Progress in Numerical Simulation of HIIPER Space Propulsion Device

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Abstract: HIIPER is an experimental space propulsion device using a helicon and an IEC as a plasma generation and acceleration stage, respectively. There is an experiment in progress, but for true rapid iteration and to model the performance of the engine, COMSOL is a strong candidate for fulfilling these roles and continuing with the project until its production phase.

The simulation is built by beginning with very simple forms of each device and as the simulations succeed, additional complexity and detail is added until the full design is achieved. Each device is also simulated separately with the goal of using the exit interface of the helicon as the entry interface of the IEC. Current results show COMSOL is a promising tool for rapid iteration and continuing design. The primary tools used are the AC/DC, DC Plasma, and Particle Tracking packages.

Keywords: DC Discharges, IEC, Plasmas, HIIPER

1. Introduction

The future of space exploration depends on faster propulsion systems, not only for manned space flight to be viable to other worlds, but so that satellites can more quickly be deployed to their destination, and be more versatile in the data they can collect. Propulsion systems to achieve that goal will need a new design and approach to overcome the barrier of thrust, lifetime, and efficiency that current thrusters face. To that end, HIIPER (the Helicon Injected Inertial Plasma Electrostatic Rocket) is an experimental space propulsion device which decouples the tasks of plasma generation and acceleration by using a helicon and an IEC (Inertial Electrostatic Confinement) device, respectively.

COMSOL's role is multi-fold. First, it is used as an initial look at the physics of the helicon and the IEC separately. The objective is to complete these simulations and as an initial complete simulation, use the output interface of the helicon as the entry interface to the IEC.

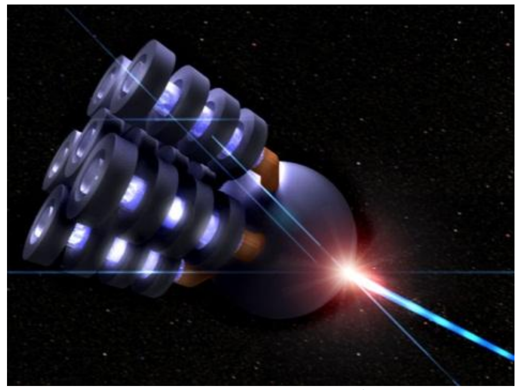

Figure 1. Conceptual Drawing of HIIPER.

The second role is to create a profile of the effects when modifying the parameters of the system, from changing the geometry of each component, to sweeping power levels of each device. Once that is complete, we can continue on to iterative design.

The final role of COMSOL will be to move HIIPER from the experimental phase to the production phase. By sweeping parameters, HIIPER can be optimized by using data collected in the previous phases. In this way, time and resources can be conserved.

This article is arranged to cover the basic physics of HIIPER, how it was translated into the COMSOL model, current progress, and the outlook for HIIPER and COMSOL's continued role in this project.

2. Governing Equations & COMSOL

Presently the priority is simulating the asymmetric IEC, the plasma acceleration stage of HIIPER. This simulation takes advantage of the AC/DC Electrostatics, DC Plasma, and Particle Tracing modules.

2.1 AC/DC Electrostatics

At first, we want to characterize an electrostatic profile for the asymmetric IEC. The electrostatic governing equations are Poisson's equations with the boundary conditions at the wall of the chamber and the biased grid at the center of the IEC. In spherical geometry:

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

The boundary conditions are zero charge and potential at ground, and -10,000 V bias at the grid.

2.2 DC Plasma

The DC Discharge in the Plasma package is at the heart of what the asymmetric IEC does. Again using the equations which are included in the DC plasma package:

$$\nabla \cdot \boldsymbol{D} = \rho_v$$

$$\boldsymbol{E} = -\nabla V$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_e = R_e - (\boldsymbol{u} \cdot \nabla) n_e$$

And

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_e + \boldsymbol{E} \cdot \boldsymbol{\Gamma}_e = S_{en} - (\boldsymbol{u} \cdot \nabla) n_e + \frac{Q + Q_{gen}}{q}$$

The closest known approximation we have to simulating the IEC Jet Mode will be done through DC Discharge. As a baseline and first attempt at creating a simulation, the Argon cross-sections provided for the DC Discharge example program were used, and the remaining conditions set similarly. The design of the simulation has been iterated through many phases, adding more complexity and building a more complete model in every new version.

2.3 Particle Tracing

The particle tracing package was also used because the trajectory of the electrons and ions in this simulation are of great interest. The particle tracing simulation is currently focused in two sections. The first is on the paths of particles in the IEC, and the second is the motion of particles through a proposed Einzel Lens type solution for an electrostatic ion/electron extraction nozzle.

3. Methods

As described, to simulate the IEC component, there are three packages that are in use to characterize the performance: AC/DC, Plasma, and Particle Tracing. As mentioned earlier, because of the complexity and the unfamiliar nature of simulating a problem, the attempt was to create simple models and slowly build complexity to develop a full simulation of the system. The IEC contains a secondary component as well, an Einzel Lens designed to focus and control the movement of electrons and their ratio to ions ejected to create the proper electrostatic channels in HIIPER.

To further simplify these calculations, a 2-D axisymmetric model was used for all the current simulations.

3.1 IEC Grid Simulation

The goal for the final IEC model is to complete a full 3-D simulation with all parts included in one simulation. The confining grid has multiple opening and a larger aperture for the jet mode. The first step towards this simulation is to create a model where the confining grid is represented with a solid sphere to create a general DC discharge between grid and wall. This will establish a working understanding and applicability of the plasma package for this geometry.

The next and current step is to replace the solid sphere with a cross-section of the confining grid. The goal is to create a DC discharge which, as in the real IEC, forms a virtual anode at the center. Two stages for this simulation were used to aid in convergence. The first stage was to use circles of large diameter to represent the grid due to ease proper meshing. The second stage was to use small circles of diameter of the wire for the confining grid. The final stage will be a full 3-D simulation using the actual aperture sizes on the physical grid.

The objective is to be able to recreate the IEC Jet Mode discharge shown in Figure 2 using COMSOL. Once this is achieved, it will aid in the characterization of the properties of this mode, and enable the ability to predict the thrust generated by HIIPER in future design iterations.

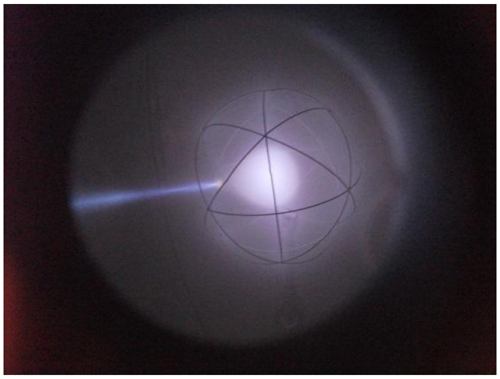

Figure 2. Photo of HIIPER IEC Chamber with Jet Mode Discharge.

3.2 Einzel Lens Simulation

The second component inside the IEC, the modified Einzel Lens, is simulated using a 2-D axisymmetric model. This can be done because the lens does not have varying geometry in 3-D like the IEC's confinement grid. Because the lens is not designed to create any plasma, only the AC/DC and particle tracing packages are used while the lens is simulated separately. With these two packages characterizing the nature of the charged particle control, there is a clear way to relate the shape of the electric field with the motion of the particles. This simulation is then configured to accept the inputs of the particle characteristics of the IEC to redesign and optimize the lens as needed. Once the IEC simulation is complete, the Einzel Lens can be imported into the IEC model, and the system can be tested together using the plasma package.

4. Current Simulation Results

The current state of results indicates a promising look at the ability of COMSOL to simulate this novel plasma discharge. 'Nonconverged' notes indicate results that are not in the steady state. Progress is being made to achieve steady state solutions.

4.1 IEC Solid Sphere Discharge

The solid sphere discharge results are as expected for a spherical DC Discharge. The proper glow and dark regions exist and ion concentrations are as expected.

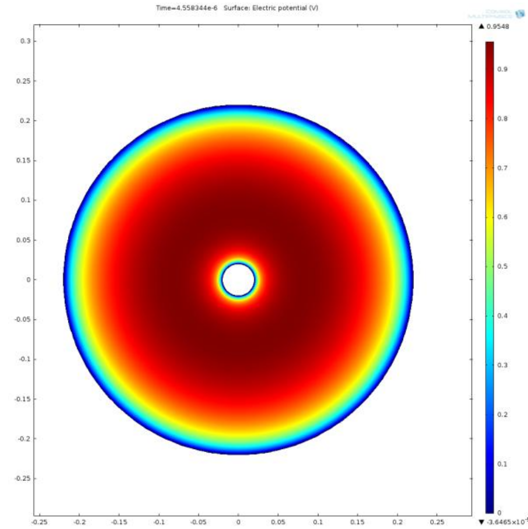

Figure 3. Electrostatic Profile of Ball DC Discharge (nonconverged)

An interesting note is that later when the grid is introduced instead of the solid ball, the plasma that is seen here, similar to a two-plate DC discharge, will actually pass through the channels in the grid and collect at the center.

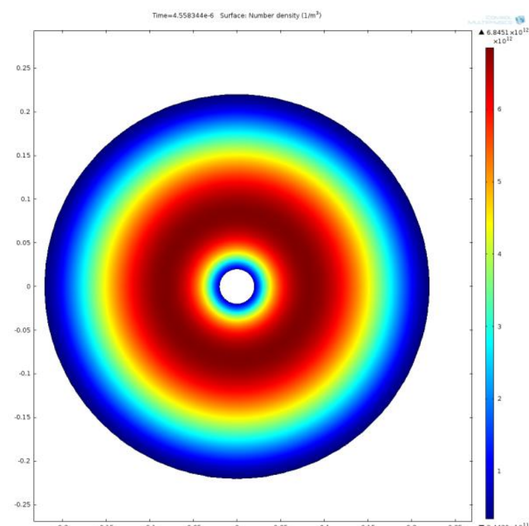

Figure 4. Ion Density Profile of Ball IEC Discharge (nonconverged)

4.2 IEC Gridded Discharge

The gridded discharge allowed us to see the results of modifying the geometry of the center grid. Figure 5 shows the profile of having a wider aperture on the electrostatic field. This opening is important because it is what gives electron extraction a preferential orifice. This electron channel will then pull ions out of the center of the grid and out of HIIPER to produce thrust.

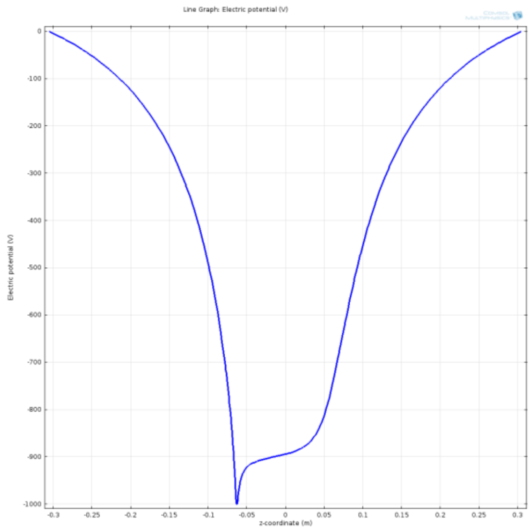

Figure 5. Electrostatic Profile Along Axis of Symmetry for Gridded IEC.

Figure 6 shows the formation of microchannels as the plasma converges towards the center of the confinement grid. Notice that there is significantly lower density plasma at the grid wire opposite of the exit aperture. At present it is unknown why this occurs, however it may be due to the potential developing at the center of the confining grid screening out charged particles passing through the exit aperture directly to that particular grid wire.

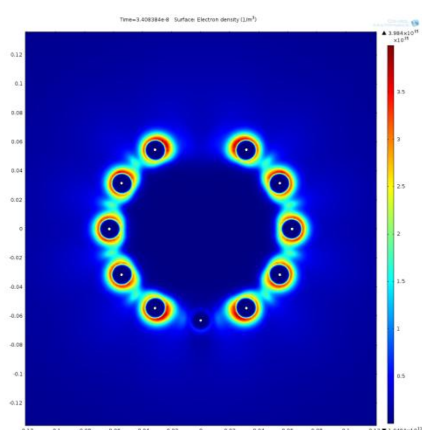

Figure 6. Formation of Microchannels in IEC Grid (nonconverged)

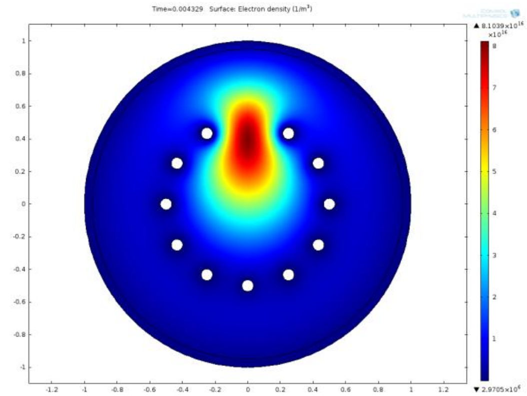

Figure 7. Large Diameter Grid Electron Density for Jet Mode

Using the large diameter grid model it was possible to achieve a converged solution for a discharge with some of the characteristics of jet mode. The velocity profile of particles does indicate that there is a preferential motion of ions in the proper direction. Of interest here is the formation of the highest density at the throat of the aperture as opposed to the center.

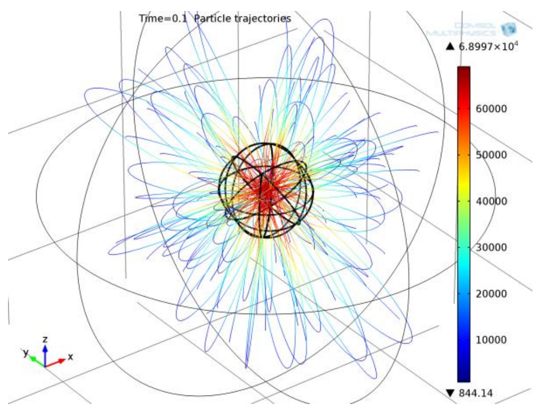

Figure 8. Particle Trace for Asymmetric IEC.

The particle tracing model for the asymmetric IEC is a work in progress, however it does give important velocity information of particles as they collide, pass through different apertures, and pass through the exit aperture. It is the intention of this simulation to be coupled with the Einzel Lens simulation to track the the ratio of ion/electron ejection from HIIPER.

Figure 9 is a first result at attempting a full, proper dimensioned 2-D axisymmetric simulation of the IEC stage of HIIPER. It follows many of the same characteristics of the large grid model and forms a spray, which is expected at a higher than nominal gas pressure for ease of convergence.

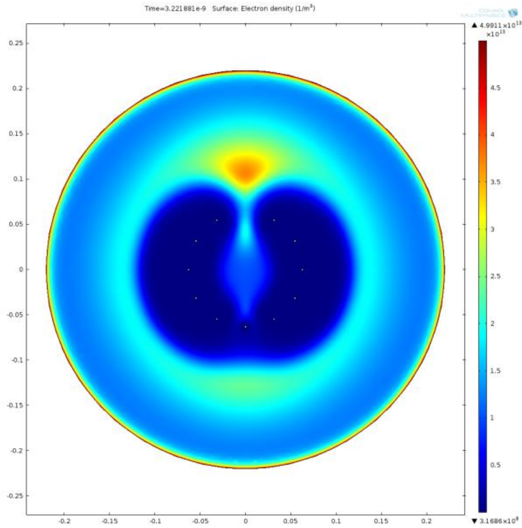

Figure 9. Electron Density with Actual IEC Grid Size (nonconverged)

4.3 Einzel Lens

The Einzel lens was simulated using the AC/DC and particle tracing packages as it alone is not designed to create plasma. Once the IEC model is complete, the Einzel Lens model can be tested attached to the IEC to simulate combined effects.

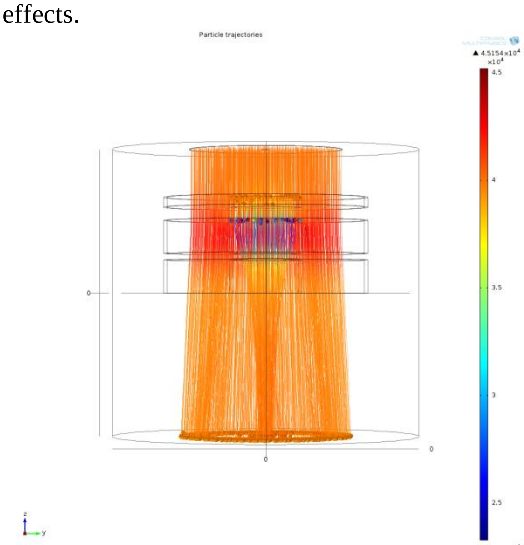

Figure 10. Einzel Lens Particle Trace

Figure 10 Shows the electrostatic field and subsequent particle trace of electrons passing through at predicted velocity. In subsequent tests the Einzel lens was capable of properly redirecting electrons off axis by several degrees into the desired stream. The intention of the device is to finely control the jet mode. Of additional interest is that the simulation has revealed that the exit velocity of the particles is higher than the input velocity, suggesting that the lens may do additional work and further accelerate the plasma.

4. Discussion and Conclusion

COMSOL has demonstrated versatility in modeling systems with no explicit model type (Inertial Electrostatic Confinement). The ability to simulate these models has enabled better understanding of the physics and a better ability to design additions and modifications to HIIPER, such as the Einzel Lens.

The next step is to work with the solvers in COMSOL and adjust conditions to consistently achieve converged solutions for all cases. Once accomplished, the simulations can be carried on throughout the lifetime of the project all the way to production ready status to minimize the material cost of development and testing time.

8. References

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