



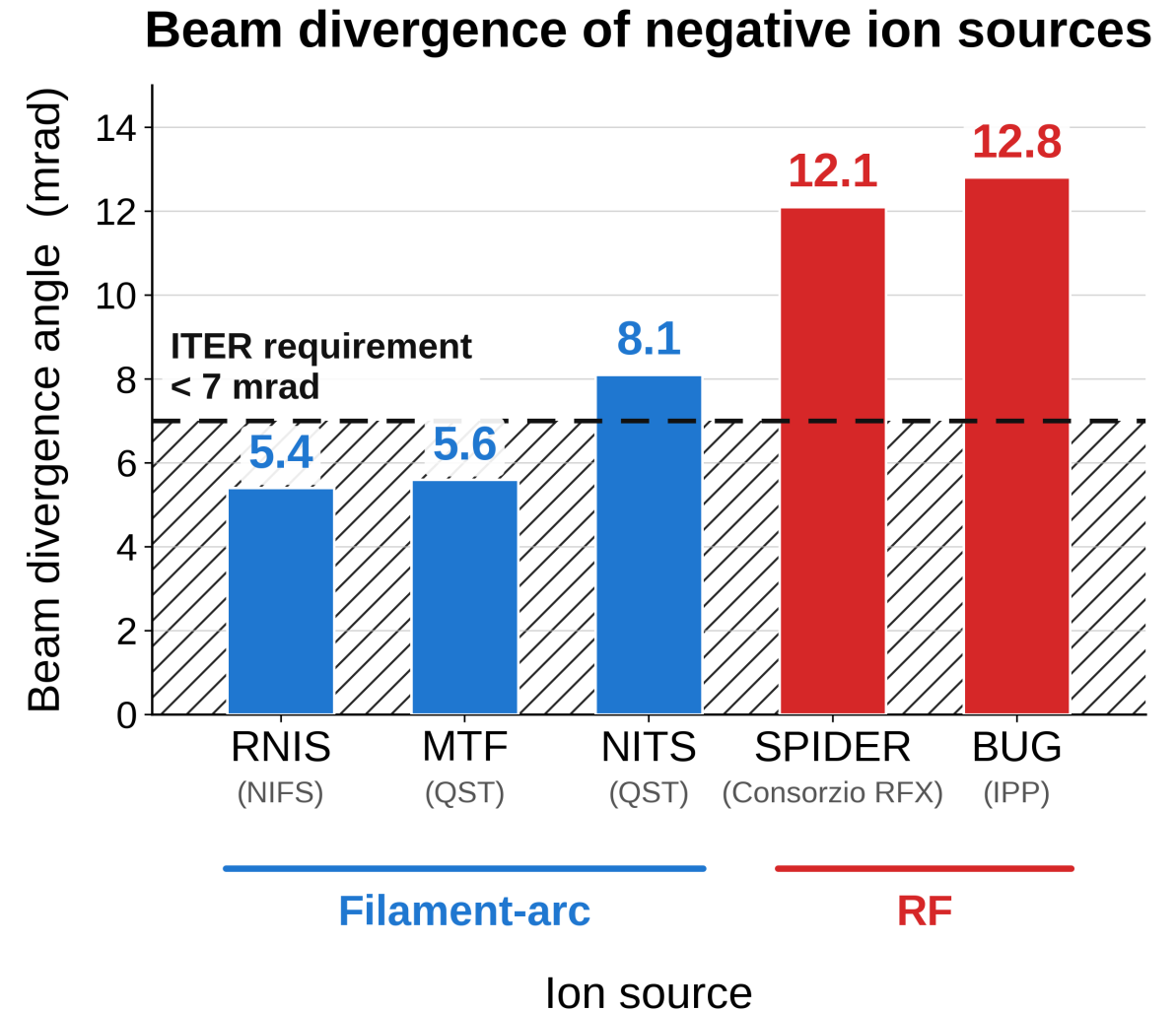
Modeling of Beam Focusing with Radio Frequency Electric Field Perturbations

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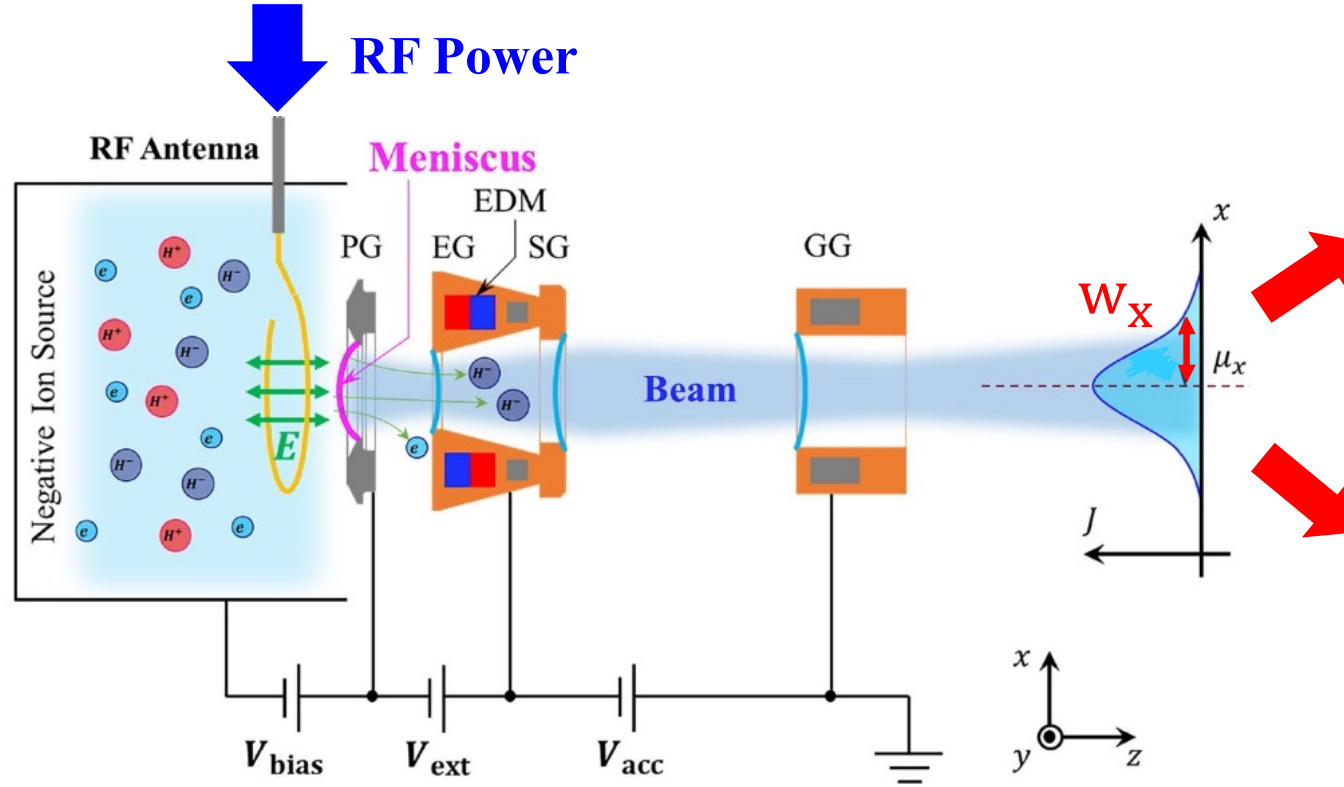
- RF negative ion sources are in development for ITER-NBI.
- Beam divergence of RF sources is about **twice** that of Filament-Arc (FA) sources.
- Improving **beam focusing** of RF sources is an **urgent issue** for ITER.
- The mechanism of **focusing degradation** must be identified.



[Previous work] Beam responses to RF

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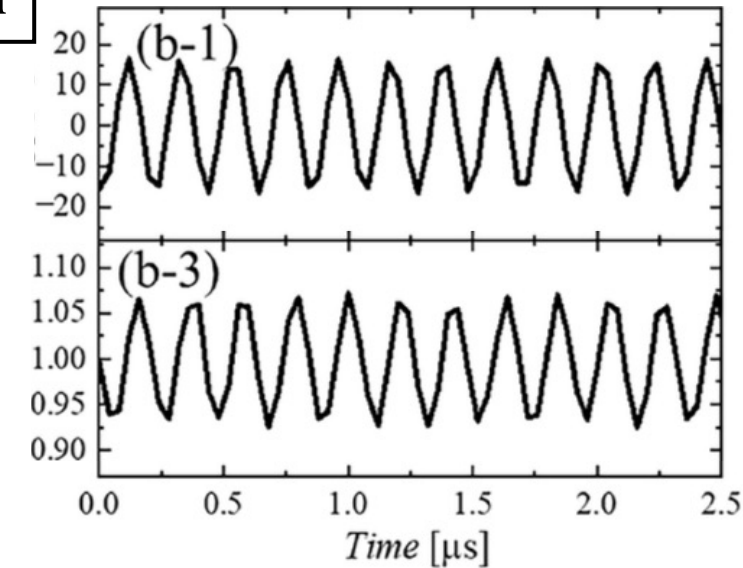
Experimental setup



W_x oscillation

RF antenna current
 $I_{RF} [A] \propto E_{RF}$

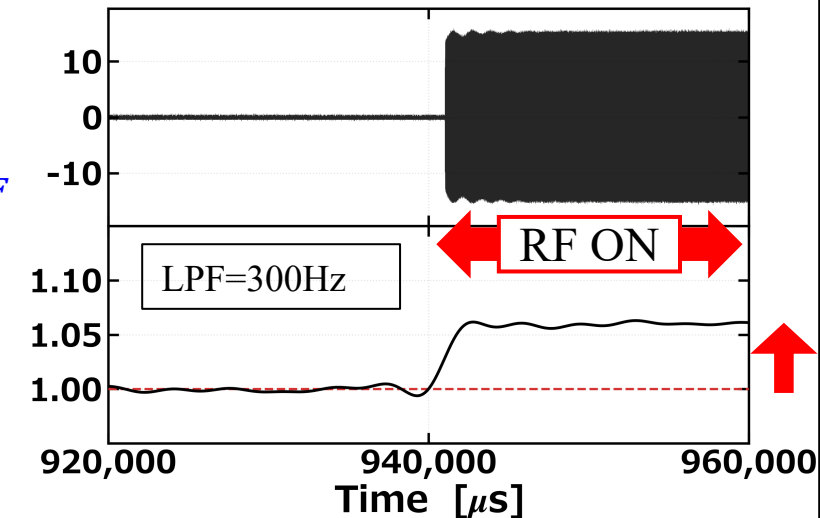
Normalized beam width
 $w_x / \langle w_x \rangle$



W_x increasing

RF antenna current
 $I_{RF} [A] \propto E_{RF}$

Normalized beam width
 $w_x / \langle w_x \rangle$

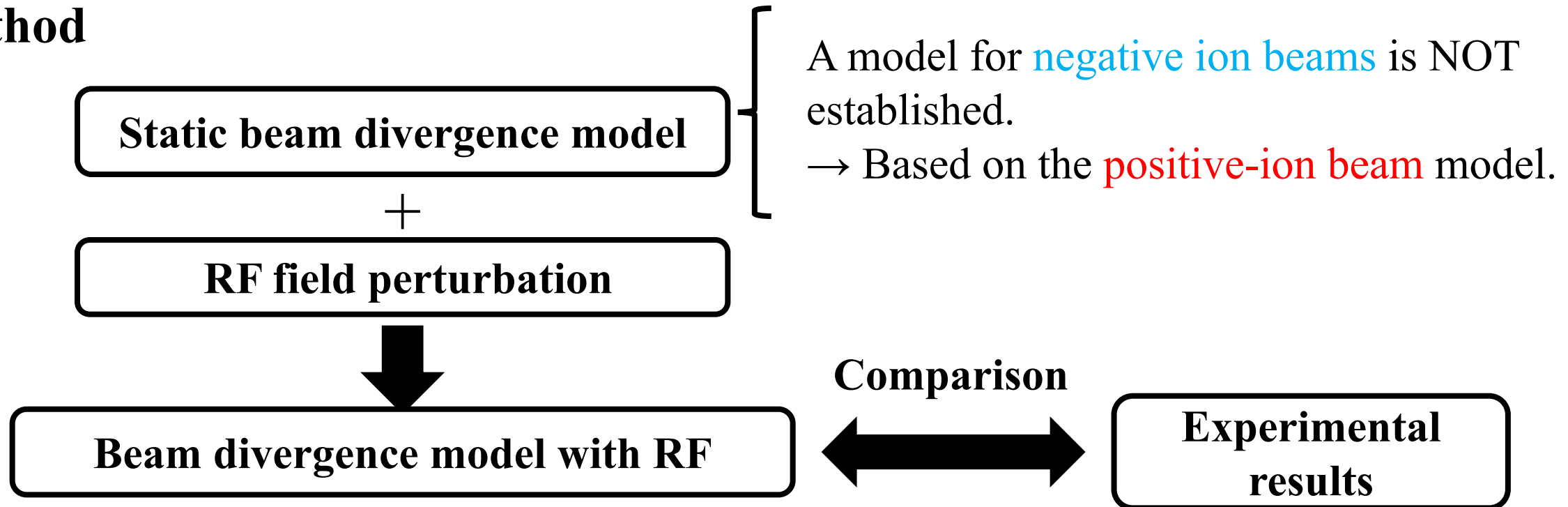


RF oscillation $\Rightarrow$ W_x oscillation and increase.
Cause: Response of the **meniscus** shape to the RF.

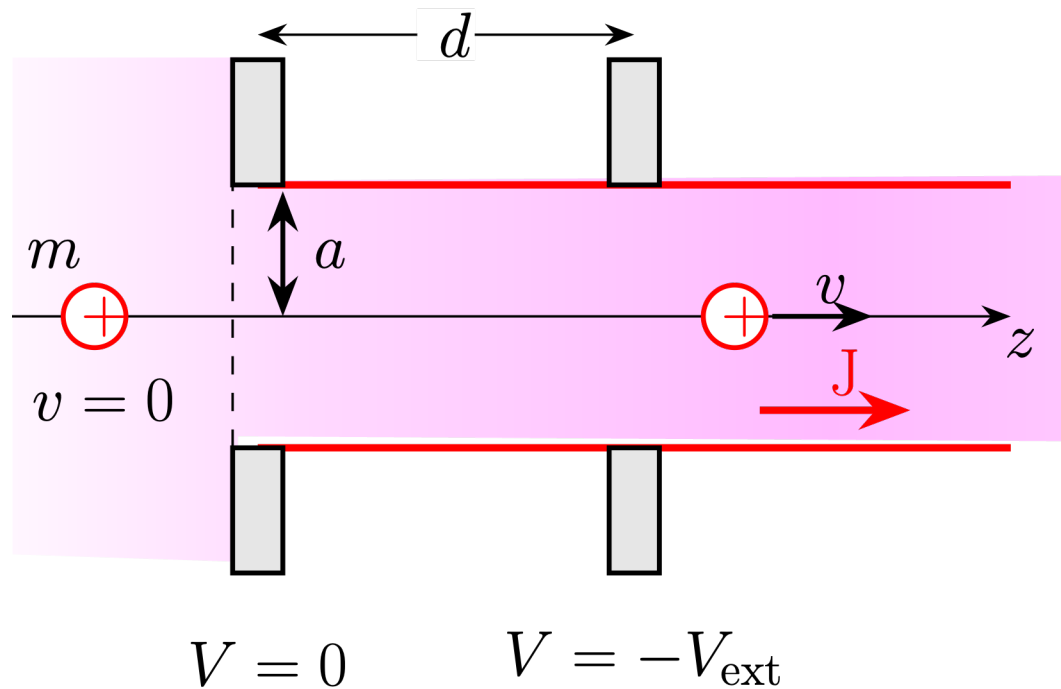
Objective

Developing a model of the negative ion beam divergence response to the RF electric field.

Method



■ 1D positive ion beam extraction model



I.Langmuir et al., Phys. Rev. **24**, 49 (1924).

- Poisson equ. $\frac{\partial^2 V}{\partial z^2} = \frac{\rho}{\epsilon_0}$
- Energy conservation $-qV + \frac{1}{2}mv^2 = 0$
- Beam current density $J = \rho v$

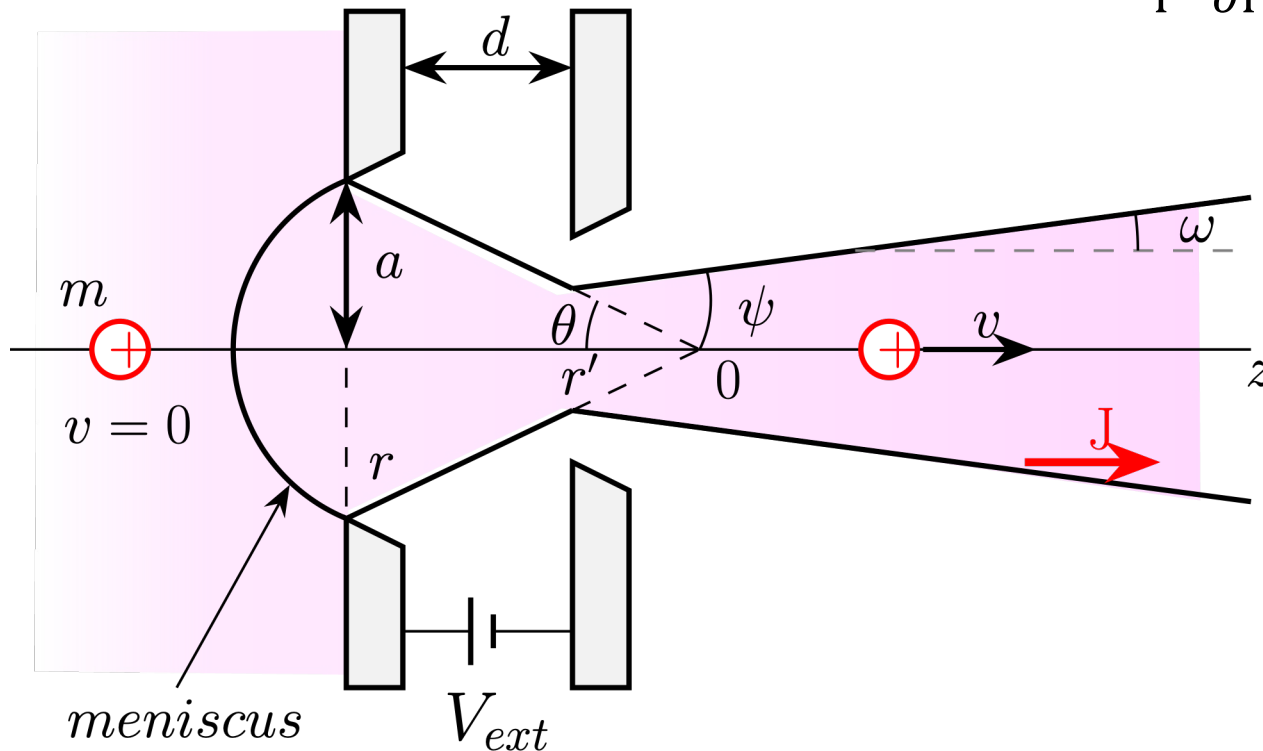
$$\frac{\partial^2 V}{\partial z^2} = \frac{J}{\epsilon_0} \sqrt{\frac{m}{2qV}}$$

- Beam current density J

$$J = \frac{4\epsilon_0}{9} \sqrt{\frac{2q}{m}} \frac{V_{\text{ext}}^{1.5}}{d^2} \quad (\text{Child - Langmuir law})$$

This model is conventionally used for negative beams.

■ Axisymmetric 2D beam extraction model



■ Poisson equ.

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial V}{\partial r} \right) = \frac{\rho}{\epsilon_0}$$

■ Energy conservation

$$-qV + \frac{1}{2}mv^2 = 0$$

■ Beam current density

$$J = \rho v$$

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial V}{\partial r} \right) = \frac{J}{\epsilon_0} \sqrt{\frac{m}{2qV}} \quad (\text{non-analytic})$$

Assuming $\theta \approx 0$
expanded to second order

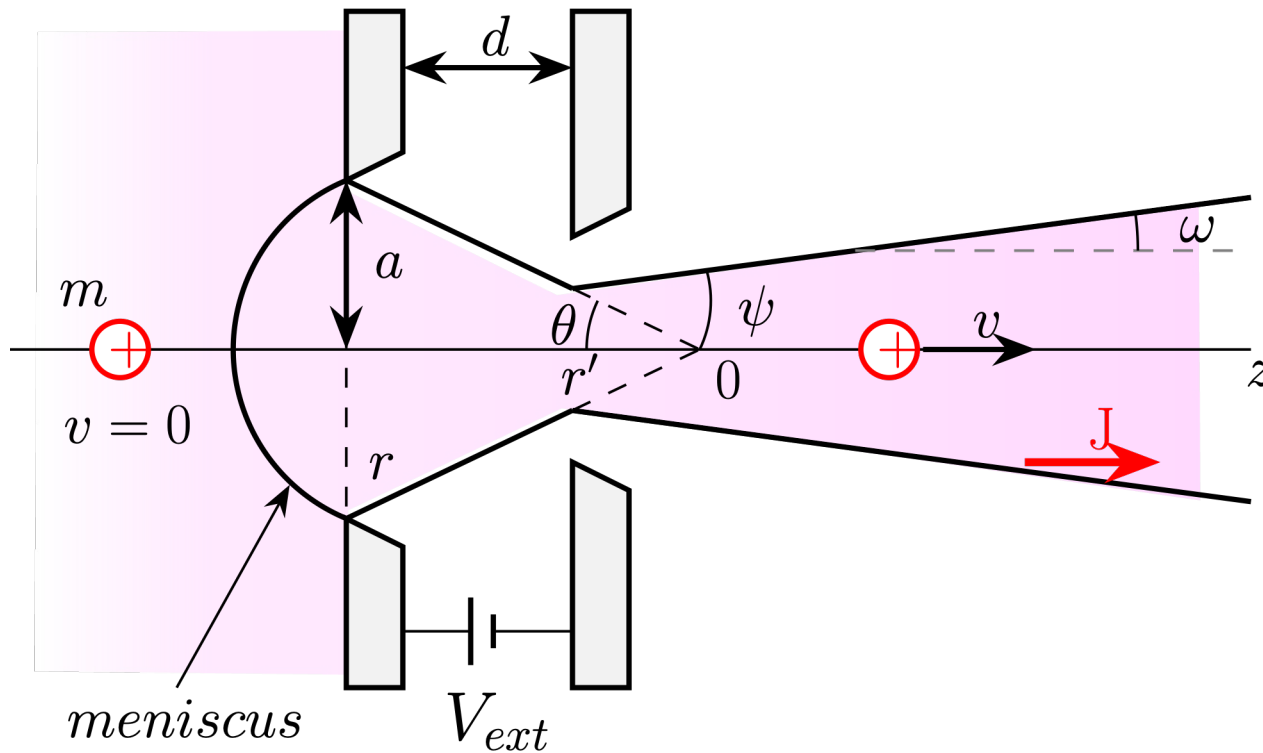
■ Beam current density J

$$J = \frac{4\epsilon_0}{9} \sqrt{\frac{2q}{m}} \frac{V_{\text{ext}}^{1.5}}{(r\alpha_0)^2}$$

$$\alpha_0 = \gamma_0 - 0.3\gamma_0^2$$

$$\gamma_0 = \ln \left(\frac{r'}{r} \right)$$

■ Axisymmetric 2D beam extraction model



J.R.Coupland *et al.* Rev. Sci. Instrum. **44**, 9 (1973).

■ ω is a function of $P_{erv} = I/V_{ext}^{1.5}$

■ Beam current density

$$J = \frac{4\varepsilon_0}{9} \sqrt{\frac{2q}{m} \frac{V_{ext}^{1.5}}{(r\alpha_0)^2}}$$

■ Beam current

$$I = \frac{8\pi\varepsilon_0}{9} \sqrt{\frac{2q}{m} \frac{V_{ext}^{1.5}}{\alpha_0^2}} (1 - \cos\theta)$$

■ Beam Focusing Angle

$$\theta \approx \frac{5}{8} \frac{a}{d} \left(1 - \frac{I/V_{ext}^{1.5}}{C} \right)$$

C : constant

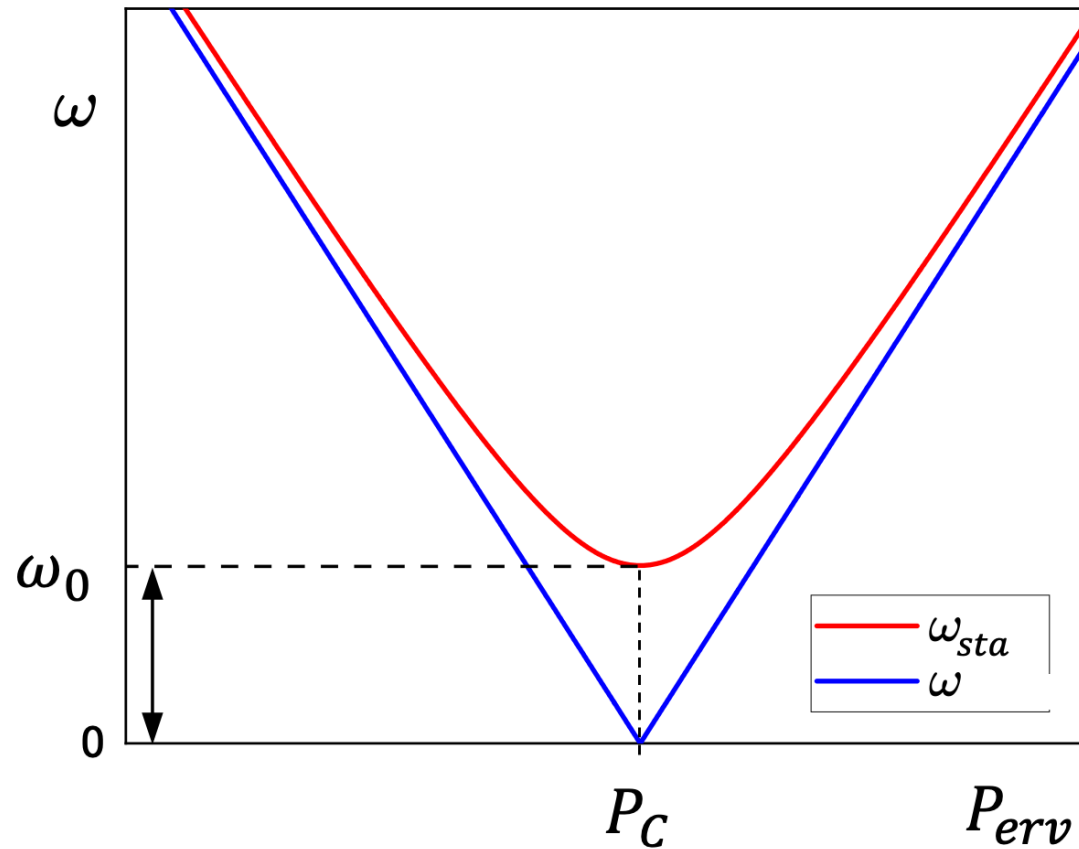
■ Beam divergence angle

$$\omega = |\psi - \theta| = \left| \frac{a}{3d} - \frac{5}{8} \frac{a}{d} \left(1 - \frac{P_{erv}}{C} \right) \right|$$

$$\omega = A \left| 1 - \frac{P_{erv}}{P_C} \right|$$

A, P_C : constant

■ ω vs ω_{sta} comparison



$$\omega = A \left| 1 - \frac{P_{erv}}{P_C} \right|$$

ω_0 minimum divergence angle

■ Static beam divergence ω_{sta}

$$\omega_{sta} = \sqrt{\left(A \left| 1 - \frac{P_{erv}}{P_C} \right| \right)^2 + \omega_0^2}$$

■ Static beam divergence ω_{sta}

$$\omega_{sta} = \sqrt{\left(A \left|1 - \frac{P_{erv}}{P_C}\right|\right)^2 + \omega_0^2} \quad \left(P_{erv} = \frac{I}{V_{ext}^{1.5}}\right)$$

+

Perturbation(E_{RF})

$$\omega(P_{erv}(E_{RF}))$$

$$P_{erv} = \frac{I(E_{RF})}{V_{ext}^{1.5}}$$

Model 1

$$P_{erv} = \frac{I}{V_{ext}(E_{RF})^{1.5}}$$

Model 2

$$\omega(P_{erv}, E_{RF})$$

$$P_{erv} = const.$$

Model 3

■ Hypotheses

① Current oscillation is dominant.

$$\omega(P_{erv}(E_{RF})), P_{erv} = \frac{I(E_{RF})}{V_{ext}^{1.5}}$$

② Current oscillation originates from ion density oscillation.

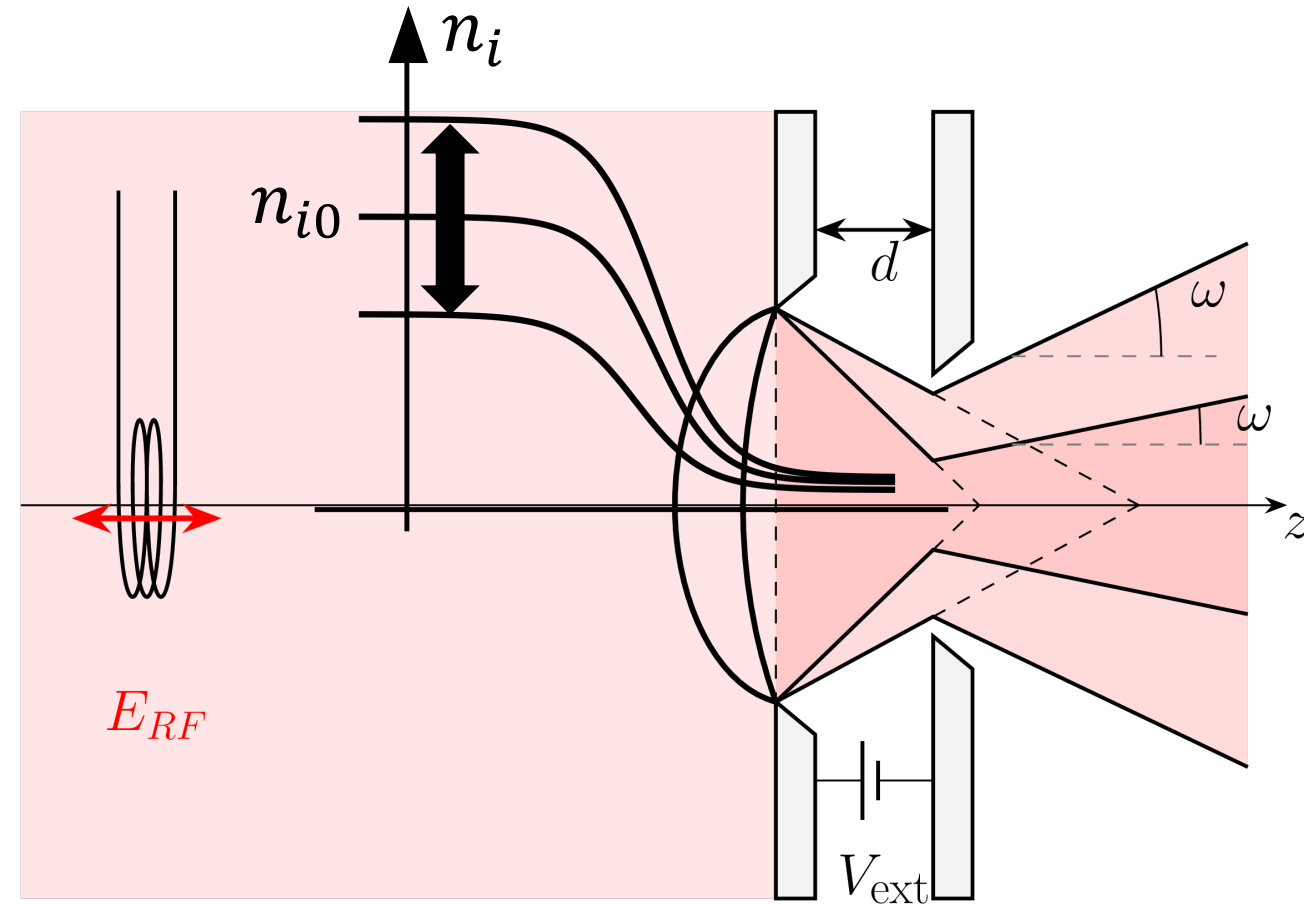
$$I = Cn_i$$

③ Ion density oscillation follows the production rate ($\propto E_{RF}^2$)

$$n_i = n_{i0} + \alpha E_{RF}^2 e^{2i\omega_{RF}t}$$

indicating beam current does not oscillate at ω_{RF}

■ Model schematic



■ Hypotheses

① Current oscillation is dominant.

$$\omega(P_{erv}(E_{RF})), P_{erv} = \frac{I(E_{RF})}{V_{ext}^{1.5}}$$

② Current oscillation originates from ion density oscillation

$$I = Cn_i$$

③ Ion density oscillation follows the production rate ($\propto E_{RF}^2$)

$$n_i = n_{i0} + \alpha E_{RF}^2 e^{2i\omega_{RF}t}$$

■ Static beam divergence ω_{sta}

$$\omega_{sta} = \sqrt{\left(A \left|1 - \frac{P_{erv}}{P_C}\right|\right)^2 + \omega_0^2}$$

$$P_{erv} = \frac{C(n_{i0} + \alpha E_{RF}^2 e^{2i\omega_{RF}t})}{V_{ext}^{1.5}}$$

$$= P_{sta} \left(1 + \frac{\alpha}{n_{i0}} E_{RF}^2 e^{2i\omega_{RF}t}\right)$$

Model 1 $\bar{\omega}_1$

$$\bar{\omega}_1 = \frac{1}{T} \int \sqrt{\left(A \left|1 - \frac{P_{sta} \left(1 + \frac{\alpha}{n_{i0}} E_{RF}^2 e^{2i\omega_{RF}t}\right)}{P_C}\right|\right)^2 + \omega_0^2} dt$$

■ Hypotheses

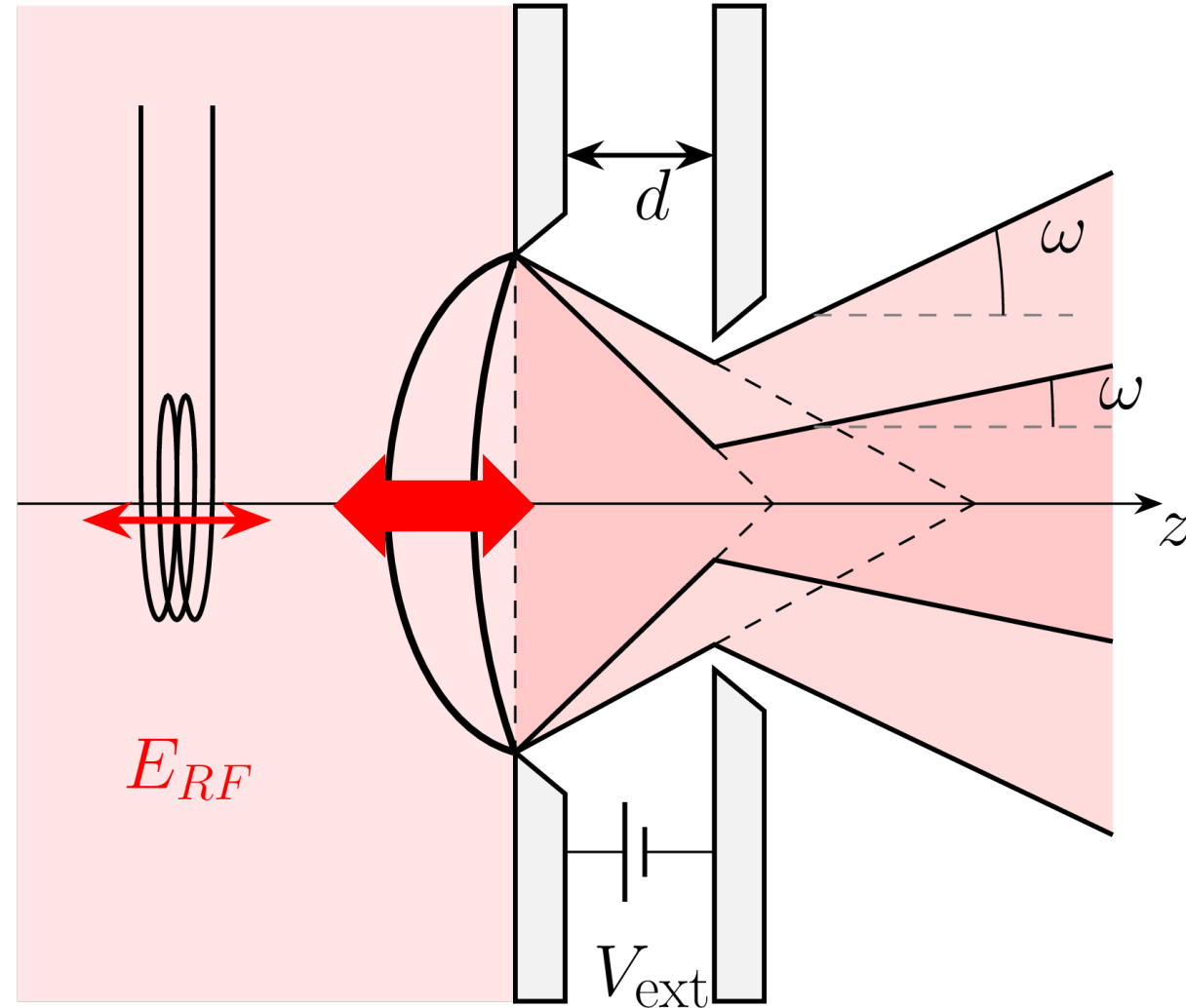
① Electric Field oscillation is dominant.

$$\omega(P_{erv}(E_{RF})), P_{erv} = \frac{I}{V_{ext}(E_{RF})^{1.5}}$$

② The RF field is superimposed on the extraction field. $\frac{V_{ext}}{d} + E_{RF}e^{i\omega_{RF}t}$

③ The RF field is much smaller than the static field $|E_{RF}e^{i\omega_{RF}t}| \ll \frac{V_{ext}}{d}$

■ Model schematic



■ Hypotheses

① Electric Field oscillation is dominant.

$$\omega(P_{erv}(E_{RF})), P_{erv} = \frac{I}{V_{ext}(E_{RF})^{1.5}}$$

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■ Static beam divergence ω_{sta}

$$\omega_{sta} = \sqrt{\left(A \left|1 - \frac{P_{erv}}{P_C}\right|\right)^2 + \omega_0^2}$$

$$P_{erv} = \frac{I}{(V_{ext} + dE_{RF}e^{i\omega_{RF}t})^{1.5}}$$

$$= P_{sta} \left\{ 1 - 1.5 \frac{d}{V_{ext}} E_{RF}e^{i\omega_{RF}t} + 1.875 \left(\frac{d}{V_{ext}}\right)^2 E_{RF}^2 e^{2i\omega_{RF}t} \right\}$$

Model 2 $\bar{\omega}_2$

$$\bar{\omega}_2 = \frac{1}{T} \int \sqrt{\left(A \left|1 - \frac{P_{sta} \left\{ 1 - 1.5 \frac{d}{V_{ext}} E_{RF}e^{i\omega_{RF}t} + 1.875 \left(\frac{d}{V_{ext}}\right)^2 E_{RF}^2 e^{2i\omega_{RF}t} \right\}}{P_C}\right|\right)^2 + \omega_0^2} dt$$

■ Hypotheses

① Direct response of the meniscus structure to E_{RF} is dominant.

$$\omega(P_{erv}, E_{RF}), P_{erv} = const.$$

② Meniscus position on the z axis l varies in proportion to E_{RF}

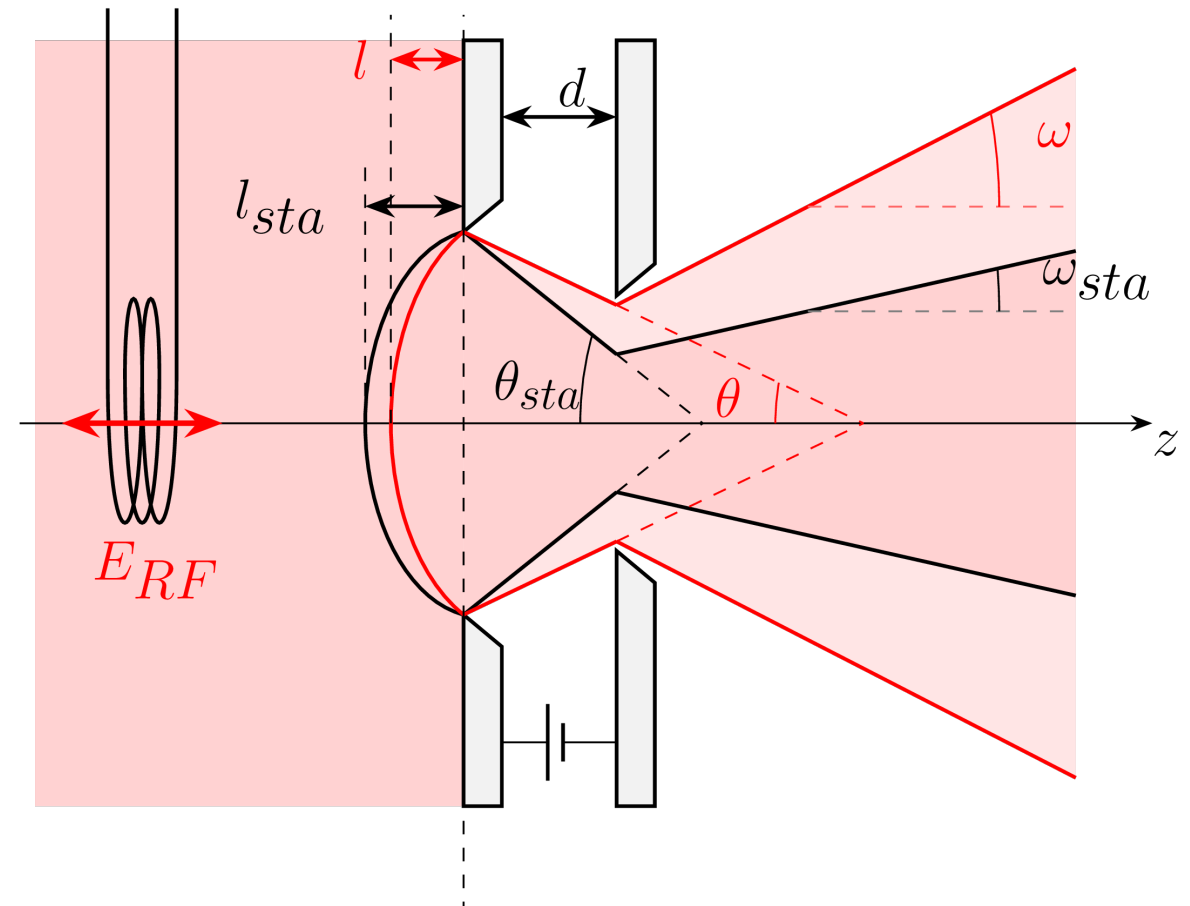
$$l - l_{sta} = \varepsilon E_{RF} e^{i\omega_{RF} t}$$

Geometrically: $l - l_{sta} \sim \frac{a}{2} (\theta_{sta} - \theta)$

$$\theta = \theta_{sta} - \frac{a}{2} \varepsilon E_{RF} e^{i\omega_{RF} t}$$

$$\omega = \sqrt{\left(\left|\frac{a}{3d} - \theta\right|\right)^2 + \omega_0^2}$$

■ Model schematic



■ Hypotheses

① Direct response of the meniscus structure to E_{RF} is dominant.

$$\omega(P_{erv}, E_{RF}), P_{erv} = \text{const.}$$

② Meniscus position on the z axis l varies in proportion to E_{RF}

$$l - l_{sta} = \varepsilon E_{RF} e^{i\omega_{RF} t}$$

■ Static beam divergence ω_{sta}

$$\omega_{sta} = \sqrt{\left(A \left|1 - \frac{P_{erv}}{P_C}\right|\right)^2 + \omega_0^2}$$

Geometrically: $l - l_{sta} \sim \frac{a}{2} (\theta_{sta} - \theta)$

$$\theta = \theta_{sta} - \frac{a}{2} \varepsilon E_{RF} e^{i\omega_{RF} t}$$

$$\omega = \sqrt{\left(\left|\frac{a}{3d} - \theta\right|\right)^2 + \omega_0^2}$$

Model 3 $\bar{\omega}_3$

$$\bar{\omega}_3 = \frac{1}{T} \int \sqrt{\left(A \left|1 - \frac{P_{sta}}{P_C} + \frac{2}{Aa} \varepsilon E_{RF} e^{i\omega_{RF} t}\right|\right)^2 + \omega_0^2} dt$$

Model 1: Ion density oscillation model

$$\bar{\omega}_1 = \frac{1}{T} \int \sqrt{\left(A \left| 1 - \frac{P_{sta} \left(1 + \frac{\alpha}{n_0} E_{RF}^2 e^{2i\omega_{RF}t} \right)}{P_C} \right| \right)^2 + \omega_0^2} dt$$

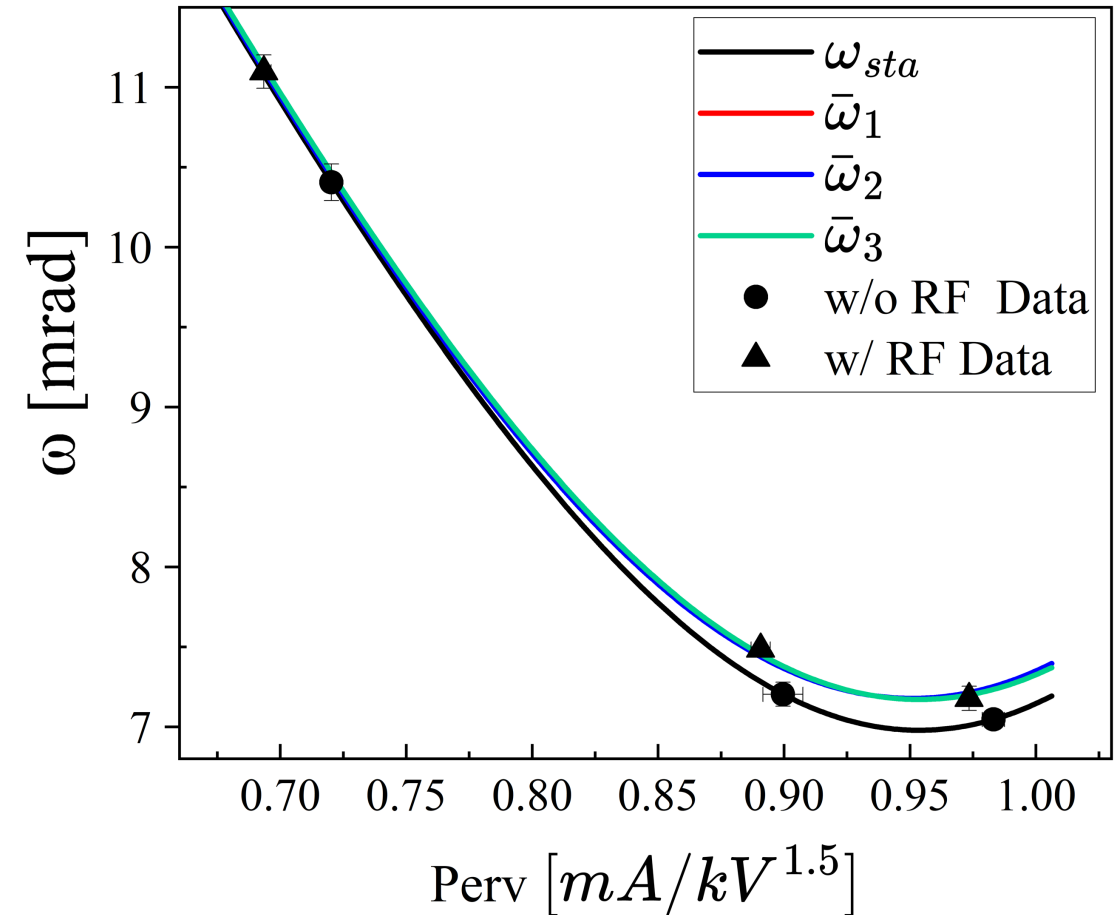
Model 2: Extraction field oscillation model

$$\bar{\omega}_2 = \frac{1}{T} \int \sqrt{\left(A \left| 1 - \frac{P_{sta} \left\{ 1 - 1.5 \frac{d}{V_{ext}} E_{RF} e^{i\omega_{RF}t} + 1.875 \left(\frac{d}{V_{ext}} E_{RF} \right)^2 e^{2i\omega_{RF}t} \right\}}{P_C} \right| \right)^2 + \omega_0^2} dt$$

Model 3: Direct meniscus response model

$$\bar{\omega}_3 = \frac{1}{T} \int \sqrt{\left(A \left| 1 - \frac{P_{sta}}{P_C} + \frac{2}{Aa} \varepsilon E_{RF} e^{i\omega_{RF}t} \right| \right)^2 + \omega_0^2} dt$$

Model vs. experimental data



All models reproduce the experimental result.

Comparison with experiment ② Divergence oscillation 16

Model 1: Ion density oscillation model

$$\bar{\omega}_1 = \frac{1}{T} \int \sqrt{\left(A \left| 1 - \frac{P_{sta} \left(1 + \frac{\alpha}{n_0} E_{RF}^2 e^{2i\omega_{RF}t} \right) \right|}{P_C} \right)^2 + \omega_0^2} dt$$

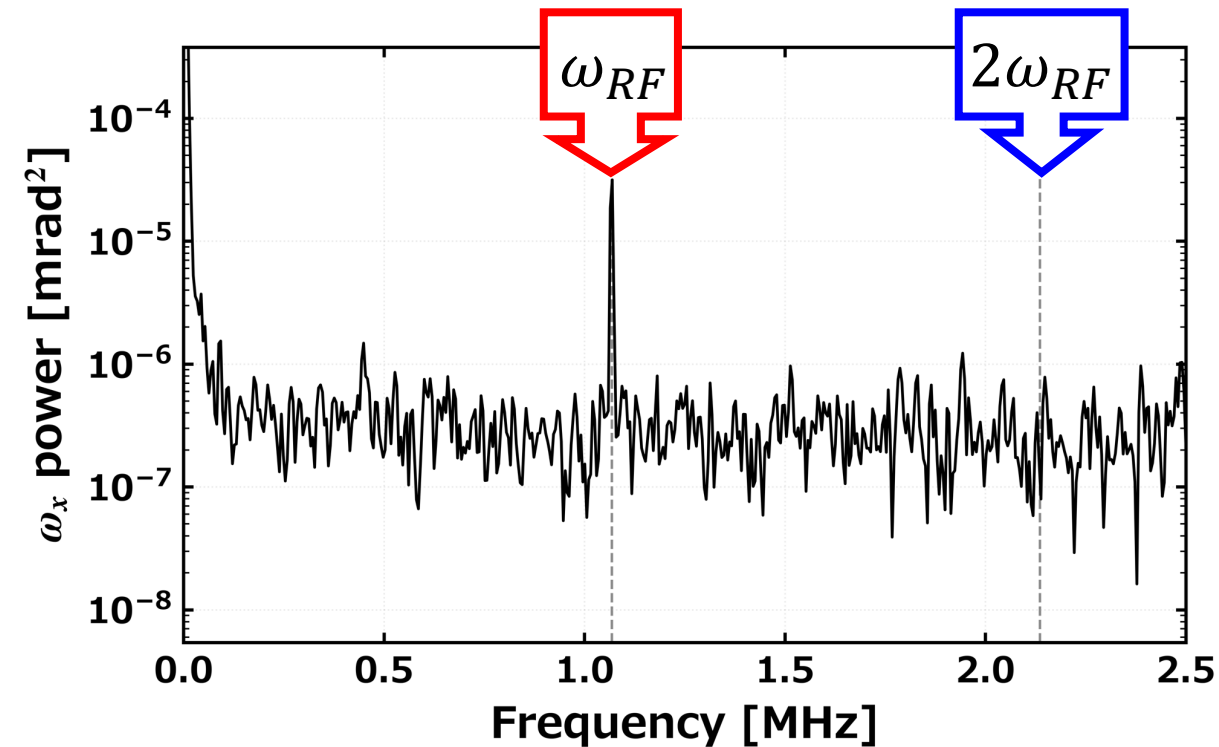
Model 2: Extraction field oscillation model

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Model 3: Direct meniscus response model

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Frequency spectrum of ω (measured)



Model 1 is inconsistent with the experimental result.

Summary

Based on the static beam focusing model, we developed three beam divergence models with RF electric field perturbations corresponding to three elementary processes.

	Elementary process	Consistency with experimental results	
		P_{erv} dependence response	Divergence oscillation period
Model 1	Ion density oscillation	○	×
Model 2	Extraction field oscillation	○	○
Model 3	Direct meniscus response	○	○

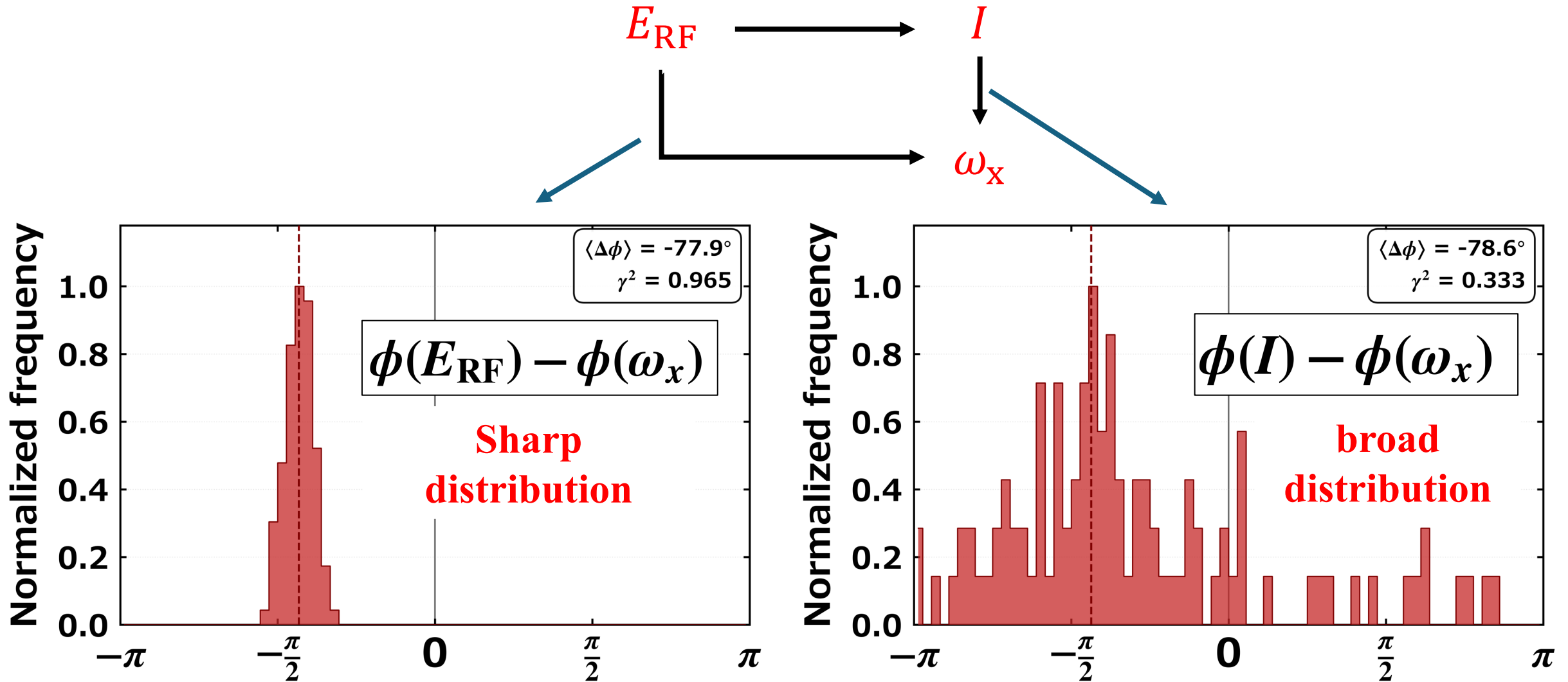
The divergence oscillation may not originate from the ion density oscillation.

Outlook

Compare Model 2 and Model 3 through additional experiments.

Identify the focusing degradation mechanism of the ITER RF negative ion source with the model.

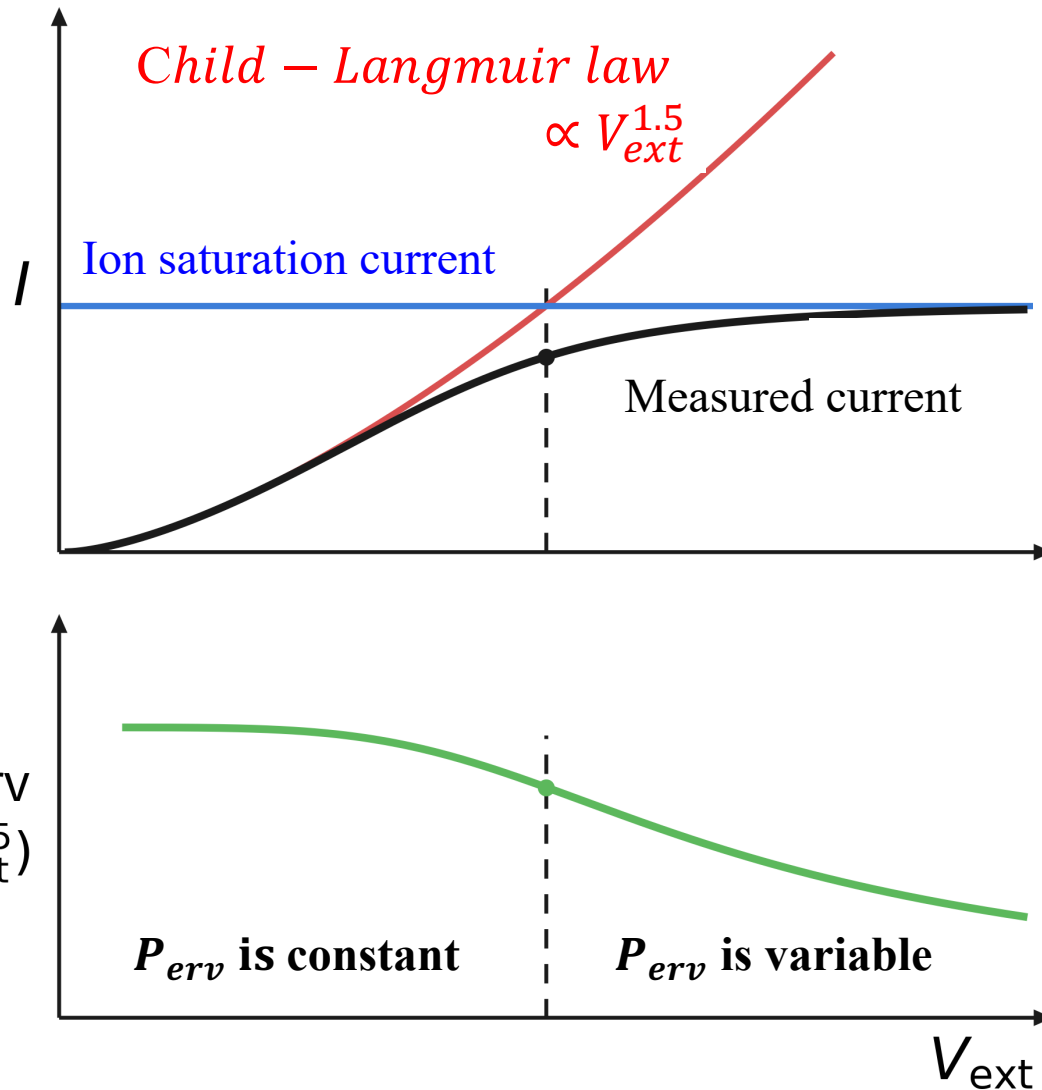
Appendix Page



The ω_x oscillation at ω_{RF} should not predominantly originate through I .

Operating regimes of negative ion sources and Perv

■ Operating regimes of negative ion sources



Low V_{ext} regime ... P_{erv} constant
(space-charge limit dominates $\rightarrow I \propto V_{ext}^{1.5}$)
 $\Rightarrow$ Only model 3 is applicable.

High V_{ext} regime ... P_{erv} variable
(ion saturation current dominates $\rightarrow I \propto n_i$)
 $\Rightarrow$ All models are applicable.

Antenna

Rogosky-type RF antenna.

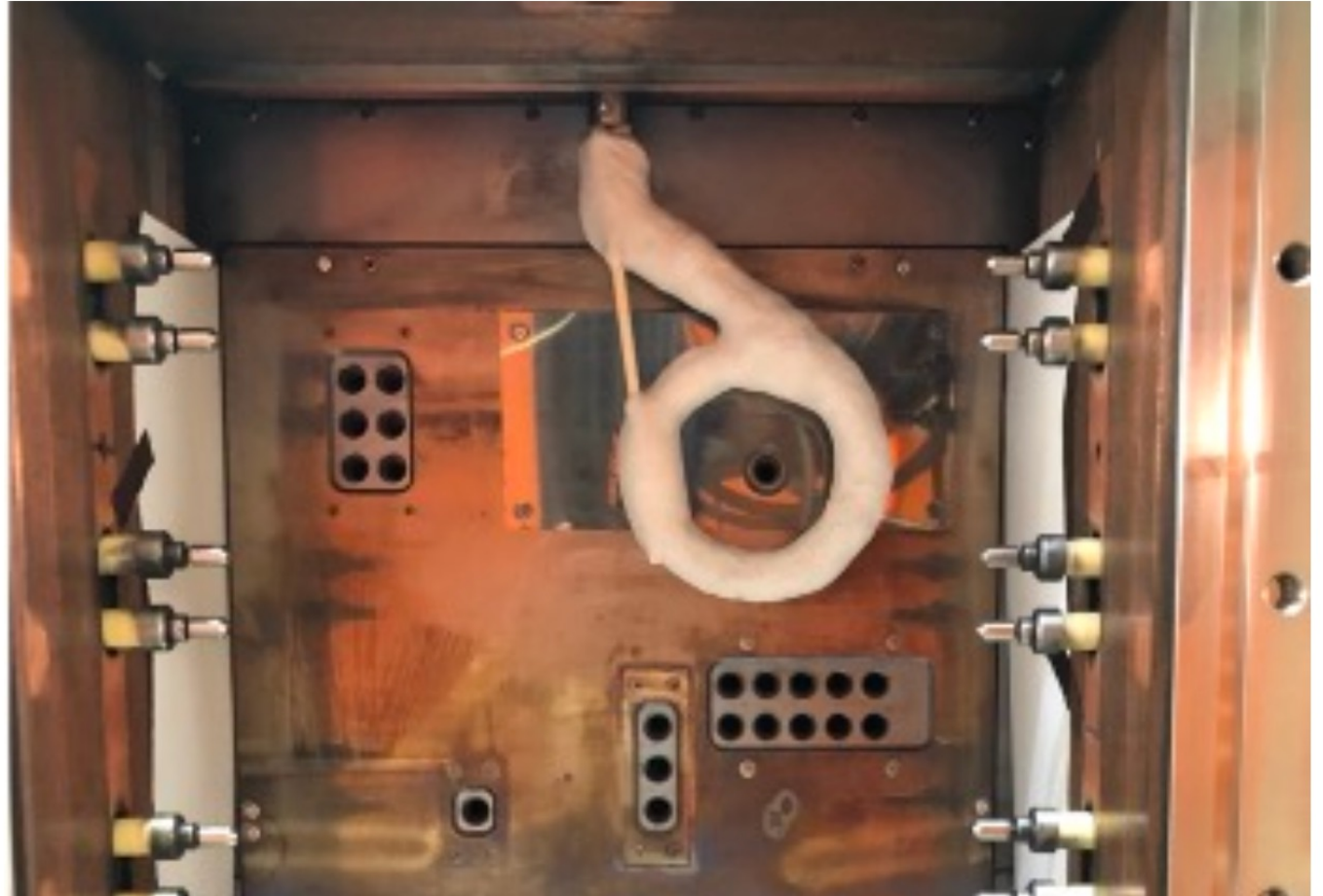
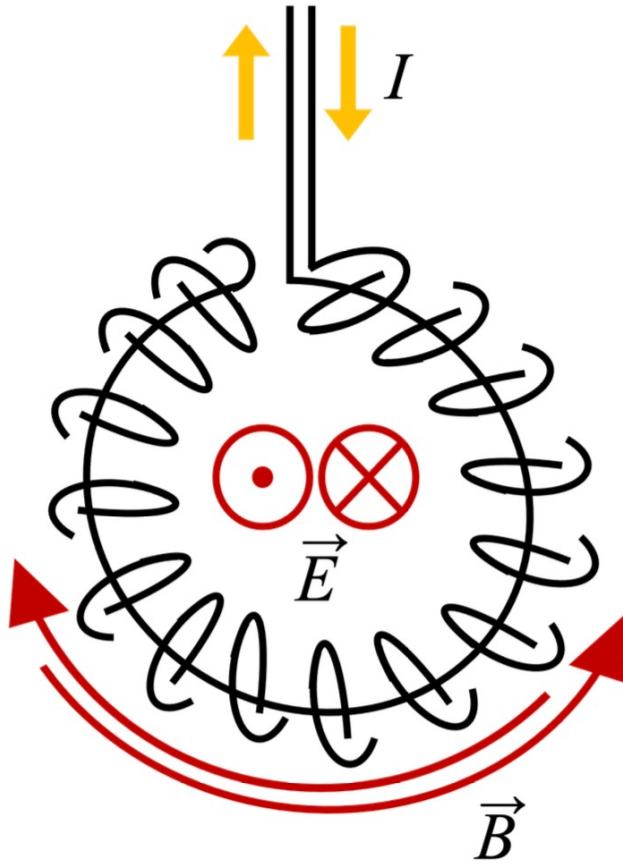


図 4.5: RF アンテナ概略図

Relationship between ω_x oscillation and value increasing

