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Optimization of the thrust-to-power consumption ratio of Ion thrusters through simulations

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Abstract
The optimization of the thrust-to-power-consumption ratio in ion propulsion systems is critical for advancing space propulsion technologies. Efficient and reliable ion engines are essential for long-duration space missions and interplanetary exploration. This study aims to develop and analyze simulation frameworks for Gridded Ion thrusters and Hall Effect thrusters to enhance the understanding and performance of these propulsion systems. The research involved defining physical parameters for both ion engines, including charge densities, magnetic field strengths, and geometric dimensions. A custom simulation software was created using Mathematica's advanced computational techniques such as differential equation solvers to simulate ion motion and electric/magnetic field distributions. Extensive parameter sweeps and sensitivity analyses were performed to identify optimal operating conditions. The simulation results were compared with empirical data from the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL) to give a basis in reality. The simulations provided a detailed understanding of the ion propulsion mechanisms and identified optimal parameters that maximize the thrust-to-power-consumption ratio. The optimized parameters for the Gridded Ion thruster and the Hall Effect thruster showed notable improvements in performance, indicating the potential for more efficient space propulsion systems. This study's findings contribute to the development of more efficient and reliable ion engines. The optimized simulation models offer a foundation for future advancements in space propulsion technology. Further research could involve refining the simulations by incorporating plasma friction and ionization processes for greater accuracy.

Keywords
Aerospace engineering, Simulation, Modeling, Ion thrusters, Gridded Ion thrusters, Hall Effect thrusters, Ion propulsion, Specific impulse, Exhaust velocity, Ion engine

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Introduction

Ion propulsion systems, such as Gridded Ion thrusters and Hall Effect thrusters, are integral to modern space exploration due to their high efficiency and suitability for long-duration missions.

A Gridded Ion thruster utilizes electrostatic magnetic fields to accelerate the ions to produce thrust. Typically, Gridded Ion thrusters consist predominantly of an anode shell, a positively charged screening grid, and a negatively charged accelerating grid (1). Electron guns are placed inside the anode shell to ionize the propellant within the anode shell as well as placed outside the thruster to neutralize the resulting ions. Once the propellant is ionized, the electrostatic forces generated by the anode push the ions toward the screening and acceleration grids. Since the grids are so close to each other and oppositely charged, a large electric field is generated which accelerates the ions up to eighty kilometers per second. Figure 1 shows the general layout of a Gridded Ion Thruster.

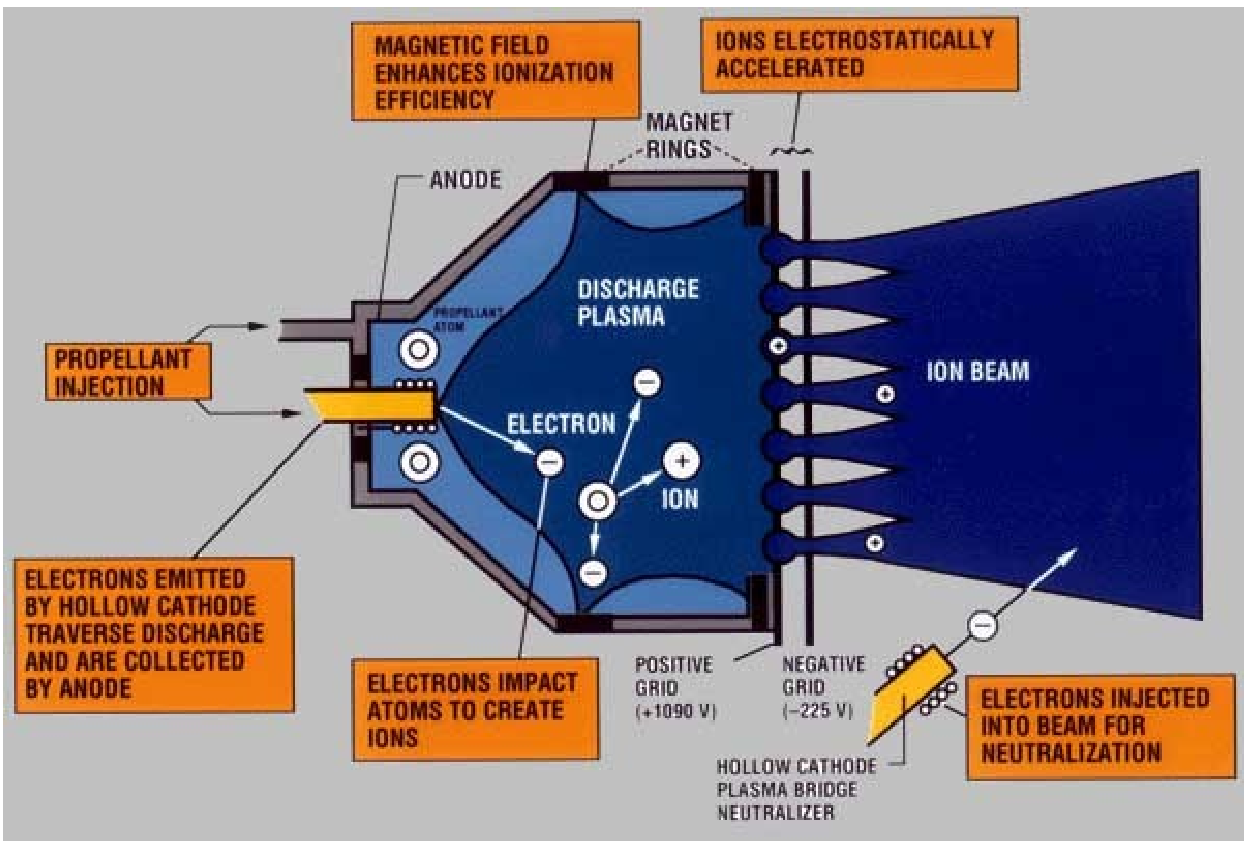

Figure 1. Labeled model of a gridded ion thruster (2)

A Hall Effect thruster is different from a Gridded Ion thruster in that it can be thought of as a coaxial device where orthogonal electric and magnetic fields are used to ionize the propellant and accelerate the resulting ions to produce thrust (3). Typically, Hall thrusters consist of multiple parts, the anode, the cathode, and the surrounding magnets. A cathode neutralizer is placed either around the thruster or in the middle which shoots electrons to be used by the thruster to ionize the propellant and to neutralize the resulting ions. Magnets are placed around the annulus to create a radial magnetic field that traps electrons in the annulus. The electrons spin around in the annulus where they are used to ionize the propellant. An anode shell is used to inject the propellant into the annulus where the propellant atoms are ionized by the constantly rotating electrons. Once the propellant is ionized, the electrostatic forces generated by the anode and cathode as well as the Lorenz force caused by the electric field accelerate the ions to high speeds up to fifty kilometers per second. Figure 2 shows the general layout of a Hall thruster.

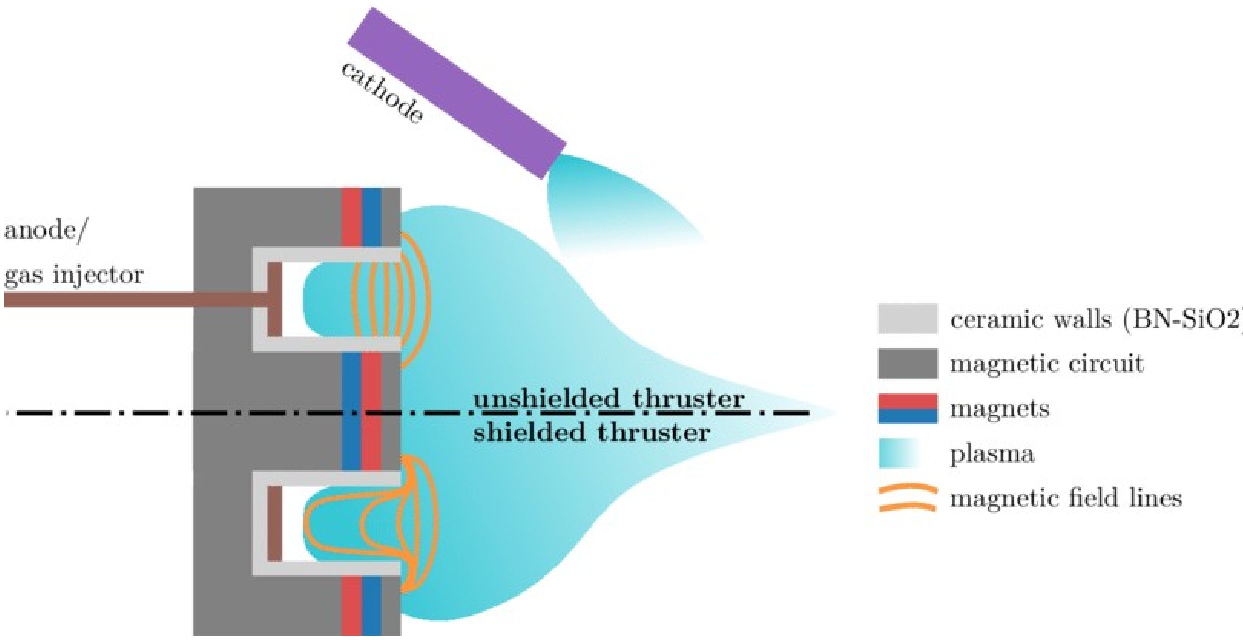

Figure 2. Labeled visualization of a hall effect thruster (4).

Despite the advantages of Ion thrusters, optimizing their thrust-to-power-consumption ratio remains a significant challenge, necessitating advanced computational models to enhance our understanding and improve performance. Maximizing the thrust-to-power (or minimizing the Power-to-thrust) consumption ratio in ion propulsion systems is crucial for making long-duration and interplanetary missions feasible. While current research provides a foundational understanding, there are still gaps in optimizing operating parameters to achieve the highest efficiency. Addressing these gaps through detailed simulations can lead to significant advancements in space propulsion technologies.

The aim of this research is to develop and refine simulation frameworks for Gridded Ion thrusters and Hall Effect thrusters. By leveraging Mathematica's® advanced computational techniques, this study seeks to enhance the understanding of ion propulsion mechanisms and identify optimal operating conditions. The findings have the potential to contribute significantly to the development of more efficient and reliable ion engines, which are vital for future space missions.

To achieve these goals, the study focused on finding the optimal geometric dimensions of Gridded Ion thrusters and Hall Effect thrusters. The research utilized Mathematica's® differential equation solvers to simulate electric and magnetic field distributions and ionization processes. Extensive parameter sweeps and sensitivity analyses were performed to identify the optimal operating parameters that maximized the thrust-to-power consumption ratio. The accuracy of the simulation results was validated by comparing them with empirical data from the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL).

This research primarily aimed to develop first approximation simulation models for ion thrusters, examining the effects of various physical parameters on engine performance. Although the simulations provided valuable insights, they were simplified and did not account for plasma friction or the detailed ionization process. Future work could address these limitations by constructing more comprehensive models. The research is grounded in the principles of electromagnetism and fluid dynamics, which govern the behavior of charged particles in electric and magnetic fields. These theoretical foundations informed the simulation models and provided a framework for analyzing ionization processes and thrust generation in ion thrusters.

Methods

Research Design

This study employed a comprehensive simulation-based approach to investigate and optimize the performance of Gridded Ion thrusters and Hall Effect thrusters. The entire simulation framework was coded independently using Mathematica's® powerful differential equation solvers and visualization tools. The code included custom functions for setting up the initial physical parameters, defining electric and magnetic fields, and solving differential equations for ion motion. The simulation was designed to enable extensive parameter sweeps and sensitivity analyses, all of which were executed using custom-developed algorithms. For transparency and reproducibility, all the code used in this study is publicly available. The complete source code can be accessed on the GitHub repository (5). Additionally, specific functions and simulation setups were documented and shared on the Wolfram Community platform, where interested readers can review and utilize the code (6).

Defining initial physical parameters

For both types of ion thrusters, the physical parameters presented in Table 1, based on real-world operating conditions, were defined for testing (7-9).

Table 1. Values of initial physical parameters

Parameter	Gridded ion thruster	Hall thruster
Charge densities (C/m^3)		
Anode	10^6	10^6
Screening grid	10^4	
Acceleration grid	-10^5	
Cathode		-10^5
Magnetic field strength (T)		
		0.02
Geometric dimensions (m)		
Anode radius	0.4	0.2
Anode thickness	0.04	0.005
Anode height	0.45	
Anode length		0.085
Cathode radius		0.04
Grid spacing	0.035	
Grid height	0.006	
Inner magnet radius		0.08
Plasma length		0.08

Simulation setup and execution

The study utilized Mathematica® for simulation setup and execution, employing its powerful differential equation solvers and visualization capabilities. All axes are modeled in meters, where 1 unit correlates to 1 meter with the x-axis being the width in meters, the y-axis being the width in meters, and the z-axis being the height in meters.

First, Implicit regions were created to represent the physical spaces of these components as shown in Figures 3 and 4. Next, the Electric and Magnetic Fields for each corresponding thruster were generated. Poisson's Equation $\nabla^2\phi = \frac{-pf}{\varepsilon}$ was used along with Mathematica's® NDSolve® function to solve for the electric potential within the defined domains. Poisson's Equation relates the charge density of a system with the potential field that it generates. It states that the Laplacian of the electric potential field is equal to the volume charge density divided by the permittivity, with a change of sign. The resulting electric field is shown in Figures 5 and 6.

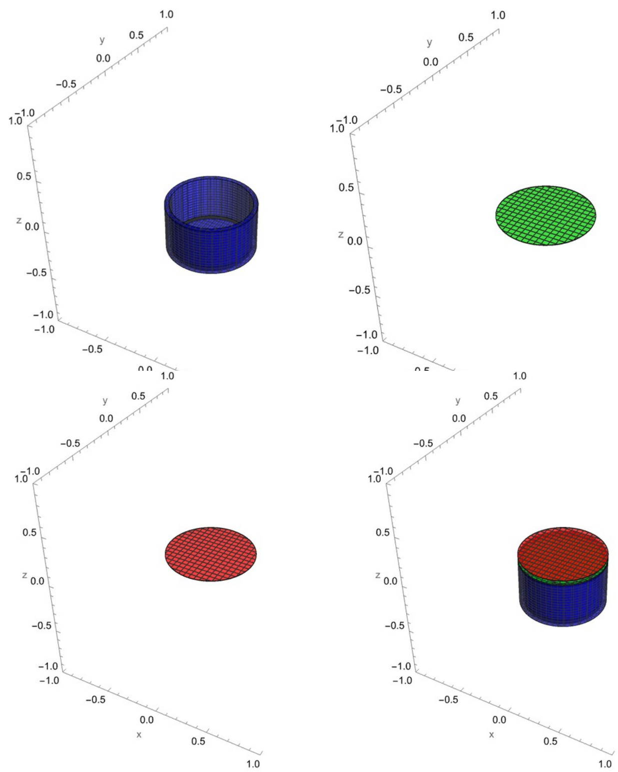

Figure 3. Visualization of the major regions of a Gridded Ion thruster given the initial physical parameters.

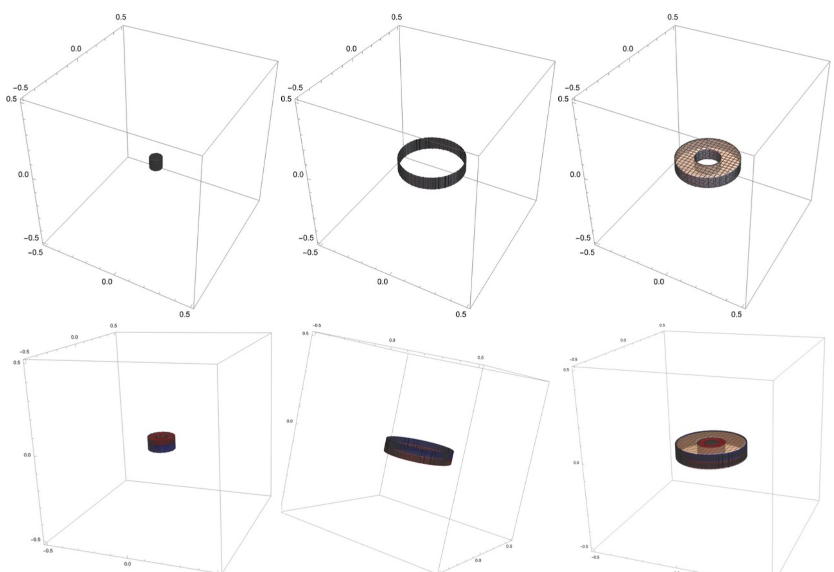

Figure 4. Visualization of the major regions of a Hall Effect Thruster given the initial physical Parameters.

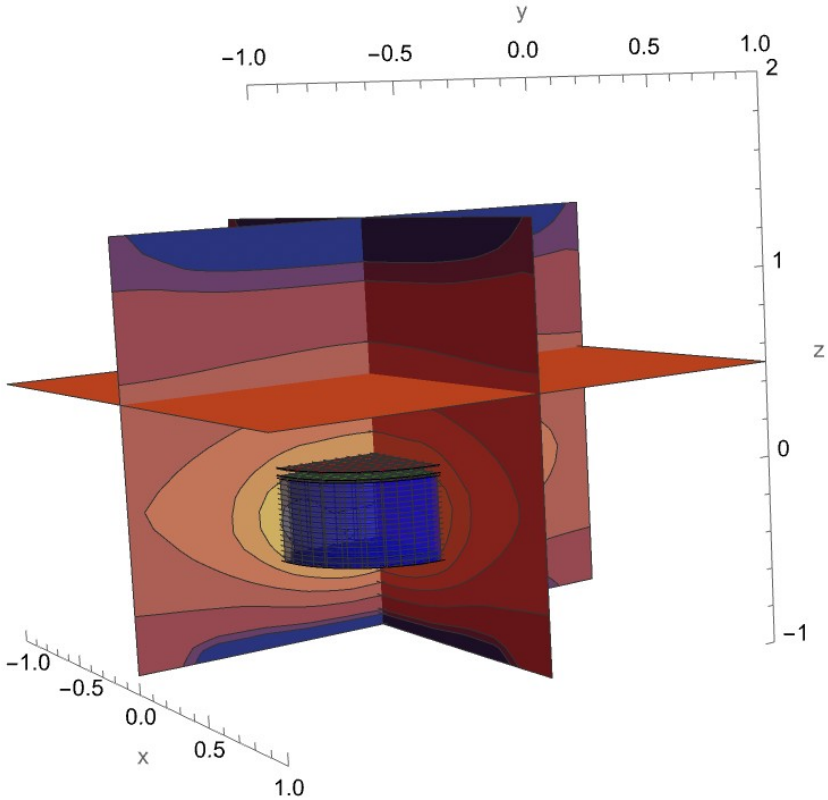

Figure 5. Visualization of electric potential fields in the Gridded Ion thruster.

For Hall Thrusters, the Biot-Savart Law,

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \frac{I\, d\boldsymbol{\ell} \times \mathbf{r}'}{|\mathbf{r}'|^3}$$

was employed to calculate the magnetic fields generated by the magnets. The Biot-Savart Law describes the generation of a magnetic field by a constant electric current. The generated Magnetic field's lines of force can be predicted from the electric current's magnitude, direction, length and proximity. C represents the current path. r' represents the displacement vector from the element of the wire (dl) at point l to the point at which the field is needed to be computed (r). The magnetic field and electric potential field can be seen presented together in Figure 6.

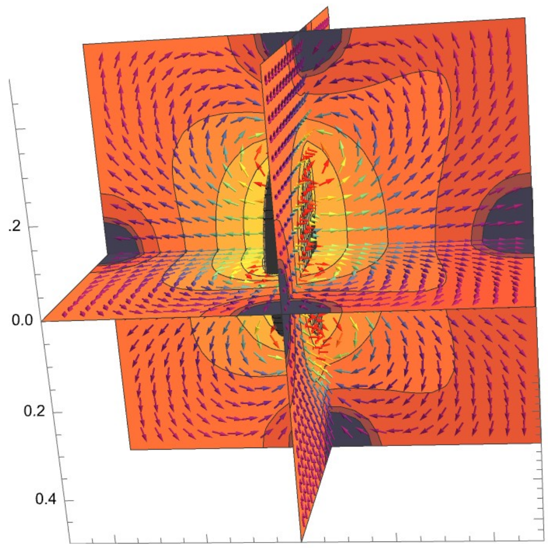

Figure 6. Visualization of both the magnetic and electric field forces on a Hall Effect Thruster.

Then, in order to simulate the ion motion, differential equations representing the equations of motion were set up and solved using Mathematica's® `NDSolve`® function. The initial positions and velocities of the ions were defined based on typical Xenon ion properties. The trajectories of ions were computed and visualized. Their paths within the thruster regions are shown in Figure 7.

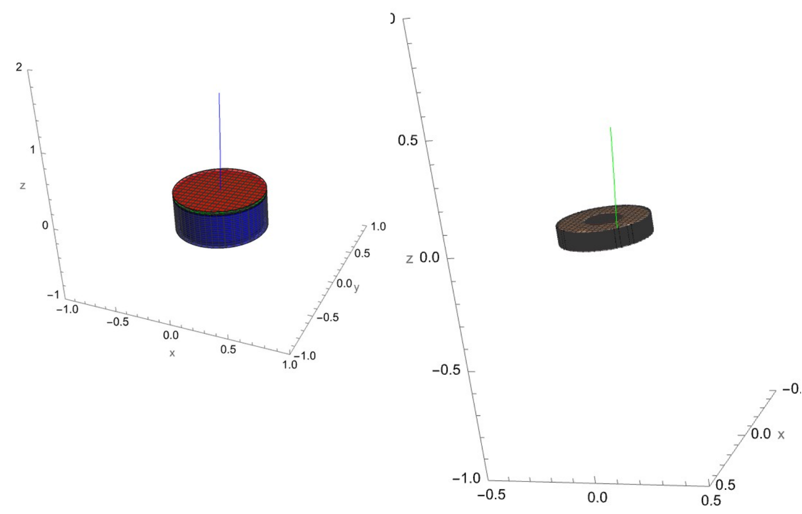

Figure 7. Plot of ion trajectory on both the Gridded Ion and Hall Effect thrusters.

Trajectory and thrust analysis

In this section, the methodology used to analyze the thrust produced by both the Gridded Ion thrusters and Hall Effect thrusters is described. This involved calculating the exhaust velocity, specific impulse, and thrust-to-power consumption ratio, which are critical metrics for assessing the performance of ion thrusters.

The exhaust velocity of the ions is a crucial parameter as it directly influences the thrust produced. The velocity was determined by taking the derivative of the interpolating function of the ion trajectory. The z coordinate represents the position the ion relative to the midpoint height of the thruster. The velocity plots can be seen in Figure 8.

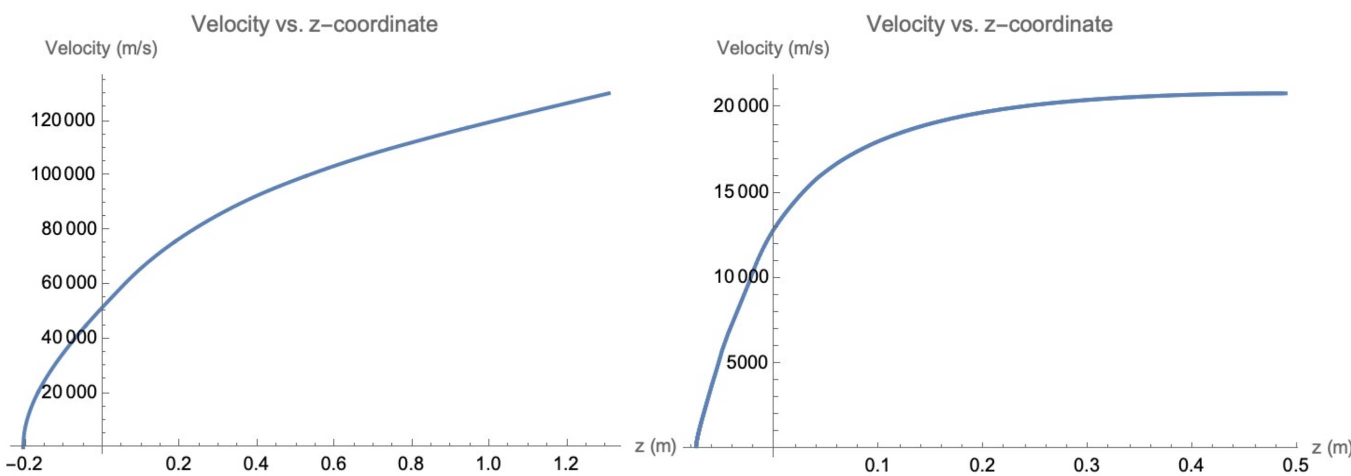

Figure 8. The velocity *vs* z coordinate plots for Grid Ion (left) and Hall Effect (right) thrusters.

The mass flow rate of ions through the thruster was calculated using the ion density, cross-sectional area of the thruster, ion mass, and ionization rate. The thrust produced by the ion thruster was computed by multiplying the mass flow rate by the exhaust velocity and the thruster efficiency. This relationship is essential to understanding how changes in physical parameters affect overall performance. The specific impulse measures how efficiently a thruster uses propellant. It is defined as the thrust divided by the mass flow rate and gravitational acceleration. This metric provides insight into the effectiveness of the propulsion system over long durations.

Calculating power consumption

The power consumption for the Hall Effect Thruster was calculated by considering both the ionization and acceleration of ions within the thruster, as well as the power required for the electron gun. The total power consumption, P, is determined by summing the power used for ionization, the power required to accelerate the ions, and the constant power consumption of the electron gun. The ionization power is calculated based on the number of ions generated per second and the energy required to ionize each ion. The ionization energy, $P_{ionization}$, is computed using the ionization energy of Xenon ions. In the equations presented, the Ion Energy is the energy required to ionize one Xenon atom. The acceleration power, $P_{acceleration}$, is determined by the energy required to accelerate the ions to the exhaust velocity. A constant power, $P_{electron\ gun}$, of 150 W is assumed for the electron gun, which is typical in thruster systems for providing the necessary electrons to neutralize the ion beam. The total power consumption, P_{total}, is the sum of these components.

$$P_{ionization} = \text{Ionization Rate} \times \text{Ion Energy} \times \text{Ions Per Second}$$

$$P_{acceleration} = 0.5 \times \text{MassFlowRate} \times \text{ExhaustVelocity}^2$$

$$P_{total} = P_{ionization} + P_{acceleration} + P_{electron\ gun}$$

Parameter optimization

The optimization process aimed to maximize the thrust-to-power consumption ratio by adjusting key parameters. Extensive parameter sweeps and sensitivity analyses were conducted to understand the effect of each parameter on the performance metrics.

For the Gridded Ion thruster, the optimization parameters consisted of the anode radius, anode thickness, anode height, grid spacing, and grid height. The simulation function comprised of a composite function combining all relevant simulation steps to evaluate different parameter sets. Parameters were varied within plausible specified ranges as seen in Table 2 (10, 11).

Table 2. Plausible ranges for each parameter in a Gridded Ion thruster.

Parameter	Plausible range under deployable conditions (considering engineering, durability, and safety limitations) (m)	Plausible range under ideal conditions (m)
Anode Radius	0.05-0.25	0.05-0.4
Anode Thickness	0.01-0.03	0.01-0.04
Anode Height	0.05-0.2	0.05-0.4
Grid Spacing	0.005-0.05	0.005-0.05
Grid Height	0.001-0.011	0.001-0.011

The P/N ratio of the minimum and maximum limits of the deployable range was calculated as 108.20 kW/N and 55.94 kW/N respectively.

For the Hall thruster, the optimization parameters consisted of the anode radius, anode thickness, anode length, cathode radius, and inner magnet radius. The simulation function comprised of a composite function to run the simulations for different parameter sets. Parameters were varied within plausible specified ranges as seen in Table 3 (12). The P/N ratio of the minimum and maximum limits of the deployable range was calculated as 41.98 kW/N and 38.58 kW/N respectively.

Table 3. Plausible ranges for each parameter in a Hall Effect thruster.

Parameter	Plausible range under deployable conditions (considering engineering, durability, and safety limitations) (m)	Plausible range under ideal conditions (m)
Anode Radius	0.05-0.2	0.05-0.3
Anode Thickness	0.005-0.03	0.005-0.04
Anode Length	0.05-0.15	0.05-0.25
Cathode Radius	0.01-0.05	0.01-0.05
Inner Magnet radius	0.02-0.1	0.02-0.1

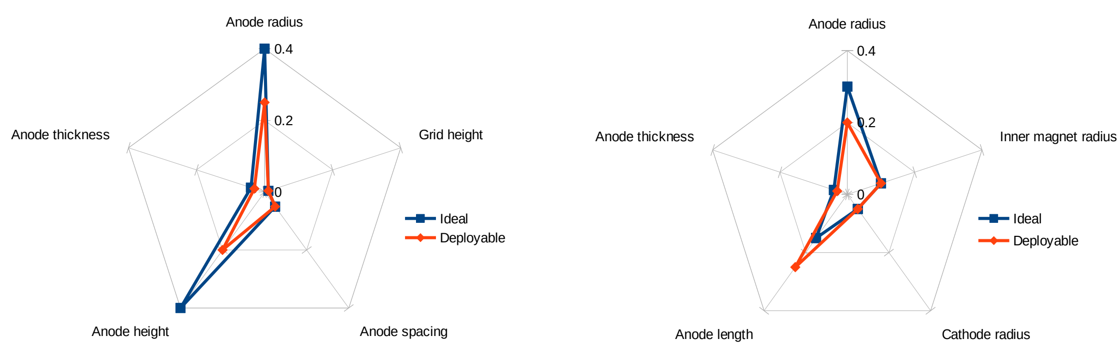

Figure 9. Radar charts of Gridded Ion thruster (left panel) and Hall Effect thruster (right panel) showing a possible design space in adjusting geometric parameters for deployable conditions compared with ideal conditions (Tables 2 and 3). Note that there could be many such design spaces that would depend primarily on the durability and manufacturability of the components.

Validation and comparison with empirical data

The accuracy of the simulations was validated by comparing the results with empirical data from the University of Michigan's PEPL lab (13). Empirical data on neutral density, plasma density, ion velocity, electric potential, ionization rate, electron temperature, cross-field electron velocity, and electric field was provided as seen in Figure 10. We then used velocity plots, thrust values, and exhaust velocities from our simulations and compared them to the empirical data to verify our simulation's accuracy. The exhaust velocity for the simulation was 18000 m/s, within 10% of the empirical data of 19884 m/s. Figure 11 shows a comparison between the ion velocity plot of the simulation versus the empirical data.

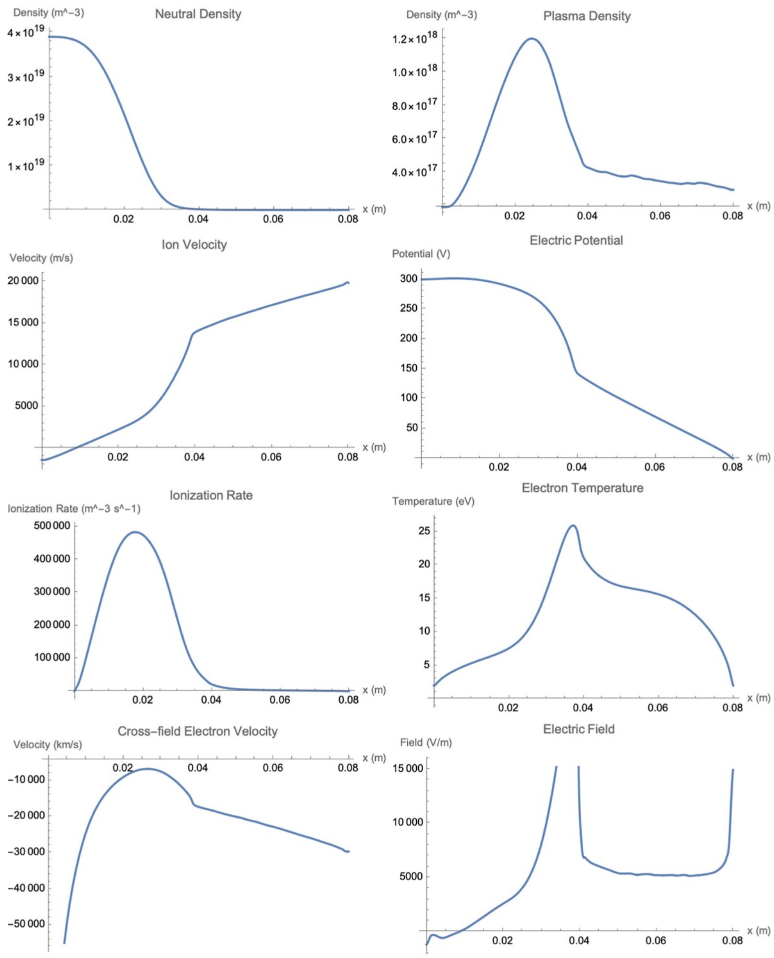

Figure 10. Plots of neutral density, plasma density, ion velocity, electric potential, ionization rate, electron temperature, cross-field electron velocity, and electric field as collected from U of Michigan's PEPL lab on a real Hall Effect thruster.

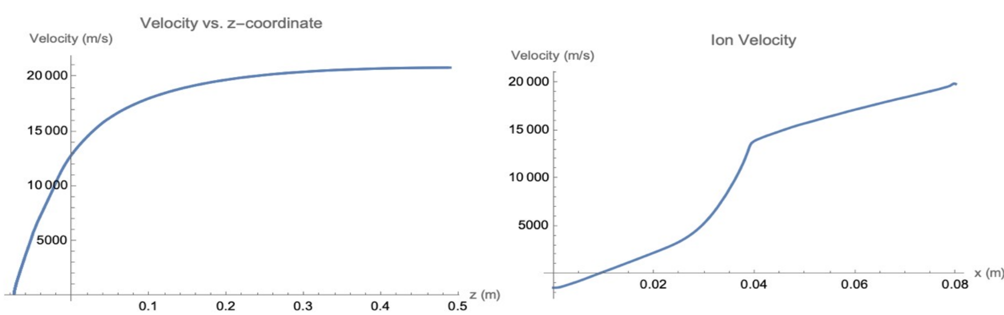

Figure 11. comparison between the ion velocity plot of the simulation versus the empirical data.

It is important to note that the empirical data from the PEPL lab only includes a single set of velocity measurements for a Hall Effect thruster, which specifically shows the velocity of ions from the innermost chamber wall as they exit the thruster. This data set ends at a distance of 0.08 m from the chamber wall, capturing the initial acceleration phase but not the subsequent ion acceleration that occurs as ions travel further away from the thruster exit. In contrast, our simulation does not account for the ionization process within the thruster and assumes that the ions are already ionized when they are released into the simulated environment. As a result, the velocity plots from our simulation differ in shape and extend beyond the initial 0.08 m, reflecting the continued acceleration of ions.

Given these differences, the velocity plots from our simulation differ from the empirical data. However, the purpose of the comparison was not to claim exact congruence with the PEPL data but rather to demonstrate that the simulated exhaust velocities are relatively similar to those observed in real-world experiments. This similarity suggests that our simulation results were not far removed from those obtained experimentally, even though the simulation simplified certain aspects of the thruster operation. The empirical data provided a valuable reference point, and the close approximation of simulated exhaust velocities supported the validity of the simulation model under the assumptions made.

Results

Gridded Ion thruster simulation

Correlation heat maps were generated to visualize the relationships between parameters and performance outcomes as seen in Figure 12. The correlation heat map shows that there is a positive correlation between thrust and many of the parameters, but the correlation between the thrust-to-power consumption ratio and the parameters is much weaker or even negative. Therefore to maximize thrust, we could simply infinitely scale up the entire thruster, but that would require an unattainable amount of input power. Therefore a balance between the thruster size and input power must be found. This balance can be found by maximizing the thrust-to-power-consumption ratio.

Scaling the power supply indefinitely could theoretically result in higher thrust values as seen in the 0.74 correlation between power and thrust. However, this approach is limited by practical constraints such as the power supply mass, thermal management, and spacecraft structural integrity. In reality, spacecraft power supplies (solar panels or nuclear reactors) cannot be scaled infinitely due to mass and material limits, and thermal management systems must handle the heat generated during extended operation. Our simulations focused on balancing size and input power by maximizing the thrust-to-power consumption ratio. The correlation heat map (Figure 12) shows that while parameters such as anode height and anode thickness are positively correlated with thrust, their effect on the thrust-to-power consumption ratio is weaker, often with negative correlations. This implies that increasing certain parameters like anode thickness may increase power consumption without a proportional increase in thrust.

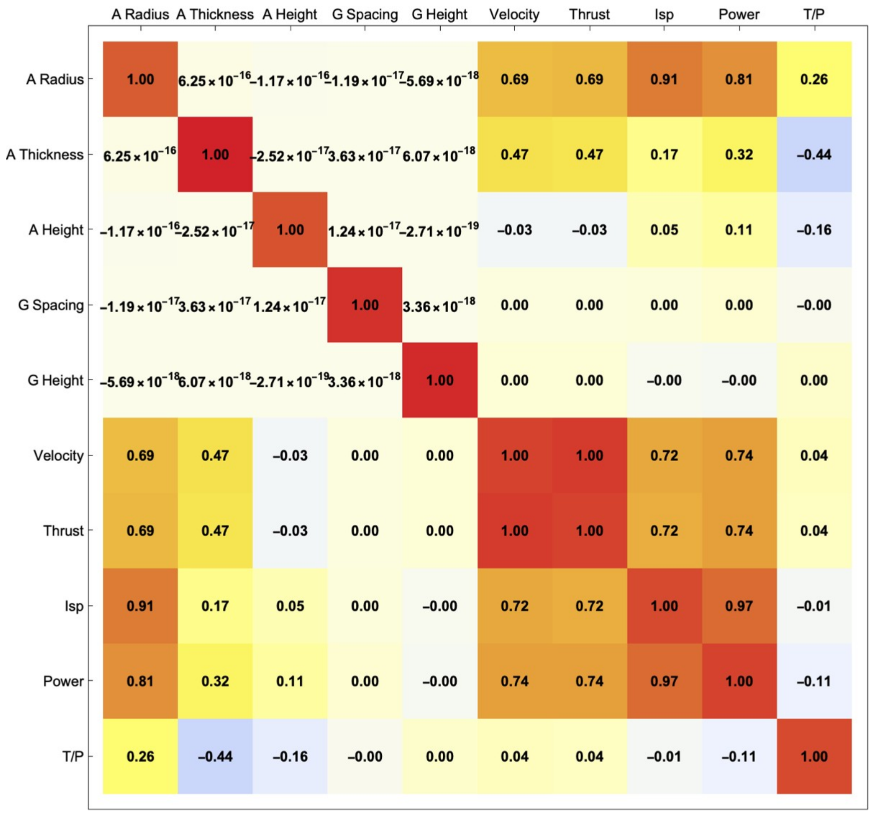

Figure 12. Correlation heatmap between parameters and performance metrics for the Gridded Ion thruster.

Therefore, our optimization aimed to find an optimal balance rather than simply scaling up the system indefinitely. By staying within the plausible parameter ranges mentioned above, we ensured that the optimized results remained grounded in practical engineering limits. The optimized geometric parameters and the optimized results of the exhaust velocity, thrust, specific impulse, power consumption and the Power-to-thrust consumption ratio are shown in Table 4.

The optimized parameters demonstrated the ability of a Gridded Ion thruster to achieve almost one-third the Power-to-thrust consumption ratio of typical ion thrusters, requiring only 364 Watts instead of the typical 1000 Watts for a similar 0.025 Newtons of thrust (14). This optimization yielded a Power-to-thrust consumption (P/T ratio) ratio of 13.6 kW/N, which is significantly better than the 24 kW/N achieved by NASA's Evolutionary Xenon Thruster (NEXT) (15). The discrepancy between the simulated results and real-world thrusters like NEXT arises primarily due to the idealized conditions under which the simulations were conducted (Table 5).

The parameters optimized in the simulation, such as anode radius (0.25 m), anode thickness (0.01 m), grid spacing (0.005 m), and grid height (0.006 m), were selected to maximize performance in a theoretical context without fully accounting for real-world operational constraints. For example, friction induced by the plasma, ionization processes, heat generation, and structural stress, could potentially lead to overheating or failure in an actual space environment using only the simulated parameters without consideration of engineering constraints.

Real-world thrusters are engineered with conservative design choices to ensure durability and reliability throughout their operational lifespan. The lower P/T ratio observed in the simulation represents an optimized condition that could be achievable under controlled laboratory settings or with advanced materials and cooling technologies, but not currently feasible for space missions (Figure 9). While the simulation results demonstrate the theoretical potential for achieving more efficient ion thrusters, they do not fully capture the engineering challenges and safety requirements necessary for real-world space applications.

Hall thruster simulation

The simulations for the Hall Effect Thruster provided valuable insights into the relationship between different design parameters and performance metrics.

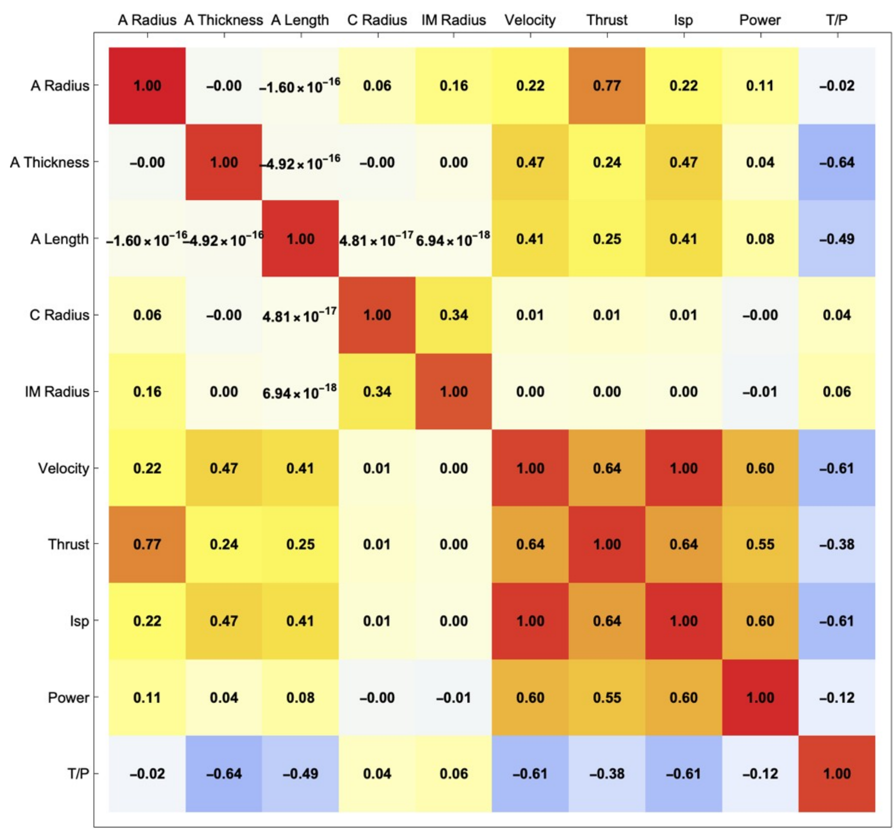

Figure 13. Correlation Heatmap of parameters against performance metrics for the Hall Effect thruster.

The correlation heatmap (Figure 13) indicated that anode radius and inner magnet radius were positively correlated with thrust. These parameters are crucial in enhancing the overall performance of the thruster. However, anode thickness and length exhibited weaker or even negative correlations with the thrust-to-power-consumption ratio (T/P), which suggested that increasing these parameters could lead to diminished efficiency in power utilization as seen in Figure 13.

The correlation map further reinforced the understanding that, while certain parameters like anode radius positively impact thrust, careful consideration must be given to the trade-offs between power consumption and thruster size. This balance ensures that improvements in performance do not come at the expense of excessive power demands. The optimized geometric parameters and the optimized results of the exhaust velocity, thrust, specific impulse, power consumption and the Power-to-thrust consumption ratio are shown in Table 4.

The optimization of the Hall Effect Thruster resulted in a significant improvement in the Power-to-thrust consumption ratio. The optimized parameters, including anode radius (0.2 m), anode thickness (0.005 m), anode length (0.05 m), cathode radius (0.01 m), and inner magnet radius (0.06 m), enabled the thruster to achieve a minimum Power-to-thrust consumption ratio of 10.59 kW/N. This represents a substantial enhancement, nearly one-third that of the typical Power-to-thrust ratio of 33.75 kW/N (14).

However, when comparing this optimized P/N ratio to those of real-world thrusters, such as the Krypton Hall Effect Thrusters used by Starlink® satellites for orbit raising, station-keeping, and deorbiting, some differences were noticeable. Based on industry standards and available information, similar commercial Hall Effect Thrusters typically operate with P/N ratios ranging from 17 to 30 kW/N (16) (Table 5). This suggests that while the simulated P/N of 10.59 kW/N is significantly lower, it does not account for the stringent design constraints needed for real-world applications, including material durability, thermal management, and operational longevity.

In practical applications, Hall Effect thrusters are designed to function under harsh space conditions, where factors such as thermal loads, material stresses, and component erosion play significant roles. The parameters optimized in this study were selected to maximize theoretical performance without fully considering these practical limitations. For instance, the smaller dimensions and tighter magnet spacing optimized in the simulation might lead to increased thermal loads and material stress, which could result in overheating or accelerated wear in an actual space environment.

Real-world Hall Effect thrusters, like those used in Starlink® satellites, are engineered with a focus on reliability, longevity, and safety, often leading to higher P/N ratios than those observed in idealized simulations. These thrusters must manage heat dissipation, avoid excessive component erosion, and mathematize the complex interactions of plasma with magnetic fields, challenges that are not entirely captured in the simulation model. Therefore, while the simulation demonstrates the potential for achieving a more efficient Hall Effect thruster under controlled conditions, the results must be interpreted with an understanding of the practical engineering challenges and operational requirements involved. Future research should refine simulation models to incorporate these real-world constraints, such as using back-propagation of operational parameters from deployed Ion thrusters (Tables 2 and 3), thereby providing a more accurate assessment of thruster performance in space environments.

Table 4. Optimized geometric dimensions (in red) *versus* initial (black) to obtain the minimum Power-to-thrust ratio (calculated from optimized dimensions).

Attribute	Gridded ion thruster	Hall Effect thruster
Charge densities (C/m^3)		
Anode	10^6	10^6
Screening grid	10^4	
Acceleration grid	-10^5	
Cathode		-10^5
Magnetic field strength (T)		
		0.02
Geometric dimensions (m)		
Anode radius	0.4 (0.25)	0.2 (0.2)
Anode thickness	0.04 (0.01)	0.005 (0.005)
Anode height	0.45 (0.50)	
Anode length		0.085 (0.05)
Cathode radius		0.04 (0.01)
Grid spacing	0.035 (0.005)	
Grid height	0.006 (0.006)	
Inner magnet radius		0.08 (0.06)
Plasma length		0.08
Simulation results using optimized metrics for minimum Power-to-Thrust ratio		
Exhaust velocity (m/s)	9545.09	18612.6
Thrust (N)	0.026	0.186
Specific impulse (s)	681.33	1897.96
Power consumption (kW)	0.365	1.97
Power-to-Thrust ratio (kW/N)	14.04	10.59

Table 5. Operational parameters of thrusters that are deployed (SMART1) or undergoing active research as improved versions of deployed thrusters (NEXT)

Attribute	NASA's (NEXT) Gridded ion thruster	European Space Agency, SMART1, PPS-1350-G Hall Effect thruster
Thrust (N)	0.23	0.03 -0.07
Specific impulse (s)	4100	1100-1600
Power consumption (kW)	0.54 – 6.9	0.46-1.19
Power-to-Thrust ratio (kW/N)	30.0	17.0

Discussion

This research provided valuable insights into the forces that generate thrust in both gridded ion thrusters and Hall effect thrusters. We were able to identify optimal operating conditions that maximize the thrust-to-power consumption (or minimize the Power-to-thrust) ratio. The use of correlation heat maps highlighted the intricate relationships between various parameters, emphasizing the importance of balancing these factors to achieve efficient thruster performance. Our findings contribute to the understanding of ion propulsion mechanisms. The enhanced simulation frameworks developed in this study provide a foundation for further advancements in ion thruster technology. By accurately modeling the electrostatic and magnetic field distributions, as well as the ionization processes, this research addresses key gaps in current knowledge and offers a robust tool for future ion engine design and optimization. This is particularly important for the development of more efficient and reliable propulsion systems for long-duration space missions and interplanetary exploration. The primary objective of this research was to optimize the thrust-to-power-consumption ratio in ion thrusters through detailed simulations. This objective was largely met, as evidenced by the fair degree of accuracy achieved in our simulations when compared to empirical data from the University of Michigan's PEPL lab. While some aspects, such as plasma friction and the detailed ionization process, were simplified, the overall goals of understanding and improving thruster performance were successfully achieved. Future research should focus on enhancing the simulation accuracy by incorporating more complex physical phenomena, such as plasma friction and detailed ionization processes. Converting the Julia Package used in this study to Mathematica® could streamline the simulation process and allow for more comprehensive data analysis. Additionally, expanding the simulations to include 3D models could provide a more detailed and accurate representation of ion thruster behavior.

There are inherent limitations in this study due to the complexity of ion propulsion systems. Without access to a real ion thruster for direct comparison, some aspects of the simulation may not fully capture the nuances of the actual physical processes. The simplifications made in modeling plasma friction and ionization also limit the accuracy of the results. These factors should be considered when interpreting the findings and their applicability to real-world scenarios. Tables 2 and 3 seek to partially alleviate this limitation by also presenting real-world manipulable geometries; although it must be recognized that many such range combinations and design spaces are possible. Simulation code such as that constructed for this study can be hence used for deployable (not only for ideal) conditions as well, by back-propagating the operational parameters such as those presented in Table 5 into the software. The advancements made in this study underscore the potential for simulation-based optimization in the field of ion propulsion. As we continue to refine these models and incorporate more detailed physical processes, the path towards developing more efficient and reliable ion thrusters becomes better defined. This research not only lays the groundwork for future studies but also highlights the critical role of computational techniques in pushing the boundaries of space propulsion technology design.

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References

1. Hofer RR, Gallimore A. Development and Characterization of High-Efficiency, High-Specific Impulse Xenon Thrusters. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, USA, 2004. https://doi.org/10.2514/6.2004-3602

2. Wang J, Polk J, Brinza DE. Ion Thruster Modeling: Particle Simulations and Experimental Validations. AIP Conf. Proc. 663, 525–532, 2003. https://doi.org/10.1063/1.1581590

3. Boyd ID, Numerical modeling of spacecraft electric propulsion thrusters. Progress in Aerospace Sci., 41(8), 669-687, 2005. https://doi.org/10.1016/j.paerosci.2006.01.001

4. Vincent B, Tsikata S, Mazouffre S, Boniface C. Thomson scattering investigations of a low-power Hall thruster in standard and magnetically-shielded configurations. The 36th International Electric Propulsion Conference, University of Vienna, Austria, 2019. https://www.researchgate.net/publication/337085936_Thomson_scattering_investigations_of_a_low-power_Hall_thruster_in_standard_and_magnetically-shielded_configurations

5. Kong E. Ion Thrusters Optimization: Simulation and Analysis. GitHub, 2024. https://github.com/DoggoOP/IonThrustersOptimizations

6. Kong E. Ion Thrusters Optimization: Simulation Functions. Wolfram Community, 2024. https://community.wolfram.com/groups/-/m/t/3217524

7. Kindberg P. Development of a Miniature Gridded Ion Thruster. Space Engineering, Master's Thesis, Luleå University of Technology Department of Computer Science, Electrical and Space Engineering 2017. https://diva-portal.org/smash/get/diva2:1143198/FULLTEXT01.pdf

8. Simmonds J, Raitses Y, Smolyakov A. A Theoretical Thrust Density Limit for Hall Thrusters. J Electric Propulsion, 2(12), 2023. https://doi.org/10.1007/s44205-023-00048-9

9. Txai L, Habl C. Investigation of DC and RF Biased Gridded Ion Thruster Plume Phenomena. Plasma Physics [physics.plasm-ph]. Institut Polytechnique de Paris, 2022. https://theses.hal.science/tel-03689405/file/114674_CALVOSO_HABL_2022_archivage.pdf

10. Fearn DG. Ion Thruster Thrust Vectoring Requirements and Techniques. paper IEPC-01-115 at the 27th International Electric Propulsion Conference, Pasadena, CA, 2001. https://electricrocket.org/IEPC/115_1.pdf

11. Scholze F, Pietag F, Adirim H, Kreil M, Kron M, Woyciechowski R, et al., Development and test of a cost-efficient gridded ion thruster propulsion system for small satellites – IonJet. J. Electric Propulsion, 1(28), 2022. https://doi.org/10.1007/s44205-022-00028-5

12. Fahey T, Muffatti A, Ogawa H. High Fidelity Multi-Objective Design Optimization of a Downscaled Cusped Field Thruster. Aerospace, 4(4), 55, 2017. https://doi.org/10.3390/aerospace4040055

13. Marks T, Schedler P, Jorns B. HallThruster.jl: A Julia Package for 1D Hall Thruster Discharge Simulation. J Open Source Softw, 8(86), 4672, 2023. https://doi.org/10.21105/joss.04672

14. Choueiri EY. New Dawn for Electric Rockets. Sci. Am., 300(2), 58-65, 2009. http://dx.doi.org/10.1038/scientificamerican0209-58

15. NASA Glenn Research Center. Gridded Ion Thrusters: NEXT-C. NASA, 2024. https://www1.grc.nasa.gov/space/sep/gridded-ion-thrusters-next-c/#:~:text=NASA's%20Evolutionary%20Xenon%20Thruster(NEXT,downstream%20end%20of%20the%20thruster

16. Perales-Diaz J, Cichocki F, Merino M, Ahedo E. Formation and neutralization of electric charge and current of an ion thruster plume. Plasma Sources Science and Tech., 30(10), 105023, 2021. https://iopscience.iop.org/article/10.1088/1361-6595/ac2a19/meta