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Plasma Acceleration using Electromagnetic Waves and Tasks for High Power Electric Propulsion

高周波を用いた加速技術と大電力電気推進技術への課題

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For the future electric propulsion (EP) systems, high power thruster utilizing plasma production and acceleration with no electrode is inevitable. A number of researches have started to develop EP systems using electromagnetic (EM) waves in plasma production and acceleration. An ion acceleration by the combination of ion cyclotron heating and magnetic nozzle was successfully demonstrated in the HITOP and VX-devices. Direct formation of acceleration potential without electrode has performed in a double layer thruster. A rotating elelctromagnetic field is used to accelerate plasma by Lorentz force with expanding magnetic field. Development of reliable and efficient power sources and formation of magnetic field are important for the utilization of EM waves in high power thrusters.

1. Introduction

An electric propulsion (EP) system is one of the key elements in future space exploration projects and has been developed for various space missions [1]. The exhaust ion velocity of EP is 10-100 times as fast as that of chemical rockets. This feature of EP makes possible long-term space missions with less consumption of propellant.

Recent remarkable achievement of the spacecraft HAYABUSA encourages further development and utilization of EP system not only for an orbital station-keeping rocket but for a main engine of spacecrafts [2,3].

A number of EP engine types have been developed for years. Ions are accelerated by electro-thermal, electro-static, electro-magnetic and combined forces in the thruster. The performance of an EP engine is evaluated by thrust F, specific impulse I_{sp} and thrust efficiency η. The ion engine is operated with high I_{sp} and η in spite of low thrust and is used in long term missions. A Magneto-Plasma-Dynamic thruster and a Hall thruster have larger thrust and application to manned flight mission is expected. Although the EP system is requisite for long term mission, electrode erosion in the thruster is one of the serious problems restricting thruster operation time.

In the further development of space exploration the EP engines with a higher specific impulse and a larger thrust are necessary. With the increase of required electric power, utilization of electromagnetic (EM) waves not only in plasma production but in ion acceleration is expected to avoid serious damage in electrodes. A number of researches have started to develop ion acceleration methods using EM waves, and Japanese activities contributes to this field, such as VASIMR, Double layer (DL), rotating EM field, microwave beaming propulsion.

Here, an investigation of electrode-less ion acceleration in EP systems using EM waves will presented and tasks for further investigation in high power EP systems will be discussed.

2. Ion acceleration by EM waves

An ion acceleration by the combination of ion cyclotron heating and magnetic nozzle has been investigated related to the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project [4], which is expected to be a main engine for manned flight to Mars. The accelerated ion energy could be controlled by the input RF power only, which has been successfully demonstrated in the HITOP experiments [5-7]. Recent progress of the VX-200 device in Ad Astra Rocket Co. reveals high potential of this engine. More than 5N of thrust was obtained at 200kW of radio frequency (RF) power with the efficiency of 72% [8].

A Helicon Double Layer Thruster (HDLT) utilizes a current-free electric double layer. The electrical potential is much higher inside the source region than in the exhaust. The large potential gap is feasible to confine most of the electrons and to accelerate the ions away from the source. This creates an accelerating electric field without inserting unreliable components like high voltage

grids into the plasma. Low power HDLT has been developed and physical mechanism of DL formation was investigated [9.10].

Direct plasma acceleration using a rotating transverse electric field has been investigated in Lissajous Helicon Plasma Accelerator (LHPA) [11]. When the frequency for the applied rotational electric field is in the range between $\omega_{ci} << \omega << \omega_{ce}$, only electrons rotates azimuthally and generates azimuthal currents j_θ. The thrust is produced due to the Lorentz force $j_\theta \times B_r$, where B_r is formed by expanding magnetic field. Experiments has been started to excite rotating field in plasmas. Utilization of rotating transverse magnetic field or ponderomotive force of EM waves is also proposed and numerical investigations have been performed [12].

Microwave can be utilized not only in plasma production but in plume acceleration. The microwave beaming propulsion was investigated in Tokyo Univ. and JAEA [13]. Microwave beam from 170GHz gyrotron was irradiated to a projectile and ionization front of atmospheric plasma was investigated. The propagation velocity of the ionization front was found to be supersonic. With a repetitive pulses the projectile was launched by the counterforce of the exhaust plume. No energy source and propellant is necessary on board in the beaming propulsion and it is expected to achieve a higher payload ratio than conventional chemical rockets.

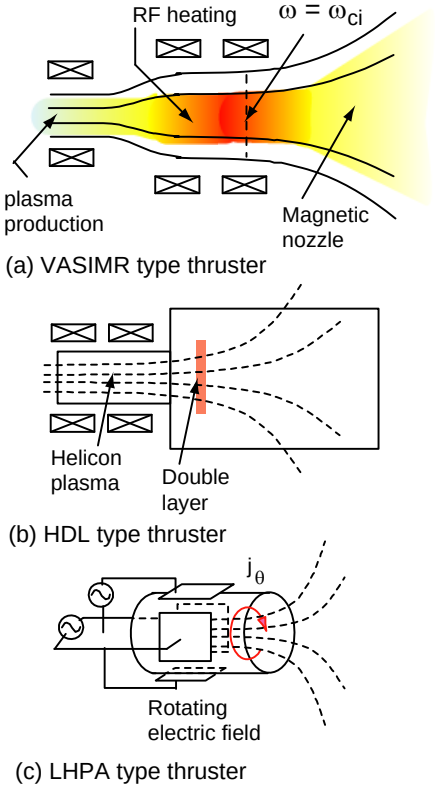

Fig.1. Schematic of several types of plasma thrusters using RF power.

3. Future tasks in EP systems with EM waves

In acceleration by EM waves, besides of no electrode, an additional advantage is that no neutralizer (electron emitter) is necessary, since the acceleration occurs in a plasma and equal numbers of electron and ions are emitted from the source.

As most of the acceleration occurs with a magnetic field, the plasma detachment from the field is one of the important problems to be solved. Ions can escape from the field due to their large Larmor radius, but electrons remains to be captured in the field. The charge separation occurs and an electric field appears to decelerate ions.

In the further activities for high power thruster, utilization of EM waves in plasma production and acceleration will be pursued in many types of EP systems. To avoid large power loss in conversion from DC to RF, reliable and efficient power sources of EM waves are also required to be developed. Most of the proposed thrusters using EM waves work with an axial magnetic field. Power consumption and mass of the magnetic coils should be considered in total evaluation of the propulsion system.

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