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Magnetic Nozzle Plasma Plume: Review of Crucial Physical Phenomena

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This paper presents a review of the current understanding of magnetic nozzle physics. The crucial steps necessary for thrust generation in magnetic nozzles are energy conversion, plasma detachment, and momentum transfer. The currently considered mechanisms by which to extract kinetic energy from the plasma include the conservation of the magnetic moment adiabatic invariant, electric field forces, thermal energy directionalization, and Joule heating. Plasma detachment mechanisms discussed include resistive diffusion, recombination, magnetic reconnection, loss of adiabaticity, inertial forces, and self-field detachment. Momentum transfer from the plasma to the spacecraft occurs due to the interaction between the applied field currents and induced currents which are formed due to the magnetic pressure. These three physical phenomena are crucial to thrust generation and must be understood to optimize magnetic nozzle design. The operating dimensionless parameter ranges of six prominent experiments are considered and the corresponding mechanisms are discussed.

Nomenclature

ρ	Density	n	Number Density
T	Temperature	p	Pressure
v, U	Velocity	m	Mass
e	Energy	J	Current Density
B	Magnetic field	E	Electric Field
r	Plume Radius	L	Characteristic Length
ω	Frequency	τ_{col}	Collision Time
q	Charge of Electron	ν	Collision Frequency
Subscript			
$\perp$	Perpendicular to Magnetic Field	$\parallel$	Parallel to Magnetic Field
0	Initial	i	Ion
e	Electron	H	Hydrodynamic (Flow+Internal)

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p	Plasma	f	Flow Characteristic
c	Cyclotron	k	Kinetic

I. Introduction

Electric propulsion can produce thrust by electrically heating propellant, electrostatically accelerating charged particles, or manipulating the flow of charged particles with electromagnetic fields. Recent developments in this discipline have come to incorporate magnetic nozzles for the purpose of plasma flow control. Electric propulsion systems utilizing magnetic nozzles are classified as electromagnetic propulsion methods and include magnetoplasmadynamic thrusters (MPD's), helicon thrusters,[1,2] and the VAriable Specific Impulse Magnetoplasma Rocket (VASIMR).[3,4] These advanced propulsion methods are necessary to meet requirements of future space missions and are designed to produce high specific impulse and greater thrust than current electric propulsion systems. The desired operational regime of electromagnetic propulsion systems is seen in Figure 1. Magnetic nozzles are set to be an intricate part of these future propulsion methods and the crucial physics must be understood for optimal design.

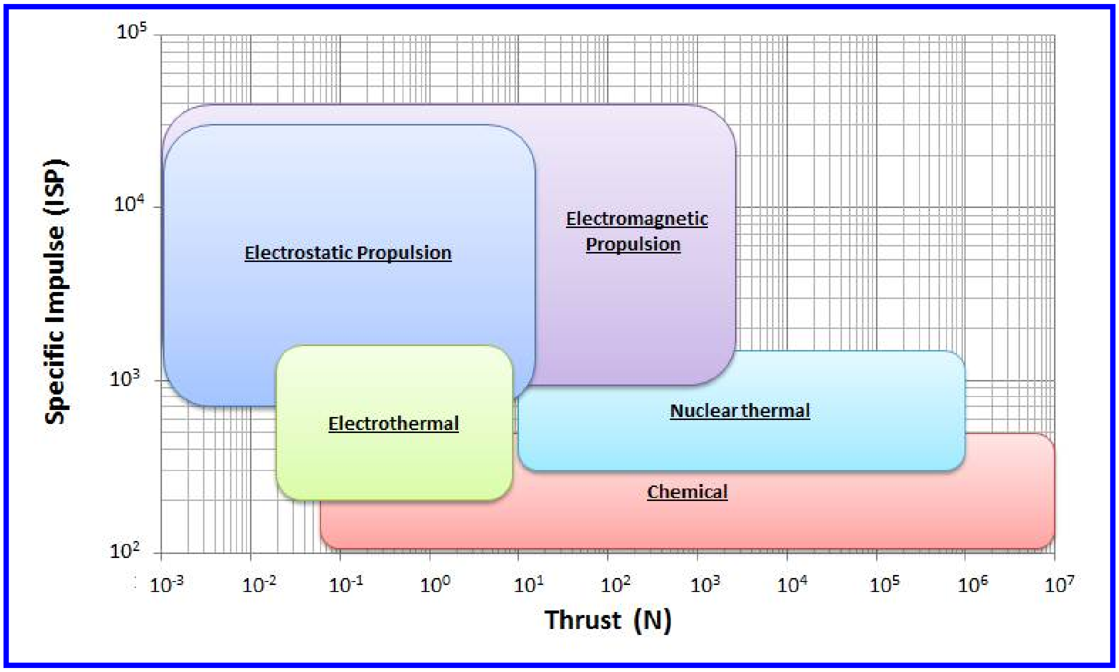

Figure 1. Specific impulse and thrust comparison for space propulsion methods

Magnetic nozzles are functionally similar to De Laval nozzles. They achieve thrust by converting thermal energy or non-directional kinetic energy to directed kinetic energy. The comparison between De Laval nozzles and magnetic nozzles is shown in Figure 2. The virtue of magnetic nozzles lies in minimizing contact between the high temperature plasma and surfaces while also providing additional mechanisms for thrust generation by plasma-field interaction. The ability to vary the magnetic field topology also gives magnetic nozzles versatility which is not possible in De Laval nozzles.

The physics of magnetic nozzle plasma flow is inherently complex, the magnetic fields must confine plasma to the correct configuration to produce kinetic energy while also ensuring efficient detachment from the closed applied magnetic field lines which tend to pull the plasma back to the spacecraft. Three key steps are required to produce thrust in magnetic nozzles:

1. Conversion of magnetoplasma energy to directed kinetic energy
2. Efficient plasma detachment
3. Momentum transfer from plasma to spacecraft

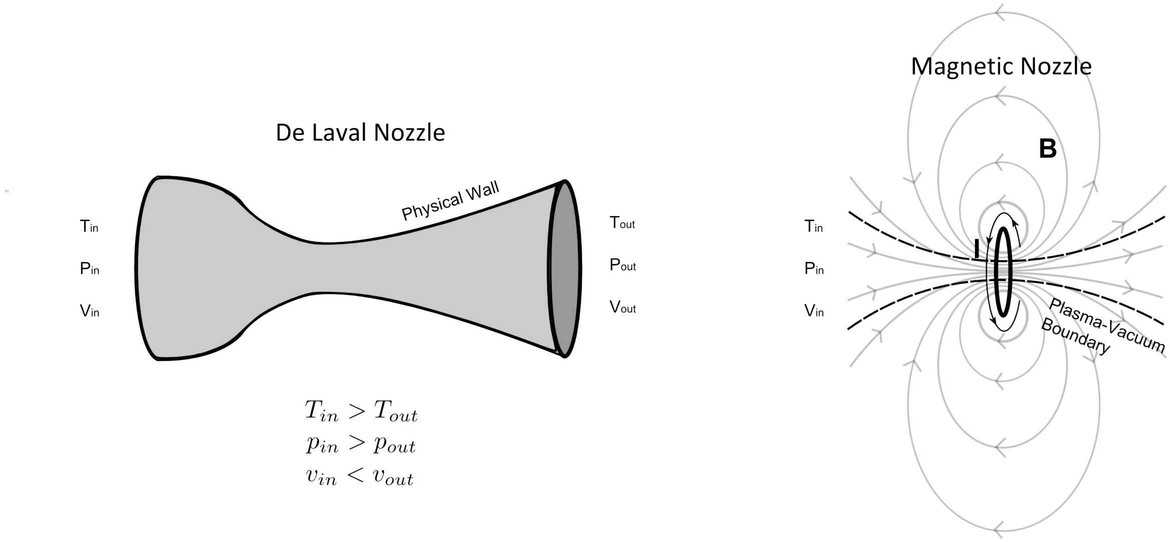

Figure 2. De Laval nozzle compared to magnetic nozzle

These steps impose conflicting requirements of confinement and detachment which present the primary challenge in magnetic nozzle design. The physics of these key processes are intimately coupled and must be understood to optimize magnetic nozzle design.

This paper presents a literature survey of the crucial physics of plasma flow in magnetic nozzles. Findings and advances on this topic will be consolidated, summarized, and analyzed to define the current status of magnetic nozzle theory while outlining areas in which additional work is required. The regimes in which the discussed magnetic nozzle physics are relevant will also be defined.

Section II, III, and IV of this paper discuss energy transfer, detachment, and momentum transfer respectively. Section V discusses operational regimes and Section VI concludes the paper.

II. Energy Transfer Physics

An outline of magnetic nozzle energy exchange mechanisms and the respective modes between which energy is transfered is shown below.

1. Conservation of magnetic moment adiabatic invariant: $v_\perp \rightarrow v_\parallel$
2. Electric field acceleration: $e_{electron} \rightarrow e_{ion}$
3. Directionalizing of thermal energy: $e_{thermal} \rightarrow e_{kinetic}$
4. Joule heating: $e_{field} \rightleftharpoons e_H$

The plasmadynamics of magnetic nozzles is a complex interplay of fluid dynamics and electromagnetism and although these mechanisms are considered separately in the following sections they are coupled. The separation of mechanisms is done in an attempt to provide physical insight on this complex system.

1. Conservation of adiabatic invariant

The magnetic moment of a particle, $\mu_m = \frac{mv_\perp^2}{2B}$, is an adiabatic constant of motion if $\Delta B << B$ over a single period of cyclotron motion. The conditions for adiabaticity may be represented by the relations shown in Equation 1. The most often used condition describes the ratio of the Larmor radius, $r_L = mv_\perp/(qB)$, to the characteristic length scale of the magnetic field change defined $1/|\frac{\nabla B}{B}|$.

$$\dot{B} \ll B\omega_c \qquad or \qquad \nabla_\parallel B \ll B\frac{v_\parallel}{\omega_c} \qquad or \qquad r_L \left|\frac{\nabla B}{B}\right| \ll 1 \tag{1}$$

To further describe the adiabatic energy exchange a simplified energy equation for an isentropic, collisionless, and equipotential plasma is assumed.

$$K_{total} = K_{\perp} + K_{\parallel} = \frac{mv_{\perp}^2}{2} + \frac{mv_{\parallel}^2}{2} = constant \tag{2}$$

It is evident from these conservation equations that a decrease in magnetic field strength results in an increase of velocity parallel to the magnetic field. This behavior is similar to the familiar physics of magnetic mirrors. Combining these equations results in the following relationship for the velocity parallel to the magnetic field.

$$v_{\parallel} = \sqrt{v_{total}^2 - 2\mu_m B/m} \tag{3}$$

Additional insight can be gained by assuming a flow which is initially dominated by perpendicular velocity that gradually flows into a region with a very small magnetic field, $B \approx 0$. The downstream velocity for this flow is shown below and represents the complete conversion of energy associated with the magnetic moment to parallel kinetic energy.

$$v_{\parallel,max} = \sqrt{2\mu_m B_0/m} \tag{4}$$

The above description is a simplified representation of complex physics which is presented by Nagatomo,[5] Kosmahl,[6] and Sercel.[7] The exchange of energy is driven by a force $F_{\mu} = -(\mu_m \hat{\mathbf{B}} \cdot \nabla)\mathbf{B}$ which may be simplified in the magnetic field direction to be $m\dot{v_{\parallel}} = -\mu_m \nabla_{\parallel} B$.

The VASIMR propulsion system proposes energy generation primarily by this mechanism and has shown promising results.[3,4,8–10] Theoretical, computational, and experimental efforts have studied and demonstrated the thrust production capabilities of this mechanism.[5–7,9,10] It should also be noted that a study of single particle motion with Lagrangian mechanics leads to a more general conserved adiabatic variable.[11]

2. *Electric Field Acceleration*

Electric field acceleration may be driven by the formation of ambipolar fields[12] or double layers.[1,13] These mechanisms are a result of the high mobility of electrons compared to ions. This increased mobility is characterized by the thermal velocity, $v_{th} = \sqrt{k_B T/m}$. In expanding magnetic nozzles the mobile electrons establish an electron pressure gradient ahead of the slow ions. To maintain quasineutrality an electric field is established which accelerates ions and slows down electrons. This results in an exchange of energy between the electron thermal velocity and the ion flow velocity.

Although both ambipolar acceleration and double layer acceleration are driven by similar physics they are distinctly different. Double layers are characterized by a potential difference over a few Debye lengths while the potential difference for ambipolar effects may be on the order of the system's dimensions. Ambipolar acceleration has been studied computationally[14] and has shown encouraging results in experiments.[12,15] Acceleration due to double layers has also been shown experimentally.[1,13] It is important to note also that fast electron diffusion may cause plume divergence leading to thrust losses.

3. *Directionalizing thermal energy*

Kinetic energy may be gained by directionalizing thermal energy. De Laval nozzles direct thermal motion into the axial direction through a converging-diverging physical wall. Magnetic nozzles do so by confining the plasma to a desired geometry with a strong guiding field. The physics of energy conversion is based on hydrodynamics while the geometry of the magnetic nozzle is determined by plasma-field interaction. This implies that relationships based on hydrodynamics similar to those in de Laval nozzle analysis can be used to analyze this energy conversion if negligible losses occur in establishing the magnetic wall.

The most basic condition for confinement in relation to thermal forces is characterized by the ratio of the fluid pressure to the magnetic pressure shown in Equation 5.

$$\beta_p = \frac{nk_B T}{B^2/2\mu_0} < 1 \tag{5}$$

If this relation is satisfied the magnetic pressure is stronger than the thermal pressure and confinement is possible but not guaranteed. Confinement of the plasma may also require the formation of a current layer at the plasma-vacuum boundary.[16,17] Diffusive and convective processes may degrade the current layer and must be understood to characterize the losses due to non-ideal confinement.

The physics of converting thermal energy to kinetic energy through the use of a magnetic nozzle has been demonstrated experimentally and computationally.[5,15,16,18,19] Kuriki[15] performed experiments and showed results which matched more closely with isentropic expansion models than with a magnetic moment conservation model. Kuriki[15] also presents a magnetic nozzle Bernoulli's equation comprised of the ion and electron energy equations coupled by an electric potential. Although this gives physical insight, it does not provide a complete description of the various energy exchange mechanisms prevalent in magnetic nozzles. It should be clarified that for the discussed hydrodynamic energy conversion ion thermal energy will primarily be converted to ion axial kinetic energy.

4. Joule Heating

Energy exchange can also occur between the electromagnetic field and the hydrodynamic field. This exchange is best demonstrated by the MHD energy equation shown below:

$$\frac{\partial e_H}{\partial t} + \nabla \cdot \left[\mathbf{U}(e_H + p) - k\nabla T + \mathbf{U} \cdot \underline{\tau} \right] = \mathbf{J} \cdot \mathbf{E} \tag{6}$$

The term on the right of Equation 6 represents the Joule heating and characterizes the energy gained by the fluid due to the energy lost by the electromagnetic field. This same term appears with an opposite sign in the energy equation for the electromagnetic field.

$$\frac{1}{2}\frac{\partial}{\partial t}\left(\epsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0}\mathbf{B}^2 \right) + \nabla \cdot \left[\frac{1}{\mu_0}\mathbf{E} \times \mathbf{B} \right] = -\mathbf{J} \cdot \mathbf{E} \tag{7}$$

The gain(loss) of energy by the fluid should be maximized(minimized). This relationship is complex and is coupled with the already mentioned methods, it is mentioned here primarily to illustrate the energy exchanges that may occur between electromagnetic and fluid fields.

III. Plasma Detachment

For magnetic nozzles to produce thrust the directed kinetic energy must detach from the applied field. Plasma detachment mechanisms have become central to magnetic nozzle design in an effort to minimize losses due to electromagnetic drag forces and divergence of the plasma plume. Plasma detachment methods can be divided into three categories: collisional, collisionless, and magnetic reconnection detachment.

A. Collisional detachment

Collisional detachment may be achieved through resistive diffusion across magnetic field lines[20–22] and recombination of the ions and electrons.[23,24]

1. Resistive diffusion

Resistive diffusion has been suggested as a means to achieve detachment and is governed by the cross field diffusion of plasma.[20] Resistive detachment exhibits conflicting requirements of initial confinement necessary for the correct nozzle geometry and eventual cross field diffusion to ensure detachment. The resistive drag must also be minimized. Moses[20] defines conditions to ensure this duality is satisfied for resistive detachment in an adiabatically cooling plasma plume. It is suggested that a gradually diverging magnetic field is preferred to ensure resistive detachment.

The magnetic Reynolds number, $Re_m = UL/\eta$ is used to quantify the confinement of a plasma in a magnetic nozzle. For high values, $Re_m > 1000$, the resistive diffusion is negligible compared to convective effects and confinement is achieved. For intermediate values, $1 < Re_m < 1000$, diffusion is important and the plasma may move across magnetic field lines. High values of Re_m are required for confinement while intermediate to low numbers are required for detachment.[22,25] It is important to note that although the magnetic Reynolds number provides insight on the diffusive behavior, quantitative comparisons should be done with caution due to the ambiguity of the scale length choice. Magnetic Reynolds numbers are best used for qualitative comparison and can only be used for quantitative comparison in systems which are physically and geometrically similar.

Predicting the extent at which plasma diffuses across a magnetic barrier has been studied and suggests that plasma may exhibit anomalous resistivity several orders of magnitude greater than predicted by classical plasma theory and Bohm diffusion.[26] The presence of anomalous resistivity should thus be considered for computational studies. As a means to achieve detachment resistive diffusion has been largely considered as ineffective due to the adverse affects it would have on thrust production and likely divergent detachment that would occur.[27] Resistive effects however can not be ignored as they may still be important experimentally. Far-field detachment due to resistive effects may also be attractive particularly near the nozzle centerline where the travel time for particle confinement may be large compared to the collision time.

2. Recombination

Recombination achieves detachment by the formation of neutral particles which are no longer affected by the magnetic fields. Creation of neutrals is driven primarily by three body recombination in which two like charged particles and one unlike particle interact with one another forming a neutral and an energized particle. Recombination requires a sufficiently high electron-ion collision frequency, ν_{ei}, to be considered an effective means of detachment. Although initial analysis of recombination as a means for detachment are not encouraging, recombination rates can be increased by sharply decreasing magnetic field configurations or rapid cooling of electrons in the expanding nozzle.[23,24]

B. Collisionless Detachment

Collisionless detachment has been the focus of most research due to the anticipated convergent detachment. The primary means for achieving collisionless detachment are due to loss of adiabaticity, electron inertial effects,[8,27–32] and induced magnetic field effects.[2,27,31–39]

1. Loss of adiabaticity

Detachment due to the loss of adiabaticity occurs when the conditions of Equation 1 are violated and the plasma effectively becomes demagnetized. The third condition relating the Larmor radius of the particle to the characteristic length of magnetic field changes is the most often used of these to quantify detachment. Demagnetization implies that particles are no longer forced to have orbits which are bound to single field lines. This behavior can best be visualized by imagining a particle which starts an orbit around one field line but then during this orbit encounters a drastically different magnetic field which alters the previous orbit.

Loss of adiabaticity is specific to each species with ions more likely to become demagnetized than electrons due to their significantly larger Larmor radii. Theory predicts that the loss of adiabaticity of ions alone does not ensure detachment due to the formation of electric fields between the bound electrons and the detached streaming ions.[27–29,31,32,40] Detachment in this particular complex scenario is referred to as inertial detachment and will be discussed in the following section. Loss of adiabaticity describes a scenario for detachment of individual plasma species,[41] but only guarantees detachment for the plasma as whole when both species are demagnetized.[27,31,32,40] Detachment due to the loss of adiabaticity can also be studied through the more complex Lagrangian invariant which defines distinct regions in which charged particles may be found.[11]

2. Inertial Detachment

As introduced in the previous section inertial detachment concerns the scenario when a only a single species becomes demagnetized and an electric field is established to maintain quasineutrality. Detachment of the plasma may still be achieved by the system of particles having enough inertia to overcome the confining magnetic field forces. A hybrid Larmor radius based on a hybrid particle mass, $m_H = \sqrt{m_e M_I}$, is introduced to better examine this behavior. Detachment in this scenario can be imagined as the drift of a hybrid electron-ion particles. The ratio of the magnetic inertia to the flow inertia is characterized by the non-dimensional parameter shown in Equation 8.[28,29,31]

$$G \approx \frac{eB_z}{m_e}\frac{eB_z}{M_i}\frac{r_0^2}{u_0^2} \tag{8}$$

Significant theoretical and computational study has been done to characterize the effectiveness of inertial detachment with some suggesting demagnetization based on the hybrid Larmor radius as an effective means for detachment[28–30,39] and others suggesting only demagnetization of electrons effectively achieves detachment.[27,31,32,40]

The condition for the detachment of the hybrid Larmor radius particle has been shown in a study by Little to be $G^{-1/2}|\frac{\nabla B}{B}| = .5$.[39] It has also been shown that imposing an initial azimuthal velocity will significantly increase detachment efficiency and decrease nozzle divergence.[30] The analysis by Hooper[28] has been criticized by Ahedo[32] due to the simplifying assumptions made, particularly that of ambipolarity.

Contrary to some theoretical and computational results, recent experiments have shown that detachment may occur even with only ion demagnetization.[42] Numerical simulations related to VASIMR have also shown detachment occurring due to ion demagnetization.[8] Detachment by inertial means is often referred to as the "lower limit" of detachment which can be enhanced by other detachment mechanisms.

3. *Induced field detachment*

Detachment through the use of induced magnetic fields is possible by either stretching the magnetic field lines to infinity or by canceling out the applied fields and thereby demagnetizing the plasma. Induced field detachment effectiveness can be studied by the currents which create these fields.

Magnetic field stretching occurs when the plasma kinetic energy exceeds the magnetic energy or equivalently when the plasma fluid velocity exceeds the Alfvén velocity. This is characterized by the non-dimensional parameter shown in Equation 9.

$$\beta_f = \frac{\rho u^2/2}{(B^2/2\mu_0)} > 1 \tag{9}$$

When this condition is satisfied the fluid is considered to be super-Alfvénic and is traveling faster than the rate at which changes in the magnetic field affect the flow. As a result of this behavior, magnetic field lines get dragged to infinity preserving frozen-in flow.[33,34] The currents required to produce super-Alfvénic detachment are paramagnetic which results in convergent detachment but produce thrust losses due to attractive forces between the applied field and induced field currents.[27,33,34] Studies have shown that sub- to super-Alfvénic transition can minimize detachment losses with a slowly diverging magnetic field. An experimental study has suggested detachment behavior due to $B_f > 1$ rather than ion demagnetization and shows agreement with computational results.[34,36,38] Field line stretching however could not be measured. Other experimental and computational results have also demonstrated super-Alfvénic detachment and have identified a mechanism for self-collimation of the plasma plume.[2]

The cancellation of the applied field by the induced field is referred to as self-demagnetization and occurs due to the formation of diamagnetic currents in the plasma. These currents create an axial accelerating force.[40] The diamagnetic currents that drive this detachment are favorable for momentum transfer to the spacecraft, but create a divergent plume. The configuration of magnetic field lines to achieve this form of detachment are similar to those that would be seen in magnetic reconnection detachment. Self-demagnetization detachment has been demonstrated computationally.[27,40]

C. Magnetic Reconnection

Magnetic reconnection is a widely studied problem in plasma physics but has not been sufficiently studied when relating to plasma propulsion detachment scenarios. Phenomenon exhibiting magnetic reconnection physics relevant to plasma detachment are evident in coronal mass ejections and magnetic confinement fusion experiments.[43]

The most elementary description of magnetic reconnection is shown in Figure 3. An initial configuration of two magnetic field lines, (1), has a finite diffusion across the magnetic field lines, (2), which eventually leads the magnetic field lines to tear and reconnect into a new configuration (3) of lower energy.[44] The reconfiguration of the magnetic field lines allows plasma flows which under the previous configuration were not possible. This characteristic of magnetic reconnection is particularly attractive for magnetic nozzle detachment because it allows magnetic islands to form which separate from the applied field.

An example of possible reconnection field configurations in magnetic nozzles is shown in Figure 4. The initial field is that of a a dipole or solenoid magnetic field. The magnetic reconnection configuration depends on the strength and direction of the induced field which results from induced currents that can be

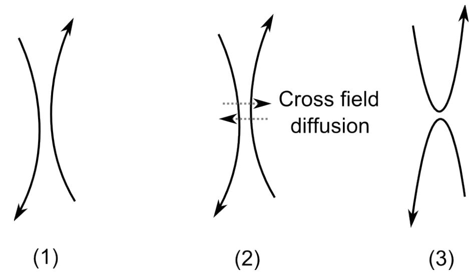

Figure 3. Magnetic field line reconnection

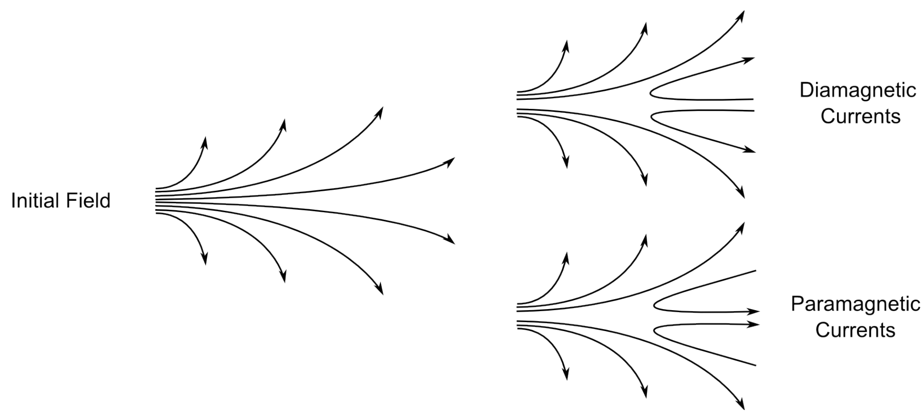

Figure 4. Possible magnetic field line reconnection configurations in magnetic nozzles

diamagnetic or paramagnetic. The diamagnetic current configuration is particularly intriguing because the interaction between the applied field currents and the induced field currents would result in a repulsive force which produces thrust. Magnetic reconnection is an inherently transient phenomenon which requires time-dependent numerical methods to study.

IV. Momentum Transfer

The momentum change as a result of energy conversion and plasma detachment must be transferred back to the spacecraft. The mechanisms for momentum transfer in the absence of a physical wall are governed by the Lorentz force. Looking specifically at the $J \times B$ terms and assuming non-relativistic flows defines two momentum transfer mechanisms by the magnetic pressure and magnetic field convection.

$$\mathbf{J} \times \mathbf{B} = -\nabla \frac{\mathbf{B}^2}{2\mu_0} + \frac{1}{\mu_0}(\mathbf{B} \cdot \nabla)\mathbf{B} \tag{10}$$

As discussed previously the magnetic pressure can confine the plasma and results in the formation of a current layer at the plasma vacuum edge. It has been shown that the forces between the currents induced in the plasma plume and currents which create the magnetic nozzle are the primary mechanisms by which momentum is transfered between the spacecraft and the plasma.[27,31,32,37,39] Induced currents are created throughout the plume due to the motion of the plasma and are primarily azimuthal due to the axisymmetry of the nozzle. The resulting currents can be either diamagnetic, opposing the applied field, or paramagnetic, increasing the applied field. Diamagnetic currents create a repulsive force which is desirable for thrust while paramagnetic currents create an attractive force resulting in drag on the plasma. Diamagnetic currents are desirable for producing thrust while paramagnetic currents can produce convergent flow by creating convergent field lines.

Paramagnetric and diamagnetic currents may exist simultaneously in a plasma due to diamagnetic surface currents and paramagnetic volumetric currents.[27,31,39] To produce thrust under these conditions the force per unit length due to the diamagnetic surface currents must exceed that of the paramagnetic volumetric currents. This relationship has been showed computationally and suggests that thrust generation may occur even in the presence of paramagnetic currents.[39]

To provide insight on this process we quote Little et al., ”surface currents are induced that effectively act as a magnetic wall that confines the expanding plasma and transmits momentum from the plasma to the applied field coil through their mutual interaction.”[39] Thus the notion of the confining magnetic pressure and the induced currents are intimately connected and provide the means for momentum transfer between the spacecraft and the plasma.

V. Operating Regimes of Magnetic Nozzles

Numerous physical mechanisms in the thrust generation process have been presented based on a review of magnetic nozzle physics literature. A summary of parameters which characterize some of these physical processes are shown in Table 1.

Physical Mechanism	**Parameter**
Adiabaticity	$r_L\|\nabla B\|/\|B\|$
Recombination	ν_{ei}
Confinement by Magnetic Pressure	$\beta_p = \frac{nk_BT}{B^2/2\mu_0}$
Resistive Detachment	$Re_m = UL/\eta$
Inertial Detachment	$\xi = G^{-1/2}\|\frac{\nabla B}{B}\|$
Super-Alfvénic Detachment	$\beta_k = \rho u^2/(B^2/\mu_0)$

Table 1. Characteristic parameters of physical mechanisms

We have also compiled Table 2 in the Appendix as a reference to experiments which have studied magnetic nozzle physics. Table 2 is by no means an exhausted list, but outlines the general parameter regimes in which some typical magnetic nozzle experiments operate. The numbers shown are calculated using equations from the NRL formulary[45] and are based on a single point in the flow. As such, the values throughout the nozzle may easily vary by an order of magnitude. The table is included to give a general idea of the regimes and how they vary between magnetic nozzle propulsion devices and brief comments about each are given in the following subsections.

A. Variable Specific Impulse Magnetoplasma Rocket

The VASIMR experiment heats ions by Ion Cyclotron Resonance Heating (ICRH) which then enter a magnetic nozzle configuration. Energy conversion by the conservation of the adiabatic invariant and ambipolar acceleration has been shown.[3,4,9,12] Detachment has been demonstrated and the responsible mechanism is currently being determined.[9] Efficiency and thrust of the device have been determined and show encouraging results.[10]

B. High Power Helicon

The High Power Helicon (HPH) is an experiment performed by Winglee et al.[2] in which a plasma produced by a helicon source flows through a magnetic nozzle. This experiment showed both collimation of the plasma plume by a magnetic nozzle and self-collimation due to super-Alfvénic flow. The acceleration of the plasma in the nozzle is attributed to directionalizing of thermal energy.

C. Detachment Demonstration Experiment

The Detachment Demonstration EXperiment (DDEX) studies plasma produced by a pulsed plasma washer gun under the influence of a magnetic nozzle.[35,36,38] Detachment is demonstrated, suggesting super-Alfvénic detachment as the driving mechanism. Super-Alfvénic flow, $\beta_f > 1$, is shown at the detachment location, but field line stretching is not measured.

D. Helicon Double Layer Thruster

The Helicon Double Layer Thruster (HDLT) produces plasma by a helicon source which expands into a magnetic nozzle configuration.[1] Energy is transfered to the ions by the formation of a current-free double layer. Detachment is predicted due to ion demagnetization.

E. Kuriki Arc Heater

The Kuriki Arc Heater (KAH) experiment studies the flow of an arc heated plasma in a converging-diverging magnetic nozzle.[15] The plasma is shown to be significantly accelerated by both electric field forces and thermal energy directionalization. An energy equation is suggested that couples ion and electron energies through the electric potential. Detachment is not significantly addressed.

F. Magnetoplasmadynamic Arcjet

The MagnetoPlasmaDynamic Arcjet (MPDA) experiment studies the flow MPD exhaust under the influence of a magnetic nozzle.[18,19] Results suggest energy conversion governed by isentropic expansion processes and not conservation of the magnetic moment. Plasma flow velocity and Mach number increase downstream as the ion temperature decreases.

VI. Conclusion

Theoretical and computational work have defined physical mechanisms that can be used to accelerate and detach plasma in magnetic nozzles. Experiments have confirmed acceleration and detachment, but questions still remain as to which of the proposed mechanisms are responsible for this behavior. To proceed further experiments must determine which of the presented mechanisms are dominant in regimes relevant to plasma propulsion. Establishing which physical mechanisms are dominant will allow theory to predict the behavior of plasma within this regime. If the predicted behavior is then confirmed by additional experiments the physics of magnetic nozzles will be sufficiently understood for design optimization. The convergence of experimental and theoretical results is crucial to the understanding of magnetic nozzles.

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Appendix

	Experiments					
	VASIMR[46]	**HPH**[2]	**DDEX**[38]	**HDLT**[1]	**KAH**[15]	**MPDA**[18]
Inputs						
Number Density ($\#/cm^3$)	1.00E+13	2.00E+13	1.00E+13	1.00E+11	6.00E+13	1.00E+14
Density (kg/m^3)	6.63E-07	5.31E-07	6.64E-08	6.64E-09	3.98E-06	6.64E-07
T_i (eV)	5.00E+01	6.58E+00	4.00E+00	2.00E-01	1.00E-01	1.50E+01
T_e (eV)	6.00E+00	6.58E+00	4.00E+00	5.50E+00	5.00E-01	9.90E+00
Flow Velocity (m/s)	2.00E+04	6.40E+03	1.00E+04	8.70E+03	1.70E+03	3.00E+04
Characteristic Length (m)	1.00E+00	4.00E-01	5.00E-01	1.50E-02	4.00E-02	4.00E-02
B (Gauss)	5.50E+02	2.00E+02	7.00E+02	1.38E+02	1.00E+03	1.00E+03
Plasma Parameters						
Debye Length (m)	5.76E-06	4.26E-06	4.70E-06	5.51E-05	6.78E-07	2.34E-06
Particles in Debye Sphere (#)	1.91E+03	1.55E+03	1.04E+03	1.67E+04	1.87E+01	1.28E+03
Plasma Criteria	5.76E-06	1.07E-05	9.40E-06	3.67E-03	1.70E-05	5.84E-05
Velocities						
Ion Thermal (m/s)	1.10E+04	6.30E+03	9.83E+03	6.95E+02	4.92E+02	1.90E+04
Electron Thermal (m/s)	1.03E+06	1.07E+06	8.38E+05	9.83E+05	2.96E+05	1.32E+06
Alfvén (m/s)	6.02E+04	2.45E+04	2.42E+05	1.51E+05	4.47E+04	1.09E+05
Ion Sound (m/s)	4.92E+03	8.13E+03	1.27E+04	4.71E+03	1.42E+03	2.00E+04
Frequencies						
Ion Cyclotron ($1/s$)	1.32E+05	1.20E+05	1.68E+06	3.32E+04	2.41E+05	2.41E+06
Electron Cyclotron ($1/s$)	9.68E+09	3.52E+09	1.23E+10	2.43E+09	1.76E+10	1.76E+10
Ion Collision ($1/s$)	2.92E+03	1.45E+05	2.94E+05	6.46E+04	4.83E+07	4.40E+05
Electron Collision ($1/s$)	2.12E+07	3.63E+07	3.68E+07	2.91E+05	3.01E+09	9.50E+07
Times and Lengths						
Ion Collision Time (s)	3.43E-04	6.91E-06	3.41E-06	1.55E-05	2.08E-08	2.28E-06
Electron Collision Time (s)	4.72E-08	2.76E-08	2.72E-08	3.44E-06	3.32E-10	1.04E-08
Residence Time (s)	5.00E-05	6.25E-05	5.00E-05	1.72E-06	2.35E-05	1.33E-06
Ion Mean Free Path (m)	3.77E+00	4.35E-02	3.35E-02	1.08E-02	1.02E-05	4.34E-02
Electron Mean Free Path (m)	4.84E-02	2.97E-02	2.28E-02	3.38E+00	9.85E-05	1.37E-02
Ion Larmor Radius (m)	8.30E-02	5.24E-02	5.83E-03	2.09E-02	2.04E-03	7.91E-03
Electron Larmor Radius (m)	1.06E-04	3.05E-04	6.80E-05	4.05E-04	1.68E-05	7.49E-05
Ion Braginskii Hybrid (m)	5.60E-01	4.77E-02	1.40E-02	1.50E-02	1.44E-04	1.85E-02
Electron Braginskii Hybrid (m)	2.27E-03	3.01E-03	1.25E-03	3.70E-02	4.07E-05	1.01E-03
Non-Dimensional Numbers						
Reynolds Number	5.03E-01	9.74E+00	1.58E+01	1.81E+01	1.41E+04	1.52E+00
Magnetic Reynolds Number	6.54E+02	9.79E+01	9.43E+01	3.11E+00	9.40E-02	8.63E+01
Alfvén Mach	3.32E-01	2.62E-01	4.13E-02	5.76E-02	3.80E-02	2.74E-01
Mach	4.07E+00	7.87E-01	7.88E-01	1.85E+00	1.20E+00	1.50E+00
Velocity Beta	5.76E-01	5.11E-01	2.03E-01	2.40E-01	1.95E-01	5.24E-01
Pressure Beta	6.66E-02	1.33E-01	3.29E-03	4.23E-05	2.42E-04	6.05E-02
Hall and Collision Numbers						
Ion Hall Collision	4.53E+01	8.29E-01	5.73E+00	5.15E-01	4.99E-03	5.47E+00
Electron Hall Collision	4.56E+02	9.70E+01	3.35E+02	8.35E+03	5.84E+00	1.85E+02
Ion Cyclotron/Residence Frequency	6.62E+00	7.52E+00	8.42E+01	5.73E-02	5.67E+00	3.21E+00
Electron Cyclotron/Residence Frequency	4.84E+05	2.20E+05	6.16E+05	4.19E+03	4.14E+05	2.35E+04
Ion Residence/Collision Frequency	6.84E+00	1.10E-01	6.80E-02	8.99E+00	8.81E-04	1.71E+00
Electron Residence/Collision Frequency	9.42E-04	4.41E-04	5.44E-04	1.99E+00	1.41E-05	7.89E-03
Knudsen Numbers						
Ion Knudsen Number	3.77E+00	1.09E-01	6.70E-02	7.20E-01	2.55E-04	1.09E+00
Electron Knudsen Number	4.84E-02	7.41E-02	4.56E-02	2.25E+02	2.46E-03	3.42E-01
Ion Braginskii	5.60E-01	1.19E-01	2.80E-02	1.00E+00	3.61E-03	4.63E-01
Electron Braginskii	2.27E-03	7.52E-03	2.49E-03	2.47E+00	1.02E-03	2.53E-02
Ion Strong Field	8.30E-02	1.31E-01	1.17E-02	1.39E+00	5.10E-02	1.98E-01
Electron Strong Field	1.06E-04	7.63E-04	1.36E-04	2.70E-02	4.21E-04	1.87E-03
Transport Properties						
Dynamic Viscosity ($kg/(ms)$)	2.64E-02	1.40E-04	2.10E-05	4.77E-08	1.92E-08	5.26E-04
Dynamic Viscosity - Perp ($kg/(ms)$)	3.98E-06	6.31E-05	1.98E-07	5.59E-08	2.39E-04	5.45E-06
Kinematic Viscosity (m^2/s)	3.97E+04	2.63E+02	3.16E+02	7.20E+00	4.81E-03	7.92E+02
Electrical Conductivity (S/m)	2.60E+04	3.04E+04	1.50E+04	1.90E+04	1.10E+03	5.73E+04
Thermal Conductivity ($W/(mK)$)	1.36E+00	2.43E+01	3.06E-01	2.71E-03	2.91E+01	9.74E+00

Table 2. Magnetic nozzle experiments