Ambipolar acceleration of ions in a magnetic nozzle

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Abstract

Generation of supersonic plasma jets usually requires a nozzle with a magnetic mirror configuration. The incoming flow becomes sonic at the mirror throat, after which the acceleration continues in the diverging part of the nozzle. The magnetic nozzle converts electron thermal energy into kinetic energy of ion motion along the magnetic field lines. As the plasma density drops downstream and the electron mean free path increases, the electron motion becomes collisionless. An interesting feature of this kinetic regime is that the magnetic mirror limits direct access of the incoming electrons to certain areas of phase space in the downstream flow. In plasma confinement systems, such as mirror machines, the otherwise inaccessible trajectories can be repopulated due to Coulomb collisions. In this work, we address a different (purely collisionless) mechanism of electron trapping that is relevant to space applications such as plasma thrusters. In contrast to confinement systems, the ambipolar potential in an expanding plume ejected by a thruster is necessarily time-dependent. Its profile involves a rarefaction wave at the leading edge. The rarefaction wave accommodates a part of the total potential drop needed to keep electrons and ions together. While travelling through the rarefaction wave, electrons lose a part of their kinetic energy associated with the motion along the field. As a result, electrons can become trapped downstream from the magnetic mirror. The trapped electrons cool down, filling up the areas of phase space that would be otherwise inaccessible. The cooling is essentially adiabatic because the electron motion is much faster than the time evolution of the electrostatic potential. In this work, we present a rigorous adiabatic description of the trapped electron population. We also examine the impact of the adiabatic cooling on the profile of the ambipolar potential and the ensuing ion acceleration. This problem can be formulated for an arbitrary distribution function of incoming electrons. However, in order to make the problem tractable analytically, we consider an incoming "water-bag" electron distribution.