Three-Dimensional Charged Particle Tracing of E×B Plasma Discharge in Hall Thrusters

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Hall thrusters (HTs) are recognized as a pivotal technology in electric propulsion for space missions, owing to their remarkable efficiency and versatility. Offering high specific impulse values ranging from 1000 to 3000 seconds, these devices significantly outperform traditional chemical propulsion engines. HTs can operate across a wide range of power inputs, from 10 W to 100 kW, and can use noble gases such as xenon and krypton as propellants, making them fitting for a variety of space missions. These thrusters can generate thrust levels from a few millinewtons (mN) to between 1 and 5 newtons (N), making them suitable for both small and large-scale missions that require quick deep-space travel. The working principle of HTs revolves around creating a powerful electric field within the plasma chamber. To achieve this, a transverse magnetic field is introduced to reduce electron conductivity. However, the longitudinally applied electric field introduces a perpendicular drift (E×B drift) in the azimuthal motion of the electrons [1]. The magnetic field is designed to strongly magnetize electrons, effectively trapping them along the magnetic field lines, while ions remain mostly unmagnetized. This configuration ensures electrons are collisional and confined by the magnetic field, whereas ions remain largely collisionless. For this cross-field discharge it is essential to have a continuous supply of electrons. This requirement is met by positioning an external hollow cathode device adjacent to the Hall discharge chamber. Typically, a hollow cathode comprises a durable tube made of refractory material, along with an insert designed to emit electrons efficiently due to its low work function. It also includes a heating mechanism, a plate positioned downstream, and an anode keeper to facilitate operation. The heating process, often initiated by coiling heaters around the cathode, raises the temperature, which in turn starts the discharge process. Subsequently, the electric field plays a crucial role in propelling the released electrons toward the anode, which operates at a high voltage [2].

In this simulation study, the HT was design based on the *Stationary Plasma Thruster-100* with a magnetic shielding configuration. In general, it consists of five copper coils in total (four outer with 1750 turns and one inner with 1440 turns), a boron nitride dielectric chamber, a stainless-steel anode, a magnetic circuit with low carbon steel, and a hollow cathode made of tungsten [3]. To efficiently simulate the vast number of particles typically involved in such systems, the study assumed each macroparticle represents 10^6 individual particles. Neutral Xenon (Xe) particles are expelled from the anode, while electrons are emitted from the hollow cathode. The movement and interaction with the electromagnetic fields were governed by the Lorentz force for the electrons and electric force for the Xe ions, whereas for the interaction between macroparticles, it was assumed a Monte Carlo collision model with elastic scattering, excitation, ionization, and double ionization collisions, using the Charged Particle Tracing module from COMSOL Multiphysics. The magnetic field was computed through a stationary Flexible Generalized Minimum Residual (FGMRES) solver using the Magnetic Field module by applying 2.5 A in the outer coils and -5 A in the inner coil, the electric field was computed through a stationary Conjugated Gradients solver using the Electrostatics module, by applying 300 V in the anode, 0 V on the hollow cathode and -25 V on the top of the magnetic structure, corresponding to the floating potential that exists near the thruster's exit [4]. A time-dependent Generalized Minimum Residual (GMRES) solver was used to capture the motion of particles from 0 μs to 3 μs in 10^{-11} s time intervals. Overall, the simulation time was 22.5 days.

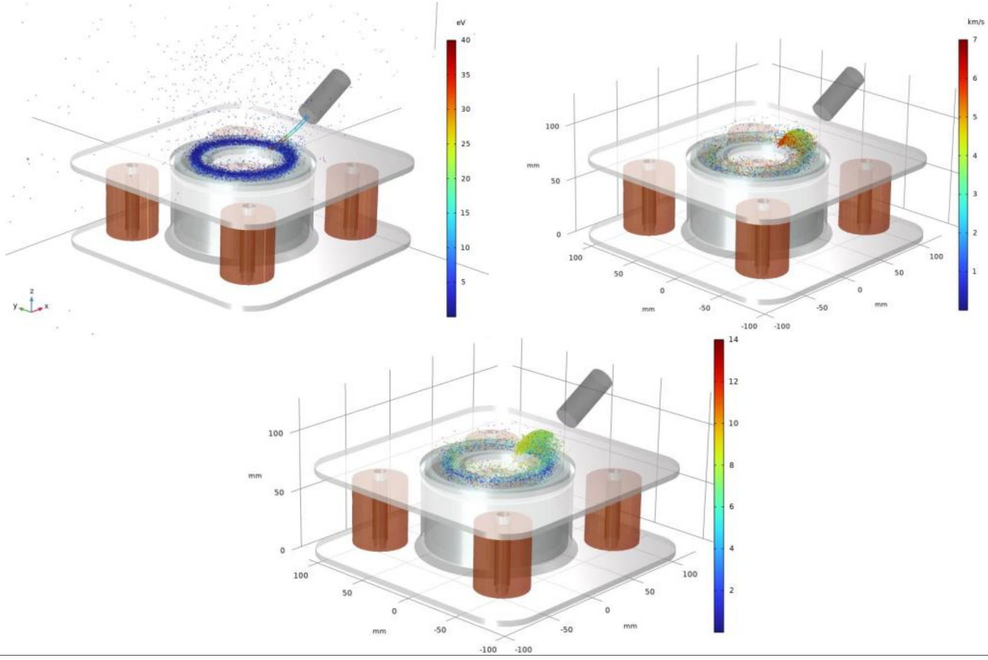

Fig. 1: Hall thruster plasma discharge at 3 μs (a) depicting electron behaviour, (b) depicting Xe^{+} ions behaviour, (c) depicting Xe^{2+} ions behaviour.

This model can output electric and magnetic fields, electric potential, particle trajectories, particle velocities, and particle densities. Figure1 presents the preliminary results of a three-dimensional charged particle tracing HT model [5]. Fig1(a) shows the electrons being emitted from the hollow cathode towards the chamber. The different colours represent the electronic temperature from each macroparticle. Here, we observe that most electrons are trapped in areas of higher magnetic field strength (20 mT), with temperatures ranging from 10 to 20 eV. It is also shown that electrons with higher temperatures tend to escape this pattern, moving towards the anode and in some cases colliding with it, highlighting the electron anomalous transport phenomena. Fig1(b) and Fig1(c) shows the motion of single charged Xe^{+} and Xe^{2+} ions that are ionized inside the chamber. The different colours represent the velocity from each macroparticle. Here, most ions are observed in this high magnetic field zone, being accelerated towards the thruster's exit by the electric field and reaching speeds up to 11 km/s for Xe^{+} and 22 km/s for Xe^{2+}. Meanwhile, some ionization occurs inside the chamber due to high-energy electrons escaping the magnetic field and moving towards the anode [1,3]. This comprehensive simulation opens new possibilities for future space research missions and contributes to our understanding of E×B plasma discharge dynamics in Hall thrusters. It also sets the way for the development of more efficient and scalable electric propulsion systems.

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