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# Effect of Electro-Negativity on Beam Extraction in Negative Hydrogen Ion Sources

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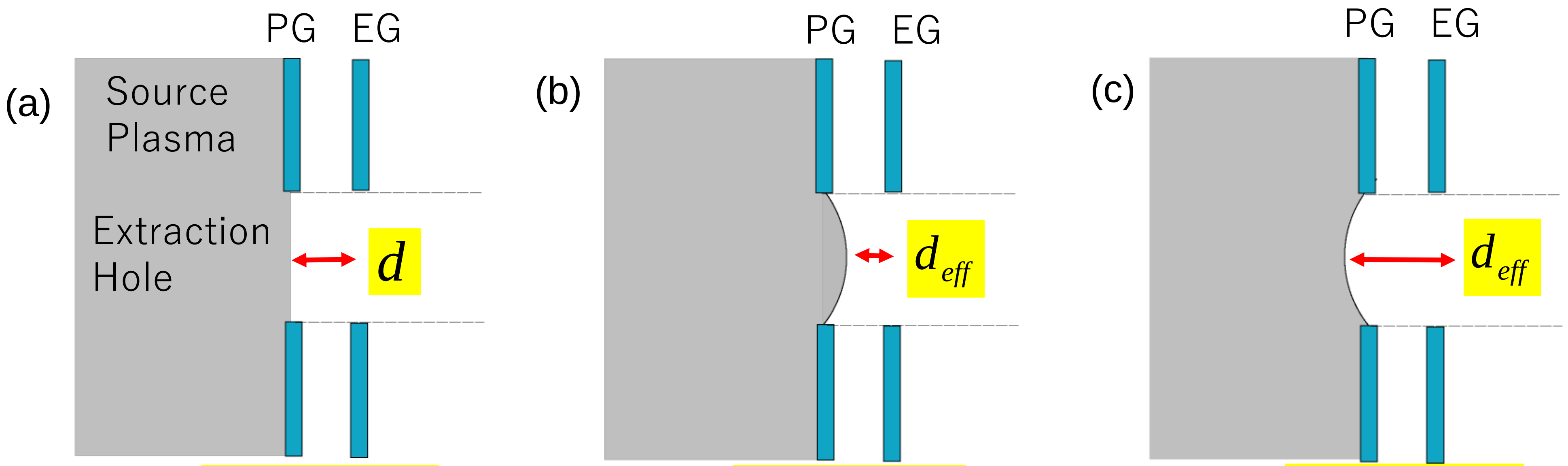
# Introduction

**Control** of **effective distance $d_{eff}$ between** the Plasma Grid (**PG**) and the Extraction Grid (**EG**)
(or equivalently **the position of the plasma meniscus**)
is very **important** to obtain **good beam quality**

$d$ : geometrical distance between the PG and the EG




$d_{eff} = d$ $d_{eff} < d$ $d_{eff} > d$

**Plasma meniscus : flat**

**Extracted beams** :
Parallel beam
**Perveance Matching**

**Plasma meniscus : Convex 凸**
comes out towards the EG

**Extracted beams** : **diverged**

**Plasma meniscus : Concave 凹**
penetrates into the source region

**Extracted beams** : converged but **over focused**

# Introduction

**Parameter dependence** of the **effective distance $d_{eff}$ between PG** and **EG**
(or equivalently **the position of the plasma meniscus**)

**What are the key parameters to determine/control $d_{eff}$?**
**How $d_{eff}$ depends on these key parameters ?**
**How to control the plasma meniscus ?**

For **ordinary plasmas** with **only positive ions** and **electrons**: well-known simple theory tells us:

(1) $$d_{eff} = \left[ \left( \frac{4\varepsilon_0}{9} \right) \left( \frac{2e}{M_i} \right) \frac{V^{3/2}}{j_s} \right]^{1/2}$$

$V$: extraction voltage
$j_s$: ion saturation current
$M_i$: ion mass

ex. $$d_{eff} \propto \frac{V^{3/4}}{n^{1/2}}$$ (2)

However **plasmas including negative ions** :
**key parameters and dependence are still unclear**

Final purpose of this study is **to make clear**
**key parameters and**
**dependence of $d_{eff}$ on these key parameters**

# 3D PIC Model (Model Geometry and PIC Basic Eqs.)

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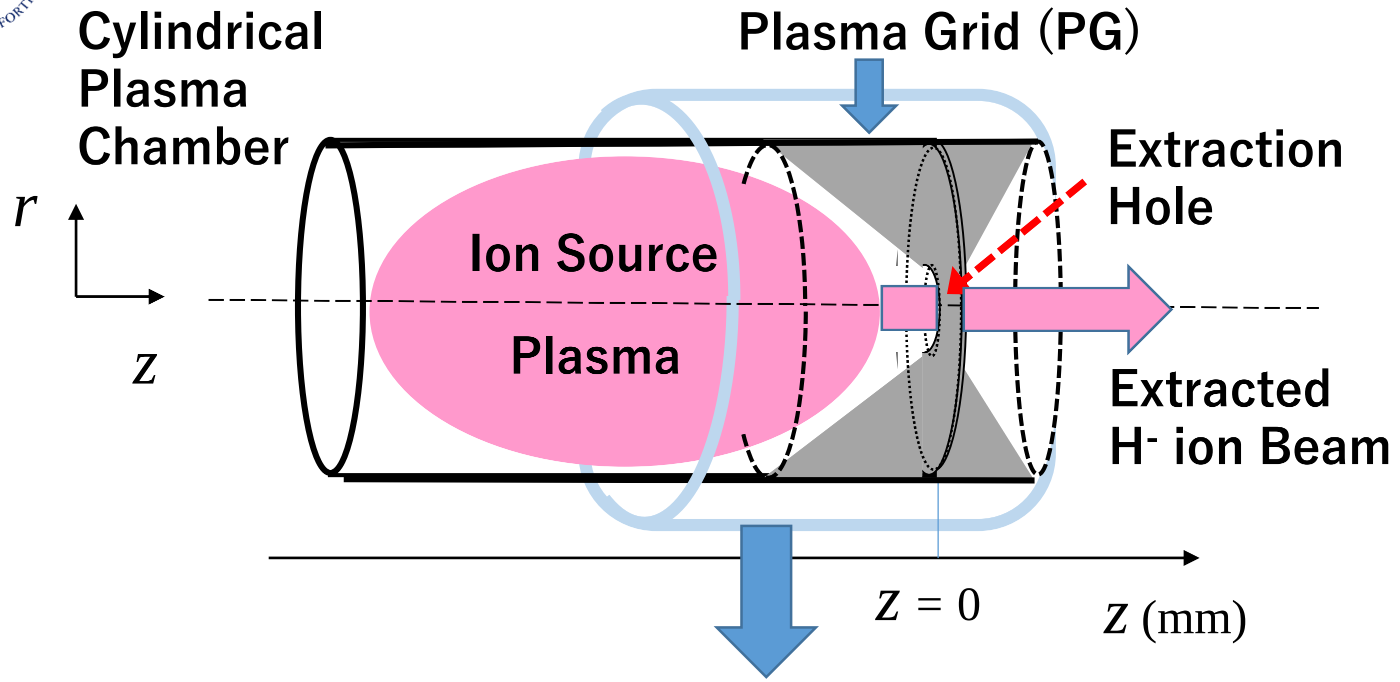
**Model Geometry**




Numerical Domain of 3D PIC simulation for a Hydrogen Negative Ion Source


[1] S. Nishioka, et al., J.Appl.Phys. **119,** 023302(2016).
[2] M. Lyndqvist, et al., J.Appl.Phys. **126**, 123303(2019).


**3D Electrostatic PIC Basic Eqs.**

**Eq. of Motion**

$$m_j \frac{d\mathbf{v}_j}{dt} = e_j\left[\mathbf{E} + (\mathbf{v}_j \times \mathbf{B})\right] \quad (3)$$

+ Monte-Carlo Collision

$(j = \mathrm{H}^+, \mathrm{H}^-, \text{electron})$

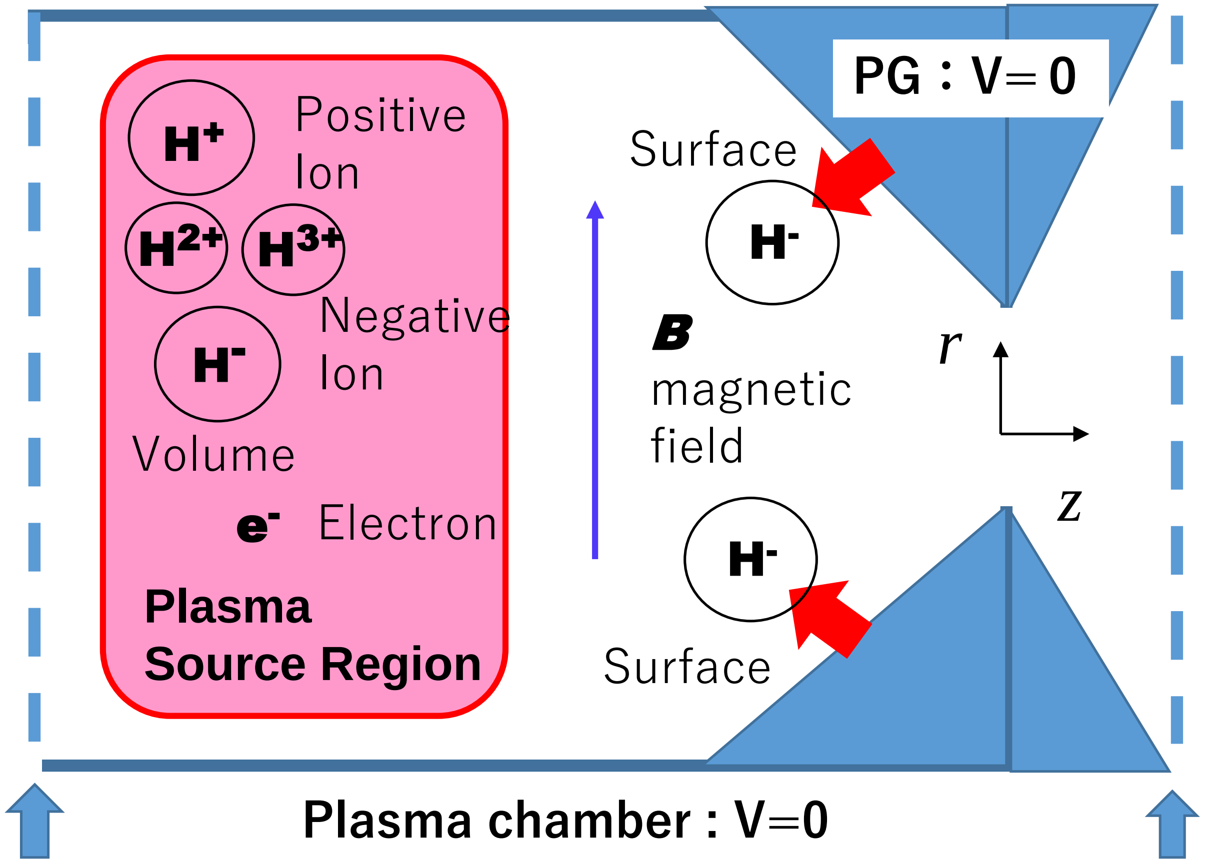
**Poisson's Eq.**

$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \quad (4)$$

$$\rho = \sum_j e_j n_j$$

# 3D PIC Model (Model Geometry and PIC Basic Eqs.)

## Cross Sectional View of 3D PIC Numerical Domain




**Up-stream side Boundary : V=0**

**EG-side Calculation Boundary : V=7 KV**

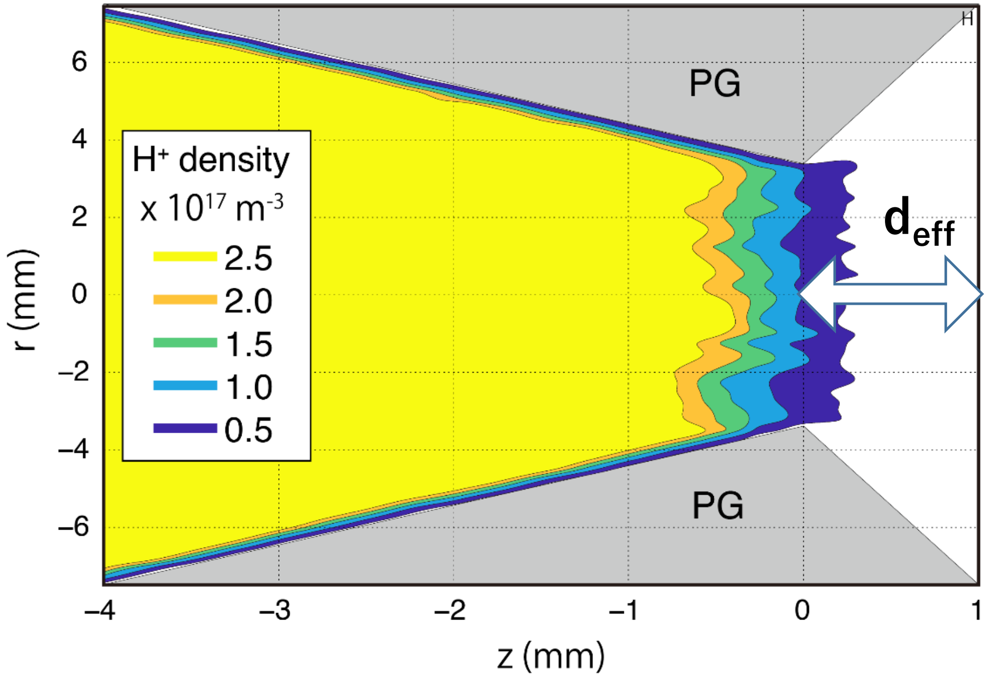
Basic Input Parameters
for **Plasma Source Region**

| Parameters | Values used for PIC simulation |
|---|---|
| Plasma Density | $1.0 \times 10^{18}\ m^{-3}$ |
| Electron Temperature | 3.6 eV |
| $H^+$ and $H^-$ Ion Temperature | 1.6 eV |
| $e^-$ : $H^+$ : $H^{2+}$ : $H^{3+}$ : $H^-$ | 59.9 : 45 : 4.5 : 11.3 : 0.9 |

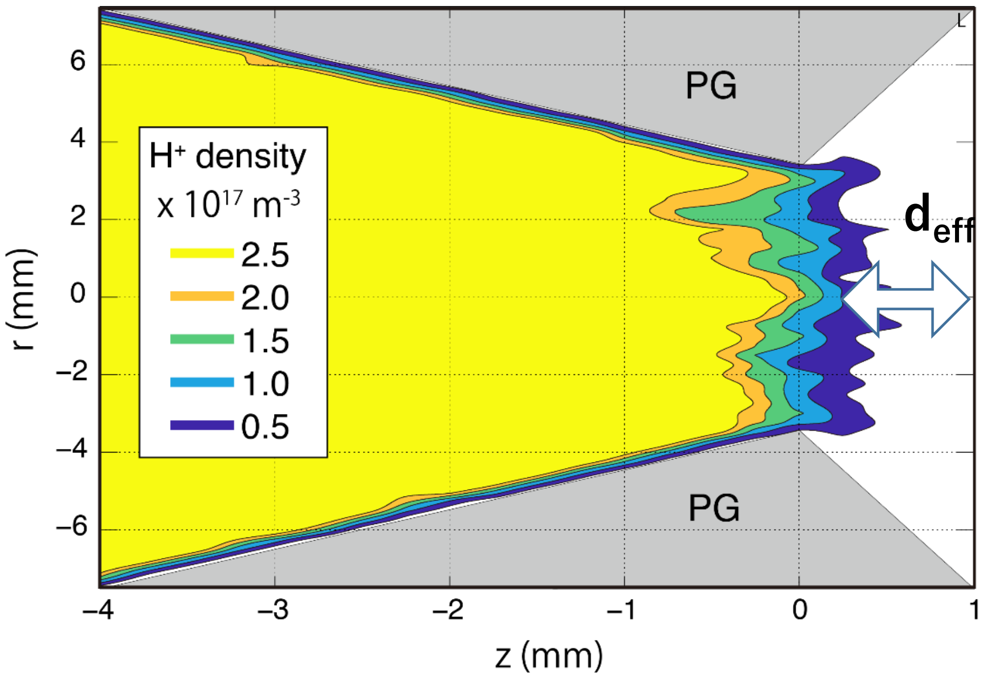
- Surface production rate is changed to study effects of the H- density.
- Plasma density at the sheath entrance is kept as almost the constant.

# Result 1 : Comparison of $n_{H+}$ Density Profile and Plasma Meniscus

Case A : small surface H- production




Case B : large surface H- production




Ordinary Plasma without $H^-$ ions → effective distance $d_{eff} \propto V^{3/4} / n^{1/2}$

For both cases, the extraction voltage $V$ and plasma density at the sheath edge $n$ are kept the same: $V = 7\text{kV}, \quad n = 0.75 \times 10^{18} \text{m}^{-3}$

However, plasma with H- ions →

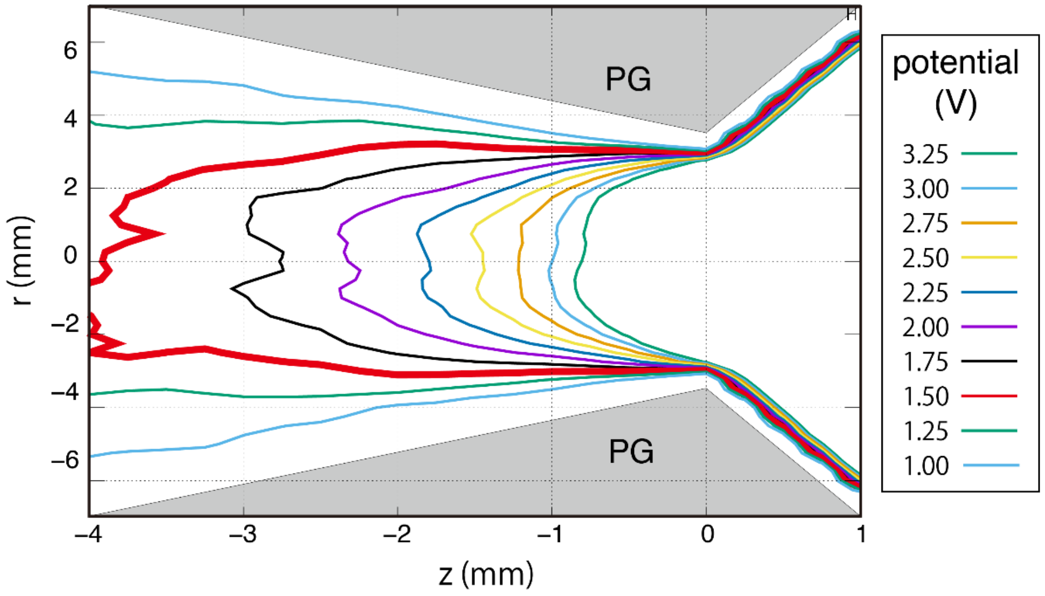
$d_{eff}$ : larger with small surface $H^-$ production (Case A)

$d_{eff}$ : smaller with large surface $H_-$ production (Case B)

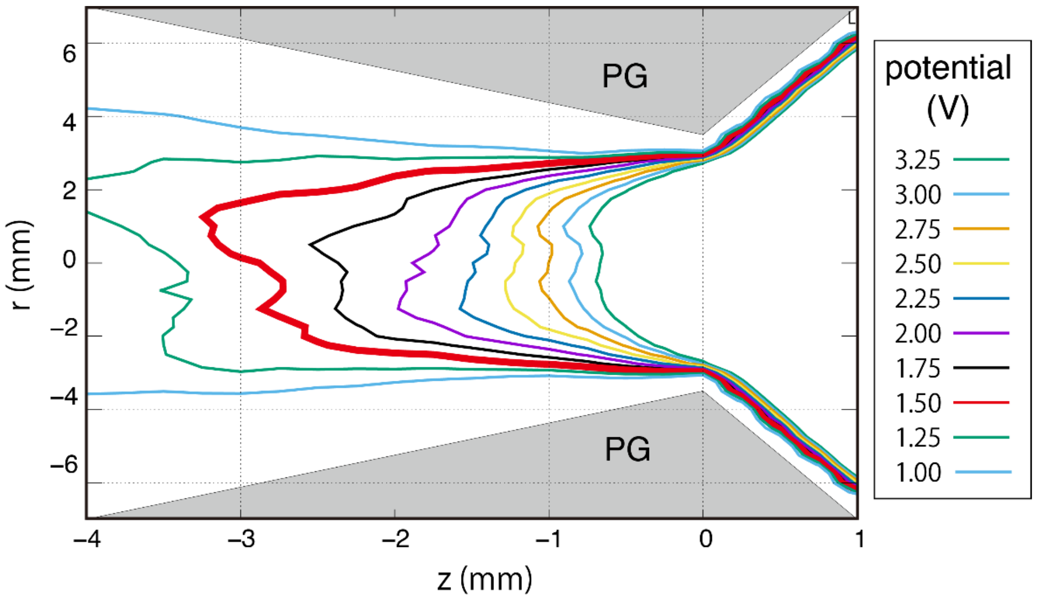
# Result 2 : 2D Profile of Potential near the Extraction Hole

## Equi-contour of Electric Potential near the Extraction Hole

**Case A** : small surface H- production




**Case B** : large surface H- production



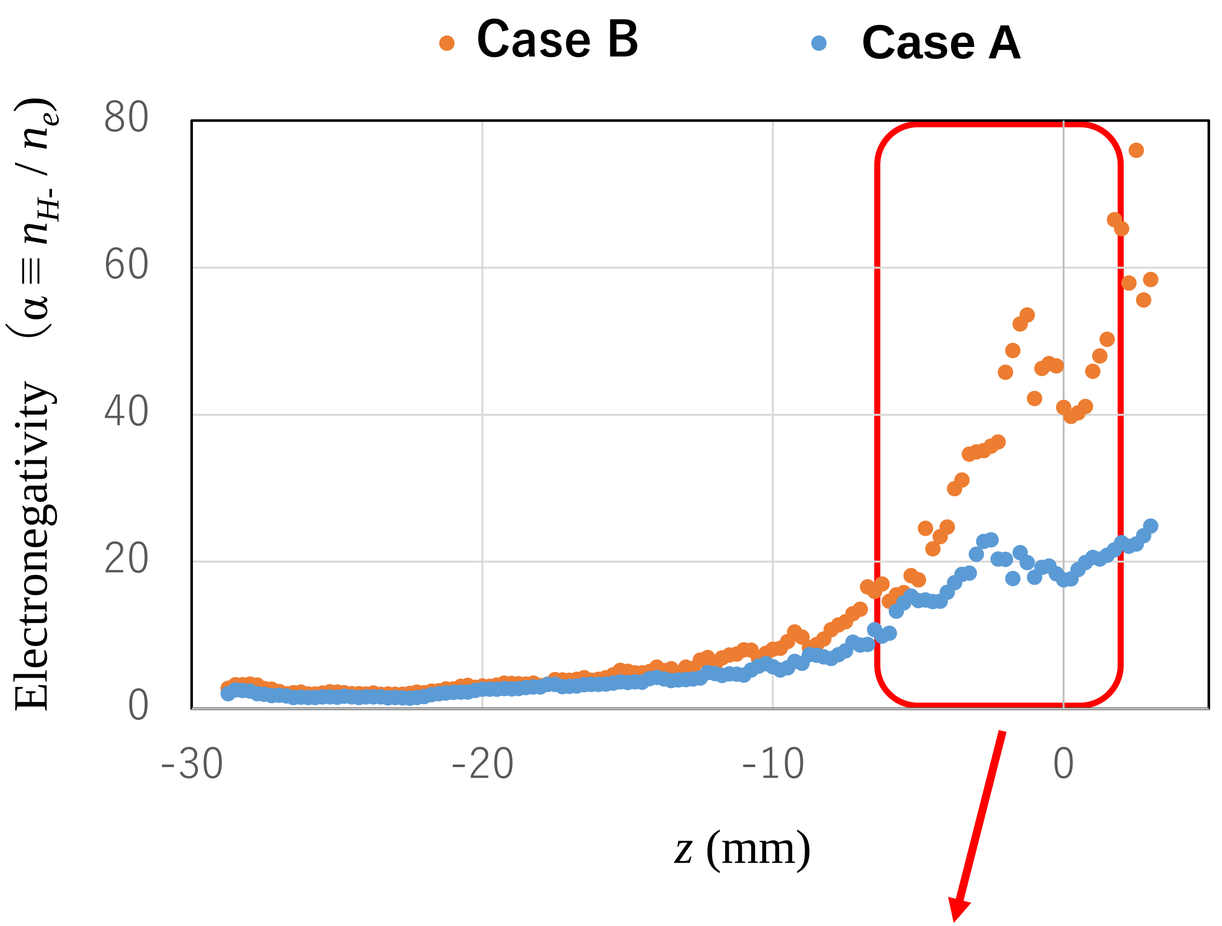

Ordinary Plasma **without $H^-$ ions** ➡ effective distance $d_{eff} \propto V^{3/4} / n^{1/2}$

**For both cases, the extraction voltage $V$ and plasma density at the sheath edge $n$ are kept the same:** $V = 7\text{kV}, \quad n = 0.75 \times 10^{18}\text{m}^{-3}$

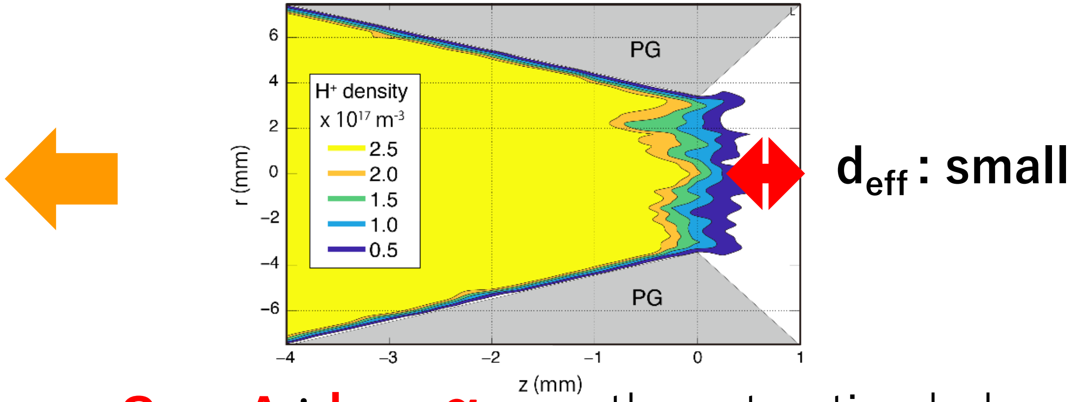
**However, plasma with H- ions** ➡
- $d_{eff}$ : **larger** with smaller surface $H^-$ production (**Case A**)
- $d_{eff}$ : **smaller** with larger surface $H_-$ production (**Case B**)

Why **? What is the key parameter for the effective distance $d_{eff}$** ?

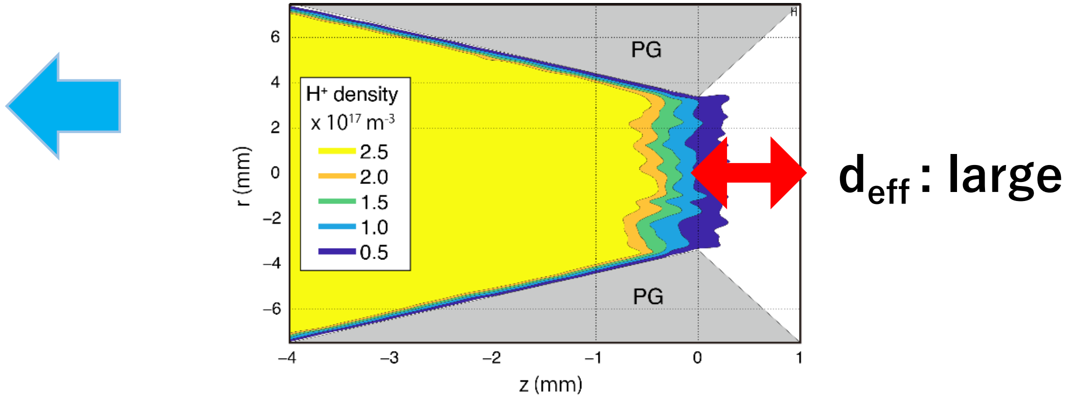
# Result 3 : Spatial Profile of Electro-negativity $(\alpha \equiv n_{H-} / n_e)$




Case B：High α near the extraction hole




Case A：Low α near the extraction hole




**Electro-negativity α : case A → low case B → high**

**deff with surface H- production is largely depends on Electro-negativity α neat the PG.**

# Modeling of NIFS R&D $H^-$ source by K. Miyamoto, *et al.*(Poster #17)

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## Main Plasma Parameters for 3D PIC simulation

| Parameters | Values used for PIC simulation |
|---|---|
| Electron Density | $1.8 \times 10^{17}$ m$^{-3}$ |
| Electron Temperature | 0.8 eV |
| **$H^+$** Ion Temperature | 0.3 eV |
| **$H^-$** Ion Temperature | a. 0.1 eV（Volume Produced $H^-$）<br>b. 1 eV / 0.25 eV<br>（Surface Produced $H^-$,<br>Initial Energy/Temperature） |
| **$H_2$** molecular density | $1.88 \times 10^{19}$ m$^{-3}$<br>（equivalently 0.3 Pa） |
| **$H_2$** molecular Temperature | 0.1 eV |
| **H** atom Temperature | 0.3 eV |
| **H/$H_2$** Density Ratio | 0.5 |

**Systematic 3D PIC modeling** of **$H^-$ extraction** for the **NIFS R&D $H^-$ source**

Detailed Information
ex. **Model Geometry** of
**Plasma Chamber**
**PG** (Plasma Grid)
**EG** (Extraction Grid)
**AG** (Acceleration Grid)
→ **Poster Presentation**

**Poster #17 K.Miyamoto et al.:**

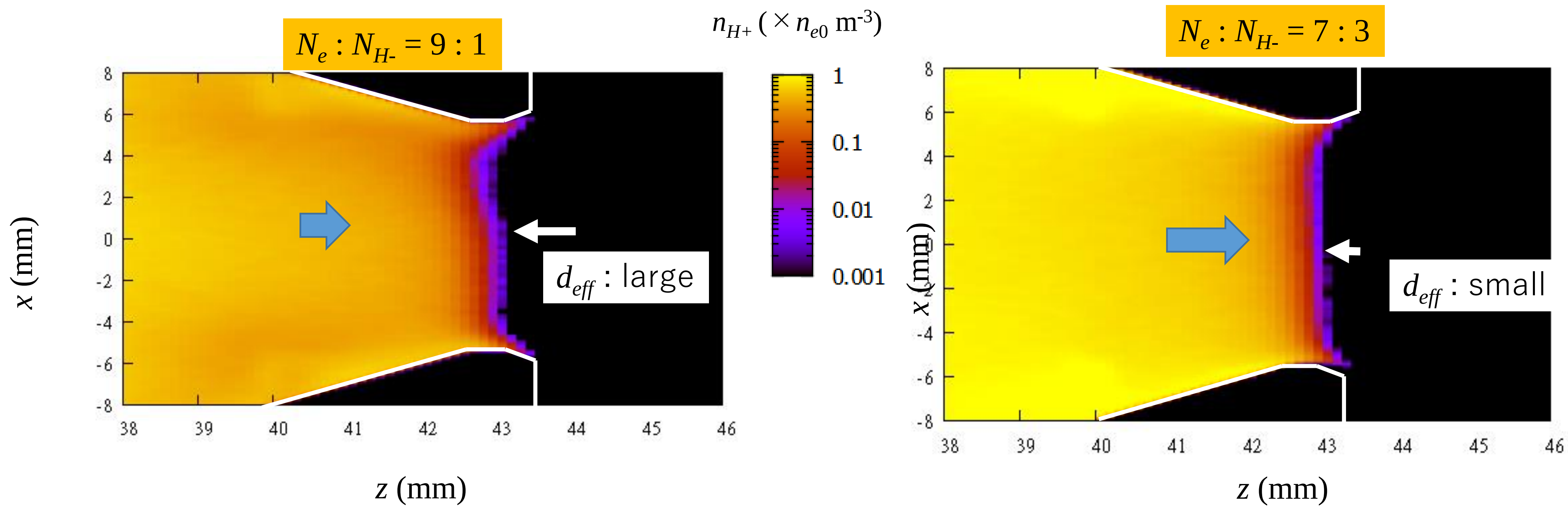
**" Study of negative ion beam emittance Characteristics using PIC-MCC simulation"**

# Modeling of NIFS R&D $H^-$ source by K. Miyamoto, *et al.*

## Spatial Profile of $H^+$ Ion Density $n_{H+}$ near the Extraction Hole
## (with **Volume** and **Surface** $H^-$ production)

**Case A**：**Low α** near the extraction hole

**Case B**：**High α** near the extraction hole




In **Case B**, i.e, in **High-α case**,

**plasma meniscus** is more **pushed towards outside**, **i.e. towards the EG**.

**Position and shape** of the **plasma meniscus largely depends** on **Electro-negativity α** neat the PG.

# Modeling of NIFS R&D $H^-$ source by K. Miyamoto, *et al.*

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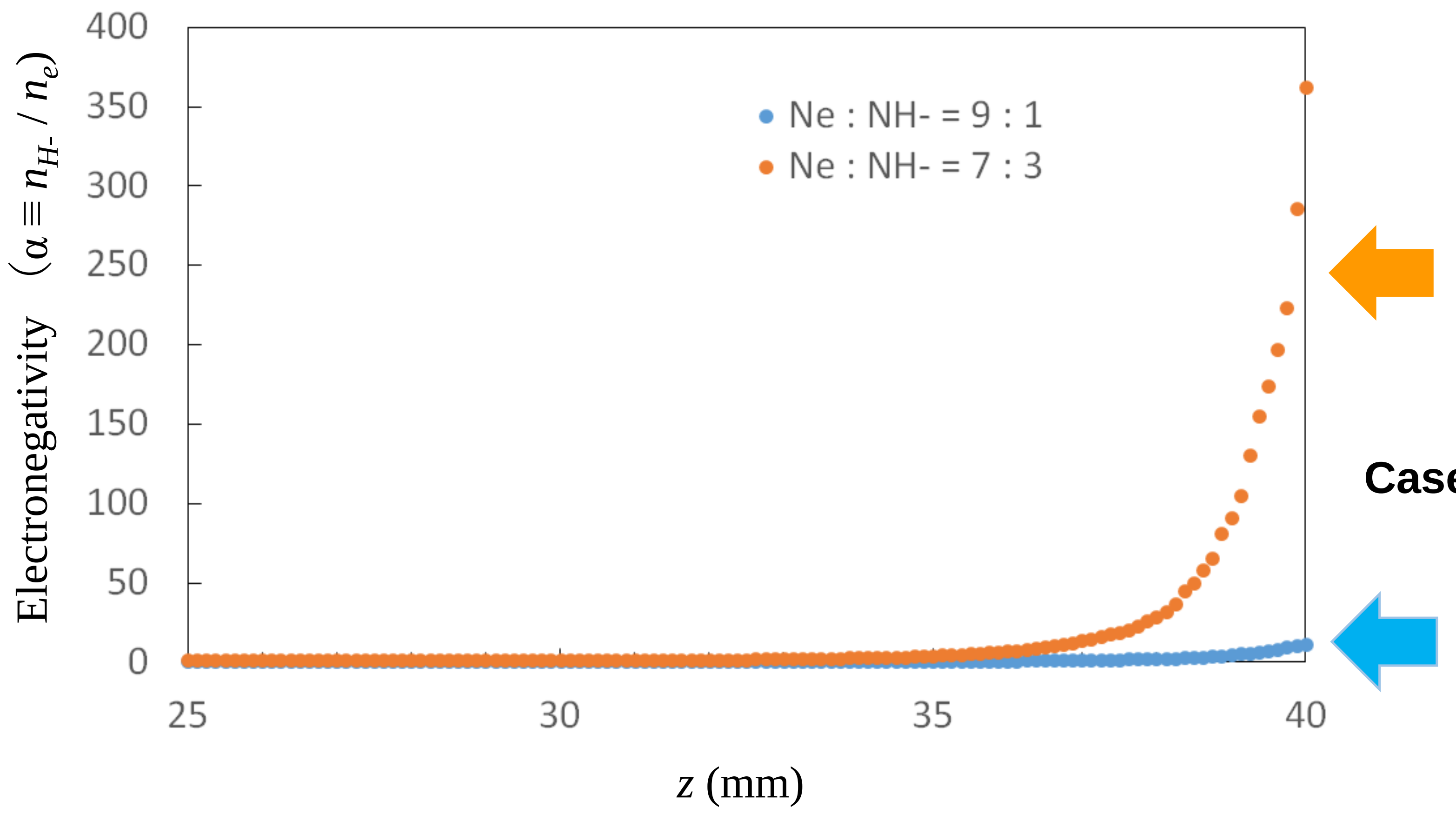
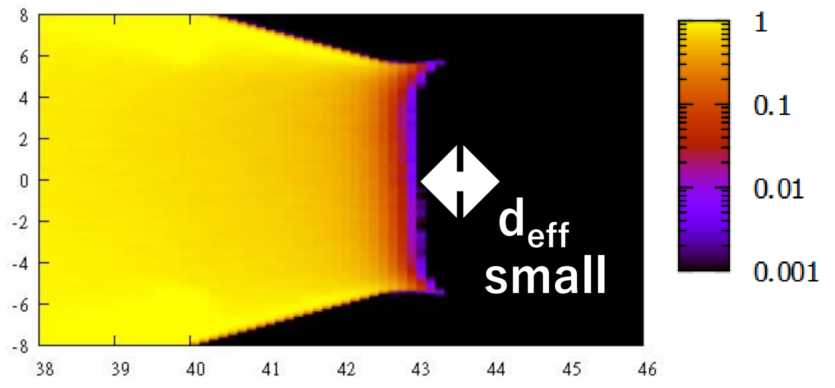
## 1D Spatial Profile of Electro-negativity ($\alpha \equiv n_{H^-} / n_e$) along the *z*-axis

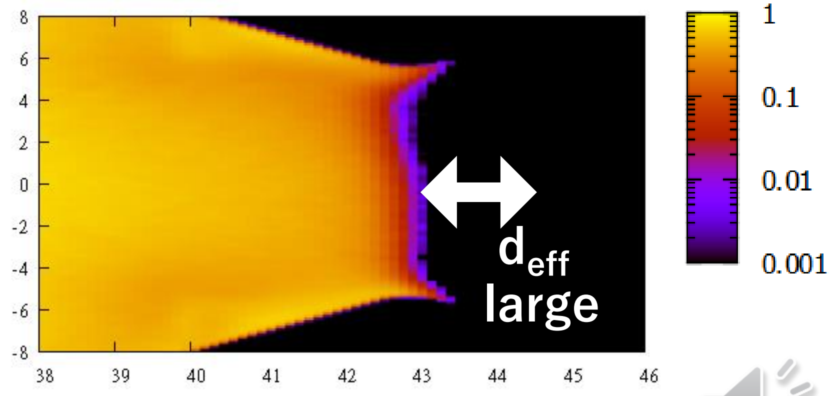
(with **Volume** and **Surface** $H^-$ production)




**Case B：High α** near the extraction hole



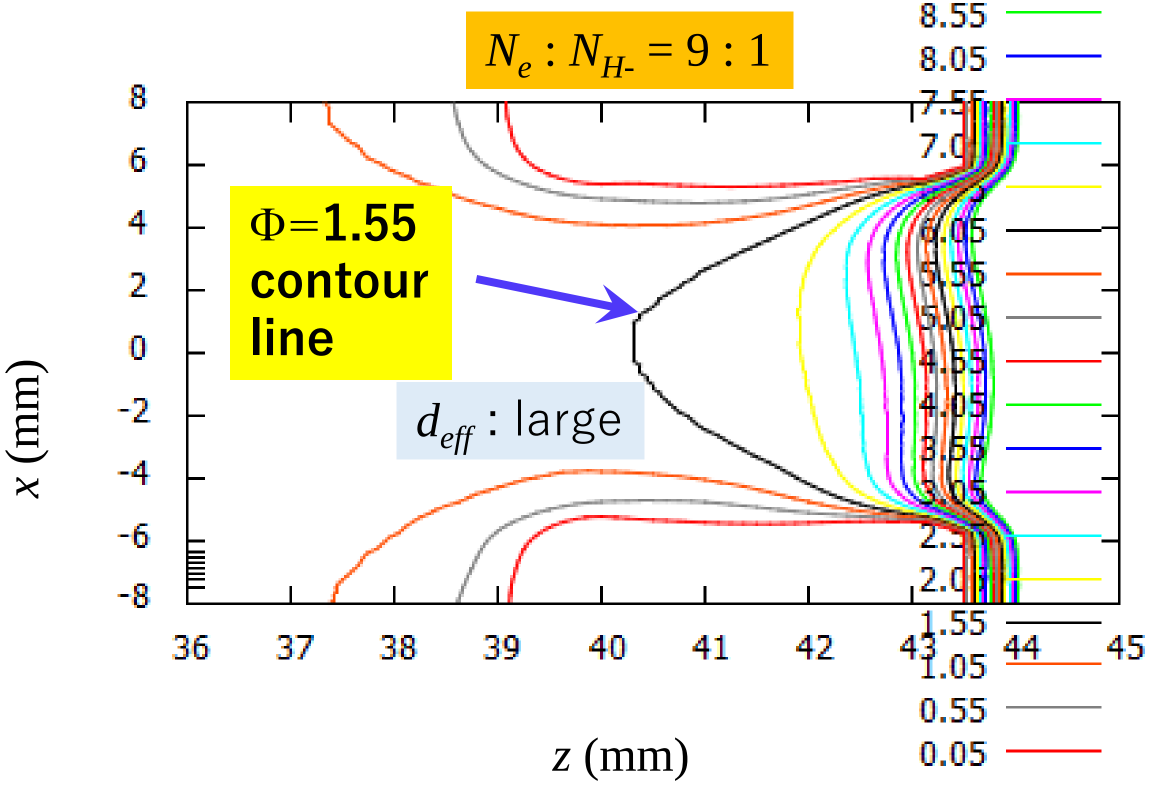

**Case A：Low α** near the extraction hole



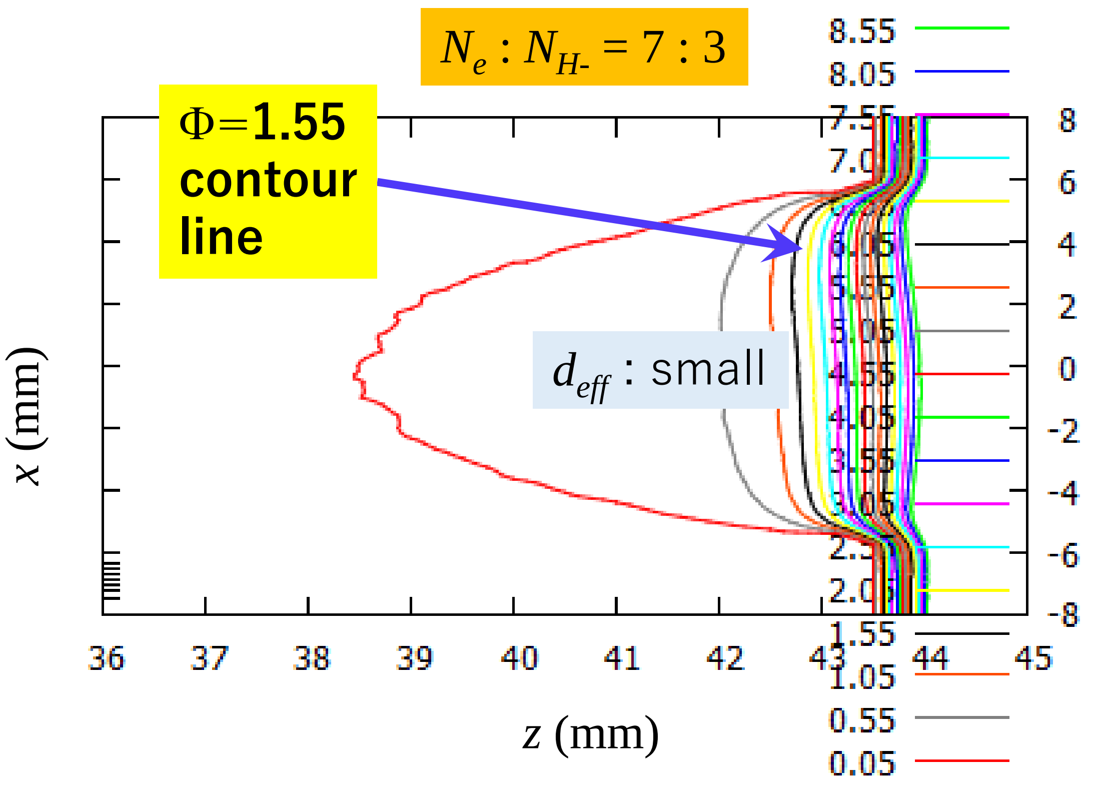
# Modeling of NIFS R&D $H^-$ source by K. Miyamoto, *et al.*

## Equi-contour lines of Electric Potential near the Extraction Hole
## (with **Volume** and **Surface** $H^-$ production)

**Case A：Low α** near the extraction hole




**Case B：High α** near the extraction hole




In **Case A**, i.e, in **Low-α case**, **EG voltage** penetrates **more deeply into** the plasma **source region,** while, in **Case B**, **EG voltage** is **well shielded,** and **not so deeply penetrates into source region.**

**Electro-negativity α** near the PG is a **very important parameter** to **control the plasma meniscus**.

# Comparison with Simple Analytic Theory (by .K.Miyamoto)

**Inside the source**
=> Current through the sheath
$J_{sat} = J_e + J_{H-}$
**(ion saturation current)**
*including effects of $H^-$ ions

$J_{sat} = J^{ext}$

current continuity

**Outside the source**
(between the PG and EG)
=> Total Extracted Current
$J^{ext} = J_e^{ext} + J_{H-}^{ext}$
**(Child-Langmuir current)**

Effective distance $d_{eff}$ between the PG and the EG ($J_{sat}=J^{ext}$)

$$d_{eff} \propto \frac{1}{n_{i0}^{1/2}} \left( \frac{M_i}{m_e} \right)^{1/4} \left( \frac{1}{1+\alpha} \right)^{1/2} V^{3/4} \quad (3)$$

$M_i$ : ion mass
$m_e$ : electron mass
$n_{i0}$ : H+ ion density $(n_{i0} \sim n_{e0} + n_{H-})$
$V$ : extraction voltage

**electro-negativity**

$$\alpha \equiv \frac{n_{H-}}{n_e}$$

$\alpha \to$ lower $\quad d_{eff} \to$ larger : plasma meniscus **penetrates deeper** into the plasma
$\alpha \to$ higher $\quad d_{eff} \to$ smaller : plasma meniscus **penetrates shallower** into the plasma

**Electro-negativity $\alpha$** near the PG is a **very important parameter** to **control $d_{eff}$ (the plasma meniscus)**.

For the case **with surface H- production**, K.Miyamoto has also derived the **expression** for $d_{eff}$ and also **strongly depends on the electro-negativity** $\alpha$ .

# Summary

Using 3D PIC Simulation (Keio-BFX code) and simple Analytic Theory

**Effects of $H^-$ density** (density ratio of $H^-$ ions and electrons) have been **studied on**

- **Plasma shielding distance** of the extraction voltage into the source plasma
  i.e. **Effective distance between the PG and EG : $d_{eff}$**
- **Plasma meniscus**

- **Ordinary $H^+$- electron plasma** (plasma density : $n = n_i \sim n_e$ )

$$d_{eff} \propto \frac{V^{3/4}}{n^{1/2}}$$

**Plasma with surface produces $H^-$ ions** ( $H^-$ density $n_{H-}$ and $n = n_i \sim n_e + n_{H-}$)

$d_{eff}$ : largely **depends on the ratio $\alpha = n_{H-} / n_e$ around the extraction hole**

$\alpha$ ⇨ low : $d_{eff}$ ⇨ large , while $\alpha$ ⇨ high : $d_{eff}$ ⇨ small

# Summary

- **The same tendency has been obtained by another 3D PIC simulation** (by Miyamoto) for the NIFS H- R&D source

- These **PIC simulation results** are also **supported by** comparison with **simple analytic theory** of the effective distance between the PG and EG (developed by K.Miyamoto)

- These **simulation and theoretical results suggests** :
  - **Control concept of the effective distance** $d_{eff}$ / **meniscus shape** (in other words how to get the perveance matching)

    **in the plasma with $H^-$ ions** is shown to be largely **different from** in the **ordinary plasma without $H^-$ ion**

  - **One** of the **key control parameters** is the electro-negativity (**density ratio $n_{H-}/n_e$ ) around the extraction hole**