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Princeton Undergrad '14
Summer 2013 PPST Report

During the summer of 2013 I worked as a research assistant in the Electric Propulsion and Plasma Dynamics Lab at Princeton University under Professor Edgar Choueiri. Support for the research was from the Program in Plasma Science and Technology. The project I was involved with was run by Matthew Feldman, a 4th year PhD student. His previous work was on the development of a novel plasma thruster concept called the Magnetic Null Thruster. Existing literature had indicated that this type of thruster was theoretically possible; my task for the summer was to determine if it was physically possible.

The Magnetic Null Thruster utilizes a magnetic field configuration in which there are two large regions of uniform magnetic field strength in opposite directions with a field reversal between them. Suppose we have a coordinate system as defined in fig. 1; there is one uniform region each above and below the y=0 plane. At the y=0 plane, the field reverses and has 0 magnitude, thus we call it the magnetic null plane. The purpose of this field definition is to direct ions in the +x direction. Fig. 2 shows how this configuration works to give particles forward motion. Ions above the null plane exhibit a clockwise Larmor precession, while ions below the null plane orbit counter-clockwise. If an ion crosses the null, it will achieve +x movement due to the direction of the orbit changing with each cross of the null.

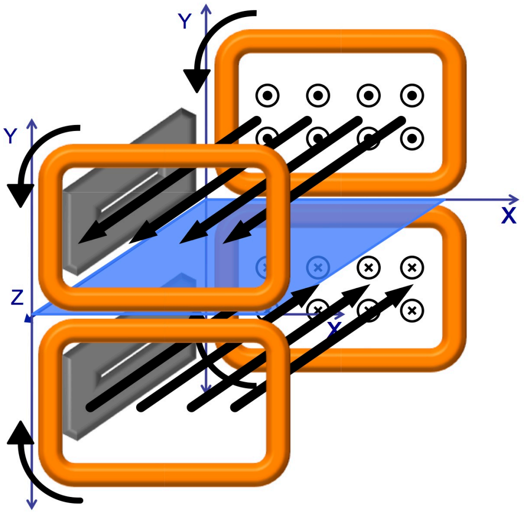

Fig. 1

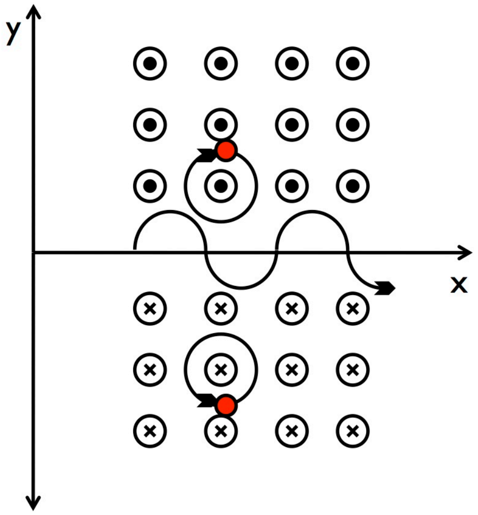

Fig. 2

Normally, most ions will be trapped in their Larmor orbits without ever crossing the null. To get ions to cross the null, we must heat them. In the MagNuT, heating is achieved with beating electrostatic waves (BEW). BEW heating gives periodic kicks in energy to an ion, slowly and steadily accelerating it. Once it is accelerated to a threshold energy level, it receives large stochastic kicks, rapidly accelerating it and causing its orbit to be large enough to cross the null.

In previous papers, it had been shown that an idealized thruster is indeed capable of producing thrust and specific impulse comparable to or better than ion thrusters that are currently in use. This idealized thruster, whose magnetic field configuration as a function of y is seen in fig. 3, used a chamber size that was arbitrarily large such that as few ions as possible would be lost to the walls.

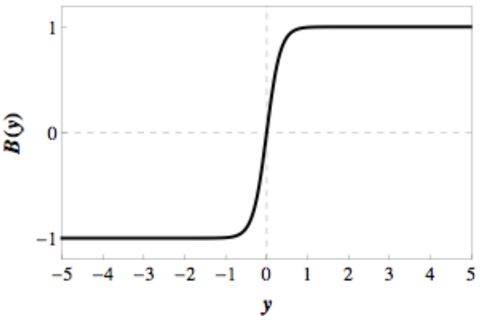

Fig. 3

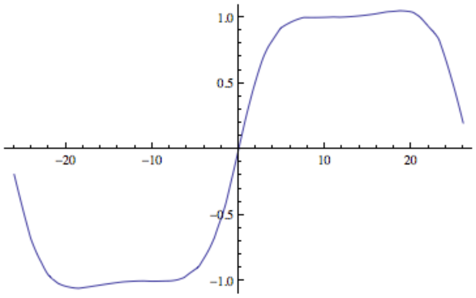

Fig. 4

My task for the summer was to design an electromagnetic coil arrangement to generate as close to a perfect magnetic null as possible, then determine if that field was feasible for application in a real-life thruster.

All my designs centered around a Helmholtz-like arrangement of coils due to the very uniform magnetic field they generate. Using circular coils was not viable for having a big enough thruster chamber, so I used rectangular coils. The arrangement consisted of one pair of rectangular Helmholtz-spaced coils with field in the +z direction and another pair directly below with field in the –z direction (similar to what is pictured in fig. 1). This arrangement posed a problem; there is twice as much current running through the center as there is on the top or bottom, causing a field gradient in towards the null on either side. The solution was to make an arrangement in which used just one wire in each the top, bottom, and middle of the setup. In order to maintain realism, this had to be designed such that the wires formed loops that could reasonably be physically built. The best design, in terms of realism and magnetic field uniformity, is shown in fig. 5. The black arrows indicate the direction of current flow in each coil. The magnetic field topography generated is shown in fig. 6. The coils can be scaled to any size while maintaining the same field topography, and changing the current simply changes the strength of the uniform sections (provided the current is the same in all 6 loops).

In order to assess the quality and viability of this magnetic field for use in a thruster, I extracted the data for the magnetic field strength at the mid-plane between the coils. This normalized field as a function of y can be seen in fig. 4. Of note is that the null is considerably wider than the idealized null. Additionally, the field falls back to 0 at the edge of the thruster region (this actually is not as much of a problem as it seems, as it produces a grad-B drift in the +x direction). Using the field data I ran Monte Carlo simulations of various sizes of thruster and beating wave parameters.

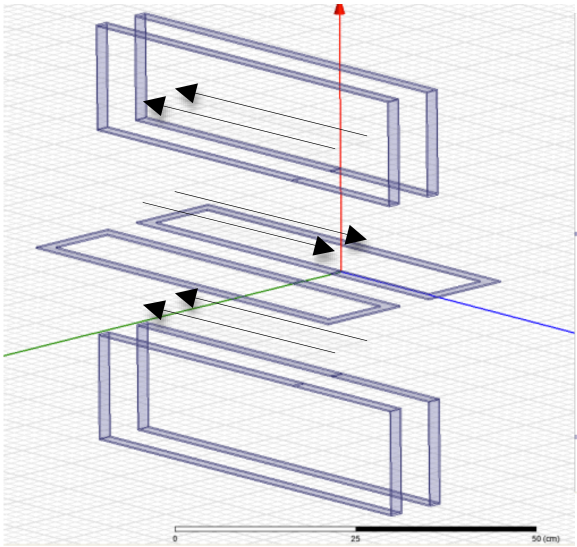

Fig. 5

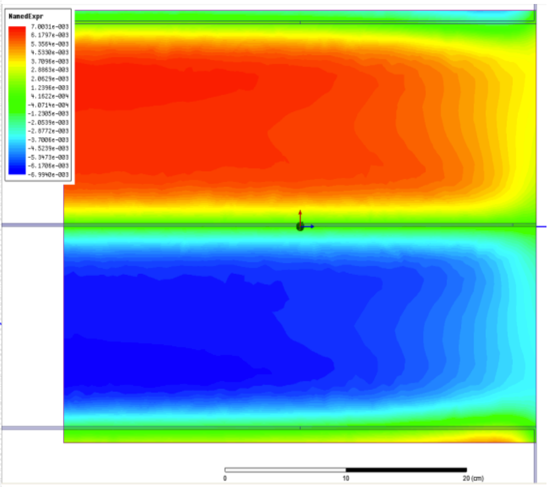

Fig. 6

The four simulations I ran were as follows: one with ideal wave parameters (as determined by Gardineer, Jorns, and Choueiri, 2011) and an unrealistically large thruster size; one with ideal wave parameters and a realistic thruster size; one with weaker wave parameters and a realistic thruster size; and one with no beating waves and a realistic thruster size. Gardineer, Jorns, and Choueiri (2011) found that using the ideal null depicted in fig. 3 and ideal wave parameters in an unrealistically large thruster, the specific impulse would be around 1500s with Argon as the propellant; this will be our basis for comparison when analyzing the realistic null.

For an unrealistically large thruster and ideal wave parameters, the specific impulse was roughly 1170s. 85% of ions exited the thruster, 15% were lost to the walls, and no ions were trapped in Larmor orbits (this is due to the fact that the ideal wave parameters are very high energy, thus every ion is accelerated to the regime of stochastic kicks). The average exit velocity of the ions was 13.4 km/s.

For a thruster with realistic size and ideal wave parameters, the specific impulse is 1040s with 79% of the ions exiting the thruster. This shows a marked decrease in the performance of the thruster, however by not as much as was initially expected. This simulation indicates that it is indeed possible to build a magnetic null thruster that exhibits comparable performance to current ion thrusters.

The next two tests showed that weaker waves decreased thruster performance, as expected. With weak waves the thruster's specific impulse dropped to around 700s, and with no waves at all most ions were trapped in Larmor orbits, not even exiting the thruster.

The results of these simulations seem to justify the construction of a magnetic null thruster to be tested. Future work could involve redesigning the coil arrangement to make use of ferromagnetic materials to reduce the width of the null. The current design has a magnetic field gradient in the –x direction at the right end of the chamber; future designs would need to alleviate this to best utilize the full chamber.