Particle-in-cell model of the helicon plasma thruster experiment at the University of Brasilia

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Abstract. In this paper we describe a numerical model of a helicon plasma thruster device currently under development at the Laboratory of Plasmas at the University of Brasilia. The two-dimensional model is obtained by representing the device using a cylindrical geometry, and neglecting variations in the azimuthal direction. The computational code solves the electrostatic equations and the equations of motion of charged particles self-consistently using the particle-in-cell approach. Our model predicts the emergence of a structure similar to a current-free double-layer in the plasma, which has been detected in similar experiments.

1. Introduction

Electric propulsion devices such as the ion thruster and the Hall thruster have achieved a high technological maturity to be employed in satellites and spacecrafts, however, their operational lifetime is limited due to several factors such as erosion of channel walls and electrodes, and loss of plasma to the internal walls [1]. The helicon plasma thruster (HPT) is an alternative concept which has attracted much attention due to their simplicity and lack of electrodes [2, 3, 4]. These devices basically work as follows. A cylindrical quartz tube is filled with a neutral gas. A radiofrequency antenna emits helicon waves that ionize the gas. A set of coils generates a magnetic field aligned with the axial direction at the center of the tube. The magnetic field confines the plasma at the center of the tube, and creates a magnetic nozzle configuration at the exit region of the tube.

The HPT can operate using a variety of gases such as argon, xenon and helium [5], and can produce a thrust of $\sim$ 10 mN [6]. It has been claimed that the formation of a double layer observed near the exit of the helicon source is responsible for the acceleration of ions, enhancing the device’s thrust [2]. However, the double layer only converts electron momentum into ion momentum, therefore it can not change the total momentum of the plasma [7]. Nevertheless, the HPT is an interesting propulsion device since it is simple to be constructed and does not require electrodes or external neutralizers [5].

Several prototypes of HPT has been developed and tested by several groups, for example, the High Power Helicon at the University of Washington [8], the Medium-Power Helicon Thruster at the Georgia Institute of Technology [9, 10], the miniHelicon Thruster at the Massachusetts Institute of Technology [11], and the Helicon Double-Layer Thruster at the Australian National University [2] and at the Laboratoire de Physique et Technologie des Plasmas at the Ecole
Polytechnique in Palaiseau [3]. The Laboratory of Plasmas at the University of Brasilia (LP-UnB) is currently developing a laboratory prototype of an HPT. Figure 1 shows the working prototype, which consists of two glass cylindrical tubes with diameters of 15 cm and 10 cm, connected using a metal flange. A plasma is generated using an helicon antenna which ionizes argon gas. Two pairs of coils with 730 and 710 loops of insulated copper wire with a 3 mm diameter generate a nearly-axial magnetic field with a maximum magnitude of ∼400 Gauss at the center of the tube. In this paper we describe a computational model of the HPT device at LP-UnB. Section 2 describes the model and the numerical approach. Section 3 describes the results obtained from numerical simulations, and Section 4 presents the conclusions.

2. Particle-in-cell model
We model the HPT at LP-UnB by adopting cylindrical coordinates and neglecting variations along the azimuthal direction. Moreover, only the upper-half of a cross-section of the device is taken into account. The simulation domain is shown in Fig. 2. The walls of the glass tubes are represented by regions with a dielectric permittivity of 4.7. The flange connecting the tubes is represented by a conducting boundary. The metal chamber at the end of the device is also represented with a conducting boundary. The z axis is defined as the symmetry axis, i.e., particles reaching this boundary are reflected back to the simulation domain. All other boundaries are conducting boundaries.

The model is implemented using the Finite Element Method Magnetic (FEMM) software [12] for the magnetic fields and the X-windows Object Oriented Particle-In-Cell (XOOPIC) code [13] for the plasma particles and electrostatic fields. The magnetic field generated using
the FEMM software reproduces measurements obtained from the laboratory device accurately, and is imported into the XOOPIC simulation as an external data file.

The plasma particle model in XOOPIC simulates the ionization due to the helicon antenna by inserting electrons and argon ions at a region between the electromagnetic coils, indicated by a pink area in Fig. 2. This approach was used by Ref. [14] to simulate the HPT experiment at the Australian National University. The interior of the glass tube is filled with argon gas at a pressure $5 \times 10^{-5}$ torr. The ionization due to interactions between electrons and the argon gas are modelled through Monte-Carlo collisions. These collisions result in production of argon ions.

In XOOPIC, the positions and velocities of charged particles (i.e., electrons and argon ions) are computed from the equations of motion due to the presence of electric and magnetic fields. The charge density is then discretized to a spatial grid by a weighting process, which allows to solve the Poisson equation to obtain new values of the electric potential and the electric field. These fields are then inserted into the equations of motion of the particles, and the cycle is restarted. The fields are solved in a spatial grid of size $512 \times 128$, which is enough to resolve the plasma characteristic scales.

To reduce the computational time we employ the “superparticle” approach to represent plasma particles. In this approach each particle in the simulation represents a cloud of real particles, is located at the center of mass of the cloud and its velocity is given by the average velocity of the cloud [15]. In our simulations each electron and ion superparticle represent $10^5$ real particles.

3. Numerical results
The simulations start with the argon gas filling the region corresponding to the glass tube. Following Ref. [14], electrons and ions are inserted into the simulation as described in Section 2 at a constant rate of $10^{19}$ particles/m$^3$s. The temperature of electrons is set to 10 eV, and the temperature of ions is set to 0.5 eV. The electrons spread along the magnetic field lines and ionize the gas producing argon ions. The ions spread as well along the tube, however they take...
a longer time because the ions are heavier than the electrons. Figure 3 shows the distribution of ions after 500000 time steps after which the number density of both electrons and ions reach a steady-state. The model differentiates between ions inserted directly to the simulation and ions produced via Monte-Carlo collisions between electrons and the neutral gas. From this figure it is clear that the ions produced by the Monte-Carlo collisions follow the magnetic field lines more closely than the ions directly inserted into the simulation. This is expected because the ions from Monte-Carlo collisions have a temperature close to the argon gas, which is lower than the temperature of ions inserted directly into the simulation.

Figure 3. The distribution of argon ions generated by the helicon antenna (pink circles), and ions produced via collisions between electrons and the argon gas (light-blue circles). The grey scale in Volts represents the electrostatic potential. Light gray rectangles represent the glass tube walls. Black lines represent magnetic field lines.

The XOOPIC code computes the electrostatic potential $\phi$ self-consistently due to the charge density of electrons and argon ions. Figure 4 shows the resulting potential profile. A positive $\phi$ occurs at the tube walls because the magnetic field reduces the mobility of the electrons and they are not able to reach the walls, whereas some ions hit the walls due to their large gyroradius. Note that a sudden decrease of $\phi$ is observed along the axial direction at $z \sim 0.8$, which may indicate the presence of a current-free double layer.

Figure 4. The electrostatic potential $\phi$ shown in Fig. 3, represented as a gray scale (Volts).

4. Conclusions
Here we presented results of a numerical model of an helicon plasma thruster being developed at the Laboratory of Plasmas at the University of Brasilia. Our results show that a positive electrostatic potential occur at the walls. This is expected since the mobility of the electrons is
restricted along the magnetic field lines, whereas the ions are able to hit the walls due to their larger gyroradius. This accumulation of charges at the tube walls leads to the positive potential observed in the numerical simulations. Our model predicts the emergence of a structure similar to a current-free double layer. A detailed characterization of this structure, previously observed in laboratory experiments [2, 16] as well as in numerical simulations [17, 14] will be the subject of a future work. Our model will allow to test different configurations before implementing new laboratory prototypes.

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