Particle-in-Cell Simulations for a variable magnet length Cusped-Field thruster

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Abstract: The Particle in Cell plus Monte Carlo (PIC-MCC) method is used to simulate a cusped field thruster. Three different magnet length arrangements of every magnetic cell are involved and convergent simulation results are obtained successfully. The simulation results indicate that the main ionization regions of three models used in the simulation are all placed deep inside the discharge channel and close to the anode. The plasma distribution in the main ionization region can be significantly controlled by magnetic field topology that the longer the first magnetic cell (the closest and largest one to the anode) is, the more diffused the plasma distribution of the main ionization region will be. All the main potential drops of the three models occur at the outermost magnetic separatrixes that are close to the exit of the discharge channel. Some factors that can contribute to the future improvement of cusped field thrusters are concluded through simulation results.

Nomenclature

Z_{max} = distance from the anode to the exit of simulated models
R_{max} = distance from the centerline to the channel wall of simulated models
T_e = simulated initial electron temperature
U_d = simulated anode voltage
Δt = time step
w_{pe} = plasma oscillation frequency
w_c = electron cyclotron frequency

I. Introduction

With a particular magnetic confinement to the plasma, cusped field thruster represents a new type of electric propulsion. A schematic view of a cusped field thruster concept combined with its magnetic field topology is shown in Figure 1. The specific magnetic field topology in cusped field thrusters, which is achieved by a sequential arrangement of magnets, can confines plasma and minimizes plasma-wall interaction efficiently. One of the most significant merits of a cusped field thruster is its long lifetime, one type of cusp field thruster named as HEMPT has been demonstrated successfully a more than 4000 hours lifetime capability[1]. Electron's movement towards the anode is strongly impeded by this magnetic field configuration, which can also form steep electrical field gradients for effective ion acceleration. Thus, due to both high acceleration efficiency and minimal plasma-wall dissipation, the cusped field thruster concept allows for a wide range of operational parameters and high efficiency[2]. Recently,

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because of these specific advantages, cusped field thruster has been paid much attention by many organizations, such as Thales Research Institute's HEMPT[3], MIT's DCFT[4] and Standford University's CCFT[5].

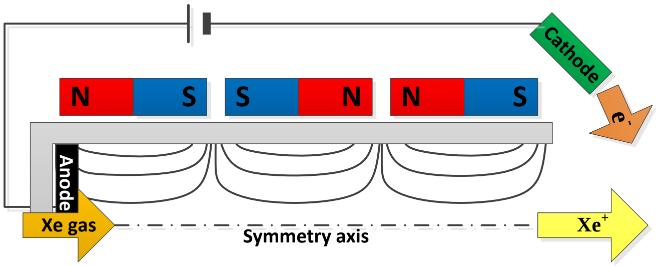


Figure 1. Schematics of the Cusped-Field thruster concept.

The electron throttling effect in a cusped field thruster is similar to that played by the radial magnetic field in Hall thrusters, except that in Hall thrusters the restriction occurs due to the large cross-field impedance, while in a cusped-field configuration the restriction is aided by magnetic mirroring effects [6]. However, the magnetic field strength applied in a cusped field thruster near the ring cusps is about 0.4 Tesla[7], which is much stronger than typically value in Hall thrusters[8]. The cusped-field configurations are intended to magnetically shield the thruster wall so as to minimize bombardment and erosion, and to provide a restriction to the motion of electrons to the anode, thus improving current efficiency and enhancing ionization. Recent HIT's research has revealed that the different magnet lengths of every magnetic cell in the discharge channel play an important role to the performance of cusped-field thrusters.

The numerical simulation method is regarded as a convenient tool to reveal the influence of magnetic field in a cusped field thruster efficiently. Since the complicated magnetic field topology and strong electric field utilized in a cusped field thruster, which will make electrons deviate from Maxwell's distribution, the Particle in Cell plus Monte Carlo (PIC-MCC) method based on the micro mechanism is more suitable to study the physical mechanism in a cusped field thruster.

Some works concerning the PIC-MCC simulation of cusped field thrusters have already been done recently. R. Schneider's PIC-MCC simulations[9] demonstrated that the HEMPT concept allows for a high thermal efficiency due to both minimal energy dissipation and high acceleration efficiency. The plasma contact to the wall is limited only to very small areas, the magnetic field cusps, which results in much smaller ion flux to the thruster channel surface than Hall Thrusters. In addition, Massachusetts Institute of Technology has simulated their Divergent Cusped-Field Thrusters (DCFT) using PIC-MCC method, which revealed some physical process of the plasma under the specific cusped magnetic field topology[10, 11, 12].

This paper is dedicated to the PIC-MCC simulation of a variable magnet length cusped field thruster designed by HIT recently. Particular emphasis is put on the differences of the plasma properties in discharge channel. The paper is organized as follow: in section 2, the cusped field thruster models of simulations are elaborated. In section 3, simulated results of plasma distribution inside three cusped field thruster models are presented, such as electron density profile, potential distribution and electron temperature distribution. At last, there are several conclusions and prospections.

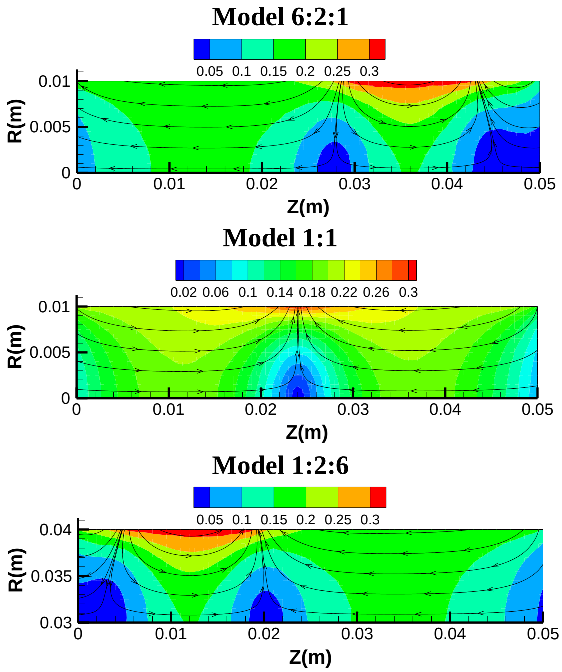


Figure 2. Magnetic field topology and strength (Tesla) used in three models (the proportions of the magnetic cell length from the anode to the exit are 6:2:1, 1:1 and 1:2:6 respectively).

II. Simulation models

In PIC-MCC simulation the kinetics of so-called "Super Particles" (each of them representing many real particles) is followed. Particles move in the self-consistent electric field calculated by the Poisson equation. Particle collisions are handled by Monte-Carlo collision (MCC) routines, which randomly change particle velocities according to the actual collision dynamics. Those following collisional processes are included in the model: electron-neutral elastic, ionizing and excitation collisions. A secondary electron emission (SEE) model for the thruster channel dielectric walls is included in the simulation. In the model, two dimensional space (radial and axial) and three dimensional velocity components (2d3v) are resolved.

Three simplified cusped field thruster models without plume zone are established in the simulation. The computational domains with magnetic fields are shown in Figure 2, all of which represents a cylindrical thruster channel with total length (distance from the anode to the exit) Z_{max} = 50 mm and radius (distance from the centerline to the channel wall) R_{max} = 10 mm. From model 1 to 3, the proportion of every magnetic cell length from anode to exit is 6:2:1, 1:1, 1:2:6 respectively. Two lateral boundaries of three models are the anode (left) and the cathode (right), and the lower and upper boundaries are the symmetry axis and dielectric wall (Boron Nitride). The cathode boundary is at the ground potential and the Quasi-neutrality cathode model is used to inject electron into the computational domain with a temperature T_e = 5 eV. At anode, the voltage U_d = 300 V, the atom flux is 1 mg/s. The time step Δt equals the smaller value of $0.1w_{pe}^{-1}$ and $0.35w_c^{-1}$, where w_{pe} is the plasma oscillation frequency, w_c is the electron cyclotron frequency. The strong magnetic field strength in a cusped field thruster will lead to a difficulty in simulation convergence since the increase of magnetic field strength will decrease the time step Δt. In order to reduce the calculated quantity and get convergent results, the atom density is given by solving the fluid flow equations, and the permittivity of vacuum has been increased 1600 times.

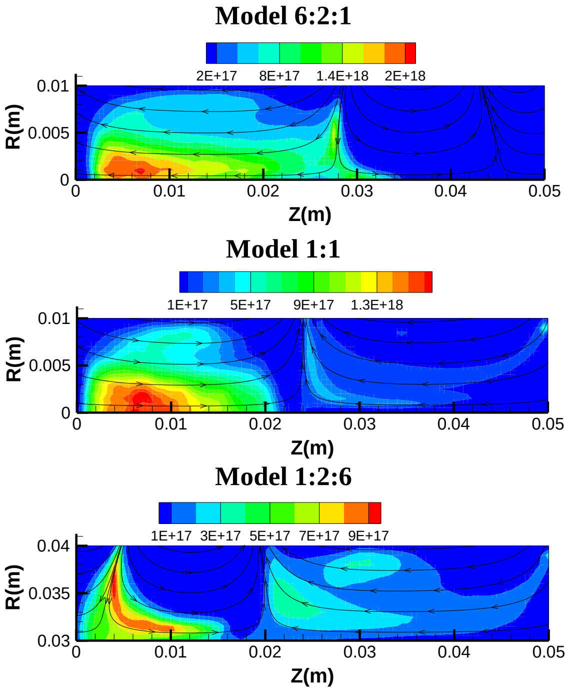
The magnetic fields of three models are calculated through the freeware Finite-Element Magnetic Method solver (FEMM) and imported into the model. The magnetic field generated by the motion of plasma is ignored in the code. Excepting the different magnetic cell (magnetic cell means those regions that surround by magnetic field lines created by only one magnet) lengths, the three models above share the same boundary conditions and parameters in the simulation.

The PIC program is calculated by AMD FX(tm)-8120 Eight-Core Processor with the above simplified model in order to increase the computing speed and make the convergence possible. After nearly five days calculation, all the convergent results are obtained successfully.

III. Simulation results

A. Electron density distribution

Through three simulated results of electron density profiles shown in Figure 3, we can figure out that the main ionization regions of three models are all placed deep inside the discharge channel and close to the anode, due to the relative high atom density there. Another ionization region occurs near the magnetic separatrix (a separatrix is the line that separates the B-lines that bend upstream at the axis of symmetry from those that bend downstream[13]) ranged from 0.02m to 0.03m, the middle position of the discharge channel. However, the distribution of electrons in the main ionization shown in model 1:2:6 that is confined along magnetic separatrix is different from the other two models which mainly surround the centerline of the discharge channel. This phenomenon suggests that the plasma distribution in the main ionization region can be controlled by magnetic field topology significantly. According to the acceleration mechanism, concentrated distribution in ionization regions is expected in order to separate the ionization region with acceleration region, and let ions gain more energy of larger potential drop to accelerate. And Figure 3 shows that the longer the first magnetic cell (the closest and biggest one to the anode) is, the more diffused the plasma distribution of main ionization region will be. Therefore, with respect to the plasma distribution in the main ionization region, model 1:2:6 is a more suitable structure for a cusped field thruster.


Model 6:2:1

Model 1:1

Model 1:2:6

Figure 3. Electron density profile of three models.

According to recent experiments' results[4-5], the possible main ionization region tends to occur more outside and near the exit of the discharge channel, which disagrees with the simulation results. Reasonable reasons of that are the unconsidered plume region and the simplified cathode boundary arrangement in the code. Thus the outermost magnetic separatrix at the exit is supposed to contribute to confine more electrons but doesn't work in the end.

B. Potential distribution

According to the simulation results presented in Figure 4, all the main potential drops of the three models occur at the outermost magnetic separatrixes that are close to the exit of the discharge channel. With the enlargement of the outermost magnetic cell of the three models, the outermost magnetic separatrixes move inward, thus the inward movement of the main potential drops will follow. Generally speaking, the main potential drop occurred near the exit is expected in order to avoid ion-wall contact, which will lead to energy loss and overheating, such as model 6:2:1 that has the main potential drop placed more outside than other two models. When compared with the electron density distribution, we can figure out that the main ionization region of model 6:2:1 is well separated with the main acceleration region occurred at the main potential drop region. Therefore, with respect to the potential distribution, model 6:2:1 is more suitable for a cusped field thruster to obtain higher efficiency.

On the other hand, from the perspective of simulation, inside the discharge channel of model 6:2:1, there have the largest area that keeps nearly constant potential distribution, which has a negative effect on ion transportation, thus the convergence of the program needs to take more time.

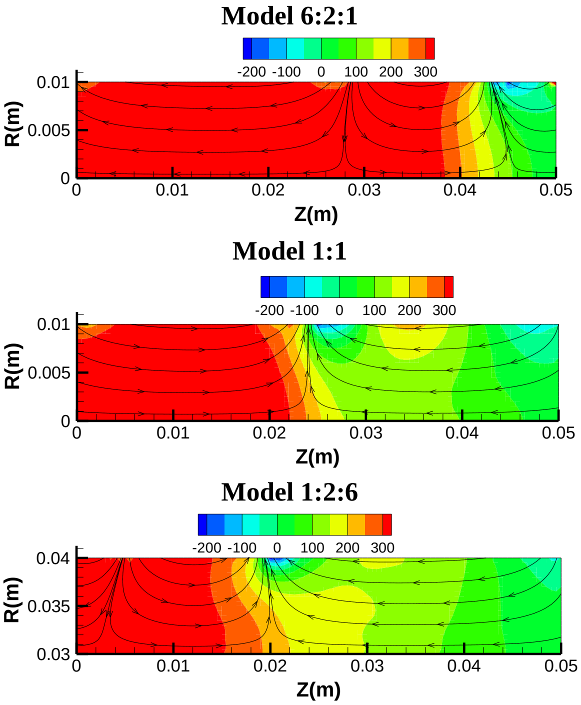


Figure 4. Potential distribution profile of three models (V).

C. Electron temperature distribution

Comparing with Figure 4 potential distribution, Electrons gain the maximum amount of energy from the main potential drops, hence the highest electron temperature, shown in Figure 5, occurs after the main potential drops. In those ionization regions shown in Figure 3, we can find relative low electron temperature, because electrons will lose a lot of energy to contact with atoms. In addition, some statistic noise is found in those regions that rarely distribute electrons.

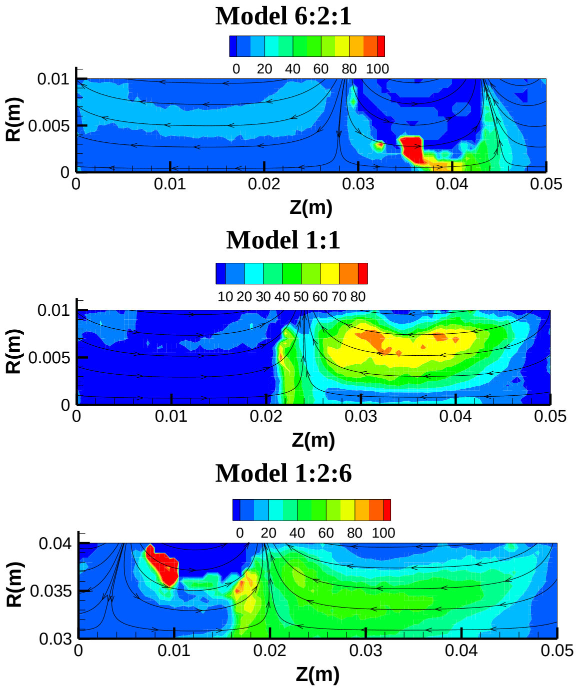


Figure 5. Electron temperature distribution of three models (eV).

IV. Conclusion

In this paper, the PIC-MCC method was used to study the concept of cusped field thrusters - in particular the plasma properties in the discharge channel due to different length of every magnetic cell. In those simulations, PIC-MCC proved itself as a powerful tool, delivering important insight into the basic physics of the thrusters. There are some significant conclusions as follows.

According to the simulated electron density distribution, the main ionization regions of three models are all placed deep inside the discharge channel and close to the anode. The plasma distribution in the main ionization region can be significantly controlled by magnetic field topology that the longer the first magnetic cell (the closest and largest one to the anode) is, the more diffused the plasma distribution of the main ionization region will be. From the simulated potential distribution, all the main potential drops of the three models occur at the outermost magnetic separatrixes that are close to the exit of the discharge channel.

Consequently, an optimized structure of a cusped field thruster should include some factors as follow:

1) Specific magnetic field is required to confine electrons near the anode in order to gain a more convergent main ionization region and place the main ionization region more close to the anode.
2) A magnetic separatrix should be placed near the exit, under the simulated simplified conditions, which will let the main potential drop move outward to separate the main ionization region with the main acceleration region.

Future works are focused on the experiment measurements in discharge channel of the cusped field thruster designed by HIT with different length of every magnetic cell. The simulation of a cusped field thruster with plume zone will be undertaken. And the influence of some parameters to the thruster performance will also be studied, such as mass flux, anode voltage and magnetic field topology.

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