

Analysis of the plasma meniscus in a negative ion source from the viewpoint of force balance

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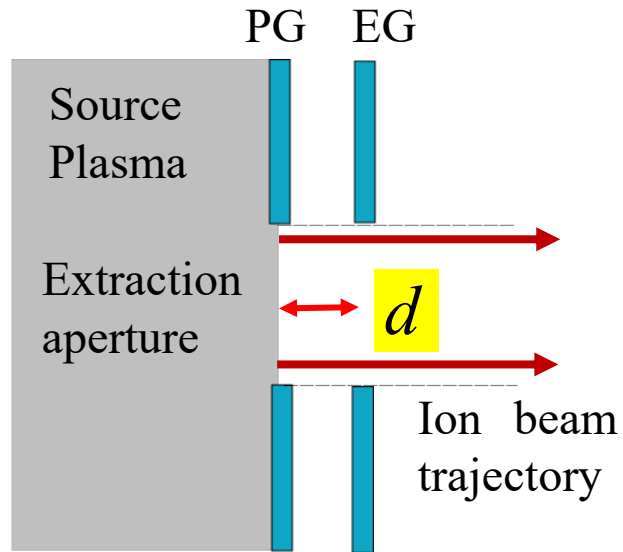
4. Summary

Relation between shape of plasma meniscus and ion beam optics

Control of **ion sheath 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

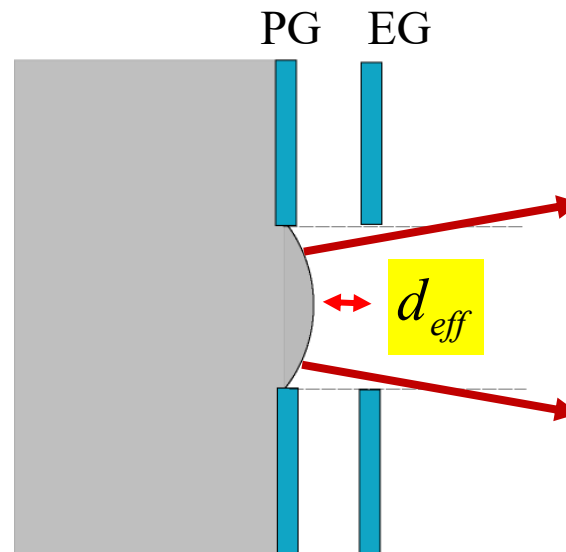
Optimum plasma density



$$d_{\text{eff}} = d$$

Plasma meniscus : flat
Extracted ion beam : parallel
Optimum perveance

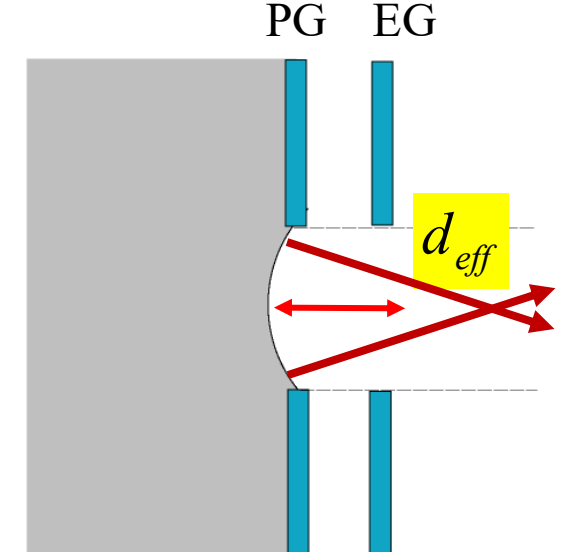
High plasma density



$$d_{\text{eff}} < d$$

Plasma meniscus : Convex $\curvearrowright$
comes out towards the EG
Extracted beams : diverged

Low plasma density



$$d_{\text{eff}} > d$$

Plasma meniscus : Concave $\curvearrowleft$
penetrates into the source region
Extracted beams : over-focused

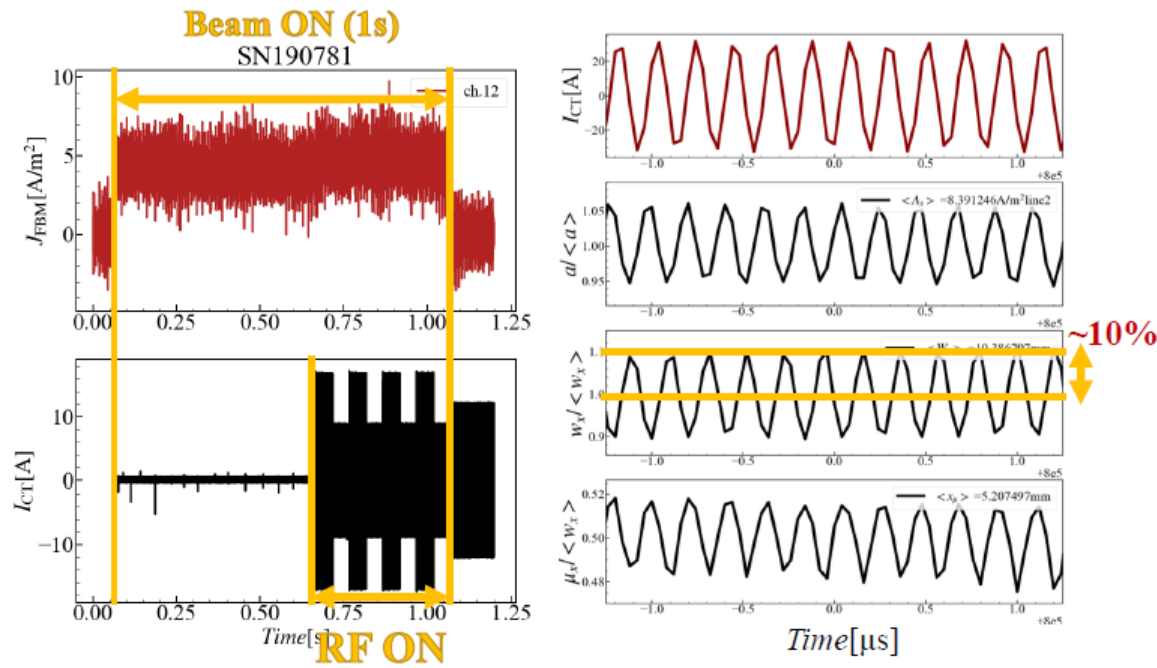
Recent studies about plasma meniscus in a negative ion source

Experiment

Oscillations of a negative-ion beamlet width and axis responding to the RF perturbation were observed in the negative ion source [1] while these oscillations were not observed in a core region of the positive ion beamlet in the case of RF positive ion source [2].

[1] K. Nagaoka et al., Scientific reports, 15, 1494 (2025)..

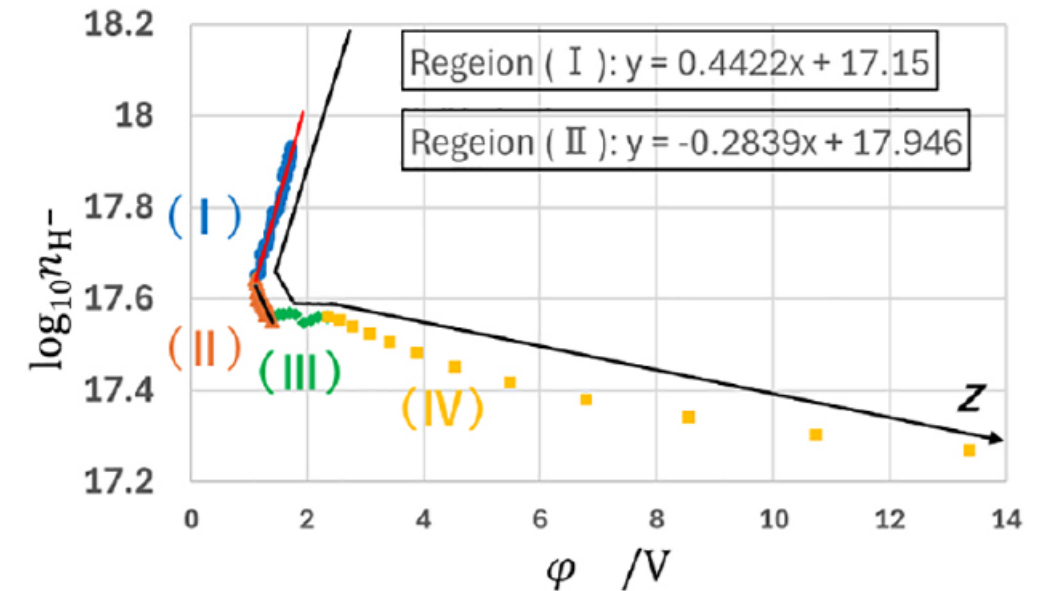
[2] K. Takahashi et al., New J. Phys., 21, 093043 (2019)..



Simulation

- (I) H^- ion density follows the Boltzmann relation
- (II) H^+ ion density follows the Boltzmann relation
- (III) Transition region
- (IV) Beam accelerating region

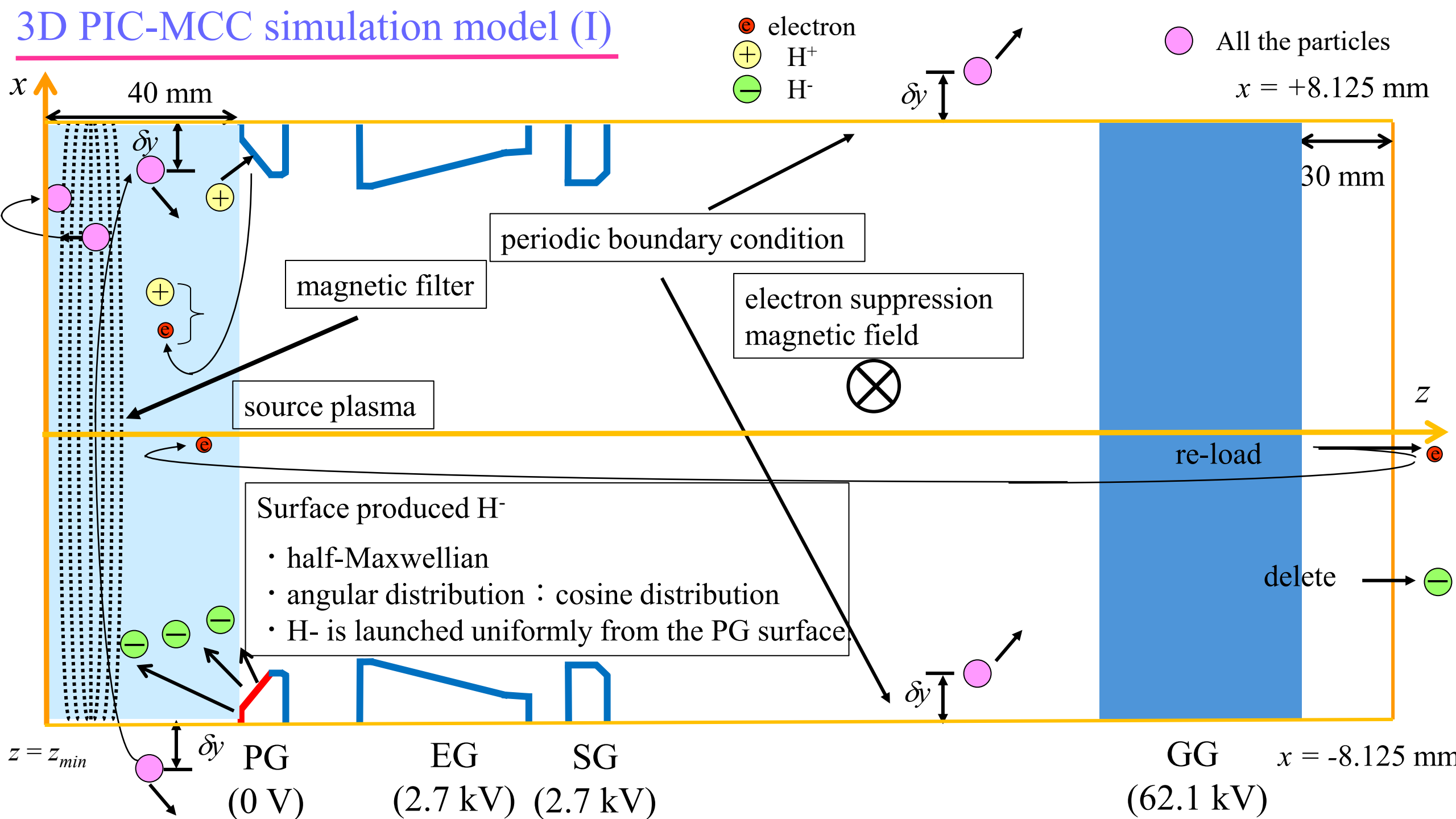
The plasma meniscus can be interpreted as the boundary between Region (III) and Region (IV).



[3] K. Hayashi et al., Plasma and Fusion Res., 21, 14019 (2026).

The **plasma meniscus and relevant physical structure** in the ion-ion plasma of a hydrogen negative source is investigated with the 3D PIC-MCC simulation from the viewpoint of the **force balance of H^+/H^- ions**.

3D PIC-MCC simulation model (I)



3D PIC-MCC simulation model (II)

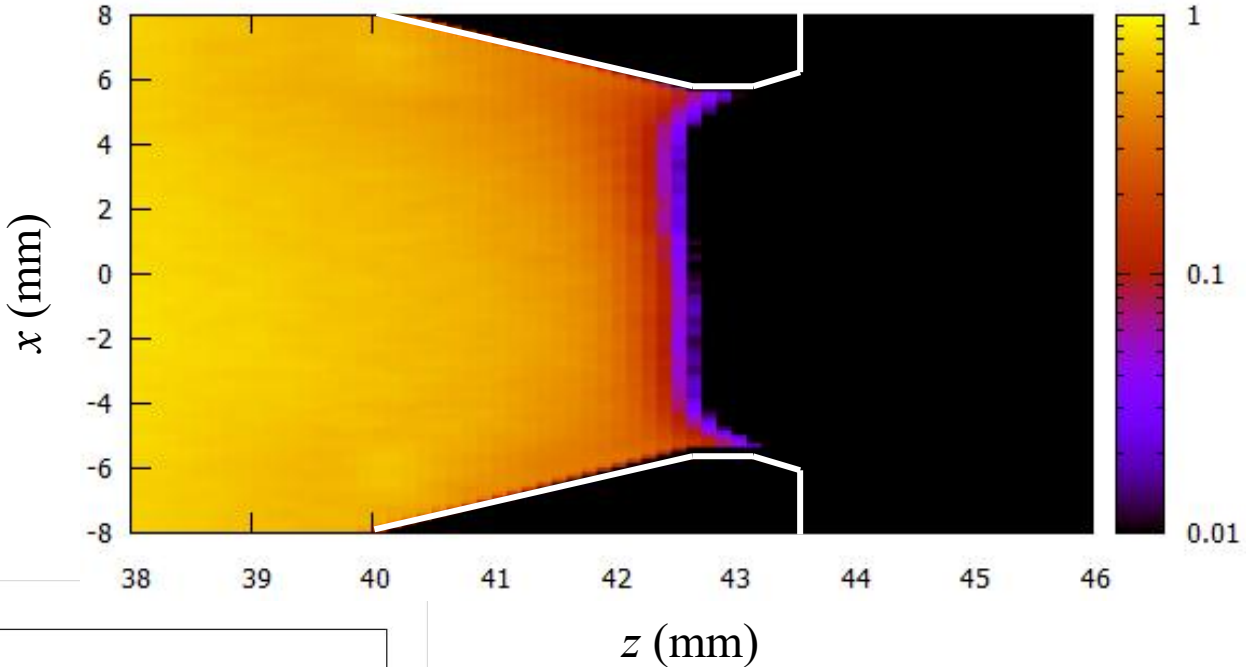
A single aperture of the negative ion source for NIFS is modelled.

Physical parameter	Value
Electron density	$1.8 \times 10^{17} \text{ m}^{-3}$
Electron temperature	0.8 eV
H ⁺ ion temperature	0.3 eV
H ⁻ ion temperature	0.1 eV (Volume produced) 1 eV (Surface produced)
H ₂ molecular density n_{H_2}	$1.88 \times 10^{19} \text{ m}^{-3}$ (0.3 Pa)
H ₂ molecular temperature	0.1 eV
H atom temperature	0.3 eV
Ratio of $n_{\text{H}_2} / n_{\text{H}}$	0.5

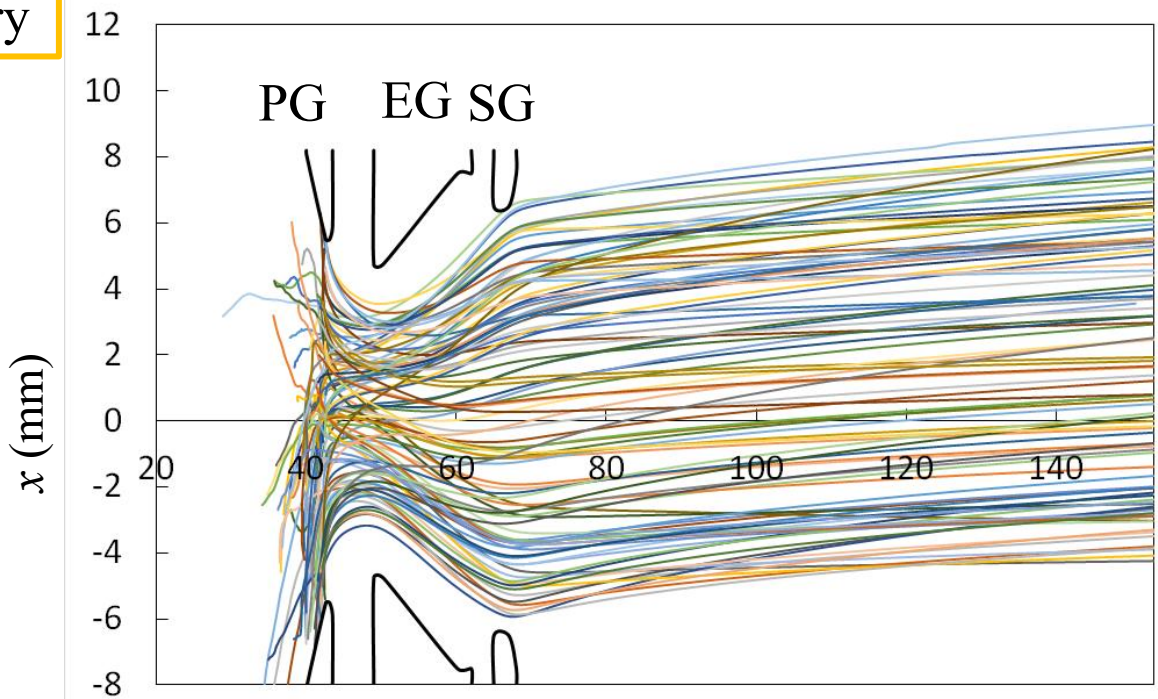
3D PIC-MCC simulation model (III)

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

Distribution of n_{H^+} around the PG $(\times n_{e0} \text{ m}^{-3})$



H⁻ ion beam trajectory



z (mm)

K. Miyamoto et al, JINST, **18**, C06014 (2023)

3D PIC-MCC simulation model (IV)

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

Coulomb collision : $\text{H}^- - \text{H}^+$, $\text{H}^- - \text{H}^-$

Charge exchange collision : $\text{H}^- (\text{fast}) + \text{H} (\text{slow}) \rightarrow \text{H}^- (\text{slow}) + \text{H} (\text{fast})$

Elastic collision : $\text{H}^- - \text{H}$, $\text{H}^- - \text{H}_2$

Mutual neutralization : $\text{H}^+ + \text{H}^- \rightarrow \text{H} + \text{H}$

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.

Scaled model

- The mesh size should be less than the electron Debye length from the PIC constraint. Since the large different size between the electron Debye length and the real negative ion source will cause considerable high computation cost, the simulation model is scaled down.

$$L_{sim} = s L_{real} \quad (s : \text{scale factor})$$

- The strengths of the applied voltages and the magnetic field are modeled followed by the scale down:

Electric field

(1) Extraction voltage

The extraction voltage is modeled in order to match the perveance for the real negative ion source.

$$\frac{\pi(r_{PG})_{sim}^2 J_{H-}}{(V_{ext})_{sim}^{1.5}} = \frac{\pi(r_{PG})_{real}^2 J_{H-}}{(V_{ext})_{real}^{1.5}} \longrightarrow (V_{ext})_{sim} = s^{4/3} (V_{ext})_{real}$$

(2) Acceleration voltages

The applied voltages in the accelerator are modeled to satisfy the law of scaling.

$$(V_{acc})_{sim} : (V_{ext})_{sim} = (V_{acc})_{real} : (V_{ext})_{real}$$

V_{acc} : acceleration voltage

Magnetic field

The magnetic field is scaled down such that the following relation for the Larmor radius of electrons r_L is satisfied;

$$(r_L)_{sim} = s(r_L)_{real}$$

$$B_{sim} = \frac{v_{sim}}{s v_{real}} B_{real}.$$

$$\frac{v_{sim}}{v_{real}} = \sqrt{\frac{V_{sim}}{V_{real}}} = s^{2/3}.$$

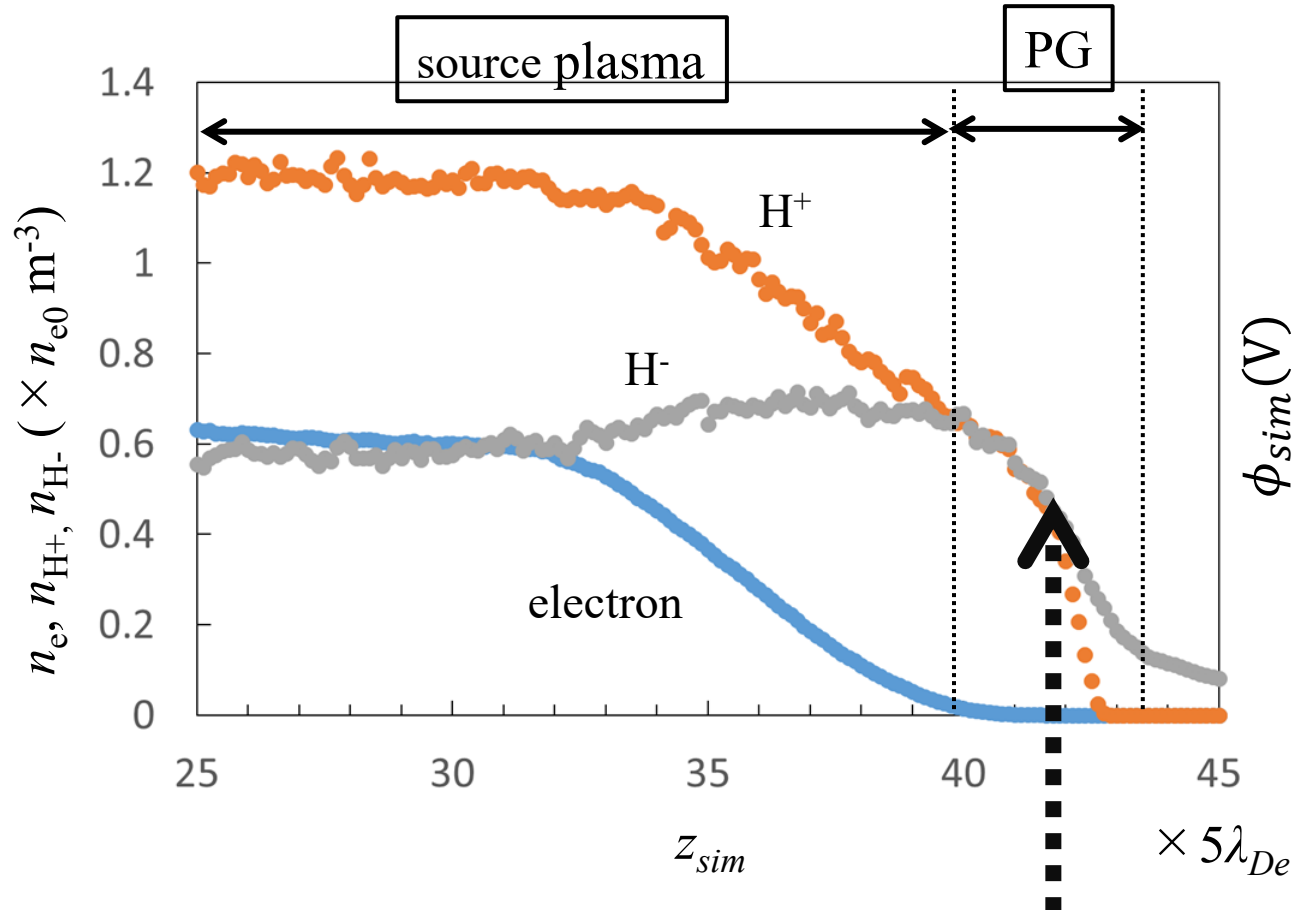


$$B_{sim} = s^{-1/3} B_{real}.$$

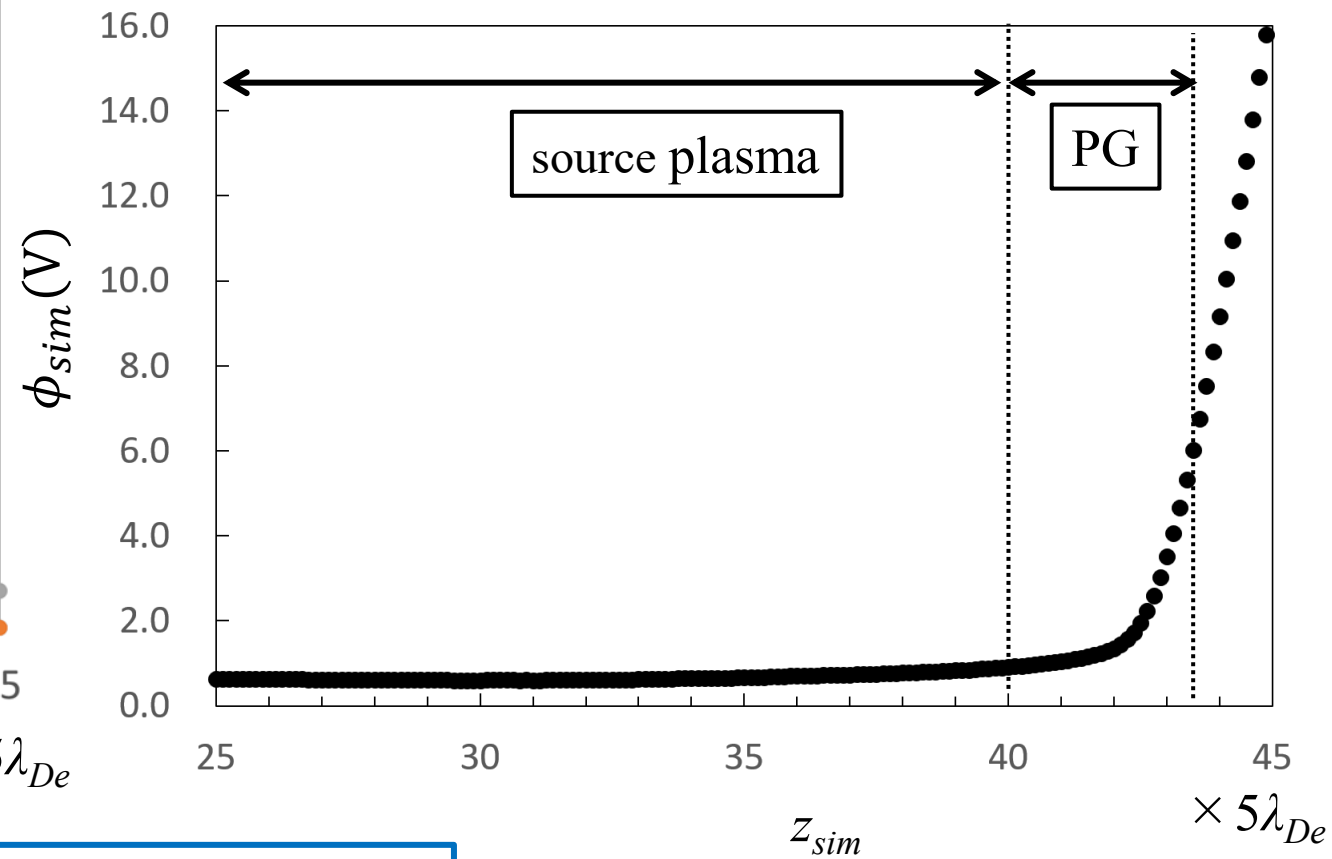
Spatial distribution of plasma density and potential along the z-axis

$$n_{e0} = 1.8 \times 10^{17} \text{ m}^{-3}, \lambda_{De} = 0.0157 \text{ mm}$$

(a) Plasma density

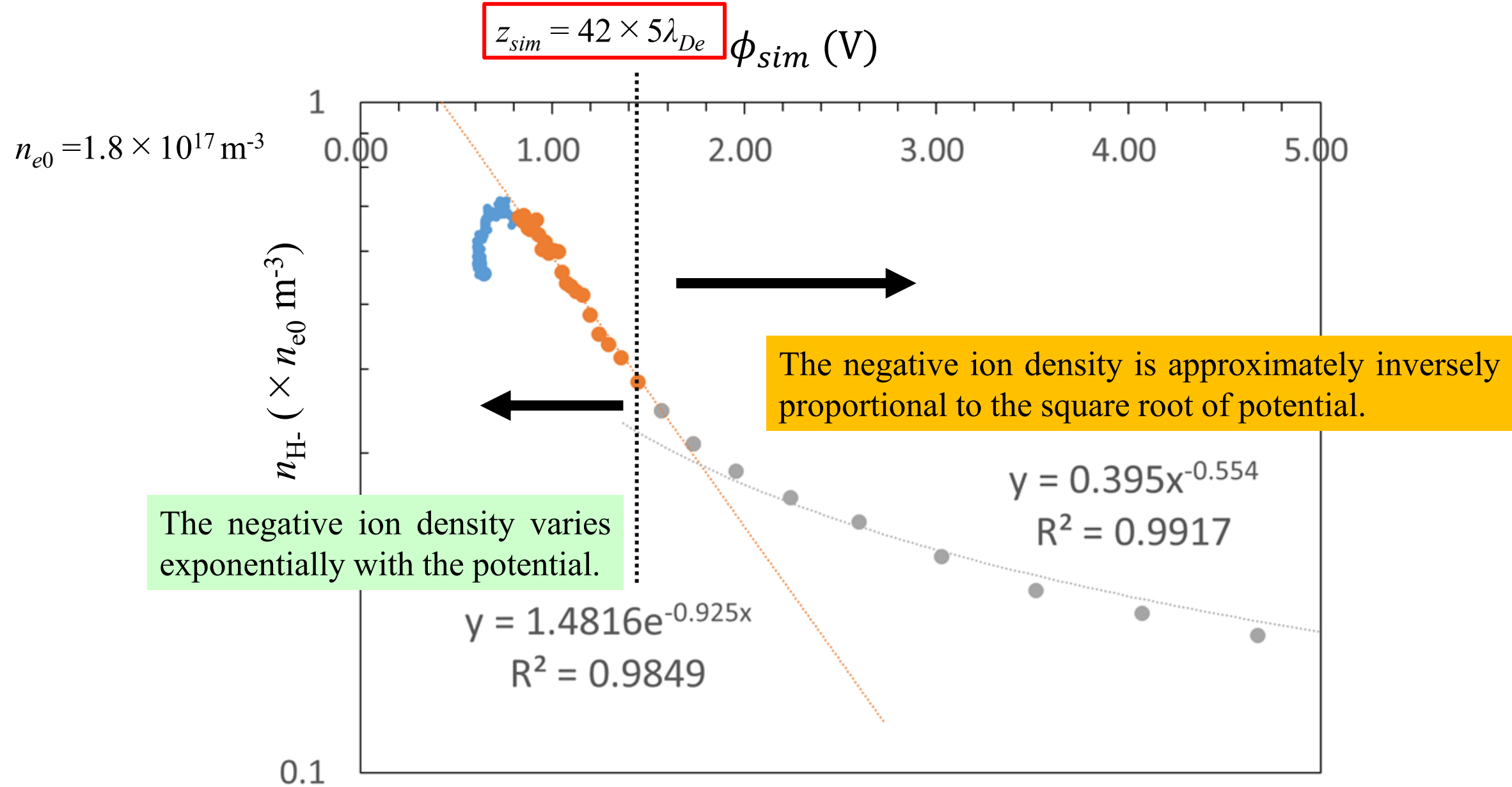


(b) Potential



Separation of H^+/H^- ions ($z_{sim} = 42 \times 5\lambda_{De}$)

Dependence of H⁻ ion density distribution on the potential



Interpretation of the potential dependence of H⁻ ion density distribution using fluid equations

Boltzmann equation
$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{e}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t} \right)_c$$

Moment equation
$$\frac{\partial}{\partial t} (n \langle A(\mathbf{v}) \rangle) + \frac{\partial}{\partial \mathbf{r}} (n \cdot \langle \mathbf{v} A(\mathbf{v}) \rangle) - \frac{ne}{m} \sum_k \langle (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial A}{\partial \mathbf{v}} \rangle = \left\{ \frac{\partial}{\partial t} (n \langle A(\mathbf{v}) \rangle) \right\}_c$$

First-order moment ($A = \mathbf{v}$)

$$mn \left[\frac{\partial \mathbf{V}}{\partial t} + \boxed{\mathbf{V} \nabla \cdot \mathbf{V}} \right] = \boxed{-\nabla p} + ne(\mathbf{E} + \mathbf{V} \times \mathbf{B}) + mn \left(\frac{\partial \mathbf{V}}{\partial t} \right)_c$$

Equation for the conservation of momentum

Contribution of V

Contribution of w

$\mathbf{v} = \mathbf{V} + \mathbf{w}$ $\mathbf{V}$: Fluid velocity $\mathbf{w}$: Random thermal velocity

In the steady state, if the Lorentz force and collision terms can be neglected, we obtain

Inertial force

Pressure gradient force

$$mn \mathbf{V} \nabla \cdot \mathbf{V} \sim -\nabla p + ne\mathbf{E}$$

$$|mn \mathbf{V} \nabla \cdot \mathbf{V}| < |\nabla p|$$

$$-\nabla p + ne\mathbf{E} \sim 0$$



$$n \sim \exp\left(-\frac{e\phi}{kT}\right)$$

$$|mn \mathbf{V} \nabla \cdot \mathbf{V}| > |\nabla p|$$

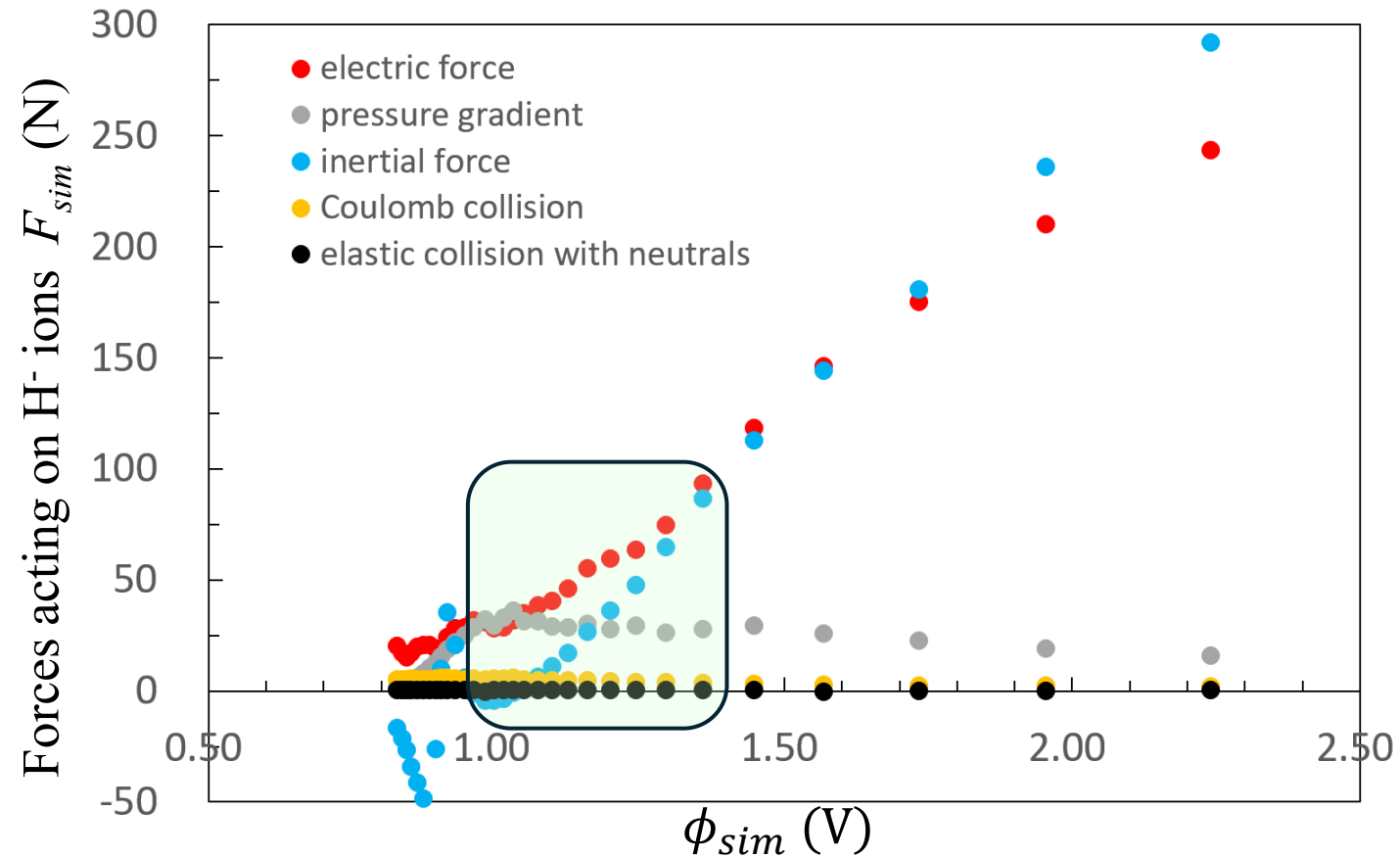
$$mn \mathbf{V} \nabla \cdot \mathbf{V} \sim ne\mathbf{E}$$



$$n \propto \phi^{-1/2}$$

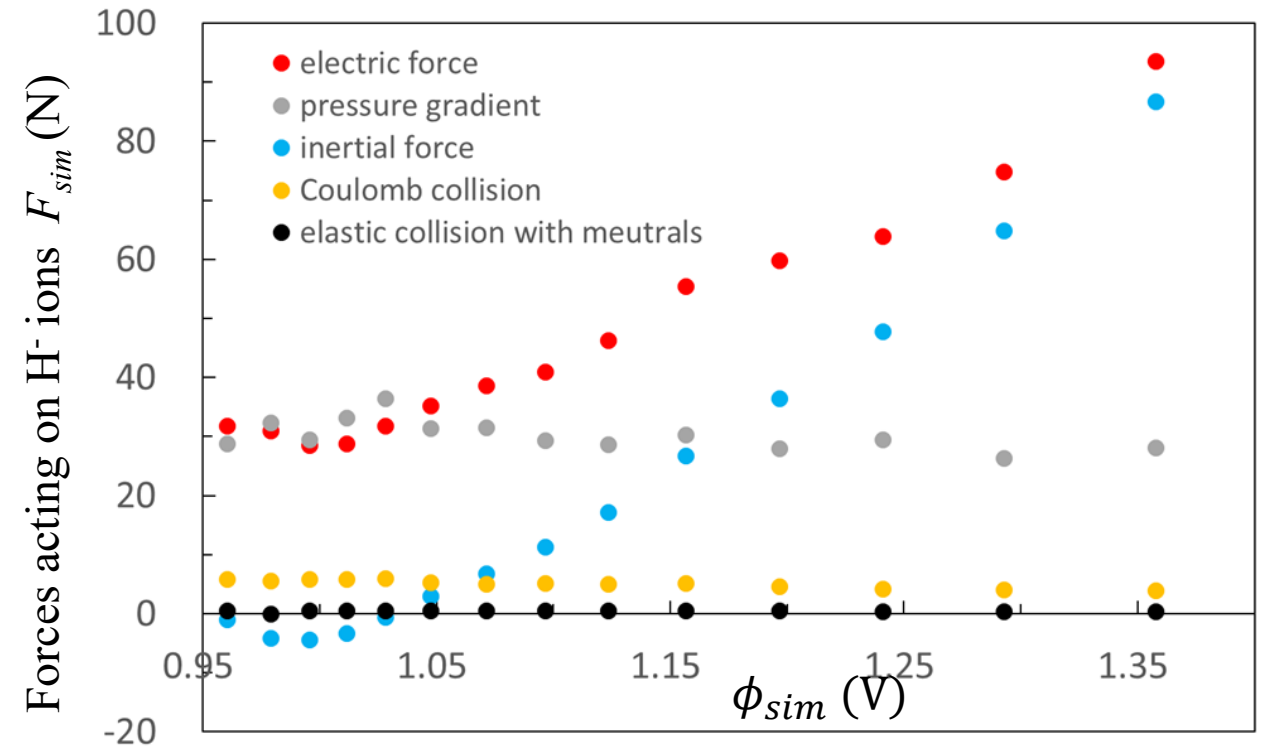
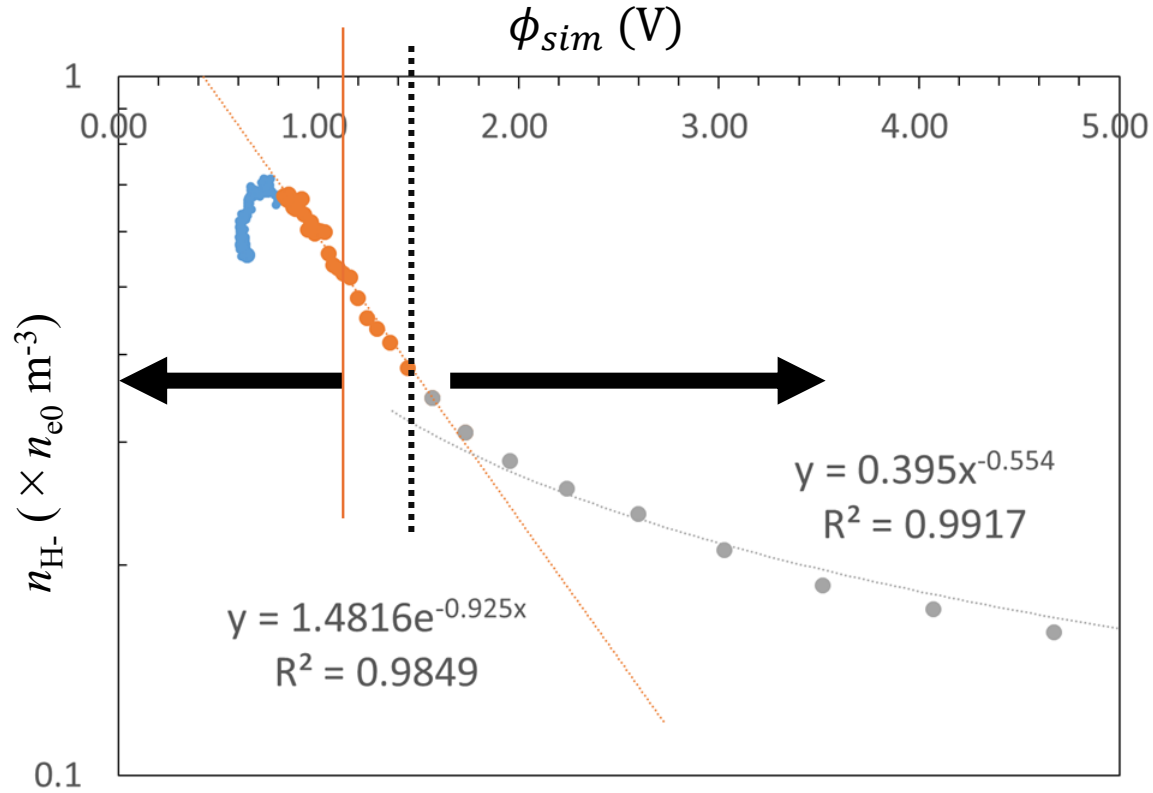
Simulation result for the force balance in H⁻ ions (I)

Electric force : $n_{H^-} q E_z$ Pressure gradient : $\gamma k_B T_{H^-} \frac{\partial n_{H^-}}{\partial z}$ ($\gamma = 5/3$) Inertia force : $m_{H^-} n_{H^-} \frac{dv_z}{dt}$ Collision terms : $\frac{m_{H^-} n_{H^-} u_z}{\tau}$



- The collision terms can be neglected.
- We can classify into (1) the region where the force due to the electric field is comparable to the force due to the pressure gradient, and (2) the regions where the force due to the electric field is comparable to the inertial force.

Simulation result for the force balance in H⁻ ions (II)



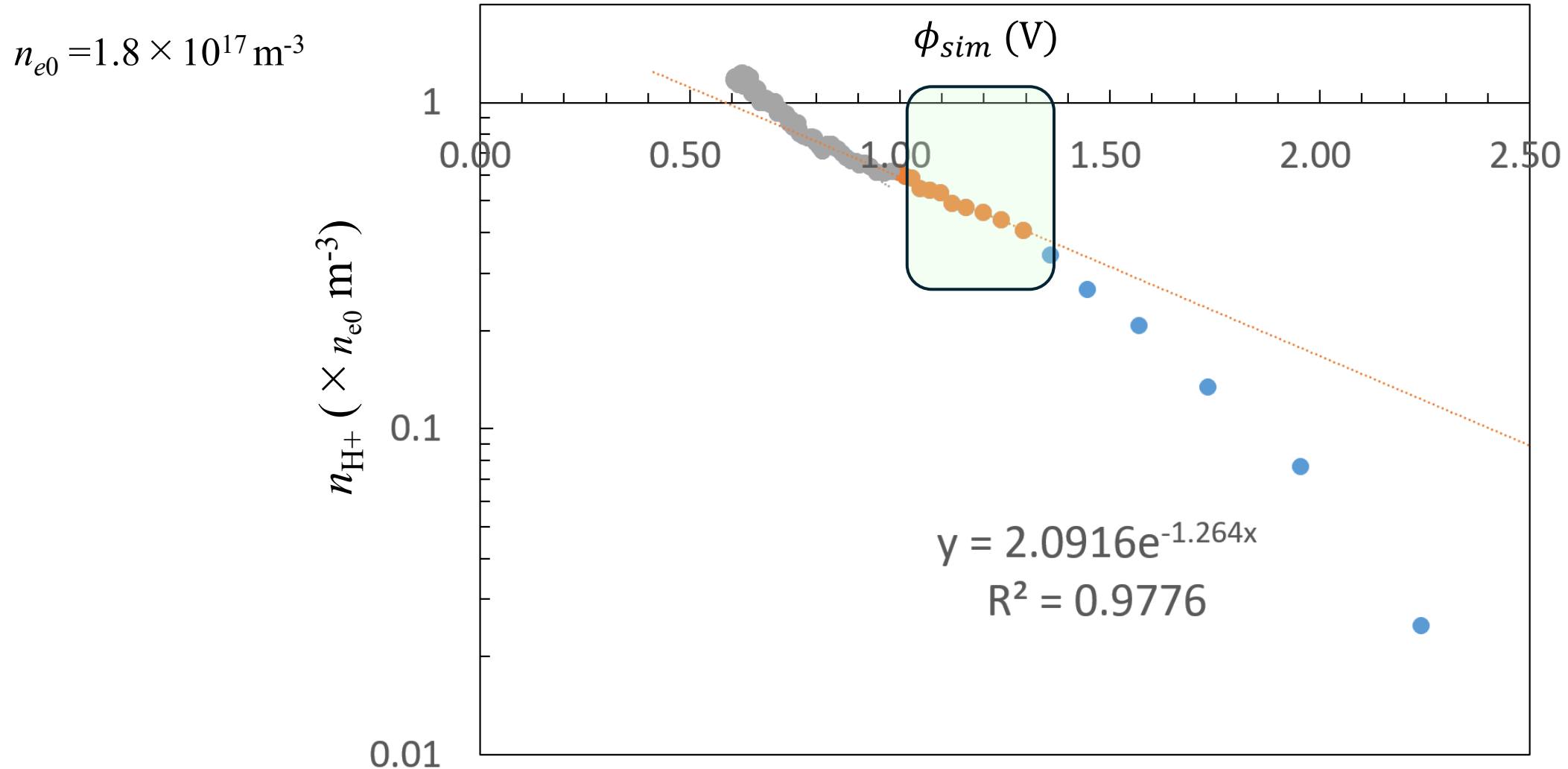
$$0.9 \text{ V} < \phi_{sim} < 1.15 \text{ V} \quad |mn\mathbf{V}\nabla \cdot \mathbf{V}| < |\nabla p|$$

$$1.15 \text{ V} \leq \phi_{sim} \leq 1.4 \text{ V} \quad |mn\mathbf{V}\nabla \cdot \mathbf{V}| \geq |\nabla p|$$

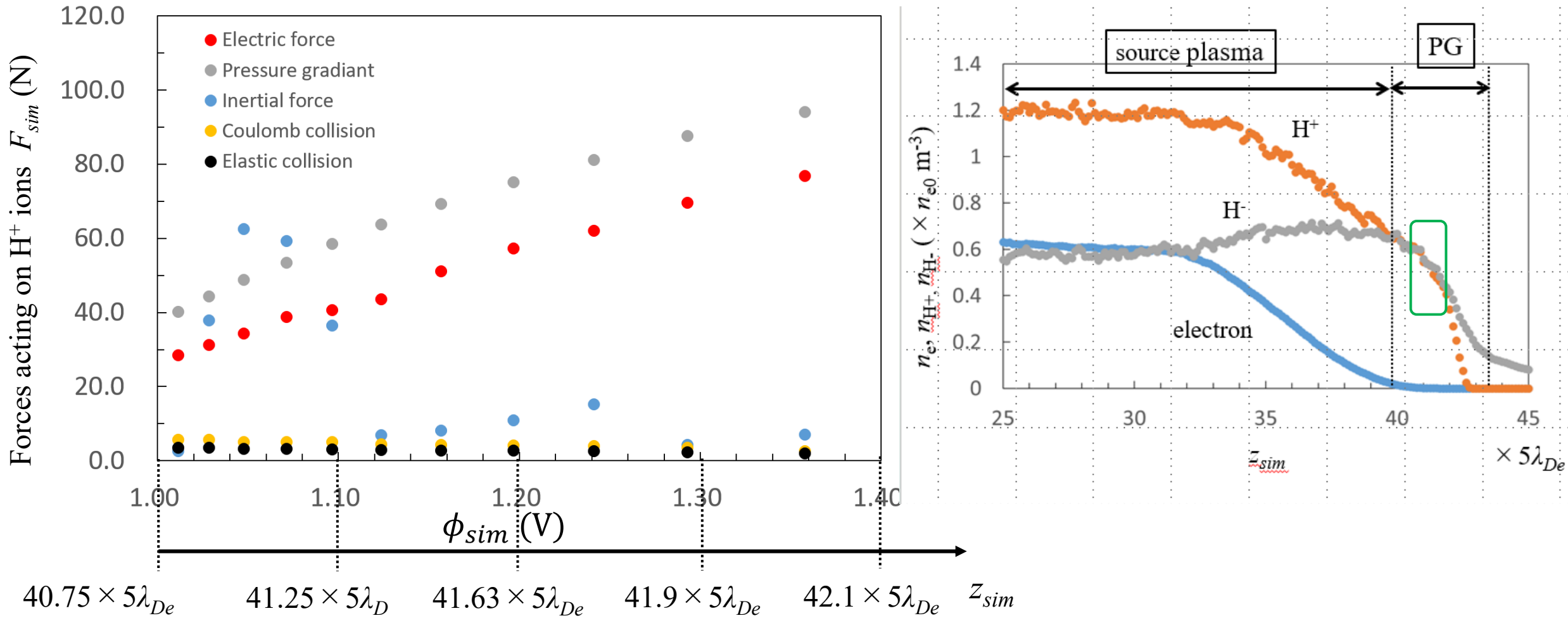
It seems that the H⁻ ion density obeys the Boltzmann relation, however, it exhibits a trend opposite to the Boltzmann relation with respect to the potential.

Dependence of H^+ ion density distribution on the potential

- It is considered that the H^+ ion density obeys the Boltzmann relation in the range of $0.9\text{ V} < \phi_{sim} < 1.4\text{ V}$.
- The H^- ion density distribution is almost consistent with that of H^+ ion density due to the plasma neutrality.



Simulation result for the force balance in H^+ ions



$1.1 \text{ V} < \phi_{sim}^e < 1.4 \text{ V} : |mnV\nabla \cdot \mathbf{V}| < |\nabla p| \quad \longrightarrow \quad ne\mathbf{E} \sim \nabla p \quad \text{Boltzmann relation}$

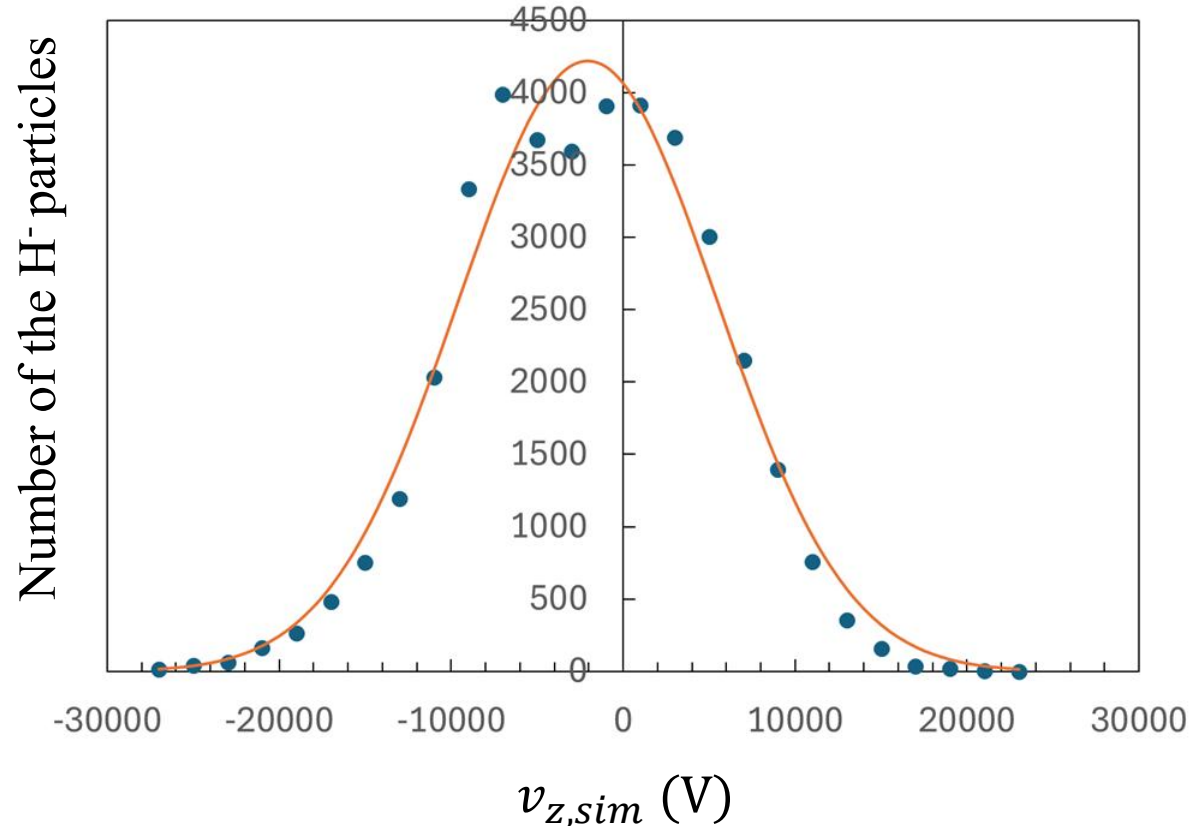
$1.0 \text{ V} < \phi_{sim} \leq 1.1 \text{ V} :$ A balance of force on the source plasma side is not satisfied.
Limitation of the scaled down model??

Summary

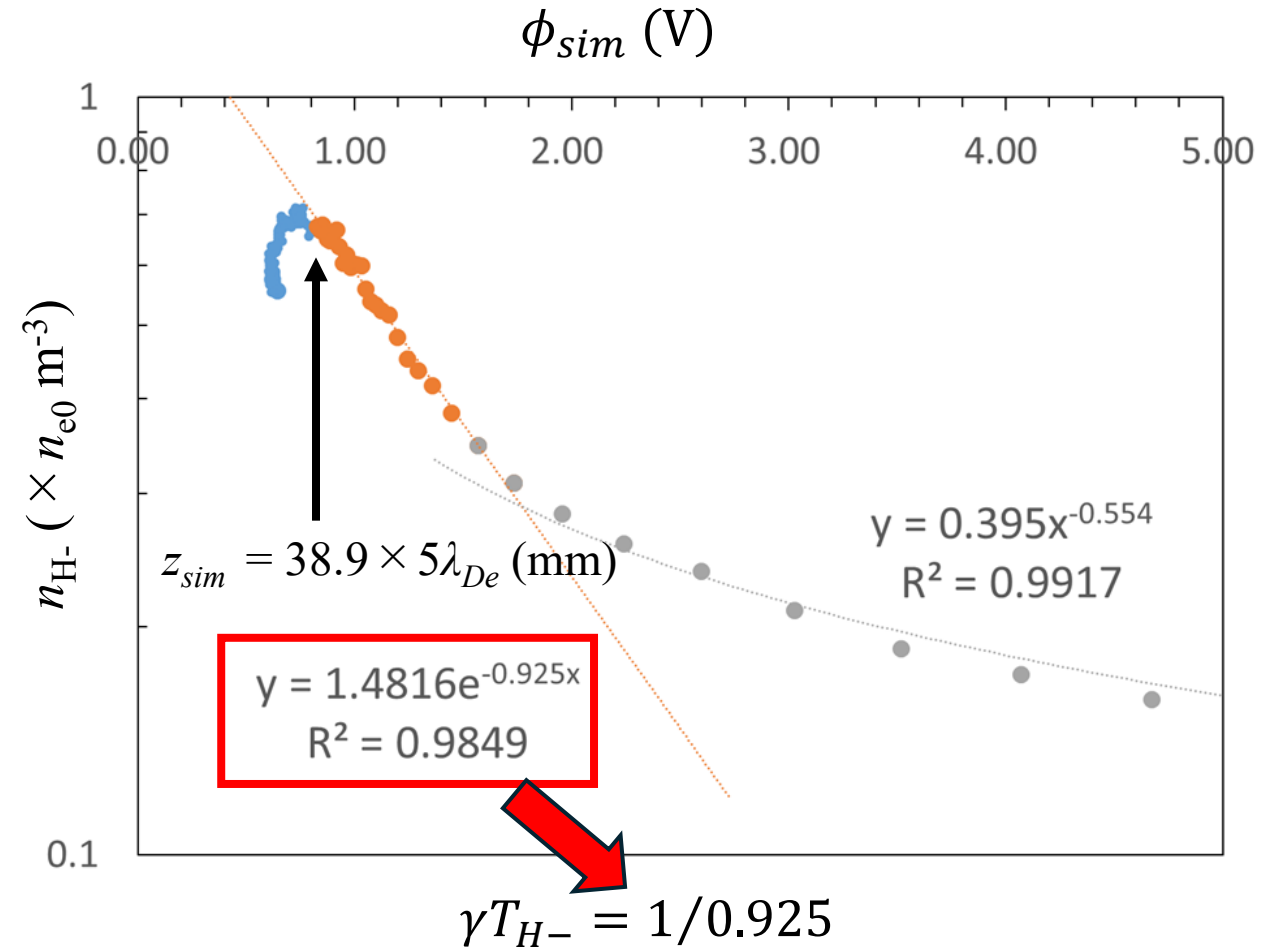
- In 3D3V PIC-MCC simulations with the scaled down model of the negative ion source in which ion-ion plasma is formed, the region around the PG can be broadly classified into two regions based on the potential dependence of the H^- ion density; the boundary between these regions is considered to correspond to the meniscus.
 - $n_{H^-} \propto \exp\left(-\frac{q\phi}{kT_{H^-}}\right)$: Plasma quasi-neutrality condition with H^+ and H^- ions
 - $n_{H^-} \propto 1/\sqrt{\phi}$: Extraction region
- The dependence of H^- ion density distribution on the potential can be explained by the force balance using the fluid equations.
(electric force) $\sim$ (pressure gradient force): n_{H^+} obeys Boltzmann relation
(electric force) $\sim$ (inertia force): $n_{H^-} \propto 1/\sqrt{\phi}$
- The limitations of scaled down models may be apparent; verification via numerical simulation with full scale, even if two-dimensional, will be carried out in the future.

Adiabatic approximation or isothermal approximation? (H⁻ ions)

The distribution of v_z at $z_{sim} = 38.9 \times 5\lambda_{De}$



The distribution of v_z is Maxwellian.
 $T_{H^-} = 0.59$ eV



By substituting $T_{H^-} = 0.59$ eV, we obtain $\gamma = 1.83$.

$\gamma = 5/3$ (Adiabatic approximation for 3D)

$\gamma = 1$ (Isothermal approximation)

Since the velocity distribution of the negative ions is a Maxwellian distribution, the heat flux $\mathbf{q}$ becomes zero, and the adiabatic approximation holds?

Let us consider the x -component:

$$q_x = \frac{nm}{2} \langle w_x w^2 \rangle \quad \mathbf{w} : \text{Random thermal velocity}$$

$$= \frac{nm}{2} \left(\frac{m}{2\pi kT} \right)^{3/2} \left\{ \int_{-\infty}^{\infty} w_x^3 e^{\frac{-mw_x^2}{2kT}} dw_x \int_{-\infty}^{\infty} e^{\frac{-mw_y^2}{2kT}} dw_y \int_{-\infty}^{\infty} e^{\frac{-mw_z^2}{2kT}} dw_z + \int_{-\infty}^{\infty} w_x e^{\frac{-mw_x^2}{2kT}} dw_x \int_{-\infty}^{\infty} w_y^2 e^{\frac{-mw_y^2}{2kT}} dw_y \int_{-\infty}^{\infty} e^{\frac{-mw_z^2}{2kT}} dw_z \right. \\ \left. + \int_{-\infty}^{\infty} w_x e^{\frac{-mw_x^2}{2kT}} dw_x \int_{-\infty}^{\infty} e^{\frac{-mw_y^2}{2kT}} dw_y \int_{-\infty}^{\infty} w_z^2 e^{\frac{-mw_z^2}{2kT}} dw_z \right\}$$

Since $w_x e^{\frac{-mw_x^2}{2kT}}$ and $w_x^3 e^{\frac{-mw_x^2}{2kT}}$ are odd functions, one obtains

$$\int_{-\infty}^{\infty} w_x e^{\frac{-mw_x^2}{2kT}} dw_x = \int_{-\infty}^{\infty} w_x^3 e^{\frac{-mw_x^2}{2kT}} dw_x = 0.$$

Therefore, q_x is 0. Similarly, q_y and q_z are 0.

Scaled physical quantities : scale factor $s = 0.07836$

- size $(\Delta)_{sim} = s(\Delta)_{real}$
- electrostatic potential ϕ : Maintain the perveance of the negative ion beam

$$(\phi)_{sim} = s^{\frac{4}{3}}(\phi)_{real} = 0.034(\phi)_{real}$$

- electric field $(E)_{sim} = \frac{(\phi)_{sim}}{(\Delta)_{sim}} = s^{\frac{1}{3}}(E)_{real} = 0.43(E)_{real}$
- magnetic field: Satisfy $(r_L)_{sim} = s(r_L)_{real}$ (r_L : Larmor radius)

$$(B)_{sim} = s^{-\frac{1}{3}}(B)_{real} = 2.34(B)_{real}$$

- velocity $(v)_{sim} = \sqrt{\frac{(\phi)_{sim}}{(\phi)_{real}}} = s^{\frac{2}{3}}(v)_{real} = 0.18(v)_{real}$

Non-scaled physical quantities : current density J

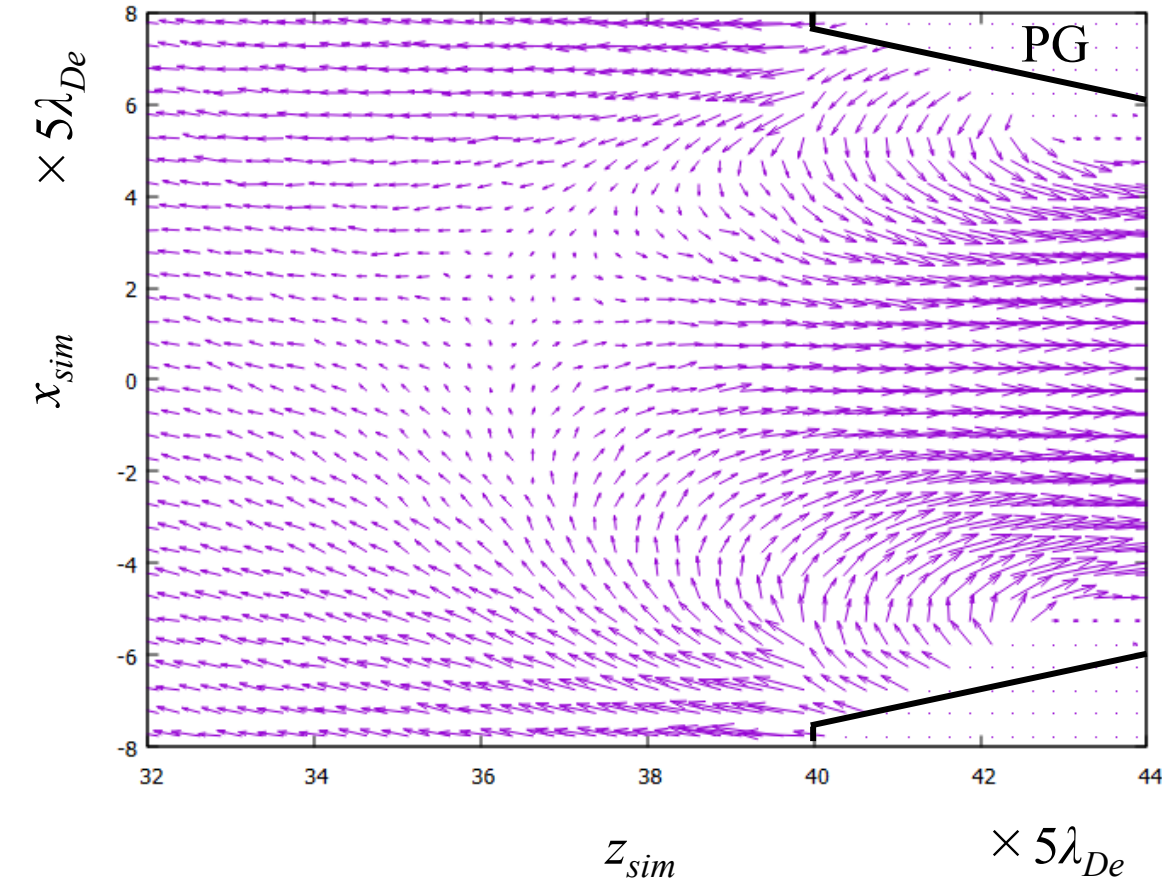
Other

- Regarding the particle densities, we apply weighting including the scale factor s , and show the values after converting them to their actual levels.

Two-dimensional distribution of H^- ion flux J_{H^-} around the PG

Negative ions generated on the surface are emitted from the PG, then reverse their direction within the bulk plasma and are extracted.

Simulation result of J_{H^-}



Experimental result of H^- flow using a Mach probe

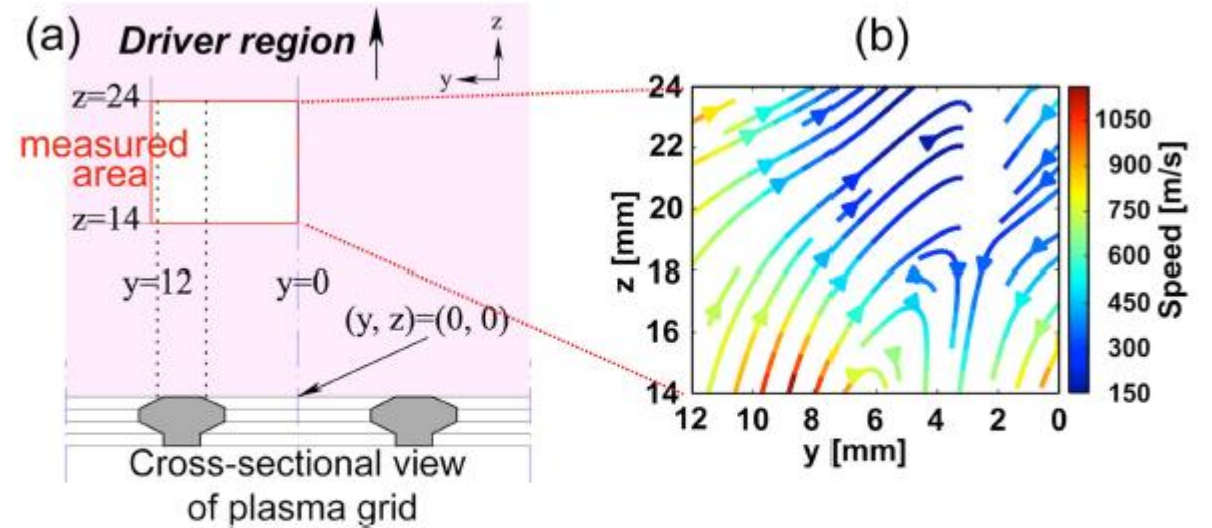


Figure 12. (a) Configuration of the measured area, red rectangle, of H^- ion flow in the beam extraction region and (b) streamlines of H^- flow in the area. This data was obtained at the operational H_2 pressure of 0.3 Pa, discharge power of 50 ± 2.5 kW and the bias voltage of 0 V. Reprinted from 'Response of H^- ions to extraction field in a negative hydrogen ion source' by Geng, Tsumori, Nakano *et al*, in Fusion Eng. Des. (2017) with permission from Elsevier (<https://doi.org/10.1016/j.fusengdes.2017.02.041>).

S. Geng et al., Fusion Eng. Des., **123**, 481-484 (2017).

Method for deriving the ion sheath distance (for plasma composed of electrons and positive ions)

Inside the source plasma

=> Current through the sheath J_{sat}
(Saturation current)

At a wall, the following condition should be satisfied in order to form the sheath:
(ion saturation current) =
(electron saturation current)

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

Current continuity

Outside the source plasma

(between PG and EG)
=> Extracted current J^{ext}
(Child-Langmuir current)

Ion sheath distance d_{eff}

M_i : Mass of H^+ ion

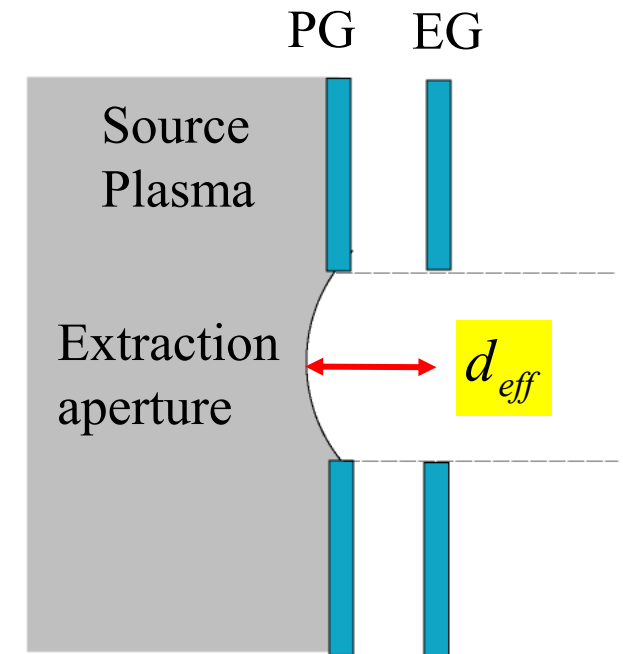
j_s : Ion saturation current

V : Extraction voltage

$$d_{\text{eff}} = \left[\left(\frac{4\epsilon_0}{9} \right) \left(\frac{2e}{M_i} \right) \frac{V^{3/2}}{j_s} \right]^{1/2}$$

or

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



For the surface-produced negative ions, an ion saturation current cannot be defined as it is for positive ions !?

After being emitted from the PG, surface-produced negative ions reverse their direction within the bulk plasma and are extracted.



The ion sheath distance d_{eff} can be evaluated using the negative ion current density J_b emitted from the PG surface, instead of the ion saturation current ?

$$aJ_b = J^{ext} \quad (0 < a \leq 1)$$

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

Substituting $J_b = 146 \text{ A/m}^2$, $a = 1$, $V_{sim} = 90.5 \text{ V}$, one obtains
 $d_{eff, sim} = 0.657 \text{ mm} = 7.23 \times 5\lambda_{De}$ ($\lambda_{De} = 0.0157 \text{ mm}$)
 $z_{sim} = 49 - 7.23 = 41.77 \times 5\lambda_{De}$

