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Numerical Studies of Ponderomotive Acceleration and Ion Cyclotron Resonance: Application to Next Generation Electric Thrusters

ポンデロモーティブ加速とイオンサイクロトロン共鳴の数値解析: 次世代電気推進の開発に向けて

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We have examined particle acceleration by external electromagnetic RF (Radio Frequency) field by means of test particle simulations, and applied this concept to the development of next generation electric thrusters, as a part of the HEAT (Helicon Electrodeless Advanced Thrusters) project. When a localized transverse electromagnetic field and a divergent background magnetic field are considered as external electromagnetic fields, two acceleration processes coexist: the ponderomotive acceleration and the ion cyclotron resonance. Based on a model that includes ion-neutral collisions and ion wall-loss, we estimate the thrust as a function of external field parameters.

1. Introduction

'Electrodeless' plasma thruster is a promising candidate for the next generation electric thrusters, and has been extensively studied worldwide. In particular, research and development of the electrodeless thruster using helicon plasma source is the main target of the HEAT (Helicon Electrodeless Advanced Thrusters) project (overview of the project will be presented in this conference [1]). As a part of the project, we report here one type of the plasma acceleration schemes, *i.e.*, the ponderomotive and the ion cyclotron resonance (PA/ICR) acceleration.

The ponderomotive force arises from a spatial gradient of an electromagnetic field energy density. The schematic picture of the PA/ICR scheme is shown in Fig. 1. Electrodes are placed outside the plasma region, so that the erosion of the electrodes can be avoided. A background magnetic field is oriented mainly along the z-axis and a linearly polarized transverse RF electric field is applied with its magnitude $E(z)$ given as a Gaussian pulse. The ponderomotive pseudopotential is then written as,

$$\Phi = \frac{q^2}{4m} \frac{E^2(z)}{\omega^2 - \Omega(z)^2}, \tag{1}$$

where ω is the RF wave frequency, and m, q, and Ω are the ion mass, charge, and the gyro-frequency, respectively. If Ω is uniform in z, Φ is symmetric

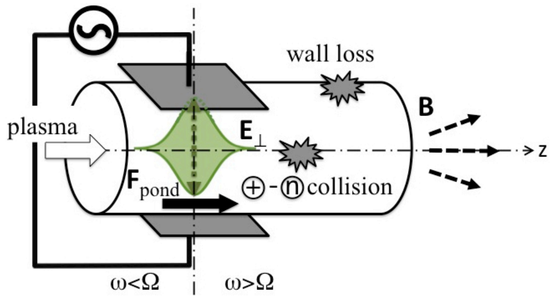

Fig.1. Schematic picture of PA/ICR scheme

with respect to z, and so the ponderomotive force is oppositely directed on the two sides of the potential. On the other hand, if Ω is given in such a way that it decreases along the z-axis and the resonance point coincides with the peak of $E(z)$, the sign of Φ is reversed at the peak and the ponderomotive force becomes uni-directional, so that an ion can obtain net energy as it passes through the potential [2]. We apply this concept to the plasma thruster.

In the above configuration, the ICR acceleration co-exists, *i.e.*, the perpendicular ion heating followed by the energy conversion from perpendicular to parallel direction by the mirroring effect. A well-known application of the ICR to the plasma thruster is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [3]. In this presentation, we discuss ion acceleration due to the PA combined with the ICR mechanism. The effects of ion wall-loss and ion-neutral collisions are included.

2. Numerical Model and Results

We have performed test particle simulations based on the configuration described above. The external field parameters are the gradient scale length along z for the divergent magnetic field, L_B, the width of the Gaussian pulse for the electric field, L_E, and the maximum intensity of the electric field, E_0. Ion species is assumed to be argon. The magnitude of the magnetic field at the resonance is 400 G, so that $\omega \sim 9.6 \times 10^4$/s. A cylinder with 20 cm diameter for $z < 1$ m and no bounded space for 1 m $< z <$ 2 m are assumed for a vacuum chamber and an exhaust region, respectively. The absorbing boundary conditions at the wall are used. For the ion-neutral collisions, we use the Monte-Carlo model [4]. It is assumed that the neutral particles are always at rest and that the particle scattering is isotropic.

Figure 2 shows a typical example of (a) the ion trajectory and (b) the energy evolution for two different initial particle velocities. Here, $\varepsilon_{//}$ and $\varepsilon_{\perp}$ are the parallel and the perpendicular ion energy components, respectively. The parameters used are L_B = 1 m, L_E = 0.4 m, and E_0 = 30 V/m. In this run, the wall-loss and the collisions are not considered. In (a), the particles are gradually accelerated along z, as they pass through the resonance point at 0.5 m. In (b), the particles gain energies, $\varepsilon_{\perp}$ and $\varepsilon_{//}$, by the ICR and the PA, respectively, and then the energy conversion from $\varepsilon_{\perp}$ to $\varepsilon_{//}$ occurs by the mirroring.

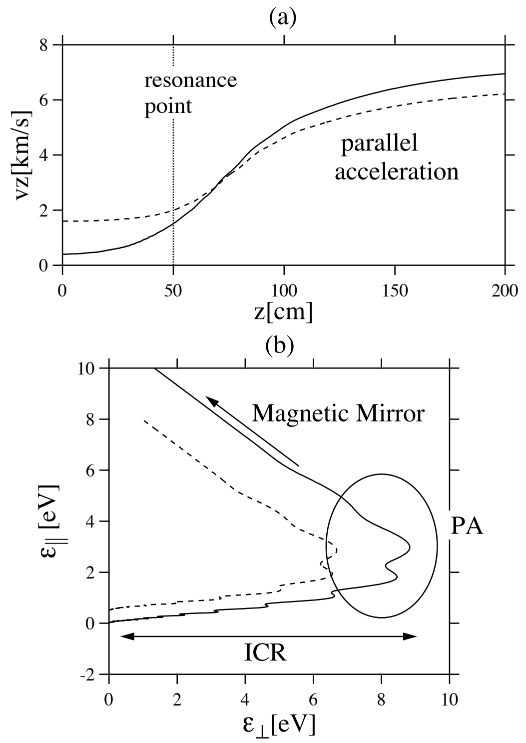

Fig.2. Typical ion orbits for initial axial velocities, v_b= 400 and 1,600 m/s, shown by the solid and the dashed lines, respectively.

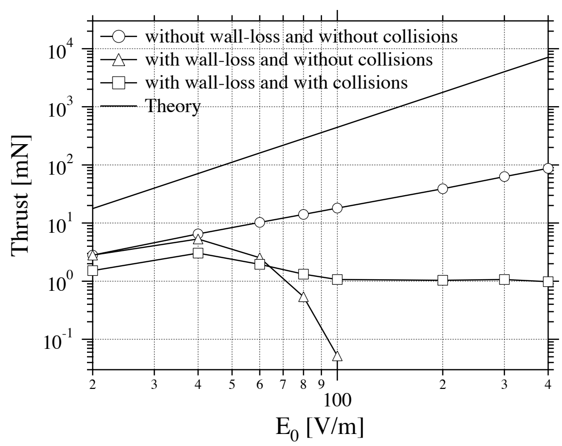

Fig.3. Thrust vs. Electric field intensity

The energy gain for v_b=400 m/s is larger than that for v_b=1600 m/s, since slower particle can stay longer time near the resonance point, leading to large energy gain by the ICR and the PA. The ratio of the energy gain by the PA to the ICR is typically around 1/3.

Figure 3 estimates the thrust, $F=(1-\sigma)(n\pi R^2 m v_z)v_z$, as a function of E_0, where σ is a rate of the absorbed to the initial macro-particles, n is the ion number density (=10^{18}/m^3), R is the plasma radius (=0.03 m), and v_z is the exhaust velocity at z=2 m. Different groups of runs with and without the wall-loss and the ion-neutral collisions are shown. Theoretical estimate is given by $\Delta\varepsilon_{//}=\Delta\varepsilon_{\perp} \sim(\pi q^2 E_0^2/2m)(L_B/\omega v_b)$, assuming the energy gain by the ICR only [2]. The parameters are v_b=400 m/s and the others are the same as in Fig. 2 except E_0. When the wall-loss and the collisions are both included, the thrust saturates at a constant level as E_0 is increased. A shielding effect of the external electric field will be also discussed in this presentation. A proof of principle experiment of this scheme has been launched recently at Tokai University.

Acknowledgments

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References

[1] H. Nishida, S. Shinohara, T. Tanikawa, T. Hada, I. Funaki et al.: proceeding of Plasma 2011 (this conference), Kanazawa, 22-25 Nov., 2011

[2] I.Y. Dodin, N.J. Fisch, and J.M. Rax: Phys. Plasmas, **11** (2004) 5046.

[3] E.A. Bering III, F.R. Chang Diaz, J.P. Squire, T.W. Glover, et al.: Phys. Plasmas **17** (2010) 043509.

[4] V. Vahedi and M. Surendra: Comput. Physics. Commun. **87** (1995) 179.