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Particle simulation of grid system for krypton ion thrusters

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Abstract The transport processes of plasmas in grid systems of krypton (Kr) ion thrusters at different acceleration voltages were simulated with a 3D-PIC model, and the result was compared with xenon (Xe) ion thrusters. The variation of the screen grid transparency, the accelerator grid current ratio and the divergence loss were explored. It is found that the screen grid transparency increases with the acceleration voltage and decreases with the beam current, while the accelerator grid current ratio and divergence loss decrease first and then increase with the beam current. This result is the same with Xe ion thrusters. Simulation results also show that Kr ion thrusters have more advantages than Xe ion thrusters, such as higher screen grid transparency, smaller accelerator grid current ratio, larger cut-off current threshold, and better divergence loss characteristic. These advantages mean that Kr ion thrusters have the ability of operating in a wide range of current. Through comprehensive analyses, it can be concluded that using Kr as propellant is very suitable for a multi-mode ion thruster design.

1. Introduction

In the last decade, ion thrusters have been widely used for various space missions,[1–3] in which xenon (Xe) is frequently used as the propellant. However, Xe is typically expensive and a cost-effective propellant is highly demanded, from the economy point of review. Recently, krypton (Kr) attracts more attentions as an alternative propellant for different electric thrusters, for example, Hall thrusters[4] and ion thrusters.[5]

The performance of an ion thruster mainly depends on the acceleration process of the propellant in the grid system. Besides experimental diagnostics, numerical simulation provides a supplementary tool to investigate the transport process of the plasma in the grid system, and to estimate the performance and lifetime of the thruster. In the past, many simulations on the transport process of Xe plasmas in grid systems

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have been performed to explore the following aspects: the electric field distribution in a grid system, the motion trajectory of ion beam, the erosion on the grids, back-streaming, cut-off current and the ion extraction process. For instance, Wang et al. used a three-dimensional Particle In Cell (PIC) method to simulate the transport process of the Xe ion-beam in a single grid gate aperture.[6] Using particle methods, Peng et al.[7] and Sun et al.[8] examined the grid erosion and the effect of the deceleration grid for two-grid and three-grid systems, respectively. Wheelock et al. investigated the neutralization process in ion beam using PIC method.[9] Liu et al. investigated the characteristics of Charge EXchange (CEX) ions in ion thruster optical system with a two-dimensional axisymmetric numerical model.[10,11] Cao et al. conducted an in-depth study on the transport process of Xe ions in the grid system by combining PIC with the Immersed Finite Element (IFE) method.[12] Jia et al. analyzed the grid system performance of LIPS Xe ion thrusters.[13] However, most of the aforementioned simulations use Xe as the propellant (hereinafter referred to as Xe ion thrusters or Xe thrusters). In this paper, Kr is chosen as a novel propellant for ion thrusters (hereinafter referred to as Kr ion thrusters or Kr thrusters). The transport processes of Kr ions in the grid system at different acceleration voltages were simulated with PIC method. By analyzing the variations of the screen grid transparency, the accelerator grid current ratio and the divergence loss, the effects of acceleration voltage on the performance of Kr ion thruster were identified to guide the design of the grid system prototype of Kr ion thrusters. The results were also compared with Xe ion thrusters for the analyses of the advantage and disadvantage of different propellant choices.

The paper is organized as follows. In Section 2, the physical model and simulation method are introduced. Simulation results including the screen grid transparency, accelerator grid current ratio, and divergence loss are described and discussed in Section 3. Finally, we summarize our results and draw main conclusions.

2. Calculation model

2.1. Physical model and simulation domain

To avoid short-circuit induced by the grid system's thermal deformation, the grid system in the classical NSTAR-30 ion thruster was used for the preliminary design and evaluations.

Table. 1 lists the specific structural parameters of this kind of grid structure.[6]

Due to the symmetry of the grid structure, only a quarter of grid aperture was selected as the computational domain.[14] As shown in Fig. 1, (a) presents 3D structure of a complete grid aperture, (b) is the left view of grid aperture, (c) is the left view of the simulation domain, and (d) is the top view of the grid aperture.

Table 1 Parameters of grid system.

Structural parameter	Value (mm)
Diameter of screen grid aperture d_s	1.91
Depth of screen grid t_s	0.38
Diameter of accelerator grid aperture d_a	1.14
Depth of accelerator grid t_a	0.51
Distance between screen grid and accelerator grid g	0.58
Distance between apertures l	2.21

An equidistant grid was used on the computational region. Considering that the density of the plasma in the discharge chamber ranges from 10^{16} m^{-3} to 10^{17} m^{-3}, the spatial grid size was set as 5×10^{-5} m and the grid number in calculation was set as $23 \times 39 \times 115$, while the time step was set as 1.0×10^{-10} s.

2.2. PIC/MCC model

PIC method is a kinetic method of simulating low temperature plasmas with the aim of tracking the motion of particles and the self-consistent electric field in a coupled way.[15,16] Monte Carlo Collision (MCC) method has been widely used for treating collisions between charged ions and neutral gas.[17,18]

In general, the PIC code consists of a cycle in every time step as follows[15]: (1) weighting the charge of the ions and electrons to the mesh nodes; (2) calculating the electric potential and the electric field of the calculation domain; (3) weighting the electrostatic field back to the ions; (4) moving the ions according to the second Newton law method with the electric field forces obtained above. The flowchart of PIC simulation can be seen in Ref. 11.

In the model, the velocity and position of ions are calculated by the Newton-Lorentz law according to

$$m_i \frac{d\boldsymbol{v}}{dt} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{1}$$

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v} \tag{2}$$

in which m_i denotes the mass of ion; e denotes the unit charge (since the ion considered in the model is monovalent, the carried charge is an element charge); $\boldsymbol{v}$ and $\boldsymbol{x}$ denote the velocity vector and position vector of ion respectively; $\boldsymbol{E}$ and $\boldsymbol{B}$ denote the electric field intensity and magnetic induction intensity respectively; t denotes time. The magnetic field was neglected in calculations since it is very weak in grid system. Only the electric potential in the grid system was updated by solving the Poisson's equation:

$$\nabla^2 \phi = -\frac{e}{\varepsilon_0}(n_i - n_e) \tag{3}$$

where ε_0 is the permittivity of vacuum, and ϕ, n_i and n_e denote the electric potential, ion number density and electron number density respectively. To accelerate the convergence of the calculation, the successive over-relaxation method is used to solve the Poisson's equation.

The number of ions injected into the simulation domain for each time step is decided by the ion number density n at the inlet boundary. For the pre-sheath is set as the inlet boundary, the ion number density n at the inlet boundary can calculated with equation: $n = 0.61n_0$, where n_0 denotes the plasma number density in the discharge chamber and is varied with the beam current needs of different operation modes.

The initial axial velocity of ions injected into the simulation domain is set as the Bohm velocity[9]: $v_{bohm} = \sqrt{kT_e/m_i}$, where k is the Boltzmann constant, and T_e is the electron temperature and set as 5.0 eV.[6]

In the model, electrons are regarded as a fluid and their number density follows the Boltzmann distribution[9]: