Magnetized Plasma Physics In Magnetic Nozzles For Space Electric Propulsion

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The acceleration of magnetized, low-temperature plasmas by electric and magnetic means is a central part of present and future space electric propulsion systems [1]. Using a magnetic nozzle is one of the many ways in which this task can be accomplished [2,3]. Such a magnetic nozzle consists in a convergent-divergent magnetic field that confines the plasma radially and expands it downstream supersonically into vacuum, similarly to a solid de Laval nozzle. This has several competitive advantages, like magnetic protection of the internal thruster walls from the plasma flow, increased plasma production efficiency, and an easily tunable nozzle that can be adapted in-flight. The applied-field MPD thruster, the helicon plasma thruster, and the VASIMR all employ a magnetic nozzle to efficiently produce a high velocity (10s or 100s of thousands of m/s) plasma jet. In contrast to the expansion of a neutral gas in a solid nozzle, where the thermal pressure acting on the walls of the device is the only thrust-generating mechanism, the physics of a plasma expanding in a magnetic nozzle are far from trivial. This is evidenced by the existence of multiple acceleration mechanisms [3], the need to separate the plasma from the closed field lines once it has been accelerated (to avoid its return back to the thruster) [4], the potential formation of electric double layers in the flow [5], the alteration of the magnetic nozzle by the plasma due to the induced magnetic field, and the collisionless cooling of the magnetized plasma along the nozzle.

The study of these topics is addressed using a 2D, two-fluid model of the plasma expansion in the magnetic nozzle that retains all the effects of interest. The plasma electric currents are shown to be central in many of the aforementioned items, with azimuthal currents driving the repulsive and confining force that generates thrust, and giving rise to a meridional magnetic field that tends to open the original magnetic nozzle. The formation of local longitudinal electric currents, even in a globally-current-free plasma jet, is indispensable in the process of plasma detachment downstream from the magnetic field. The role of the induced magnetic field is studied in detail, to show that it can be beneficial for plasma detachment when moderate. Finally, the process and mechanisms of collisionless electron cooling in a magnetized plasma are discussed.

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