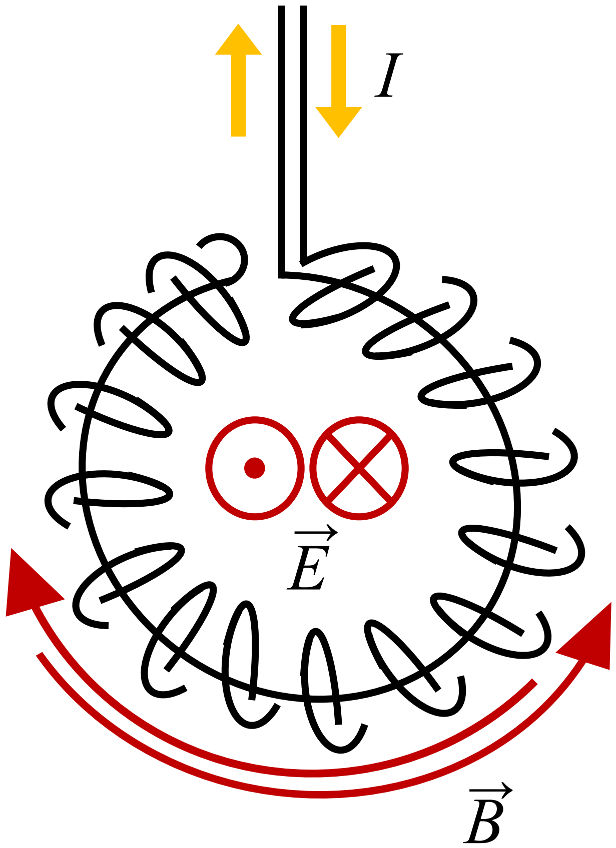


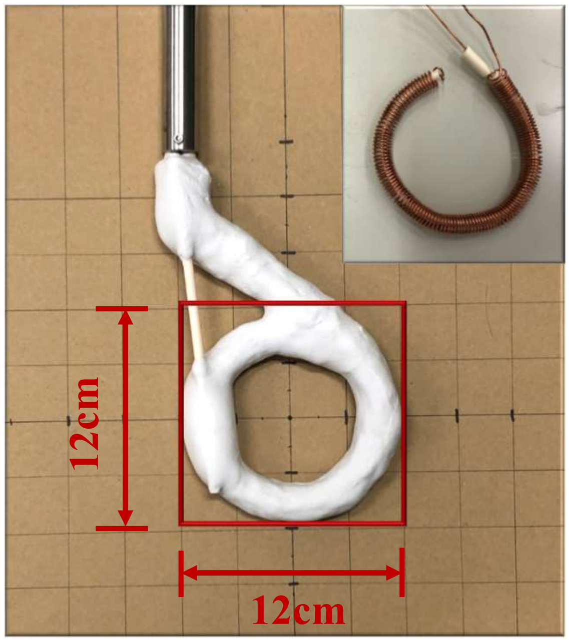


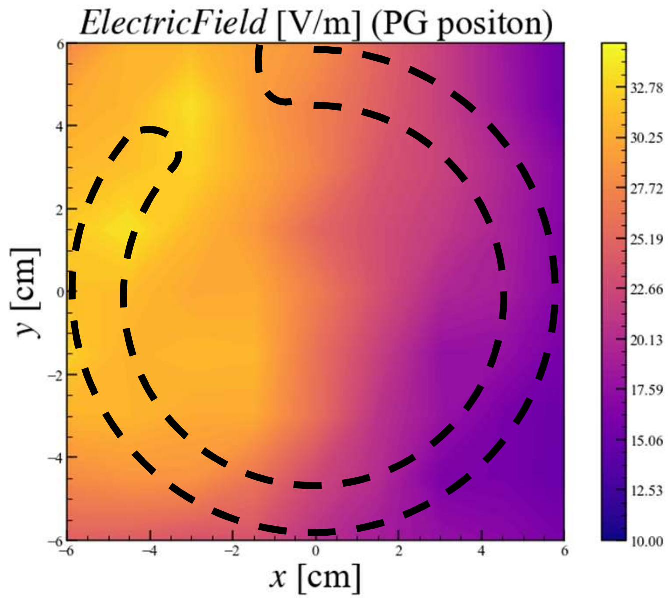
An RF electric field is applied to the plasma in front of the meniscus,
and the responses of the beamlet is experimentally investigated in this study.

RF antenna

Rogosky-type RF antenna.



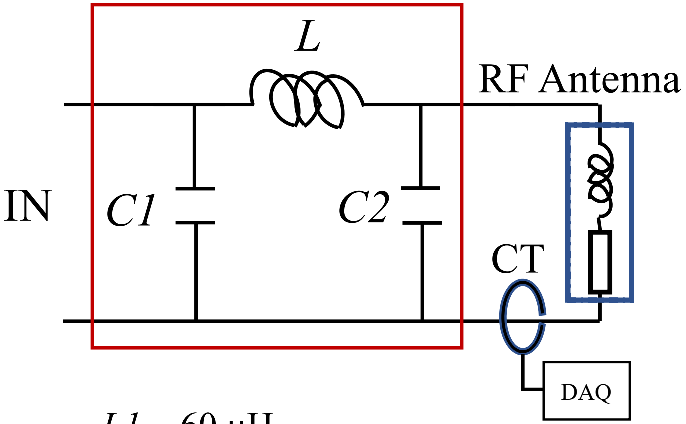




$P_{RF} = 100$ mW , Center position $E_{RF} \sim 30$ V/m

RF Matching Circuit

π-matching circuit

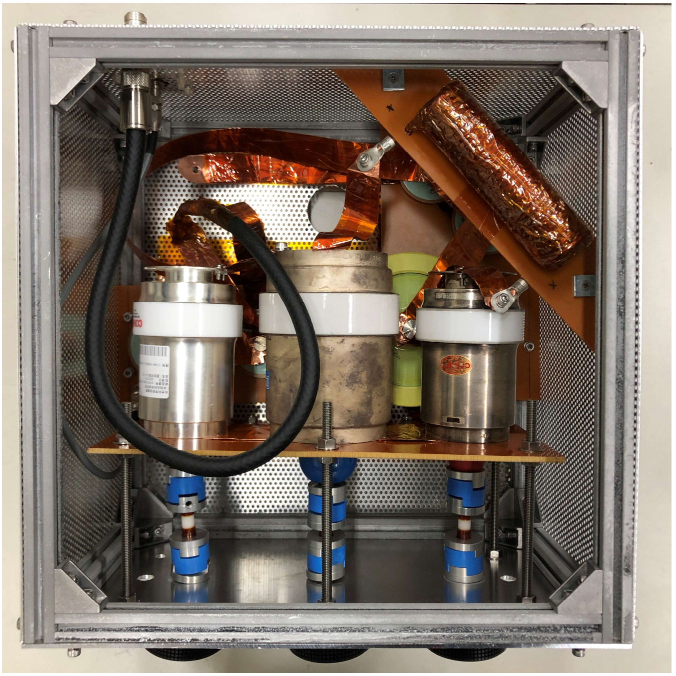


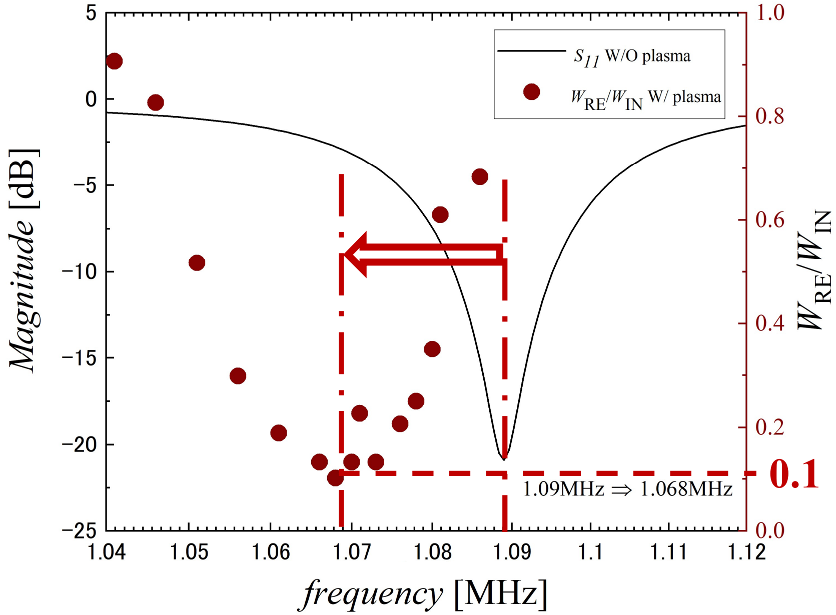
$L1 \sim 60\ \mu H$

$C1 = 2000\text{-}4000$ pF

$C2 = 3500\text{-}4500$ pF

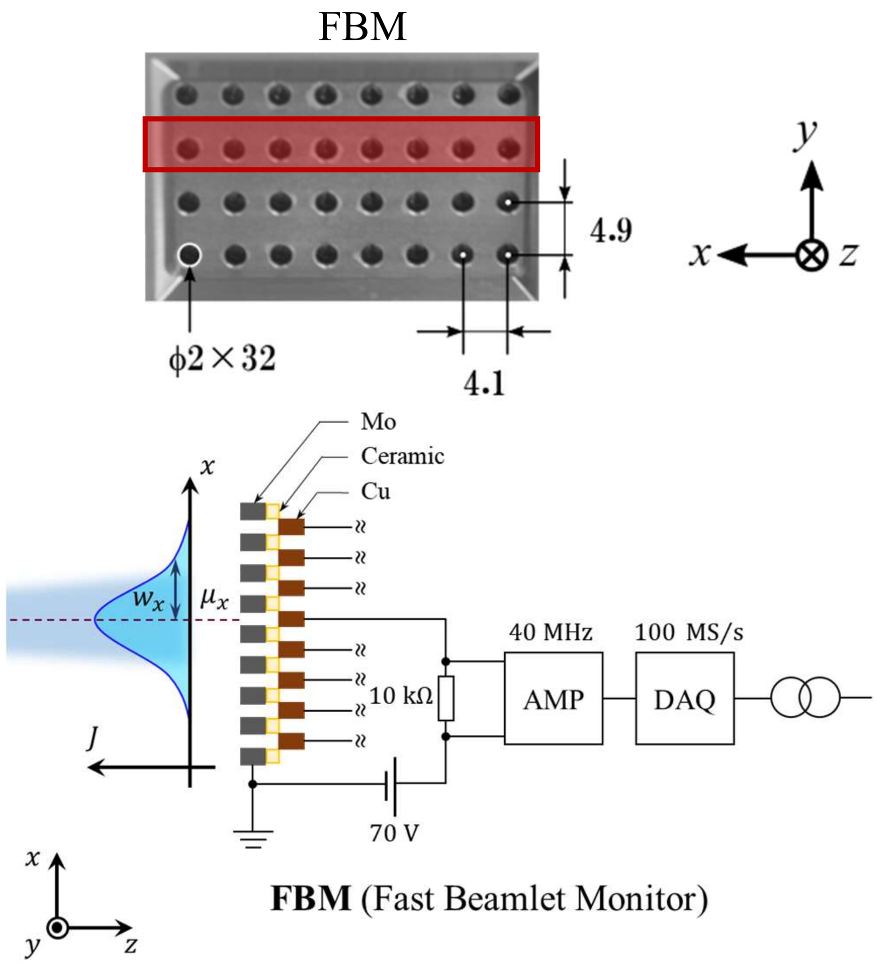
RF Antenna = 7.3 μH, 2.7Ω

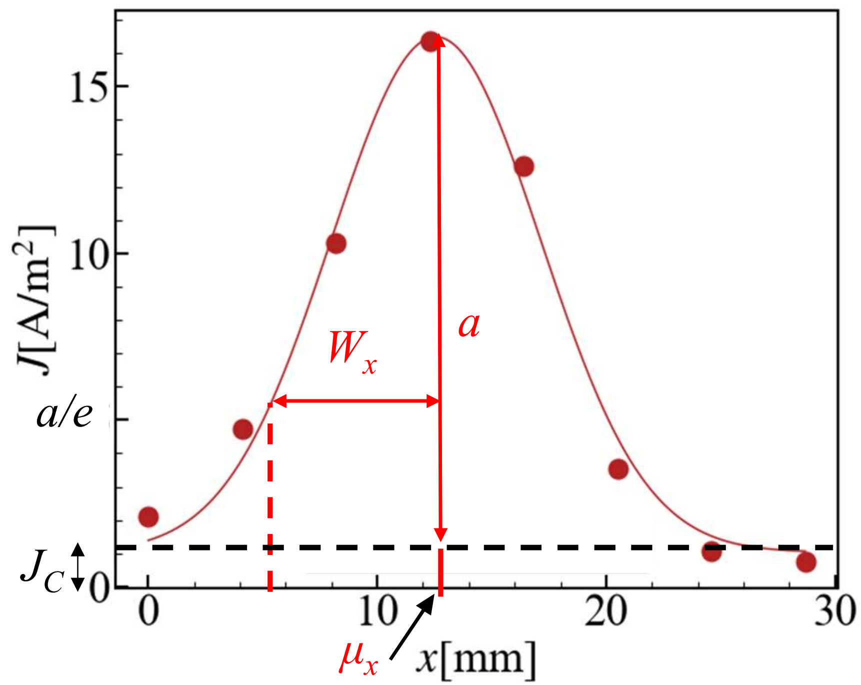




Although matching frequency is slightly(~0.02MHz) shifted between w/ and w/o the plasma.
Reflection rate is suppressed less than 20% in this experiment.

Fast Beamlet Monitor





$$J(x) = a \exp\left[-\left(\frac{x-\mu_x}{w_x}\right)^2\right] + J_C$$

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3. Results and Discussions
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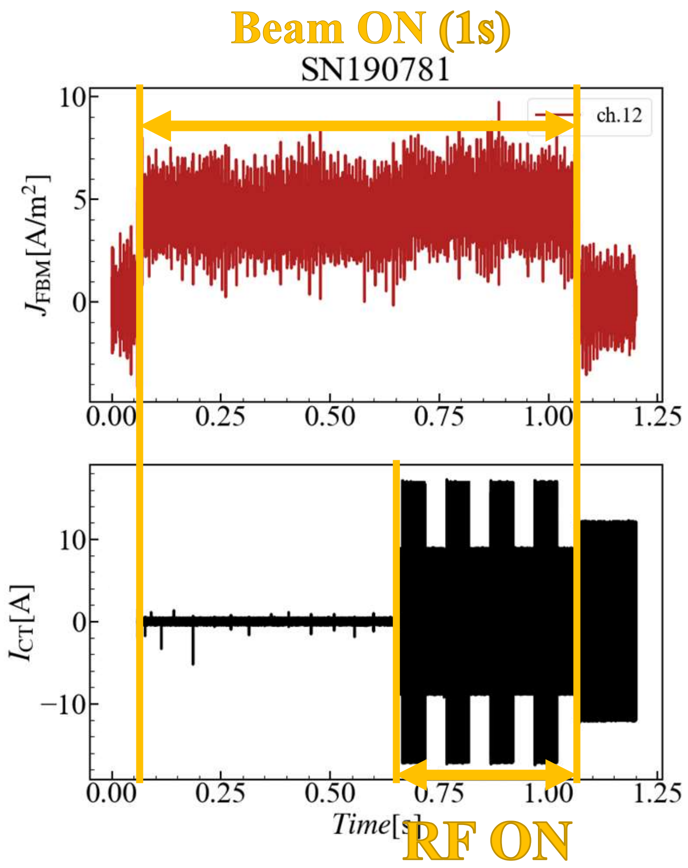
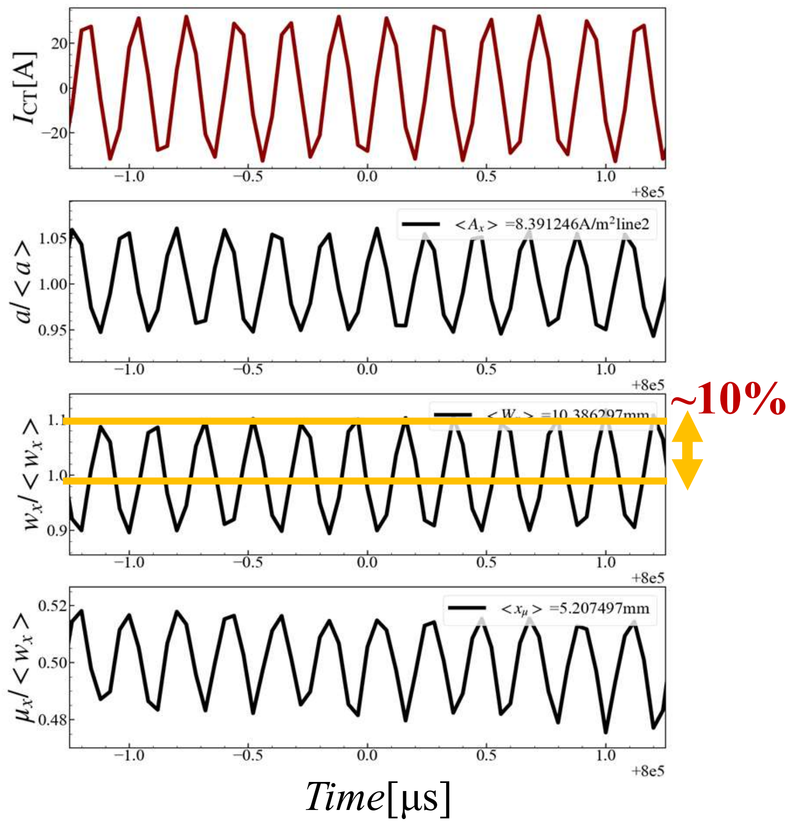
Beamlet Responses to RF Electric Field

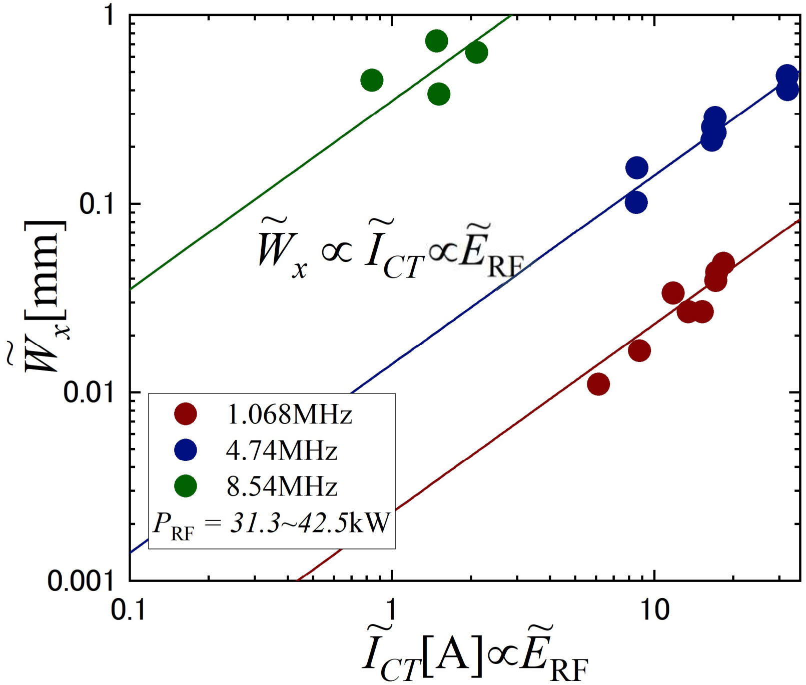




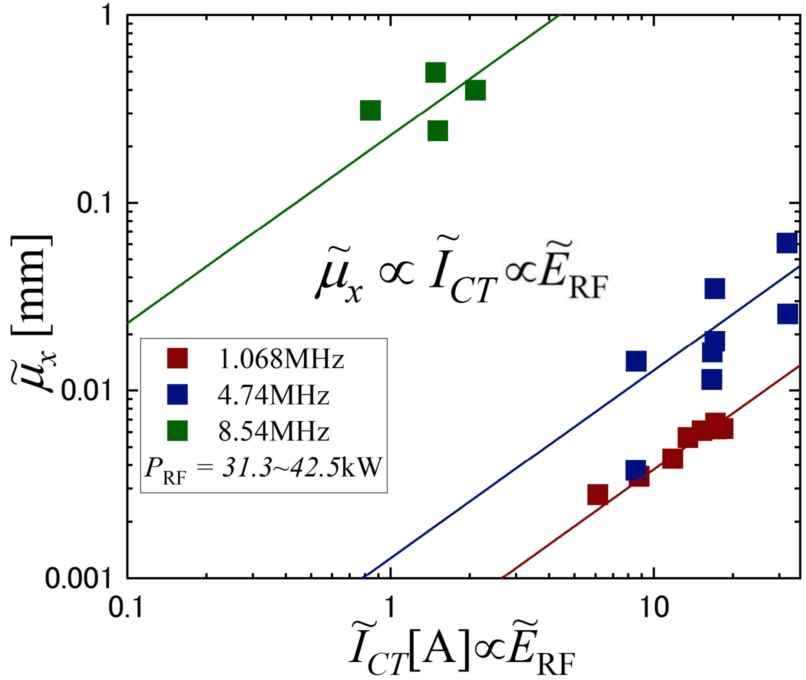
RF electric field may cause the degradation of the beamlet focusing.

RF Power Dependence

Response of Width



Response of Axis

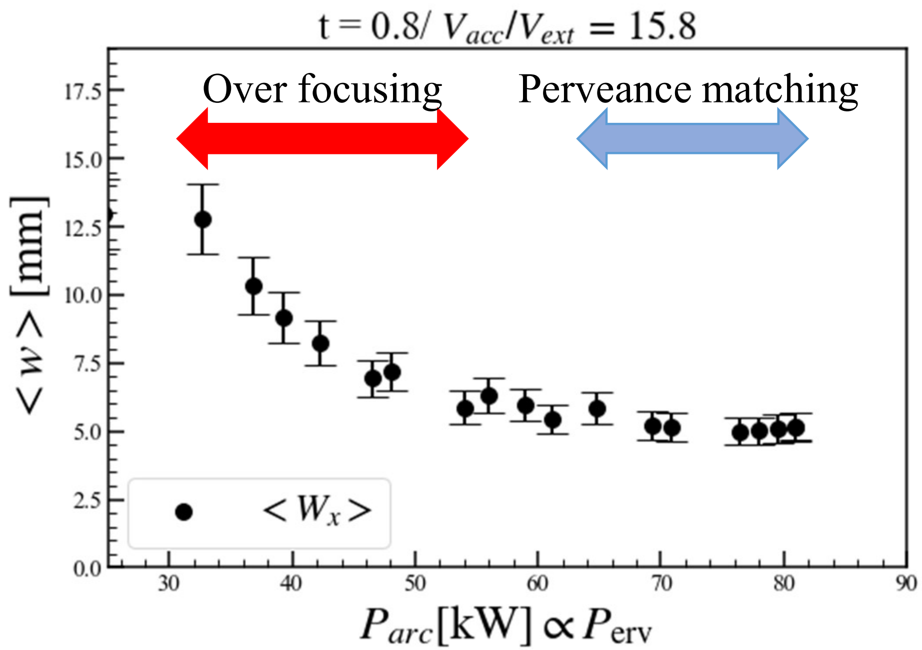


The responses of the beamlet width is proportional to RF electric field.
The similar response can be seen in the responses of beamlet axis position.
The higher frequency of the RF, the stronger response of the beamlet.

$\tilde{W}_x \propto \tilde{E}_{\mathrm{RF}}$

$\tilde{\mu}_x \propto \tilde{E}_{\mathrm{RF}}$

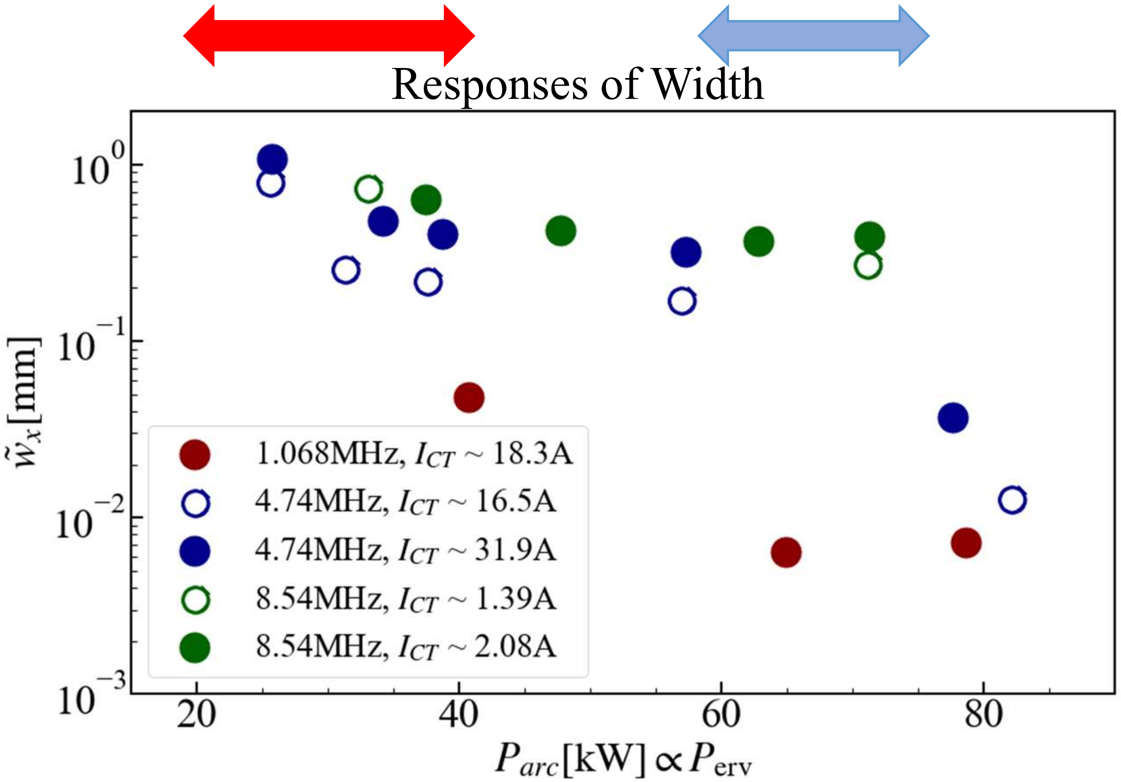
Characteristics of Beam Focusing



Meniscus ⇒ Perveance

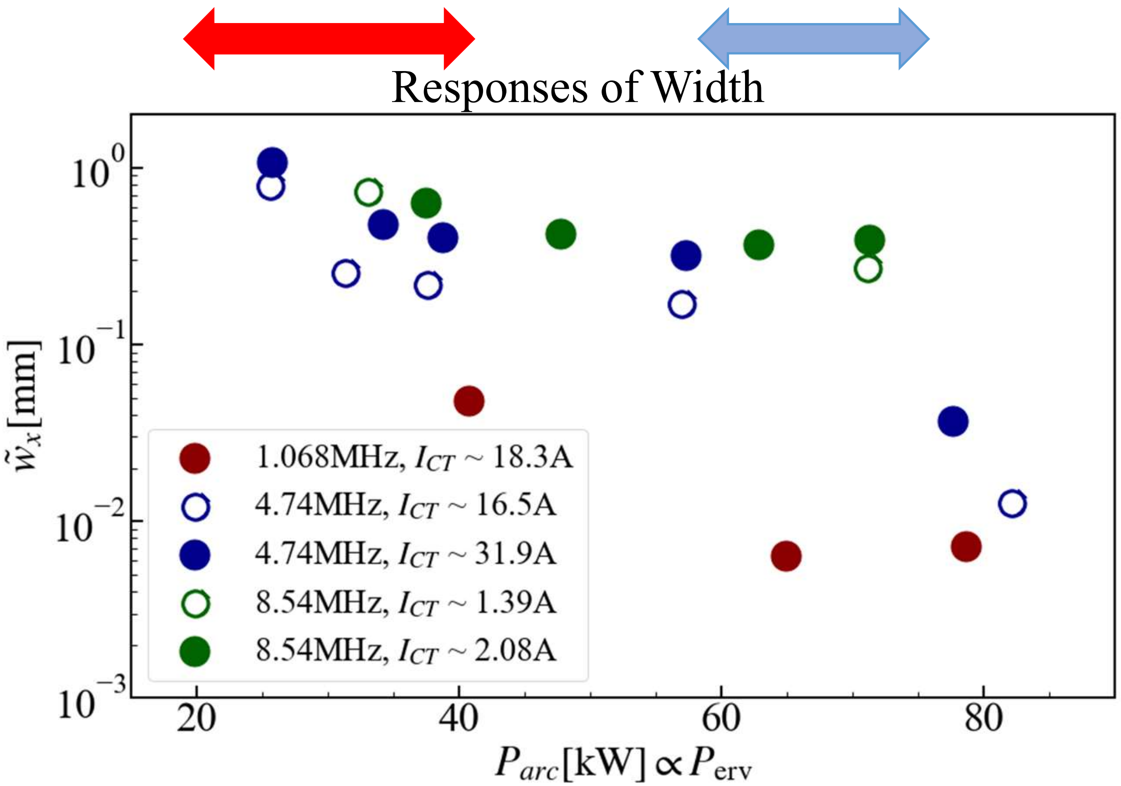
$$P_{\mathrm{erv}} = \frac{I_{\mathrm{beam}}}{V_{\mathrm{ext}}^{1.5}} \propto \frac{P_{\mathrm{arc}}}{V_{\mathrm{ext}}^{1.5}}$$

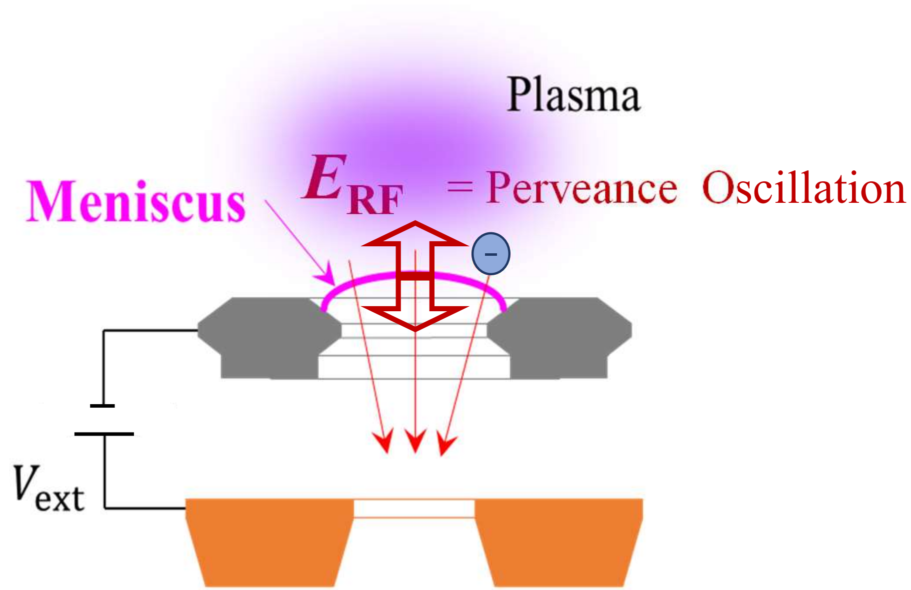
Arc Power Dependence



In the region where beam is over focusing, the responses are large.
In the perveance matching region, the responses become weaker.

Arc Power Dependence





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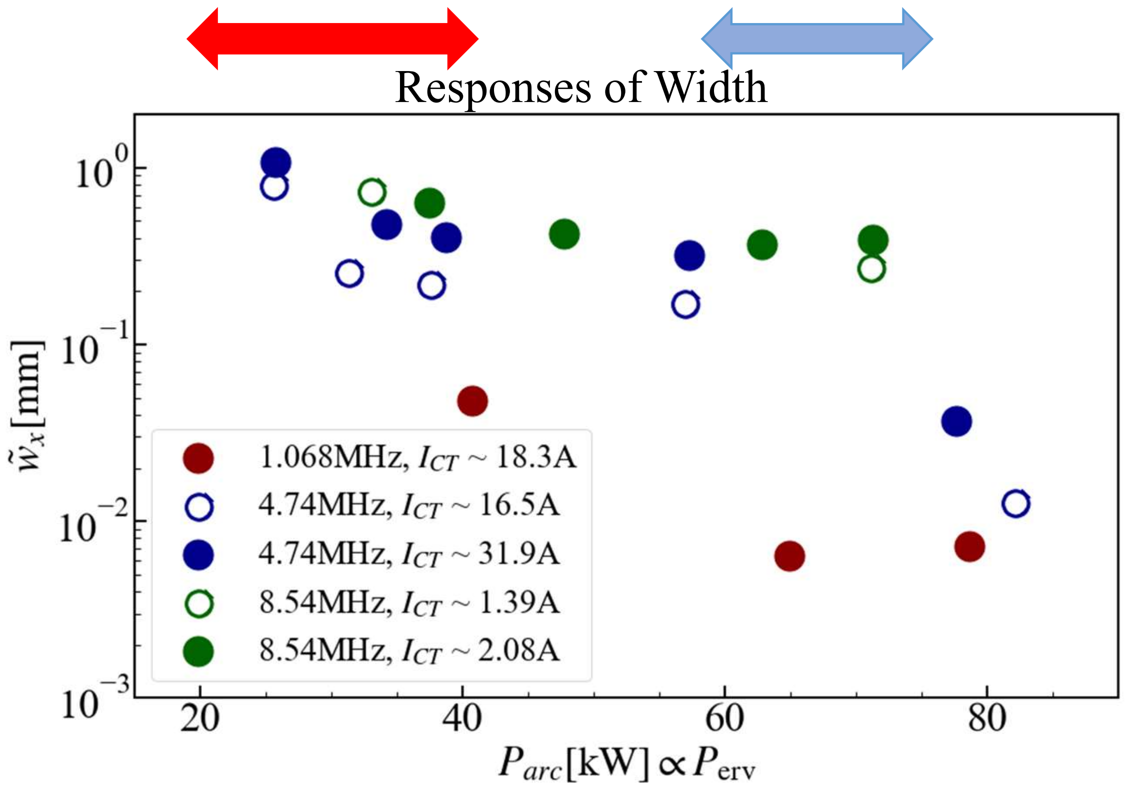

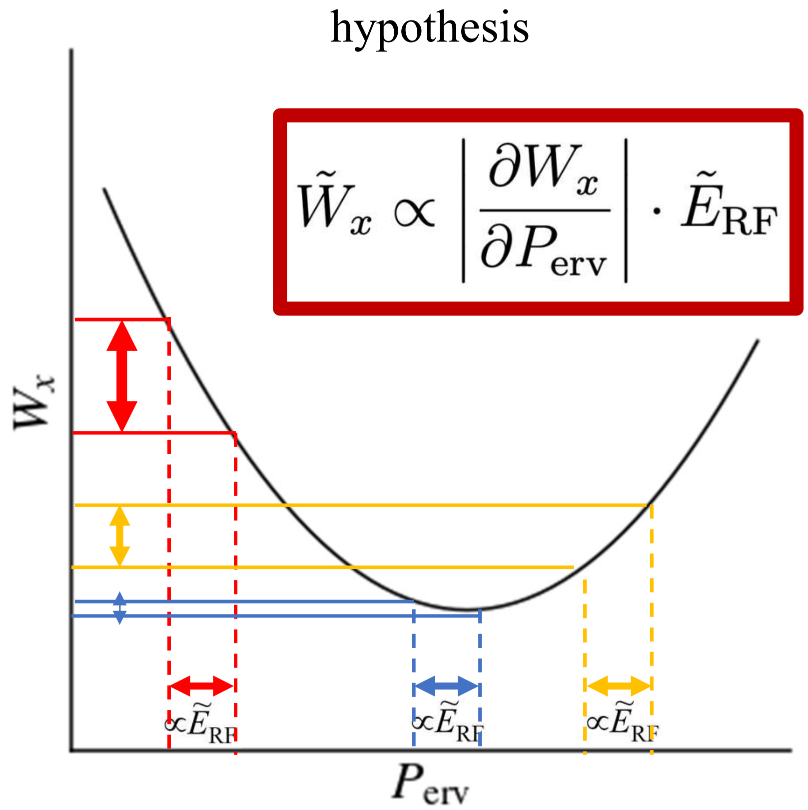

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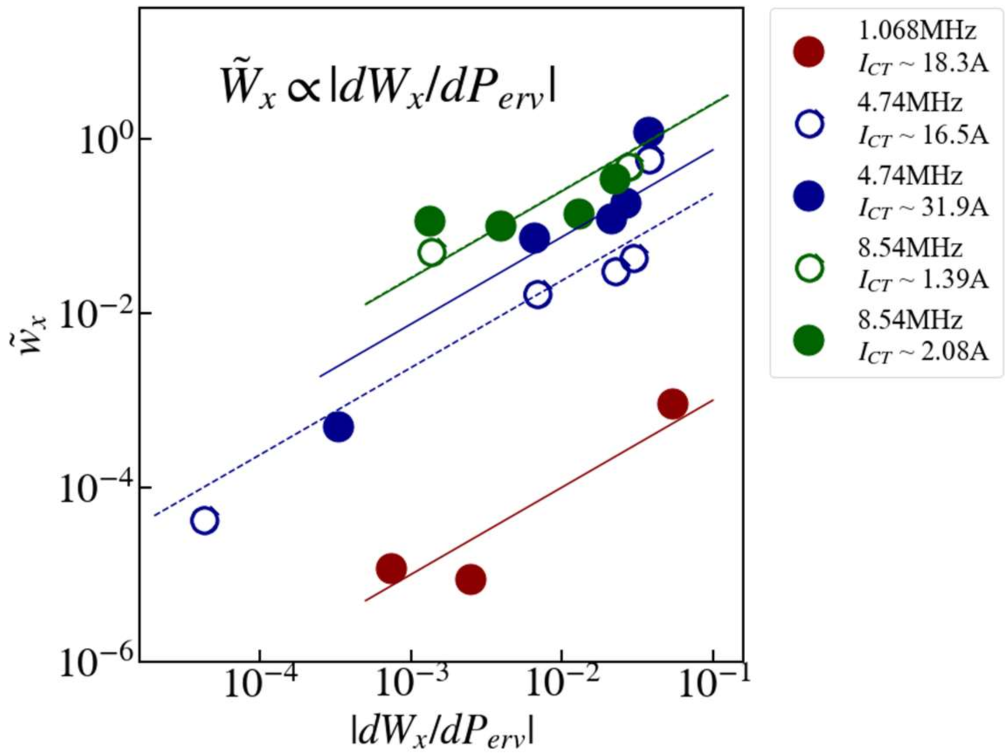
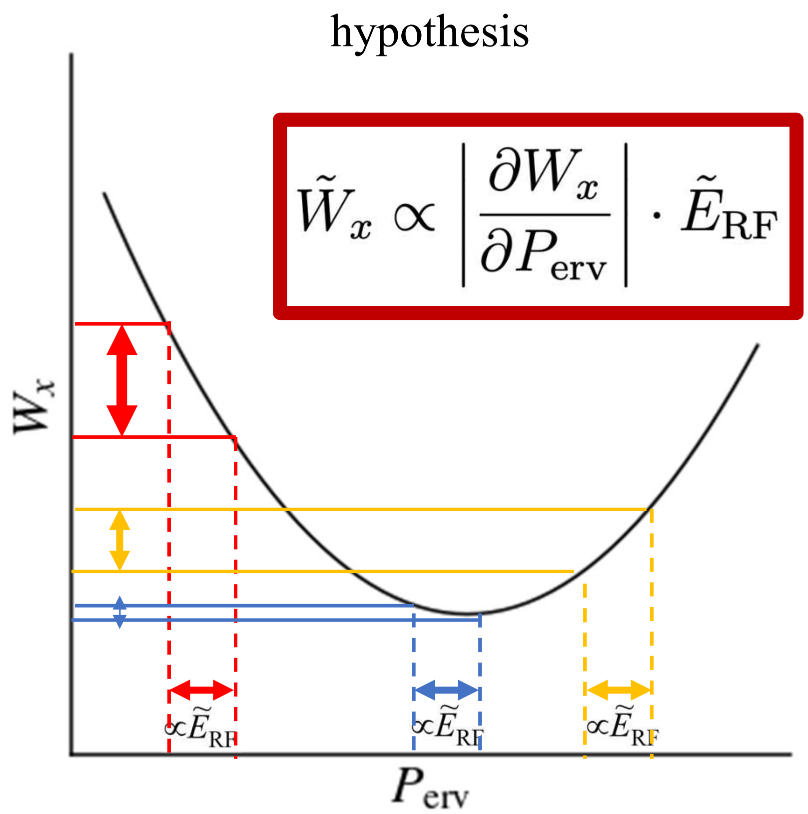
Arc Power Dependence



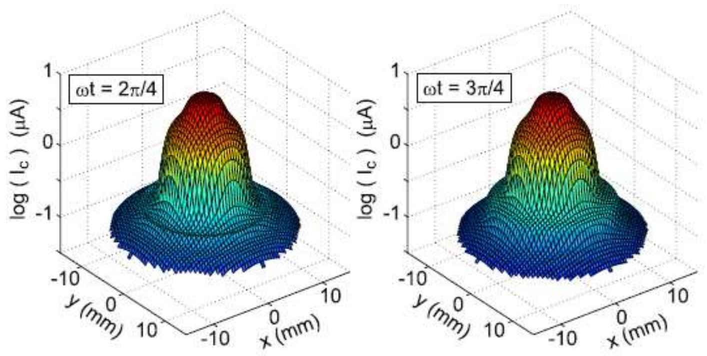


The linear relation can be seen. Our assumption is confirmed.
The effect of the RF electric field on the beam focusing can be suppressed by the optimization of the perveance matching.

Comparison with Positive beam experiment

Positive ion beamlet

K. Takahashi, New J. Phys. 2019



No significant effect in the core

Robust meniscus in the core and relatively large **deviation in the very edge**

Summary of beamlet responses to RF field

	Positive Source	Negative Source
$\frac{\theta_{\mathrm{div\_RF}}}{\theta_{\mathrm{div\_Arc}}}$	**~1**	**>1**
$\tilde{w}$ Osci. of width	*None*	***Yes** (mitigation)*
$\tilde{\mu}$ Oscil. of axis position	*None*	***Yes***

The oscillation of beamlet width and axis position at the RF frequency is a possible candidate to explain the different beam divergence between RF- and Arc-negative-ion sources.

Summary

Superpose RF electric field on the plasma in front of the meniscus and measure the responses of the beamlet.

- **Beamlet width** and **beamlet axis position oscillate with RF frequency**.
- Amplitude of beamlet width is **proportional to RF electric field and to the gradient of the perveance curve dW_x/dP_{erv}** .
  - ⇨ the beamlet width oscillation **can be suppressed by perveance optimization**

$$\tilde{W}_x \propto \left(\frac{\partial W_x}{\partial P_{\mathrm{erv}}}\right) \cdot \tilde{E}_{\mathrm{RF}}$$

- **Distortion aberration** + **meniscus oscillation** => **oscillation of the beamlet axis position**
  - ⇨ This may explain the reason why the beam divergence angle is relatively large only for RF negative ion source

In near future, more clear results with hybrid ion source experiments