Helicon Optimization Within the HIIPER Space Engine Through the Charged Particle Tracing Module

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Introduction

Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) [1] is an advanced space propulsion system being studied in University of Illinois Urbana-Champaign. It has been depicted in Figure 1. It consists of a helicon (quartz tube) source to generate plasma and inertial electrostatic confinement (IEC) grid to extract the plasma out of the helicon.

An experimental setup is already being used to gather dynamics of plasma with the help of Langmuir probe measurements. The experimental procedure involved is complex and thus numerical simulations are used as a simplification tool. Computational studies in COMSOL reduces the cost of running the experiment and time taken in investigating results of unfavorable operating conditions. Optimization of the system is being done by COMSOL using inductively coupled plasma (ICP) in the simulations [3].

This paper describes the studies being done on the helicon component of HIIPER, that generates plasma using Argon as propellant gas. Ion extraction from the system creates the thrust force needed to propel the spacecraft. Electromagnetic waves are generated due to the radio frequency (RF) antenna wrapped around the quartz tube which in turn convert the Argon gas into a plasma. Simulations of the helicon part in HIIPER involve integrating the Magnetic Field model along with the Plasma Electromagnetic Waves model. Based on previous experimental and numerical results, there are not enough ions going to the IEC grids from the helicon source [1,3]. To understand what system designs are causing these heavy ion losses, Charged Particle Tracing model is used to determine the ion trajectory within the helicon quartz tube.

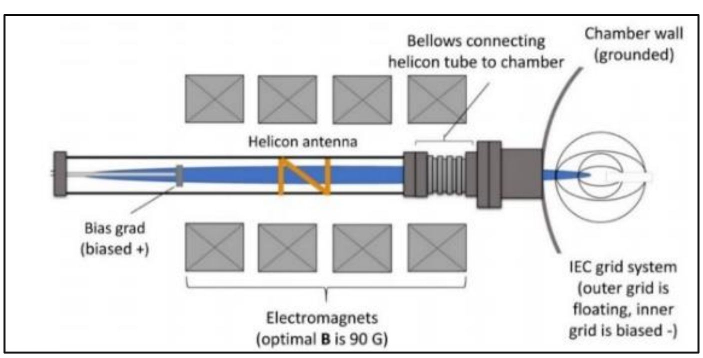


Figure 1. HIIPER Schematic

Computational Model

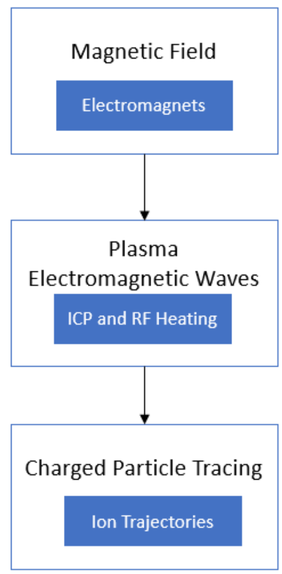


Figure 2. Computational Chart

The COMSOL model (figure 2) consisted of three parts: Magnetic fields (mf), plasma (electromagnetic waves) and charge particle tracing (cpt). Electromagnetic analysis of the coils required solving Maxwell's equations to certain boundary conditions in the time-varying field:

$$\nabla \times H = J + \frac{dD}{dt} \quad (1)$$

$$\nabla \times E = -\frac{dB}{dt} \quad (2)$$

where:

- E is the electric field intensity
- D is the electric flux displacement
- H is the magnetic field intensity
- B is the magnetic flux density
- J is the current charge density

The Inductively Coupled Plasma (ICP) interface is applied to note the discharges sustained from induction current. The induction currents are solved in the frequency domain and electron heating is automatically dealt with by the software.

The Charged Particle Module equation was formulated under static conditions by rewriting Gauss' Law as a form of Poisson's equation:

$$-\nabla(\varepsilon_0 \nabla V - P) = \rho \qquad (3)$$

where:

- ε_0 is the permittivity of vacuum
- V (SI unit: V) is the electric potential
- P (SI unit: C/m2) is the polarization
- ρ (SI unit: C/m3) is the charge density

Though helicon waves were used to generate the plasma, they were not directly included in the results. The model diagram describing the simulation parameters and boundary conditions is shown below.

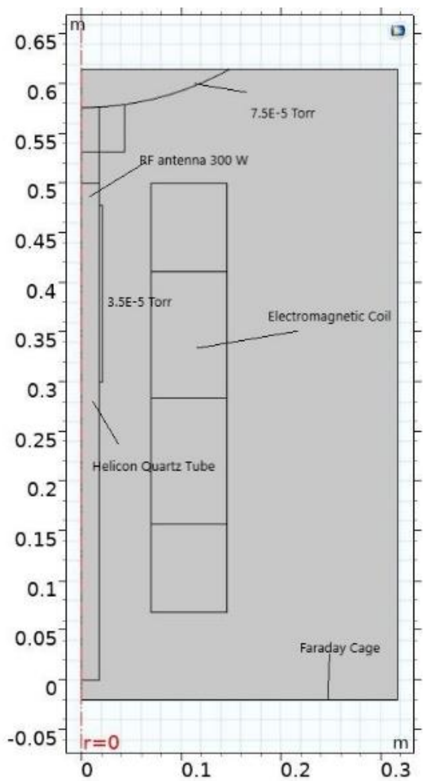


Figure 3. COMSOL Model Diagram

Computational Results

Numerical studies were performed at four different rf powers: 10 W, 300 W, 1 kW, and 100 kW. The first two values were the minimum and maximum power levels of the current HIIPER setup. 1 kW is a possible power for a future upgrade to HIIPER while 100 kW would be the theoretical requirement for an actual deep space thruster. The following results were generated at 90G electromagnetic field:

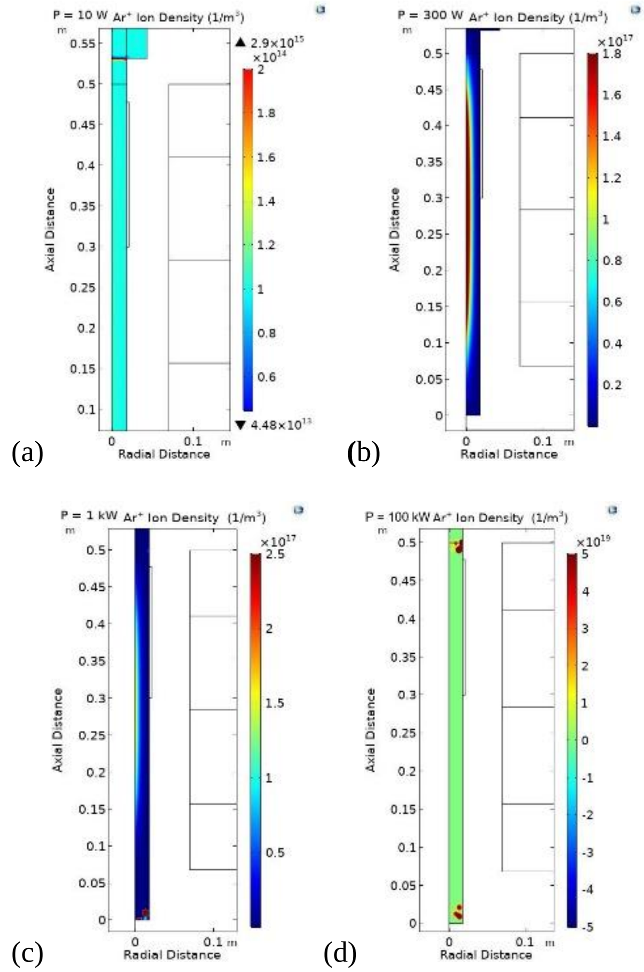
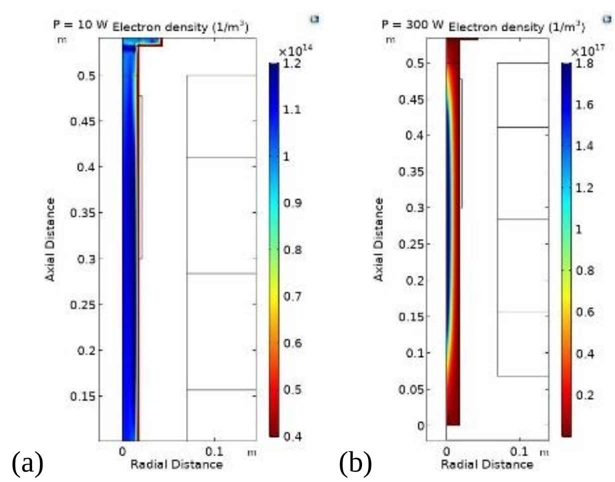


Figure 4: Ion Densities at (a) 10 W, (b) 300 W, (c) 1 kW & (d) 100 kW



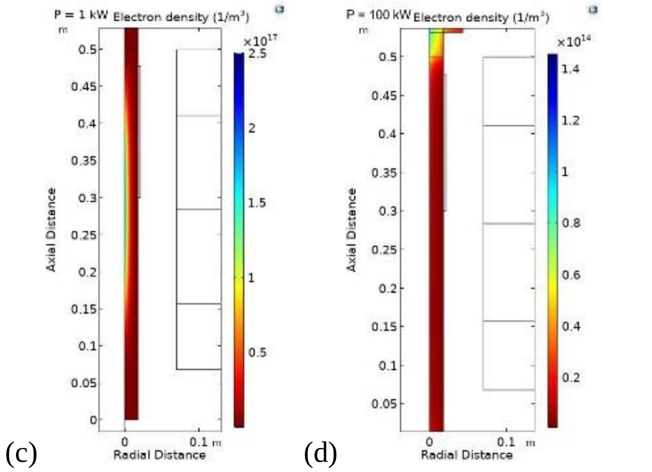


Figure 5: Electron Densities at (a) 10 W, (b) 300 W, (c) 1 kW & (d) 100 kW

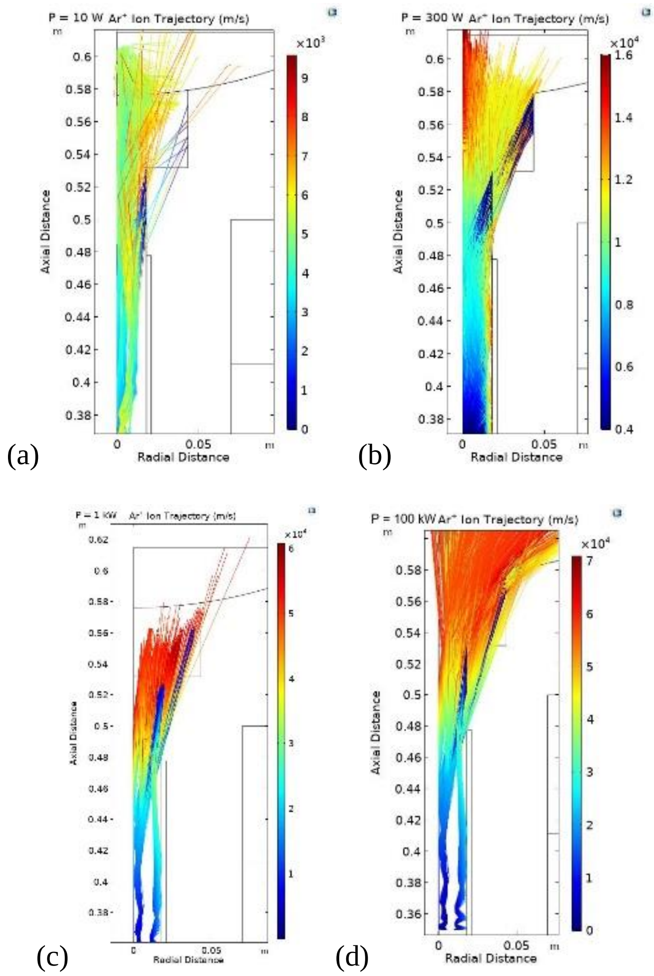


Figure 6: Ion Trajectories at (a) 10 W, (b) 300 W, (c) 1 kW & (d) 100 kW

Conclusions

Ion densities of the order 10^{17} m^{-3} are found at the 300 W to 1 kW rf power range. Langmuir probe experiments done at 300 W have found similar ion densities. While there are spikes at 100 kW power at specific positions, the average remains the same throughout the kW range. Particle trajectories are plotted to study the location of ion losses in the current helicon setup. From the results, we can see that the ions are lost to the wall at the downstream end of the helicon tube. With increase in rf power, the percentage of high energy (kinetic energy) particles hitting the wall also increases considerably. This firmly indicates that the increase in rf power does not impact ion density as much as it effects the ion velocity.

References

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3. Drew Ahern, “Investigation of a Space Propulsion Concept Using Inertial Electrostatic Confinement”, PhD Dissertation (2018), University of Illinois at Urbana-Champaign.