7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Demonstrating a thrust generation by electrons in a magnetic nozzle rf plasma thruster

Soya Sumikawa[1] and Kazunori Takahashi[1,2]
[1]Department of Electrical Engineering, Tohoku University, Sendai 980-8579, Japan
[2]National Institute for Fusion Science, Toki 509-5292, Japan
e-mail (speaker): sumikawa.soya.t6@dc.tohoku.ac.jp

In the last few decades, electric propulsion systems such as a gridded-ion thruster, an electron cyclotron resonance thruster, and a Hall thruster [1-3], which generate thrust by ions, have been vigorously investigated. Especially in recent years, a magnetic nozzle (MN) radiofrequency (rf) plasma thruster [4,5] (called a helicon thruster) is often the subject of studies. The MN rf plasma thruster typically consists of an rf antenna, an insulated glass tube, and a solenoid; it has an electrodeless structure that allows a long lifetime even in a high-power operation. The processes of thrust generation have been investigated [6-8] in detail, and now the thruster efficiency approaching thirty percent has been obtained [9], while further clarification of the mechanism is required yet.

The total thrust imparted by the MN rf plasma thruster can be given by [10]

$$T_{\mathrm{total}} = T_s + T_w + T_B, \qquad (1)$$

where T_s, T_w, and T_B is the static electron pressure force onto the back wall of the plasma source, the axial momentum lost to the radial source wall, and the Lorentz force exerted to the MN, respectively. The terms on the RHS in Eq. (1) can be measured individually [10] by attaching the back wall, the source tube, and the solenoid to the thrust balance, respectively. The previous study shows that the Lorentz force T_B arising from the azimuthal internal current j_θ and the radial magnetic field B_z is the major contributor to the thrust; T_B and j_θ are given by [10]

$$j_\theta = \frac{1}{B_z}\frac{\partial p_e}{\partial r} + e n_e \frac{E_r}{B_z} + \frac{1}{B_z}\frac{\partial p_i}{\partial r} - e n_i \frac{E_r}{B_z} + \frac{1}{B_z}\left[\nabla \cdot \left(m_i n_i \boldsymbol{v}_i^2\right)\right]_r \qquad (2)$$

$$T_B = \int j_\theta \times B_r \, dV \approx -2\pi \int_0^z \int_0^{r_p} r \frac{B_r}{B_z}\frac{\partial p_e}{\partial r} dr dz, \qquad (3)$$

where, r_p, B_z, p_e, p_i, n_e, n_i, $\boldsymbol{v}_i$, E_r, and e are the plasma radius, axial magnetic field, electron and ion pressure, density, ion velocity, radial electric field, and elementary charge, respectively. In previous studies [7,10,11], only the first term of the RHS in Eq. (2), i.e., the electron diamagnetic current, was considered, assuming that an axisymmetric plasma with cold ions and electron and radial ion inertia is negligible. As a result, the form of the RHS in Eq. (3) can be derived, which indicates that even though the mass of an ion is much heavier than the mass of an electron, most of the thrust imparted to the MN rf plasma thruster is contributed from the electrons. Textbooks on the electric propulsion, e.g., [12], said that the major contributor for the thrust is the ions due to their significant momentum; deep understanding on the thrust generation by the electrons will be useful to improve the thruster performance. Especially, it is challenging and interesting to demonstrate the thrust generation by the electrons in the MN.

In this study, an electron beam plasma source that can provide a plasma potential V_p close to zero [13] is used to demonstrate the above-mentioned electron-oriented thrust generation, where only the solenoid is attached to the thrust balance to measure T_B solely as shown in Fig. 1. The results show that the electrons generate the thrust with a 1.2 cm diameter plasma source (diameter of the filament).

References

[1] J. R. Brophy, Rev. Sci. Instrum. **73**, 1071-1078 (2002)
[2] A. Sánchez-Villar *et al*, Plasma Sources Sci. Technol. **30**, 045005 (2021)
[3] J. P. Boeuf, J. Appl. Phys. **121**, 011101 (2017)
[4] C. Charles, J. Phys. D: Appl. Phys. **42**, 163001 (2009)
[5] K. Takahashi, Rev. Mod. Plasma Phys. **3**, 3 (2019)
[6] A. Fruchtman, Phys. Rev. Lett. **96**, 065002 (2006)
[7] K. Takahashi *et al*, Phys. Rev. Lett. **107**, 235001 (2011)
[8] M. Merino and E. Ahedo, Phys. Plasmas **23**, 023506 (2016)
[9] K. Takahashi, Sci. Rep. **12**, 18618 (2022)
[10] K. Takahashi *et al*, Phys. Rev. Lett. **110**, 195003 (2013)
[11] K. Takahashi *et al*, Plasma Source Sci. Technol. **25**, 055011 (2016)
[12] D. M. Goebel and I. Katz, "Fundamentals of Electric Propulsion: Ion and Hall Thrusters" (John Wiley & Sons, NJ, USA, 2008)
[13] K. Takahashi *et al*, Phys. Rev. Lett. **120**, 045001 (2018)

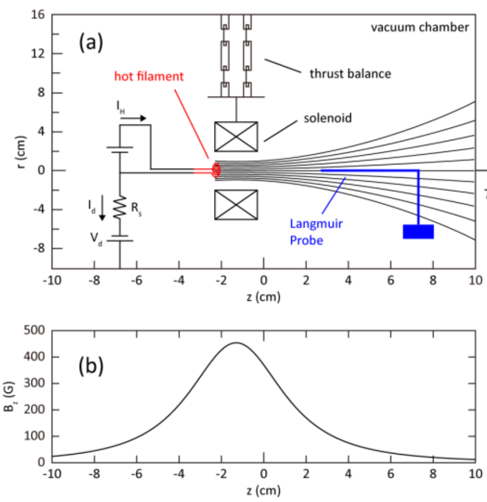

Figure 1. (a)Schematic diagram of the experimental setup. (b)The axial profile of the magnetic field on the axis.