Numerical study of the plasma meniscus shape and beam optics in RF negative ion sources

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Summary

In negative hydrogen ion sources, it is important to control the effective distance d_{eff} between the Plasma Grid (PG) and the Extraction Grid (EG) in order to obtain good beam quality.
However, the parameter dependence of d_{eff} is unclear for the plasma including H⁻ ions. Therefore, the purpose of this paper is to investigate the dependence of d_{eff} on the bulk plasma density n.
As a result of 3D PIC simulation for negative ion sources with surface produced H⁻ ions, we concluded that

- The effective distance d_{eff} is proportional to $n^{-1/2}$, where n is the bulk plasma density even for a large amount of surface H- production. This tendency is the same as the ordinary plasma consisting of only H+ ions and electrons without H⁻ ions.
- Therefore, if the bulk plasma density n is too small, the beam is easily over focused.

1. Introduction

cross sectional view of the region near the extraction hole

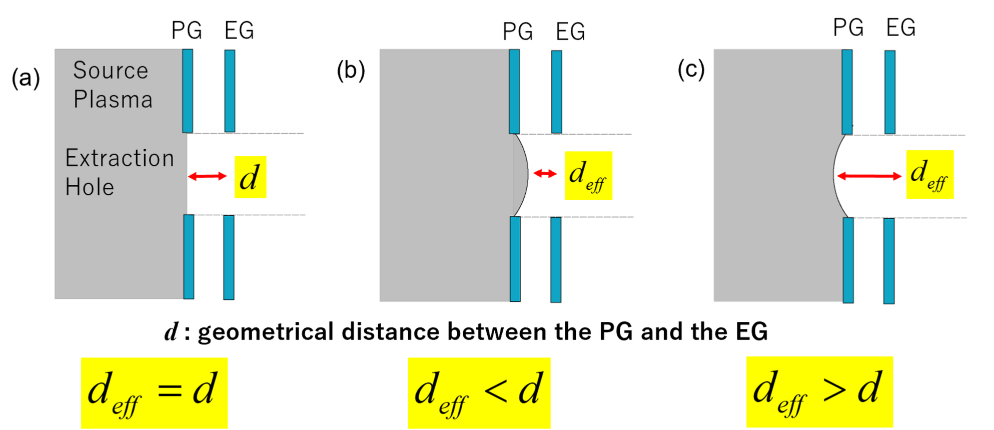


Fig. 1 The dependence of meniscus shape on the effective distance

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

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

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

For **ordinary plasmas** with **only positive ions** and **electrons, the parameter dependence is clear.**
However, for **plasmas including negative ions, key parameters and dependence are still unclear.**

・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.
・In the case(a) plasma meniscus is flat , so perveance matching is good and We can get good beam quality.
・in the case (b) plasma is over-dense. Then meniscus becomes convex. As a result, the extracted beam is diverged.
・in the case (c) plasma is under-dense. Then meniscus becomes concave. As a result, the extracted beam is over-focused then diverged.

Purpose of this paper

Investigation of the dependence of the plasma meniscus on the bulk plasma density in negative ion sources

2. Simulation Model

3D-PIC code[1,2]

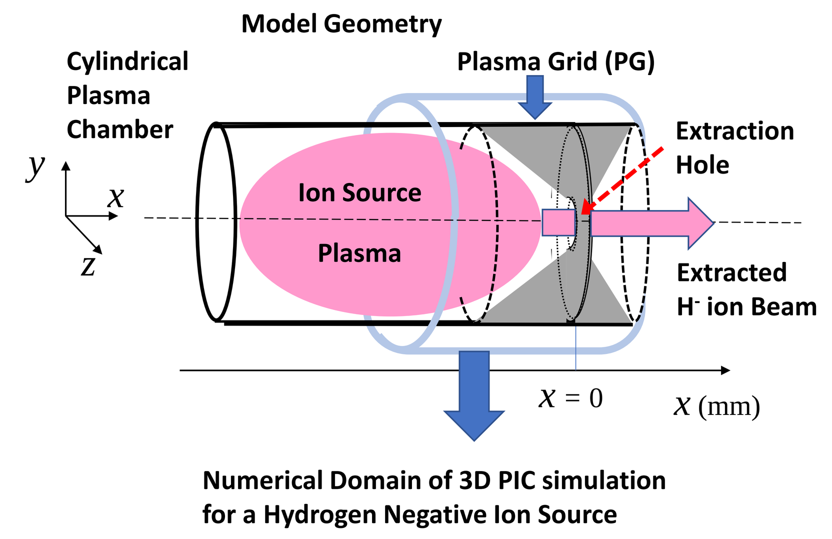


Fig. 2 The model geometry of 3D PIC code

3D Electrostatic PIC Basic Eqs.

Eq. of Motion

$$m_j \frac{d\boldsymbol{v}_j}{dt} = e_j\left[\boldsymbol{E} + (\boldsymbol{v}_j \times \boldsymbol{B})\right]$$
+ Monte-Carlo Collision
$(j = \mathrm{H}^+, \mathrm{H}^-, \text{electron})$

Poisson's Eq.

$$\nabla^2\phi = -\frac{\rho}{\varepsilon_0}$$

$$\rho = \sum_j e_j n_j$$

The following effects are taken into account

- Filter magnetic field. (the direction is parallel to the y axis)
- Dissociative Attachment for electrons, i.e., Volume Production. → Monte-Carlo Collision
- Surface Production on the PG.
  → negative ions injected from the random position on the PG. the velocity is produced by the Box-Muller Method.
  → the amount of Surface Produced negative ions increases "k" times as the bulk plasma density increases k times. (k =0.5, 0.75, 1.25, 1.5) → calculation condition

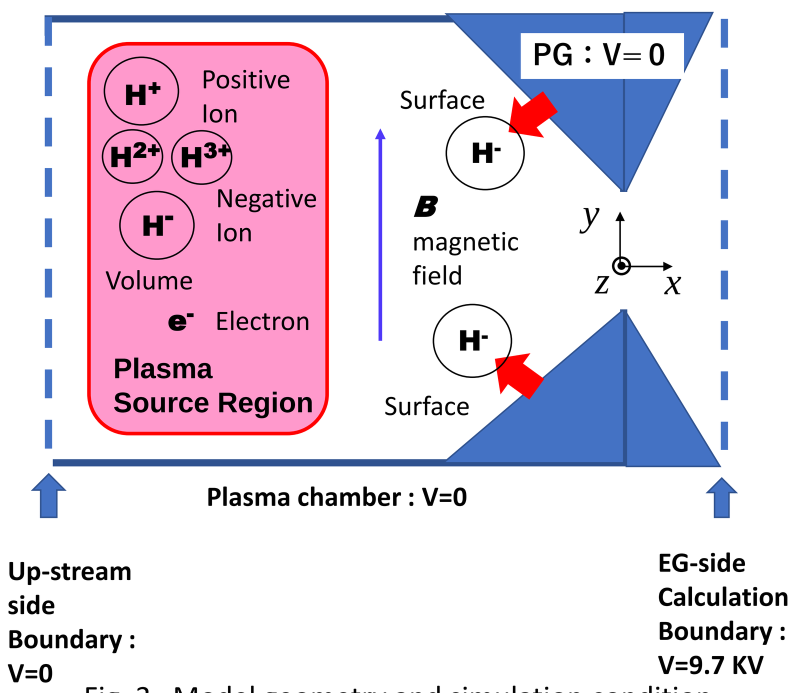


Fig. 3 Model geometry and simulation condition

Table. 1 The plasma parameter in the simulation

Parameters	Values used for PIC simulation
Reference Bulk Plasma Density (n_{p0})	1.0×10^{18} m^{-3}
Electron Temperature	3.6 eV
H⁺ and H⁻ Ion Temperature	1.6 eV
e⁻ : H⁺ : H²⁺ :H³⁺:H⁻	59.9 : 45 : 4.5 : 11.3 : 0.9
Reference Surface produce rate(Sp_0)	1168 A/m ²

Calculation condition

The effective distance depends on V and n for the ordinary plasma.
→ the extracted voltage V is constant.(9.7 kV)
→ the bulk plasma density n is changed by the plasma density inserted into Source Region (electron density is n_{p0} and the others particle's density is followed in the ratio on the Table .1.)
→ electron density is $k \times n_{p0}$ → the bulk plasma density is k times (k =0.5, 0.75, 1.25, 1.5)
Surface production rate is $k \times Sp_0$ as electron density increases k times.

Investigation of the dependence of the plasma meniscus on the bulk plasma density

3. Results and Discussion

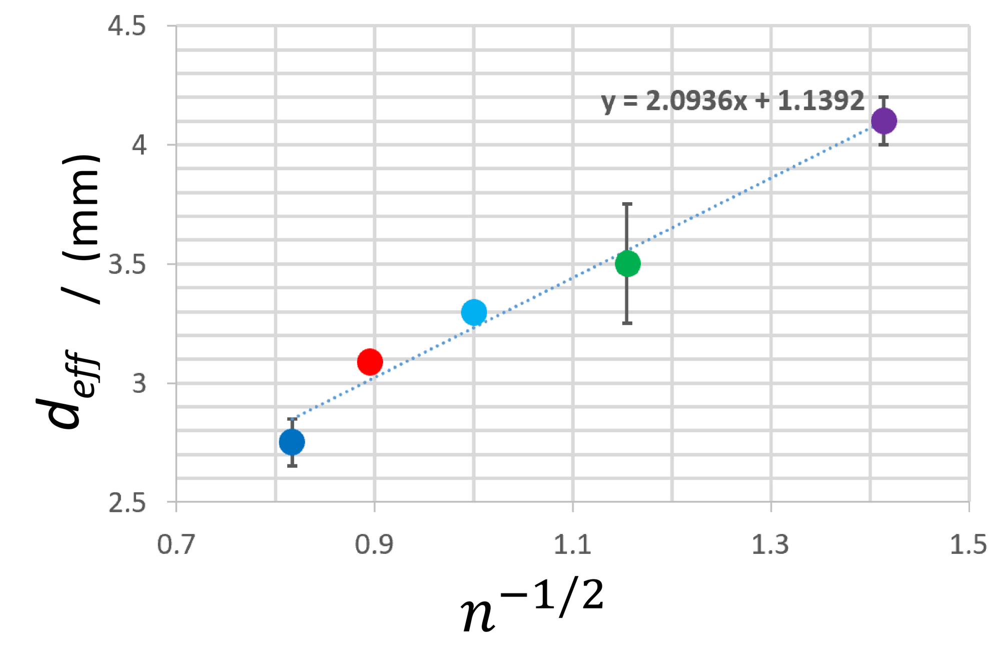


Fig. 4 The dependence of the bulk plasma density on the effective distance
(Here we define the effctive distance deff as deff=(dmin +dmax)/ 2 , where dmin and dmax are the respectively minimum and maximum distance between $n = 0.1n_{p0}$ equi-contour line and the Line A.)

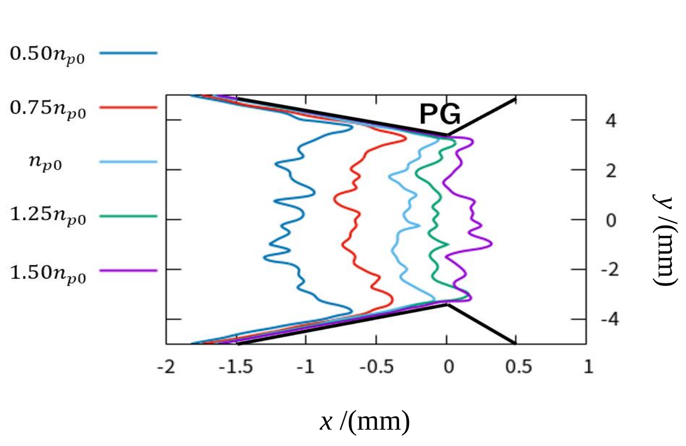
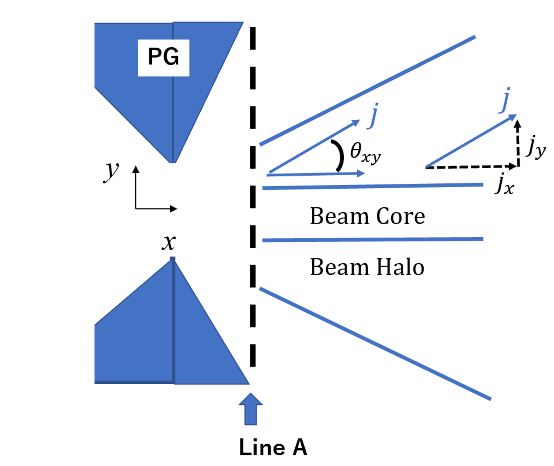


Fig.5 Comparison of the plasma meniscus for each case of the bulk plasma density
($n = k \times n_{p0}$ with k =0.5,0.75,1.0,1.25 and 1.50, where n_{p0} is the bulk plasma density for the reference case and set to be 10^{18}. We define here plasma meniscus as the equi-contour line of n =0.1 n_{p0}.

・The effective distance d_{eff} is proportional to $n^{-1/2}$ same as the ordinary plasma which consists of only electrons and positive ions.

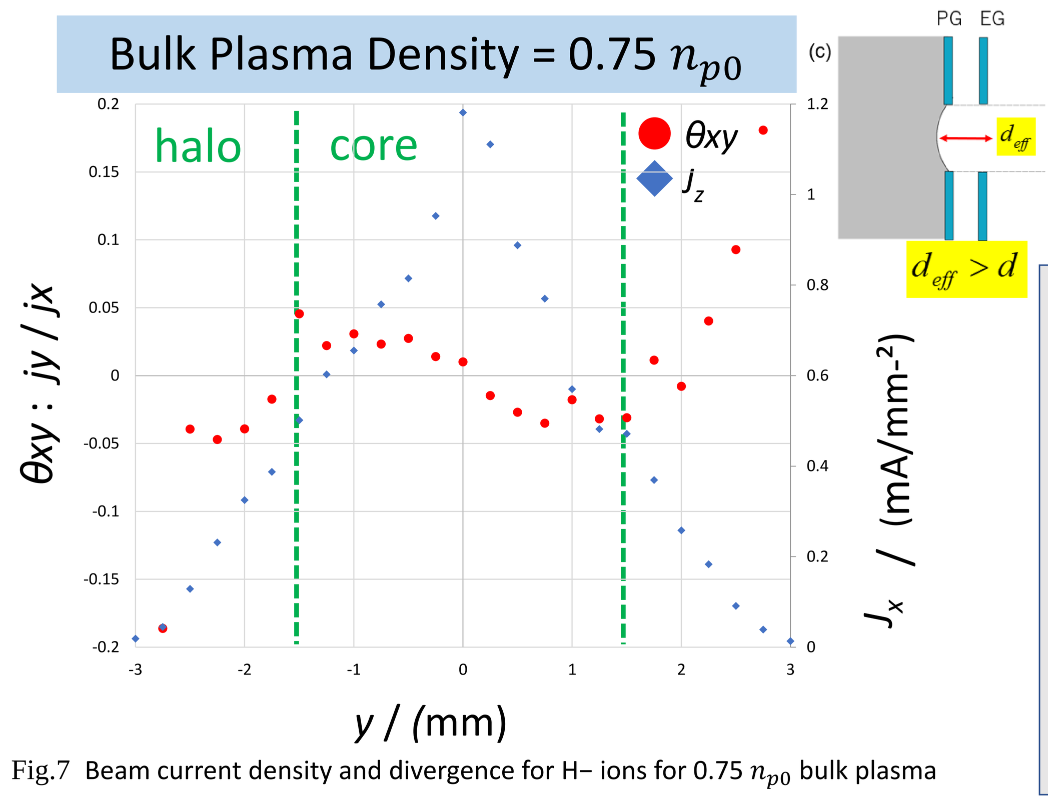


j : current density through the Line A
j_y : y-component of j
j_x : x-component of j
θxy : jy / jx

We investigate the beam divergence used by the current density through the Line A.

Fig.6 Beam divergence θxy and Beam current density

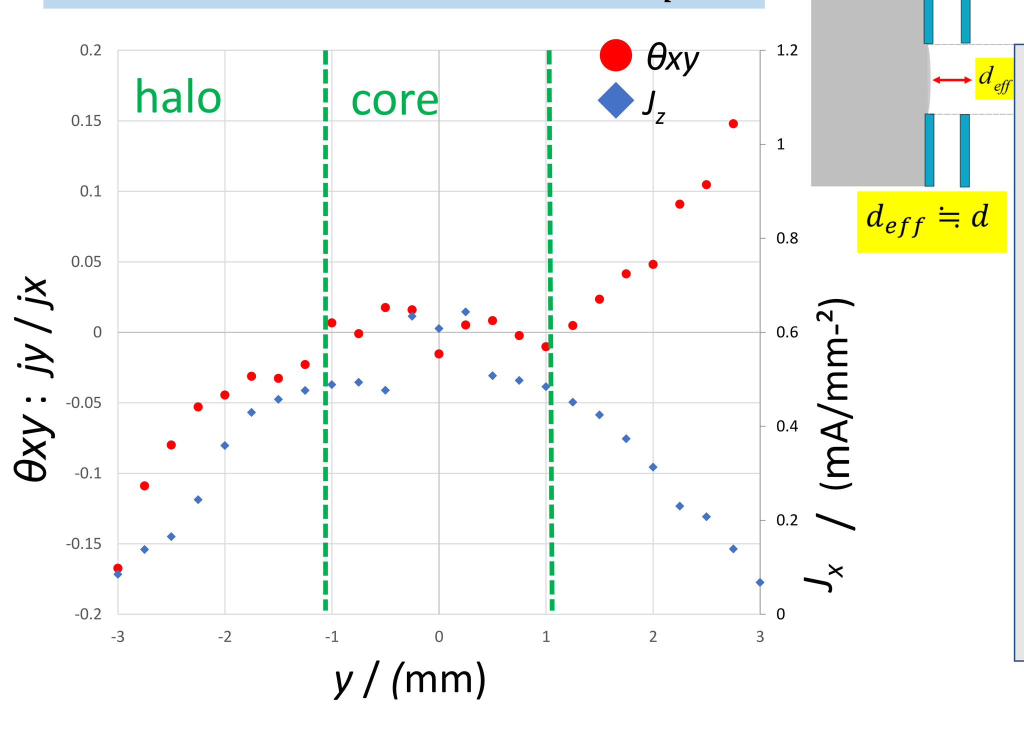
Bulk Plasma Density = 0.75 n_{p0}



The meniscus shape is concave.
Beam optics is poor than that of 1.25 n_{p0}.
In this low density case, the beam core component tends to be converged, i.e., θxy < 0 for r > 0, while θxy >0 for r < 0.
However, the value of θxy is relatively large. As s result, these beam components with large θxy is possibly over-focused and then becomes halo-component in the right hand side region of their focal points after passing through the Line A.

Fig.7 Beam current density and divergence for H– ions for 0.75 n_{p0} bulk plasma

Bulk Plasma Density = 1.5 n_{p0}



The meniscus shape is a little convex.
Beam optics is a little poor.
In this high density case, the beam core component has relatively small divergence angle. This means the meniscus shape becomes almost flat.
In addition, the beam halo components exist outside the core component. Their focal points are located at the left hand side of the Line A.
If we calculate the case with higher density, then the meniscus shape possibly becomes convex.

Fig.8 Beam current density and divergence for H– ions for 1.5 n_{p0} bulk plasma

4. Future Problem

① Calculate higher density cases to confirm that the meniscus shape becomes convex
② Systematic study of other key parameters as the effective distance
ex. plasma temperature, extraction voltage, the amount of surface produced H⁻ ions
③ More systematic survey of effective collision
・For low neutral gas pressure, it is pointed out in Ref [3] that Coulomb collision is important for extracting SP H⁻ ions due to the velocity reversal.
・For high pressure case, elastic collision of neutral particles may be important.
④More realistic model of surface production

Reference

[1] S. Nishioka, et al., J.Appl.Phys. **119**, 023302(2016).
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[3] K. Nisida, et al., J. Appl. Phys. **119**, 233302 (2016).