Particle-in-Cell simulation of an Ion Gun

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Abstract: In this paper, we intend to study the plasma profiles at the exit of an ion gun. Ion guns are close to the electrostatic ion thrusters. The ions are allowed to escape through an electrostatic potential difference of 100 V. The plasma density is considered to be a variable. A code is employed, based on Particle-in-cell method to study the plasma behavior at the exit of the ion gun. The code is written in 2D (r, z) coordinates. Initially, the ion velocities are sampled out of a Maxwellian distribution. However, the velocity evolves under the electrostatic potential difference with time. Computationally a sparse gridding is assumed. Various plasma profiles such as the density of ions and maximum z-directional velocity are calculated. The maximum z-velocity has been found to be on the order of 20 km/sec.

Key Words: Ion Gun, PIC, Plasma, Ion thrusters, Maxwell-Boltzmann Distribution

1. Introduction

Electric propulsion is an important concept required for the motion of satellites in outer space [1]. Even for deep space missions, electric propulsion serves as a promising technology [2]. Over the last few decades many types of thrusters have been designed and tested [1,3]. However, since with time the paradigm of satellites has been shifted to small and efficient scales such as micro-to-nano satellites, the thrust requirement has also gone down to the micro-to-milli Newton scale. Electric propulsion finds its best suitability in this regime [4]. Electric propulsion uses electrical energy to energize and ionize the propellant. The resulting plasma is used to achieve the required thrust or acceleration. However, the charge-exchange ions cause to erode the accelerator grids leading to limiting life span of these grids [2]. This is a potentially strong point for the failure of long duration operation of satellites. It is therefore important to have a computer aided modelling of such acceleration mechanisms to understand its operation better.

Simulation of ion acceleration systems is a long time ventured problem and acts as an important consideration for industrial as well as academic research interest [4]. As mentioned above, thruster-plume interaction is one of the major challenges in the field of electric propulsion. A plasma plume is a narrow beam of ion ejected out through an exhaust in ion thrusters [5,6]. In order to understand this, it is important that the plume at the exhaust of an ion thruster is studied well.

There are mainly three categories of thrusting device namely, electro-thermal, electrostatic and electromagnetic [1]. Simultaneously, other extended concepts also being looked for are the electron cyclotron resonance plasma thrusters, electrode less plasma thrusters etc. [7,8]. Electric Propulsion such as Hall Thrusters and Ion Thrusters generate a much larger exhaust velocity of the order of $10^4$ to $10^5$ m/s. Hall Thrusters have higher thrust for operation at a given power but
Ion Thrusters have the highest efficiency [4]. The ion thrusters have higher specific impulse than chemical rockets and are more efficient per unit mass of fuel [9].

This paper is mostly motivated by the academic interest in the problem and intends to study the narrow ion beam coming out of a specified potential difference. Equivalently this can be said to be an ion gun, which is an instrument that produce a beam of heavy ions with well-defined distribution of energy. Ion sources have their application in many diverse areas including mass separation, ion implantation, space propulsions, and accelerators. Plasma is generated within the tube volume via volume ionization mechanism and the resulting ions make an exit through the potential gradient. Schematic of the problem is shown in figure. 1. Computationally it is modelled via particle in cell method in a cylindrical geometry. The code employed for the purpose is 2D in (r, z) coordinates. Following equations depict the volume production mechanism of positive ions [10].

\[
\begin{align*}
    & e + X = X^+ + 2e \ (singly \ charged) \\
    & e + X^{i+} = X^{(i+1)+} + 2e \ (multiply \ charged)
\end{align*}
\]

![Figure 1. Schematic diagram of the tube](image)

2. **Numerical simulation and execution**

The geometry chosen for the given problem is cylindrical in nature. A 2D code is employed to study the ion density variation at the exit of the ion gun. 35 × 12 (z, r) grid points are executed while solving for the problem. The defaults parameters are shown in the Table 1.

| Simulation/Physical parameter | Value                      |
|------------------------------|----------------------------|
| Mass                         | 40 a.m.u (Ar), 131.293 a.m.u (Xe) |
| Plasma density               | \(10^{12} \text{ m}^{-3}\)    |
| Electron Temperature \(T_e\) | 5 eV                       |
| Time step (dt)               | \(5 \times 10^{-9} \text{ s}\) |

Electrons are assumed to be Boltzmann distributed because of their low inertia and high thermal velocity [11–13].

3. **Results and discussions**

Figure 2(a) and (b) shows the contour plot for the plasma density and electric potential for the ion gun. The plots are for the Argon (Ar) as the default gas. The plasma density considered is \(10^{12} \text{ m}^{-3}\). The horizontal axis represent the z-direction and the vertical direction represents the radial coordinate.
As shown in the figure 2(a), density remains close to the horizon without much defocusing effect. Potential profile as shown in figure 2(b) does not show much variation in the extended region of space because of the dominant role played by the applied difference in potential as compared to the self-generated potential difference within the plasma. There is a weak coupling between these two. There might be interesting physics to be explored in the strong coupling regime of this coupling. This is however beyond the scope of this discussion. The electric field provides the necessary focusing of the ion-beam.

The variation of the maximum z-velocity is shown in the figure 3. Figure 4 depict the variation of ion density at different radial locations for the same plasma configuration shown above. It is seen from the figure 3, the maximum z-velocity is attained within a short span of time and it roughly stays constant throughout the remaining time. It is to be noted that a volume production mechanism is considered for the sustainment of the ion gun.
Figure 3. Maximum z-velocity profiles

Figure 4. Variation of density at different z-locations.

Figure 4 depicts the steep fall of density profiles at the exit of the ion gun. While the plasma is within the ion gun, density gradually falls off to zero. However, at the extreme exit there is a steep fall followed by the fact that maximum density is confined with the horizon. There is not much vertical rise of the density. This is important to maintain an appropriate flow velocity.

For many of the practical cases Xe (xenon) gas is used instead of argon for ion thrusters. In the following a comparison plot is shown for the previous results between Xenon and Argon gas.
As obvious from the results shown in figure 5, Xenon is slower than the Argon and achieves the maximum z-velocity at a much slower rate. Nearly 50% speed reduction is noted from the figures. Moreover, the maximum velocity achieved is less in magnitude portraying a less steep graph in comparison to the Argon. Regarding the density distribution, the width of the radial distribution although remains same, however, Xenon offers a higher deposition rate for density. The reason behind is the inertia of the Xenon ions. Previously such comparison is done by Jarrige et al. in the case of an electron cyclotron resonance (ECR) plasma thruster [5]. However, other parametric analysis gives Xenon an edge over the Argon.

Figure 6 (a) and (b) displays the potential and density variation at the 7th grid location (which is inside the chamber volume). Potential seems to increase radially along with its difference at higher applied boundary voltage. Contrary to this, density at the same node is higher for the lower applied potential. Electric field at the lower potential does not provide the required thrust to allow for the fast exit of plasma, which as a consequence gives higher deposition radially. In the following the
maximum velocity profiles are shown (figure 7) for comparison among different applied potentials.

![Image of Maximum velocity profiles at different applied potential]

**Figure 7. Maximum velocity profiles at different applied potential**

4. Conclusions
Plasma flow is studied for an ion gun at its exit to understand the plasma plume structure. The base gas considered is Argon and it is compared with that of the Xenon. Xenon being a heavier gas, offers higher deposition rates for its density. A reduction in velocity of the order of 50% is viewed in Xenon in comparison to Argon. There could be interesting physics driven by the strong electrostatic coupling between the applied and the self-generated fields. Plasma profiles are viewed at different boundary potential. Low level of velocity is seen for low applied potential along with higher density deposition within the chamber.

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