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Magnetic field structure influence on primary electron cusp losses for micro-scale discharges

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An experimental effort was used to examine the primary electron loss behavior for micro-scale discharges (≤3 cm diameter). The experiment uses an electron flood gun source and an axially arranged alignment of ring-cusps to guide the electrons to a downstream point cusp. Measurements of the electron current collected at the point cusp show an unexpectedly complex loss pattern with azimuthally periodic structures. Additionally, in contrast to conventional theory for cusp losses, the overall radii of the measured collection areas are over an order of magnitude larger than the electron gyroradius. Comparing these results to Monte Carlo particle tracking simulations and a simplified analytical analysis shows that azimuthal asymmetries of the magnetic field far upstream of the collection surface can substantially affect the electron loss structure and overall loss area. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4871724]

I. INTRODUCTION

Magnetic cusps are commonly used for plasma confinement to achieve higher overall density and improved efficiency in lab-scale discharges.1–3 For low-beta plasma, multi-cusp devices have been effective in generating uniform unmagnetized plasma of relatively high densities for applications which include plasma processing, electric propulsion, and experiments for plasma physics research. For these discharges, researchers have consistently defined and demonstrated a semi-empirical “leak width” through which the plasma is lost at the cusp. This behavior has been described by using an ambipolar-type description of the interaction between the ions and electrons within the cusp region.4,5 Several researchers have found the leak width, \( w_l \), to be proportional to the hybrid gyroradius, \( \rho_h \), such that \( w_l \approx 4 \rho_h \approx 4 \sqrt{\rho_i \rho_e} \). This simplified expression is widely used for modeling of discharge devices 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 found in electron bombardment discharges amongst other plasma properties.5-8 The prevailing theory and experimental data show that the primary electron loss half-width is very near the electron gyroradius.5,9,10

To date, the experimental research on the plasma loss for cusp confined plasma and primary electrons have been commonly performed using larger plasma discharges (>20 cm in diameter), that generally have large region of relatively low magnetic fields (~20–60 G) in the center “bulk” region of the device. Such discharges are well-suited for primary confinement since these generally low magnetic fields provide a large magnetic mirror ratio \( (B_{\text{max}}/B_{\text{min}}) \) relative to the high magnetic field values at the cusp (~1000–3000 G). In contrast, micro-scale discharges (≤3 cm diameter) exhibit a lower mirror ratio since the bulk magnetic field is typically much stronger (~200 + G). As such, micro-scale discharges exhibit relatively poor primary electron confinement that leads to plasma discharge behavior that is dominated by primary electrons that are readily lost to the walls.9,11

The objective of this research is to conduct an experiment to investigate the dominant factors that influence the loss of primary electrons in a micro-scale discharge. In particular, the effects of upstream magnetic field structures to the loss behavior in conditions unique to micro-scale confinement. In an effort to analyze the data obtained from the experiment, Monte Carlo simulations and analytical analysis are performed. An improved understanding of the primary electron loss mechanisms will aid in a better description of the loss mechanisms for other plasma species and is necessary to develop efficient micro-scale discharges.

II. EXPERIMENTAL SETUP

The experiment shown in Fig. 1 is a 3 cm ring cusp confinement device designed to examine primary electron collection behavior at a magnetic point cusp and was conducted in the Micro-Scale Plasma Confinement Facility (MSPCF) at UCLA. The experiment utilizes an EGA-1012 electron flood gun which provides a well-characterized electron source. It can produce monoenergetic electrons within the device without the need of a plasma discharge. The gun is spaced a short distance from the chamber in order to not exceed the cathode’s maximum operation pressure of 10⁻⁵ Torr at the emission surface. Injected electrons that enter the device are then confined by multiple ring cusp magnets located behind the radial wall and a cylindrical point cusp magnet behind the downstream “Wall Probe.” Xenon neutral gas is injected upstream through a gas feed plenum to pressurize the device from the facility base pressure (10⁻⁸ Torr) to the desired background pressure.

The permanent magnets are configured to replicate a ring cusp confinement conditions within a micro-discharge device, with a point cusp magnet at the end of the discharge to allow measurements of species loss to a single cusp. The magnetic field is created by 4 ring cusps of decreasing strength in the downstream direction to encourage electrons...
toward the point cusp. The point cusp is a cylindrical samarium cobalt magnet of 6.35 mm diameter \times 6.35 \text{ mm} length, while the ring magnets are composed of individual 6.35 mm \times 6.35 mm \times 2.54 mm samarium cobalt block magnets stacked and oriented as shown in Fig. 1. In the azimuthal direction, each ring magnet around the chamber and electron gun have 18 blocks and 16 blocks, respectively. Similar to other ring cusp discharges, discrete block ring magnets are used in lieu of a continuous ring magnet when there is a possibility for thermal expansion of the discharge chamber.

The current and spatial location of particles that are lost to the point cusp are measured using the moveable “Wall Probe.” This surface serves as the downstream wall for the discharge and has a cup-like probe orifice in the center of the wall to make precision measurements of the current collected at the point cusp. This embedded probe is designed to measure charged particle flux in a non-Debye shielded environment by suppressing far-field impact from biasing of the probe’s collector plate. As diagrammed in Fig. 2, the probe features a 0.4 mm chamfered orifice upstream of the collector plate. The entire assembly is 1.2 mm thick which enables loss measurements very near the point cusp magnet face. The potential contour shows the collector plate biased at \(-40 \text{ V}\) with respect to the orifice plate used to collect the ion saturation current. The result demonstrates minimal disturbance of potential upstream of the orifice plate, and therefore, minimal expansion of the effective collection area. The probe is mounted onto translational stages with capabilities for 2D raster scans of 0.4 mm incremental resolution.

III. EXPERIMENTAL RESULTS

For the data presented in Fig. 3, the electron gun was operated at a constant 35 eV electron energy and 15° divergence angle in absence of magnetic fields. All surfaces in the device including the wall probe collection plate are kept at ground potential. The current density measurements taken at base pressure (Fig. 3(a)) exhibit a current density peak close to the center of the cylindrical magnet with an azimuthal pattern of radially aligned ridges. The loss width measures between \(\sim 1.6–2.0 \text{ mm}\) Full Width at Half Max (FWHM), depending on whether the fringe of the ridge structures is included. These values are more than an order of magnitude greater than the electron Larmor radius of \(\sim 0.1 \text{ mm}\) for the field strength at the collection surface.

Figure 3(b) shows the result with the addition of xenon neutral gas at \(5 \times 10^{-4}\) Torr. These data show a periodic loss structure of coinciding “peaks and ridges” that surrounds the point cusp with a general trend of decreasing current density in counterclockwise direction. Although the
azimuthal position and total number of the ridges remain unchanged from the base pressure result, the spatial distribution of current is significantly altered and the highest current density is located off-axis at a radius of ~2 mm. While the average angular spacing for the 18 block magnets is 20°, the angle between each of the ridges varies from 16° to 27°. This angular spacing and the azimuthal orientation of the ridges is similar for experimental conditions over a range of electron energies and xenon pressures. For all data taken, there are 17 ridges in the loss pattern which does not equal to the 18 block magnets around the circumference of the device. This discrepancy is later discussed in light of the forthcoming analysis.

For the xenon pressure of $5 \times 10^{-4}$ Torr and 35 eV electron energy, the elastic and single ionization path lengths correspond to 0.5 m and 1.5 m, respectively. The mean free path for electron-electron collision is orders of magnitude higher based on conservative estimates using Spitzer equilibration. The total ion current collected at the point cusp by biasing the probe’s collector plate to 40 V is more than two orders of magnitude less than the electron current and has negligible impact to the observed data. In addition, a calculation of the plasma density based on the ion collection indicates that the Debye length of the plasma is much greater than the size of the discharge. This suggests that the plasma is not quasi-neutral and that the primary electron trajectories remain largely non-collisional and non-diffusive.

IV. ANALYSIS AND DISCUSSION

A. Particle tracking simulation

A Monte Carlo electron tracking model is used to gain a better understanding of the observed loss behavior. The model uses analytical equations for magnetic fields induced by permanent block \(^13\) and cylindrical \(^14\) magnets to provide accurate determination of the field for particle tracking. This approach minimizes the error associated with interpolation of the fields, particularly very near the cusps. These equations assume a constant magnetization throughout a magnet, which is reasonable for samarium cobalt. The model also uses a modified Boris integrator that utilizes a predictor corrector algorithm. The algorithm allows for accurate particle trajectories in the highly divergent magnetic fields near the cusp. \(^15,16\)

The presence of an off-axis electron population is predicted from the experimental data in Fig. 3(b). Preliminary comparisons of experimental and particle tracking results showed that the vast majority of electrons injected by the gun are lost to the upstream ring cusps, while only a small fraction reach the region near the point cusp. The simulations also showed that a large number of electrons are needed to obtain reasonable fidelity of the complex structures measured at the point cusp. Therefore, to provide a phenomenological investigation of the annular loss pattern at the point cusp, with reasonable runtimes, primary electrons are injected with an isotropic velocity pattern at the point cusp, with reasonable runtimes, primary electrons exhibit behavior that is more than two orders of magnitude less than the electron current and has negligible impact to the presented data. In addition, a calculation of the plasma density based on the ion collection indicates that the Debye length of the plasma is much greater than the size of the discharge. This suggests that the plasma is not quasi-neutral and that the primary electron trajectories remain largely non-collisional and non-diffusive.

B. Azimuthal drifts

A general trend of decreasing current density in the counterclockwise direction about the point cusp is seen in the following figure:

![Figure 4](image-url)

**FIG. 4.** Simulation result of current density (A/m\(^2\)) for ring magnets composed of 10 and 18 block magnets, and a continuous ring magnet. Within the white contour, the current density values exceed 7 A/m\(^2\).
both the experimental data and computational results shown in Figs. 3(b) and 4, respectively. The effect is caused by a combination of guiding center drifts in the azimuthal direction and the continuous electron loss to the cusps. Among the various guiding center drifts, curvature and grad-B drifts are found to dominate within the region between the point cusp and the adjacent ring cusp. The drifts are primarily a consequence of the high gradient and low magnetic field near the null region inherent to ring cusps (the region of low magnetic fields in Fig. 1). Some representative trajectories from Fig. 5 show that confined electrons generally travel along the magnetic field lines and experience a short azimuthal turning event only while traversing the high drift region. The confined electrons continue to drift azimuthally about the centerline until lost to the chamber walls.

For the conditions simulated in Fig. 5, the azimuthal precession rate is seen to be independent of the number and locations of the ring cusp block magnets. Instead, the precession angle per mirroring cycle is predominantly established by the closest distance between the electron’s guiding center and the null field region. In general, particles trapped on field lines closer to the centerline axis have higher precession rates and vice versa. For that reason, it is unlikely that the azimuthal drift is a major contributing factor to the formation of the peak and ridge structures.

C. Axial drifts

To examine the cause of the peak and ridge structures, an approximate analytical description of the axial drifts of the electrons between the point cusp and the closest ring cusp is discussed. First of all, the azimuthal magnetic field contour in Fig. 6 show a strong periodicity near the ring cusp produced by the discrete magnets that comprise the ring cusp just upstream of the point cusp. This asymmetric field will give rise to drifts in the axial direction across the field lines. From the simulations used to generate the results shown in Fig. 4, the electron loss to the furthest downstream ring cusp on the $\theta$-$z$ plane is shown in Fig. 7. These results show a slight discontinuous zig-zag loss pattern across the face of a ring cusp block magnet. Although the deviations are small, the forthcoming analytical description shows a shift in the guiding center location can translate to larger shifts in the particle

FIG. 5. Representative particle trajectories of electrons confined between the point cusp and an adjacent ring cusp comprised of 10 block magnets (left) and 30 block magnets (right). The red dots around circumference represent the locations of the center faces of each block magnet.

FIG. 6. The (top) total and (bottom) azimuthal magnetic field contours (Gauss) at the ring cusp magnet in the $r$-$\theta$ plane. The field is nearly azimuthally symmetric in the center “bulk” region in comparison to the high level of asymmetry near the cusps.

FIG. 7. Computational results of the particles loss to the ring magnet directly upstream of the point cusp for 18 blocks. The loss width is about twice the electron Larmor radius and traces out a slight periodic zig-zag pattern between individual each block magnets, where “on-face” is closest to the magnet face and “off-face” is the location between magnets.
trajectory further downstream where the field is weaker. Figure 8 shows magnetic field lines traced from the simulated loss locations in Fig. 7 onto the z-r plane. These field lines represent the electron guiding center and show a noticeable difference in paths between different azimuthal planes.

Based on the observations from the preceding figures, a simplified analytical description is used to describe the impact of an axial drift on the collection pattern at the point cusp for an off-axis population of confined electrons between the point cusp and adjacent ring cusp. The combined curvature and grad-B drift for an individual electron can be integrated along the radial direction by assuming its trajectory is purely radial, $dr = dr/v_r$, such that

$$\Delta z_d(r, \theta) = \int (v_{\perp} B + v_r) dt$$

$$= \left[ \frac{m}{q} \left( \frac{v_{\perp}^2}{2} + \frac{1}{2} v_{\parallel}^2 \right) \frac{\vec{R}_r \times \vec{B}}{R_c^2 B} \right] \frac{dr}{v_r},$$

where $m$ is the electron mass, $q$ is the electron charge, and $v_{\perp}$ and $v_{\parallel}$ are the velocity components perpendicular and parallel to the magnetic field, respectively. $R_r$ is the radius of curvature of the magnetic field, and $\Delta z_d$ is the integrated drift in the z-direction diagrammed in Fig. 9. From Eq. (1), the total axial drift of each particle is dependent on both its local pitch angle and the magnetic field structure. However, when a particle undergoes magnetic mirroring at the cusp, the velocity is entirely perpendicular to the magnetic field at the location of reflection, $v_{\perp} = v_0$ at $B = B_0$. Adiabatic invariance is assumed because each particle remains confined for most of its radial trajectory. Therefore, using basic equations for magnetic mirroring, $v_{\perp} \approx v_0 \sqrt{B/B_0}$ and $v_{\parallel} \approx \sqrt{v_0^2 - v_{\perp}^2}$, Eq. (1) can be expressed as a function of only the local magnetic field.

The integrated value then represents the total drift in the axial direction for particles reflected at each spatial location. Since the axial drift is more significant at the high field cusp region, the drift values are scaled to account for the expansion of the field lines in the radial direction, $\Delta z_w$; this is approximated by assuming constant magnetic flux in the $z$-direction at each radial cross-section.

$$\Delta z_w = \Delta z_d \frac{B_r}{r_0 B_w}.$$  \hspace{1cm} (2)

Here, $r_w$ and $B_w$ represent the radius of the chamber wall and the associated magnetic field, respectively. As diagrammed in Fig. 9, $\Delta z_w$ is an effective axial drift displacement across field lines normalized to the condition at the ring cusp wall. In addition, the total value is doubled to account for the reverse trajectory after the reflection. The final expression can then be rewritten as

$$\Delta z_w(r, \theta) = 2 \frac{m v_0}{q B_w r_0} \int_0^{r_0} \left( \frac{\vec{R}_r \times \vec{B}}{R_c^2 B} \right) \left( 1 + \frac{B}{B_0} \right) r dr,$$  \hspace{1cm} (3)

where $r_0$ is the radial location of reflection. Figure 10 is a contour plot of Eq. (3) and represents the normalized axial drift for electrons reflected at each spatial location within the plane. The result indicates the existence of a non-negligible alternating axial drift for electrons reflected near the ring cusp. There is a pair of forward and backward drift regions for each off-face block magnet region very near the ring cusp. At the outer edge, the contour values predict half the maximum axial displacement for electron loss to the ring.
cusp and is consistent with the simulated results shown in Fig. 7. Although the analysis is inaccurate near the center region where particles are relatively unconfined, the contribution to the integral is negligible due to the scaling factor.

The overall effect of the axial drift is a slight cross field transport of electrons that are reflected close to the ring cusp. These same electrons will have lower magnetic moments which imply that they are less confined, and thus are more likely to be lost at the subsequent point cusp. Electrons that experience a forward axial will follow field lines that terminate to larger radii at the point cusp, contributing to the radially extended ridges in the loss structure. A backward axial drift causes electrons to follow field lines that pass further into the null region where their motion becomes more “non-invariant,” leading to an increase in the diffusion rate of the electrons’ pitch angle. This causes an increase in the loss rate of the originally confined electrons to the point cusp, which contributes to the current density peaks in the loss structure.

D. Effect of azimuthal variation in magnet strength

Several possible experimental inaccuracies were investigated to understand the discrepancy between the 18 blocks ring magnet and the 17 ridges measured in the experiment. The most probable explanation is a reduction in the effective magnetic field strength of one of the block magnets at the downstream ring cusp. As simulated in Fig. 11, a 25% reduction in the magnetic field of one of the 18 block magnets in the array can result in 17, instead of 18, ridge structures. Using the analytical description from Eq. (3), Fig. 12 shows that the presence of a weakened magnet will cause the region very near the magnets to essentially “skip” a pair of forward and backward drift regions near the weakened magnet, which would lead to the loss of a ridge structure at the point cusp. In addition, the weakened magnet creates much larger drift values that also affect the surrounding cusps and could lead to greater losses at the point cusp in relation to this azimuthal position. The variation of angular separation and length of the ridge structure in the experimental data indicate a non-uniform spacing and/or magnetization of the block magnets. This uncertainty, coupled with the possibility of a small gap between the block magnet face and the cylindrical chamber, can potentially create a magnetic field deficit adequate for similar behavior with the simulation result. These effects of the variation in magnet strength along the ring cusp is further evidence of the importance of the upstream field structure.

V. CONCLUSION

A 3 cm ring cusp confinement device is used to investigate the primary electron loss behavior at a point cusp in a micro-scale discharge. Measurements at the cusp are the first to exhibit a complex pattern and suggest that the electron loss behavior to the cusp is strongly influenced by the upstream magnetic field structure. The resulting collection radius is over an order of magnitude greater than the electron gyroradius, which is in contrast to conventional descriptions that cusp collection for plasma and electron discharges is primarily determined by the magnetic field at the cusp. Computational simulations and analytical descriptions are used to understand the mechanisms responsible for the multiple features exhibited in the experimental data. In particular, azimuthal asymmetries of the electron injection and magnetic field far upstream of the collection surface can substantially affect the loss structure and size.

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