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Energy distribution of charged particles in a magnetically expanding plasma and their application to electric propulsion
発散磁場配位下プラズマ中の粒子エネルギー分布と電気推進への応用

Kazunori Takahashi[1,2,3], Christine Charles[1], Rod Boswell[1] and Tamiya Fujiwara[2,3]
高橋和貴[1,2,3], Christine Charles[1], Rod Boswell[1], 藤原民也[2,3]

[1]*Space Plasma, Power and Propulsion Group, Research School of Physics and Engineering, The Australian National University*
Canberra, ACT 0200, Australia

[2]*Department of Electrical Engineering and Computer Science, Iwate University,*
4-3-5 Ueda, Morioka, Iwate 020-8551, Japan
岩手大学工学部 電気電子・情報システム工学科 〒020-8551 岩手県盛岡市上田4-3-5

[3]*Soft-Path Engineering Research Center (SPERC), Faculty of Engineering, Iwate University,*
4-3-5 Ueda, Morioka, Iwate 020-8551, Japan
岩手大学ソフトパス工学総合研究センター 〒020-8551 岩手県盛岡市上田4-3-5

Experimental and theoretical investigations of electron energy distribution functions (EEDF) in a magnetically expanding plasma system are reported. The experimental EEDF has a depleted tail above the energy corresponding to the double layer (DL) potential drop, instead of the electron beam or hot electron tail required for DL formation in the previous theoretical models. Here, an analytical particle-balance model using the Druyvesteyn distribution is successfully compared to the experimental results. Both the upstream particle balance and the DL formation are sustained by a Druyvesteyn-like EEDF, and the depleted tail of electrons overcome the DL and neutralize the ion beam. Direct measurements of the thrust from the permanent magnets helicon double layer plasma is also presented.

1. Introduction

It is well known that electric fields of electric double layers (DLs) spontaneously formed in plasmas accelerates or trap charged particles. Recently, the investigations of current-free double layers (CFDLs) in magnetically expanding rf helicon-wave and/or inductive-mode plasmas are progressed in a number of laboratory experiments, via analytical models, and computer simulations [1]. The electrical and optical diagnoses of the ion energy distributions in these experiments have shown that the ions produced inside the source tube are accelerated by the CFDLs and the supersonic ion beams are generated in the downstream diffusion chamber. Some theories of the CFDLs include the electron beam accelerated by the CFDLs from the downstream to upstream plasmas, or take into account of a bi-Maxwellian electron energy distribution with a hot tail for finding CFDL solutions [2,3]. However, only a few experiments have shown the experimental electron energy distributions, and its feature is the depleted tail at the break energy corresponding to the potential drop of the DL [4]. Hence, it is important to model the electron energy distribution of the CFDL plasmas.

Here the electron energy distribution upstream of the helicon CFDL is analytically modeled: the EEPFs with the depleted tail are approximately fitted by a Druyvesteyn distribution and the effective electron temperatures are analytically obtained. The theoretical results are successfully compared with the experimental results obtained for two system geometries and two operating gases. Furthermore, the direct measurement of the thrust from the permanent magnets helicon CFDL plasma is also reported.

2. Particle balance for Druyvesteyn distribution

The balance equation between volume ionization and surface loss of the charged particles is a simple and powerful method to determine the electron temperature. It is written as

$$K_{iz} n_g \pi R^2 l = u_B (2\pi R^2 h_l + 2\pi R l h_R) , \quad \cdots (1)$$

where K_{iz}, n_g, R, l, u_B are the ionization rate constant, the gas density, the plasma radius, the plasma length, and the bohm velocity, respectively. h_R and h_l are the axial and radial center-to-edge density ratios and described in Ref.[5]. The generalized electron energy probability function (EEPF) g_p can be expressed as

$$g_p(\varepsilon) = g_x \frac{n_e}{T_{eff}^{3/2}} \exp\left[-C_x\left(\varepsilon/T_{eff}\right)^x\right], \quad \cdots (2)$$

then the electron energy distribution function (EEDF) g_e can be given by $g_e = \varepsilon^{1/2} g_p$, and T_{eff} is the effective electron temperature in units of volts. x is the parameter giving the shape of the EEPF/EEDF, and x = 1 and x = 2 correspond to the Maxwellian and Druyvesteyn distribution functions. The Bohm velocity and the ionization rate constant for the generalized EEPF can be obtained as reported in Ref. [6]. Equation (1) and the generalized Bohm velocity and ionization rate constant can give the effective electron temperature.

The experimental EEPFs observed in two different machines (Chi-Kung at the Australian National University and PMPI at Iwate University) have shown similar distributions with the depleted tails. The shapes of the EEPFs are very close to the calculated EEPF for x = 2, i.e., the Druyvesteyn distribution function. Figure 1 shows the experimental and theoretical effective electron temperatures in two types of gases and in two different machines. It is found that the theoretical results are successfully compared with the experimental ones. Although the previous models

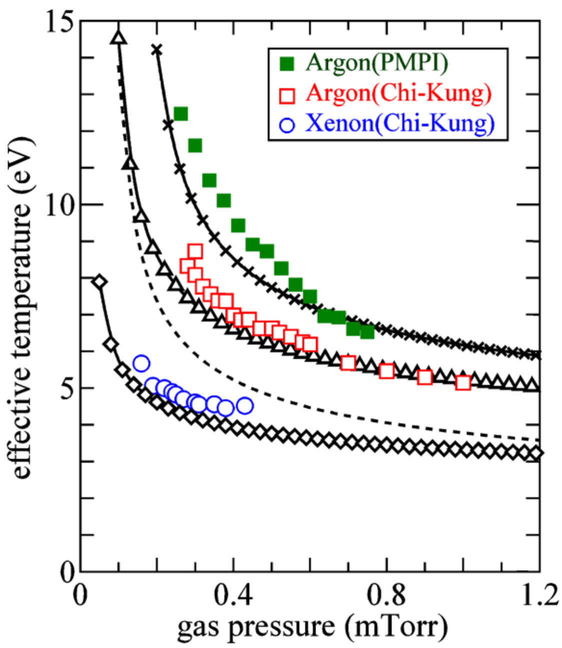

Fig.1. Theoretical and experimental effective electron temperature Teff in argon in PMPI (crosses with solid line and filled squares), in argon in Chi-Kung (open triangles with solid line and open squares), and in xenon in Chi-Kung (open diamonds with slid line and open circles) as a function of the operating gas pressure. The dashed line is the analytical results for Maxwellian distribution in argon in Chi-Kung for comparison.

of the CFDLs have assumed the electron beam accelerated by the DL or the bi-Maxwellian EEPF/EEDF with the hot tail, the present results do show that the particle balance in the source tube can be sustained by the Druyvesteyn-like EEPF with the depleted tail. This CFDL solution for the Druyvesteyn-approximated distribution is not in accordance with the result of the previous models. Hence, this seems to indicate that the CFDL in the magnetically expanding plasmas is a new class of CFDLs.

3. Thrust measurement

The results of the EEPFs have shown that the supersonic ion beams accelerated by the CFDLs are neutralized by the electrons overcoming the CFDLs. Hence, this type of plasma system can be useful for the development of electrodeless and neutralizer-free electric propulsion systems, because equal fluxes of ions and electrons are emitted by the system. Since the physical mechanisms of thrust generation by electrodeless plasma thrusters are not clarified and verified experimentally yet. Here we report the direct measurement of the thrust from the permanent magnets helicon double layer thrust (PM-HDLT). The pendulum thrust balance is used to measure the thrust and the detailed plasma parameters are measured by a Langmuir probe and a retarding field energy analyzer. It is found that the thrust from the PM-HDLT is about 3 mN for 700 W effective rf power. This value agrees well with the cross-sectional electron pressure estimated from the upstream probe diagnosis. Moreover, the supersonic ion beam is detected in the diffusion chamber. In this sense, the plasma momentum is conserved and the momentum is transferred from the upstream axial electron pressure into the downstream axial ion momentum through the CFDL [7].

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