Computational Study of Adding Magnetic Nozzle in HIIPER Using Multiphysics Module

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Abstract: Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) [1] is a plasma thruster being researched at University of Illinois Urbana-Champaign. It has been shown in Figure 1. It involves a helicon source along with an Inertial Electrostatic Confinement (IEC) chamber. IEC is a fusion concept that has the potential to be applied to advanced space propulsion systems. The setup involved 2D axisymmetric simulations that will utilize a constant plasma density and study its effects with changing magnetic field inside the nozzle. Charged Particle Tracing is used to study the particle movement through the magnetic nozzle. The results involve the magnetic flux density, particle velocity, force due to particle momentum and kinetic energy. Results from the simulations quantify the improvements in thrust achieved by HIIPER [3] by the addition of a magnetic nozzle.

Keywords: IEC, HIIPER, magnetic nozzle, plasma, helicon

Introduction

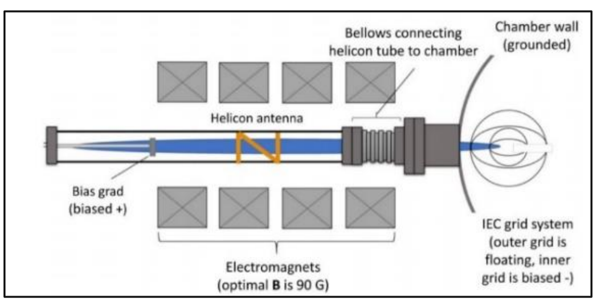


Figure 1. HIIPER Schematic

Current designs of space propulsion systems that use IEC suffer from excessive losses that make it difficult to generate significant thrust. HIIPER will utilize a conical magnetic nozzle that confines and accelerates the plasma to generate thrust [2]. Use of numerical simulations will allow to test various nozzle designs without investing large amount of time and money on manufacturing. Since installing a magnetic nozzle to the existing HIIPER setup is an intricate and costly job, COMSOL simulations are being used to finalize an optimized design for the same. After designing and installing a magnetic nozzle, experimental results will be obtained to validate the COMSOL results.

Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) is a two-stage space propulsion system comprising of a helicon plasma injector and an Inertial Electrostatic Confinement (IEC) grid to extract and neutralize the plasma from helicon. Existing experimental setup of HIIPER was able to achieve thrust of a few micronewtons. Performance augmentation of adding a third stage, magnetic nozzle (MN), is studied using COMSOL.

Numerical Model

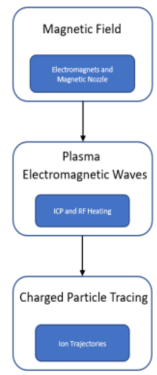


Figure 2. Computational Chart

Numerical studies done involved the following models – magnetic fields (mf), plasma electromagnetic waves and charged particle tracing (cpt). Interparticle effects were not added due to increased computational time and power requirement. The ion parameters were recorded at the end of first stage and input in the next stage to overcome the aforementioned issue. Ion flow rate during the simulations was set as 10^{18} $m^{-3}s^{-1}$. This was done to replicate the previous experimental and computational characteristics of HIIPER plume. Figure 2 is a flow chart of the COMSOL physics used in the simulations. Figure 3 shows the HIIPER model diagram of the study and depicts the various numerical parameters and boundary conditions followed throughout the simulations.

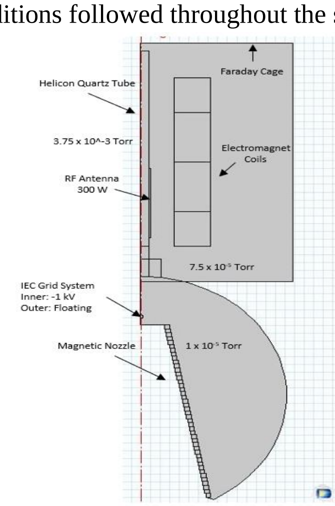


Figure 3. COMSOL Model Diagram

Governing Equations

Charged Particle Tracing: Coil current was used to generate magnetic field based on the theory of electromagnetic lensing. Lorentz force equation was then solved to trace the motion of a charged particle in a magnetic field:

$$\frac{d}{dt}(m\boldsymbol{v}) = q(\boldsymbol{v}\ x\ \boldsymbol{B})$$

Expressions were formulated to use the generated results based on experimental parameters of HIIPER.

Simulation Results

The results depict how the parameters – magnetic flux density, ion velocity, ion force and ion kinetic energy – change with electromagnetic coil current (I_c). The induced magnetic field was directly proportional to the current in the coils. It is seen in the plots that higher magnetic field increases the ionic force due to an increase in ion velocities.

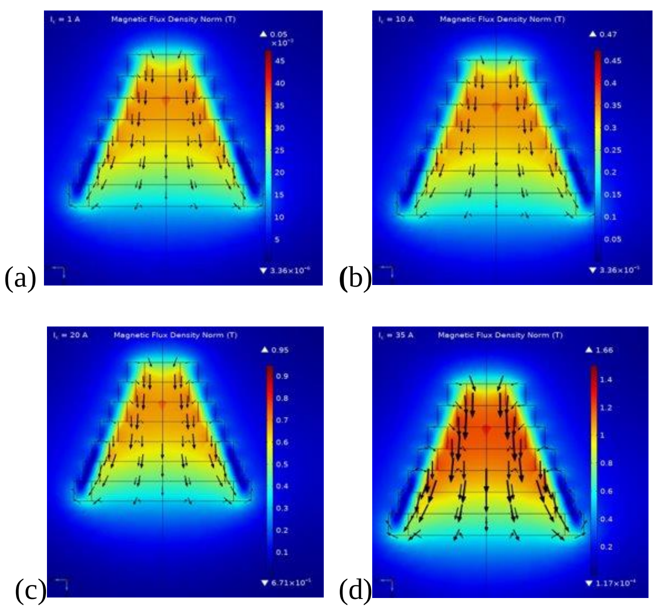
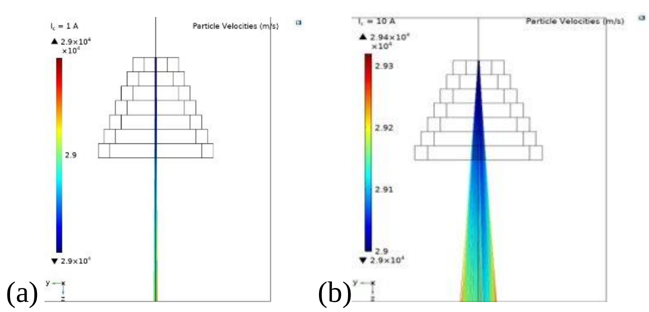


Figure 4: Magnetic Flux Density Norm (a) I_c = 1 A, (b) I_c = 10 A, (c) I_c = 20 A & (d) I_c = 35 A



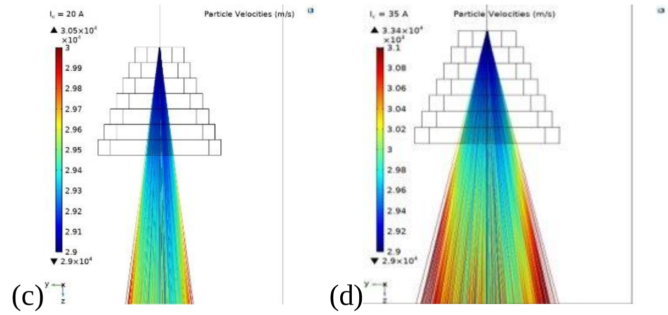


Figure 5: Particle Velocity (a) I_c = 1 A, (b) I_c = 10 A, (c) I_c = 20 A & (d) I_c = 35 A

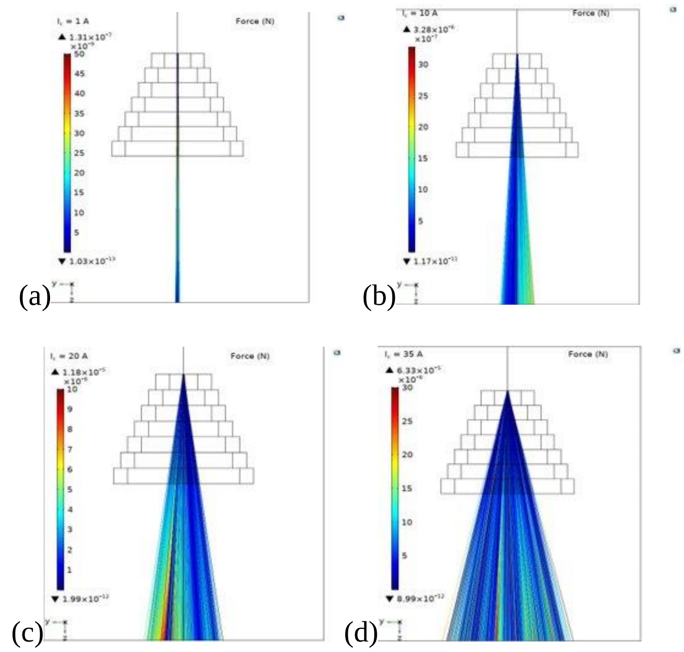


Figure 6: Particle Force (a) I_c = 1 A, (b) I_c = 10 A, (c) I_c = 20 A & (d) I_c = 35 A

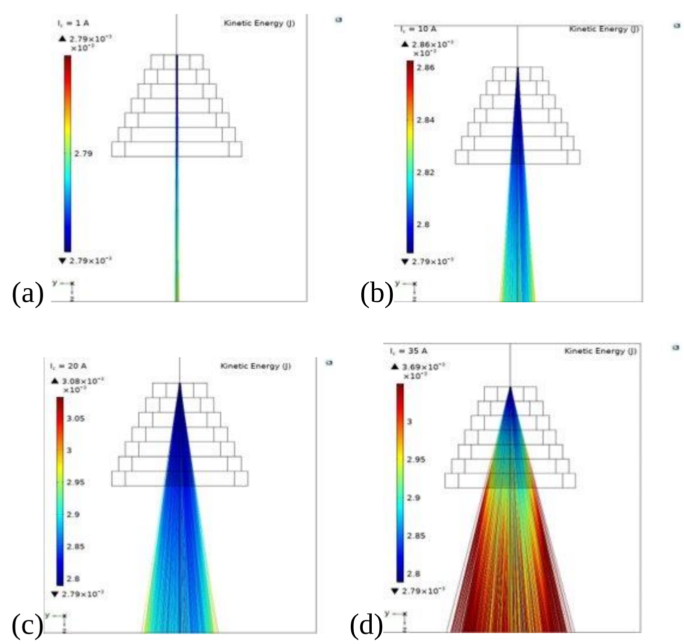


Figure 7: Particle Kinetic Energy (a) I_c = 1 A, (b) I_c = 10 A, (c) I_c = 20 A & (d) I_c = 35 A

A summary of the expected experimental results based on this computational study can be seen in Table 1. The tabulated values are based on using the thruster in a pulsed mode of operation, with each pulse lasting 60 seconds.

Table 1. Summary of Results

	Magnetic Flux Density Norm (T)	Particle Velocity (m/s)	Particle Force (mN)	Particle Kinetic Energy (J)
1A	0.05×10^{-3}	1.74×10^6	0.0079	0.17
10A	0.47	1.76×10^6	0.20	0.17
20A	0.95	1.83×10^6	0.71	0.18
35A	1.66	2.00×10^6	3.80	0.22

Conclusions

COMSOL simulations made it possible to prove the advantages of having magnetic nozzle in HIIPER. Increase in performance of the propulsion system is expected and preliminary results indicate it to be linearly proportional to the coil current (induced electromagnetic field). With reasonable magnetic field, thrust can be seen to have increased by a factor of 100. Experimental studies will be done to compare with these numerical trends and validate the COMSOL model of HIIPER.

References

1. Drew M. Ahern, Hussein Al-Rashdan, Oguzhan Altun, Grant Berland, Emil Broemmelsiek, Zhengyu Chen, Patchara Choakpichitchai, Zongxu Dong, Patrick Drew, Nicklaus Richardson, Nicholas St.Lawrence, Kyle Stanevich, Albert Valiaveedu, and George H. Miley. "Experimental Studies of the Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER)", 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA, 2017.

2. YungAn Chan and Georg Herdrich, “Inertial Electrostatic Confinement: Innovation for Electric Propulsion and Plasma Systems”, 5th International Electric Propulsion Conference, October 8-12, 2017, Georgia Institute of Technology, Atlanta, Georgia.

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