Theory and Development of Plasma Based Propulsion in VASIMR and Hall Effect Thrusters

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This report discusses the fundamental concecpts utilized by the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and the Hall Effect Thruster (HET). The modes of operation of both thrusters are explored in detail as well as the fundamental physics behind the use of plasma in both thrusters. Emphasis is placed upon the different applications of both the VASIMR and HET including their current stages of development as well as future technology. The design challenges presented by using plasma propulsion systems on spacecraft is also discussed. One note of interest is the markedly different methods the two thruster systems utilize to produce the thrust while also using similar physical principles.

Nomenclature

VASIMR	=	Variable Specific Impulse Magnetoplasma Rocket
HET	=	Hall Effect Thruster
$\vec{F}$	=	Lorentz force
$\vec{E}$	=	electric field
q	=	charge
$\vec{v}$	=	velocity
$\vec{B}$	=	magnetic field
ω_c	=	cyclotron frequency
R_L	=	Larmor radius
λ_D	=	time step
L	=	characteristic length
P	=	absorbed power of RF emitter
j	=	plasma current
T_c	=	electron temperature
V_H	=	Hall Voltage
Ω	=	Hall parameter

I. Introduction

The concept of Electric Propulsion dates all the way back to 1911 when Konstantin Tsiolkovsky first introduced it in a publication of his. It was not until July of 1964 however that the first electric propulsion engine would be tested in space. This particular NASA mission was known as SERT-1 (Space Electric Rocket Test 1) and it was equipt with an electrostatic ion thruster which operated for a total of 31 mintutes and 16 seconds. During this same decade, both Russia and the United States began the development of the Hall Effect Thruster. The United States soon discontinued pursing the HET in favor of the ion engine. Luckily, Russia struggled with the ion engine optics and concentrated on developing HET which led to decades of technological development and testing. It was not until 1998 that the United States flew their first HET which was made by Russia; nearly a decade later in 2006, Busek Co. Inc. delivered the first American HET to fly in space. Hall Effect Thrusters are certainly making their way back into the spotlight; as of 2013 they have been selected to be the propulsion system for NASA's Asteroid Retrieval Mission

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While the Hall Effect Thruster is a relatively old, frequently tested, and well-understood concept, the VASIMR engine is a relatively new concept which also utilizes principles of plasmadynamics.

The technology for the VASIMR engine started with research done by Dr. Chang Diaz of AdAstra Rocket Company while he was conducting research at NASA which was detailed in his 1982 paper on a "Hybrid Plume Plasma Rocket". The first experiement conducted on the VASIMR concept was completed at MIT in 1983 which yielded the first patents on the technology by 1989. In the early 1990's, the plasma gun in the original design was replaced with the highly efficient helicon plasma injector. The first modern VASIMR engine was tested in 1998 at NASA JSC and produced 10 kW of RF power. By 2002, higher power models named the VX-25 and VX-50, which were 25 kW and 50 kW respectively, were demonstrated in the laboratory. In 2005, Dr. Chang Diaz and AdAstra signed a Space Act Agreement with NASA which privatized the VASIMR technology to AdAstra Rocket Company. In 2009 the current 200 kW design was first fired and the performance mapping began and by 2010 the VX-200 set an efficiency record of 72% which has been replicated in subsequent laboratory tests. Recently AdAstra has signed another Space Act Agreement with NASA to continue development of the VASIMR as well as been awarded a contract to demonstrate a prolonged firing of the engine. VASIMR has shown significant promise as a future propulsion system, however it is not without design issues to overcome.

A. Plasma Physics Principles

The Hall Effect thruster and the VASIMR require multiple concepts from plasma physics to describe their functionaility. One such concept is the Lorentz force which is the force experienced by a charged particle as it travels in an electromagnetic field. This force is characterized by Equation 1, where q is the charge of the particle in Coulombs, $\vec{E}$ is the electric field vector, $\vec{v}$ is the particle velocity vector, and $\vec{B}$ is the magnetic flux density. As seen in the equation, an electric field will exert a force in the direction of the the electric field and the magnetic field will exert a force perpendicular to the velocity of the particle and the magnetic field.

$$\vec{F} = \pm q\left(\vec{E} + \left(\vec{v}x\vec{B}\right)\right) \tag{1}$$

These forces give rise to a concept known as the cyclotron frequency. Since the magnetic field as defined by the Lorentz force equation exerts a centripetal force on the particle, the particle begins to act in a cyclic manner so long as the particle has some component of velocity that is perpendicular to the magnetic flux density. The natural frequency of this cyclical motion is called the cyclotron frequency and is defined by Equation 2. Figure 1 depicts the motion of a particle within a uniform magnetic field where the cyclical motion is due to the Lorentz force.

$$\omega_c = \frac{qB}{2\pi m} \tag{2}$$

The cyclical motion of the particles within a uniform magnetic field carries with it a radius of gyration known as the Larmor radius. This radius is defined by Equation 3, where $\overrightarrow{v_\perp}$ is the perpendicular velocity component of the particle relative to the magnetic flux density.

$$r_L = \frac{mv_\perp}{|q|B} \tag{3}$$

Another important physical concept used in studying plasma dynamics is the Debye length or Debye radius. This value is the measure of a charged particles net electrostatic effect within a solution and how far that effect extends beyond the particle. The Debye length in a plasma is characterized by Equation 4, where λ_D is the Debye length, ε_0 is the permissivity of free space, k_B is the Boltzmann constant, q_e is the charge of an electron, T_e is the temperature of the electrons, T_i is the temperature of the ion species "i", n_e is the electron density, and n_i is the ion density of species "i" with an ionic charge of $z_i q_e$.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 \frac{k_B}{q_e^2}}{\frac{n_e}{T_e} + \sum_i z_i^2 \frac{n_i}{T_i}}} = \sqrt{\frac{\varepsilon_0 K T_e}{ne^2}} \tag{4}$$

λ_D is a valuable parameter for determining whether a species is a plasma or not. In the case of a plasma the debye length should be much smaller than the characteristic length i.e. $\lambda_D \ll L$.

II. Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is an electromagnetic plasma rocket engine being developed by AdAstra Rocket Company headed by Dr. Chang-Diaz working in conjuction with NASA. The engine takes it's name from its unique ability to vary the specific impulse to tailor the performance of the engine to mission criteria as well as it's magnetic field driven plasma characteristics. The VASIMR works by heating and accelerating a plasma through the use of electromagnetic fields. A gas such as hydrogen, helium, or argon is injected into the main chamber and is excited into a plasma through the use of radio-frequency waves generated by a helicon antenna. The plasma is then guided down the main chamber by a series of powerful electromagnets which also impart a rotation to the plasma. Near the end of the chamber the plasma is heated using a process known as ion cyclotron resonance heating which raises temperature of the plasma to millions of degrees K by exciting the cyclical resonance of the travelling plasma flow. The superheated plasma is then directed out of the engine using a magnetic nozzle. The VASIMR's three main features that describe its functionality: helicon ionization, ion cyclotron resonance heating, and magnetic flow control, are discussed in detail below.

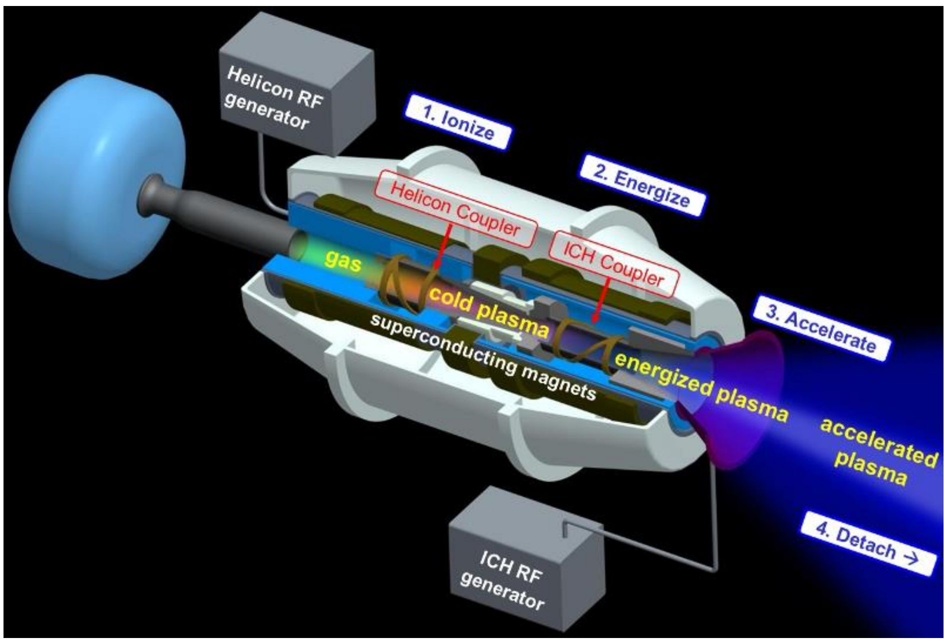


Figure 1. Diagram of the VASIMR operations

B. Helicon Ionization

The VASIMR engine requires a high plasma density to produce it's thrust so a plasma must be generated at the inlet of the engine. In order to produce this gaseous plasma, the VASIMR makes use of helicon radio-frequency waves to ionize the propellant gas within a magnetic field. These RF waves are produced by a helicon conductive coil that produces the alternating electric field. These waves are specifically tailored to excite the eigenmode of the electrons within the propellant gas.

The energy from the RF wave is transferred to the electrons via elastic colisions between the electron and the ion and neutral particles. In order to effectively excite the electrons, the helicon system must operate at a frequency near the eigenmode of the electrons. This eigenmode is related to a specific value for plasma density. As the plasma density increases and nears the specific plasma density, the energy deposited into the system increases exponentially with the resonance. Plasma is then produced rapidly from this reaction once the electron energy exceeds that of the ionization energy. Electrons that have decoupled with an ion continue to collide with other molcules and propogate the ionization throughout the plasma. The rate of the ionization of the gas is directly related to the power supplied by the radio frequency waves and the rate of partical transport through the helicon coil as shown in the local energy balance of Equation 5[5]. After the resonant excitation the plasma density increases until it reaches a stable equilibrium temperature and density.

$$P =< j \cdot \vec{E} > \tag{5}$$

This plasma produced by the helicon antenna is classified as a cold plasma due to temperature of the order of 10,000 K. Despite being the plasma being considered a cold plasma, the heat of the plasma could damage the engine so a method of containment is necessary.

The helicon plasma injection the VASMIR operation has important implications on the variability of the specific impulse and thrust of the engine. Applying more power to the helicon source antenna increases the plasma production and flow rate through the inlet of the engine and reducing the power applied will reduce the plasma flow rate. Additionally, plasma production through helicon radio-frequency waves has the added benefit of being an efficient ionization process due to the nearly one to one ratio of energy produced to energy deposited at the electron eigenmode resonance.

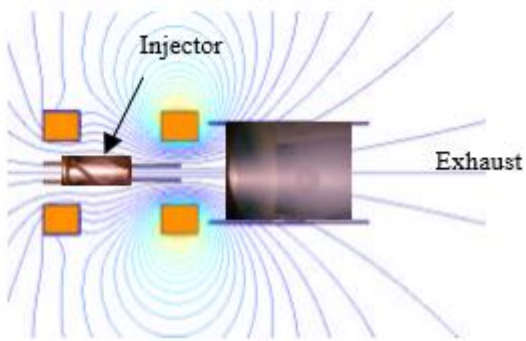


Figure 2: VASMIR Helicon Injector Diagram [3]

C. Ion Cyclotron Resonance Heating

In order to produce thrust the VASIMR engine must heat plasma rapidly and efficiently to generate the increases in energy necessary to create a substantial exit velocity of the plasma. To accomplish this the VASIMR makes use of a technology known as Ion Cyclotron resonance heating. Due to the Lorentz forces within a magnetic field such as the one found in the VASIMR, the ions have a cyclical motion to their velocity. The Lorentz force equation shows that for a given magnetic field and particle that their exists a centripetal force on a particle so long as there is a component of it's velocity that is perpendicular to the magnetic flux density. Due to this circular motion there exists a frequency of motion that is dependant on the magnetic flux density, the partical charge, and the particle mass as shown in Equation 8 which is derived from the Lorentz force.

$$\frac{mv^r}{r} = qvB \tag{6}$$

$$\omega_c = \frac{v}{2\pi r} \tag{7}$$

$$\omega_c = \frac{qB}{2\pi m} \tag{8}$$

Ion cyclotron heating utilizes this resonant frequency to impart energy into the plasma. To do this, a cicular polarized electric wave is imparted to the plasma. The frequency of the imparted wave must closely match that of the cyclotron resonant frequency to maximize the energy imparted to the ions. The ions pass through the antenna only hitting resonance once (single pass resonance) gaining substantially more energy than it's intial state. This type of excitation is also mostly collision less so the energy imparted is only limited to the time that the ions spend in resonance with the electromagnetic wave. The total power imparted to the plasma takes the form of Equation 9.

$$Q = \frac{\omega|k_0 l_a| r_p^2}{\pi^2 c^2 r_a^2} I_a^2 \tag{9}$$

$$k_0 = \frac{\omega}{c}\sqrt{\frac{\varepsilon+g}{2}} \tag{10}$$

$$\varepsilon + g = \sum_i \frac{\omega_{pi}^2}{(\omega-\omega_{ci})} \tag{11}$$

Where $\varepsilon + g$ are the cold plasma dialetric tensor componenets [Z].

One element of consequence taken from Equation XX is that when power is increase to the antenna, the energy deposited into the plasma resonance increases. This effect is an integral component to the VASIMR's capability to vary Isp and thrust and the ICRH can vary how much energy and radial velocity is imparted to the plasma. The circular polarized radio-frequency wave excites the plasma's velocity perpendicular to the flow and magnetic flux density such that the velocity of the particle around the circumference of their rotation increases dramatically. This rotational component to the plasma velocity is converted into axial velocity within the magnetic nozzle of the VASIMR. Due to the resonance characteristics of the ion cyclotron resonance heater, the efficiency of absorption of energy into the plasma is near 100%.

D. Magnetic Chamber and Magnetic Nozzle

Due to the physics of plasmas a magnetic field is needed for both device protection and manipulating the plasma itself. The VASIMR accomplishes this by having a series of powerful supercooled toroidal electromagnets which generate a magnetic field around 1 to 2 T. As a consequence of their shape and locations, the produced magnetic field has a linear magnetic flux density down the thruster axis as shown in Figure 3. This field serves dual purposes: to guide the plasma down the thrust axis from the plasma source to the cyclotron resonance heater and to provide protection against the temperature of the plasma in the chamber.

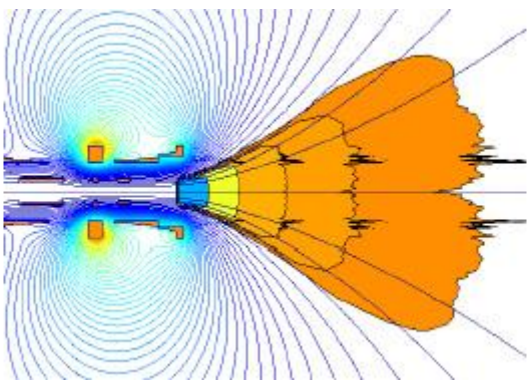


Figure 3: VASIMR Magnetic Field Lines [NASA]

The linear magnetic flux density through the plasma tube applies a centripetal acceleration to any particles that posess a radial component to their velocity due to the Lorentz forces applied by the magnetic field on the ionized particles. This effect keeps the plasma contained to a cylindrical section in the center of the chamber by redirecting the velocity of the plasma in a cyclical motion. Confinement of the plasma prevents structural damage due to the high termperatures within the plasma.

Additionally, the magnetic field plays an integral part in the generation of thrust in the motor. Due to the vast amounts of energy in the ICRH phase being added to the rotational motion of the particles rather than the axial motion, the angular momentum of the plasma needs to be redirected in the axial direction. This redirection and eventual detachment occur due to the divergence of the magnetic field lines in vaccum within the nozzle. As the field diverges, the gyroscopic momentum of the plasma is coverted to axial momentum due to the Lorentz forces cross-product relationship between the velocity vector and the magnetic field vector. As the particles velocity is redirected, the gyroscopic kinetic energy decreases. However as the particles move outward the magnetic flux density decreases at a faster rate and once the magnetic field energy drops below that of the rotational kinetic energy the plasma flow separates from the magnetic field lines. The resultant pushing effect on the magnetic field is what produces the thrust force of the engine. At the exit, the plasma flow is super-Alfvénic which will in effect stretch the magnetic field lines in vaccum. The overall thrusting affect can be approximated using Equation 12 [5].

$$T = \Phi\sqrt{2m_iK_i} \tag{12}$$

III. The Hall Effect Thruster

In 1879, American Physicist Edwin Herbert Hall discovered what we now refer to as the "Hall Effect". The Hall Effect describes a Voltage created across an electrical conductor which is transverse to both the current in the conductor and the magnetic field created by this current. This voltage is created by the accumulation of charge on one side of the material; since the magnetic field applied is perpendicular to the conductor, the Lorentz force causes the flowing electrons to favor one side of the material. This Hall voltage can be derived using the Lorentz Force

$$\vec{F} = \pm q(\vec{E} + \vec{v}x\vec{B}) = 0 \tag{13}$$

$$|\vec{E}| = |\vec{v}|\,|\vec{B}| \tag{14}$$

For conductor of width d

$$V_H = Ed = vBd \tag{15}$$

For a given charge carrier density n and surface area A we arrive at

$$V_H = \frac{IBd}{nqA} \tag{16}$$

In the application of propulsion, where a plasma is used (as opposed to a solid plate assumed in the previous derivation) the Hall Parameter is used to quantify the magnetization of both the ions and electrons. The Hall Parameter is the ratio of the cyclotron frequency to the collision frequency given by

$$\Omega = \frac{\omega_c}{\nu} \tag{17}$$

For example, if this parameter is greater than unity, it implies that a particle orbits a magnetic field line before a collision occurs. For a Hall Effect thruster, it is ideal that the electrons be magnetized and for the ions be non-magnetized. This implies that for the characteristic length scale L

$$\Omega_e^2 \gg 1 \rightarrow r_L^e \ll L$$

We can logically conclude that for ions, the most desirable Hall Parameter will be small and therefore, $r_L^{ion} \gg L$. The reason that having non-magnetized ions is desirable is that a torque will be imparted on the spacecraft if the ions are ejected with an angular velocity component in the ExB direction.

A. Design and Operation

The Hall Effect Thruster is a type of electric thruster which accelerates a propellant by an Electric field to produce thrust. The process begins by creating a potential (commonly referred to as the "discharge voltage") between the anode and the cathode. Applied across the discharge channel is a radial magnetic field which is used to trap electrons to keep them from making their way through to the anode. This need to trap electrons is where the condition for a large electron Hall Parameter comes from (in the previous section). The presence of this radial magnetic field in the plasma causes resistivity to increase greatly which creates an axial electric field. The combination of the radial magnetic field and axial electric field creates an electric field which causes an azimuthal drift of the electrons to form a Hall Current.

The equally important effect of this electric field is that it accelerates ions out of the aft end of the discharge channel to produce thrust. It is insufficient however to eject ions alone and this is where the cathode's second function applies; as ions are ejected, they are met with electrons coming from the cathode to form a net neutral plume. If the cathode did not perform this function, a charge buildup would occur and the thruster would not work.

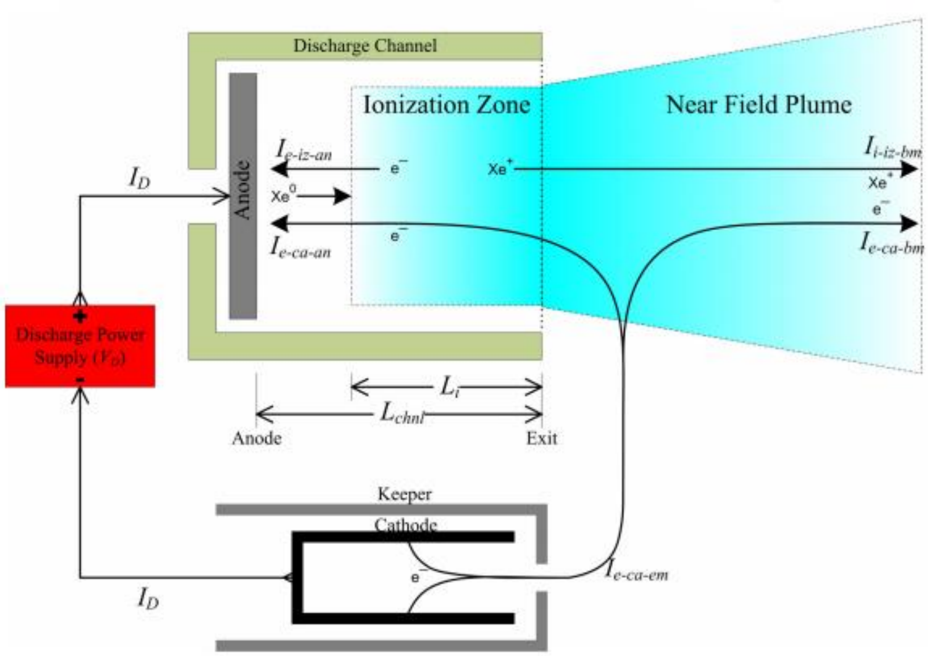


Figure 3: The top portion of a Hall Effect thruster from a side view. []

The process described previously is depicted above in Figure 3 where we see the top half of a Hall Effect Thruster and the associated electron and ion transport. In this type of Hall Effect Thruster, the cathode is in the center (the diagram does not display the entire thruster). It has been common practice to place the cathode *external* to the thruster rather than within the as shown in the Figure above; while it is easy for electrons to travel into the plume with this configuration, it is however difficult for the electrons from the cathode to re-enter the discharge channel as they are also supposed to do. The cathode in the center however allows for easier electron plume transport as well as discharge channel access.

The gas used in this example is Xenon. Xenon is a common propellant of choice in Hall Effect Thrusters; while it can be quite expensive ($1,200/kg) it is often chosen for missions due to its relatively *large* mass and *low* ionization energy (compared to other noble gases). Krypton and Iodine are other commonly used Hall Effect Thruster propellants however and they are cheaper however they suffer from lower performance due to the lower mass and higher ionization energies. For missions where cost is more important than engine performance, these propellants are good candidates. For example, SpaceX has plans to launch a total of 4,000 satellites to create a global internet; SpaceX plans to fit these satellites with Hall Effect Thrusters for in-orbit maneuvering. The price of Xenon will certainly become an issue for such a large endeavor and it is therefore likely that they will move forward with Krypton as the propellant.

B. Erosion and Magnetic Shielding

Since Hall Effect Thrusters are low thrust propulsion systems, they require very long operating times to create large ΔV. For decades a major problem that has vexed engineers who work with electric propulsion systems is the erosion that occurs in the discharge channel over time; this erosion is caused by ion sputtering and can inhibit the operation of the HET once the erosion becomes severe enough to expose the circuit which creates the magnetic field. To mitigate this issue, magnetically shielded Hall Effect Thrusters are being built. This magnetic shielding takes place inside of the discharge channel and works to keep the plasma interactions with the wall to a minimum. In an unshielded HET the electron temperature toward the exit end of the discharge channel becomes very high; at this region of high temperature, a large potential forms and ions are accelerated directly into the wall of the discharge channel. In a magnetically shielded thruster however, the discharge channel and magnetic field is shaped in such a way that this temperature remains constant throughout the length of the discharge channel. In Figure 4, we can see the difference in electron temperature at the exit of the discharge channel between the shielded and unshielded Hall Effect Thrusters. The electron temperatures are actually higher in the diagram of the magnetically shielded HET but these temperatures occur *after* the point where the ions exit the discharge channel, solving the issue.

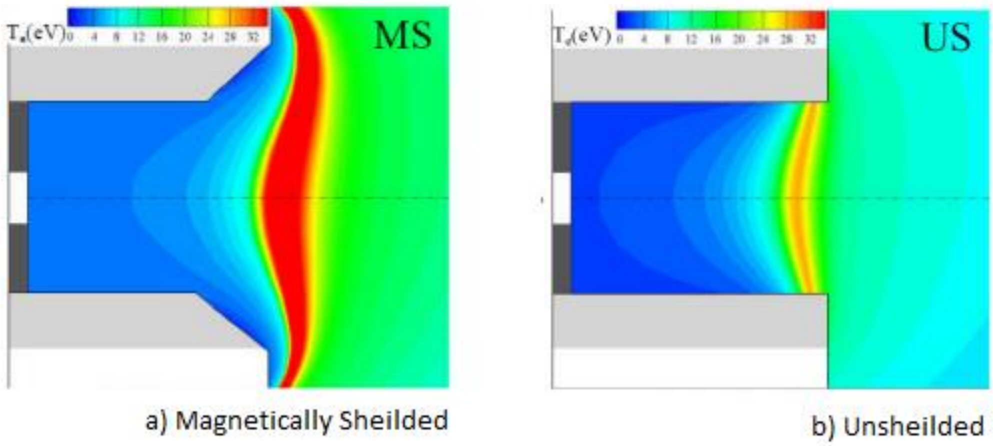


Figure 4: Electron Temperature of a) Magnetically Shielded Hall Effect Thruster and b) Unshielded Hall Effect Thruster

IV. Comparison Between Hall Effect Thrusters and VASIMR

The VASIMR has been currently been laboratory tested up to an operational power of 200 kW. The 200 kW engine designated TC-1 has undergone many years of testing iterations and mass improvements. As part of the test regime, multiple propellants have been tested and their performances characterized over operating Isp's of 2500-5000 seconds and up to 12 N of thrust. AdAstra has been able to achieve a consistent efficiency of over 60% and a maximum system efficiency of 73%. Through physics-based predictions which are anchored in the years of test data on the TC-1, AdAstra has developed also developed an analytical tool to predict motor performance and characteristics over a range of operating powers to assist in motor scaling. With this tool, a low power 40 kW motor has been characterized for possible applications to SEP spacecraft for asteroid rendezvous and debris de-orbiting designated the TC-1m. The VASIMR technology has achieved a minimum specific mass of approximately 3kg/kW for a single string thruster operating around 150 kW. Additionally multi-string thruster systems show that the VASIMR is best utilized with 1-2 thruster strings.

The single channel Hall Effect Thruster has been tested over a long period of time. The United States and Russia both began investigating this technology back in the early 1960s. In the 1970s, just around the time that the United States discontinued the development of Hall Effect Thrusters (in favor of Ion thrusters), the USSR began launching HETs for satellite station keeping and have since launched over 150. The United States did not fly their first HET until 1998 for the National Reconnaissance Office's Space Technology Experiment Satellite (STEX). In 2003 the ESA launched Small Missions for Advance Research Technology 1 (SMART-1), a satellite mission to the Moon, which contained a PPS-1350-G Hall Effect Thruster. This 1.5 kW thruster had an I_{sp} of 1,650s, a thrust of 0.088N, at an efficiency of 55%. The latest Hall Effect Thruster to be launched was the BPT-4000 on the USA-235 satellite in 2012; it has an input power of 4.5 kW and a thrust of 0.27 N and a specific impulse of 1,950s. Over the course of less than a decade between these implementation of these two engines, the I_{sp} increased by 300s (which alone is comparable to the total I_{sp} of a contemporary Launch Vehicle) and the thrust value more than tripled. It is worthy of noting that the BPT-4000 was also used in 2010 to save the USA-214 military communication satellite; after the satellite's liquid apogee engine failed to fire, it was deemed inopperable after a three day period of attempts to fix it. As a last resort, the attitude control Hall Effect Thrusters were used in such a way to raise its orbit and save the satellite.

V. Future Development of Plasma Propulsion

A. Development Plans for VASIMR

AdAstra Rocket Company currently is planning on multiple improvements to the VASIMR engine. The VX-200 unit has been disassembled and is being upgraded to resume testing in the near future with a reduced specific mass and increased efficiency. Another engine, the TC-1m which is a smaller version of the TC-1 engine, is being developed to make the VASIMR system more mass competitive in the lower power regimes. The initial work done on the TC-1m was in AdAstra's predictive code derived from plasma physics models and operational test data. Possible space applications and test beds for the VASIMR are being pursued by AdAstra, specifically operations on the space station as well as orbital debris management. The designed TC-1m reduce the specific mass of the system due to scaling down of the equipment for a lower power level. This yields a maximum operation power of 150 kW, however the mass savings makes it more competitive with the high power hall effect thrusters.

Additionally, AdAstra was awarded a three year continuing development contract from NASA worth $10 million to continue to develop the VASIMR technology in regards to it's application in interplanetary travel. The VX-200SS is specifically to be developed under the contract which aims to prove engine endurance by operating for over 100 consecutive hours. The test plan aims to increase the TRL of the VASIMR above level 5 and provide laboratory data on component lifespan and efficiency of the new thermal control system. Ultimately AdAstra hopes to use the VASIMR for interplanetary transfers, making use of the variable specific impulse to save on propellant weight.

B. VASIMR Mission to Mars

One of the proposed applications of AdAstra's VASIMR engine is a reduced period transfer trajectory to Mars, utilizing the variable specific impulse to reduce overall propellant costs of the mission while maintaining a short transfer period. A study was recently done by AdAstra Rocket Company to analyze a VASIMR propelled mission to Mars [BLAHBLAH]. The company utilized the Copernicus software suite developed at the University of Texas at Austin to compare two different Mars transfer trajectories with power levels of 12 MW and 200 MW respectively.

The 12 MW trajectory analysis started with a set initial mass of 165,000 kg at the L1 Lagrange point. It was assumed that the spacecraft would take and unmanned high Isp low thrust spiraling trajectory from LEO to L1 and that the crew would take a high thrust chemical rocket to L1 to rendevouz with the VASIMR spacecraft. This was to maximize mission efficiency for the VASIMR spacecraft while minimizing the travel time for the human crew. From L1, the VASIMR would use an optimized Isp profile for minimized fuel consumption to make a 91 day heliocentric transfer to Mars using approximately 36,000 kg of fuel and arriving with a relative velocity of 6.8 km/s. The assumed alpha for this mission is 4 kg/kW so the required mass of the propulsion system is 48,000 kg. This propulsion system mass includes a 21,000 kg thruster, 21,000 kg nuclear reactor, and 6,000 kg of radiators. Once at Mars, a crew service module would detach from the main spacecraft and continue to the surface using an identical entry profile to the NASA Mars Design Reference Mission (DRM). The main spacecraft would jettison empty tanks and would continue on passed Mars switching to a high Isp mode. Using approximately 6,000 kg of fuel, the VASIMR spacecraft would swing back by Mars and the crew would rendevouz with the main craft after a period of 110 days. The spacecraft would then make the transfer back to Earth during the following planetrary approach. There was an assumed contingency of an Earth return module with a lower power VASIMR onboard the cargo module which was planned to be sent ahead of the manned mission.

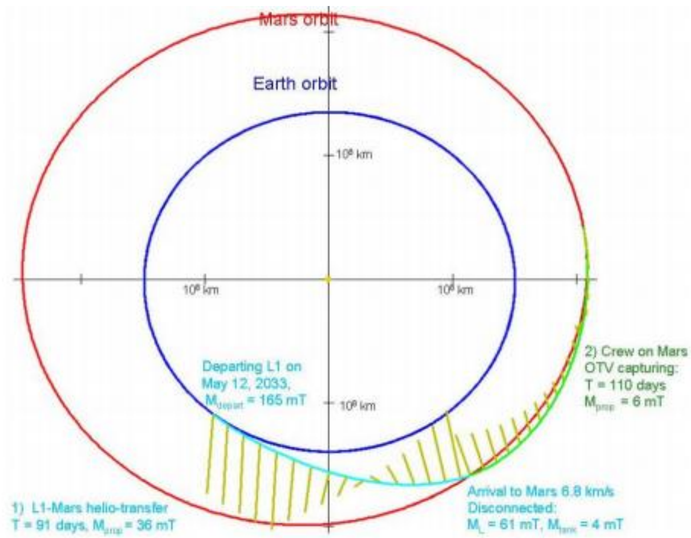


Figure 5: 12 MW Mars Transfer Trajectory Using VASIMR[1]

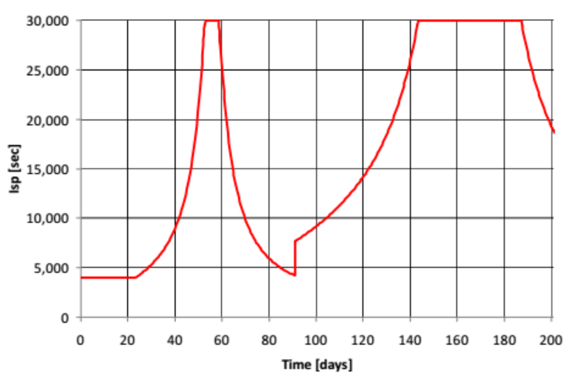


Figure 6: Isp Profile for 12 MW Mission to Mars[1]

For the 200 MW mission trajectory analysis, a starting mass of 600,000 kg was assumed launching from Earth LEO at 1000 km. The spacecraft would then spiral out to the Earth's sphere of influence at constant Isp which would take 9 days and be unmanned. Like the 12 MW mission, the crew would rendevouz with the spacecraft on board a chemical rocket for reduced transit time. From Earth's sphere of influence, the 200 MW Mars transit would take approximately 39 days an use 203,000 kg of propellant with the Isp varying to minimize the mass of the propellant used. Once the spacecraft arrives at Mars, it will be travelling at a relative velocity of 6.8 km/s at which point the crew service module would detach from the main spacecraft and descend to the surface using an indentical entry profile to the Mars DRM. After separation, the main spacecraft will dump empty tanks and will continue passed Mars switching to a high Isp mode of operation. After the 36 days and 10,000 kg of propellant, the spacecraft returns to Mars and the crew returns to the spacecraft for the return flight. For the 200 MW mission, the maximum thrust achieved by the VASIMR is 7.14 kN at a specific impulse of 4000 seconds.

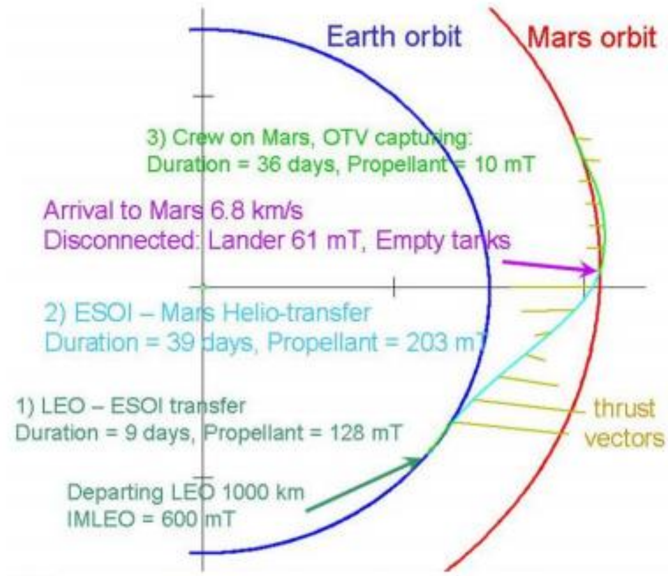


Figure 7: 200 MW VASIMR Mars Mission Trajectory[1]

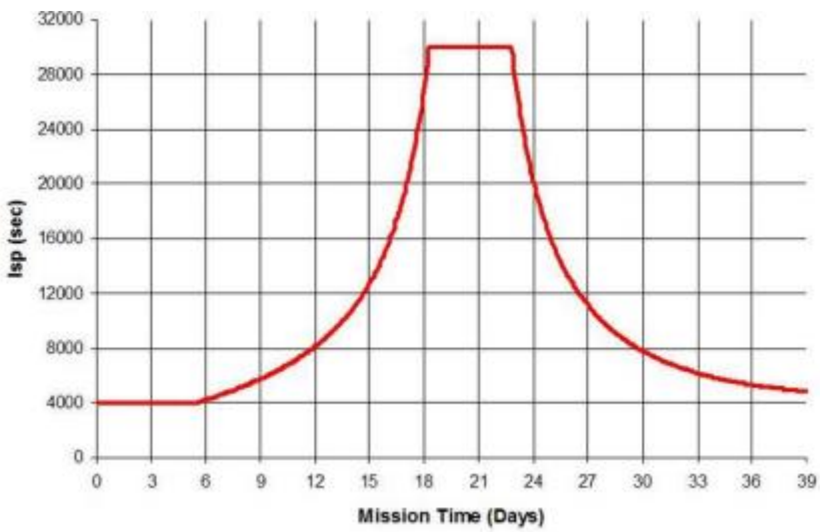


Figure 8: 200 MW VASIMR Mars Mission Isp Profile[1]

C. Clustered Hall Effect Thrusters

To increase thrust of a spacecraft, one logical step to take is to add more thrusters. While this may be a well-understood concept by now for chemical rockets (boosters) what is the consequence of adding multiple Hall Effect Thrusters to a spacecraft? This design is referred to as "clustering" and it can be a very beneficial direction to step into for Hall Effect Thrusters; instead of scaling up the size of a single HET for the increase in power required, clustering allows the use of contemporary HET engines working in conjunction so that redesign of the engines and vacuum chamber test facilities are not necessary. Additional advantages of this concept include throttleability by *intentionally* turning certain engines on/off and redundancy for if one or more of the thrusters *unintentionally* become inoperable during a mission. The University of Michigan is investigating the concept of nested Hall Effect Thrusters since 2004 and continues to do so. A picture of their BHT-600 cluster can be found in Figure 9 operating at 600 W.

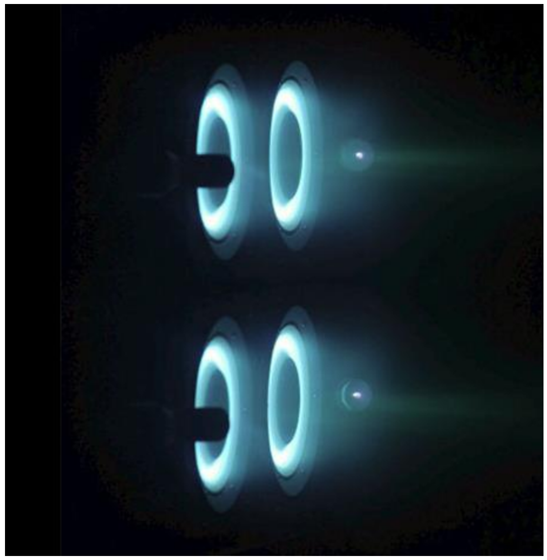


Figure 9: BHT-600

While there are many attractive features, challenges do however arise in this concept. Due to the fact that, unlike chemical propulsion systems, HET obtain their power externally and therefore the power distribution system becomes rather complex. The propellant feed system also requires extensive redesign due to the fact that the noble gas is now being distributed to multiple discharge channels.

D. Nested Channel Hall Effect Thrusters

Another concept of obtaining higher thrust in a HET is the “nested channel” Hall Effect Thruster. Instead of clustering multiple engines to produce more thrust, the clustered formation contains multiple concentric annular channels; in Figure 10 we can see a cut-out view of a two-channel nested thruster. Compared to a classic single-channel HET this system can produce more thrust and provide redundancy; like many current single-channel Hall Effect Thrusters, it is also throttleabe.

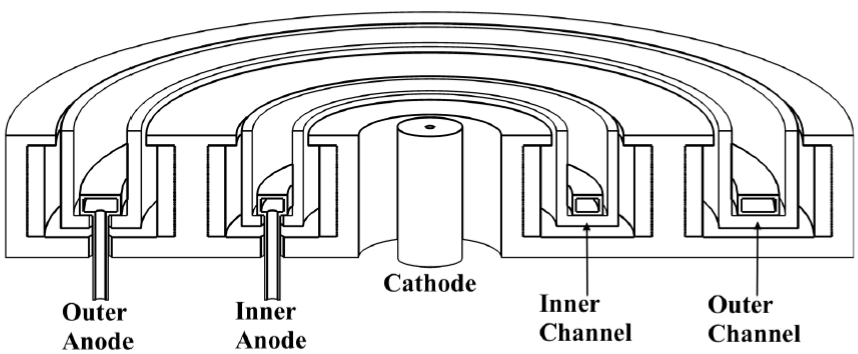
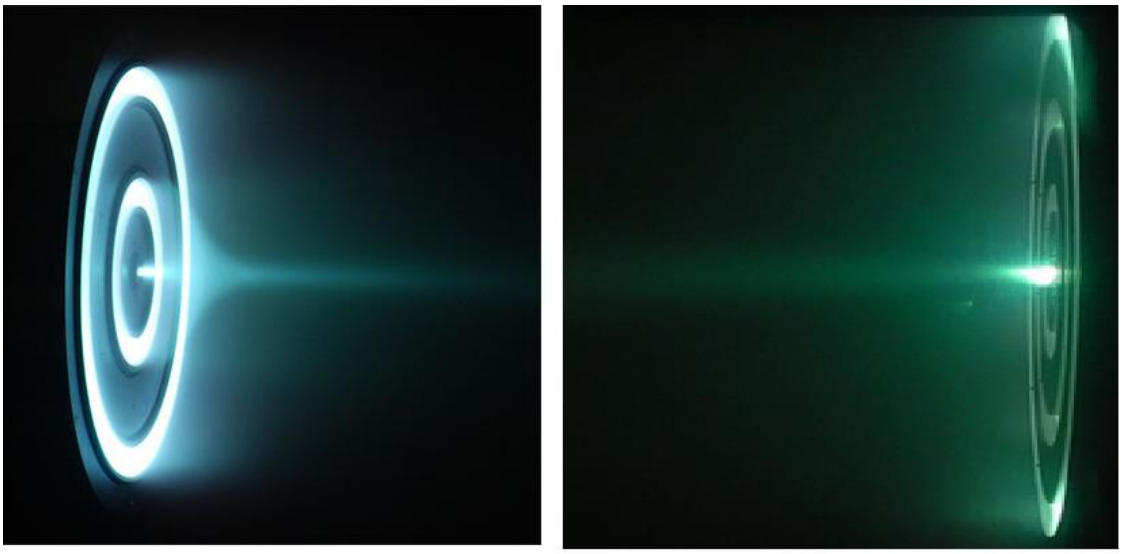


Figure 10: Diagram of a Nested Hall Effect Thruster

While the clustered system has these same attributes, the glaring advantage of the nested system over clustered HET design is the much lower mass required for construction. This is a very important aspect of mission design and for future missions which will require hundreds of kilowatts or more, the clustered formation of single-channel HETs will not be feasible considering the mass that will be required for even the most advanced flight ready Hall Effect Thrusters available to us today (BT-4000).

The University of Michigan currently has two versions of the nested channel Hall Effect Thruster, the X2 (two-channel) and the X3 (three-channel). Figure 10 contains a cross-sectional cutout of the X2 and Figure 11 provides a picture of the X3 in operation at 61kW. This thruster has the capability of producing 10’s of N of thrust compared to a single channel HET which can produce 100's of mN of thrust at the same power level. The X3 also has the advantage of having several permutations of operation i.e. it can operate with all three channels, three combinations of two channels, or three combinations of a single channel. Each separate permutation operates at a different power and I_{sp} range, also shown in Figure 12.



a. b.

Figure 11: Nested Hall Effect Thruster Test Fire

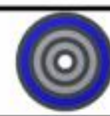
Maximum Exit Area (Low ISP—High T/P operation)	ISP Range (1400s-3200s) / Power Range	Medium Exit Area (Mid ISP operation)	ISP Range (2000s-3600s) / Power Range	Minimum Exit Area (High ISP Operation)	ISP Range (2000s-4600s) / Power Range
			20 kW–170 kW		10 kW-140 kW
	30 kW-240 kW		15 kW–120 kW		5 kW-90 kW
			10 kW-80kW		1 kW-50 kW

Figure 12: Nested Hall Effect Thruster – X3:
Combintations with I_{sp} ranges

E. Miniature Hall Effect Thruster

As we have seen in the previous sections, it is not easy to "scale" a Hall Effect Thruster in size. The last two efforts mentioned however (clustered and nested channel HET) require "scaling up" in terms of size and power. There are applications though that require scaling *down*. Colorado State University (CSU) has successfully developed the world's smallest Hall Effect Thruster in the world to successfully

1. Implement a center mounted hollow cathode
2. Employ magnetic shielding.
3. Utilize 3-D printed components

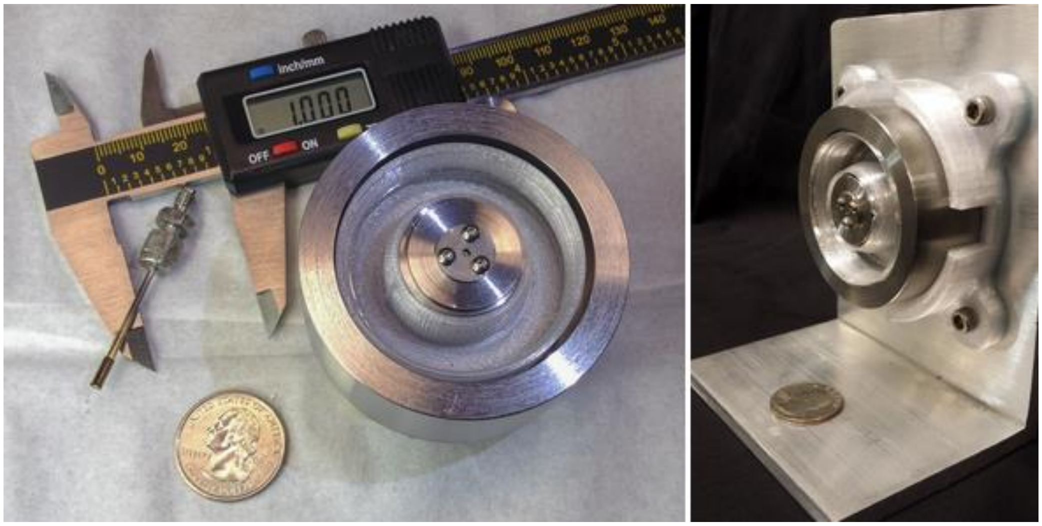


Figure 13: Miniature Hall Effect Thruster Size Comparison

The CSU Miniature Hall Effect Thruster has the ability to be continuously throttleable which implies that it has a wide operating power range; this model currently has a range of 20-400W. The lifetime of this thruster also has a wide range of operation time; it can operate for periods on the order of seconds or for as long as thousands of hours. While electrospray thrusters/micro-thrusters are commonly regarded as a great prospect for cubesat propulsion, the miniature Hall Effect Thruster is a competing candidate for such endeavors.

VI. Conclusion

While both the Hall Effect thruster and the VASIMR engine have considerable advantages when it comes to efficient spacecraft propulsion, both are not without issues to overcome. Assuming an operating power of 200 kW for either thruster, a total of 950 m^2 of solar panels would be required to generate enough power for the thrusters alone disregarding onboard systems for the spacecraft. While not completely infeasible, this large surface area required means that a nuclear reactor may be a more efficient means of power generation. However, the TRL of nuclear power for spacecraft applications which require such high power budget is very low and development of the technology has been limited. Additionally in the case of the VASIMR, there still remains a relatively high specific mass for the system primarily due to the electromagnets and power source. This required mass per unit power is prohibitive for smaller spacecraft and for larger spacecraft means a massive engine. While AdAstra has developed a plan for addressing specific mass in the TC-1m, the engine remains in it's preliminary design phase. The VASIMR also generates a substantial magnetic field which can have an adverse effect on spacecraft components. This magnetic field can be drastically reduced by operating a system of two engines with inversely polarized magnets. However this benefit comes at a significant weight cost. In the case of the Hall Effect thruster, development of higher power thrusters represents significant design challenges. In order to meet these challenges, hall thruster systems such as the nested hall effect thruster and the clustered hall effect thruster are in development, however these are not flight ready as of yet.

Despite the significant design challenges ahead of both the Hall Effect Thruster and the VASIMR, both systems represent significant potential for advancement of long duration space missions. Certain missions such as Dawn, the first spacecraft to orbit two extraterrestrial bodies, are not possible without electric propulsion. While Dawn uses a series of ion thrusters to accomplish its msission, the need for flight-ready versions of both the VASIMR and HET is evident because missions will only become more challenging with this renewal of solar system exploration.

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