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Numerical analysis of negative hydrogen ion beam optics by using the 3D3V PIC simulation

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Introduction (I)

- A negative ion source which can produce negative ion beams with high power and long pulse is the key component for the negative ion based NBI system for plasma heating and current drive of magnetic fusion reactors.

- It is essential for the development of such a negative ion source to suppress heat loads of the acceleration grids and beamline components.

- The heat loads of acceleration grids are mainly caused by the direct interception of H^- ion beam as well as electrons stripped from negative ions in the accelerator.

- Especially, a beam halo can result in the heat loads even at the optimum perveance for the beam core.

The beam halo is observed directly as the beam profile, or indirectly as a component of the heat loads in the accelerator grids.

Beam halo component in the negative ion beam profile

1. H.P.L. de Esch, L. Svensson, Fusion Engineering and Design **86**, 363 (2011)

Beam halo can be clearly observed on the log scale.

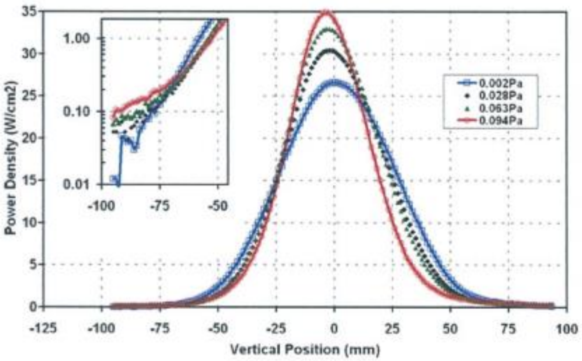
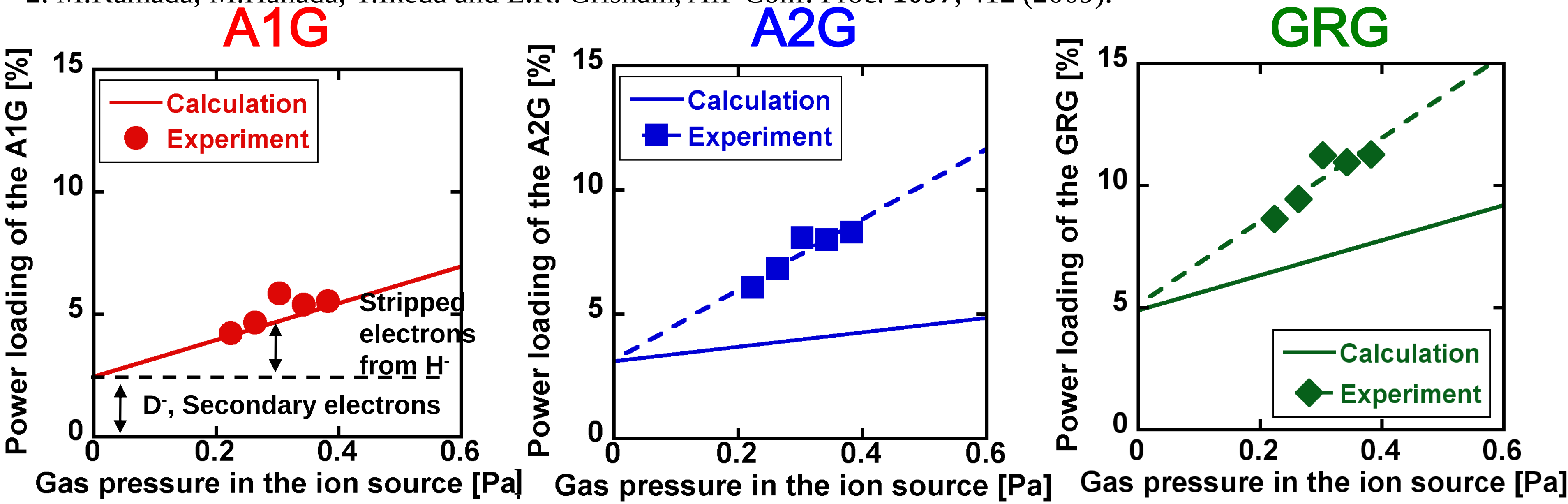


Fig. 7. Measurement of the single beamlet profiles on the carbon beam target using the infrared camera. Four beamlet profiles, each taken at a different helium gas background pressure, are shown. The inset shows the beam halo more clearly on a logarithmic scale.

Heat load on the acceleration grids due to the interception of negative ion beam

2. M.Kamada, M.Hanada, Y.Ikeda and L.R. Grisham, AIP Conf. Proc. **1097**, 412 (2009).



Introduction (II)

- In order to clarify the physics of the H^- ion extraction and beam optics such as the beam halo formation, and contribute to the design of a negative ion source, the previous 3D3V PIC model combined with a Monte Carlo calculation is extend to the integrated model of negative ion beam from plasma meniscus formation to the beam acceleration.

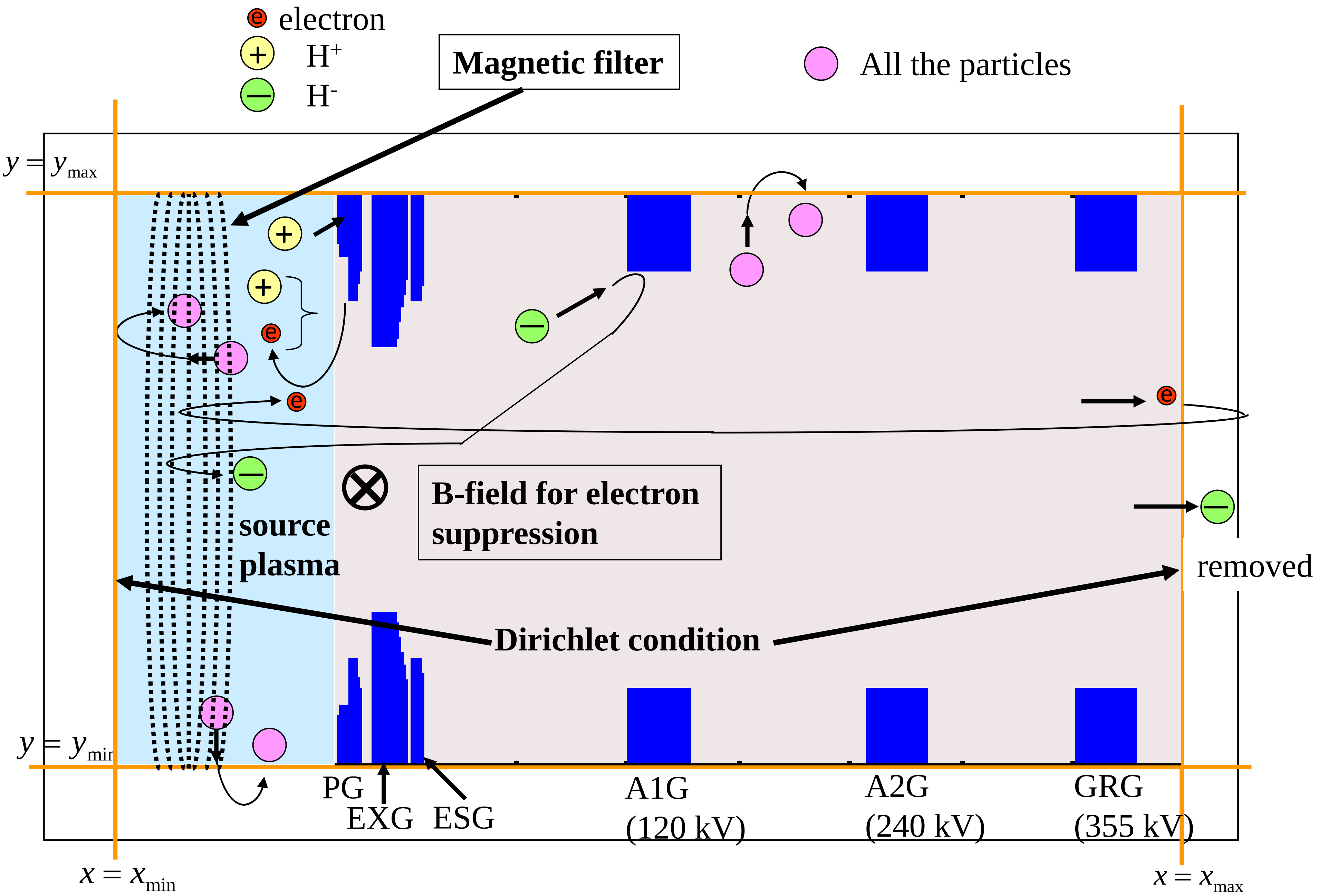
- Our model makes it possible to simulate not only the source plasma with surface H^- production, but also the H^- acceleration self-consistently without any assumption of plasma meniscus, while the most of the conventional beam acceleration codes/models need the assumptions for the plasma meniscus.

- Furthermore, different from the previous model[3] in which the negative ion trajectories from the plasma meniscus to the extractor are calculated with the 3D3V PIC, and those in the accelerator are calculated with the commercial software separately, the artificial electric fields generated around the boundaries can be avoided.

- In this study, the beam optics including the beam halo is estimated quantitatively from the viewpoints of the heat loads in the accelerator and the emittance of the negative ion beam.

3. K. Miyamoto, S. Nishioka, I. Goto, A. Hatayama, A. Kojima, and J. Hiratsuka, Rev. Sci. Instrum., **87** 02B124/1-3 (2016).

3D3V PIC simulation model (I)



Main physical parameters

Physical parameter	**Value**
Electron temperature	1 eV
Hydrogen ion temperature	0.25 eV （H^+） 0.25 eV（volume produced H^-） 1 eV（surface produced H^-）
Electron density	1.0×10^{18} m^{-3}
Hydrogen atom temperature	0.2 eV
Hydrogen molecule temperature	0.1 eV
Hydrogen molecular density	1.88×10^{19} m^{-3}
Density ratio n_H/n_{H2}	0.5

3D3V PIC simulation model (II)

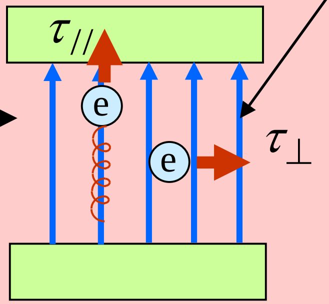
Electron Diffusion process across the transverse magnetic field due to Coulomb collision and electron-neutral collision

A random-walk process with step lengths

$$\Delta\tilde{x}_d = \sqrt{2\tilde{D}_\perp \Delta\tilde{t}} \times \xi_x \times \sqrt{\tau_{//}/\tau_\perp}$$

normalized random number

Magnetic filter

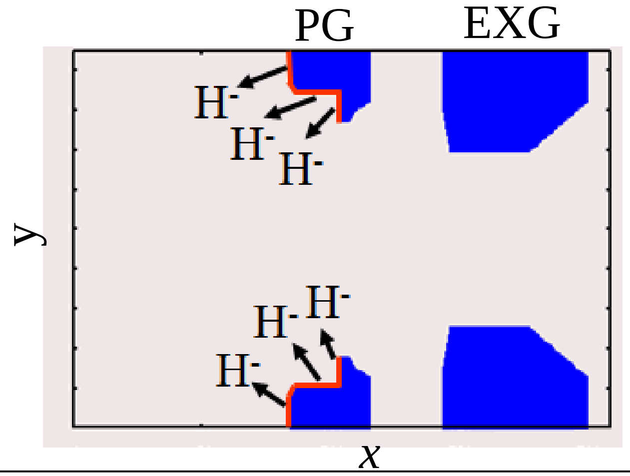


$\tau_{//}$ A characteristic time of electron escape to the arc chamber

$\tau_\perp$ A characteristic time of electron diffusion across the magnetic filter

Modeling of the surface produced negative ions

Surface produced negative ions are uniformly launched from the PG surface with a half-Maxwellian distribution.



3D3V PIC simulation model (III)

- Initial number of super-particles :

  2.96×10^7 (electron), 3.11×10^7 (H^+), 0.15×10^7 (volume produced H^-)

- The number of numerical grid is 2472 × 153 × 153 in the x, y and z directions respectively, which corresponds to 309 mm × 19 mm × 19 mm in real size.

- Electrons, H^+ ions, and volume produced H^- ions are assumed to be launched with Maxwellian distributions. The surface produced H^- ions are assumed to be launched with half-Maxwellian distribution.

- The following collision processes are taken into account as the energy relaxation processes of H^- ions.

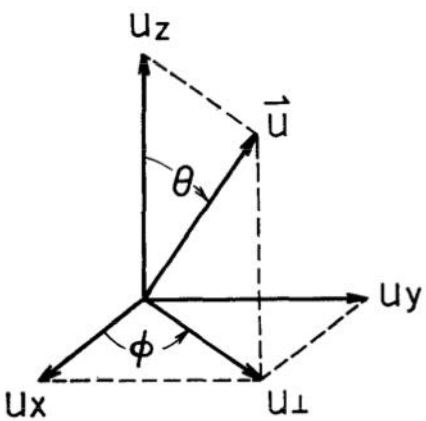
1) Coulomb collision
A binary collision model by the Monte Carlo method is used.

2) Charge exchange collision (H^- (fast) + H (slow) → H^- (slow) + H (fast))
The null collision model is used.

- In the present model, the mutual neutralization ($H^- + H^+ \rightarrow H + H$) is taken into account as H^- ion destruction process.

Binary collision model by the Monte Carlo method

A binary collision model (BCM)[2] by the Monte Carlo method is applied to the Coulomb collision with the H^+ ions.



$$\Phi = 2\pi\delta_1 \qquad \langle \delta_2 \rangle = 0$$

$$\theta = 2\arctan\delta_2 \qquad \langle {\delta_2}^2 \rangle = \frac{n_L (e_1 e_2)^2 \ln\Lambda}{8\pi\varepsilon_0^2 m_{\alpha\beta} u^3}\Delta t$$

δ_1, δ_2 : uniform random number

n_L : particle density

$m_{\alpha\beta}$: reduced mass

$\ln\Lambda$: Coulomb logarithm

Δt : time step

$$\Delta u_x = \frac{u_x}{u_\perp} u_z \sin\theta\cos\Phi - \frac{u_y}{u_\perp} u \sin\theta\sin\Phi - u_x(1-\cos\theta)$$

$$\Delta u_y = \frac{u_y}{u_\perp} u_z \sin\theta\cos\Phi - \frac{u_x}{u_\perp} u \sin\theta\sin\Phi - u_y(1-\cos\theta)$$

$$\Delta u_z = -u_\perp \sin\theta\cos\Phi - u_z(1-\cos\theta)$$

$$u_\perp = \sqrt{u_x^2 + u_y^2}$$

4. T. Takizuka and H. Abe, J. Comput. Phys. **25**, 205-219 (1977).

Model of the charge exchange collision

- As for the charge exchange collision, an electron moves from the surface produced H^- ion (fast ions) to a slow H atom, which is then leaves behind a slow scattered H^- ion.
- This slow H^- ion is scattered isotopically: the scattering angles are randomly chosen as

$$\theta = \pi U_1, \Phi = 2\pi U_2 \qquad (U_2, U_3\text{: a uniform random number})$$

- The speed of the scattered H^- ion is chosen to match the H atom velocity distribution (T_H = 0.2 eV).
- Whether the charge exchange collision occurs or not is determined by using the null collision model[3]. In the present model, the mutual neutralization ($H^- + H^+ \rightarrow H + H$) is taken into account other than the charge exchange collision.

$$R \le \upsilon_1(E_i)/\upsilon' \text{ (collision type 1)}$$

$$\upsilon_1(E_i)/\upsilon' < R \le (\upsilon_1 + \upsilon_2)/\upsilon' \text{ (collision type 2)}$$

$$\vdots$$

$$\sum_{j=1}^{N} \upsilon_j(E_i) \Big/ \upsilon' < R \text{ (null collision)}$$

E_i : energy of the particle i

$$\upsilon' = \max(n_T \sigma_T \nu)$$

$$\sigma_T = \sigma_1 + \cdots \sigma_N$$

υ_j collision frequency for the collision type j

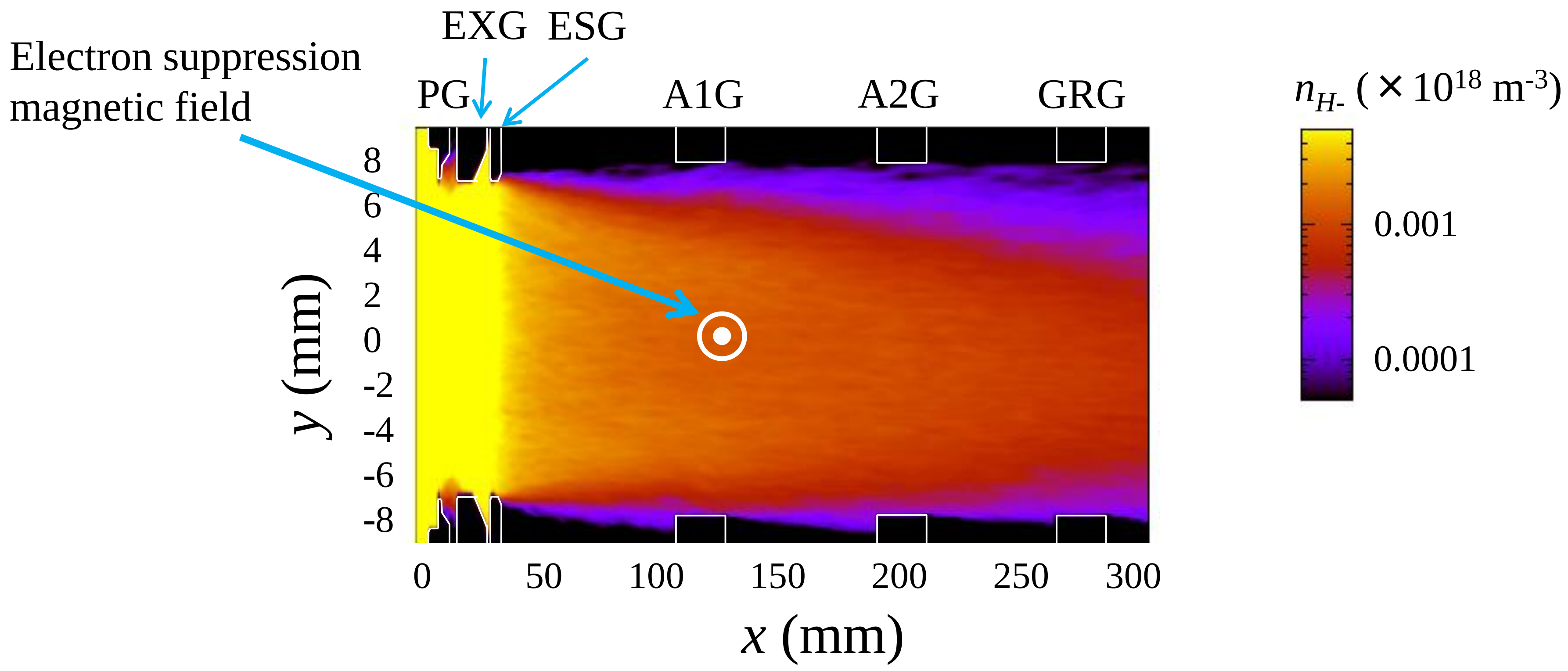
R : uniform random number

5. V. Vahedi, M. Surendra, *Comput. Phys. Commun.*, **87**, 179-198 (1995).

Two dimensional profile of the H^- density

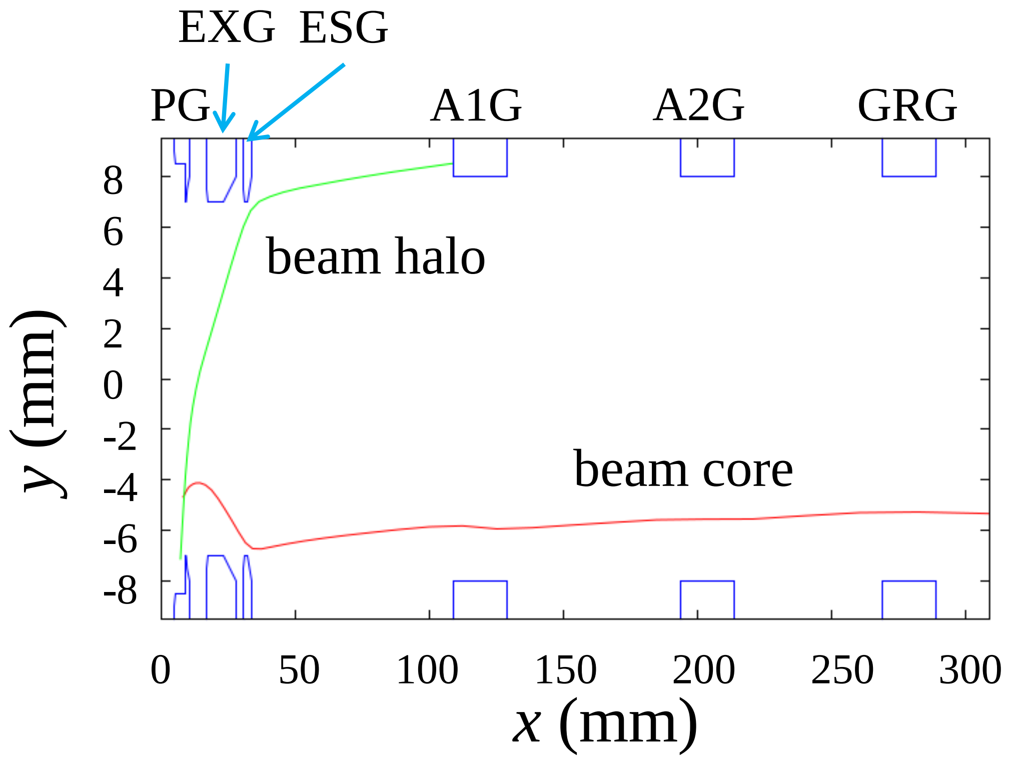
Some of the negative ions are intercepted on the grids in the accelerator, although most of the negative ions pass through the GRG aperture without interception.

The intercepted negative ions correspond to the beam halo, and cause the heat loads of the grids in the accelerator.



An example of the trajectories of the beam core and the beam

As reported in our previous study[6], the beam halo consists of the negative ions extracted from the periphery of the plasma meniscus, while the beam core consists of the negative ions extracted from the center of the plasma meniscus. The beam halo is over-focused in the extractor due to the large curvature at the periphery of the plasma meniscus and then, divergent.



6. K. Miyamoto, S. Okuda, A. Hatayama, M. Hanada, and A. Kojima, Appl. Phys. Lett., **102**, 023512/1- 3(2013).

Estimation of the heat loads due to the beam halo in the accelerator

K : the negative ion beamlets intercepted at each acceleration grid
N : a total negative ion beamlet

$$\sum_{k} V_k I_k \Big/ \sum_{j=1}^{N} V_j I_j$$

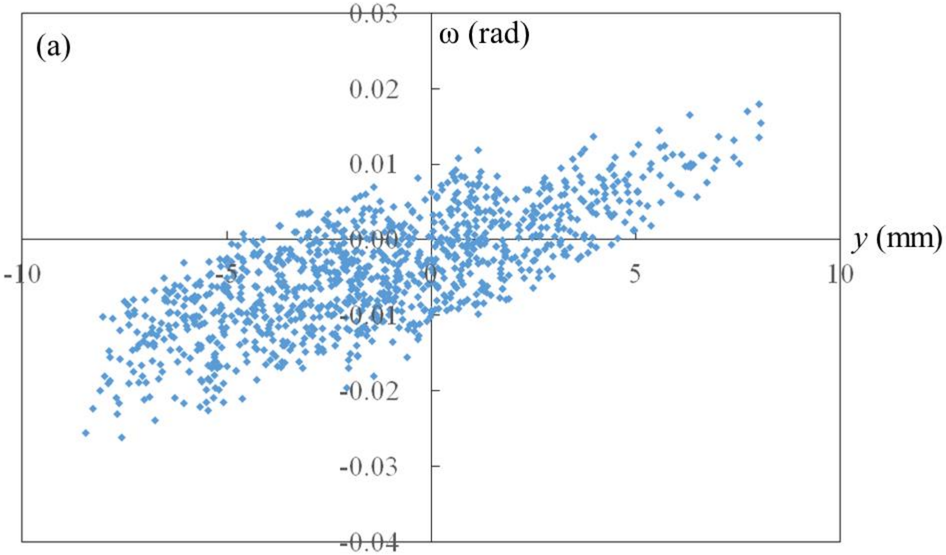
Acceleration grid	Experimental result (extrapolated to 0 Pa)	3D3V PIC simulation result
A1G	2.4 %	0.9 %
A2G	3 %	2.3 %
GRG	5 %	3.6 %

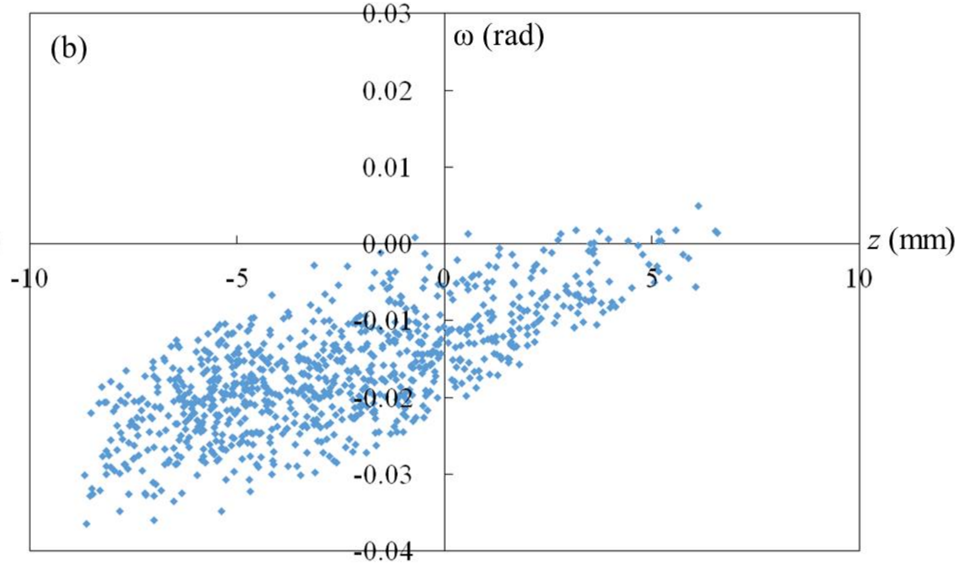
As fort the A2G and the GRG, the simulation result almost agrees with the experimental result.

The contribution of the secondary electrons will be one of the reasons for the difference of the heat load of the A1G between the 3D PIC simulation and the experimental result.

Emittance of the negative ion beam

Emittance diagrams of the negative ion beam after the exit of the GRG on the plane perpendicular to (a) the magnetic filter, and (b) the electron suppression magnetic field





The normalized rms emittances ε_y and ε_z are estimated to be 0.24π mm mrad, and0.26π mm mrad, respectively. These values are compatible with the typical normalized rms emittances of the negative ion source.

$$\varepsilon_y = 4\sqrt{\overline{(y-\bar{y})^2}\,\overline{(y'-\bar{y}')^2} - \overline{(y-\bar{y})(y-\bar{y}')}^2} \times \frac{\beta}{\sqrt{1-\beta^2}},$$

$$\varepsilon_z = 4\sqrt{\overline{(z-\bar{z})^2}\,\overline{(z-\bar{z}')^2} - \overline{(z-\bar{z})(z-\bar{z}')}^2} \times \frac{\beta}{\sqrt{1-\beta^2}},$$

$$\beta = \frac{v_x}{c}.$$

Summary

The beam optics including the beam halo is estimated quantitatively from the viewpoints of the heat loads in the accelerator and the emittance of the negative ion beam by using the 3D3V PIC model combined with a Monte Carlo calculation. The negative ion beam from plasma meniscus formation to the beam acceleration is modeled, and the plasma meniscus can be solved self-consistently.

- It is shown that for the heat loads of the A2G and the GRG, the simulation result almost agrees with the experimental result.
- It is indicated that the contribution of the secondary electrons will be one of the reasons for the difference of the heat load of the A1G between the 3D3V PIC simulation and the experimental result.
- The emittance of the normalized rms emittance of the negative ion beam after the exit of the GRG is estimated to be around 0.25 π mm mrad, which are compatible with the typical values of the negative ion sources.

Future Plane

The secondary electrons from the extractor will be taken into account, and the contribution of these secondary electrons to the heat loads of the A1G in particular will be analyzed.