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Development Status of the Helicon Hall Thruster

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Abstract: The development status of a two-stage Hall thruster, the Helicon Hall Thruster, is presented. The Helicon Hall Thruster combines the efficient ionization mechanism of a helicon source with the favorable plasma acceleration properties of a Hall thruster. Conventional Hall thrusters rely on direct current electron bombardment to ionize the flow in order to generate thrust. Electron bombardment typically results in an ionization cost that can be on the order of ten times the ionization potential, leading to reduced efficiency, particularly at low specific impulse and discharge voltage. Helicon sources have been demonstrated to be an efficient means of producing a high-density, low-temperature plasma. The goals of the program are to design, manufacture, and test a thruster that operates efficiently over a range of input power from 3 to 10 kW with discharge voltages ranging from 150 to 500 V and discharge currents ranging from 12 to 40 A. The potential benefits of a reduced ionization cost with the helicon ionization stage are outlined. The design and manufacturing challenges involved in the development of the thruster are discussed, followed by plans for testing.

I. Introduction

The increase in available spacecraft power observed in recent years has made possible the use of electric propulsion (EP) devices for orbit raising of satellites intended for use in geosynchronous earth orbit (GEO).^{1,2} Using EP systems for a portion of the low earth orbit (LEO) to GEO or geosynchronous transfer orbit (GTO) to GEO transfer provides significant mass reductions and cost savings due to the much higher values of specific impulse (I_{sp}) of these devices compared to typical chemical systems.³ For many near-Earth missions, the Hall thruster provides an attractive combination of thrust and specific impulse for achieving acceptable trip times while still realizing large reductions in propellant mass. Maximum thrust operation at specific impulse values of 1000-1500 seconds enable rapid Earth satellite deployment, reusable space tugs, and rapid planetary escape trajectories for large interplanetary spacecraft. A high specific impulse mode for the same thruster for less time-critical functions, such as station keeping, maximizes propellant savings.

The Air Force Research Laboratory awarded ElectroDynamic Applications (EDA) a Phase I Small Business Innovative Research (SBIR) grant to investigate the feasibility of a Helicon Hall Thruster (HHT). The HHT design is a novel two-stage Hall thruster with an efficient helicon ionization first-stage coupled to a state-of-the-art Hall accelerator stage. Conventional Hall thrusters rely on direct current electron bombardment to ionize the flow in order to generate thrust. Electron bombardment typically results in an energy cost per ion that can be on the order of ten times the ionization potential, leading to reduced efficiency, particularly at low specific impulse and discharge voltage.

Helicon ion sources ionize the flow by coupling radio frequency (RF) energy into a plasma without electrodes using helicon waves, which are cylindrically bounded whistler waves.⁴ Commonly used in plasma physics, helicon

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sources have been demonstrated to be an efficient means of producing a high-density, low-temperature plasma.^{5,6} In addition to a potential increase in ionization efficiency, a helicon source ionization processes from the acceleration processes. This means that low ionization costs could be maintained over a wide range of specific impulse. Finally, helicon ionization is effective for a range of propellants beyond xenon. With low enough ionization costs, it may be feasible to use lower mass, less expensive propellants.

A key to the feasibility of the HHT concept is creating an annular helicon source to couple effectively into an annular acceleration stage. In phase I, Aerojet mathematically proved the feasibility of an annular helicon source and determined the necessary boundary conditions.⁷ Also in Phase I, EDA performed an initial characterization of a helicon source at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL). Figure 1 shows a helicon source generating an argon plasma inside of a 15-cm-diameter quartz tube. Two coils of electromagnets wrapped around the outside of the tube creating the axial magnetic field necessary for helicon operation. The source is excited in the $m = 0$ mode using a single band copper antenna. The plasma density can be controlled by adjusting the RF power input to the plasma, and the axial magnetic field.

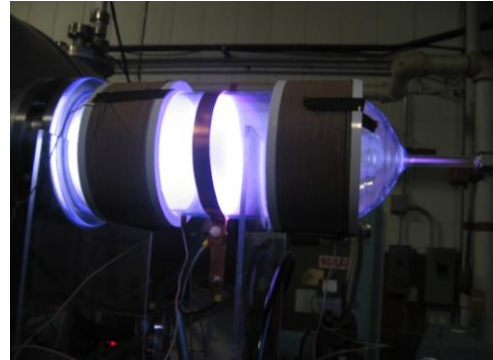


Figure 1. Argon plasma in helicon mode.

The goal of Phase II is to design, manufacture, and test a Helicon Hall Thruster that operates efficiently over a range of input power from 3 to 10 kW with discharge voltages ranging from 150 to 500 V and discharge currents ranging from 12 to 40 A. This paper gives the status of this effort, first outlining the potential benefits of and requirements for reducing the ionization cost with the helicon ionization stage. The design and manufacturing challenges involved in the development of the thruster are then discussed, followed by plans for testing.

II. Impact of Ionization Cost on Overall Thruster Efficiency

In order to evaluate the potential benefit of lower ionization costs with the HHT, it is useful to consider a very simplified description of current and power flow in a conventional Hall thruster (Figure 2). The current in Figure 2 is shown as the conventional current, although only the beam current, I_B , exiting from the acceleration zone depicts the actual particle direction. All other currents are actually electrons that physically travel in a direction opposite that of the arrows.

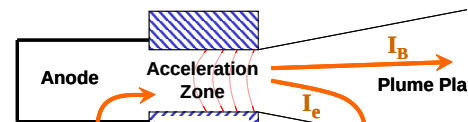


Figure 2. Conventional Hall Thruster Current Flow

Typically an electron current, I_e , is defined as

$$I_e \equiv I_D - I_B, \quad (1)$$

where the electron current is understood to be the electrons that travels upstream, gaining energy in the potential gradient and ionizing the flow through electrode bombardment.

If the effects of divergence, multiply charged ions, mass utilization and fall voltages are neglected in order to highlight the impact of ionization cost, thrust power could be approximated as

$$P_{Thr} \approx I_B V_D, \quad (2)$$

Likewise, neglecting the small portion of the power invested in heating the cathode through the cathode fall, the power invested in ionizing the flow through electron bombardment is approximated as

$$P_{Ioniz} \approx I_e V_D, \quad (3)$$

The ionization cost per beam ion for an electron bombardment Hall thruster would then be

$$\frac{I_e V_D}{I_B} \equiv \bar{V}_{eb} = \bar{N} V^+, \quad (4)$$

The ionization cost per ion, $\bar{V}_{eb}$, of the BPT-4000 at typical operating conditions has been empirically determined to be approximately 120 eV, or over ten times the first ionization energy of xenon, 12.1 eV.⁸ This means that nearly 90% of the incident energy intended for ionization is rejected as waste heat, primarily in the anode and insulating rings, and the single largest loss mechanism in that device.⁸

Combining (1) through (4), the thrust efficiency is approximated as

$$\eta \approx \frac{P_{Thr}}{P_{Thr} + P_{Ioniz}} = \frac{1}{1 + P_{ioniz}/P_{Thr}} \approx \frac{1}{1 + \bar{V}_{eb}/V_D}, \quad (5)$$

At a discharge voltage of 300 V, ionization cost (defined here in equation 4) in the BPT-4000 already limits the efficiency to 70% even before other loss mechanisms are taken into account. If the ionization cost can be reduced the efficiency, even at a typical discharge voltage, can be increased. Equation (5) also shows that as the discharge voltage is decreased to reduce specific impulse and obtain a higher thrust-to-power ratio, ionization cost will drive the efficiency down even lower. This is the primary effect limiting the minimum specific impulse and therefore the maximum thrust-to-power ratio of electron bombardment Hall thrusters. If the cost per ion can be reduced, a Hall thruster can be operated at lower specific impulse with higher efficiency, resulting in a higher thrust-to-power ratio.

In a Helicon Hall Thruster, equation (3) becomes

$$P_{Ioniz} \approx I_e V_D + P_H, \quad (6)$$

where P_H is the power input to the helicon discharge. If the ionization cost per ion in the helicon is

$$\bar{V}_H \equiv P_H / I_B, \quad (7)$$

then (5) can be rearranged as

$$\eta \approx \frac{1}{1 + I_e / I_B + \bar{V}_H / V_D}, \quad (8)$$

Equation (8) shows that for a Helicon Hall Thruster to provide improved performance, it must significantly reduce or eliminate electron current, as well as reducing the cost per ion relative to that of an electron bombardment thruster. In the past, researchers have reported helicon sources to have ionization costs approaching the theoretical minimum for some gases.⁶ Recent data on a high powered helicon source has measured an ionization cost of approximately 80 eV/ion on argon,¹⁰ which still indicates the potential for a helicon source to significantly improve efficiency, assuming that other losses neglected above for clarity are the same. In addition, it should be noted that all other things being equal, the same discharge voltage with argon will still yield a lower thrust-to-power ratio due to its lighter atomic mass. In order to increase the maximum thrust-to-power, the reduction in ionization cost must also be demonstrated on a heavy propellant such as xenon.

The primary goal of Phase II is to verify an improvement in performance due to lower ionization costs by the test of an actual Helicon Hall Thruster.

III. Development of a Helicon Hall Thruster

Over the course of this project, EDA has worked in conjunction with Aerojet to design and fabricate the HHT based on the magnetic circuit developed by EDA. The goal is to demonstrate optimized performance of the HHT using a conventional hollow cathode on xenon propellants. This effort will conclusively demonstrate the ability of two-stage Hall thrusters using highly-efficient helicon ionization sources to outperform today's SOA in spacecraft propulsion. Further discussion on the theoretical benefits of a helicon ionization source (specifically an annular source) for a Hall thruster can be found in References 11-13. The HHT should be able to efficiently operate from 3 to 10 kW with discharge voltages ranging from 150 to 500 V and discharge currents ranging from 12 to 40 A.

A. Design

The ionization augmentation will be accomplished by having a discharge channel separated into two main regions. The upstream region will be the location of the helicon ionization source with an $m = 0$ antenna configuration. The channel width was determined from annular helicon source theory with a purely axially applied magnetic field. The annular geometry is ideal for mating with the Hall thruster second stage and has been experimentally demonstrated at multiple laboratories.^{13,14} The benefits of the $m = 0$ mode include low-magnetic field requirements, small form factor, generation of the plasma near the antenna location, and the ability to axially move the antenna. The primary disadvantage of this mode (compared to the $m = 1$ mode) is that the radial plasma profiles

reach a maximum near both the inner and outer walls of the discharge potentially leading to increased wall losses compared to a profile peaked in the center of the annulus. The $m = 1$ will be studied by a separate laboratory.¹³

The downstream portion of the channel will contain a Hall current ionization and acceleration region similar to what one would expect from a SOA Hall thrusters. The HHT discharge channel will contain additional features to improve operation at the high thrust-to-power regime. The first will be the concept of separating the propellant distribution from the electrical circuit of the acceleration process. To achieve this, the propellant distributor will be electrically and thermally isolated from the system anode. This separation will help reduce the heating of the propellant, thereby increasing the residence of the neutrals in the ionization regions of the HHT. The separation will also prevent a static electric field from being applied across the helicon source region. The second feature will be the incorporation of a small channel diameter-to-width ratio for the Hall region of the thruster. This feature has been shown to improve Hall thruster operation on alternative propellants, such as krypton, and very high power Hall thrusters (50 to 100 kW).¹⁵⁻¹⁷ Several of the problems of using krypton propellant in a Hall thruster are the high ionization potential and greater thermal velocity of the krypton compared to xenon. By increasing the width of the discharge channel, the applied magnetic field is stretched and concurrently the potential field. By increasing the potential field of the acceleration region, the Hall current and propellant interaction region increases thereby allowing more time for propellants to ionize. Both the helicon and modified Hall stage features should increase the likelihood of neutral particle ionization compared to a SOA Hall thruster thus benefitting the goal of high thrust to power operation.¹¹

Following completion of the magnetic circuit analysis and channel geometry, the next task was to develop the mechanical design of the laboratory HHT. Aerojet leveraged features from the BPT-4000 and previous HiVHAC designs. These key design features include a highly integrated magnetic structure, a low cost gas distributor design, a low cost propellant line isolator and a thermally efficient, robust electro-magnet coil design.

Other mechanical design objectives for the laboratory thruster are to minimize mass, part count, the use of tight tolerance features, and the use of complex manufacturing process without comprising the thruster's design fidelity. In addition, the use of low cost, easily machinable magnetic circuit materials will increase the manufacturability of the engine. Figure 3 shows a 3-D mechanical design model of the HHT. Figure 4 shows schematic of the cross section. Informal design reviews were held throughout the design processes on key challenges between Aerojet and EDA personal to improve the likelihood of a successful thruster design.

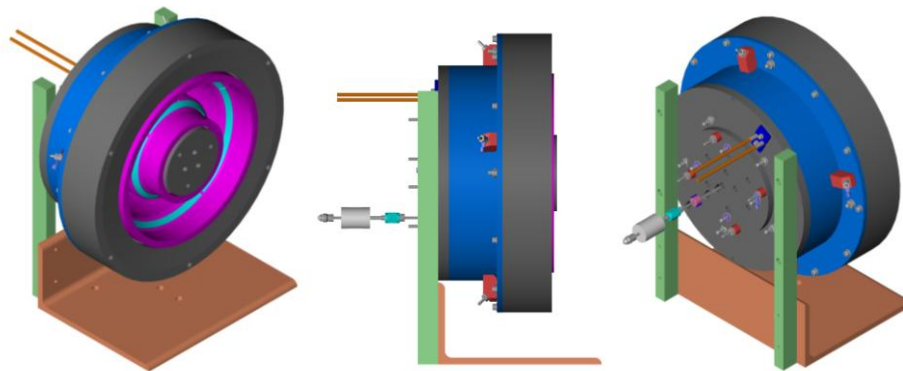


Figure 3) 3-D Model of the Helicon Hall Thruster

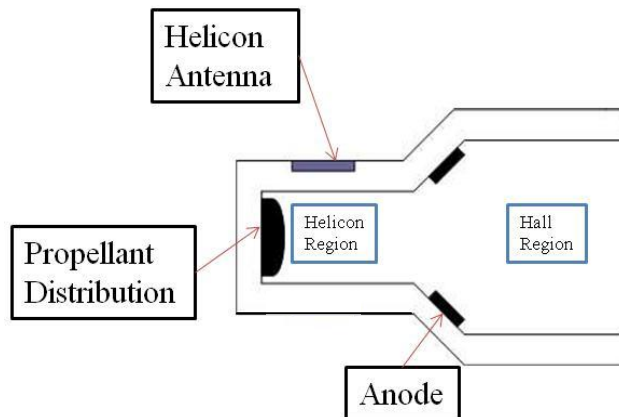


Figure 4) Helicon Hall Thruster cross section

Numerous design features were incorporated into this thruster to improve performance. As stated above, it is desired to eliminate a static potential field from being applied across the helicon source region. To assist in this goal, a ceramic ring is placed just downstream of the gas distributor to prevent a line of sight to any metallic component inside the chamber and is located upstream of the antenna. The ceramic cap has slits to allow the flow to escape. The slotted BN piece can also be easily removed to test a traditional gas distributor configuration/set-up. The gas distributor design leverages Aerojet's patented porous metal gas distributor design to achieve uniform flow rates over a wide operating range.¹⁸ The anode bands (shown in light blue inside the discharge channel in Figure 3) are designed to allow operation up to 40 A.

The HHT will be capable of running with both single stage (Hall Thruster mode) and two stage (Helicon Hall Thruster mode) mode. The main premise behind the two-stage configuration is to minimize the ionization cost by introducing the secondary ionization source (the helicon). The first stage mode will be conducted both with and without the ceramic cap sitting just above the gas distributor surface. The second stage mode, as discussed above, will always have the ceramic cap in place to shield the metallic surface of the gas distributor. Extensive single stage Hall thruster data will be gathered to assess the impact of the helicon ionization stage.

The helicon antenna is a single loop $m = 0$ design and therefore only needs to surround the outer ceramic channel.¹⁹ The ability to create an efficient discharge directly under a single-loop antenna introduces the option of creating a short, compact ionization stage for the helicon Hall thruster aiding in the creation of a relatively simple magnetic circuit requiring field strengths similar to traditional Hall thrusters. The thruster is designed to easily allow the antenna to move axially to study the impact of different positions on performance.



Figure 5. HHT piece parts.

The thruster uses a single coaxial outer electromagnet as opposed to the four individual coils that have been traditionally used in Hall thruster design. There are two additional coils used to generate the necessary axial field strength during helicon operation. All coils are potted to increase thermal conductivity.

The discharge channel is made of boron nitride material and is maintained in position using disc springs to allow for the different thermal expansion characteristics between the ceramic and surrounding iron material.

B. Manufacturing

Following successful completion of the laboratory thruster design reviews, thruster fabrication began. With the exception of the thruster mounting bracket which was designed by EDA, all fabrication and assembly is taking place at Aerojet's Redmond Washington Facility where flight BPT-4000 Hall thruster systems are built. This manufacturing facility has capabilities spanning from part machining and electronics manufacturing to subsystem assembly and test. However, Aerojet will only be fabricating the thruster while EDA will handle the helicon RF power delivery system. Figure 5 shows a photograph of some of the thruster piece parts including the boron nitride

channel walls, disc springs to help maintain thrust chamber location, and the gas distributor. The majority of the magnetic structure is constructed of magnetic iron rather than exotic materials to provide for affordable fabrication.

The low cost gas distributor has completed flow symmetry testing resulting in acceptable flow uniformity of +4%/-5% at 130 sccm flow (percent deviation from average) measured 2" downstream of the gas distributor face and +5.4%/-7% at 130 sccm measured 0.6" downstream of the gas distributor. The gas distributor will sit on a ceramic ring to isolate it from the thruster. The propellant isolator will be of a type that has successfully been used by Aerojet for thrusters covering the full voltage and current range expected for the HHT. The HHT coil design leverages heavily on experience gained from Aerojet's 4.5 kW Hall thruster development and flight qualification program. The magnet coils have all been insulated, wound, and potted. The inner coil is wrapped directly onto the inner core to increase thermal conductive paths and create more space for windings. The outer coil uses an aluminum bobbin with hard anodized surfaces to achieve high temperature, electrical insulation properties. The inner helicon coil uses a copper bobbin (pictured in Figure 5) while the outer helicon coil is maintained in place without a bobbin due to the structural integrity provided by the potting material. Coil bobbins (when used) are physically attached to the iron structure to conduct heat to the cooler mounting plate of the thruster. A key characteristic of the $m=0$ mode is that the magnetic field strengths required for the helicon are comparable to those of a Hall thruster lowering the required mass and volume of the ionization stage. All iron, ceramic, and copper pieces have been fabricated.



Figure 6. Copper antenna.

Figure 6 shows the single loop copper antenna required for the $m=0$ helicon mode chosen for the HHT. The antenna will fit securely around the outer boron nitride channel wall and be surrounded by multiple sheets of mica for isolation. Copper welding is used to eliminate the weak soldering connection sometimes used for the antenna and copper leads in conventional helicon experiments. As stated above, a key characteristic of the $m=0$ mode is the ability to create an efficient discharge directly under the loop antenna. A feature of the HHT is the freedom to move the antenna axially in the ionization stage.

The HHT is pictured in Figure 7. The partial assembly pictured shows the thruster without the ceramic cap downstream of the gas distributor (i.e., single stage Hall thruster mode) and does not include the externally mounted cathode. The current weight of the thruster is 60 lbs. Fabrication of the final parts is expected by the end of the month.

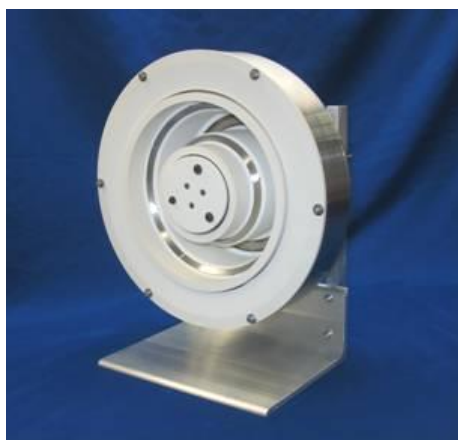


Figure 7. Photograph of the Helicon Hall Thruster

C. Testing Plan

Following final fabrication and assembly of the laboratory thruster, a magnetic field map of the discharge channel will be performed on the bench top to assure that the radial magnetic field profile and magnetic streamline shape match the design profile and shape. Functional testing, including electrical insulation resistance and component isolation tests, will be performed to ensure hardware readiness for vacuum discharge testing.

Performance mapping of the thruster with a hollow cathode will be performed by EDA in the Large Test Facility at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL). These tests will cover a

range of operating conditions from 150 to 500 V and 12 to 40 A. To establish a reference database, initial testing will be conducted in single stage Hall thruster mode with and without the gas distributor ring isolated. In both non-isolated and isolated single stage configurations, ionization is accomplished with electron bombardment. In the non-isolated configuration, the distributor is at anode potential along with the anode ring, as it is in a conventional Hall thruster such as the BPT-4000. The isolated distributor configuration duplicates the gas distributor electrical configuration used in the two stage helicon mode. Isolation is accomplished with both a cryobreak in the propellant line feeding the gas distributor and an insulating ring covering the gas distributor. Finally, full two stage, helicon mode will be tested. Optimization of the thruster performance over a range of inner and outer magnetic coil amp turns will also be performed for each of the configurations covering the range of operating conditions. Plasma probes will measure beam currents, current density and divergence, beam ion velocity distributions, and double to single ion ratios. The beam current to discharge current ratio in the helicon mode will demonstrate the reduction in electron bombardment energy. The measured radio frequency power deposition will measure the cost per ion.

IV. Conclusion

This paper briefly discussed the concept of the helicon Hall thruster and the potential benefits that a HHT type of EP device could bring to future missions that require high thrust-to-power and low-Isp propulsion systems. The basic concept of the HHT is to achieve high efficiency operation of a high thrust-to-power, low-Isp Hall thruster by employing the efficient ionization mechanism of a helicon source while maintaining the efficient acceleration characteristics of Hall thrusters. A brief overview of the HHT was discussed including the helicon ionization stage design. The HHT thruster is currently undergoing final design modifications and fabrication at Aerojet and should be delivered to EDA for characterization in late 2009.

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