Plasma Dynamics in a Beating Electrostatic Wave Powered Magnetic Null Thruster

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I. Introduction

The Magnetic Null Thruster Topology was first proposed by Jorns and Choueiri[1] as a mechanism for channeling ion acceleration from beating electrostatic waves into directed thrust. The current thruster concept shown in Fig. 1 operates by launching electrostatic waves in the positive-$\hat{x}$ direction. These waves stochastically accelerate ions and channel them towards a magnetic field reversal, which tends to direct them in the forward, positive-$\hat{x}$ direction out of the thruster. The beating electrostatic wave magnetic null thruster has certain intrinsic advantages that deserve further study. The design is inherently steady-state and electrodeless, which allows the thruster to avoid lifetime limitations of other electric devices. Additionally, because the thrust mechanism occurs across magnetic field lines, the proposed device avoids magnetic detachment issues, which can harm efficiency.

Beating wave ion acceleration itself is a non-resonant mechanism for accelerating low energy ions. While vigorous stochastic acceleration of a particle can occur with a single electrostatic wave when the particle's velocity is resonant with the phase velocity of an electrostatic wave,[2] the beating wave process has been shown to accelerate non-resonant ions to higher energies where they can subsequently experience stochastic acceleration. The beating wave criterion was proposed by Benisti in 1998,[3,4] and subsequently, the necessary and sufficient conditions for single particle acceleration subjected to beating waves were derived by Spektor and Choueiri.[5] Recently, Jorns and Choueiri[6–8] have shown the beating wave heating can in fact be superior to single electrostatic wave heating in certain regimes.

Further more, Jorns and Choueiri[1] analytically demonstrated the potential for directed ion acceleration by showing that the stochastic heating process could channel energized ions into a magnetic field reversal, which would subsequently direct ions in a cross-field direction and out of the thruster. Gardineer, et. al.[9] predicted unoptimized ion exhaust velocities of up to 10 km/s by numerically simulating the single particle ion dynamics in the magnetic topology subjected to beating electrostatic waves. A recent single particle analysis of small electron orbits by Feldman and Choueiri[10] showed that electrons could also experience significant drifts in the positive-$\hat{x}$ direction. However, so far, all analysis and simulation has been done at a single particle level, which ignores the fields that may develop through ion and electron interaction.

Without taking into account the dynamics between the ion and electron fluids, the overall picture lacks self-consistency. In order to explore the beating electrostatic wave magnetic null thruster further, in this paper, we examine analytically the plasma dynamics in the given magnetic topology. To accomplish this, we must look at the dynamics in two parts: the beating wave process for driving ions into forward drifting orbits, and the detachment process wherein ions drag electrons across the magnetic field lines out of the thruster. Following along the work of Jorns and Choueiri,[1]

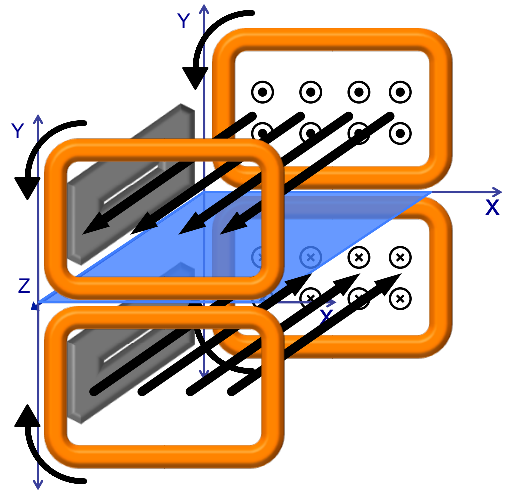

Figure 1. Beating Wave Magnetic Null Thruster Representation. Current conducting Helmholtz-like coils are depicted in orange both above and below the $y = 0$ plane. This creates a magnetic field topology with a magnetic null shown in blue at the $y = 0$ plane. Beating electrostatic waves are launched from the black antennas at the $x = 0$ plane. The thrust direction is the positive-$\hat{x}$ direction.

we will calculate the rate at which ions are accelerated and pushed into forward drifting orbits based on beating electrostatic wave and plasma parameters. After which, a non-dimensional parameter will be derived to show when electrons can be assumed to simply follow ions out of the thruster. Finally, these two aspects will be combined to determine regions of optimal operation for a beating electrostatic wave magnetic null thruster and compared with numerical PIC simulations.

References

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