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Plasma dynamics of a magnetic nozzle helicon plasma thruster
磁気ノズルヘリコンプラズマ中の粒子挙動と無電極電気推進機の開発

Kazunori Takahahsi
高橋和貴

Department of Electrical Engineering, Tohoku University
6-6-05, Aramaki Aoba, Aoba-ku, Sendai 980-8579, Japan
東北大学工学研究科 〒980-8579 仙台市青葉区荒巻字青葉6-6-05

The plasma dynamics of a magnetic nozzle helicon plasma are presented. When applying a magnetic nozzle, a current-fee double layer or ambipolar electric field is spontaneously formed near the thruster exit: then the ions are electrostatically accelerated by supersonic and the energetic part of the source electrons can overcome the potential drop and neutralized the ion beam. The direct measurement of the thrust corresponding to the plasma momentum clearly indicates that the double layer does not impart the momentum to the plasma, where the role of the double layer is an efficient conversion from the electron pressure to the ion dynamic momentum. The presently shown individual measurement of the thrust components and a fluid model demonstrate the contribution of the magnetic nozzle on the thrust generation via a interaction between the magnetic field and the electron diamagnetic model. The recently progressed helicon plasma thruster performance will be shown and furthermore a new concept of magnetic nozzle thruster of helicon magnetoplasmadynamic (MPD) thruster (including some electrodes) will also be introduced for further development of the high power electric propulsion devices.

1. Magnetic plasma expansion

Plasma dynamics in an expanding magnetic field are inherent in the space and laboratory plasmas such as solar corona, astrophysical jet, and electric propulsion. When applying the expanding magnetic field on a current-free radiofrequency laboratory plasma source, a number of experiments have shown the spontaneous formation of a current-free double layer and/or ambipolar electric fields [1]. Subsequently to the formation of the potential drop, the source ions are electrostatically accelerated and the downstream ion energy distribution function has shown the presence of the supersonic ion beam. As the system is entirely “current-free”, some of the electrons can overcome the potential drop and neutralized the supersonic ion beam. This fact has been confirmed by the measurement of the electron energy probability function, where the upstream tail electron corresponds to the downstream electrons [2]. Hence the present system is useful for the neutralizer-free electric propulsion device. As all of the metallic parts are not exposed to the plasma in such system, it can be applicable to the electrodeless propulsion device called helicon plasma thruster. When the measurements are extended from one dimension on axis to two dimensions in *r-z* plane, the conical structure is formed near the nozzle surface. This phenomenon is also well understood via the measurement of the electron energy distribution, which has shown the peripheral energetic electrons transported from the source along the magnetic nozzle [3]. These complex plasma dynamics would be associated with the thruster performance hereafter.

2. Helicon plasma thruster

Thrust imparted by the plasma source is equal in magnitude and opposite in direction to the plasma momentum emitted from the system. The helicon plasma thruster has a simple structure consisting of the source tube wound by the rf antenna, and the magnetic nozzle as shown in Fig.1. Our simple model shows that the total thrust can be expressed by three terms of plasma pressure inside the source cavity, loss of the axial plasma momentum onto the radial source wall, and the Lorentz force due to the radial magnetic field and an azimuthal plasma current, where the electron diamagnetic drift is responsible for the azimuthal current in the simplest model [4]. These force components are exerted onto the back plate, radial source wall, and the solenoid providing the magnetic field. Hence the components can be individually measured by attaching either the back plate or source wall or solenoids to the thrust balance. Here the detailed results relating to the thrust generation mechanisms will be shown, which is performed in HPT-I machine at Iwate (2012-2013) and Tohoku Universities (moved in 2013). The thrust

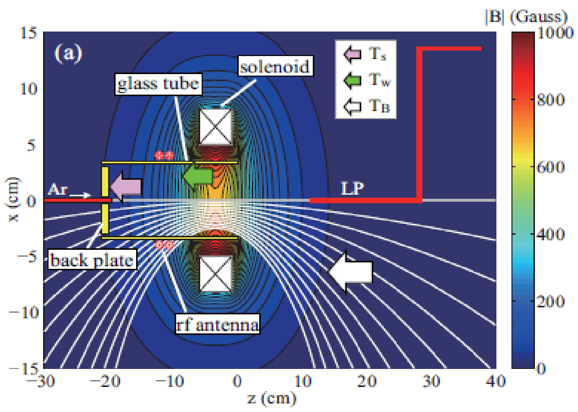

Fig.1. Schematic diagram of the helicon plasma thruster.

components arising from the magnetic nozzle is observed to be increased by inhibiting the cross-field diffusion in the magnetic nozzle, which is performed by increasing the magnetic field strength while maintaining the plasma production [5].

A simple set of particle and power balance equations is well known to give the typical electron temperature and the plasma density. Assuming a plasma expansion with no cross field diffusion in the nozzle, the maximum of the thruster performance can be very roughly estimated from the model, which predicts that the thrust value can be increased by increasing the source diameter. As the chamber diameter of HPT-I machine is too small to operate the larger diameter thruster head, the bigger tank is now used to evaluate the thruster performance [Mega-HPT machine]. The ratio of thrust to the input power was 10mN/kW for 65-mm-inner diameter thruster head. The newly designed thruster head having a 90-mm-inner diameter thrust head is found to give a larger thrust of ~20 mN/kW for 1 kW rf power. Moreover, the rf power is increased up to ~6kW; then the measured thrust is 60 mN, which seems to be a largest value (at least in the published works) to this date.

3. Helicon magnetoplasmadynamic thruster

The above-described helicon thruster is typically operated at a few kW rf power because of the cost, size, and weight of the high power rf amplifier. For future manned exploration and massive material transport mission, a high power electric propulsion device above a few hundreds of kW such as MPD thruster is required. However the specific impulse and the thruster efficiency of the MPD thruster are still lower than that of the ion engine and hall thrusters due to the injection of massive propellant gases to trigger and sustain the arc discharge. Here a new concept of the high power electric propulsion device is suggested to operate it with low mass flow rate and high input power above a few hundreds of kW, which is called "Helicon MPD Thruster".

The preliminarily experiments are performed by attaching the thruster head to HPT-XS machine at Tohoku University. A cathode and an anode are located downstream and upstream of the helicon source, respectively, and connected to a 2.2mF electrolytic capacitor charged up to ~400 V. Once the pulsed helicon plasma is produced inside the source cavity, a large current above a few kA is triggered between the cathode and the anode, then the high density plasma above 10^{20} m^{-3} is successfully obtained at 15 cm downstream of the thruster exit. The measurement using the Mach probe indicates the supersonic plasma flow of about Mach 1.8. By surveying the external parameters such as magnetic field strength, the voltage between the cathode and the anode, and the mass flow rate of argon, it is demonstrated that the source can be operated with a low mass flow rate of propellant in the range of a few mg/s, while the mass flow rate for the traditional MPD thruster is a few hundreds of mg/s [6]. The helicon MPD thruster might be more efficient high power propulsion device operated at low gas flow rate. The assessment of the thruster has not been done yet.

4. Application to astrophysical object

Most of the astrophysical objects such as astrophysical jet are fully ionized, high beta, and high magnetic Reynolds number. The laboratory simulations of such plasmas are vigorous challenge to clarify the detailed dynamics of the astrophysical plasmas. In the last of the presentation, the application of the helicon MPD source to the laboratory simulation of astrophysical plasmas is discussed for further research.

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