Study of plasma meniscus including the surface produced negative ions by using PIC-MCC simulation

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Introduction

It is essential for a **hydrogen negative ion source** to generate the **negative ion beams with good beam optics** as well as with the high current density. For example, a negative ion beamlet with a divergence angle of 3 ~ 7 mrad is required for the negative ion source in the negative ion based NBI for ITER [1, 2].

If the negative ion **beam divergence angle is large**, the negative ion beam will impinge on the acceleration grid and other components during beam acceleration and transport, and then causes **the heat loads, loss of the negative ion beam current, and break down of voltage holding** due to the resultant secondary electrons.

Therefore, the negative ion beam optics has been studied intensively in development of the hydrogen negative ion sources. In general, an **ion beam optics depends on the shape of plasma meniscus**, which is **an ion emitting surface**.

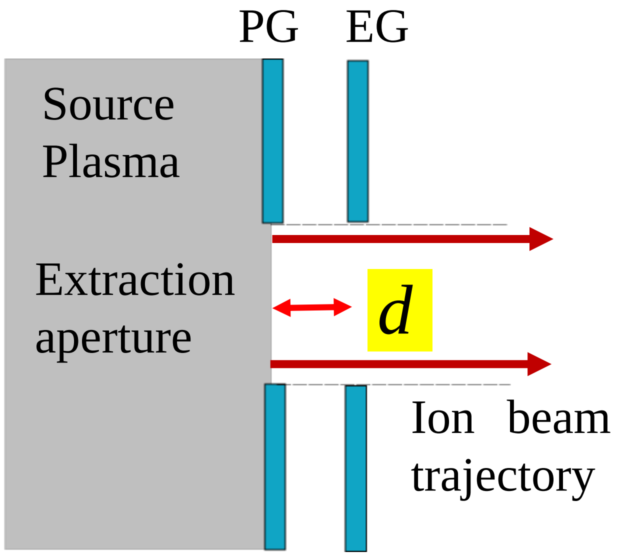
[1] Hemsworth S R, Boilson D, Blatchford P, Palma D M, Chitarin G, Esch de L P H, Geli F, Dremel M, Graceffa J, Marcuzzi D 2017 New J. Phys. **19** 025005.
[2] M. J. Singh, D. Boilson, A. R. Polevoi, T. Oikawa, and R. Mitteau 2017 New J. Phys. **19** 055004.

Relation between shape of plasma meniscus and ion beam optics

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 PG and EG

Optimum plasma density



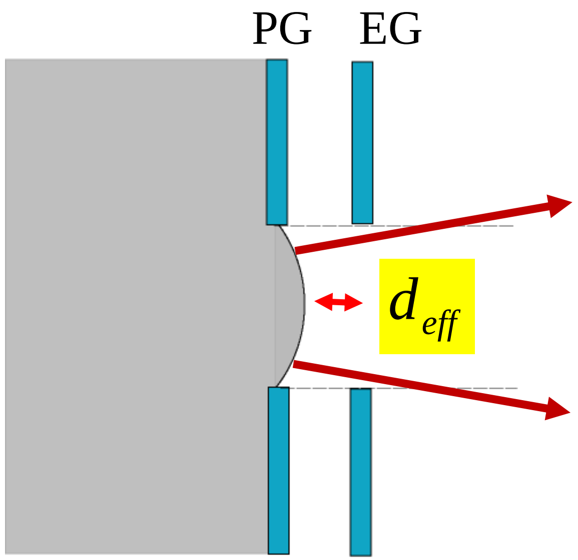
$d_{eff} = d$

Plasma meniscus：flat

Extracted ion beam：parallel

Optimum perveance

High plasma density

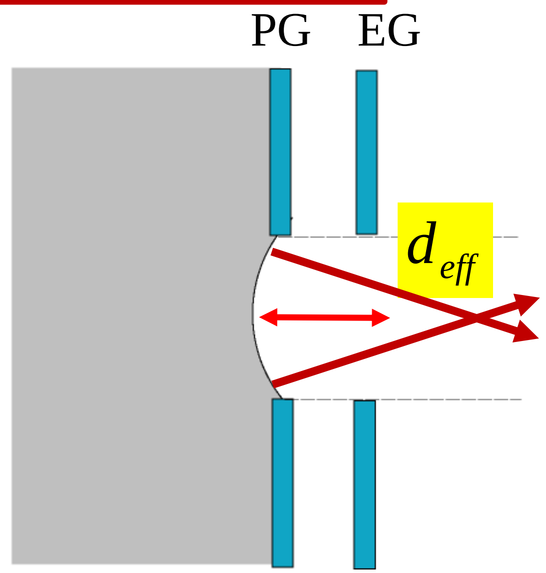


$d_{eff} < d$

Plasma meniscus : Convex 凸
comes out towards the EG

Extracted beams : diverged

Low plasma density



$d_{eff} > d$

Plasma meniscus : Concave 凹
penetrates into the source region

Extracted beams : over-focused

- **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 single positive ions and electrons: well-known simple theory tells us:

$$\mathrm{d_{eff}} = \frac{2^{5/4}}{3} \exp\left(\frac{1}{4}\right) \left(\frac{\varepsilon_0}{e}\right)^{1/2} n_{\mathrm{p}}^{-1/2} \left(\frac{kT_{\mathrm{e}}}{e}\right)^{-1/4} V_{ext}^{3/4}$$

M : mass of a positive ion
n_p: plasma density
T_e : electron temperature
V_{ext} : extraction voltage

However, for the electronegative plasma including the surface produced H^- ions in the negative ion sources, the key parameters to control the plasma meniscus and the dependence on these parameters are still unclear.

↓

In this study, the plasma meniscus and relevant physical structure such as the sheath in the electronegative plasma including the surface produced H^- ions was investigated by using both analytical theory and 3D PIC-MCC simulation.

Analytic theory of the effective distance d_{eff} including surface produced H^- ions

Inside the source plasma
=> Current through the sheath
$J_{sat} = J_e + J_{H-}$
(Saturation current)

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

Current continuity

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

Effective distance $\mathbf{d_{eff}}$ between the plasma meniscus and the EG ($J_{sat}=J^{ext}$)

$$d_{\mathrm{eff}} \propto \left(\frac{M_{\mathrm{i}}}{m_{\mathrm{e}}}\right)^{1/4}\left(1+\frac{\sqrt{\frac{M_{\mathrm{n}}}{m_{\mathrm{e}}}}}{\alpha}\right)^{1/2} n_{\mathrm{i0}}^{-1/2} V_{\mathrm{ext}}^{3/4}$$

m_e : mass of electron
M_i : mass of H^+ ion
M_n : mass of H^- ion
n_{i0}: H^+ ion density at the sheath edge
V_{ext} : extraction voltage

Electro-negativity

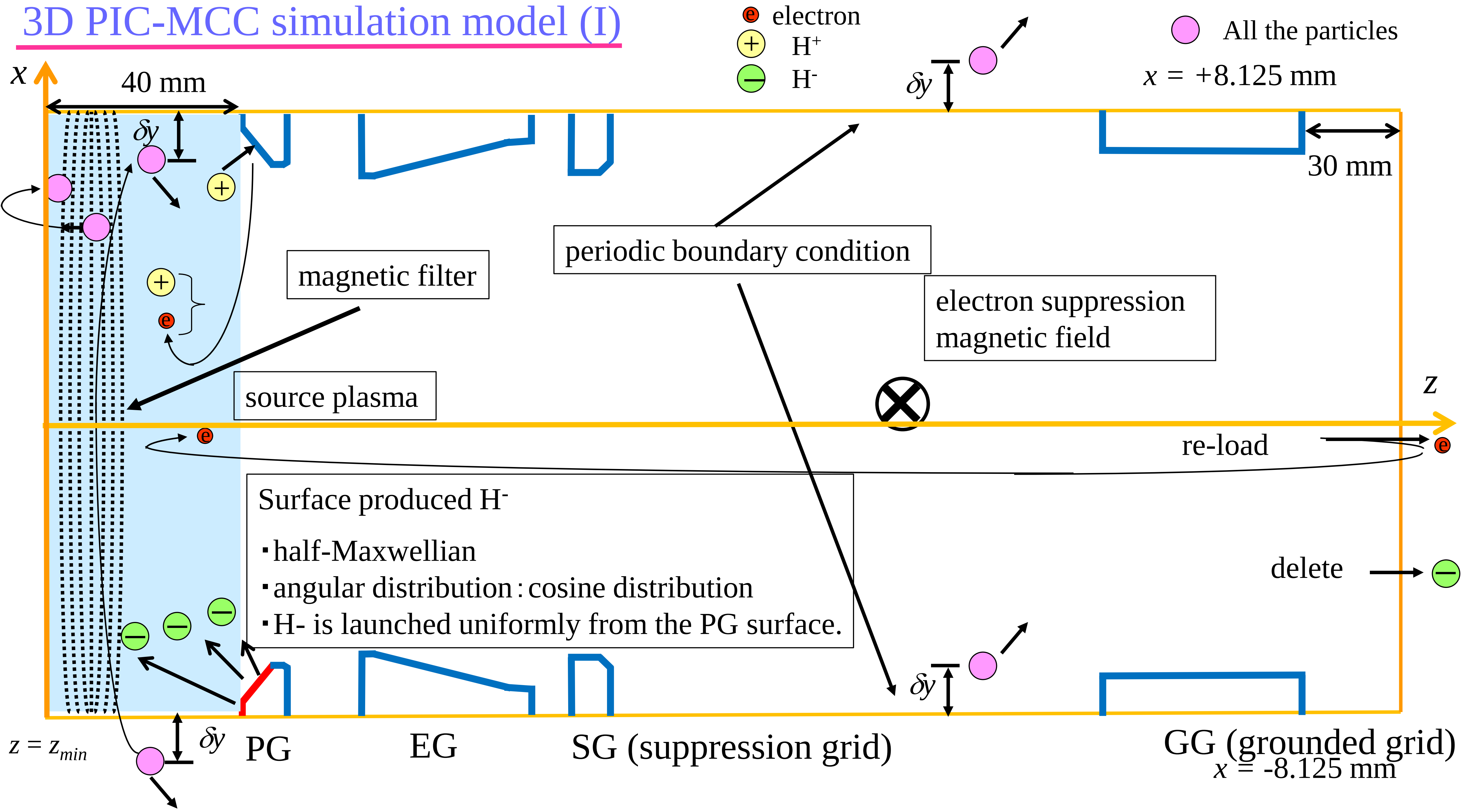
$$\alpha \equiv \frac{n_{\mathrm{H-}}}{n_{\mathrm{e}}}$$

α lower → d_{eff} larger : plasma meniscus **penetrates deeper** into the plasma

α higher → d_{eff} smaller : plasma meniscus **penetrates shallower** into the plasma

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

3D PIC-MCC simulation model (I)



3D PIC-MCC simulation model (II)

Physical parameter	**Value**
Electron temperature	1 eV
Hydrogen ion temperature	0.3 eV （H^+） 0.1 eV（volume produced H^-） 1 eV（surface produced H^-）
Electron density	1.8×10^{17} m^{-3}
Hydrogen atom temperature	0.3 eV
Hydrogen molecule temperature	0.1 eV
Hydrogen molecular density	1.88×10^{19} m^{-3} (at 0.3 Pa)
Density ratio n_H/n_{H2}	0.5

In order to investigate the effect of electro-negativity ($\alpha \equiv n_{H-}/n_e$) on the effective distance d_{eff}, the following numbers of the surface produced H^- ion super-particles per timestep were surveyed:

Number of H- particles / time step / process	**Surface produced H^- ion flux from PG (A/m^2)**
20	39
60	146
100	255

3D PIC-MCC simulation model (III)

・The following collisions related to the H^- ions are taken into account:

Coulomb collision : H^- ─ H^+, H^- ─ H^-

Charge exchange collision : H^- (fast)+ H(slow) → H^- (slow)+ H(fast)

Elastic collision : H^- ─ H, H^- ─ H_2

Mutual neutralization : $H^+ + H^- \rightarrow H + H$

Other simulation conditions

・Initial super-particle numbers :
Electron (8.715×10^7), H^+ ion (1.245×10^8), H^- ion (3.735×10^7)

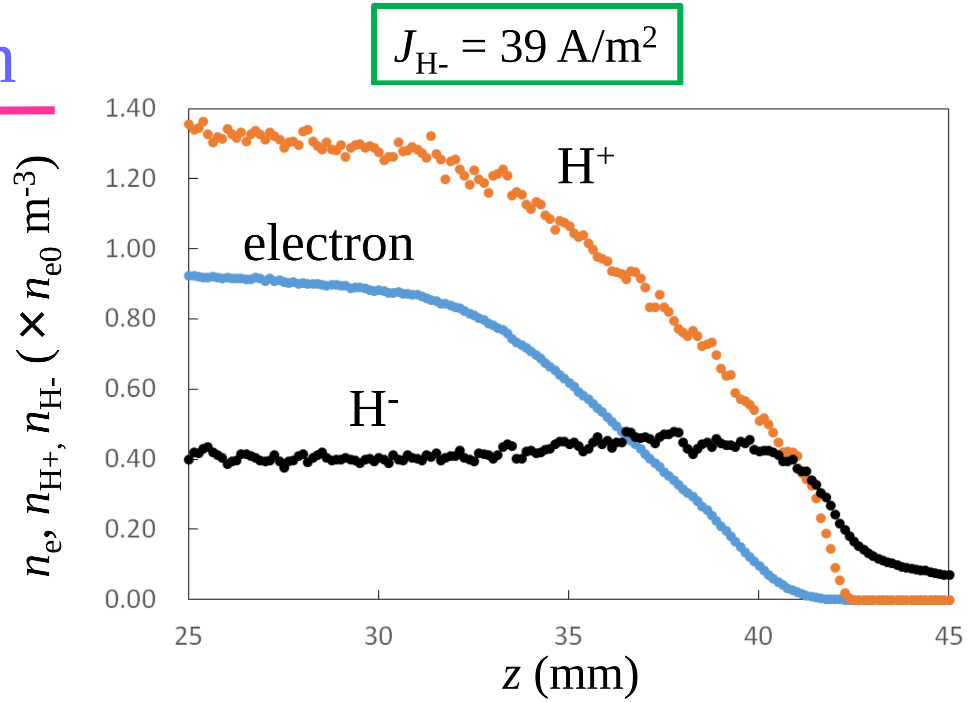
10 particles per mesh in average

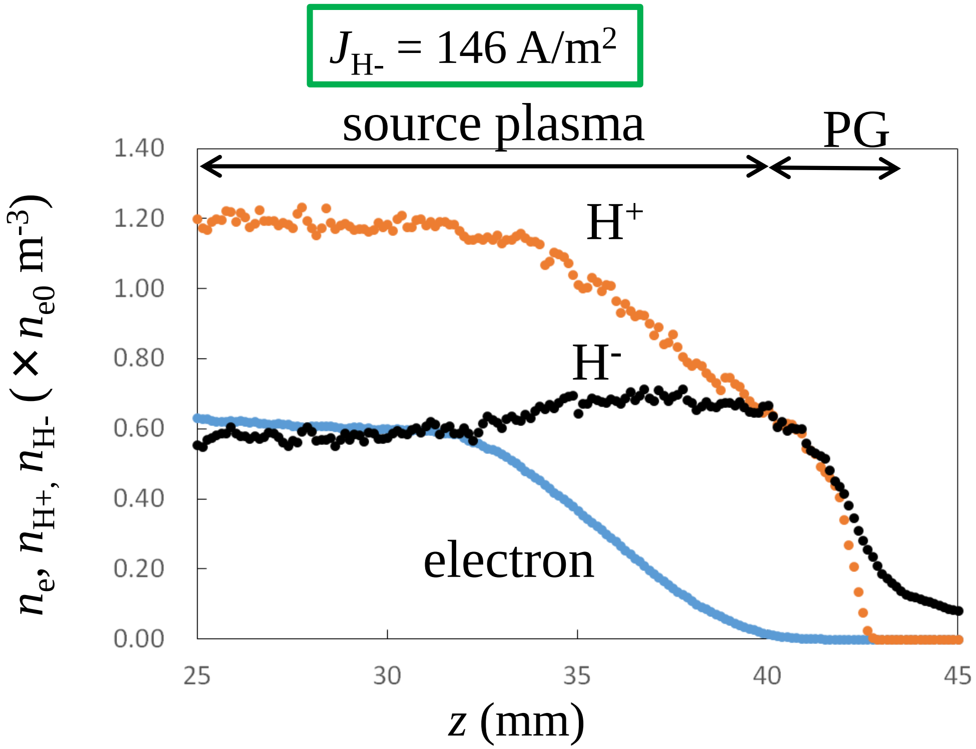
・Neutral particles (H, H_2) are assumed to be the background particles.

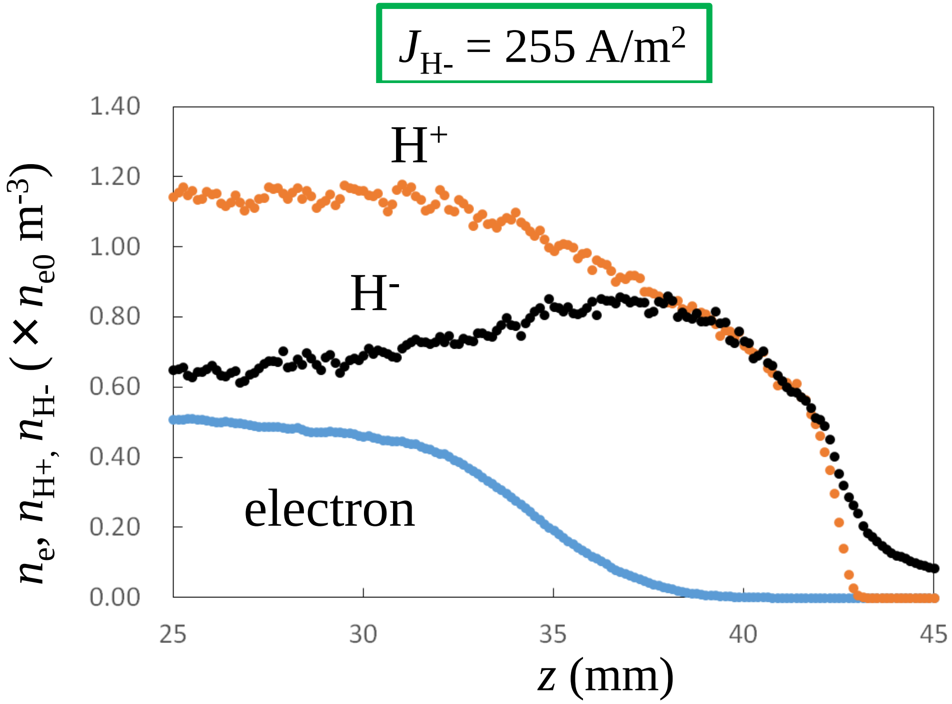
・ Extraction and acceleration voltage:
$V_{PG} = 0$ V, $V_{ext} = V_{SG} = 2.7$, $V_{acc} / V_{ext} = 22$

Spatial distribution of electron, H^+ on, and H^- ion

- Spatial distributions of electron H^+ ion, and H^- ion densities along the *z*-axis are compared.
- The ratio n_{H-}/n_e increases as the flux of surface produced H^- particles per time increases.

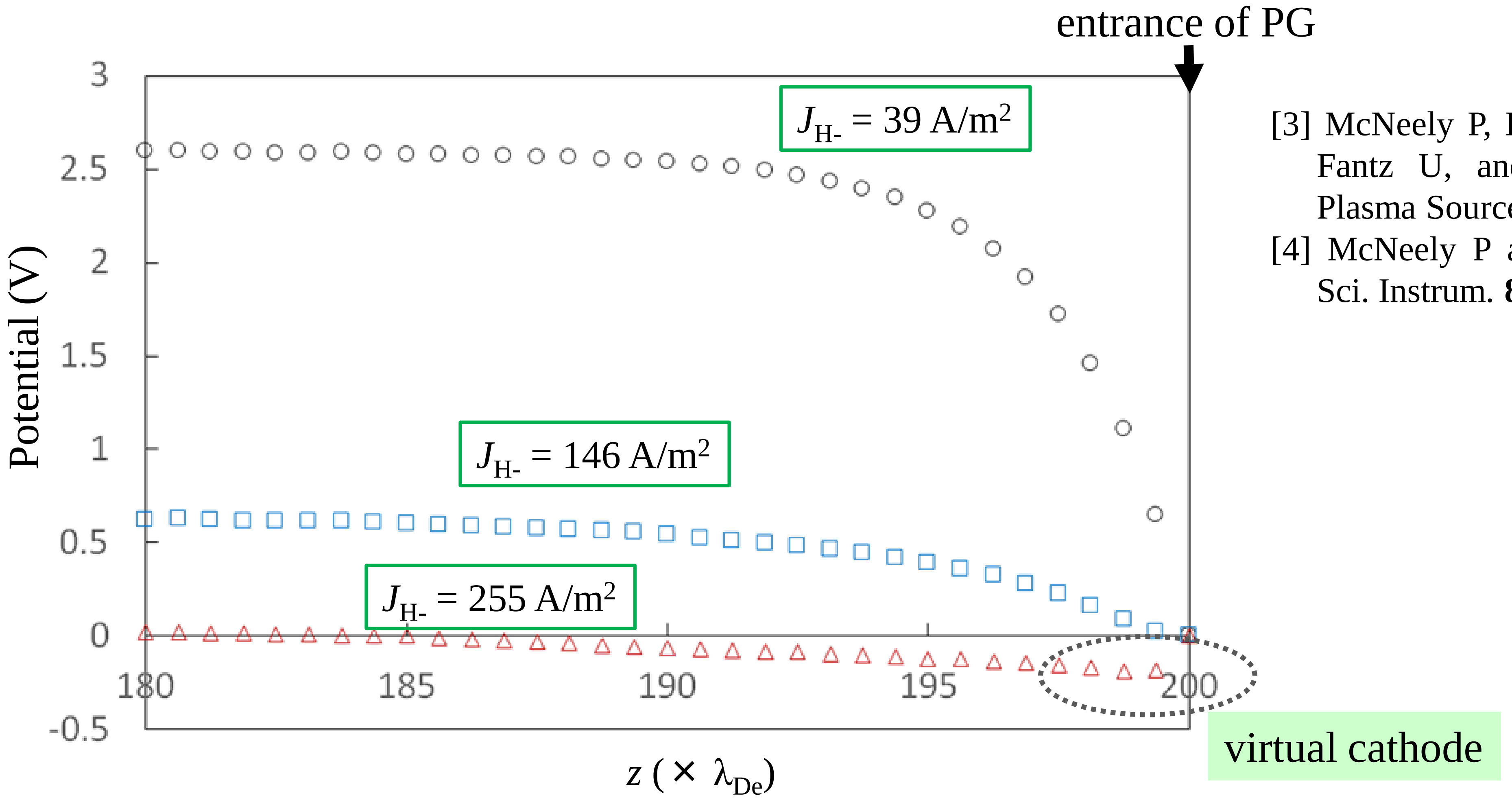






Potential profile in the sheath

- Sheath potential becomes lower compared with that without the surfaced produced H^- ions, which agrees with the experimental results [3, 4].
- Sheath potential decreases with the increase in the surface produced H^- ion flux.
- The onset of virtual cathode appears with the increase in the surface produced H^- ion flux.



[3] McNeely P, Dudin V S, Christ-Koch S, Fantz U, and the NNBI Team 2009 Plasma Sources Sci. Technol. **18** 014011.

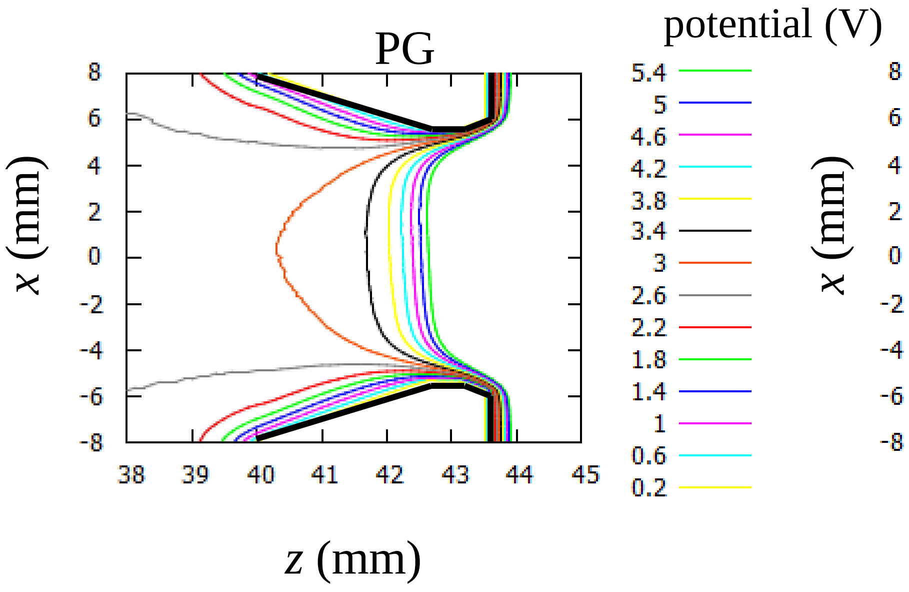
[4] McNeely P and Schiesko L 2010 Rev. Sci. Instrum. **81** 02B111.

Effect of the ratio n_{H-}/n_e on the penetration of electric field

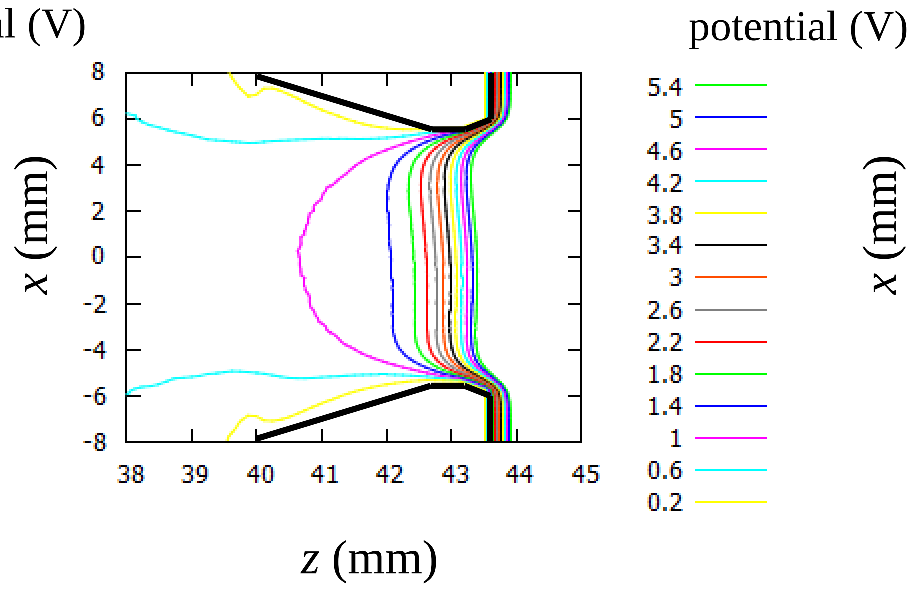
- **Penetration of electric field** for extraction becomes **shallower with the increase of ratio n_{H-}/n_e**.
- For the small ratio n_{H-}/n_e, the surfaced H^- ions are extracted directly from the PG surface rather than enter into the bulk plasma.

Contour map of the electrostatic potential near the PG

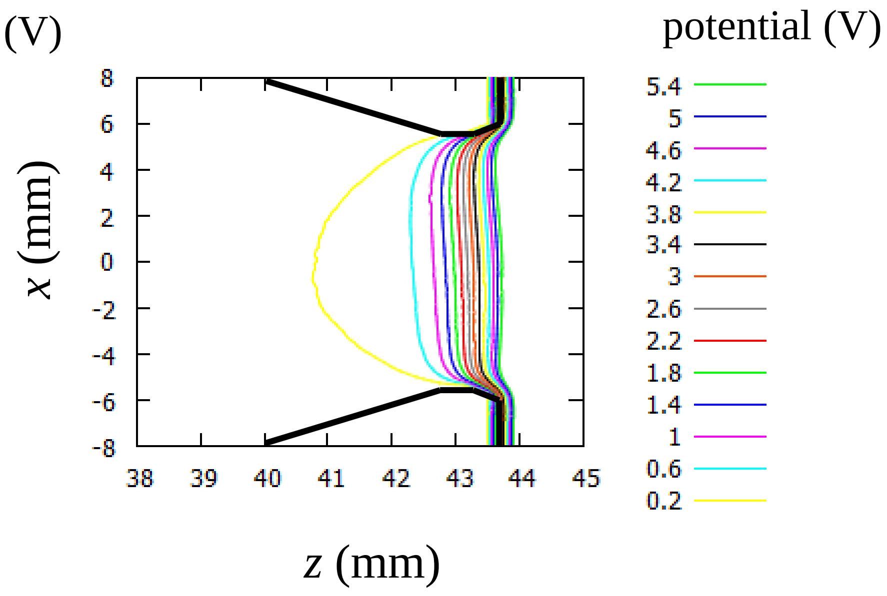
J_{H-} = 39 A/m^2



J_{H-} = 146 A/m^2

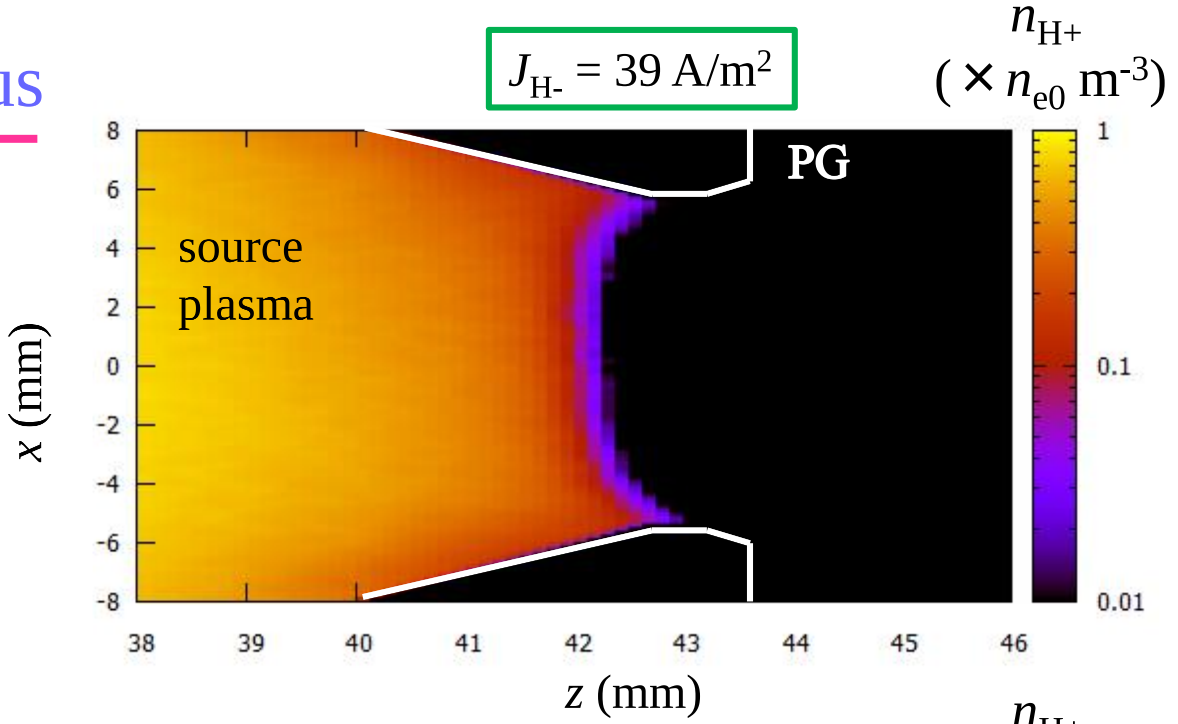


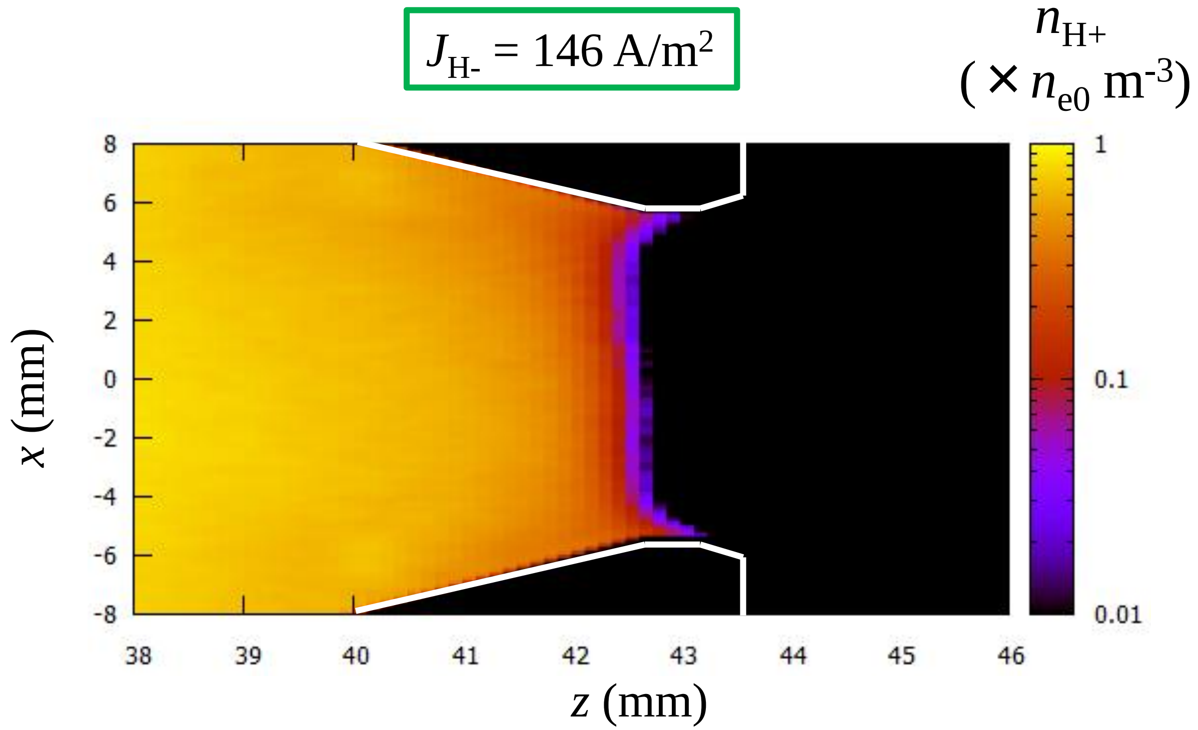
J_{H-} = 255 A/m^2

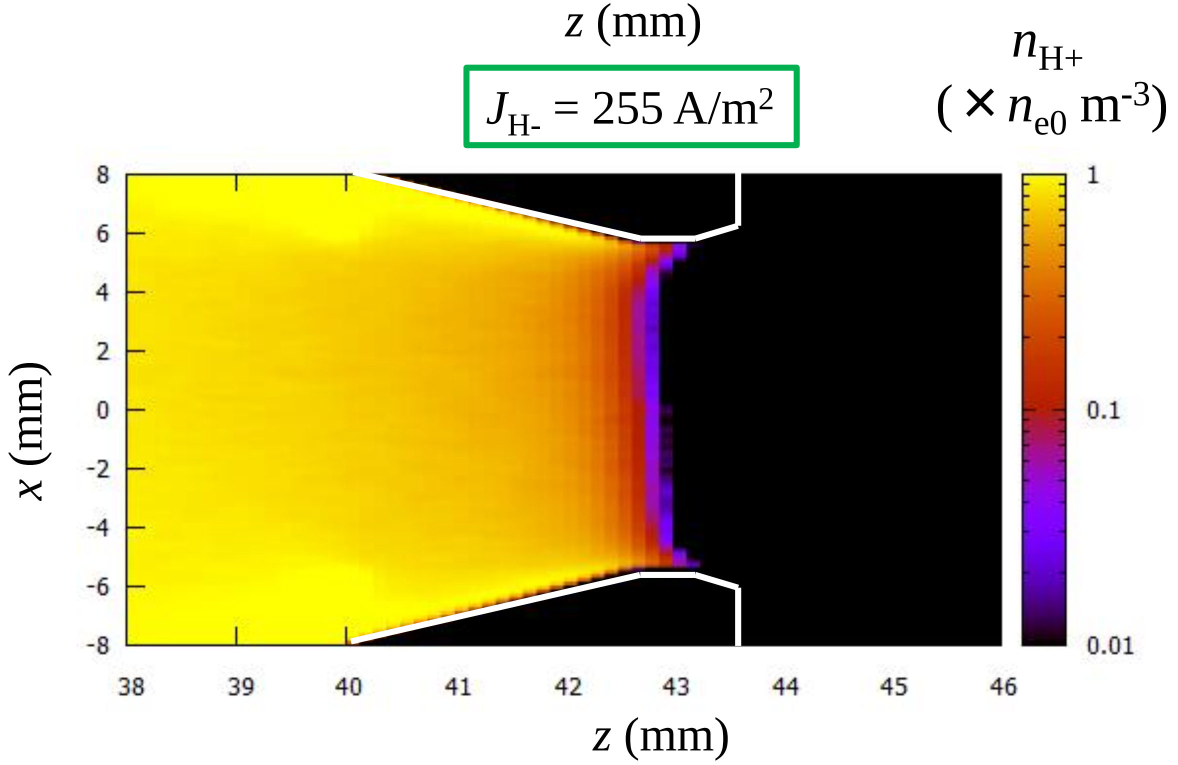


Comparison of the shape of plasma meniscus

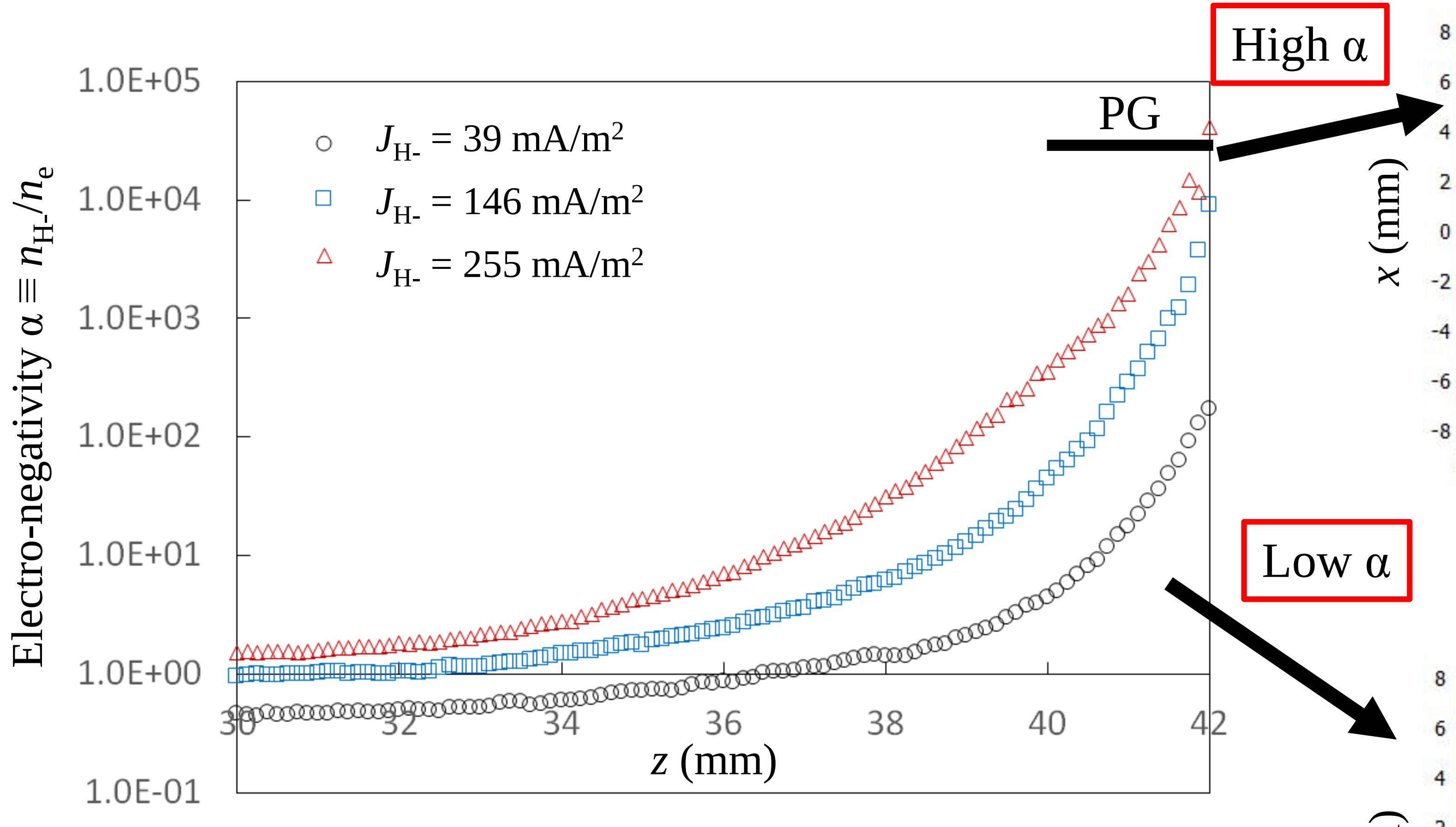
- The location of plasma meniscus is estimated from $n_{H+} \sim 0$.
- The shape of plasma meniscus becomes **flat** with the **increase of ratio n_{H-}/n_e** .

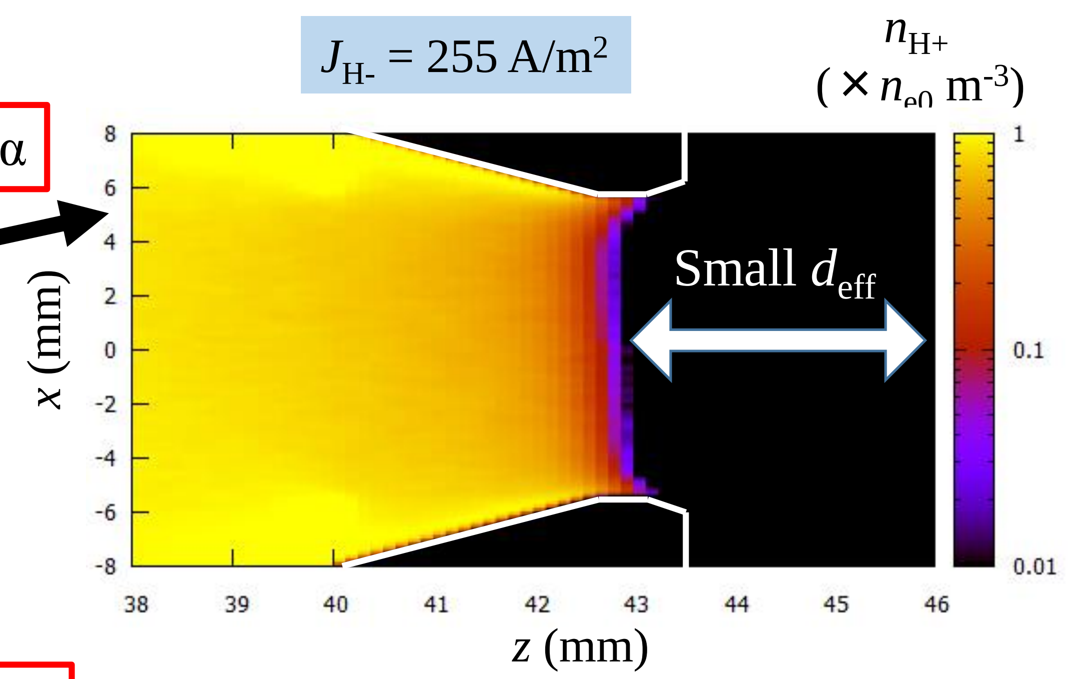


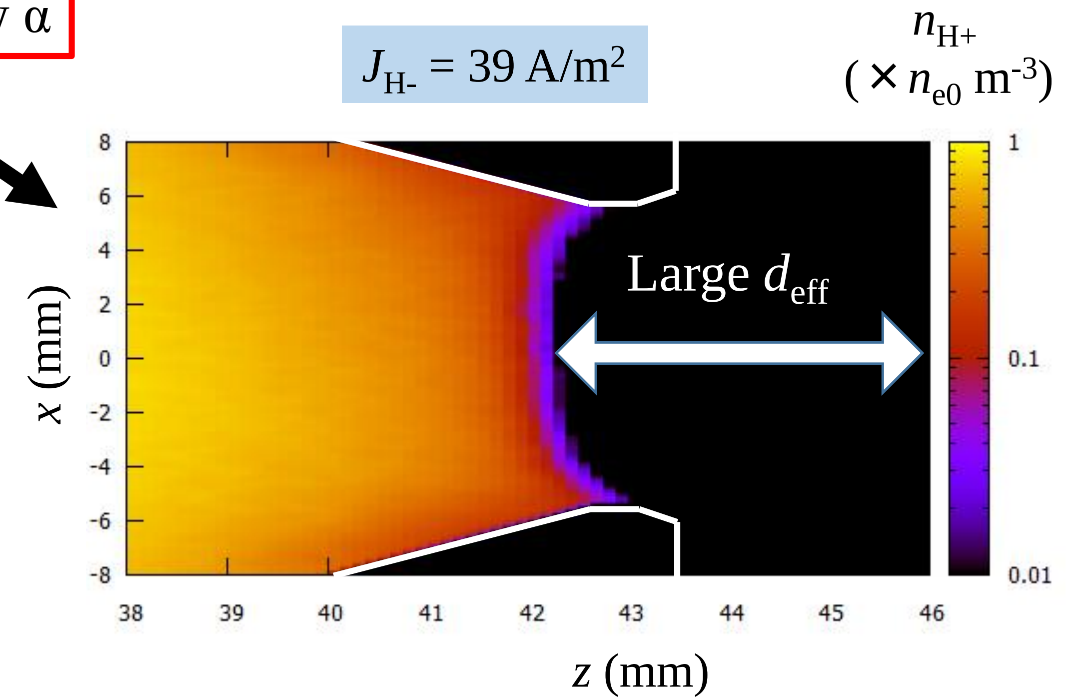




The dependence of plasma meniscus on n_{H-}/n_e





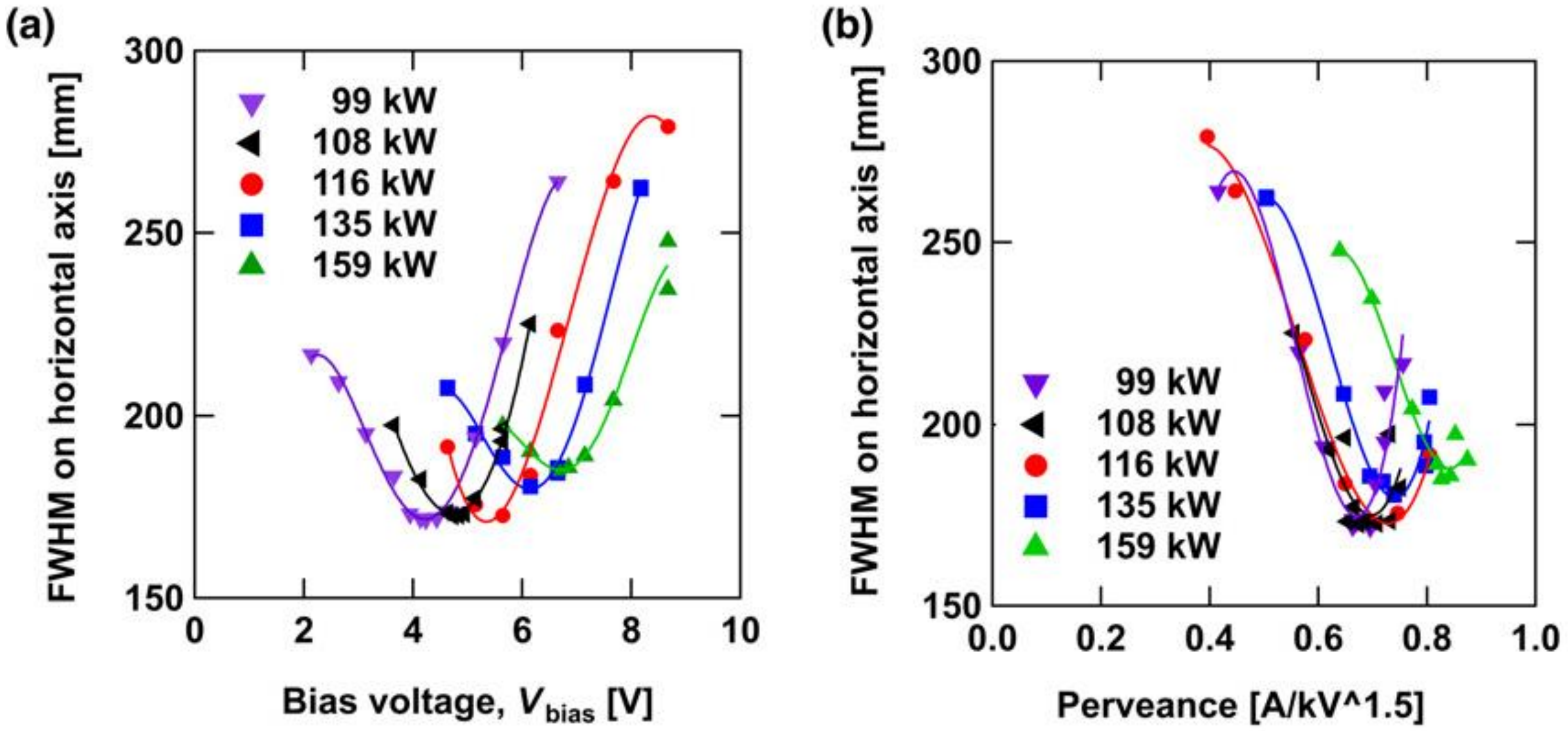


The shape of plasma meniscus or the effective distance d_{eff} depends on the electro-negativity $\alpha \equiv n_{H-}/n_e$.

High α (J_{H-} = 255 A/m^2) : **Small d_{eff}**

Low α (J_{H-} = 39 A/m^2) : **Large d_{eff}**

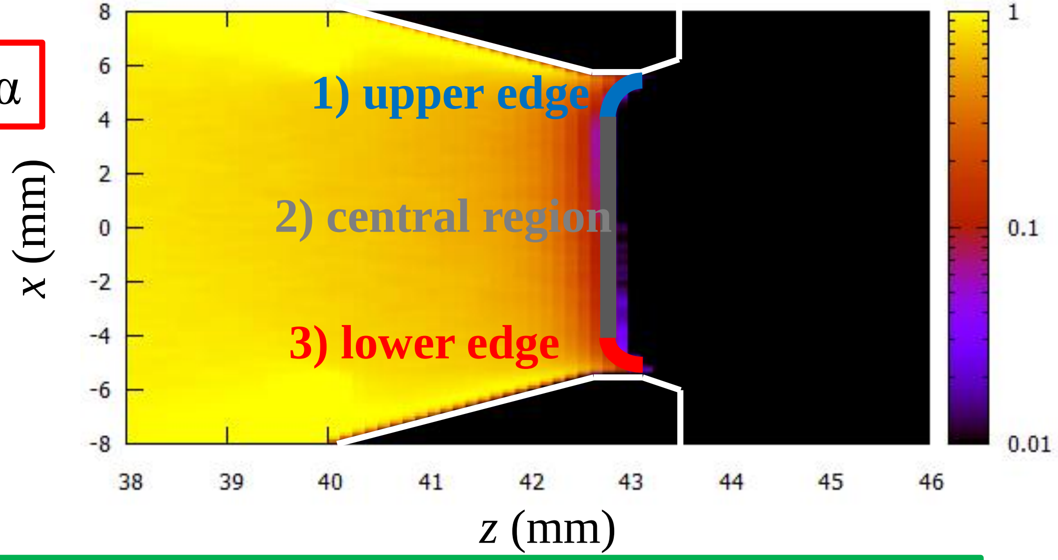
The experimental result in ref. [5] may support the present simulation result that the shape of the plasma meniscus depends on electro-negativity α.



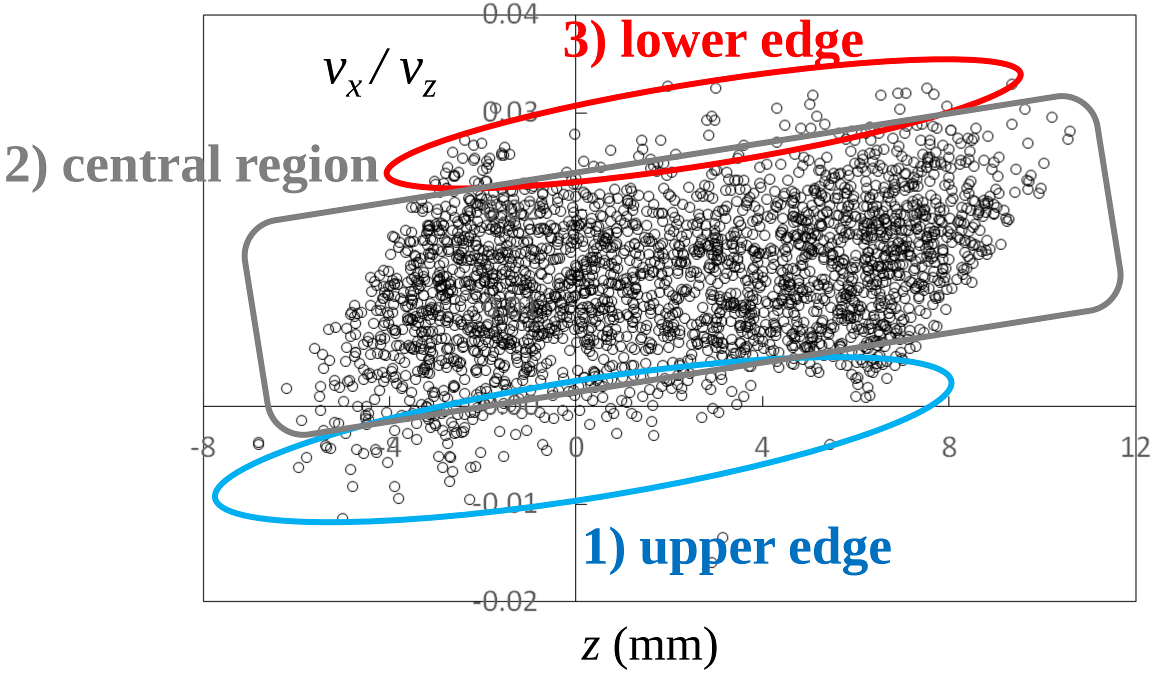
[5] Kisaki M, Ikeda K, Nakano H, Tsumori K, Fujiwara Y, Haba Y, Kamio S, Nagoka K, Osakabe M 2018 Plasma Fusion Res. **13** 1205110.

Effect of the ratio n_{H-}/n_e on the beam optics

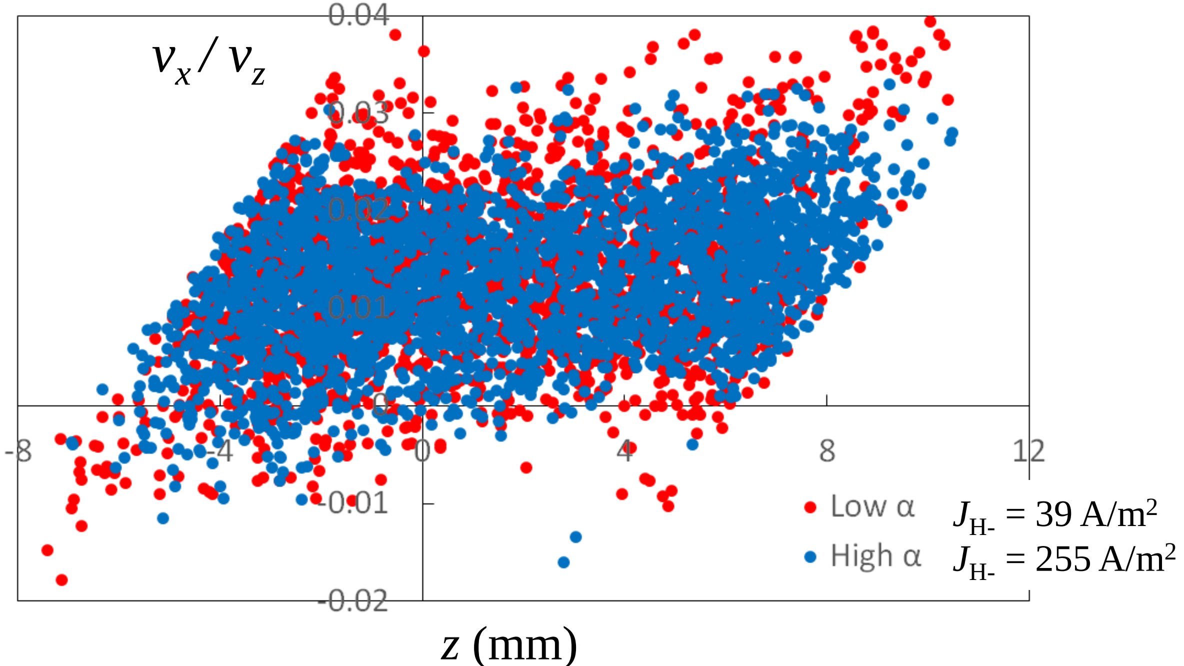
High α



Emittance diagram at the location of 30 mm from the exit of GG



Comparison of emittance diagram for low α and high α



- The H^- ions **extracted from the edge of plasma meniscus** become more **pronounced** for the **low electro-negativity α** in the emittance diagram.
- It is verified that the ratio of n_{H-}/n_e affects the H^- ion beam optics.

Summary and future plan

The plasma meniscus and relevant physical structure in the electronegative plasma with the surface produced H^- ions was investigated from analytical theory and 3D PIC-MCC simulation.

- It is shown that the distance d_{eff}, **between the plasma meniscus and the extraction grid depends on the electro-negativity** $\alpha = n_{H-}/n_e$ as well as the plasma density.
- Especially under the constant plasma density,

  Higher α → **Smaller** d_{eff}, while Lower α → **Larger** d_{eff}

- This dependence of the distance d_{eff} on the electro-negativity α is considered to be caused by the **larger space charge effect of the H^- ions**, preventing penetration of the electric field for H^- extraction into the source plasma.

The future plans for the study of the plasma meniscus and H^- ion beam optics are as follows:

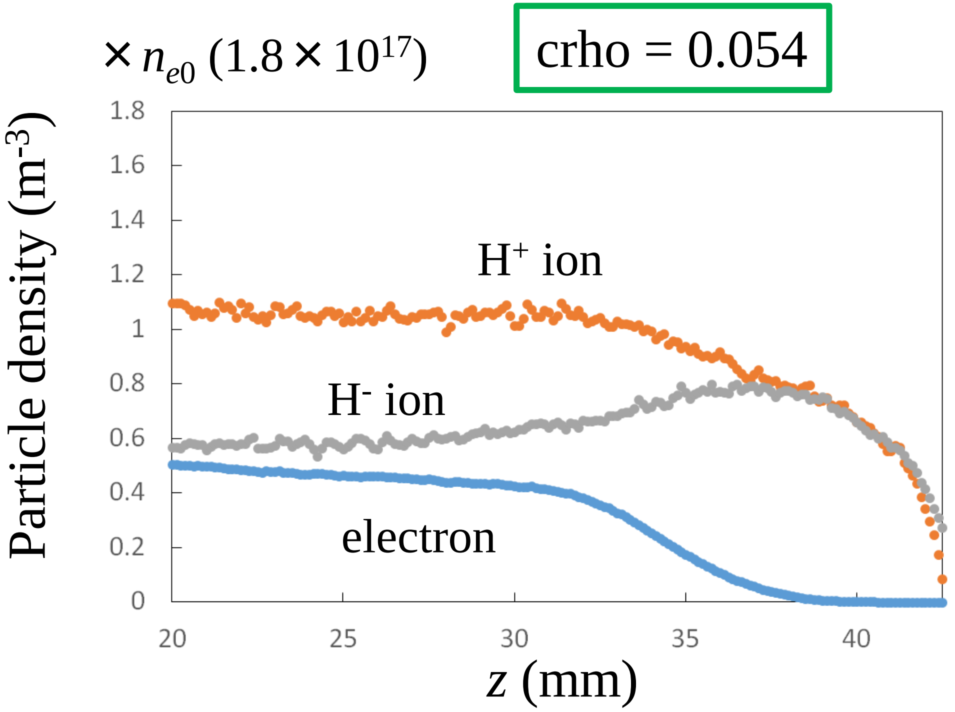
1) A systematic comparison with the experimental result

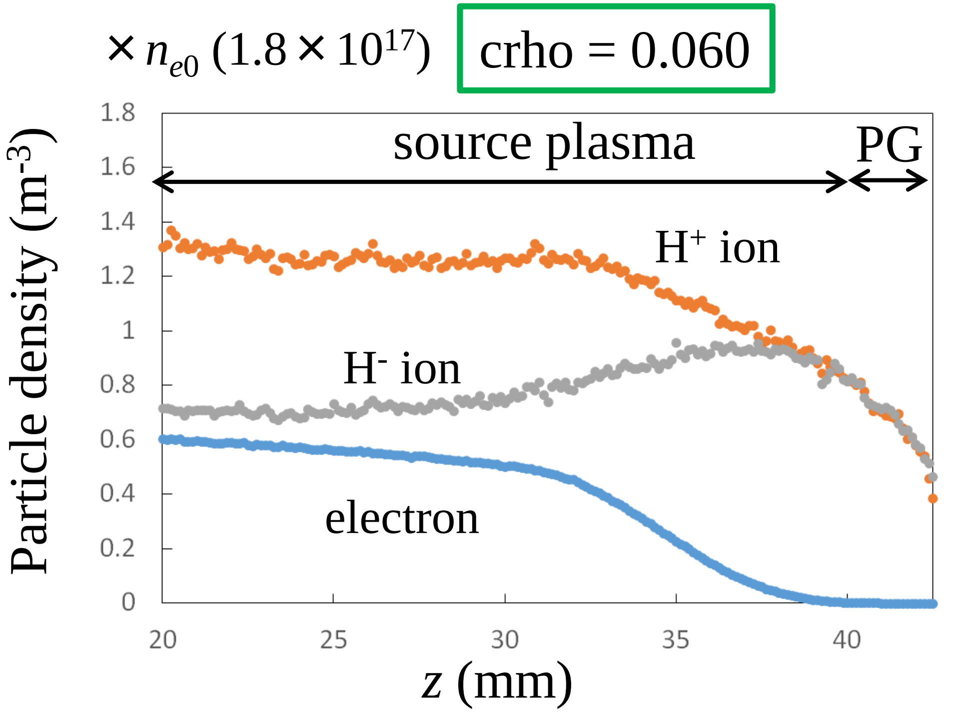
2) Further investigation of the relevant physics of the plasma meniscus, for example

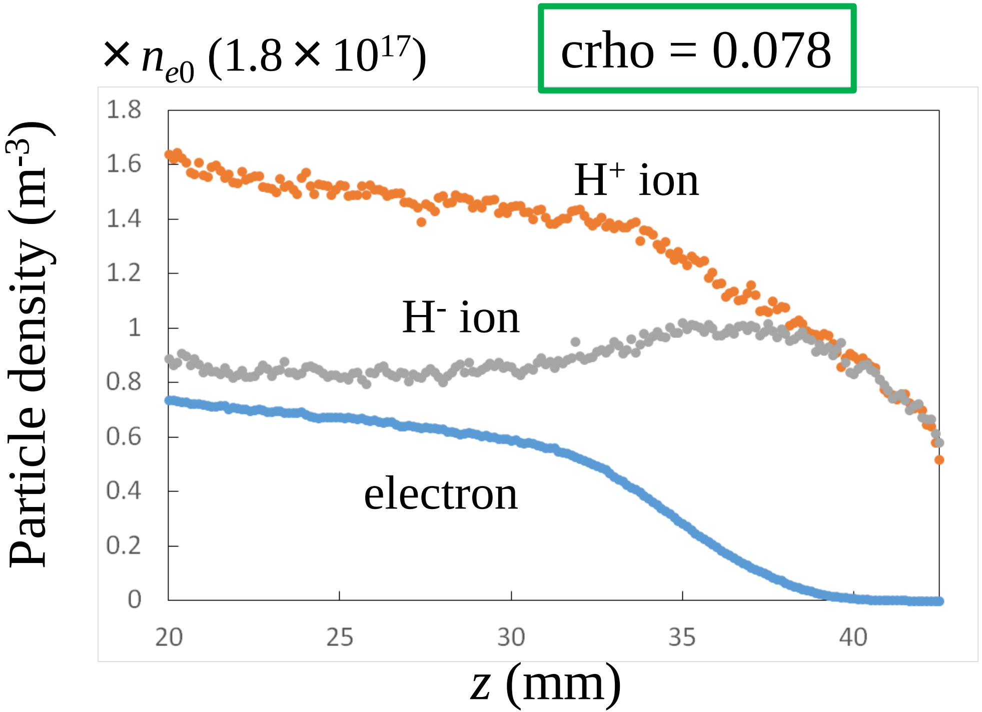
- asymmetry structure of the plasma meniscus
- relationship between extraction mechanism of surface produced H^- ions and beam optics

Dependence of shape of plasma meniscus on plasma density(I)

- The charged particle densities n_e, n_{H+}, and n_{H-} along the z-axis.
- In the simulation, the plasma density was varied by changing the weighting parameter "crho", which correspond to the number of real particles per super-particle of the simulation.
- The plasma density increases with increase in the value of crho.







Dependence of shape of plasma meniscus on plasma density (II)

- It is verified that he shape of plasma meniscus depends on the plasma density.
- With the increase in the plasma density, the shape of plasma meniscus varies as follows:

concave 凹 → almost flat → convex 凸