

Electron Loss at a Magnetic Cusp for a Range of Upstream Magnetic Field Conditions

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An improved understanding of the electron loss behavior for permanent magnet cusps is needed to enable the design of efficient micro-scale plasma devices. Multiple experiments were designed to investigate the primary electron loss behavior within a permanent magnetic cusp that is coupled to a range of upstream field structures. The experiments utilized an electron flood gun to inject monoenergetic primary electrons towards a target magnet cusp through a range of increasingly complex magnetic field topologies. Mechanisms responsible for the distinct collection patterns observed during the experiments were explored through computational particle tracking and analytical methods. These analyses reveal that the primary electron collection can exhibit features closely tied to upstream magnetic field and can result in loss widths over an order of magnitude larger than the electron gyroradius. Therefore, the results collectively show that electron collection area can be strongly influenced by the upstream magnetic field for a range of field conditions.

Nomenclature

B	= local magnetic field
B_0	= upstream magnetic field
m	= electron mass
q	= elementary charge
R_c	= local radius of curvature of the magnetic field
r	= radial direction
$v_{\parallel}$	= velocity component parallel to the magnetic field
$v_{\perp}$	= velocity component perpendicular to the magnetic field
v_{R_c}	= curvature drift
$v_{\nabla B}$	= grad-B drift
v_0	= electron total velocity
z	= axial direction
$\Delta\theta_d$	= hybrid loss width
ϵ	= electron energy
ρ_e	= electron gyro-radius
ρ_i	= ion gyro-radius

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I. Introduction

THE development of an efficient permanent magnet microdischarge on the scale of 1 cm requires an improved understanding of magnetic cusp confinement physics very near the anode. Larger magnetically confined discharges benefit from relatively low surface-to-volume ratios, which can provide favorable electron confinement and high ionization efficiency. As a result, designers of many larger cusp confined devices, such as ring-cusp ion thrusters, have been able to yield favorable performance for large discharges by focusing on the design of the macroscopic magnetic field structure far from the magnet surfaces.^{1–3} However, these permanent magnets also result in strong microscopic cusp structures that dominate a large region in smaller discharges, a region that involves interactions between a divergent magnetic field, multiple plasma species, and the sheath conditions near the surface.⁴

Much of the research on cusp confinement has been performed using relatively larger plasma discharges with free-standing electromagnetic "picket fence" and spindle cusps far from the anode^{5–7} or multi-magnet ring and line cusps for permanent magnet discharges.^{8–10} These efforts have consistently defined and demonstrated a semi-empirical "leak width" through which the plasma is lost near the cusp, a behavior that can be described by ambipolar-type effects between the ions and electrons in the cusp region.¹¹ Several researchers have found the leak width, w_l , to be proportional to the hybrid gyroradius, ρ_h , such that $w_l \approx 4\rho_h = 4\sqrt{\rho_e\rho_i}$. This expression is commonly used for modeling of ion thrusters and is dependent only on the local cusp field strength and basic particle properties. However, some researchers have experimentally shown that the hybrid leak width is also strongly influenced by the presence of high energy primary electrons as well as other plasma properties.^{7,12,13} Results from the DC-ION model have confirmed inferences from experimental data that the main challenge to discharge utilization efficiency is the prodigious loss of primary electrons to the chamber walls.¹⁴ In addition, the primary electron density and its role in ionization is substantially higher for reduced discharge size. Previous research efforts with primary electrons have experimentally measured the local cusp density for a 10 cm discharge¹⁰ and computationally improved confinement using a particle tracker.¹⁵ However, their findings are focused on large scale general confinement and do not address the intricate field structures inherent in microdischarges.

The objective of this paper is combine experimental, computational, and analytical effort to investigate the importance of the upstream field structure on the primary electron collection behavior at a single magnet. The paper is a compilation of several experimental efforts utilizing an electron flood gun to measure the primary electron behavior at a single magnetic cusp with varying upstream field conditions. This knowledge is being used to develop analytical and computational tools to aid the design and optimization of multi-magnet micro plasma discharges (~ 1 cm).

II. Approach

The experimental effort investigates the physical processes of primary electron confinement within a magnetic cusp. These phenomena are methodically examined by utilizing a range of magnetic field configurations that can be readily compared with results from the computational efforts.

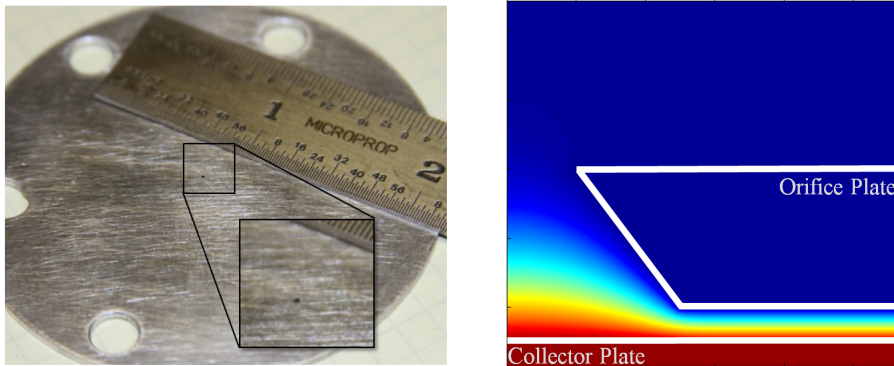


Figure 1. Wall Probe with 400 μm diameter orifice (left). Potential contour plot of the Wall Probe orifice with the collector plate biased 30 V (right).

The vacuum chamber is cryogenically pumped by two 10" CTI Cryo-Torr pumps, supplying a total pumping speed of 6000 l/s and base pressure of 5×10^{-8} Torr. For this effort, the experiment utilizes an EGA-1012 electron flood gun that is mounted to the chamber. The gun provides a well-characterized electron source that is easily adjustable to specified electron energies and currents, and thus produces electrons at energies independent of plasma potential and without the need for discharge potential in the device. The current loss to the conducting wall at the magnetic cusp is measured using an embedded wall probe shown in Fig. 1. The probe consists of a 400 μm orifice and effective collection width that is embedded into a 1 mm thick sliding anode plate and is pressed against the downstream end of the device to contain the injected gas. The entire assembly is mounted onto the 3-axis translational stage assembly that is capable of 50 μm movement resolution. Figure Fig. 1b shows that the collector plate biased to 30 V creates minimal potential disturbance upstream of the orifice; this design is well-suited for conditions with relatively large Debye lengths in low density and electron plasmas.

A. Single Cusp Experiment

The first experiment utilizing the electron flood gun source was to measure the collection area in the simplest of cusp configurations. As shown in Fig. 2, the electron gun was aimed directly at a single cylindrical permanent magnet while measurements were taken using a thin wire probe at chamber base pressure. An AlNiCo magnet was chosen to generate a weaker cusp in order to obtain a larger leak and, hence, provide a higher effective measurement resolution within the cusp region. The electron gun was spaced at an adequate distance from the cusp to allow the electrons to be born in a relatively field free environment. The data was used to validate and characterize the electron gun and to validate components of the computational effort. Further details of the experimental setup can be found in Ref. 16.

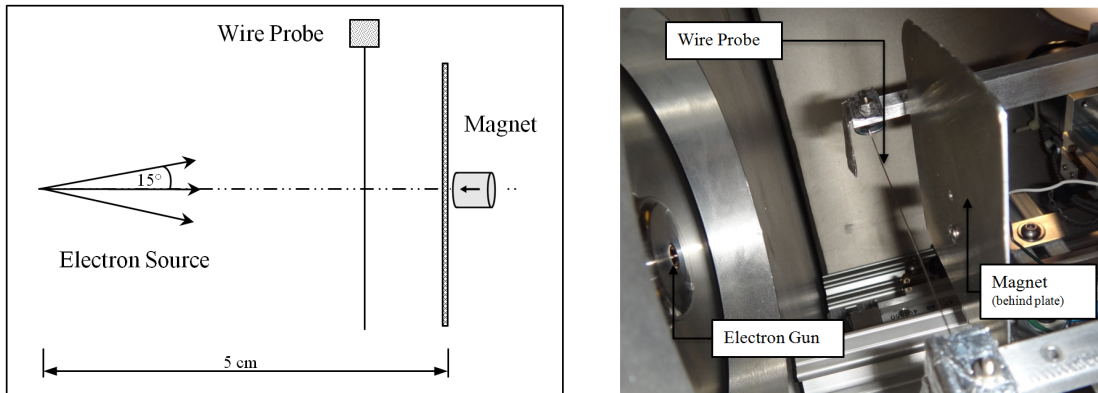


Figure 2. Diagram (left) and picture (right) of the single cusp experiment.

B. Helmholtz-Cusp Experiment

The Helmholtz-Cusp experiment shown in Fig. 3, incorporated two additional magnetic field elements to the single cusp experiment to control the upstream magnetic field structure. An AlNiCo magnet was again chosen to generate a weaker cusp. The field in the bulk region incident to the cusp is adjusted through the Helmholtz coils while the cathode coils control the field at the electron gun where the particles are generated. In addition, the configuration creates a magnetic bottle where the electron confinement can be adjusted. Particles are measured at the target cusp using the Wall Probe. The screen mesh prevents charged insulated surfaces in the apparatus from affecting the electrons. The screen as well as the Wall Probe are kept electrically grounded while the potential of the cathode coil and electron gun housing can be adjusted.

C. Multi-Cusp Experiment

The Multi-Cusp experiment is designed to examine electron collection behavior at the target magnet with a complex magnetic field upstream. As a result, a samarium cobalt multi ring-cusp configuration, shown in Fig. 4, is adopted to provide a high level of confinement before the electrons reach the target magnet. For

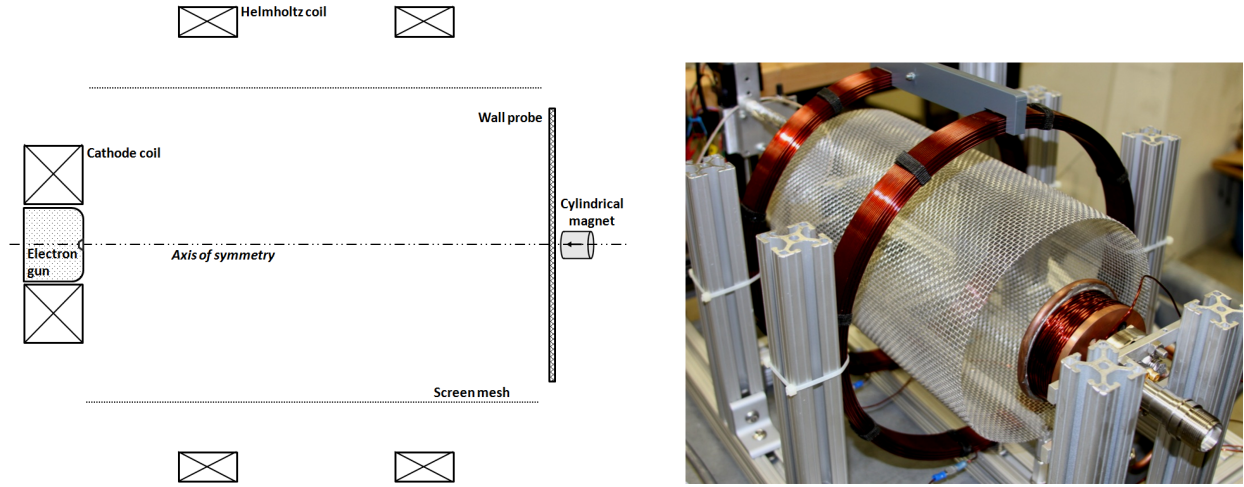


Figure 3. Diagram (left) and picture (right) of the Helmholtz cusp experiment.

this experiment, the target magnet is also samarium cobalt to match the ring cusp magnets. The magnetic field was configured to improve confinement and alignment sensitivity of the electron gun to the discharge chamber by increasing the low field region in the chamber. The neutral gas is injected on the upstream end through a ring shape plenum to provide a relatively uniform xenon neutral pressure. In the azimuthal direction, each ring magnet around the chamber and electron gun has 18 blocks and 16 blocks, respectively. Measurements of the collection area are taken using the Wall Probe that 2-dimensionally slides against the downstream surface of the device. Further details of the experimental setup can be found in Ref. 17.

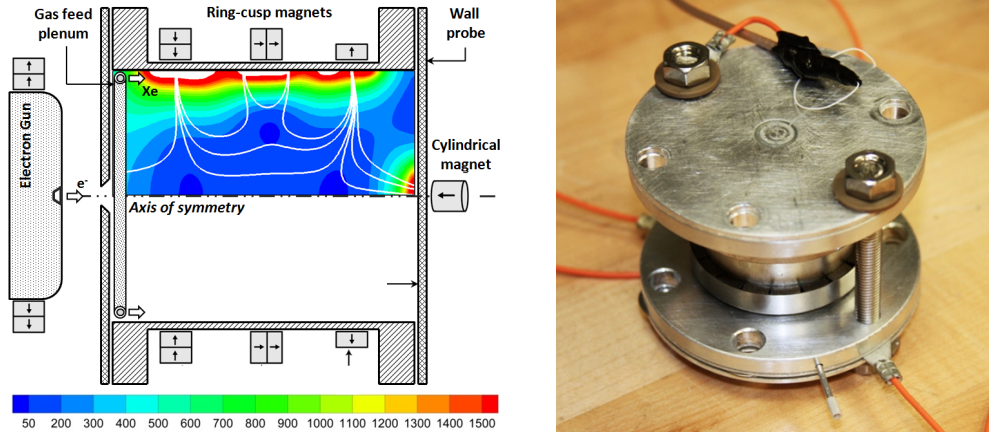


Figure 4. Diagram (left) and picture (right) of the multi-cusp experiment.

D. Computational Model Description

The computational simulations employ the iterative Monte-Carlo (MC) method, tracking super-particles of different species (primary electrons, ions, and plasma electrons) separately. In order to obtain fast and accurate trajectories for primary electrons, the model uses analytical equations for magnetic field induced by permanent block and cylindrical magnets, and modified Boris method for integration of the equation of motion.¹⁸ The use of analytical equations for the magnetic field allows accurate determination of the magnetic field at particle locations, thus eliminates the error associated with interpolation of the fields. These equations assume a constant magnetization in a magnet, which is a reasonable assumption for the samarium cobalt magnets used in the experiment. Further details of the computational simulation can be found in Ref. 17 and Ref. 19.

III. Results and Discussion

A. Single Cusp Experiment

The data and analysis for the single cusp experiment is a review of results from Ref. 16. Figure 5 is a comparison of the experimental data and computational results for the line current density profile at incremental distances upstream of the target magnet. For these data, 50 μA of electron current was injected at an energy of 25 eV with 15° half angle divergence and wire probe measurements are taken at 1 mm axial increments starting from 2.5 mm upstream of the target magnet. The results show a decreasing total current moving towards the magnet surface as electrons are reflected. The line current data can be converted to a current density profile using a reverse Abel transformation; however, the data presented herein is kept unprocessed for direct comparison with the virtual wire scans produced by the computational model. The electron loss width at the cusp is also measure within 2 to 4 times electron gyro-radius. The apparent fluctuations in the line current density and the overall loss width is a consequence of the point source of the electrons. They are ejected from the electron gun towards the cusp with an axis-symmetric distribution which causes the them to gyrate at a semi-synchronous trajectory. Therefore, the majority of the population will roughly converge at the centerline after a full gyro-rotation. The computational results show a good quantitative and qualitative agreement to the experimental data. This indicates that the particle tracking technique and the magnetic field calculations are fairly accurate. One of the causes of the slight disagreement is likely the misalignment of the magnet and electron gun axes during the experiment, as seen in the asymmetric scan profile in the data.

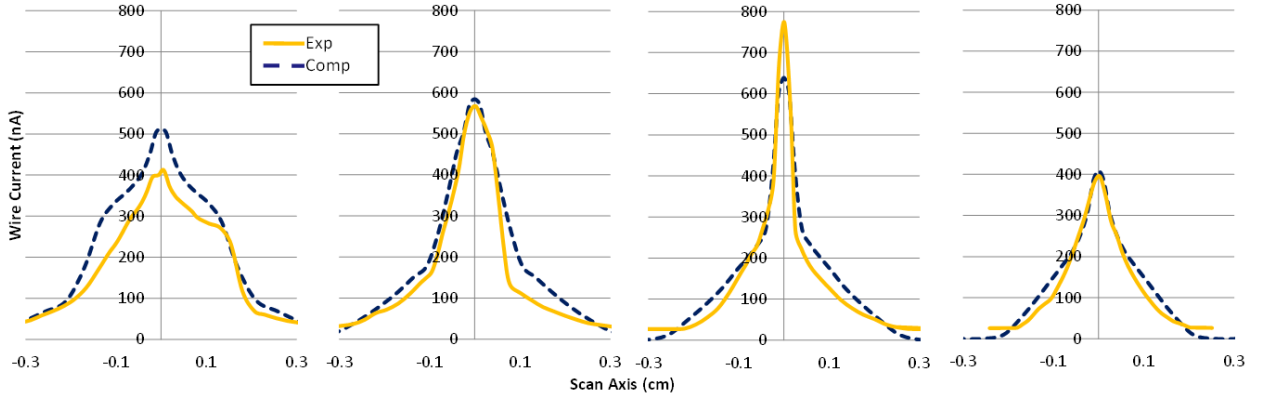


Figure 5. Experimental (Exp) and computational (Comp) wire probe measurements and across the cusp at 5.5 mm, 4.5 mm, 3.5 mm, and 2.5 mm from the permanent magnet face show good agreement. A fluctuating peak current density and loss width are caused by the point injection of electrons upstream.

B. Helmholtz Experiment

The experiment was operated with the magnetic field strength at the cusp and the uniform upstream region at 1600 Gauss and 60 Gauss, respectively. In addition, the cathode coil and electron gun were allow to float to create an electrostatic reflective boundary; measurements with these surfaces at ground potential gave expected results of a point cusp similar to the single cusp experiment. The results shown in Fig. 6 are planar measurements taken 3 mm upstream of the target magnet with the electron gun energies at 15 eV, 25 eV, and 35 eV. At all energies, the results display an annular collection region of the same radius of ~ 2 mm. However, the angular separation of the current density peaks within the ring increases with higher election energies. The loss width of the individual peaks are within the order of magnitude of the electron gyro-radius. The annular collection area at the cusp is caused by a combination of the non-axial entry of the electrons to the centerline magnetic field and the azimuthal drifts in the cusp region. Unlike the single cusp experiment, the initial electron population is confined from birth to the upstream magnetic field. They are guided to the cusp region slightly off axis and undergo a finite curvature and ∇B drift in the azimuthal direction along a drift shell that surrounds the centerline. The multiple current density peaks are a result of subsequent mirroring cycles of the less confined population from the electron gun in combination with the finite drift precession of each cycle. The lower current density ring in which the peaks coincide is caused by

electrons that were originally better confined and became part of the diffuse background population. To do an analysis of the angular precession of the current density peaks, the combined expression for the two drifts can be integrated:

$$\begin{aligned}\Delta\theta_d(r, z) &= \frac{1}{r} \int (v_{\nabla B} + v_{R_c}) dt \\ &= \frac{1}{r} \int \left[\frac{m}{q} \left(v_{\parallel}^2 + \frac{1}{2} v_{\perp}^2 \right) \frac{\vec{R}_c \times \vec{B}}{R_c^2 B} \right] \frac{dz}{v_{\parallel}}\end{aligned}\quad (1)$$

where m is the electron mass, q is the elementary charge, and $v_{\perp}$ and $v_{\parallel}$ are its velocity component perpendicular and parallel to the magnetic field, respectively. R_c is the radius of curvature of the magnetic field, and $\Delta\theta_d$ is the integrated drift in the θ -direction. The instantaneous velocity components can be related to the magnetic field through the basic equations for magnetic mirroring using $v_{\perp} \approx v_0 \sin \gamma \sqrt{B/B_0}$ and $v_{\parallel} \approx \sqrt{v_0^2 - v_{\perp}^2}$, where γ is the initial pitch angle. Combining these terms gives the expression:

$$\Delta\theta_d(r, z) = \frac{m}{q} v_0 \int \left(\frac{\vec{R}_c \times \vec{B}}{R_c^2 B} \right) \frac{2 + \frac{B}{B_0}}{\sqrt{1 + \frac{B}{B_0}}} \frac{dz}{r} \quad (2)$$

To calculate the actual drift values would require numerical integration along the particle's guiding center trajectory as well as the local magnetic field data. However, electrons emitted from the source are confined to the same initial guiding center field lines regardless of energy as the magnetic field remains unchanged. Therefore, the value of the integral in Eq. 2 is constant and independent of the electron's initial velocity. The total azimuthal precession is found to be directly proportional to the velocity of the electrons:

$$\Delta\theta_d \propto v_0 \propto \sqrt{\epsilon} \quad (3)$$

where ϵ is the total energy of the electrons. This dependency can be readily seen in Fig. 6 through the angular spacing between each subsequent current peaks in the annular ring.

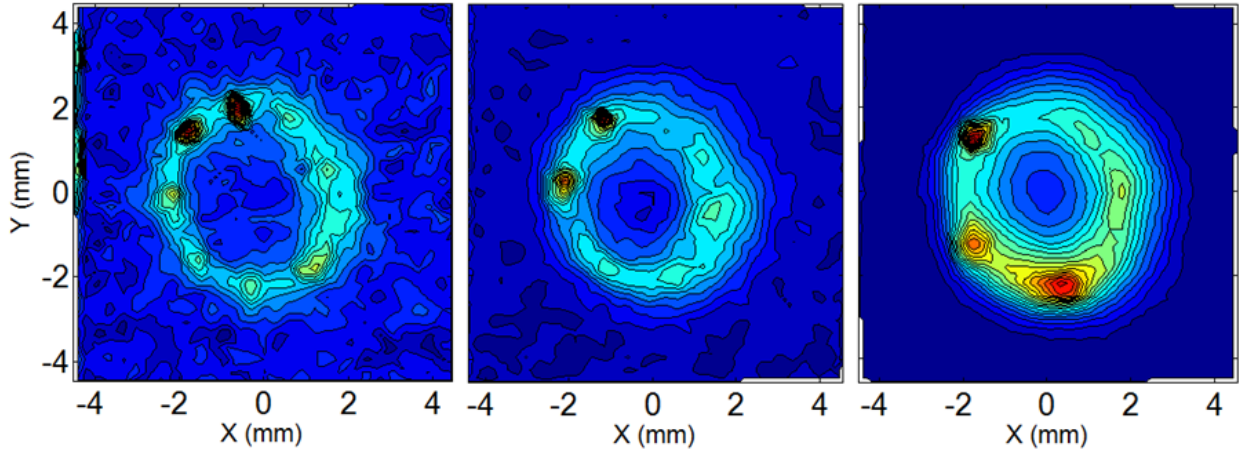


Figure 6. Contour plots of measured current density measured 2 mm upstream of the target magnet face at base pressure with primary electron energies of 15 eV (left), 25 eV (center), and 35 eV (right). The contours are plotted on a linear scale with a maximum current density of 14 $\mu\text{A}/\text{m}^2$ (left), 32 $\mu\text{A}/\text{m}^2$ (center), and 88 $\mu\text{A}/\text{m}^2$ (right). Data shows a constant radius annular loss region with increasing angular displacement of the current density peaks. Orientation is from the perspective of the cylindrical magnet viewing upstream.

C. Multi-Cusp Discharge Experiment

The data and analysis for the Multi-Cusp Experiment is a review of recent results from Ref. 17. At chamber base pressure, the loss width measured in Fig. 7(left) was found to be approximately 1.6 to 2.0 mm FWHM (full width at half max) and exhibits a periodic ridge pattern around a central current density peak. This value is more than an order of magnitude greater than the corresponding maximum local

primary electron gyro-radius calculated to be ~ 0.1 mm. When neutral gas is introduced, the loss region transitions from a centered peak into an annular pattern of periodic ridges as shown in Fig. 7(center). Although the angular location and characteristic of each ridge remains the same as in the base pressure case, the highest current density is seen at the radius of 2 mm with the current density decreasing in a counterclockwise direction. For 35 eV electron energy, the ion current density collected at electron repelling potentials measures over two orders of magnitude lower than the electrons' and calculations of each species' collision path lengths are $\lesssim 1$ m. This suggests that the plasma is not quasi-neutral and that the electron trajectories remain largely non-collisional and non-diffusive. For the computational particle tracking results shown Fig. 7(right), primary electrons are artificially injected with isotropic velocity distribution at an off-axis location between the target magnet and the ring cusp directly upstream at $(z, r) = (40 \text{ mm}, 3 \text{ mm})$. The same annular ridge structure is seen as the experimental data. The correlation of ridges to magnets indicates that the ridge structure is a result of the discretization of the upstream ring cusp; the cause of which is described in the forthcoming analysis.

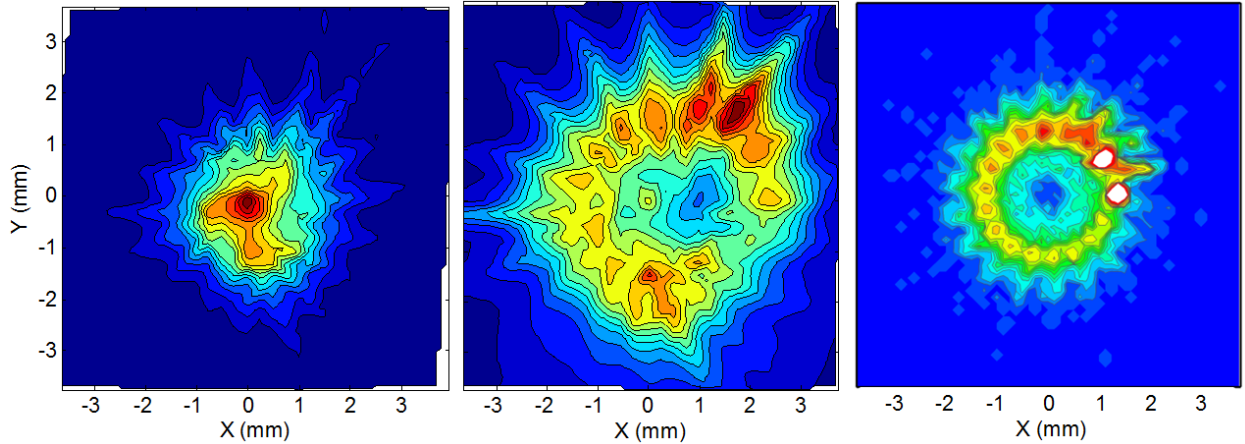


Figure 7. Contour plots of measured current density (A/m^2) measured 2 mm upstream of the cylindrical magnet face at base pressure (left) and xenon pressure of 5×10^{-4} Torr (center). Origins of the plots are set at the location of peak current for the base pressure case, which are near to the center of the cylindrical magnet. Simulation result for current density (A/m^2) for a ring magnets composed of 18 block magnets of particles injected at $(z, r) = (40 \text{ mm}, 3 \text{ mm})$ with isotropic velocity distribution. Orientation is from the perspective of the cylindrical magnet viewing upstream.

Similar to the results from the Helmholtz experiment, the counterclockwise reduction of the current density around the point cusp is predominately caused by the curvature and grad-B drifts in the azimuthal direction and the continuous electron loss to the cusps. A azimuthally asymmetric collection pattern is also seen in the Helmholtz experiment due to azimuthal periodicity based on the axial transit times of the primary electrons along the device length. In this case, the radial ridge structures are a consequence of the azimuthal periodicity of the discrete block magnets that form the upstream ring cusp. This results in a small alternating drift in the axial direction caused by the azimuthal fields very near the ring cusp, particularly at the edge region of each individual block magnet. Although the actual magnitude of this axial drift is much smaller compared to the azimuthal drift, small displacements of the guiding center in the cusp region translate to large shifts in particle trajectory further downstream. The overall effect is a dispersion of the electrons' guiding center field lines which then terminate at a larger radial region at the point cusp as well as enter further into the the magnetic null region where the particles become less confined.

IV. Conclusion

A combined experimental, computational, and analytical effort was undertaken to improve the understanding of near-surface cusp confinement for micro discharge. Experimental measurements of the primary electron losses were taken at increasing complexity to the magnetic field upstream of the target cylindrical magnet point cusp. For the cases with an imposed upstream magnetic field, the loss structure consistently exhibited an intricate collection pattern that had not been observed by other researchers. This result is in contrast to the supposition that cusp collection for plasma and electron discharges is primarily determined

by the magnetic field strength at the cusp collection surface. From these observations, the primary electron leakage to the cusp can be strongly influenced by the upstream magnetic field structure. These results are particularly important for small discharges, where the primary electrons can dominate the discharge plasma behavior. The future work for this effort will be to replace the electron flood gun with a hollow cathode source in the Helmholtz cusp experiment. Measurements of the cusp wall losses as well as bulk plasma properties will be taken while varying the field strength for each magnetic field element with the objective to understand the possible effects the unique primary electron collection area will have on the individual and collective behavior of other plasma species.

Acknowledgments

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References

- ¹Beattie, J. and Matossian, J., "Inert-Gas Ion Thruster Technology," NASA CR-191093 21, March 1993.
- ²Wirz, R. and Goebel, D., "Effects of magnetic field topography on ion thruster discharge performance," *Plasma Sources Science and Technology*, Vol. 17, No. 3, Aug. 2008, pp. 035010.
- ³Goebel, D. M., Wirz, R. E., and Katz, I., "Analytical Ion Thruster Discharge Performance Model," *Journal of Propulsion and Power*, Vol. 23, No. 5, Sept. 2007, pp. 1055–1067.
- ⁴Martinez-Sanchez, M. and Ahedo, E., "Magnetic mirror effects on a collisionless plasma in a convergent geometry," *Physics of Plasmas*, Vol. 18, No. 3, 2011, pp. 033509.
- ⁵Leung, K., Hershkowitz, N., and MacKenzie, K., "Plasma confinement by localized cusps," *Physic of Fluids*, Vol. 19, No. 7, 1976, pp. 1045–1053.
- ⁶Hershkowitz, N., Leung, K. N., and Romesser, T., "Plasma Leakage Through a Low- Line Cusp," *Physical Review Letters*, Vol. 35, No. 5, Aug. 1975, pp. 277–280.
- ⁷Bosch, R. and Merlino, R., "Confinement properties of a lowbeta discharge in a spindle cusp magnetic field," *Physic of Fluids*, Vol. 29, No. 6, 1986, pp. 1998–2006.
- ⁸Christensen, T., Hershkowitz, N., and Leung, K. N., "Mass Scaling of Permanent Magnet Line Cusp Plasma Leaks," *IEEE Transactions on Plasma Science*, Vol. 5, No. 1, 1977, pp. 23–26.
- ⁹Matlock, T., Lozano, P., and Martinez-Sanchez, M., "Discharge Chamber Wall Flux Measurements in a Diverging Cusped-Field Thruster," *ESA/3AF Space Propulsion Conference*, San Sebastian, Spain, 2010.
- ¹⁰Hubble, A. and Foster, J., "Spatially resolved study of primary electron transport in magnetic cusps," *Journal of Vacuum Science and Technology A*, Vol. 30, No. 1, Nov. 2012, pp. 011301.
- ¹¹Knorr, G. and Merlino, R. L., "The role of fast electrons for the confinement of plasma by magnetic cusps," *Plasma Phys. and Control. Fusion*, Vol. 26, No. 2, Feb. 1984, pp. 433–442.
- ¹²Jones, R., "Cusp leak width reduction by electron beam injection," *Plasma Physics*, Vol. 23, No. 4, April 1981, pp. 381–383.
- ¹³Anukaliani, A. and Selvarajan, V., "Loss of plasma scaling with magnetic field, pressure and discharge current in a CUSP confined plasma," *The European Physical Journal - Applied Physics*, Vol. 15, No. 3, Sept. 2001, pp. 199–206.
- ¹⁴Wirz, R., "Computational Modeling of a Miniature Ion Thruster Discharge," *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, No. July, American Institute of Aeronautics and Astronautics, Tucson, Arizona, July 2005.
- ¹⁵Mahalingam, S. and Manart, J., "Computational Study of Primary Electron Confinement by Magnetic Fields in the Discharge Chamber of an Ion Engine," *Journal of Propulsion and Power*, Vol. 23, No. 1, 2007.
- ¹⁶Wirz, R., Araki, S., and Dankongkakul, B., "Near-Surface Cusp Confinement for Weakly Ionized Plasma," *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, American Institute of Aeronautics and Astronautics, San Jose, California, July 2012.
- ¹⁷Dankongkakul, B., Araki, J., and Wirz, R., "Electron Loss for Micro-Scale Magnetic Cusp Discharges: A New Perspective," Submitted to Physical Review Letters.
- ¹⁸Boris, J. P., "Relativistic plasma simulations-optimization of a hybrid code," *Proceedings of the 4th Conference of Numerical Simulation of Plasmas*, Washington DC, 1970.
- ¹⁹Araki, S. and Wirz, R., "Particle Simulation of Near-Surface Cusp Confinement of Weakly Ionized Plasma," *IEPC-2013-349, 33rd International Electric Propulsion Conference*, Washington D.C., USA, Oct. 2013.