Investigation of Detachment in a Miniature Magnetic Nozzle Source

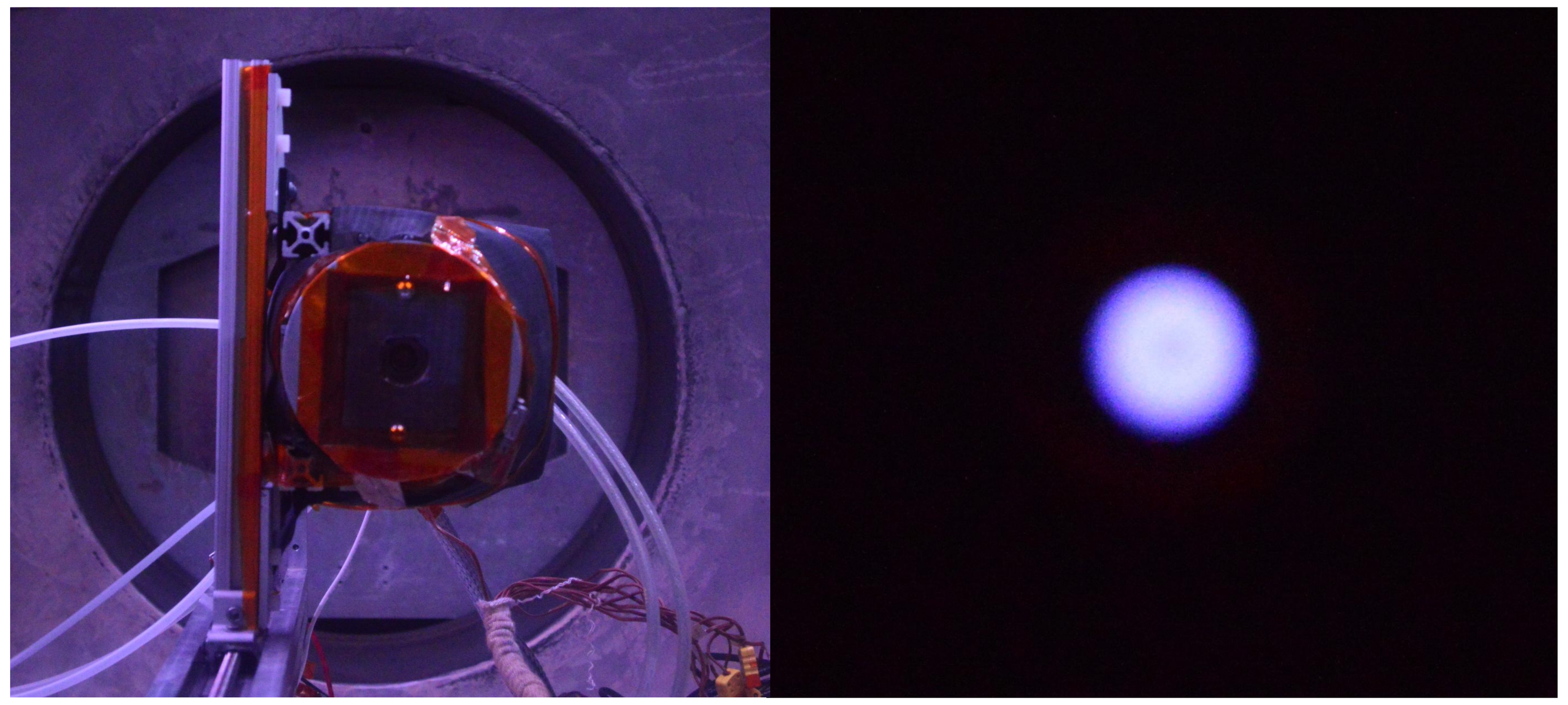
Timothy A. Collard,[1] Matthew P. Byrne,[2] Shadrach T. Hepner,[1] Christopher J. Durot,[1] and Benjamin A. Jorns[1]
[1]*Aerospace Engineering, University of Michigan and* [2]*Applied Physics, University of Michigan*

Motivation

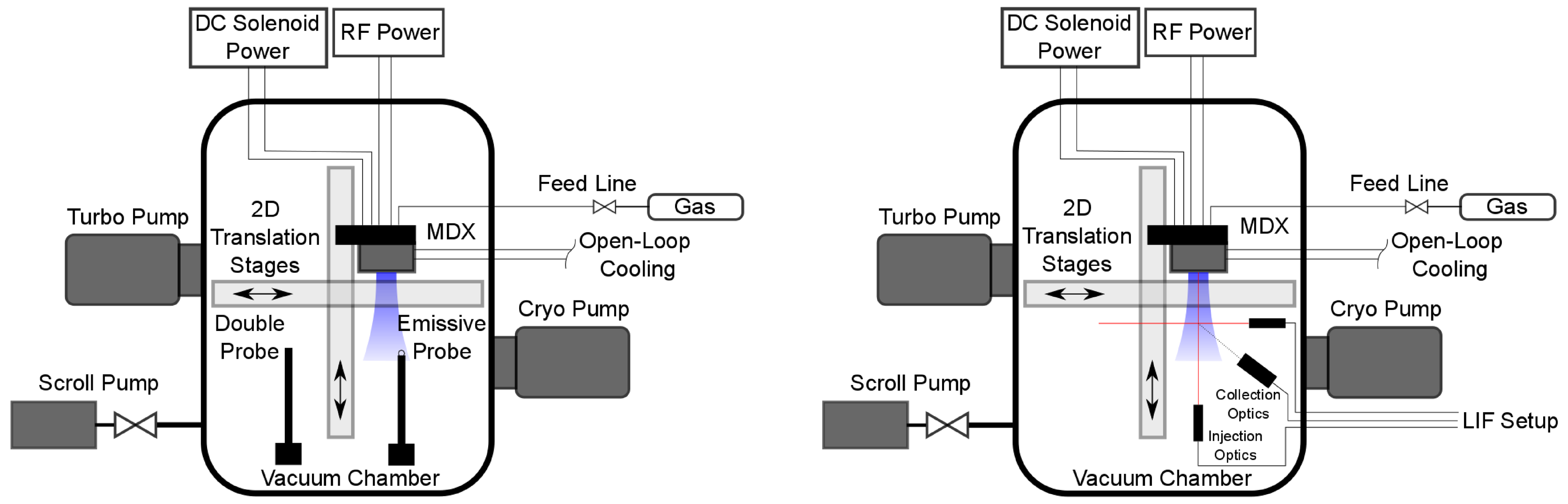
Magnetic nozzles have been proposed as electric propulsion devices due to their ability to convert thermal energy into directed kinetic energy. However, state-of-the-art devices have low measured performance: ~8% total efficiency at 2 kW input power [1]. To provide insight into what is limiting the thrust performance of these devices models have been created by Lafleur [2] and Collard, et. al. [3], but the diverging nozzle section is described solely by geometric criteria. To accurately predict thrust performance the physics underlying plasma detachment from the magnetic field lines must be understood.

The Magnetic Detachment eXperiment (MDX)

To investigate plume detachment a new, flexible magnetic nozzle source was designed. This source is ~13 cm in diameter, allowing for smaller vacuum facilities to be used for testing, and is capable of generating a converging-diverging magnetic nozzle with a peak centerline magnetic field strength of ~900 G. This experiment has five degrees of freedom: power, frequency, neutral flow rate, liner geometry, and magnetic nozzle strength. In the work presented here the source was operated at 13.56 MHz with an input power of ~120 W and a neutral flow rate of 3 mg/s of xenon. The magnetic field was set to a peak value of 98 G and 586 G for the low and high magnetic field condition, respectively.

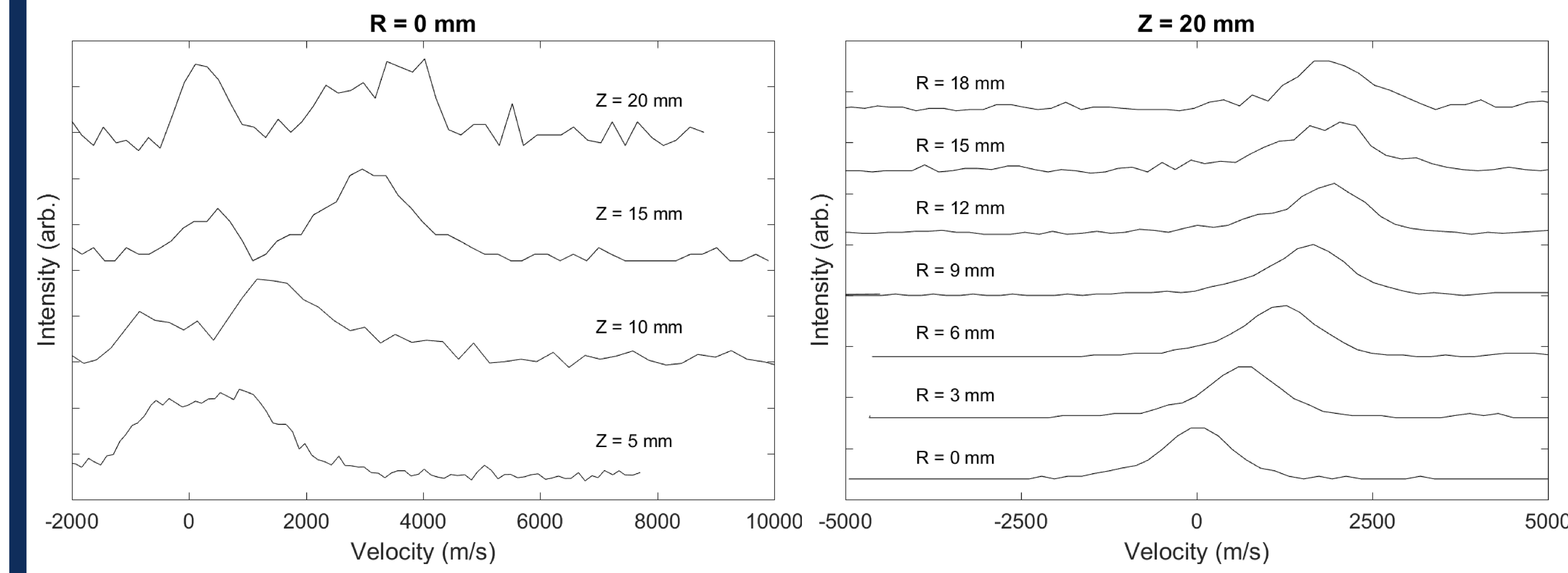


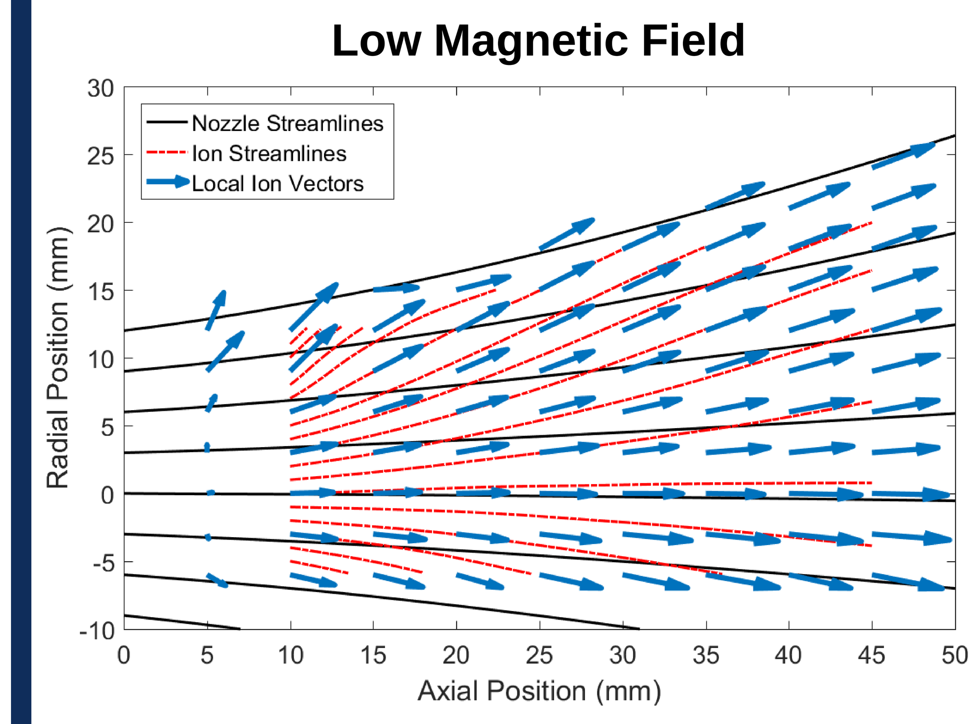
Experimental Setup

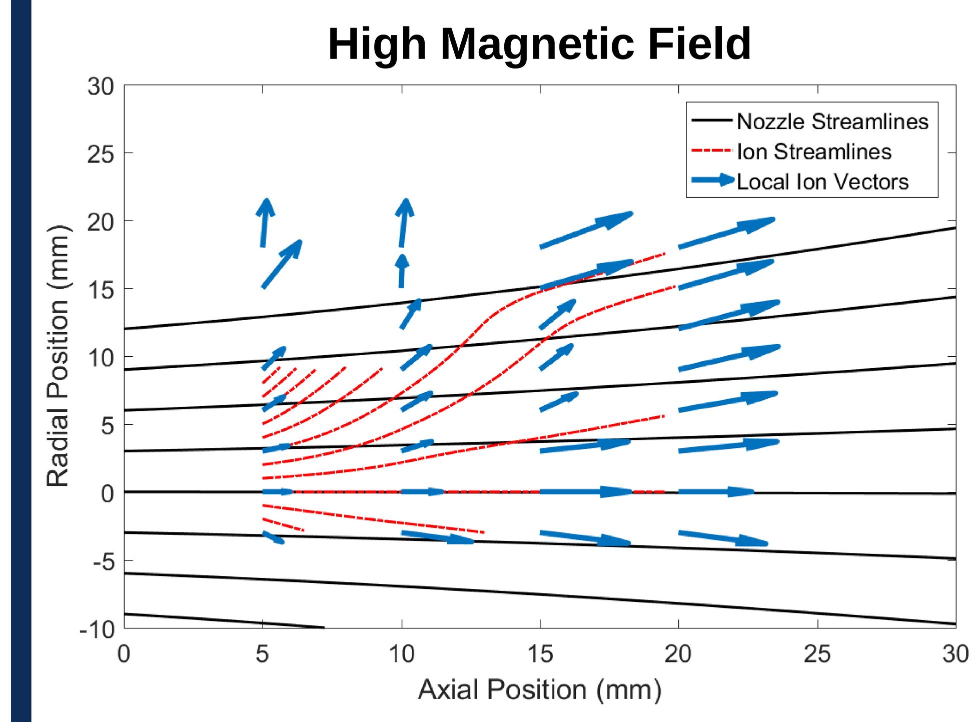


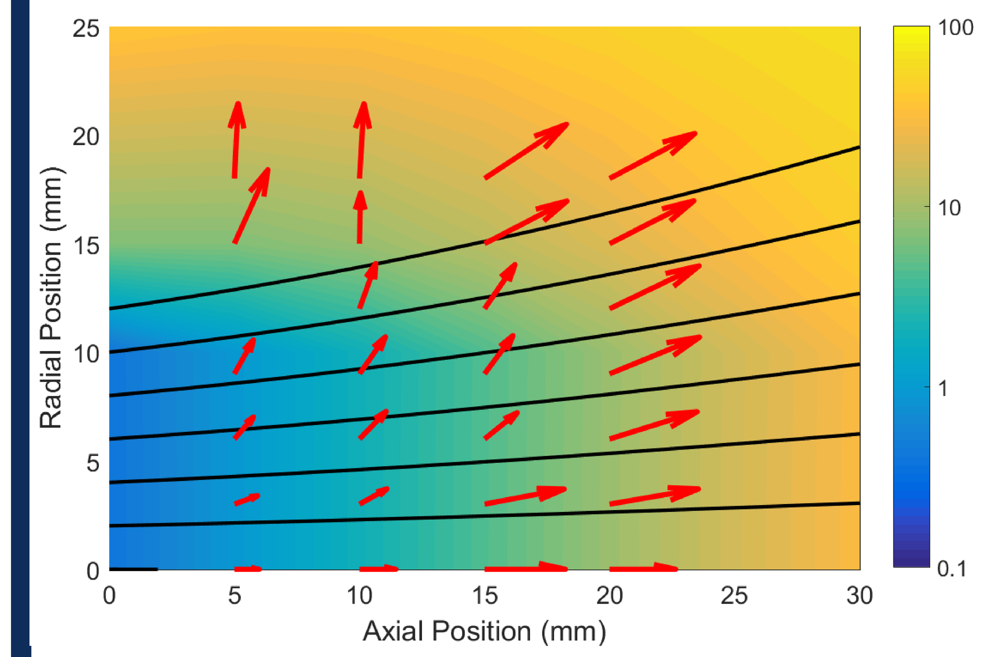
A diagnostic suite comprised of 2D Laser Induced Fluorescence (LIF), a 3-axis Gaussmeter, an emissive probe, and a double-Langmuir probe was used to interrogate the MDX plume. To maintain optical alignment of the LIF components all diagnostics were fixed to the chamber while the source was translated by 2D motion stages. All experiments were conducted in the Junior Test Facility at the Plasmadynamics and Electric Propulsion Laboratory.

LIF Results









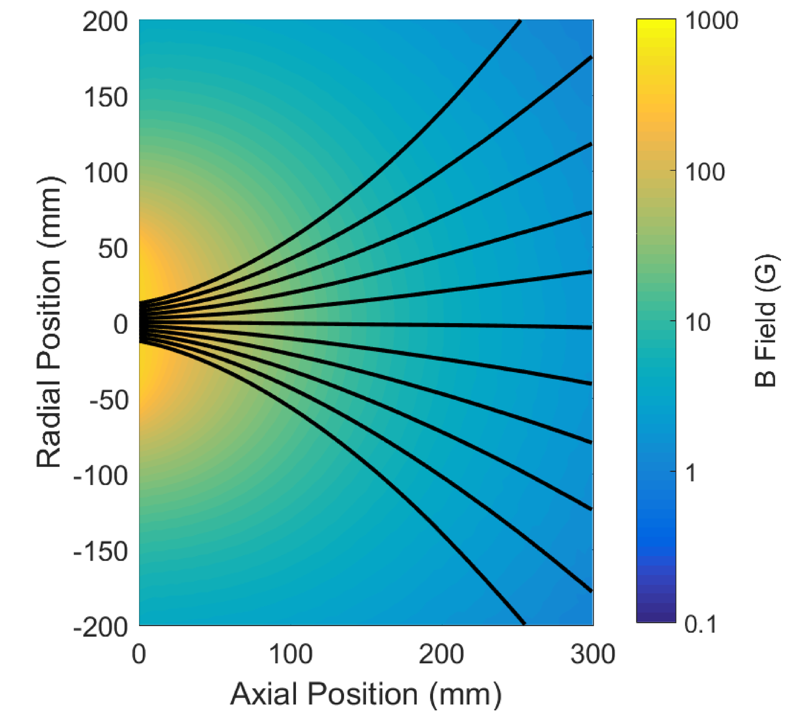
In both the low and high magnetic field conditions the MDX plume near-field was mapped using 2D time-averaged LIF. The local average velocity vector of the ions was extracted from the traces (high magnetic field examples above) by finding the moment.

In the low magnetic field condition the ions appear to diverge isotropically, starting from the exit plane of the source. This suggests that the magnetic nozzle does not influence the plume.

In contrast, in the high magnetic field condition the ions initially expand isotropically upon leaving the source, but then deflect inward downstream. This suggests that the plume is initially detached, and then reattaches to the magnetic nozzle where the ions are deflected inward. This ion deflection is accompanied by the formation of a potential well at the outer nozzle field lines, which is correlated with attachment [4].

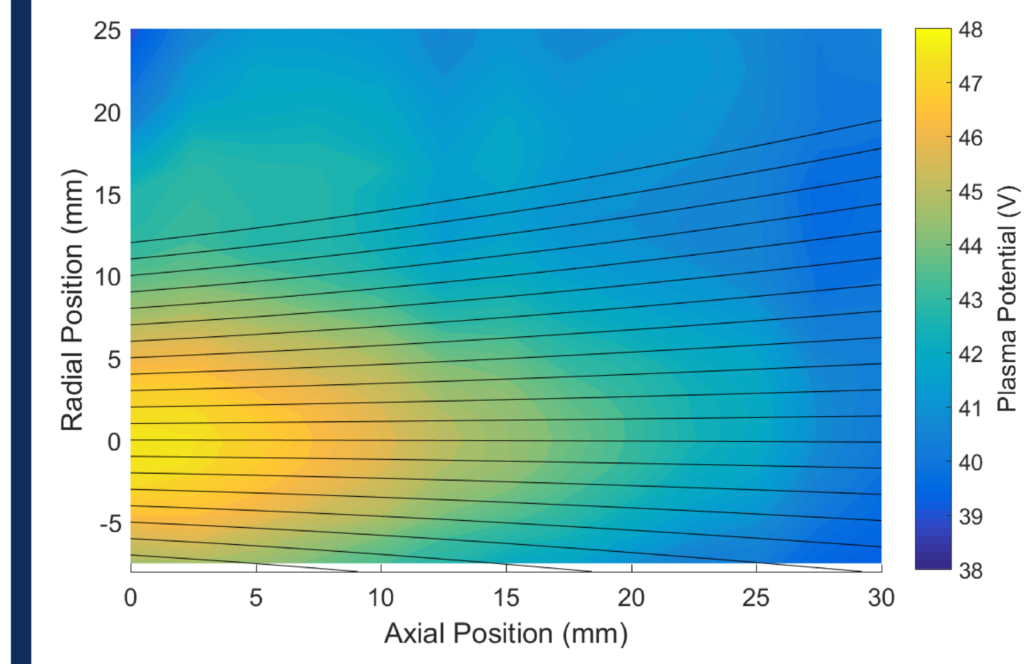
Neutral pressure measurements in the near-field show that the Hall parameter is less than unity in this region. This indicates that the electrons are experiencing numerous collisions with neutrals, enhancing cross field mobility. Since the ions are unmagnetized the magnetic nozzle is only imposed on the electrons; if the electrons are not confined, then the plume is not attached.

Gaussmeter Results



The magnetic nozzle was spatially mapped at atmosphere using a 3-axis Gaussmeter at a variety of magnetic field strengths with 5 mm increments in both the axial and radial directions. In all conditions the MDX electromagnet produced a well defined diverging nozzle section, like high magnetic field condition nozzle shown here. Across the magnetic field sweeps that electromagnet demonstrated excellent linearity, and was with 1% of the expected values in all cases.

Emissive Probe Results



The emissive probe results revealed that, in the high magnetic field condition, an ion confining potential well forms near the vacuum interface nozzle line at the location that the LIF measured inward ion deflection. This suggests that the electrons are tied to the nozzle lines, and the potential well is confining ions to maintain quasineutrality.

Conclusions

A near-field detached region within the plume has been observed for the first time. This may be due to high neutral densities within this region, which would enhance electron cross field mobility through electron-neutral collisions. This implies that the plume isotropically expands in the near-field and that the magnetic nozzle does not influence the plume expansion. In the high magnetic field case a potential well was observed downstream of this isotropic expansion at the location that LIF measured inward ion deflection. This suggests that the plume becomes reattached to the nozzle, and that the true nozzle is formed downstream.

Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1256260. The authors would like to thank the members of the Plasmadynamics and Electric Propulsion Laboratory for their insightful discussion concerning this research.

[1] Takahashi, K., Charles, C., Boswell, R., and Ando, A., "Performance improvement of a permanent magnet helicon plasma thruster," Journal of Physics D: Applied Physics , Vol. 46, No. 35, 2013, pp. 352001.
[2] Lafleur, T., "Helicon plasma thruster discharge model," Physics of Plasmas, Vol. 21, No. 4, 2014, pp. 043507.
[3] Collard, T. A., Sheehan, J. P., and Jorns, B. A., "A Numerical Examination of the Performance of Small Magnetic Nozzle Thrusters," 2017, doi:10.2514/6.2017-4721.
[4] Little, J. M., Performance Scaling of Magnetic Nozzles for Electric Propulsion , Ph.D. thesis, 2015.