28Cp04

磁気ノズル中のプラズマダイナミクスと宇宙推進

Plasma dynamics in a magnetic nozzle and space propulsion

高橋和貴[1-4], Christine Charles[2], Rod W. Boswell[2]
Kazunori TAKAHASHI[1-4], Christine CHARLES[2], and Rod W. BOSWELL[2]

[1]東北大院工, [2]オーストラリア国立大, [3]東北大非平衡プラズマ, [4]核融合研
1)Dept. Electrical Eng., Tohoku Univ., 2)Australian National Univ., 3)Nonequilibrium Plasma, Tohoku Univ., 4) NIFS

1. Thrust generation physics and performance

During the plasma expansion in the divergent magnetic field resembling the nozzle, the momentum conversion processes can frequently occur as results of interaction with the spontaneously formed electric fields and the magnetic fields [1,2]. The electrostatic ion acceleration by the electric fields does not increase the total axial momentum [3], where the electron pressure is converted into the ion dynamic momentum [4], while the Lorentz force arising from the internal plasma current and the applied field enhances the axial momentum of the plasma flow [5-7]. These processes are useful for the electric propulsion device called a magnetic nozzle rf plasma thruster. The thrust generation physics has been vigorously investigated over the last several years; the thruster performance has been improved based on the scientific understanding of the physical processes [8-10].

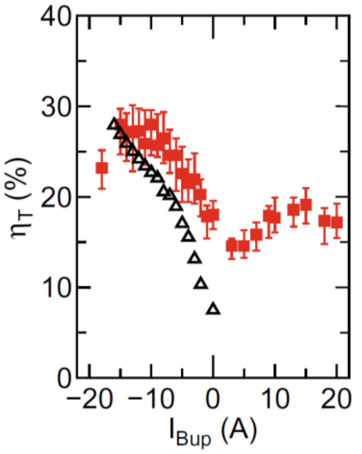

Fig.1: Assessment of the thruster efficiency in a laboratory test (filled squares), together with the estimated efficiency from a thruster model considering the particle and power balances, and the plasma expansion along the one-dimensional magnetic nozzle. *Reproduced with permission from Sci. Rep.* ***12****, 18618 (2022), licensed under CC BY 4.0.*

Here the highest thruster efficiency of the magnetic nozzle rf plasma thruster, approaching 30% thruster efficiency, is presented as in Fig.1 [11]. In the experiment, a cusp magnetic field, which isolates the plasma from the source wall, is applied inside the source, while maintaining the magnetic nozzle structure downstream of the source, as shown in Fig.2. The result can be qualitatively well explained by considering the change in the loss area and the plasma volume in a global model of the plasma production and a magnetic nozzle model.

2. Electron cross-field transport

When operating it in space, the plasma has to be finally detached from the magnetic nozzle inevitably forming closed magnetic field lines further downstream; otherwise, the plasma will return to the thruster along the closed fields and provide zero net thrust. The unmagnetized ions having a larger gyro-radius than the plasma scale can be easily detached from the field lines as shown by Fig.3, while the electrons are magnetized in typical magnetic field strength. In the thruster configuration, a coherent fluctuation around 40 kHz has been detected at the

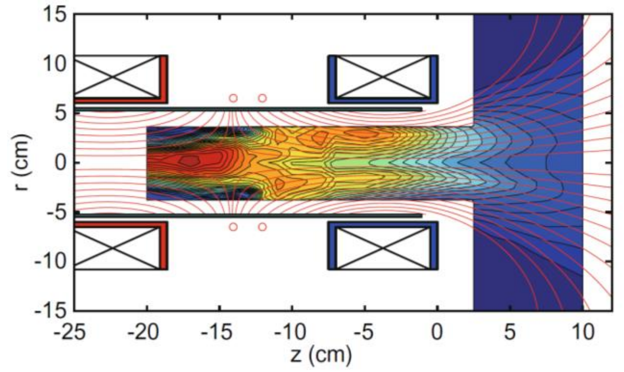

Fig.2: Calculated magnetic field lines and measured ion saturation current of the magnetic nozzle rf plasma thruster providing 30 % efficiency. *Reproduced with permission from Sci. Rep.* ***12****, 18618 (2022), licensed under CC BY 4.0.*

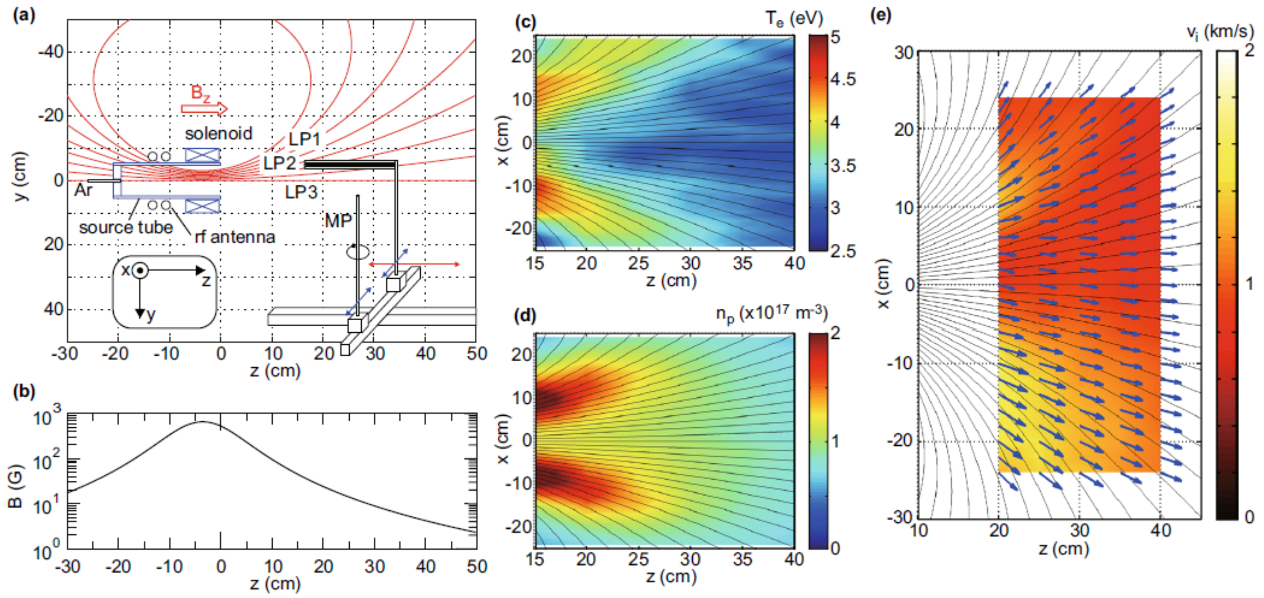

Fig.3: (a) Schematic diagram of the experimental setup for the wave-driven transport. (b) Magnetic field profile on the *z* axis. Two-dimenaional mapping of (c) the electron temperature and (d) the plasma density, (c) the ion velocity vector (arrows) and magnitude (colored scale), together with the magnetic field lines. *Reproduced with permission from Sci. Rep.* ***12****, 20137 (2022), licensed under CC BY 4.0.*

peripheral region of the magnetic nozzle, where the ion deviation from the magnetic field lines is significant. The inward cross-field transport of the electrons has recently been discovered in our laboratory experiment for the first time [12], which is induced by the spontaneously excited electrostatic mode wave in the magnetic nozzle. Comparison between the wave-induced electron flux and the steady-state ion flux suggests that the cross-field inward electron transport significantly contribute to neutralize the ion flux deviating from the magnetic field lines. Spontaneously excited plasma waves often degrade the performance of the plasma-based device (e.g., fusion reactors), while the present study shows the beneficial effect on the thruster operation in space. Therefore, the result will open the new perspective for the role of the plasma waves in the plasma application technology.

Acknowledgments

K.T. would like to thank master course students in the research group. K.T. also would like to express his gratitude to Ms. R. Sato for her assistance. This work is partially supported by Grant-in-Aid for Scientific Research (Grant No. 23H05442) from the Japan Society for the Promotion of Science.

References

[1]C. Charles, Plasma Sources Sci. Technol. **16**, R1 (2007).
[2]K. Takahashi, Rev. Mod. Plasma Phys. **3**, 3 (2019).
[3]A. Fruchtman, Phys. Rev. Lett. **96**, 065002 (2006).
[4]T. Lafleur, K. Takahashi, C. Charles, and R.W. Boswell, Phys. Plasmas **18**, 080701 (2011).
[5]A. Ahedo and M. Merino, Phys. Plasmas **17**, 073501 (2010).
[6]K. Takahashi, T. Lafleur, C. Charles, P. Alexander, and R.W. Boswell, Phys. Rev. Lett. **107**, 235001 (2011).
[7]K. Takahashi, C. Charles, and R.W. Boswell, Phys. Rev. Lett. **110**, 195003 (2013).
[8]K. Takahashi, A. Komuro, and A. Ando, Plasma Sources Sci. Technol. **24**, 055004 (2015).
[9]K. Takahashi, Sci. Rep. **11**, 2768 (2021).
[10]K. Takahashi, T. Sugawara, and A. Ando, Sci. Rep. **10**, 1061 (2020).
[11]K. Takahashi, Sci. Rep. **12**, 18618 (2022).
[12]K. Takahashi, C. Charles, and R.W. Boswell, Sci. Rep. **12**, 20137 (2022).