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磁気ノズル中の電子の動的輸送ダイナミクス
Electron dynamic transport in a magnetic nozzle

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The plasma expansion in a magnetic nozzle is a key element for development of an electrodeless radiofrequency plasma thruster called a helicon plasma thruster [1,2]. The high density plasma produced by the helicon discharge is transported and expanded along the magnetic nozzle, where various plasma acceleration and momentum conversion processes can occur. Such a plasma expansion in the magnetic nozzle configuration seems to be ubiquitous in space, e.g., the solar coronal funnel, the astrophysical jet, the poles and the geomagnetic tail of the Earth, and so on. The massive plasmas are ejected from the Sun, where the high-speed plasma flows are detached the system by taking away the Sun's magnetic field [3]. This process is also important for the plasma thruster for the plasma detachment from the magnetic nozzle [4]. Recent experiment has observed the increased axial magnetic field implying the stretching the field lines, while the change in the strength is only a few percent of the applied magnetic field [5].

The magnetic field strength of the plasma thruster is about 1 kG in the source and decreases to a few G at several centimeter downstream of the source. For this condition, the ions are unmagnetized and their orbits are mainly affected by the electrostatic fields. Several experiments have shown that the accelerated ions are deviated from the magnetic field lines [6-8], while the electrons are still magnetized. In order to get the thrust in space, the cross-field electron transport process is required to neutralize the accelerated and detached ions; otherwise, the plasma will turn back to the spacecraft.

Here the wave-driven cross-field electron transport is investigated in the magnetic nozzle. The measurement shows the fluctuation in the frequency range of 40 kHz, which is much higher than the ion cyclotron frequency and slightly lower than the lower hybrid frequency. The measurement of the wavenumber implies that the wave propagates in the azimuthal direction, perpendicular to the magnetic field and compared with the linear dispersion theory. The cross-field electron transport can be induced by the nonlinear effect of the density and velocity fluctuations, where the latter is originated from the azimuthal electric field fluctuation. In the present experiment, the Langmuir probes are used to measure the density fluctuation and the **E**x**B** drift velocity fluctuation [9].

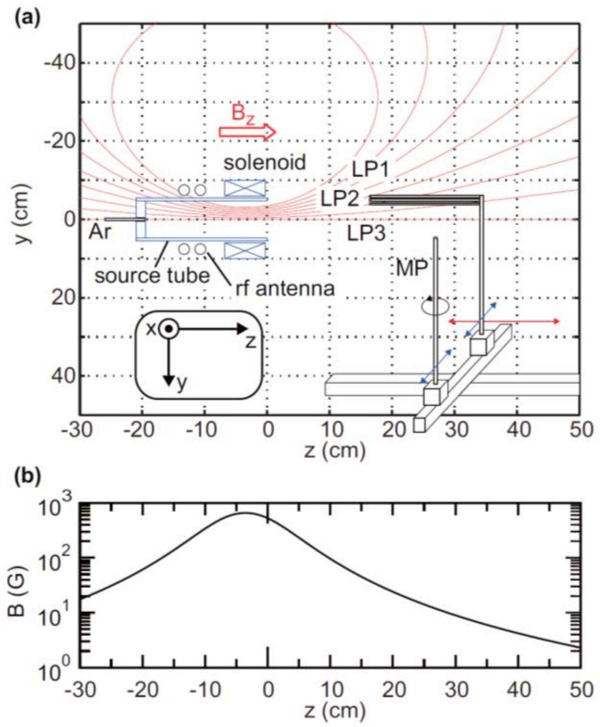

Fig.1: (a) Schematic diagram of the experimental setup. (b) The calculated magnetic field strength on axis.

Experiments are performed in a 1-m-diameter and 2-m-long cylindrical vacuum chamber evacuated by three turbomolecular pumping systems providing the effective pumping speed of 4500 ls^{-1}. A helicon

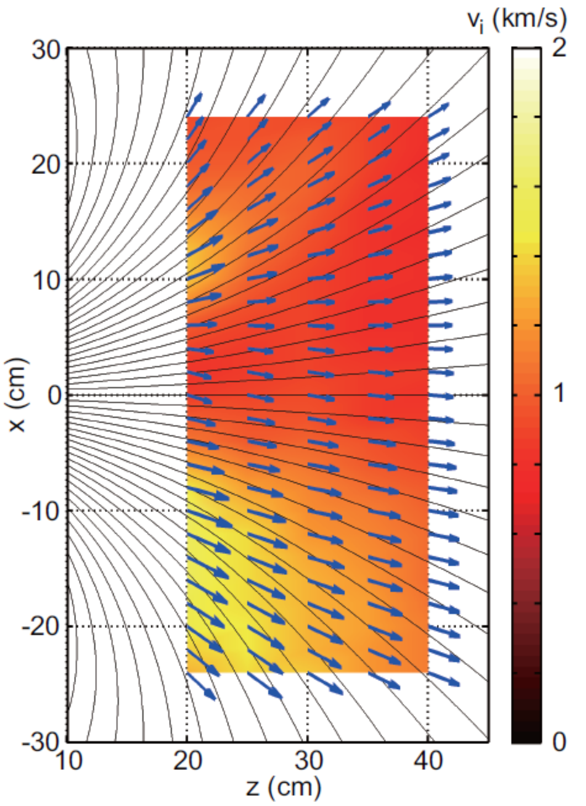

Fig.2: The ion velocity vectors (arrows) and magnitude (contour color) measured by the Mach probe.

plasma thruster consisting of the insulator source tube wound by an rf antenna and a solenoid providing the axial magnetic field on axis. Ar gas is continuously introduced from the upstream side of the source tube and the gas flow rate is maintained at 70 scmm, resulting in the chamber pressure of about 25 mPa. A solenoid current is supplied by a dc power supply, creating the magnetic field of about several hundreds of Gauss in the source and decreasing to about 10 Gauss at 30 cm downstream of the source. The antenna is powered by a 13.56 MHz rf generator via an impedance matching circuit; the Ar gas is efficiently ionized in the source and expands along the magnetic nozzle.

The vertically aligned three Langmuir probes (Labelled as LP1, LP2, and LP3) are mounted on the axially and horizontally movable motor stage. The density fluctuation is measured by LP2; the electric field fluctuation is obtained from the difference of the floating potential V_{f1} and V_{f3} of LP1 and LP3. Furthermore, the Mach probe consisting of two detection tips is attached to another motor enabling the probe shaft to be rotated. This structure can give the axial and horizontal ion Mach number. The velocity is calculated from the measured Mach number and the local Bohm velocity with taking the non-uniform electron temperature into account as presented in Fig.2. It can be found that the ion velocity vector is deviated from the magnetic field lines, where the vector is found to be directed to the nozzle axis, compared with the magnetic field lines. Hence, the orbits of the ions are detached from the field lines.

In the presentation, the profile of the detected fluctuation, the wave dispersion relation, the cross-field electron transport will be shown. Although the research for fusion plasma confinement have been a struggle with the particle transport and heat loss induced by waves, instabilities, and turbulence, the present results show the inward electron transport, which contribute to the neutralization of the accelerated and detached ions. The authors would like to discuss with the audience on the connection with the space plasma phenomena.

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