

Laser-Collisional Induced Fluorescence Study of Electron Distributions in a Magnetic Cusp

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Abstract: The spatial distribution of electrons in a magnetic cusp region was measured using laser-collisional induced fluorescence (LCIF). These spatial density profiles were used to study the plasma leak width. Leak widths were found to scale with the hybrid gyroradius, with a constant of proportionality that was found to increase with pressure, consistent with theoretical predictions.

I. Introduction

The transport of plasma through magnetic cusps remains a poorly understood process. Ion sources such as gridded ion thrusters, both line and ring cusp magnetic circuits have been used successfully to improve the ionization efficiency of these sources. This is achieved predominantly by increasing the residence time ionizing electrons thereby increasing the likelihood of an inelastic electron neutral collision. The geometry of the magnetic field is such that electron losses occur predominantly along the magnetic cusps rather than between cusps, where the field is primarily normal to radial flow. In this regard, the magnetic cusps establish the effective loss surface for plasma electrons in particular. Because this loss area affects not only ion source efficiency but also stability and thermal energy transport, it is of great interest to understand not only the nature of the electron flow through the cusps but also the effective area projected to the plasma by the magnetic cusps. Probing the magnetic cusp region with electrostatic probes is in general problematic owing to sheath perturbation and shadowing effects. In this latter effect, the body of the electrostatic probe can actually obstruct the flow of charge in and out of the cusp. Furthermore, Langmuir probes are difficult to use in strong magnetic fields due to the associated complex electron motion near the probe. The structure of the magnetic cusp proves an additional

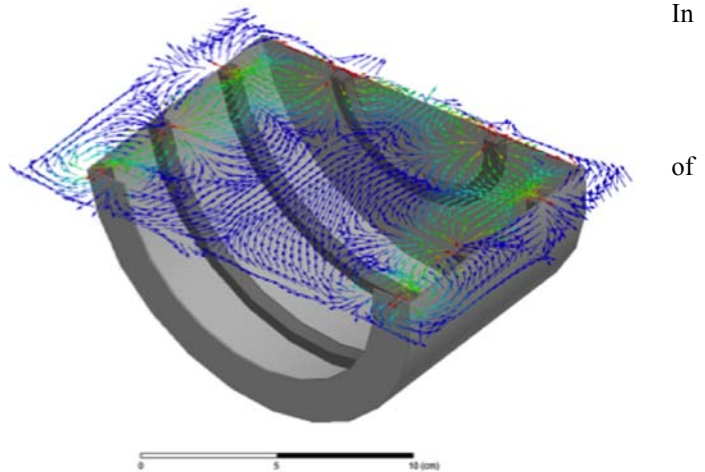


Figure 1. Cutaway of ring cusp discharge chamber. Magnetic cusp feature is apparent at magnetic rings.

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challenge: the magnetic field direction changes from near-normal at the anode surface (purely in the r-direction) to perpendicular (purely in the z-direction); this prevents orienting a planar probe in such a way to avoid the probe body from blocking lines of guiding center transport. In addition, the plasma potential in the cusp region is not spatially uniform due to the presence of the anode sheath, and the probe bias will disturb the local plasma [1].

It is possible to determine electron behavior at distances sufficiently far enough away from the magnetic cusp. Here if Larmor radii are sufficiently large compared to probe diameter, then a biased probe can be used to collect electron current representative of electron flows. Such “pre-cusp” measurements are important in that they yield a great deal of insight into the development of the electron flow field just above the magnetic cusp. This pre-cusp region is also important in that the electron flows established in these regions can impact the plasma uniformity both radially and axially. Figure 2 illustrates spatial variations in electron density mapped in the vicinity of cusps as well as in bulk plasma. Also shown here is the vector field associated with the magnetic field. The exit plane is located in the plane above magnet ring four. As can be seen the plasma is spatially nonuniform. What is most interesting is the apparent electron “flow” fields established between the bulk plasma and the magnet rings. The plasma flows are clearly shaped by the magnetic field. At ring two, the magnetic cusp structure is apparent with the electron density gradient taking the shape of the magnetic cusp even though the associated magnet ring is centimeters away. Also apparent in the magnetic bulge which develops between cusps. This field curvature is also reflected in the spatial distribution of plasma in the bulk, essentially pushing the plasma toward centerline. Distorted flow is observed at rings 3 and 4 as well. While cusp development extending from the bulk plasma to ring 3 is apparent, such structure is absent at ring 4. The orientation of ring 4 is with magnetic vector pointed upstream. The supposition of the field contribution of this ring and ring 3 gives rise to the formation of a virtual cusp that does not terminate at any magnet ring. The lost cone associated with this virtual cusp is labeled “Loss Cone 1” while the true loss cone of ring 4 is labeled “Loss Cone 4.” The geometry associated with rings 3 and 4 affects overall effective collection area at the anode. Indeed, it can be argued that effectively ring 4 is magnetically isolated in this case thus reducing the effective anode collection area. Figure 3 illustrates the distribution of current at the various rings. Consistent with the magnetic map, ring 4 is essentially isolated, accounting for less than 10% of the total discharge current. While such a reduction may be useful for improving efficiency through improved electron confinement, it often makes the discharge susceptible to instabilities at higher operating discharge current owing to inadequate anode surface area. As can be seen in Figure 2, probe measurements indeed can yield great insight into the behavior of the discharge away from the high field regions.

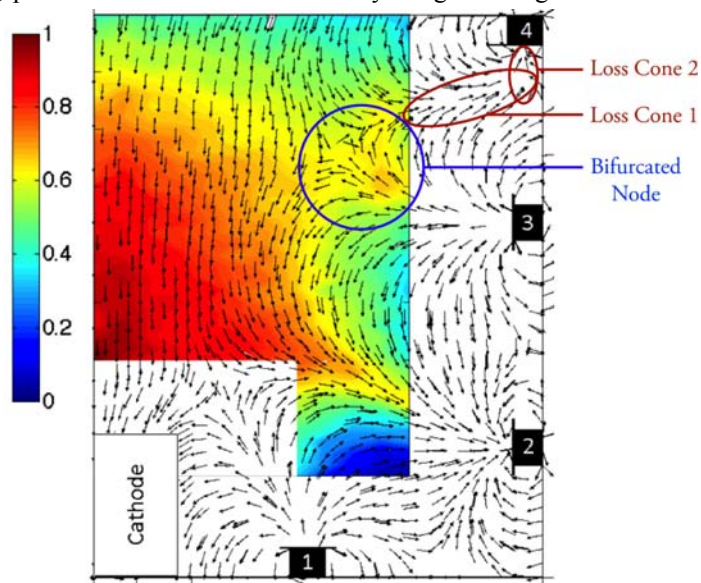


Figure 2. Electron Density map of bulk plasma and pre-cusp regions of a 20 cm ion source containing 4 alternating polarity magnet rings.

The high field regions however determine ultimately the nature and magnitude of the loss area and therefore a noninvasive diagnostic is needed to study this poorly understood region.

It is possible to nonperturbatively infer the electron distribution within the magnetic cusp by laser based methods. For example, Thompson scattering can be used to determine the electron density in nonuniform plasmas provided the plasma density is sufficiently high $\sim 10^{11}/\text{cc}$, which exceeds values expected in the magnetosheath region of a magnetic cusp [13]. Another laser-based method capable of measuring the plasma density at lower densities the laser-collisional induced fluorescence (LCIF). The LCIF method has recently been used to make spatially resolved electron density and temperature measurements in high magnetic fields [2]. This diagnostic has been well developed for helium plasma [3]. In this

technique as applied to a helium plasma, a pulsed 389 nm laser is used to populate the excited 3^3P state through pumping of the metastable 2^3S state in helium. Electron collisions with the excited 3^3P state redistribute the pumped electrons to surrounding states (3^3S , 4^3D , and 3^3D). The distribution of these three states is dependent on electron density and temperature. The redistributed states relax via emission to the 2^3P state. Electron temperature and

density can be calculated from this emission.

Determining electron density and temperature from emission spectra requires the use of a collisional radiative model (CRM) [3]. In helium, the emission ratio of the 3^3D to 2^3P (588 nm emission) to the 3^3P to 2^3S (389 nm emission) transitions is linearly related to electron density. The energy separation between the 3^3D and 3^3P states is only about 0.07 eV, so this ratio is largely independent of electron temperature [3]. This allows a measurement of electron density that is not only nonperturbative of the test plasma, but independent of electron temperature.

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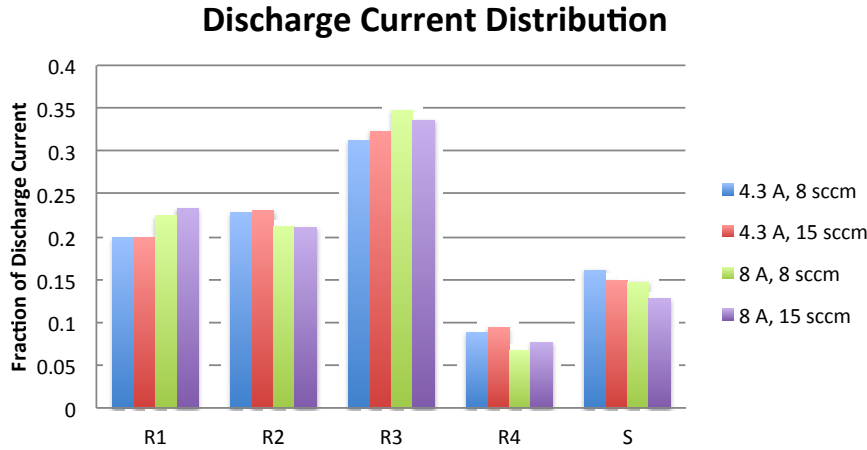


Figure 3. Current distribution at each magnet ring and the anode shell (S). Ring 4 (R4) accounts for less than 10 percent at all conditions investigated.

principle, once electron density is determined, the electron temperature may be determined from the ratio of the 4^3D to 2^3P (447 nm) transition to the 3^3D to 2^3D (588 nm) transition. This ratio depends on both electron temperature and density [3]. Unfortunately, in this experiment plasma density was too low to observe sufficient intensity of the 447 nm transition to calculate electron temperature. Instead, a fixed Langmuir probe was used to give a general estimate of plasma temperature in the bulk discharge.

II. Experimental Setup

Accommodating the LCIF diagnostic required a re-imagining of traditional multi-cusp anode geometry. Optical access was required to allow the laser beam to pass above the anode surface and probe the cusp region. This would be difficult to achieve in a conventional ion source, where the fluorescence would be visually blocked from traveling to the detector by the magnet rings. The key difficulty lies in implementation—in order to illuminate the cusp region, the laser sheet must lie in the plane of the magnetic cusp, with the fluorescence image collected normal to this plane. Instead of a conventional style discharge chamber, in this work the plasma distribution at a magnetic cusp was studied in an Inverted Multi-Cusp Anode (IMCA)—composed of a cylindrical anode in which magnet rings of alternating polarity are affixed externally. The anode was 3.2 cm in diameter and 17.8 cm long with five alternating polarity NdFe permanent magnet rings, each of which were covered with a thin mild steel, electrically isolated collection electrode. The intervening material between the magnet rings was also electrically isolated so that collected current at various anode surfaces could be made independent. The anode was immersed in a helium glow discharge plasma supplemented by a thoriated tungsten filament. Pictures of the magnetic and spacer segments are given in Figures 2.a and 2.b, respectively. A photograph of the assembled anode is shown in Figure 4. The electrical leads for each segment of the anode are fed through the center bore of the structure. The segmented anode was supported by threaded rods isolated from the main body with glass tubing.

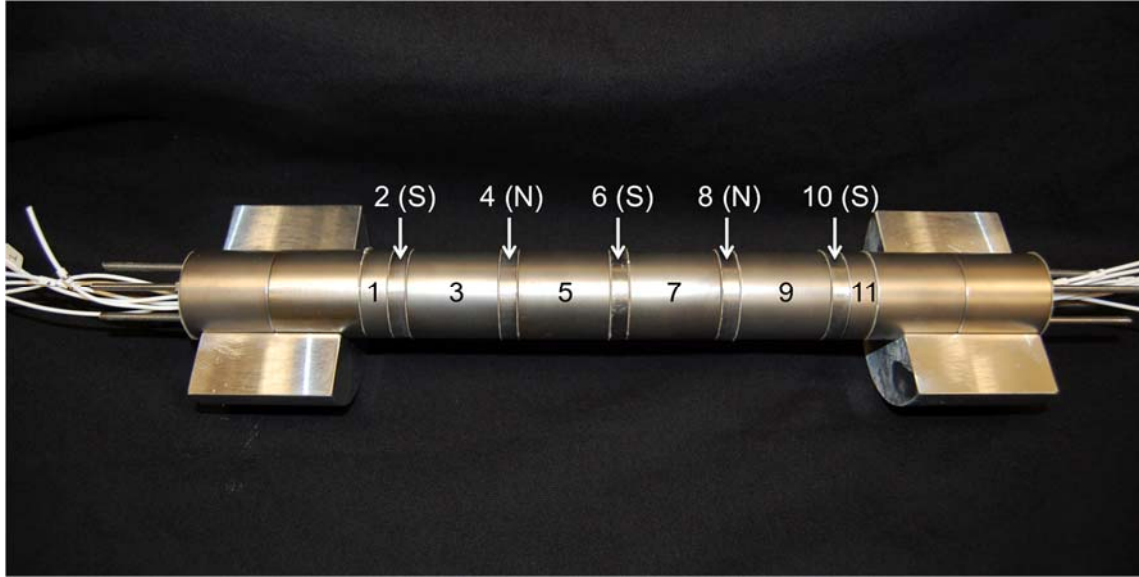


Figure 4: Photograph of assembled anode.

A schematic of the anode setup is shown in Figure 5. The laser sheet passes above the anode at the 12 o'clock position. Fluorescence from this excited region is imaged using an intensified CCD camera. A Langmuir probe was mounted above the anode in a relatively field free region to assess local electron temperature and plasma potential. An electrical schematic of the experiment is given in Figure 6. The anode was pulsed at 20 Hz positively relative to ground for a duration of 160 μ s. Depending on chamber pressure and pulse voltage, steady-state current draw near the end of the pulse is between about 200 and 500 mA. A bias applied to the anode was used to collect afterglow current following the voltage pulse. Three operating points were investigated for this study. They are outlined in Table 1.

Operating Point	Conditions
1	Pressure: 10 mTorr Pulse Voltage: 1 kV Discharge current: 440 mA
2	Pressure: 20 mTorr Pulse Voltage: 0.82 kV Discharge current: 450 mA
3	Pressure: 30 mTorr Pulse Voltage: 0.40 kV Discharge current: 200 mA

Table 1: Operating points.

A pulsed Nd:YAG laser was used to pump a tunable optical parametric oscillator (OPO), which generated a 777 nm beam. This beam was doubled in frequency to the 388.5 nm laser output used for plasma interrogation. The output beam was passed through an array of beam-shaping optics to produce a planar beam, which was then aligned to pass over the surface of the inverted multi-cusp anode at the 12 o'clock position, before being collected at a beam dump. Perpendicular to the passage of the beam, an intensified charge-coupled device (ICCD) camera was mounted externally and focused on the region through which the probe beam was passed. The voltage pulse applied to the anode was used to trigger the ICCD camera at the chosen interrogation time.

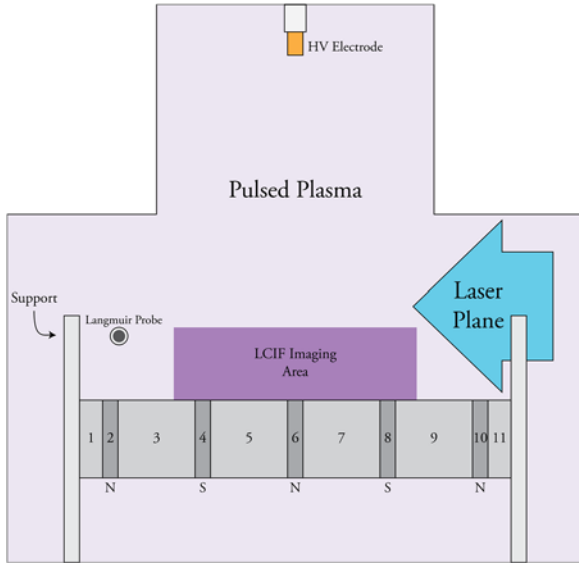


Figure 5: Schematic of IMCA setup.

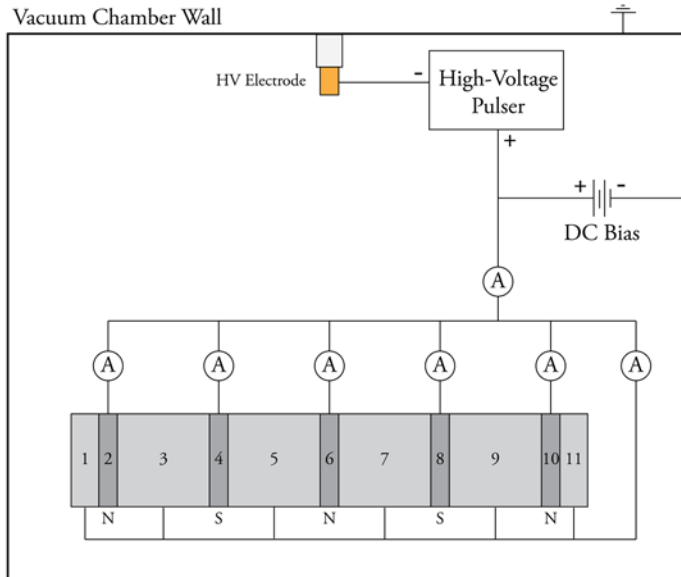


Figure 6: Electrical schematic of IMCA setup.

III. Results

Time-resolved current and voltage outputs were measured by LeCroy Waverunner 6001a oscilloscopes, with a

sample rate of 5 GS/s. Currents were measured by Pearson 149 coils and voltages with high-voltage probes. The anode voltage and current draw are plotted as a function of time in Figure 7 for a typical case. LCIF data were acquired at two time points in time for all operating conditions studied: 150 μ s, in the steady-state region shortly before the end of the pulse, and at 170 μ s, in the afterglow, 10 μ s after the pulse ends. A DC bias of 30 V was maintained between the anode and ground at this time point to maintain the afterglow plasma. The 150 μ s time step occurs after the metastable population in the cusp region has reached a steady-state, as determined from monitoring the 388 nm transition emission. During the afterglow, the potential difference between the anode and plasma was approximately 20 V, as inferred using a Langmuir probe. Only afterglow data is presented herein.

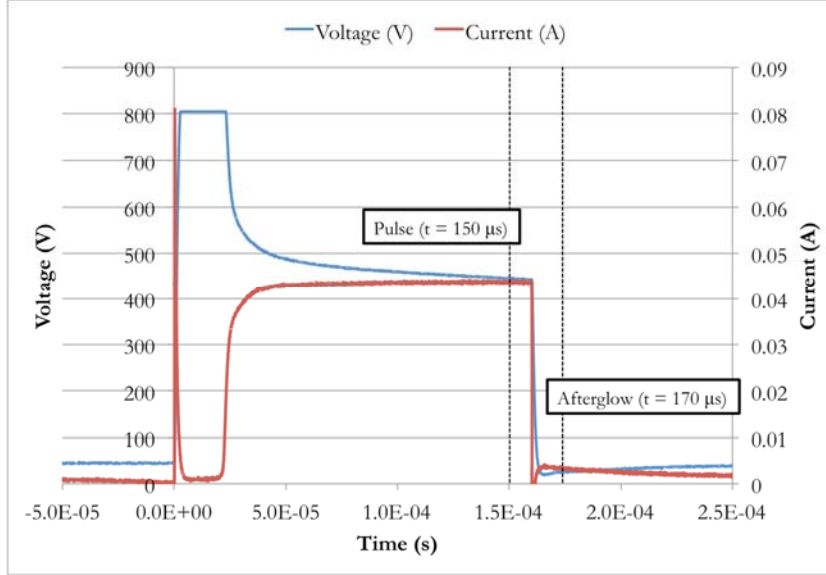


Figure 7: A typical anode current and voltage vs. time at 10 mTorr. □

Pearson coils monitored the current draw on four of the five magnetized segments and the spacers, as well as total current draw. This allowed for an immediate assessment of the effective magnetic confinement at the anode at various operating points. Current was measured from anode segments 2, 4, 6, and 8. In this work, the non-magnetic spacer segments (1, 3, 5, 7, 9, and 11) were tied together to yield the total current draw from all the spacers, I_{sp} . The remaining magnetic segment current draw was determined by:

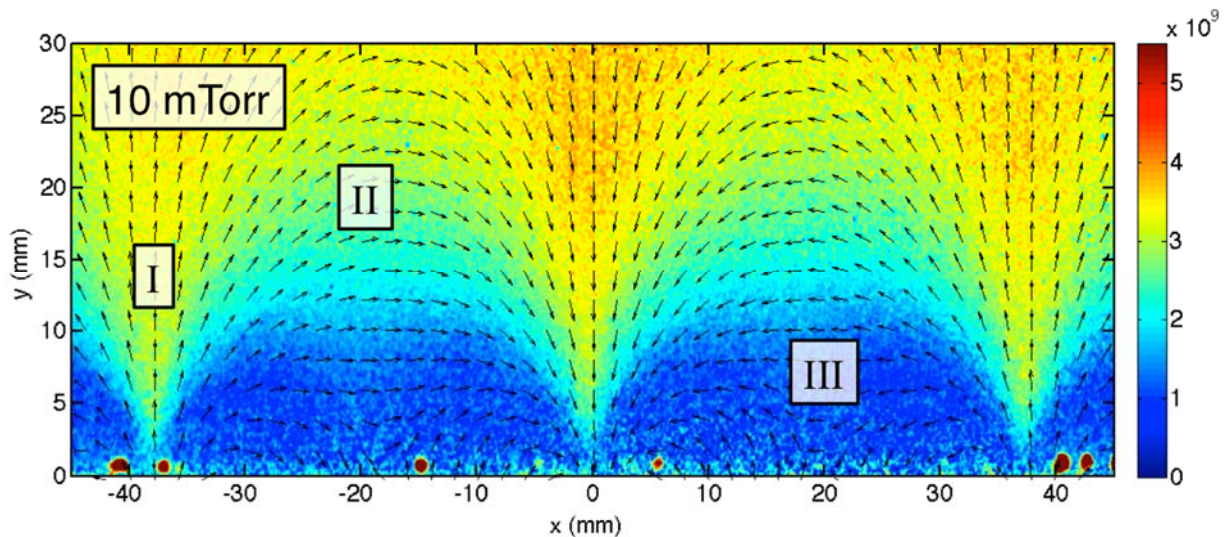
$$I_{10} = I_{tot} - I_{sp} - I_2 - I_4 - I_6 - I_8 \quad (1)$$

A. Electron Density Measurements

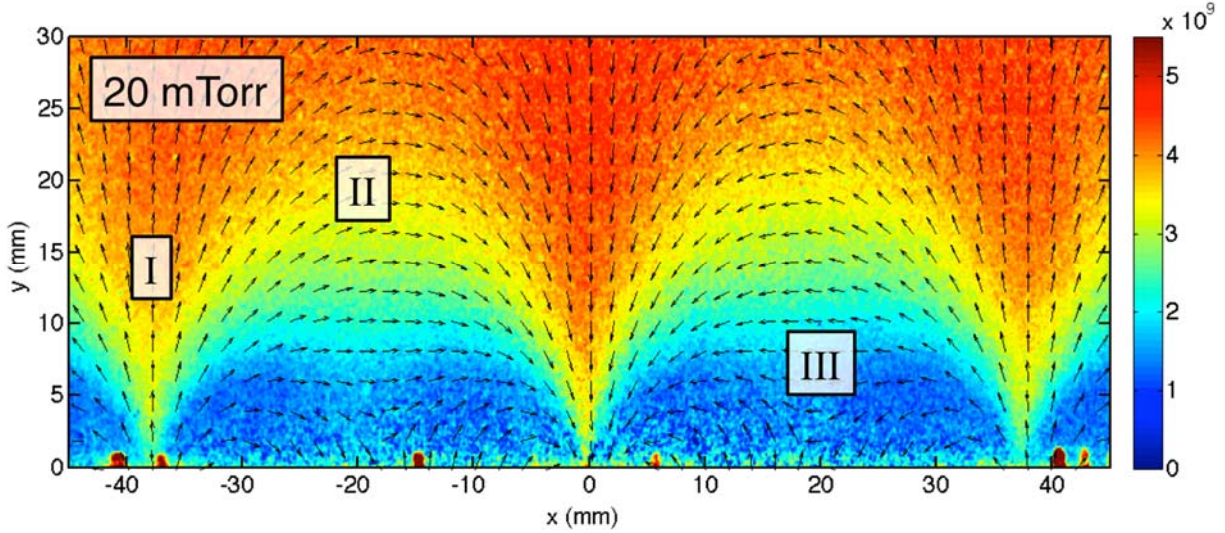
To investigate the behavior in plasma afterglow, a 50 V DC bias was applied between the HV electrode and the anode to sustain the plasma after the pulse. LCIF images were then acquired 10 μ s after the pulse ended. The current draw at the anode was approximately 30 mA at 10 mTorr pressure. Discharge voltage (that is, the voltage drop between the anode and ground) was approximately 30 V, with a plasma potential that was positive of the anode by 9V suggesting that the electrons are falling into the anode about this voltage.

LCIF images taken in the afterglow over the inner three magnet rings at 10 and 20 mTorr are shown in Figure 8.a and 8.b. These images represent a snapshot of electron flow through the magnetic cusps. Superimposed on each image is an experimentally determined magnetic field vector plot. Clearly, the spatial distribution of the electrons mirror that of the magnetic field lines—essentially shaped by the magnetic field. These images are consistent with theoretical predictions of the spatial distribution of electrons in the magnetic cusp. Indeed, consistent with theoretical predictions, one can identify three regions characteristic of multicusp systems. These are labeled in Roman numerals in Figure 8. Region I represents the cusp structure itself with its characteristic funnel shape. On

axis, the field is nearly parallel and those particles with low pitch angles are readily lost along the axis. As can be seen in both figures, the electron density is peaked near the centerline of the magnetic cusp. This is consistent with magnetic cusp 1-D profiles inferred from electrostatic probes. [6,7] The width of the peak decreases however as one approaches the anode. This is due to the variation in the magnetic gradient off axis as one approaches the anode. Off axis, radial field gradients increase and charged particles can become trapped. Here cross field diffusion rates are low so that plasma density tends to drop with distance off axis. Region II represents the intercusp region. Here, electrons tend to be trapped, mirroring between adjacent magnetic cusps. Flow normal to this region toward the anode is restricted because the field is essentially parallel to the anode in this region. The final region, region III, designates the region immediately below the intercusp region. This region is relatively devoid of electrons as diffusion into these regions is arduous, requiring diffusion or scattering across the intercusp region first. Also observable in figure 8 is the variation in the spatial distribution with increasing pressure. As can be seen here, with increasing pressure, magnitude of the electron density throughout the system increases. Additionally, the spatial extent the region of high density on axis also expands. The attachment of the cusp structure at the anode is also more distinct in comparison to the 10 mTorr case. The penetration of plasma deeper into the cusp is readily apparent. The width of the attachment of the cusp at the anode surface also increases. The volume of region III decreases as the intercusp region expands toward the anode. These changes in spatial length scales with increasing pressure are attributed to increased diffusion. A doubling of the pressure increases the transverse diffusion coefficient to first order by a factor of 4. In this regard, regions that were poorly populated with electrons are filled as collision drive electrons across field lines into those regions. It should also be pointed out that with increased pressure, an electron population near the anode surface is also observable. The origin of this plasma is most likely attributed to plasma diffusion through the intercusp field region II. The intercusp field is weakest midway between cusps. It is not surprising therefore that the populating of region III is derived from plasma diffusion from this mid-region.



(a) Electron density (cm^3) at 10 mTorr.



(b) Electron density (cm^3) at 20 mTorr. □

Figure 8: Electron density spatial maps obtained with LCIF at $t = 170 \mu\text{s}$.

B. 30 mTorr

An additional operating condition was tested at a pressure of 30 mTorr. This was the highest pressure under which the plasma could be stably with the high voltage pulser. Operation could only be stably maintained at a pulse voltage of approximately 400 V, resulting in a 50% reduction in discharge current. The reduced discharge current made it difficult to compare the electron density profiles obtained at this operating condition with the 10 and 20 mTorr conditions discussed above. Electron density above the inner three magnet rings was obtained with LCIF during the in the afterglow ($t = 170 \mu\text{s}$) and is plotted in Figure 9.

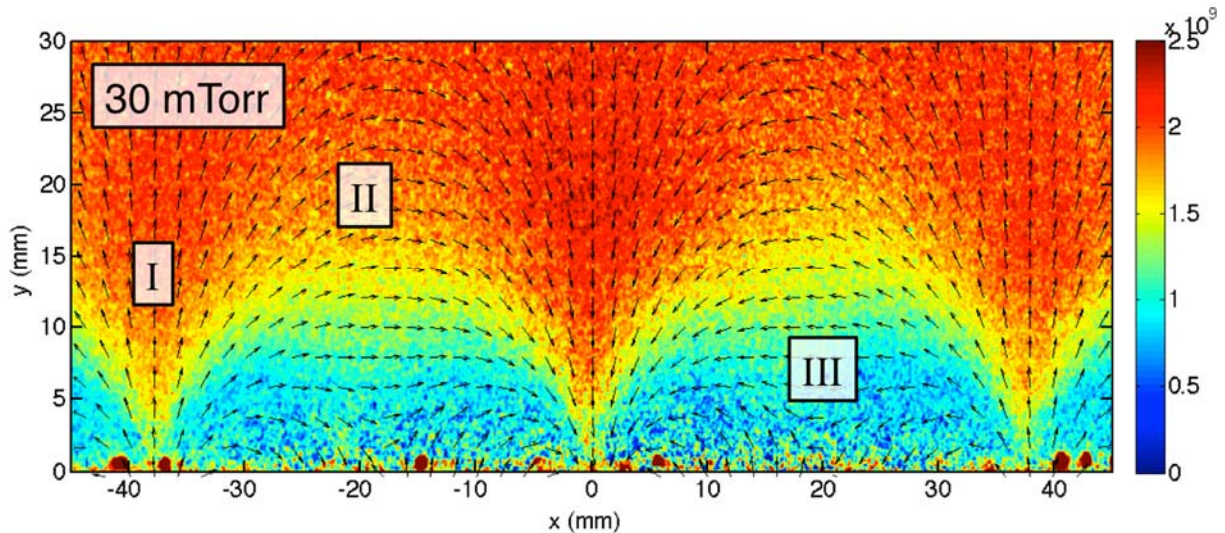


Figure 9: Electron density spatial maps obtained with LCIF at 30 mTorr.

As can be seen in Figure 9, the cusp region at 30 mTorr has further enlarged. Additionally, the cusp region appears more integrated with the interscusp region. The profiles still follow the field lines and the three regions of

interest are still recognizable. Plasma penetration into Region III from Region II is readily observable as is an electron population near the anode surface. The cusp attachment point near the anode surface is also wider. The density gradient appears to smooth out along the axis of the cusp as well. Indeed, the zones of highest electron density along the cusp axis penetrate deeper into the cusp, approaching the anode wall as the pressure increases. In this regard, with increasing pressure, the density gradient appears to shift toward the anode surface. These affects are attributed to collisions with neutral particles. Langmuir current-voltage traces taken in the afterglow are plotted in Figure 10. From these traces we can calculate the bulk plasma electron temperature and plasma potential at the 30 mTorr operating condition. Again, these values are representative of the bulk discharge and not the cusp region. Overall, the electron density, as measured with LCIF, was low compared to the 10 and 20 mTorr cases, which is expected since discharge current was reduced (reduced voltage).

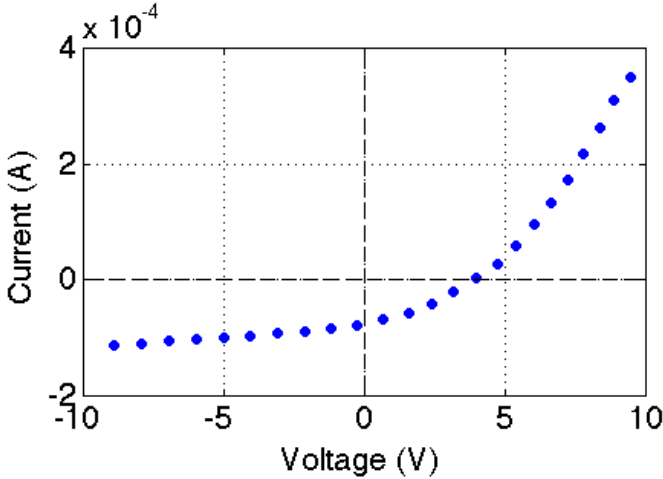


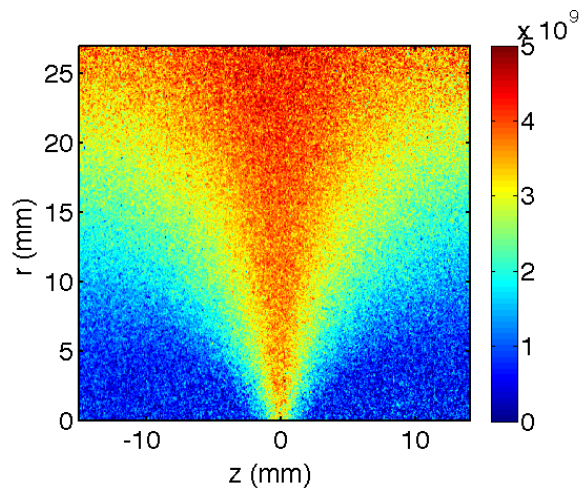
Figure 10: Langmuir probe IV traces at $t = 170 \mu\text{s}$ at 30 mTorr pressure.

C. Leak Width

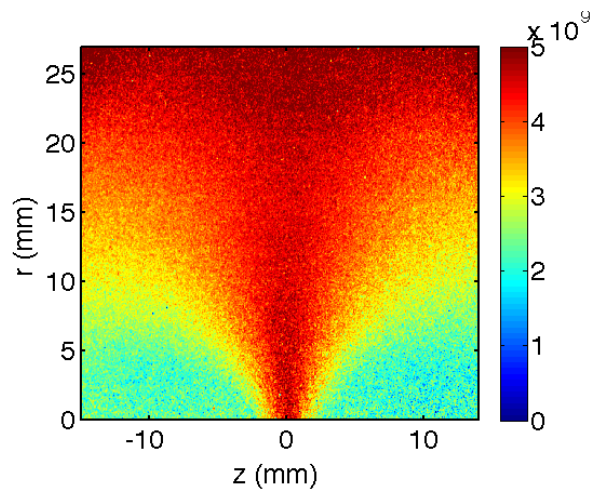
One characteristic of plasma flow through a magnetic cusp is the converging nature of the flow field. This electron flow field is modified in a manner self consistent with magnetic field geometry and local electric fields present. One may define a plasma leak width at any point along the axis of the cusp. Defined in this manner, the leak width is essentially a measure of the cusp opening or aperture size to plasma flow at that particular axial location. As inferred from the density profiles, the leak wide reduces to some limiting value at the anode. In this context, the leak width is not the loss area, rather it is a measure of the loss area at a particular location within the cusp. That is to say the particle flow at some axial position z , must pass through the leak width to reach spatial locations closer to the anode surface. The leak width at the anode itself does have special significance however in that its projection into the bulk plasma represents the effective collection area that the anode projects to the bulk plasma for those electrons that have very low incident pitch angles. In this respect, the leak with is effectively the loss area if one neglects radial components of the magnetic field, which has the effect of spatial broadening. Spatial variation in the leak width along the axis of the cusp yields insight into the nature of the density gradient—indicating attenuation effects due to mirroring for example. One of the fundamental questions of plasma transport in magnetic cusps asks the question how does leak width vary within the magnetic cusp as a function of position. Additionally, related to this question is one important to the design of efficient plasma sources: how is leak width related to the effective loss area of the magnetic cusp? A number of previous studies aimed at quantifying leak width are described in the literature, often with contradictory results [4-10]. Electron density profiles obtained via LCIF have afforded a means of quantifying this width without plasma perturbation, in the cusp region extending to the anode surface.

The close-up images of electron density in the afterglow were used for this analysis and are shown in Figures 10.a-c. In order to infer the leak width as a function of axial position along the axis of the cusp, a Gaussian fit was made to the density profile at discrete axial locations using commercially available peak analysis software. In this context, the full width half maximum is defined as the leak width. A sample peak with Gaussian fit is shown in Figure 12.

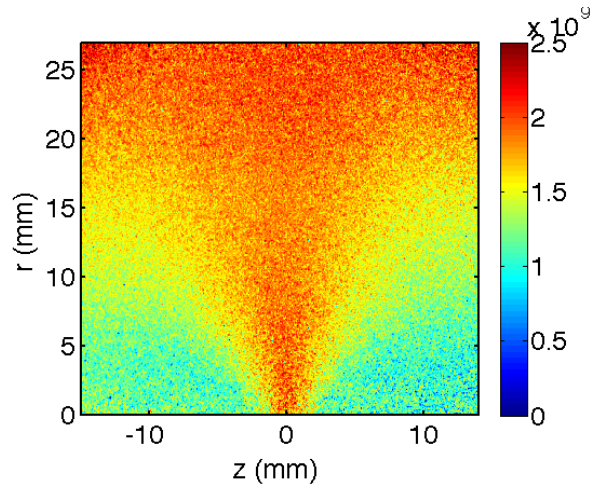
This peak was taken at $z = 5$ mm at 10 mTorr.



(a) 10 mTorr



(b) 20 mTorr



(c) 30 mTorr

Figure 11: Close-up images of electron density at $t = 170 \mu\text{s}$ for 10, 20, and 30 mTorr pressure.

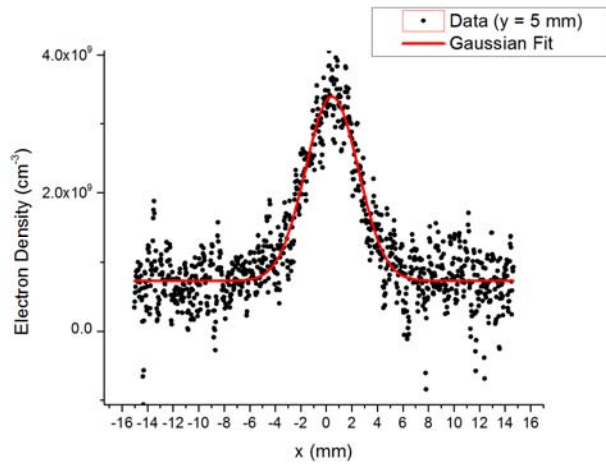


Figure 12: Sample peak with Gaussian fit taken at the center cusp at 5 mm above the anode surface and 10 mTorr pressure.

The FWHM of the Gaussian fit is plotted against height above the anode for the 10, 20, and 30 mTorr cases in Figure 13. Error bars stem from the error in the Gaussian fit to the electron density profile.

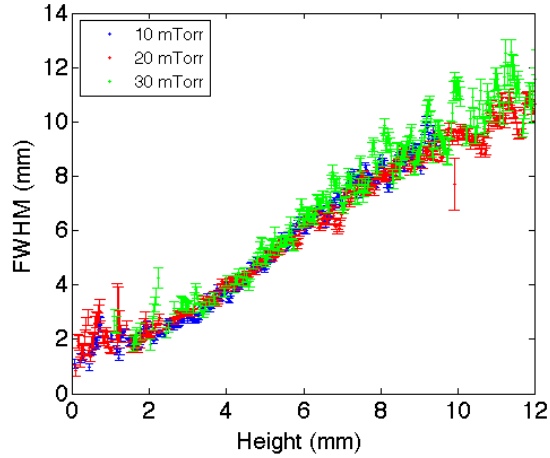
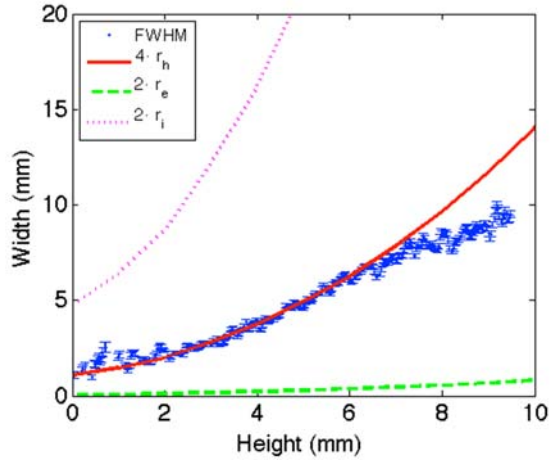
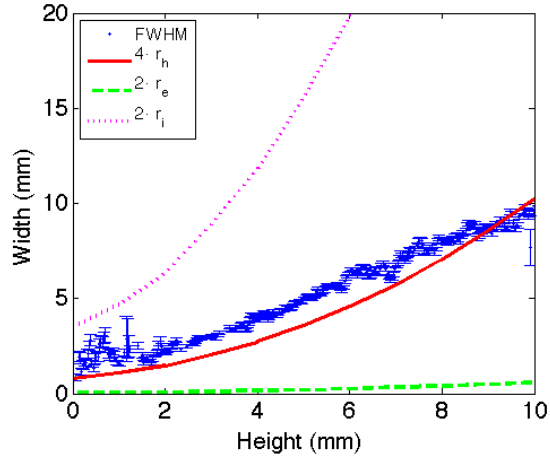


Figure 13: FWHM (mm) versus height above the anode (mm) at 10, 20, and 30 mTorr.

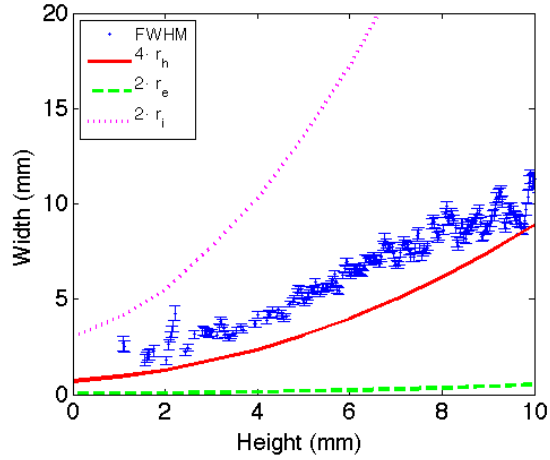
Previous research has given the physical leak width values ranging from twice the electron gyroradius to twice the ion gyroradius [4-10]. Many studies suggested four times the hybrid gyroradius, which is the geometric mean of the ion and electron Larmor radii. The electron and ion Larmor gyroradius was calculated from the electron temperatures determined by the bulk Langmuir traces and the measured magnetic field. Ion Larmor radius is determined using the Bohm speed [7]. Widths are plotted against twice the electron gyroradius, twice the ion gyroradius, and four times the hybrid gyroradius for 10, 20, and 30 mTorr (Figure 14.a-c).



(a) 10 mTorr



(b) 20 mTorr



(c) 30 mTorr

Figure 14: Measured FWHM (mm), twice the electron gyroradius, four times the hybrid gyroradius, and twice the ion gyroradius versus height above the anode surface (mm).

In all cases investigated here, the measured leak width appears to track most closely in magnitude and form, the hybrid radius. This finding is consistent with observations made by Hershkowitz and colleagues in multipole and picket fence sources. The agreement does appear to degrade with increasing pressure. This pressure effect may be intuitively thought of as a consequence of higher collisionality. Indeed, the characteristic collisional mean free path is of order the length scale of the cusp (cm). As pressure rates go up, collision rates also increase. This pressure scaling appears to be consistent with theoretical studies aimed at elucidating the functional form of the leak width. Bosch [11] and Koch [12] showed that the leak width is expected to scale inversely with the electron and ion mean free paths with a constant of proportionality, k :

$$k = \frac{1}{\lambda_e \cdot \lambda_i} \quad (2)$$

In this regard, the constant of proportionality between the leak width and hybrid gyroradius is pressure-dependent. The ratio of profile FWHM to the hybrid gyroradius was calculated for the central cusp in the plasma afterglow at

10, 20, and 30 mTorr. This ratio is the constant of proportionality, k , which relates the hybrid gyroradius to the leak area, and is plotted as a function of height above the anode for all three pressures in Figure 16. As can be seen here, the ratio is roughly constant for distances between 0 and 6 mm. More scatter is observed in the high pressure case. Its interesting to note that the 10 and 20 mTorr cases appear to break in trend above 6 mm. This trend may be a consequence of changes in the magnetic field profile where the off axis component increases with distance above the anode; that is, beyond 6 mm, the cusp fields are no longer predominantly axial. Off axis field components naturally broadens the profile. The leak width interpretation is most meaningful if the field is predominantly axial.

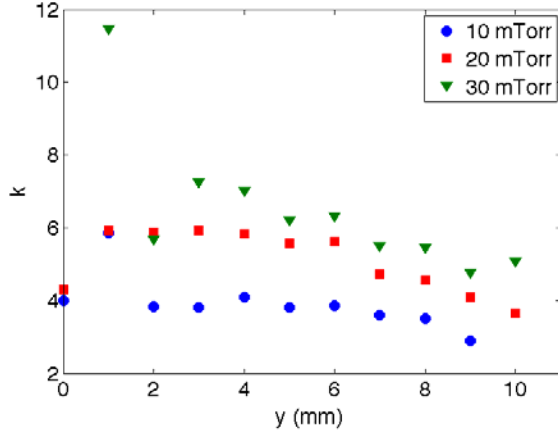


Figure 16: Constant of proportionality k vs. y (mm) at 10, 20, and 30 mTorr.

If one takes the average value of k for each pressure and plots it as a function of pressure, it can be more clearly shown that this parameter increases with pressure as current theory put forth by Bosch and Koch asserts. This variation is shown in figure 17 for the 3 pressure points.

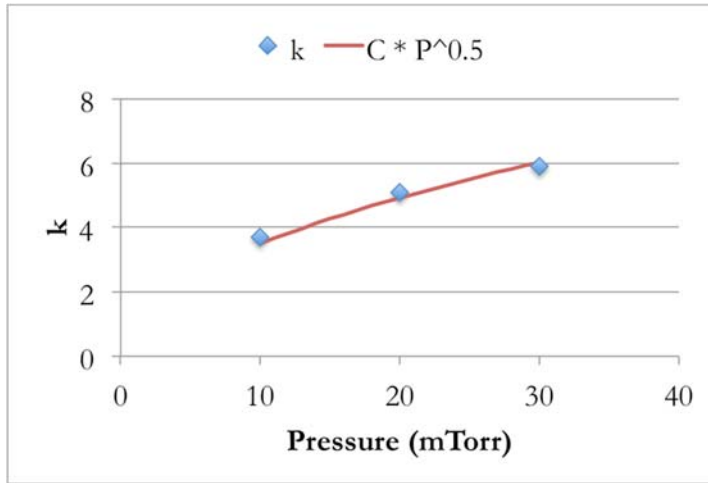


Figure 17: Constant of proportionality k vs. pressure (mTorr), which scales roughly with P .

One would expect the value of k to vary as the square of the pressure owing to its inverse relationship with the electron and ion mean free paths. This behavior does not hold in this case with the true trend varying between linear and the root of pressure at least for this limited set of data.

IV. Conclusions

Spatial maps of electron density in the magnetic cusp region above an inverted multi- cusp anode were obtained

using Laser-Collisional Induced Fluorescence. Unlike probe measurements, the LCIF technique offers the prospect of accurate measurement of electron density without perturbation to the plasma sheath. Electron density spatial profiles were obtained in the region above three magnet rings were obtained for a pulsed discharge at 10, 20, and 30 mTorr in a helium afterglow sustained by a DC bias using LCIF. Profile widths measured were found to scale with the hybrid gyroradius, which has also been observed by other groups using electrostatic probes [11-12]. The leak width had a pressure dependence that tended to broaden with increasing pressure. Though the observed trends in this leak width broadening is in qualitative agreement with theoretical predicts, the rate of change in broadening with pressure did not match theory.

Acknowledgments

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