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HIIPER Space Propulsion for Future Space Missions

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Abstract: A coupled helicon/IEC plasma jet is in development for space propulsion applications. This device decouples the ionization and plasma acceleration process into separate stages. The ionization source utilizes an inductively wound antenna driven at 13.56 MHz. A critical parameter is the propagation of electromagnetic fields which radiate from the antenna into a cylindrical tube. The electric field patterns are important because they are responsible for the ionization process. Geometric effects on wave propagation such as domain radius, antenna length, and oscillator frequency are also considered to solve for an optimal antenna resonance configuration. The initial dielectric domain considered was vacuum, epsilon = 1.0, however, a more realistic model is to consider a plasma media in which the relative permittivity is negative or imaginary. Toward this end, COMSOL readily considers complex permittivity values, enabling a first attempt at modeling a plasma domain in terms of permittivity values.

Keywords: AC/DC, RF, Helicon, IEC, Thruster.

1. Introduction

The Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) is an advanced, IEC type electric thruster for space missions. It uses an electrostatically confined plasma and ejects the plasma through a designated orifice in its asymmetric confining grid. This grid design ejects the plasma in a tight beam, preserving linear momentum and maximizing propellant efficiency, as shown by Figure 1.

By decoupling the tasks of plasma generation and acceleration into two separate stages, more control is gained over efficiency and thrust of the engine. A helicon was chosen as the primary plasma generation stage because of its high ionization fraction and efficient energy deposition, while the IEC was chosen for its excellent plasma acceleration properties.

While this simplifies the control of the device by compartmentalizing changes in characteristics, it creates a complex issue in simulation and prediction. Analytical solutions of the electromagnetic fields and plasma flow would be difficult, time consuming, and would have to be made using assumptions that may ignore important effects. In addition, the dynamics inside an IEC confinement grid are difficult to measure using conventional, physical probes such as Langmuir probes and potential probes. By using COMSOL, we hope to gain insight into the flow of the plasma, and the effects of changing geometry, voltage, power, and working fluid. After a reliable simulation is designed, we can compare the COMSOL simulations with data collected from the current device in the laboratory. We want to be able to make rapid improvements to the design of HIIPER without having to manufacture or purchase new components through the aid of simulations.

In the long term, simulations in COMSOL can be used in the final engineering of HIIPER to be installed on a satellite or probe by measuring power requirements, and heat dissipation requirements. Using these measurements appropriate material selections and dimensions can be made as a starting point for final design and testing.

From this we can see that COMSOL can play an integral part from the most preliminary design all the way to final development of a device; its role for a complex system such as HIIPER is invaluable to rapid improvement, design, and testing.

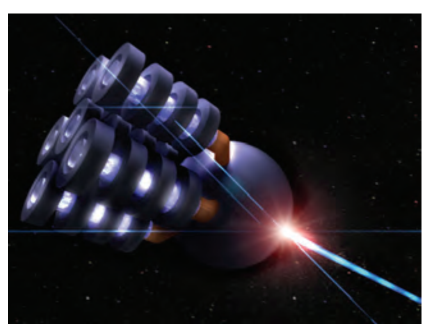

Figure 1. Conceptual Drawing HIIPER in Flight

2. Governing Equations

The IEC Potential Governing Equation is Poisson's Equation in spherical geometry:

$$\left(\frac{1}{r^2}\right)\left(\frac{d}{dr^2}\right)\left[r^2\left(\frac{dV}{dr}\right)\right] = 4\pi(|\rho_e| - \rho_i) \qquad (1)$$

With boundary conditions V(r) = 0 at r = R.
And V(r) = V at r = A. Where A is the radius of the confinement grid and R is the internal radius of the IEC chamber.

Helicon Governing Equations:

$$\nabla^2\vec{b} + \alpha^2\vec{b} = 0 \qquad (2)$$

Where the z-component of the wave magnetic field is in cylindrical coordinates is.

$$\frac{\partial^2 b_z}{\partial r^2} + \frac{1}{r}\left(\frac{\partial b_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 b_z}{\partial \theta^2} + \frac{\partial^2 b_z}{\partial z^2} + \alpha^2 b_z = 0 \qquad (3)$$

The radial and angular components of the governing equation for use in a potential three dimensional simulation:

$$b_r(r) = \frac{iC}{T^2}\left(\frac{m\alpha}{r}b_z(r) - k_z b_z'(r)\right) \qquad (4)$$

$$b_\theta(r) = \frac{C}{T^2}\left(\frac{mk_z}{r}b_z(r) - \alpha b_z'(r)\right) \qquad (5)$$

Boundary Conditions:

$$b_z(r) = CJ_m(Tr) \qquad (6)$$

$$b_r(a) = 0 \qquad (7)$$

3. Theory

As shown in Figure 2, neutral inert gas, in this experiment argon, is injected at one end of the helicon, where the gas is ionized and converted into plasma as it passes through the antenna. It then diffuses into an asymmetric IEC confinement grid where it is accelerated in the potential well and aligned to the large aperture in the grid before it is ejected. Figure 3 shows a photo of the IEC operating with the helicon as a demonstration of the particle beam exiting from the confinement grid. The helicon's plasma can be seen at the very edge of the photograph. The larger aperture in one side of the confinement grid allows the accelerated particles to exit from the IEC and provide thrust. Theoretically, ions will be ejecting at high velocity with electrons unable to enter the confinement grid and pushed to the side.

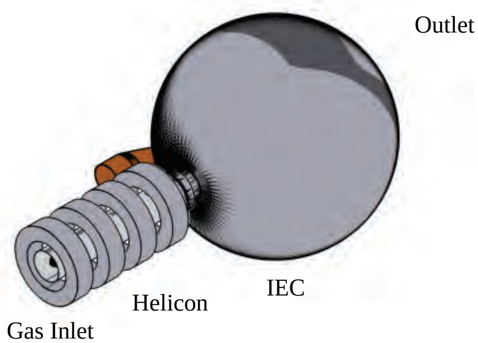

Figure 2. Drawing of Current HIIPER Design

There are several potential issues currently under investigation in this design, particularly the flow of particles from the helicon into the IEC. Because the energy of ions and electrons in the helicon are expected to be on the order of a few eV, and the IEC grid is operated currently on the order of kV, we wish to see if assistance will be needed to inject the ions from the helicon into the center of the IEC grid. If so, several concepts of small magnetic nozzles and guide grids are potential candidates that also can be tested using COMSOL, eliminating much of the extra time needed to design and build each candidate to check the design.

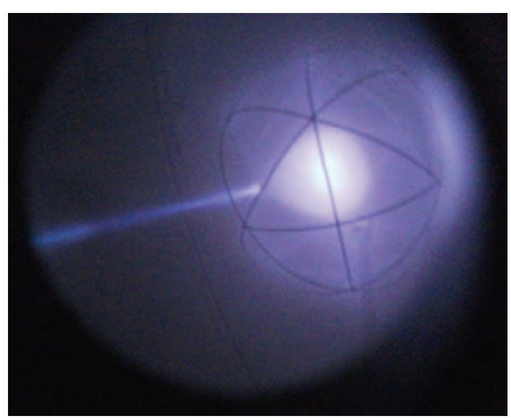

Figure 3. Photo of IEC Jet with Helicon On.

Additionally, experiment have shown the potential to use a variety of gases in this system to produce thrust, including molecular gases. The advantage of using a molecular gas is the impartation of higher momentum, which will enable HIIPER to generate higher forces than current electric thrusters. To this end, COMSOL would be a very useful tool to see rapidly the effects on performance by changing gases.

4. Use of COMSOL Multiphysics

In this project, there are two primary packages that are a priority to use for modeling: AC/DC for the IEC device and RF for the helicon antenna, with the long term potential of adding the plasma package to model the flow of plasma and the heat transfer package to model thermal load on the device.

The IEC's electrostatic potential wells used for plasma confinement will be modeled along with the magnetic field lines of the helicon attached. The behavior of the potentials and magnetic field lines in the system are of interest, especially at the interface of the two devices. One of the long term objectives is to use the plasma modeling package to see the relation and the changes in the potentials in the coupled system, and the flow of plasma from the helicon into the IEC. Then, modeling of the potentials in the interior of the IEC grid would be conducted, as physical probing of the IEC has shown to be highly non-trivial in previous attempts.

The plasma package will also be used to simulate the use of different gases. Currently the working medium is argon, but helium, hydrogen, xenon, nitrogen, and oxygen are all gases of interest and will have different performance values in this engine.

Overall, the objective is to model the flux of particles exiting the IEC after acceleration is complete. The temperature, composition, density, and velocity of these particles are of particular importance as they will be used to predict the efficiency and force of this space thruster. The results from the predicted thrust will be compared with a physical force probe used to measure the thrust generated by the system.

In the long term the addition of the thermal package can be used to determine the heat load on the materials of this device. Being able to simulate the heat load would simplify the task of carrying this device from a laboratory setting to an application setting by giving foresight into potential material selection and sizing.

5. Method

The procedure to achieve a full simulation of HIIPER will involve several small simulations of individual components, comparing them with measurable data, and then combining simulations for more complex systems. The helicon can be separated into its magnetic coils and the RF antenna to gain a basic familiarity with COMSOL's EM and RF packages. Similarly the IEC without plasma will be modeled first to gain familiarity with the AC/DC package. After, the complete helicon and IEC models will be joined and a first simulation of magnetic and electric fields will be conducted.

Once confidence in the model has been attained, variations on the IEC confinement grid's geometry can be conducted to see the effects. Additionally, changes in the helicon geometry and frequency are also desired to determine the influence that each parameter has to the overall performance of the system.

6. Anticipated Results

The magnetic field lines, potential wells, and plasma flow for the coupled HIIPER system are unknown, but several known properties of the component devices will be used to test the accuracy of the uncoupled small simulations in preparation for the large simulation. Figure 4 shows a simple prediction for the magnetic field lines and the location for highest plasma density in the helicon. As seen in previous research, plasma forms in a preferential location at the end of the helicon, towards the south pole of the magnets, with the helicon configured to generate a wave propagating with a clockwise rotation traveling downstream.

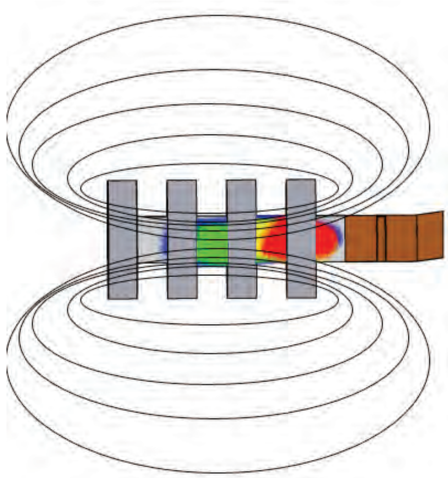

Figure 4. Predicted Helicon Magnetic Field and Plasma

The IEC potential well without a plasma is expected to be a linear drop from the grounded walls to the negatively biased confinement grid, with a flat potential in the center of the grid as shown in Figure 5. When plasma is added, the dynamics of the system change, and probing the inside of an IEC confinement grid physically is non-trivial. To that end, the COMSOL simulation will be an invaluable tool to give an idea of the formation of virtual cathodes inside the IEC, micro-channel formation in the confinement grid orifices, and plasma flow leaving the exit aperture in the confinement grid.

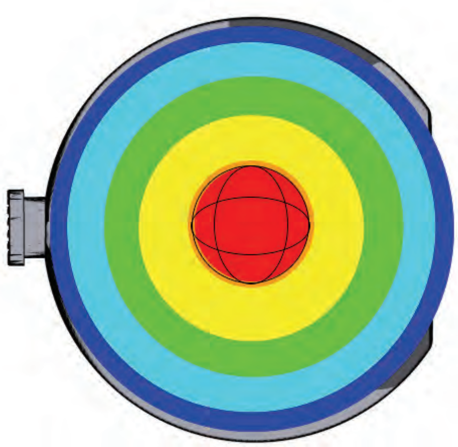

Figure 5. Predicted IEC Potential Well

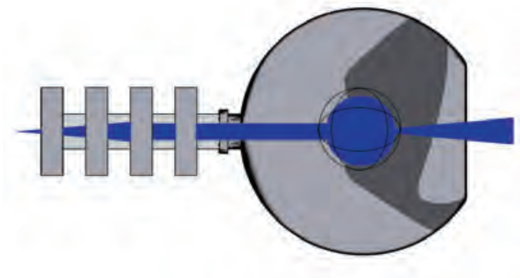

Figure 6. Drawing of Predicted Plasma Flow in HIIPER

Combining these two smaller simulations and adding the COMSOL plasma package, an attempt will be made to simulate the flow of plasma through the system. Figure 6 is a simplified drawing of where plasma is expected to be present. It will originate in the helicon, diffuse into the IEC where it will be accelerated out of the system.

7. Conclusions

There is great potential application of COMSOL to real-world design, and HIIPER is a unique opportunity to put COMSOL's multiphysics simulations to the test on three to four physics simultaneously. Over the course of several months these simulations will be assembled, tested, and combined to help design this system.

8. References

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