Fully kinetic analysis of radio frequency plasma generation and acceleration in magnetic nozzle thrusters

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Fully kinetic analyses were conducted to evaluate the kinetics of plasma generation and acceleration in magnetic nozzle thrusters. The momentum conversion and energy transport in the magnetic nozzle were also clarified through simulations. The main topics of this study are high-energy electron transport, internal plasma currents, axial momentum gains, and energy losses in magnetic nozzle thrusters. To perform fully kinetic simulations, a two-dimensional and symmetric calculation model was employed, including both the plasma source and diffusion region in the magnetic nozzle.

Electron heating and density profile transitions were evaluated by changing the intensity of the magnetic field. The bimodal plasma profile observed in the previous experiments was reproduced in the simulations. The density profile transition is discussed with respect to the ionization, electron temperature, and high-energy electron number density. It is shown that high-energy electrons are transported by an elastic collision across the magnetic field lines and generate a bimodal density profile in the strong magnetic nozzle, implying a longer existing time for high-energy electrons that move radially inward away from the rf antenna.

The internal plasma currents in the magnetic nozzle were numerically obtained in the simulations and were found to be diamagnetic and $\boldsymbol{E} \times \boldsymbol{B}$ drift effects in addition to other drift components. The diamagnetic drift current increases and becomes dominant in a strong magnetic nozzle, whereas the $\boldsymbol{E} \times \boldsymbol{B}$ drift current decreases with increasing magnetic field strength, which is consistent with previous experimental results. The electromagnetic thrust induced by the internal plasma currents was also calculated, indicating an increase in the electromagnetic thrust with increasing magnetic field intensity.

The electrostatic and Lorentz forces in the magnetic nozzle were obtained in the simulations, and the axial ion and electron momentum gains from these forces were calculated. The simulation results show that the Lorentz force in the magnetic nozzle exceeds the electrostatic force with a strong magnetic field. In this situation, the axial electron momentum gain due to the Lorentz force also exceeds the axial ion momentum gain, implying that the axial electron momentum gain becomes dominant in the magnetic nozzle. Additionally, it was confirmed that the electron momentum gain was due to the momentum conversion from the radial to axial directions.

The energy losses in the magnetic nozzle were calculated to further improve the thruster efficiency. The major energy loss in a weak magnetic field is the energy loss to the dielectric wall. As the magnetic field strength increased, the energy loss to the dielectric was suppressed, and the plasma beam energy contributing to thrust generation increased. Although there is essential energy loss due to electron-neutral collisions and the divergent ion beam, it is indicated that the thruster efficiency in the magnetic nozzle could be further improved by increasing the intensity of the magnetic field.