

## Multi-scale aspects of magnetic nozzle modeling

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Some plasma propulsion concepts rely on a strong magnetic field to guide the plasma flow through the thruster nozzle. The question then arises of how the magnetically controlled plasma can detach from the spacecraft. One practical option is a magnetohydrodynamic detachment scenario in which the plasma stretches the magnetic field lines to infinity as the exhaust plume becomes super-Alfvénic [1]. The dynamical problem of plasma detachment involves multiple time scales, such as ion and electron travel times through the nozzle, propagation time of magneto-acoustic perturbations across the flow, and propagation time of sonic waves along the flow. The detachment scenario also requires a significant change of parameters along the flow (sonic and Alfvénic Mach numbers), as the nozzle transforms an incoming subsonic sub-Alfvénic flow into an outgoing supersonic super-Alfvénic flow. These features make a brute force approach of using an existing “comprehensive” code for a dynamical simulation impractical. Practical applications require a tool capable of performing parameter scans with modest computational requirements. We tackle the problem by splitting it into components that can be treated independently and use the multi-scale aspects to treat some components analytically. These components should then be assembled into a multi-scale model tailored to the problem of plasma detachment. The components discussed in this presentation are electron kinetics and ion dynamics with self-consistently generated magnetic field distortion. The rate of plasma expansion is determined by plasma ions and, therefore, can be treated as adiabatic when considering electrons. This feature allows us to formulate a semi-analytical model for collisionless plasma expansion into vacuum with a fully kinetic description of electrons. In order to extend the detachment model beyond the idealizations of analytical theory, a Lagrangian fluid code has been developed [3] to solve steady-stated MHD equations and to optimize nozzle detachment efficiency by adjusting the magnetic coil configuration. In its current form, the detachment code assumes cold plasma electrons. The next step is to incorporate the semi-analytical model for the electrons into the detachment code to account for ion acceleration via the ambipolar electric field generated by electron pressure.

[1] A. Arefiev and B. Breizman, *Phys. Plasmas* **12**, 043504 (2005).

[2] A. Arefiev and B. Breizman, *Phys. Plasmas* **15**, 042109 (2008).

[3] B. Breizman, M. Tushentsov, and A. Arefiev, *Phys. Plasmas* **15**, 057103 (2008).