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

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Directing and accelerating a plasma jet are fundamental objectives of many Space Propulsion and Advanced Manufacturing systems. Magnetic Nozzles are an excellent mechanism to accomplish both these functions, while providing adequate means for flow control.

This work presents the results of an ongoing research on the characteristics of the plasma flow in a divergent Magnetic Nozzle. An axisymmetric, two-dimensional model is employed to study the supersonic expansion of a collisionless, low-beta, current-free plasma with fully magnetized electrons (electron streamtubes coincide with magnetic streamtubes). The model has been simulated numerically, employing the Method of Characteristics (MoC) to reduce the partial differential equations of the ion flow into a set ordinary differential equations.

A total of two different electron thermodynamics (isothermal and polytrophic) have been simulated and compared. Experimental results [3] point out that electrons are adequately characterized with an effective specific heat ratio in the range 1–1.2.

The influence of (a) the divergence rate of the magnetic lines, (b) the ion magnetization strength, and (c) the characteristics of the plasma flow at the Nozzle throat, on the performance and efficiency of the Nozzle is investigated.

Hall currents (both distributed inside the jet volume and concentrated in a thin plasma-vacuum transition layer) play a central role in the radial confinement and axial acceleration of the plasma, and seem to be an essential element as well for achieving the plasma detachment, required for propulsion applications. Results show that partial (non-complete) ion magnetization causes a slight separation between ion and electron streamtubes, which is responsible for the formation of longitudinal electric currents within the jet that violate current ambipolarity. The plasma rotation that arises from this separation contributes negatively to nozzle efficiency. The analysis of the different mechanisms participating in the plasma acceleration reveal the dual thermoelectric and electromagnetic origin of the axial kinetic energy of ions.

The main results include the simulated bidimensional plasma response to the applied magnetic field and the acceleration profiles of the jet. Nozzle performances for plasma propulsion, including specific impulse, thrust and plume efficiency (radial or divergence losses, which the 2D model can evaluate) are also discussed.

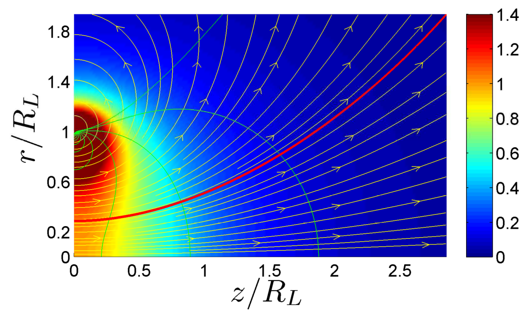

Fig. 1: Magnetic field of a single current loop of radius R_L placed in the $z = 0$ plane. Yellow lines with arrows show magnetic field lines. The red line denotes one of the magnetic lines used for the simulations as outer plasma streamline. Green lines show B_z =const lines.

From the point of view of the propulsive performances of the Magnetic Nozzle, the optimal configuration seems to consist on a slowly diverging magnetic field of mild intensity, and an initially non-uniform plasma jet, focalized about the Nozzle axis. This last statement is encouraging, since recent studies show that these types of plasma profiles are expected in many engine configurations. The results of this work show that nozzle plume efficiencies — in terms of ion axial power — of 0.83 and higher are obtainable for the nozzles described above. The simulations with these types of nozzles show as well that the gain in thrust and specific impulse provided by the Magnetic Nozzle, relative to the flow properties at the nozzle throat, is greater than 2. The fact that longer nozzles require heavier magnetic field generators and larger power consumptions leads to a situation with conflicting design criteria for space propulsion, in which a trade-off must me reached.

All analysis led us to conclude that ion magnetization should be kept at a minimum to confine and guide the plasma through the nozzle up to a desired section. An elevated value of this parameter increases plasma rotation, which reduces the total usable energy for axial acceleration. It also decreases efficiency performances, since the separation angle between ion streamtubes and magnetic streamtubes becomes smaller, causing an increase in the radial losses of the jet.

Two different sets of boundary conditions have been used to study a globally-current free jet expanding into vacuum — oriented to space propulsion applications — and a jet expanding against a dielectric wall. This second case is of interest for advanced manufacturing techniques, relying on a plasma jet that impinges on the material to be processed.

Finally, although the validity of this model is reduced to the divergent part of the magnetic nozzle, and is not able to delve into the phenomenon of magnetic detachment, a first indication of the most prominent physical mechanisms participating in the downstream detachment from the magnetic field has been assessed, showing that for the analyzed flow conditions electron inertia can become an important player.

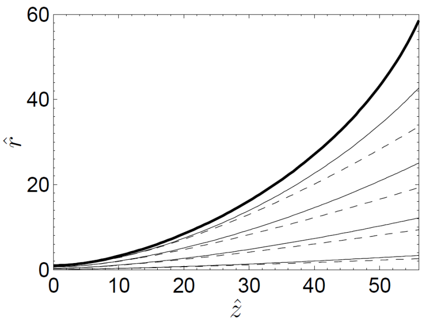

Fig. 2: Electron & magnetic (solid) and ion (dashed) streamtube separation for one particular nozzle configuration with low ion magnetization strength.

Reference

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