2D plasma flow in Magnetic Nozzles for Propulsion and Processing applications

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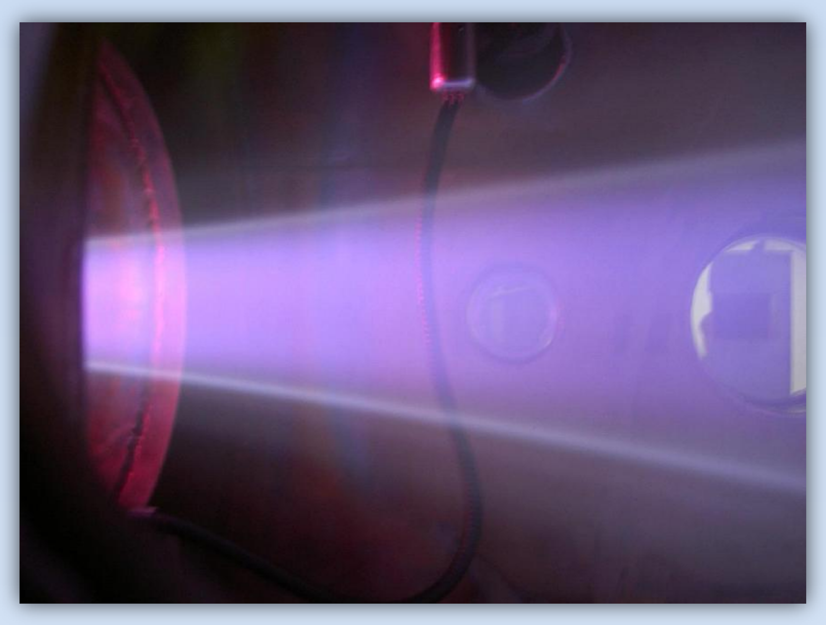
The ability to produce, direct and accelerate a plasma jet are critical aspects of many space propulsion and advanced manufacturing systems. Magnetic nozzles are excellent devices to accomplish all these functions, which avoid material contact with the plasma and provide adequate means to control thrust, beam velocity, and jet divergence.

What are Magnetic Nozzles?

A magnetic nozzle consists on a converging-diverging magnetic field that confines and guides a plasma jet. The plasma presents a sonic transition at the throat, and it accelerates and expands supersonically in the diverging part of the nozzle, in a similar manner to a neutral gas in a *de Laval* nozzle. Nonetheless, plasma dynamics in a magnetic nozzle are more complex than gas dynamics in a solid nozzle due to:

1. Plasma conditions upstream of the magnetic nozzle,
2. The variety of plasma acceleration mechanisms depending on the particular device,
3. Downstream detachment of the plasma from the guide magnetic field, required for space applications.



How do they work?

Under typical conditions, electrons are completely magnetized, meaning that they precisely describe the geometry of the magnetic field.

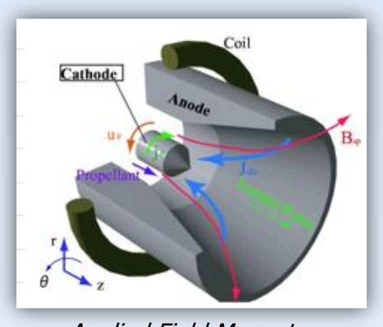
These electrons then pull from the heavier ions – which are only partially magnetized – to keep the plasma quasineutral. In this way, ions are forced to expand, and hence, to accelerate, converting thermal energy into directed kinetic energy. In general, there is also a small electromagnetic contribution to ion energy.

Where can they be used?

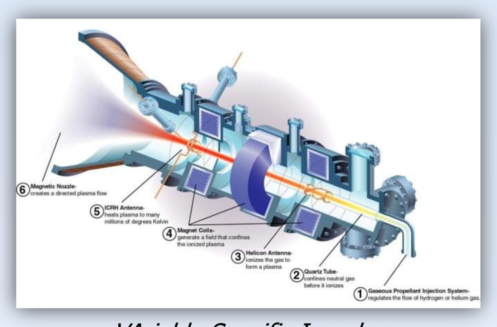
In **Electric Space Propulsion:** the Applied-Field MPD, Helicon, DCFT and VASIMR thrusters all use magnetic nozzles as their plasma acceleration device to obtain high specific impulses.

In **Advanced Processing and Manufacturing applications:** a magnetic nozzle can be used to provide and accelerate an energetically-homogeneous jet of plasma for different etching and surface treatment methods, as well as ion deposition techniques.

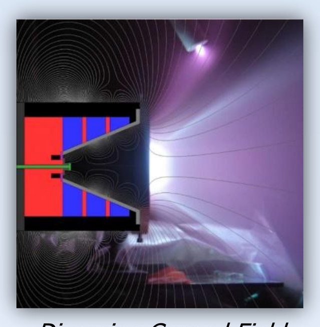
Other applications include dangerous waste processing.



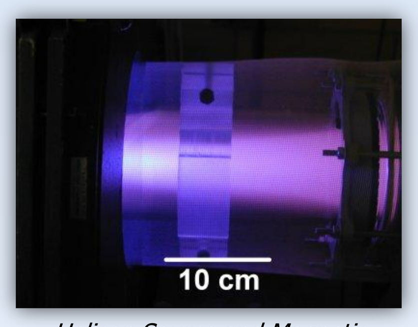
Applied Field Magneto-Plasma-Dynamic Thruster.



VAriable Specific Impulse Magnetoplasma Rocket (VASIMR).



Diverging Cusped Field Thruster

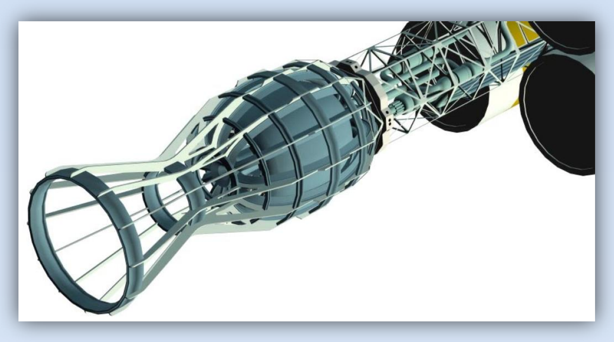


Helicon Source and Magnetic nozzle for Material Processing

What are their advantages?

Apart from saving weight associated with a material nozzle (field-generating coils being lighter), some of the main advantages are:

- Plasma-wall contact is avoided. Material interaction with the plasma causes severe heat-transfer problems, reduced efficiency and wall life,
- Thrust, Specific Impulse (exit velocity) and radial jet properties can be easily modified during operation – changing applied field geometry and strength.



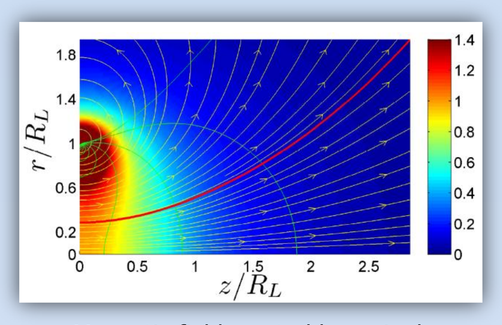
Objectives of this work:

By first establishing a 2D physical model of a collisionless, low-beta plasma flow in a diverging magnetic nozzle, and then by simulating it numerically, in this ongoing research we strive to study:

- The different accel. mechanisms and their relevance,
- 2D characteristics of the plasma jet,
- Influence of the nozzle divergence rate, the ion-magnetization strength, plasma properties at the nozzle throat, and electron thermodynamics,
- Formation and role of Hall and swirl currents,
- The presence of surface currents at the plasma/vacuum interface,
- The relevance of thermoelectric and electromagnetic energy contributions to the ion jet,
- The plume efficiency (divergence or radial losses) and propulsive performances for space applications,
- The no-fulfillment of current ambipolarity condition.

Mathematical Modeling

To model the axisymmetric, quasistationary, completely ionized (single-charged, cold ions and hot, isothermal or polytrophic electrons), current free plasma flow in the magnetic nozzle, we shall assume the following relations between orders of magnitude:



Magnetic field created by a single current loop. The outermost field line where plasma exists behaves as the virtual nozzle wall.

$\lambda_D \ll \ell_e \ll R_V \ll \lambda_{ie}$ →Plasma is quasineutral, →Plasma is collisionless, →e^- 100% magnetized.

$\Omega_i \ll R_V/c_s$ →Ions are partially magnetized.

$m_e/m_i \ll 1$ →Electron inertia is neglected

$\beta \ll 1$ →Electron pressure is much smaller than magnetic pressure: plasma induced field is neglected.

Ion and Electron Equations

$$\frac{\partial u_{zi}}{\partial z} + \frac{\partial u_{ri}}{\partial r} + \frac{e u_{zi}}{c_{si}^2 m_i}\frac{\partial \phi}{\partial z} + \frac{e u_{ri}}{c_{si}^2 m_i}\frac{\partial \phi}{\partial r} = = \frac{e u_{\theta e}}{\kappa_e T_e}\left(u_{ri}B_z - u_{zi}B_r\right) - \frac{u_{ri}}{r}$$

$$u_{zi}\frac{\partial u_{zi}}{\partial z} + u_{ri}\frac{\partial u_{zi}}{\partial r} + \frac{e}{m_i}\frac{\partial \phi}{\partial z} = -u_{\theta i}\frac{e}{m_i}B_r$$

$$u_{zi}\frac{\partial u_{ri}}{\partial z} + u_{ri}\frac{\partial u_{ri}}{\partial r} + \frac{e}{m_i}\frac{\partial \phi}{\partial r} = u_{\theta i}\frac{e}{m_i}B_z + \frac{u_{\theta i}^2}{r}$$

$$r m_i u_{\theta i} + e\psi = D_i\left(\psi_i\right)$$

$$p_e = n_e T_e \qquad h_e - e\phi = H_e(\psi) \qquad \frac{n_e \tilde{u}_e}{B} = G_e(\psi)$$

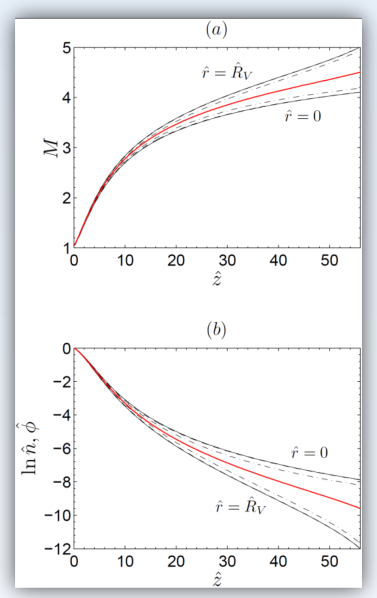
$$h_e = f(n_e) \qquad u_{\theta e} = -\frac{1}{eB}\frac{\partial H_e(\psi)}{\partial \mathbf{1}_\perp}$$

Axial and Radial Expansion

A 2D analysis reveals the development of radial non-uniformities and focalization around the axis, for all simulated cases. 1D-model (red lines) matches well radially averaged values.

Φ falls downstream and outwards, accelerating and expanding the plasma axially and radially.

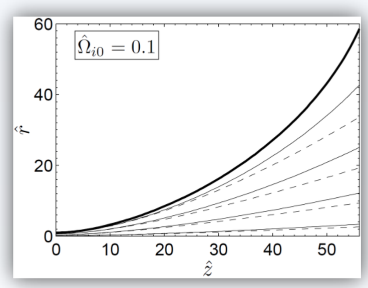
Polytrophic electrons yield a higher Mach number, a lower ion exit velocity, and an asymptotic value for the potential downstream not present with isothermal e^-.



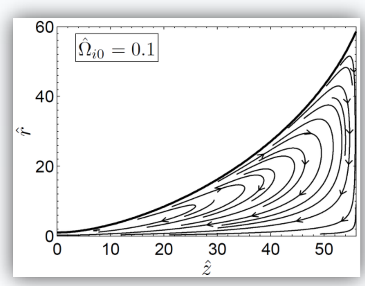
Plasma response with isothermal electrons. Experimental studies favor a specific heat ratio between 1 (isothermal) and 1.2.

Magnetization Strength

Non-full ion magnetization means ion streamlines do not coincide with magnetic (and electron) streamlines (except at the edge, due to quasineutrality, and at the axis). This ion-electron separation gives rise to:



- A mild plasma rotation (swirl current),
- Electric currents in the longitudinal plane that cannot be neglected, breaking current ambipolarity.



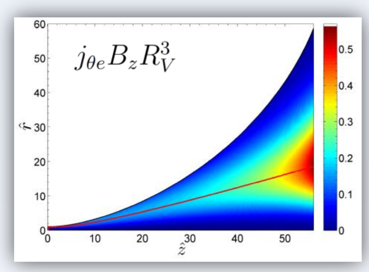
These currents arise independently of the presence of a floating surface downstream (application for material processing; see figure).

As magnetic field strength increases, ion magnetization increases too. Ion gyrofrequency, Ω_i, quantifies the magnetization degree. This parameter decreases downstream, meaning that for practical devices, ion magnetization is low in the greater part of the nozzle.

Ion magnetization is undesired, since it lowers plume efficiency and the energy invested to put the plasma into rotation is unuseful for space/processing applications.

Hall and swirl currents

Azimuthal currents play an essential role in every magnetic nozzle: for magnetic fields without a theta component, the *only external force* acting on the plasma in the meridian plane is the product $j_\theta B$. Therefore, all the confining and accelerating responsibility falls solely on azimuthal currents. Moreover, any gain in plasma momentum is transmitted as a reaction force back to the magnetic nozzle generator circuits upstream via the induced magnetic field of these currents.



For a radially non-uniform, non-rotating plasma cylinder, all radial pressure gradients are initially balanced off by the Hall force, $-enu_{\theta e}B$. When such a plasma flows into a diverging magnetic nozzle, the Hall force limits the radial expansion and causes the axial acceleration. This force is maximal somewhere inside the nozzle (red line in figure).

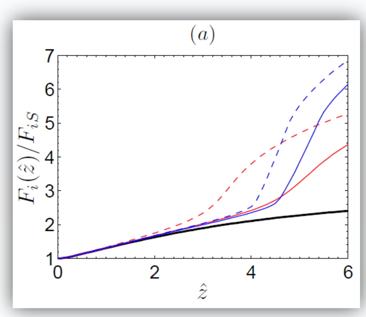
For our collisionless plasma, electron azimuthal frequency is conserved. This means that, for an initially radially-uniform jet without volume Hall currents, no Hall current develop downstream. A detailed analysis reveals that in this case all the necessary Hall current is concentrated in a current sheet at the plasma edge (plasma-vacuum transition) of a thickness of about two electron gyroradii.

The generation of an ion swirl current (see *Magnetization Strength*), $+enu_{\theta i}B$, tends to decrease the total net azimuthal current, as it competes with the Hall current. This translates in a less confined, less accelerated, and less efficient plasma jet.

Hot & Cold electrons

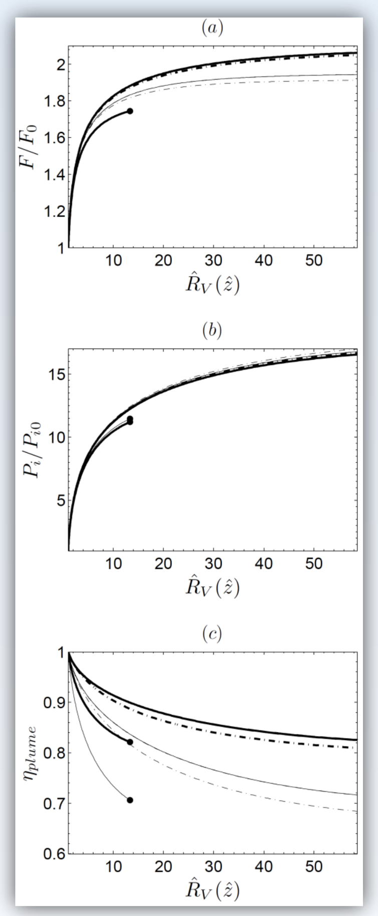
The addition of a small population of hot electrons (representative of some helicon sources) can cause the formation of special flow features such as double layers and ambipolar potential steepenings, depending on the hot-to-cold temperature and density ratios.

Simulations show an increase in potential fall and ion kinetic energy proportional to the temperature ratio, located at the position where these phenomena take place.



Relative ion momentum thrust gain along the nozzle with different fractions of hot electrons

Propulsive Performances



Thrust, specific impulse, and efficiency are of paramount importance in space applications.

The relative thrust gain along the nozzle, F/F(0), coincides with the specific impulse gain, $I_{sp}/I_{sp}(0)$, and is proportional to the square root of the potential fall.

Plume efficiency evaluates radial (or divergence) losses of the jet as axial to total ion kinetic power,

$$\eta_{plume} = \frac{P_{zi}}{P_i}$$

Initially radially non-uniform jets, long nozzles, and low ion magnetization yield larger thrust and efficiency.

Plasma Detachment

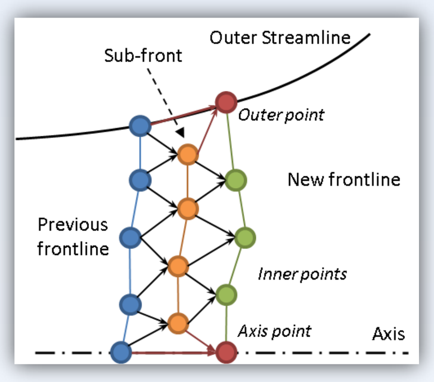
A central concern in the use of magnetic nozzles for space applications is the need to detach the plasma from magnetic field at a certain point. Otherwise, plasma would run along the closed field lines and return to the spaceship, cancelling thrust and posing serious plasma interaction problems for sensible equipment and surfaces.

Three main detachment mechanisms have been envisioned so far:

1. Magnetic detachment, whereby plasma induced field becomes more important downstream, effectively modifying the geometry of the applied one,
2. Electron inertia detachment, which claims that non-negligible electron inertia effects can release the plasma from field lines,
3. Resistive detachment, where downstream collisions may allow electrons to diffuse across field lines.

This ongoing research shows that Hall currents are a fundamental element for the three detachment modes.

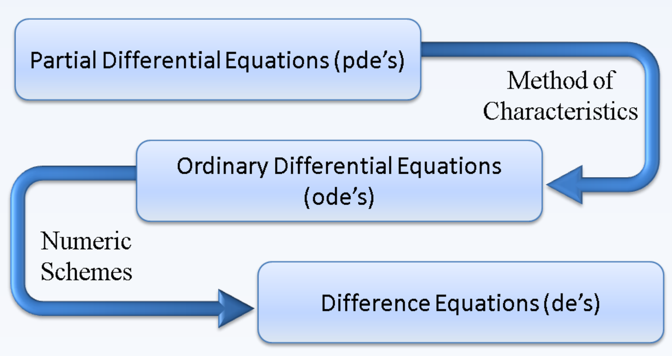
Numerical Simulation

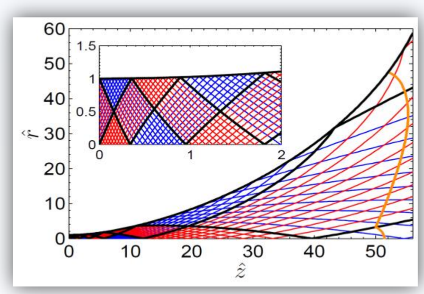


Advance of the solution frontline.

Ion equations constitute a set of 3 pde's. In order to render the model tractable, the Method of Characteristics (MoC) is used to reduce them to 3 ode's along 3 characteristic lines (ion streamline and 2 Mach lines).

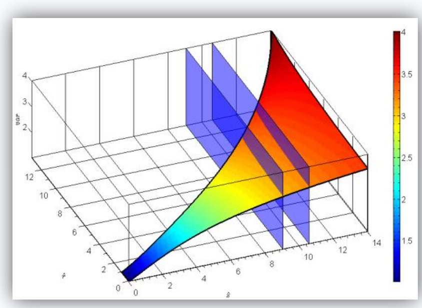
The ode's are then discretized into difference equations to be numerically integrated with a predictor-corrector scheme.





Characteristic line mesh.

Starting from an initial, ion-supersonic line, the 3 families of characteristic lines need to be propagated simultaneously as the solution frontline advances downstream, therewith generating the primary data mesh.



'DiMagNo 2D' Graphical User Interface.

This procedure has been implemented in a program, *'DiMagNo 2D'*, which is a fast and accurate software for magnetic nozzle simulation under many flow conditions. Its modularity allows immediate adaptation for the simulation of many other systems: hypersonic atmospheric reentry, conventional de Laval nozzle flow, and supersonic multi-species flows.

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