

Laser Based Electron Density Measurements in a Ring-Cusp Magnetosheath

IEPC-2017-529

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology – Atlanta, Georgia – USA
October 8–12, 2017*

Neil A. Arthur* and John E. Foster†
University of Michigan, Ann Arbor, MI, 48109, USA

Edward V. Barnat‡
Sandia National Laboratory, Albuquerque, NM, 87123, USA

Abstract:

Nomenclature

A	= Einstein spontaneous emission coefficient
FWHM	= Full width half maximum
$h\nu$	= Photon energy
I	= Intensity
ICCD	= Intensified charge-coupled device
K^e	= Electron collision rate
LCIF	= Laser collisional induced fluorescence
LIF	= Laser induced fluorescence
n_e	= Electron density
OPO	= Optical parametric oscillator
η	= Optical measurement efficiency

*Ph.D. Candidate, Nuclear Engineering & Radiological Sciences, arthurne@umich.edu

†Professor, Nuclear Engineering & Radiological Sciences, jefoster@umich.edu

‡Member of Technical Staff, Physical, Chemical, and Nano Sciences, evbarna@sandia.gov

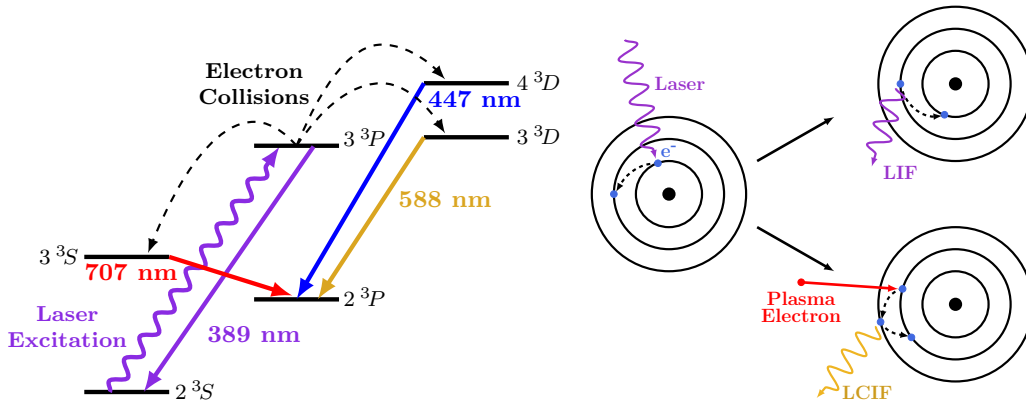
I. Introduction

STATE of the art ion thrusters employ magnetic confinement schemes to increase ionization efficiency and discharge stability. The magnetic confinement scheme most widely implemented is the ring cusp magnetic multipole geometry. Ring cusp magnetic fields are created using a series of magnet rings in alternating polarity. The ring cusp circuit increases ionization efficiency by limiting the anode area available for electron collection. The discharge current is carried primarily to the anode by electrons lost through the magnetic cusps. Consequentially, a side effect of the increased ionization efficiency provided by ring cusp designs is a limitation on operational discharge current that can be collected through a reduced anode area. When operated beyond a threshold discharge current, ion thrusters will enter a high impedance mode and tend to become unstable.^{1,2} The magnetic field design, and specifically the magnetic cusps themselves, is crucial in modulating all properties of the bulk plasma (e.g. density and potential) and achieving optimum performance (high efficiency and stability) in ion thrusters.

Magnetic circuits are typically designed via either trial and error or by rules of thumb. Ring cusp ion thrusters have extensive flight heritage, however the nature of plasma collection through the magnetic cusp is not well understood. Here we use a laser diagnostic to measure the electron density response in the bulk plasma and the cusp itself in response to voltage changes at the magnet surface. Modifying the magnet bias voltage changes the current collection through the cusp, and in turn modifies the properties of the bulk plasma. Past studies have shown that biasing magnet rings within ion sources can modify the plasma potential, induce ion drift, as well as impact ion thruster performance under simulated beam extraction.³⁻⁶ Here we examine the mechanism that bring about these changes, by directly measuring electron density distributions in the magnetic cusp. The onset of anode spot formation and instability is also observed.

II. Theory

In magnetic multipole discharges, the magnetic cusp represents the anode sheath. Langmuir probes can not make measurements within sheaths because the probe voltage imposes too large of a disruption to the sheath potential. The probe acts as an additional boundary with its own sheath and does not measure the plasma properties of the anode sheath.⁸ The magnetic cusp is also a region of high magnetic field strength, and probe theory in complex geometry magnetic fields is not well developed. The plasma flow in regions of high magnetic field is anisotropic. Particles become trapped on magnetic field lines, and the effective probe area becomes the cross sectional area projected along the magnetic field lines, which is no longer easily measured.⁹ The magnetic field limits cross field diffusion, causing non-uniform expansion and distortion of the sheath.¹⁰ An alternative to using intrusive, electrostatic probes is to use laser based diagnostics.



(a) Helium level LCIF diagram. Adapted from Ref. 7. (b) Schematic diagram of the LIF and LCIF process.

Figure 1: Schematics showing the LCIF process in energy level and diagram form.

Laser collisional induced fluorescence (LCIF) is a diagnostic technique for capturing two-dimensional images of electron density and temperature.^{7, 11-15} Figure 1 depicts the LCIF process. A laser excites a low-lying metastable state in the discharge gas. This intermediate excited state has two possible interactions:

Table 1: Target states in Helium LCIF.⁷

Transition	Wavelength (nm)	A (10^6 / sec)	$\Delta\epsilon$ (eV)	Transition Type
$2^3S \rightarrow 3^3P$	388.9	9.47	—	Laser excited transition
$3^3P \rightarrow 2^3S$	388.9	9.47	—	LIF
$3^3S \rightarrow 2^3P$	706.5	3.09	0.289	LCIF
$3^3D \rightarrow 2^3P$	587.6	7.07	-0.067	LCIF
$4^3D \rightarrow 2^3P$	447.1	18.4	-0.729	LCIF

1) the atom de-excites, releasing a photon, which gives the LIF signal or 2) while in the intermediate state the atom undergoes a collision with a free plasma electron further exciting the atom to a higher state. This final state can then de-excite releasing the photon that contributes to the LCIF signal. The emitted light is measured and related to the electron density and temperature through a collisional-radiative model (CRM). LCIF has the advantage of being spatially and temporally resolvable and does not perturb the plasma. Table 1 shows the important transitions in helium LCIF. Within the plasma, there is a significant density of 2^3S metastable states, which have an excitation energy of 19.8 eV, lower than helium's ionization energy of 24.6 eV. A 388.9 nm laser excites the 2^3S to the 3^3P state. Electrons can collide with the 3^3P to produce the 3^3S , 3^3D , and 4^3D states. These states all radiate down to the 2^3P state. The A value is the Einstein coefficient for spontaneous emission. The $\Delta\epsilon$ is the energy difference between the intermediate state (3^3P)

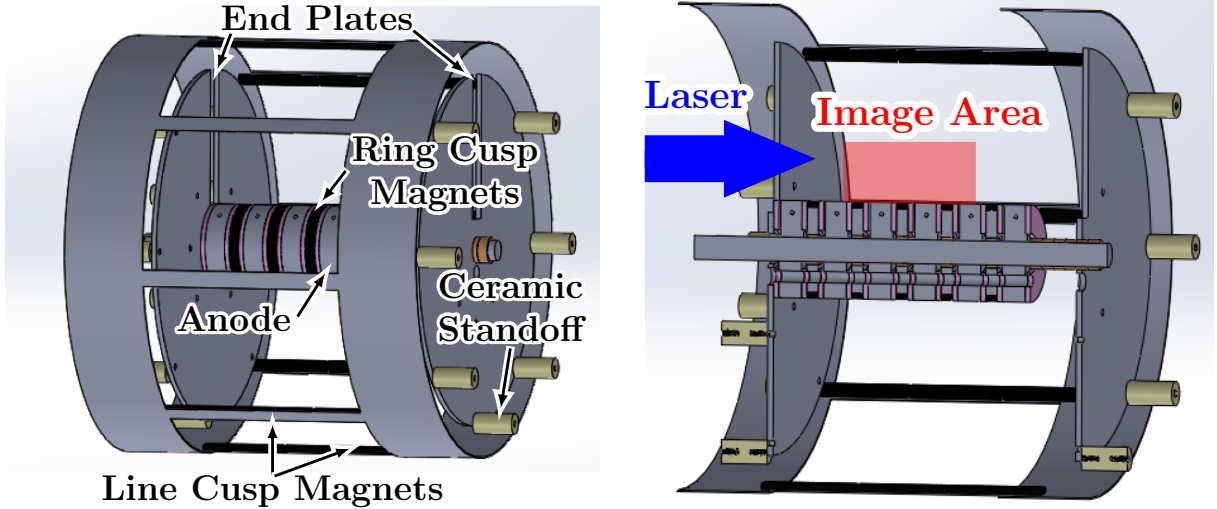


Figure 2: Experimental setup renders. The apparatus is 22 cm in diameter, and the end plates are separated by 15 cm. The image area is a 9 cm $\times$ 4 cm rectangle.

and the final state (3^3S , 3^3D , or 4^3D). The most prominent LCIF signal is 587.6 nm because the 3^3D state is closest energetically to the 3^3P state (0.067 eV).

The ratio of the intensity of the LCIF signal, I_{LCIF} , to the LIF signal, I_{LIF} , can be used to determine the electron density from the equation

$$\frac{I_{\text{LCIF}}}{I_{\text{LIF}}} = \frac{\eta_2}{\eta_1} \frac{K_2^e}{A_1} \frac{h\nu_2}{h\nu_1} n_e, \quad (1)$$

where η is the collection efficiency of measurement optics, K^e is the electron collision rate, A is the Einstein spontaneous emission coefficient, $h\nu$ is the energy of the photon, and the subscripts 1 and 2 represent the LIF and LCIF signal respectively.^{11, 14} The values of $h\nu$ and A are known, η is determined during system calibration and K^e can be approximated from semi-empirical expressions found in the literature.^{16, 17} Equation (1) can then be used to determine the electron density.^{7, 13} In table 1 there are three LCIF

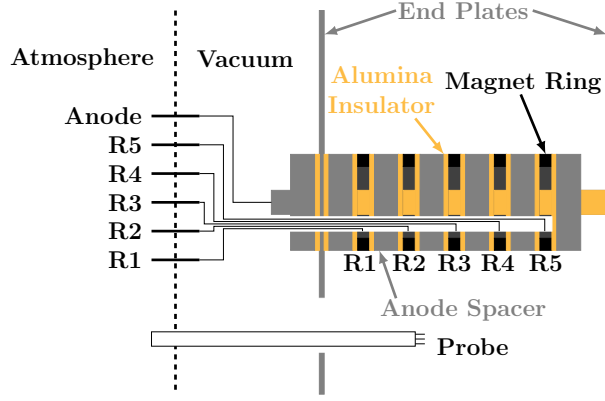


Figure 3: Schematic of the discharge apparatus, showing the isolated magnet rings.

transitions, but the state with the weakest dependence on electron temperature (K^e approximately constant) is chosen to determine density. This is the 588 nm transition, which has the smallest $\Delta\epsilon$. Typical uncertainties in LCIF measurements are estimated as 50% and are due to mostly to uncertainties in determining the rate constant K^e .^{12,18} LCIF electron density measurements have been benchmarked against Langmuir probe measurements and agree to within a factor of 2.⁷

III. Experimental Setup

The LCIF measurements require sufficient optical access to the discharge plasma and magnetic cusp regions. To accomplish this, a new discharge apparatus had to be designed that allowed for both the laser propagation through the magnetic cusp, and the collection of the fluorescence perpendicular to the laser propagation direction. Renders of the discharge apparatus design are shown in fig. 2 and a schematic diagram of the setup is shown in fig. 3, which shows the magnet rings numbering 1 to 5 from left to right. This is the convention for all data presented herein. The central structure consists of the anode and five magnet rings in ring-cusp configuration, each electrically isolated from the anode. The magnet rings are comprised of block samarium cobalt ($\text{Sm}_2\text{Co}_{17}$) magnets. Alumina (Al_2O_3) washers isolate the magnet rings from the anode segments. A central support rod holds the anode structure together. The apparatus is mounted within the vacuum chamber using two steel endplates. The endplates are isolated from both the anode structure and the vacuum chamber. Surrounding the central anode structure is a shell with neodymium ($\text{Nd}_2\text{Fe}_{14}\text{B}$) line cusp magnets and cut-out windows for optical access. The line cusp magnets function to increase plasma density and confine the bulk plasma radially, creating a bulk plasma region between the line cusp and ring cusp magnets.

A pulsed Nd:YAG laser is used to pump an optical parametric oscillator (OPO), Continuum Sunlite™

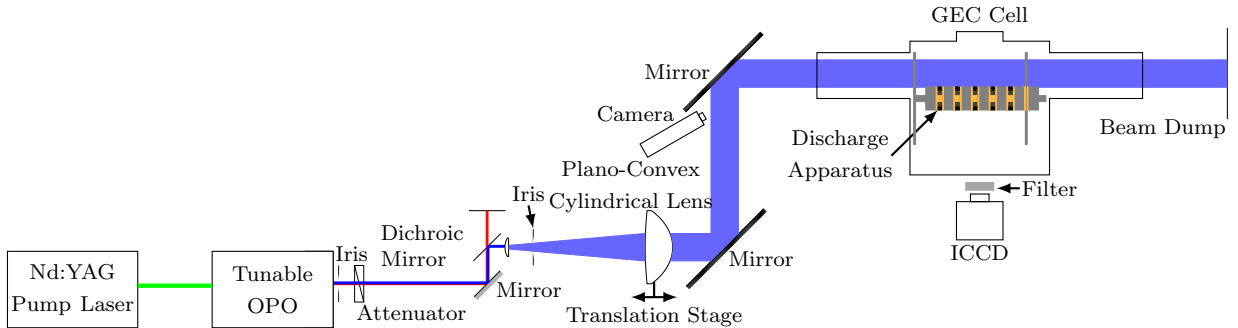
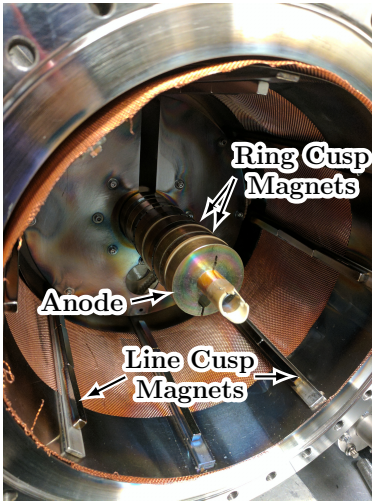
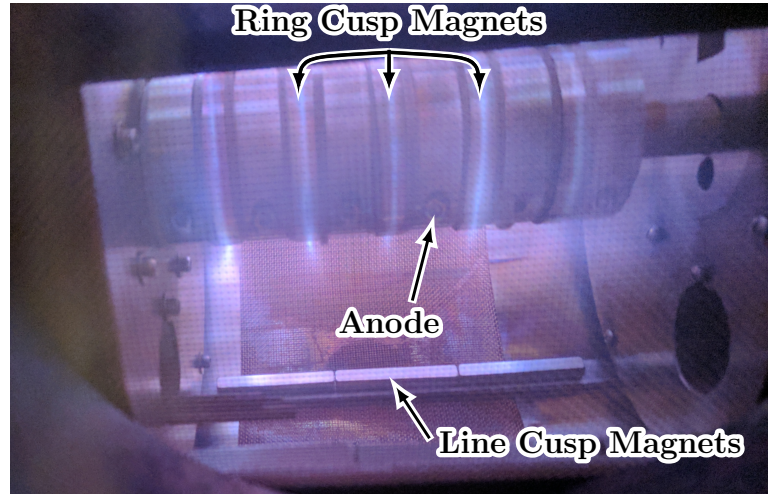


Figure 4: Optical experimental setup.



(a) Picture of the discharge apparatus installed in the GEC chamber.



(b) Picture of the discharge plasma.

Figure 5: Photographs showing the setup and discharge.

FX OPO, which generates a 777 nm beam. This beam is frequency doubled to 388.9 nm, which is used to excite the helium 3^3P state. The laser is pulsed at 20 Hz with a 5 ns pulse width. The laser beam enters the chamber with a power of ~ 10 mW. The OPO outputs both a red and blue beam, a mirror raises the height of the beam, and a dichroic mirror reflects only the blue beam. The red beam passes to a beam dump. The blue beam passes through a beam expanding lens and an iris. A plano-convex cylindrical lens produces a planar sheet laser beam. The planar beam is focused by adjusting the translation stage upon which the cylindrical lens is mounted. Two more mirrors direct the planar beam to the GEC cell, where the beam passes through the discharge apparatus and exits the chamber to a beam dump. An ICCD camera captures the fluorescence perpendicular to the direction of laser propagation. The optical schematic is shown in fig. 4.

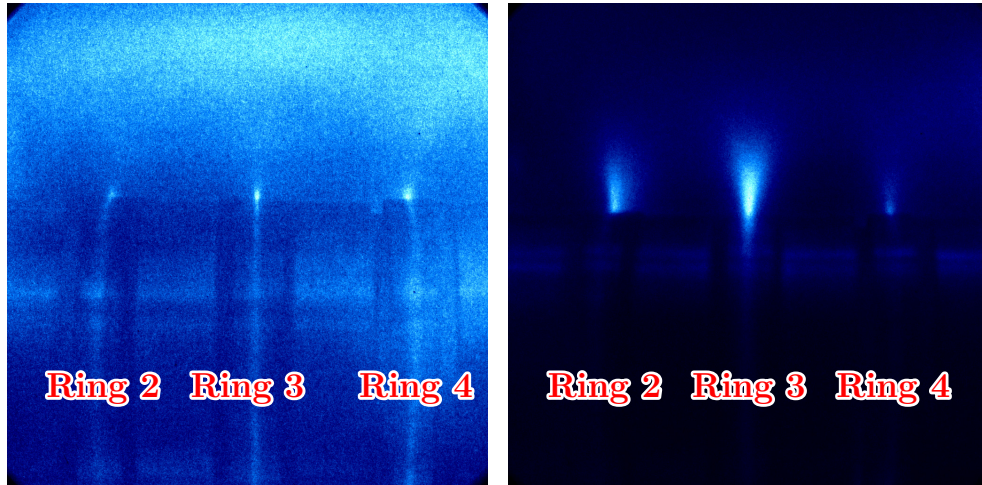


Figure 6: Pictures of the plasma discharge taken with the ICCD camera.

The experiments used a helium discharge because helium allows for measurements with better signal-to-noise ratios at lower electron densities as compared to other noble gasses.^{7,13} The reason is the fact that the lifetime of the lowest lying metastable state in helium, 2^3S , is the longest lived neutral atomic excited state.^{19,20} To get a reasonable LIF/LCIF signal, the laser must excite a significant number of metastable

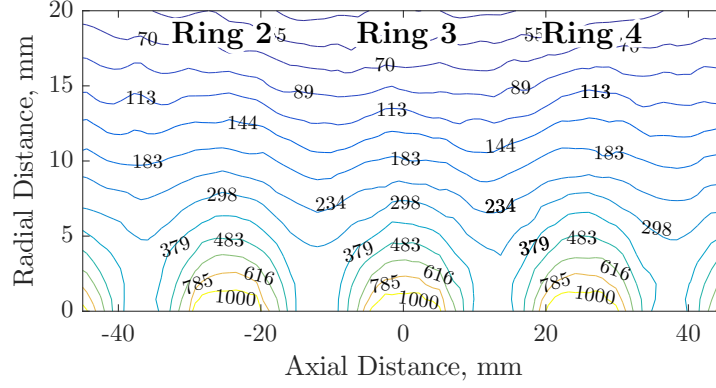
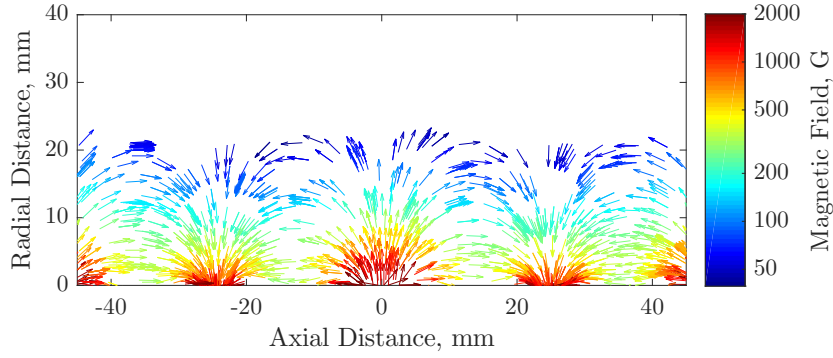
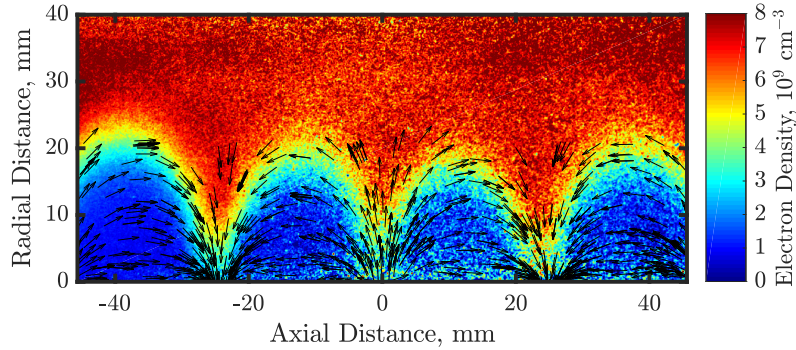


Figure 7: Simulated magnetic field contours above the three central magnet rings.

atoms. Images are acquired with the laser beam blocked to determine the light contribution due solely to plasma induced emission. These reference images are then subtracted from the laser induced emission



(a) Magnetic field vectors colored to display magnitude.



(b) LCIF measured electron density with magnetic field vectors overlaid.

Figure 8: Simulated magnetic field vectors plotted alone and with LCIF measured electron density.

images. 590 nm filtered images were acquired with a 60 s count time (1200 laser pulses), and the 390 nm filtered images were acquired with a 30 s count time. Images are corrected for the optical efficiency of the system and normalized by their count times. Each figure presented herein is an average of ten measurements. A triple Langmuir probe is used to measure the plasma properties for comparison.

Figure 5 shows the discharge apparatus installed in the GEC vacuum chamber and the plasma discharge seen through the GEC window.

IV. Results

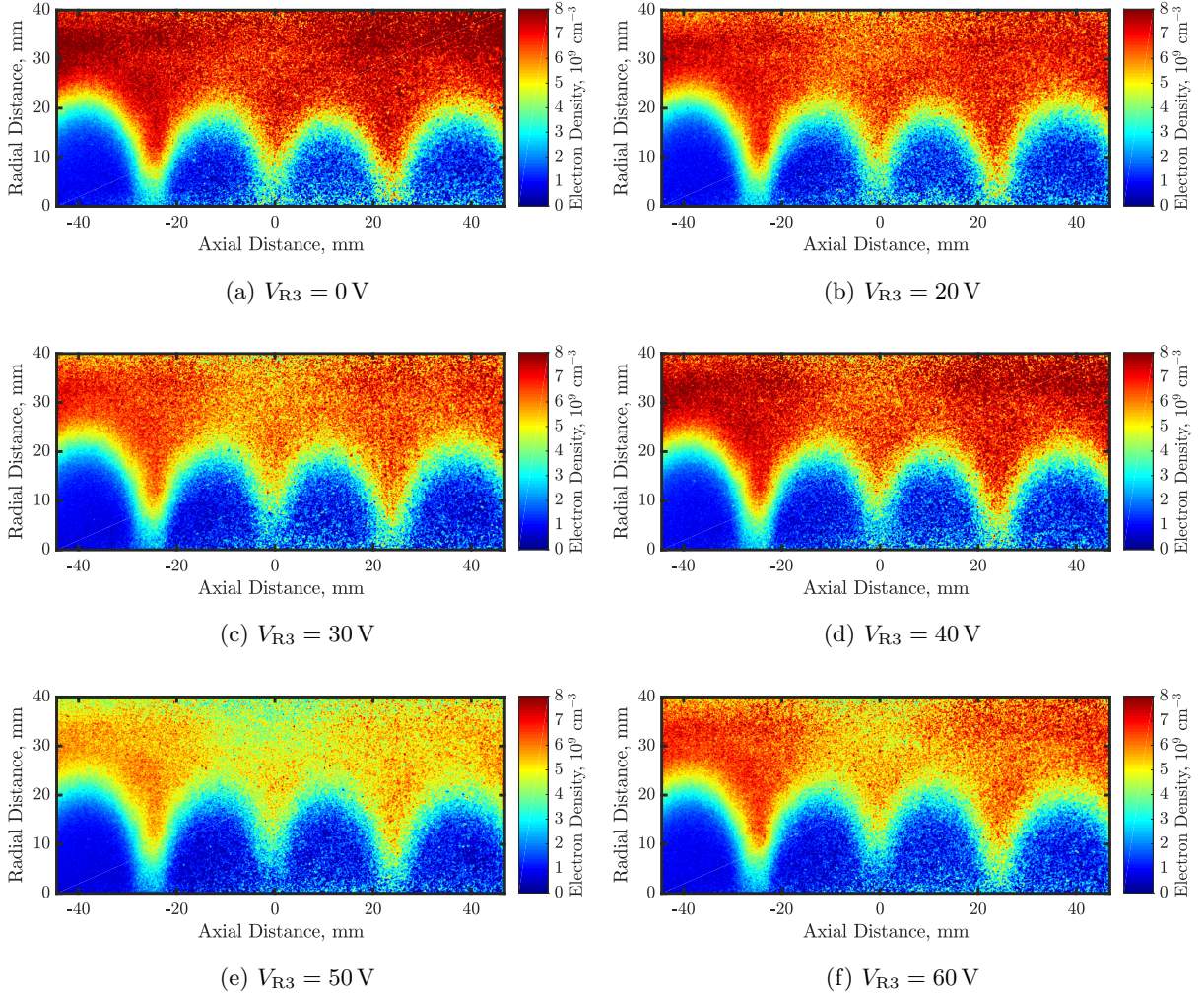


Figure 9: LCIF measured electron density as magnet ring 3 bias is increased.

False color pictures of the discharge taken with the ICCD camera are shown in fig. 6. The strong plasma collection can be seen at each of the magnet rings, with the cusp structure visible above the anode surface. The magnetic field profile was designed using a commercial EM field solver and magnetic field contours are shown in fig. 7. The magnetic field vectors, colored for magnitude, are displayed in fig. 8a. Figure 8b shows the measured electron density with the magnetic field vectors overlayed. The electron density shows the distinct cusp structure seen in magnetic multipole discharge and follows the magnetic field vectors extremely closely.

Images are taken with both the 380 nm and 590 nm filter and then the electron density is calculated according to Eq. (1). The values of the optical efficiency of the system are $\eta_1 = 0.12$ and $\eta_2 = 0.28$. The measured electron density spatial distribution above a biased magnet ring is shown in fig. 9. The bias voltage on the middle ring, located at 0 mm, is increased from 0 to 60 V moving from panels (a) to (f).

In all plots, magnet ring 2 is at an axial distance of -25 mm , ring 3 is at 0 mm , and ring 3 is at $+25 \text{ mm}$. Measured electron densities are order $1 \times 10^9 \text{ cm}^{-3}$.

A. Density Contours

To quantify the effect of ring bias on structure of the plasma, lines of constant density can be examined. The method for this analysis is outlined in figure 10. Starting with 10a, only the points of constant density,

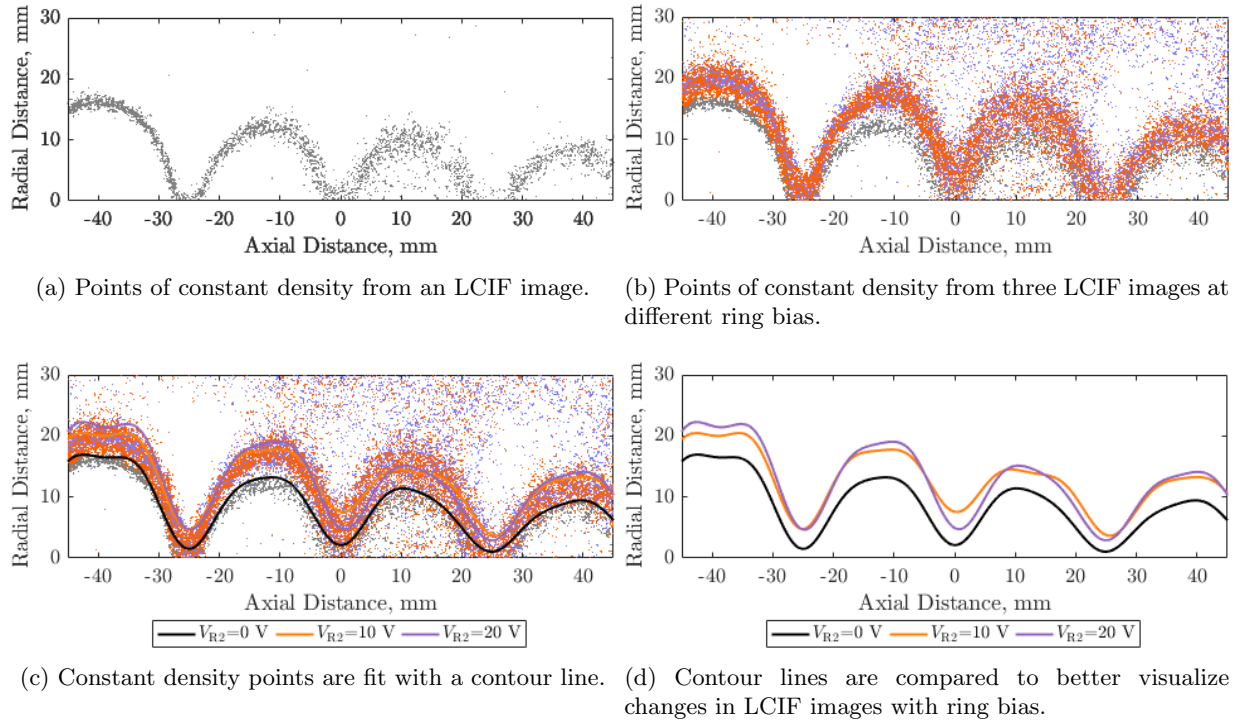


Figure 10: Points of constant density taken from the LCIF images. The constant density points are fit with a line to observe changes in the cusp structure.

in this case $n_e = 2 \times 10^9 \text{ cm}^{-3}$ in a single LCIF image are plotted. The electron density of $2 \times 10^9 \text{ cm}^{-3}$ is chosen by inspection to approximately trace the edges of the cusp structure. Plotting this density for several different LCIF images at different ring biases results in figure 10b. A line can be fit to the points of constant density from each image, shown in 10c. Then these lines are extracted and plotted separately for clarity in figure 10d. Then a trend in the structure of the plasma can be visualized from this set of curves.

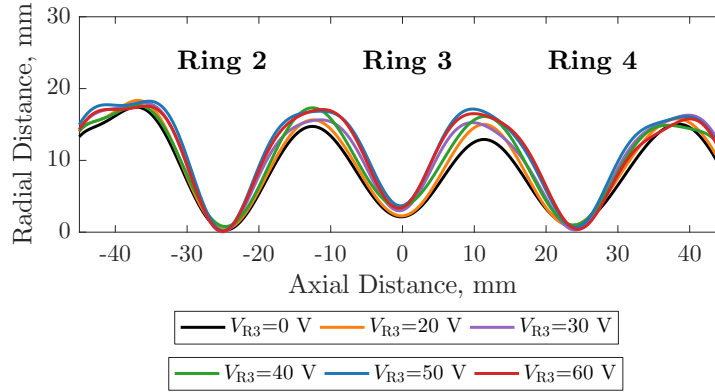
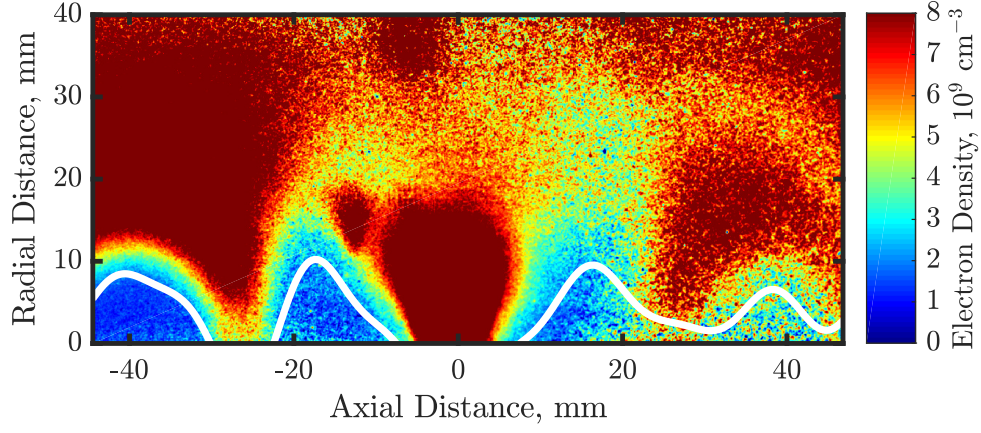
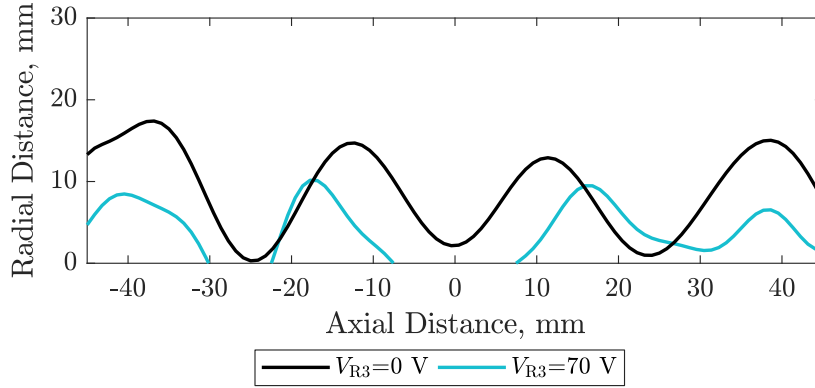


Figure 11: Contours of $n_e = 2 \times 10^9 \text{ cm}^{-3}$ as ring 3 bias voltage is increased from 0 to 60 V in 10 V increments.

Figure 11 shows the results of biasing magnet ring 3 from 0 to 60 V. It is apparent in the figure that as the bias voltage is increased the contours shift further from the magnet ring surface, to larger radial distances. The effect is most pronounced at the biased ring, 0 mm, but contours also move radially outward at the other magnet rings, ± 25 mm. This demonstrates that cusp bias can have effects that reach beyond the locality of the cusp. The magnetic cusp region represents the anode sheath, and fig. 11 demonstrates that bias causes the sheath to expand. The contours shift by approximately 5 mm as the ring is biased to



(a) LCIF measured electron density at 80 V ring 3 bias. The white line shows the $n_e = 2 \times 10^9 \text{ cm}^{-3}$ contour.



(b) The high voltage contour compared to the nominal contour with no ring bias.

Figure 12: Comparison of a constant density contour for the nominal case and ring 3 at high bias voltage.

60 V. For reference the Debye length is approximately 0.25 mm. There are two reasons that the sheath may be expanding. First, the electron density drops as the cusp bias draws in the more electrons. Secondly, cusp bias tends to increase the bulk plasma potential, leading to an increase in the potential difference between the bulk plasma and the magnet surface.⁶ The shift in the bulk/cusp interface seen in the contours of fig. 11 demonstrates the ability of cusp bias to affect the plasma globally.

At high bias voltages, the cusp structure breaks down completely. The electron density for a central magnet ring bias of 80 V is shown in fig. 12a. A white line is drawn to show the $2 \times 10^9 \text{ cm}^{-3}$ contour. Figure 12b compares the constant density contours for 0 and 80 V of ring bias. The electron density measurement shows bright plasma formation at an axial distance of 0 mm, attached to the magnet surface, suggestive of anode spot formation. Anode spots occur when the anode surface, in this case the magnet ring being biased, becomes positive of plasma potential, creating an electron accelerating anode sheath.²¹ Electrons are heated to the point that they can cause ionization within the sheath, which results in breakdown of the sheath. The anode spot is a bright plasma ‘fireball’ with a large spatial extent compared to the typical sheath structure, which increases the effective surface area of the anode allowing for more current collection.¹⁰ Theoretical calculations and two-dimensional particle-in-cell (PIC) simulations have shown that anode spots can form at electrodes that are small enough to be biased positive of the plasma potential, at which point the anode spot is necessary to provide additional collection area for the electron current.^{21,22}

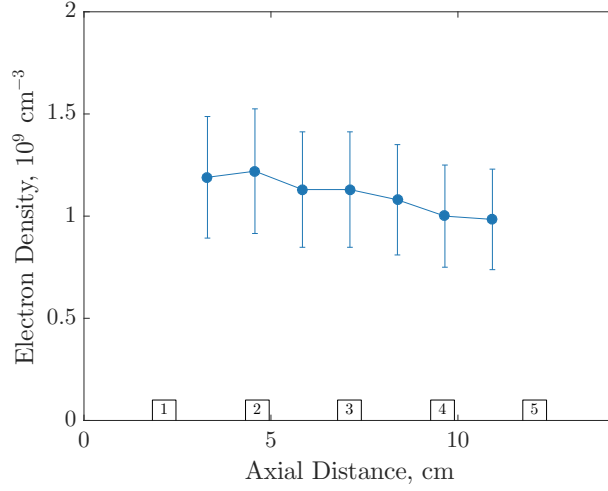


Figure 13: The electron density as measured with the triple Langmuir probe.

B. Triple Probe Measurements

A triple Langmuir probe was used to verify the magnitude of the LCIF electron density measurements. Figure 13 shows the electron density as measured with the triple probe. The triple probe was attached to a linear motion stage that allowed it to be moved through the chamber. The triple probe took measurements 5 cm below the anode structure surface, 180° azimuthally from the planar laser sheet. The measured electron density agrees to within an order of magnitude with the LCIF measurements.

C. Plasma Leak Width

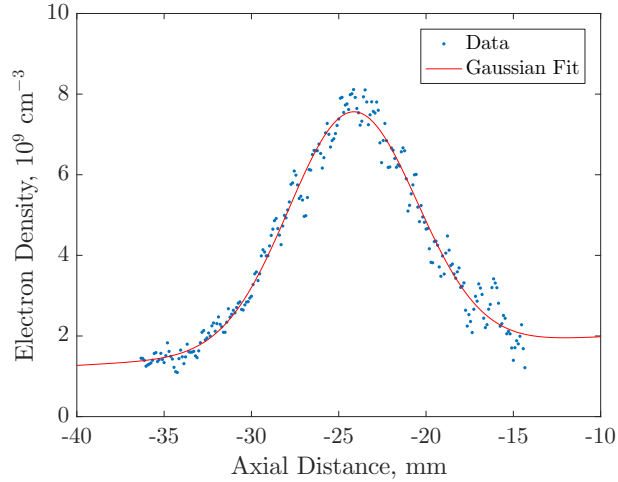


Figure 14: Example of Gaussian fit method for determining the leak width in the magnetic cusp.

The benefit of magnetic multipole discharge is increased ionization efficiency, which is accomplished by increasing the primary electron path length through reduction of the effective anode collection area. The magnetic field geometry reduces the current collection area from the physical anode area to a narrow “leak width”, located on the magnet. The leak width can be visualized in the lefthand image of fig. 6, which shows the bright plasma collection bands at the center of each magnet ring.

As a magnet ring is biased, it begins to collect more current, which was observed in both this experiment and previous studies.^{3–6,23} If the current density funneled through the cusp is constant, the collection area at the magnet surface necessarily increases. Measuring the change in the plasma leak width with increasing

ring bias (current collection) is of interest. Contours of constant density illustrate the change in the structure

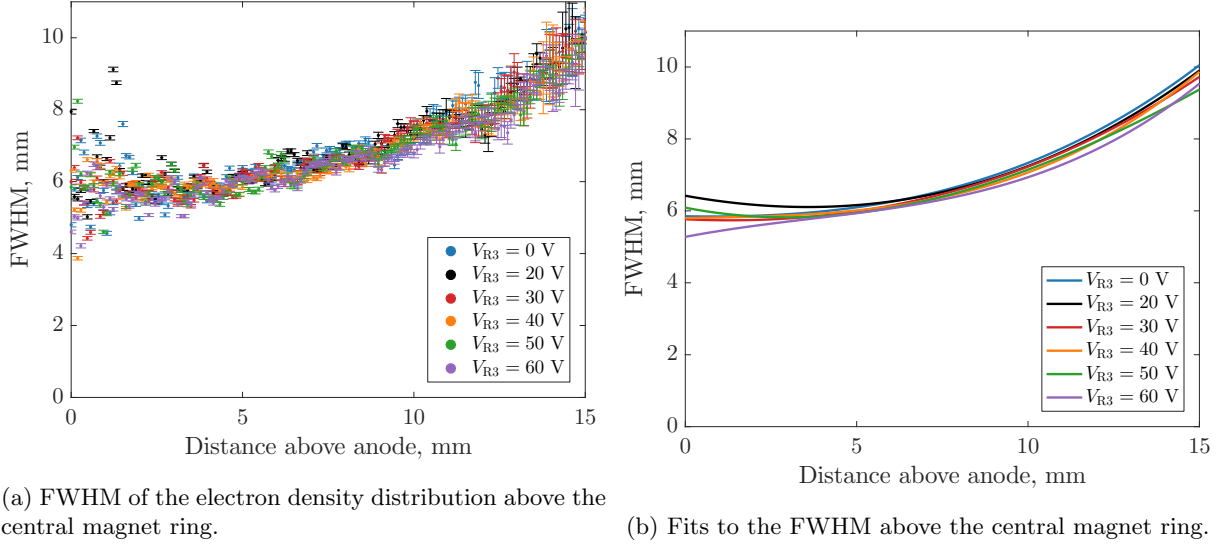


Figure 15: The width of the magnetic cusp above the central magnet ring as measured using the FWHM. There is no change with increasing ring bias.

of the cusp with bias. To measure the leak width, density line-outs at constant radial distance are plotted and fit with a Gaussian curve. This method has been used in previous studies.^{15,24} A demonstration of this technique is shown in fig. 14. The electron density at a radial distance of 3 mm above magnet ring 2 is plotted. The full width half maximum (FWHM) of the fitted Gaussian curve is a measure of the length scale of the cusp. Repeating this procedure across every line of pixels at constant radial distance creates the points of a single color in fig. 15a. Repeating for different magnet ring bias voltages (each subfigure of fig. 9) produces the points of various colors in fig. 15a. Examining fig. 15a, it can be seen that most of the points effectively lie on top of each other. The FWHM increases further from the anode (magnet) surface, as expected for a cusp-like shape. Error bars are determined from the 95% confidence bounds of the Gaussian fit. The FWHM measurements are noisy along the magnet surface, where the LCIF and LIF signals are relatively low.

Figure 15b shows the best fit lines to better visualize the measurements in fig. 15a. Again, as ring bias is increased the trend in FWHM appears unchanged. This is quite remarkable and unexpected. This suggests that the collection area does not change and current density is not constant. Instead, the cusp bias is enhancing electron mobility along field lines, increasing electron velocity, and potentially increasing electron temperature. Further study is needed to confirm this. The LCIF diagnostic has the potential to spatially resolve electron temperature in the cusp, but during these studies the electron density, and hence LCIF signal, was insufficient to do so.

V. Conclusion

The LCIF diagnostic was used to measure the two-dimensional electron density distributions in the magnetic cusp above an isolated, biasable magnet ring. The impact of the bias on the cusp/bulk interface was quantified with constant density contours at electron densities of $2 \times 10^9 \text{ cm}^{-3}$. The contours showed that increasing magnet ring bias tends to shift the cusp/bulk interface further from the magnet ring surface. As the cusp represents the anode sheath, the bias causes sheath expansion. This is due to both the decrease in electron density and increase in plasma potential near the biased magnet ring.

Line outs of the electron density at a constant radial distance were used to quantify electron leak widths. Surprisingly, the leak width did not change with increasing ring bias. This suggests that electron collection area does not change and the current density collected at the cusp is not constant. It seems that the ring bias enhances electron mobility along magnetic field lines, allowing more electrons to traverse the cusp. Further studies are required to spatially resolve the electron temperature in the cusp.

At high bias voltages, the cusp structure breaks down and an anode spot forms. The spot is necessary to transport the large current through the cusp. The formation of these anode spots has implications for instabilities observed in ion thruster discharges that become resistive at high discharge currents. Further work is needed to observe anode spot formation in xenon discharges, where the xenon ionization potential is less than that of helium, 12.1 eV compared to 24.6 eV.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE-SC0014664. The authors would like to acknowledge Gary Pettee for his assistance.

References

- ¹D. M. Goebel and I. Katz, *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, vol. 1 of *JPL Space Science and Technology Series*. Hoboken, NJ: John Wiley & Sons, 2008.
- ²D. M. Goebel, "Ion Source Discharge Performance and Stability," *Phys. Fluids*, vol. 25, no. 6, pp. 1093–1102, 1982.
- ³N. A. Arthur, *Increasing the Extracted Beam Current Density in Ion Thrusters*. PhD thesis, University of Michigan, Ann Arbor, MI, 2017.
- ⁴N. A. Arthur and J. E. Foster, "Increasing Extracted Beam Current Density in Ion Thrusters through Plasma Potential Modification," in *68th Gaseous Electronics Conference*, vol. 60, (Honolulu, HI), 2015.
- ⁵N. A. Arthur and J. E. Foster, "Performance Characterization of an Ion Thruster with Isolated Magnet Rings," in *58th APS Division of Plasma Physics*, (San Jose, CA), 2016.
- ⁶N. A. Arthur and J. E. Foster, "Characterization of a Cylindrical Ring-Cusp Ion Source with Electrically Isolated Magnet Rings," *J. Vacuum Sci. Technol. A*, vol. 35, no. 2, p. 021310, 2017.
- ⁷E. V. Barnat and K. Frederickson, "Two-Dimensional Mapping of Electron Densities and Temperatures using Laser-Collisional Induced Fluorescence," *Plasma Sources Sci. Technol.*, vol. 19, no. 5, pp. 1–14, 2010.
- ⁸J. P. Sheehan and N. Hershkowitz, "Emissive Probes," *Plasma Sources Sci. Technol.*, vol. 20, no. 063001, pp. 1–22, 2011.
- ⁹M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. John Wiley & Sons, 2nd ed., 2005.
- ¹⁰B. Song, R. L. Merlino, and N. D'Angelo, "The Effect of a Magnetic Field Gradient on Anode Double Layers," *Physica Scripta*, vol. 45, no. 4, pp. 395–398, 1992.
- ¹¹K. Tsuchida, S. Miyake, K. Kadota, and J. Fujita, "Plasma Electron Density Measurements by the Laser- and Collision-Induced Fluorescence Method," *Plasma Phys.*, vol. 25, no. 9, pp. 991–999, 1983.
- ¹²B. R. Weatherford, E. V. Barnat, and J. E. Foster, "Two-Dimensional Laser Collision-Induced Fluorescence Measurements of Plasma Properties near an RF Plasma Cathode Extraction Aperture," *Plasma Sources Sci. Technol.*, vol. 21, no. 5, p. 055030, 2012.
- ¹³E. V. Barnat and B. R. Weatherford, "2D Laser-Collision Induced Fluorescence in Low-Pressure Argon Discharges," *Plasma Sources Sci. Technol.*, vol. 24, no. 5, pp. 1–14, 2015.
- ¹⁴K. Dzierzega, K. Musiol, E. C. Benck, and J. R. Roberts, "Electron Density Measurements in a RF Helium Plasma by Laser-Collisional Induced Fluorescence Method," *J. Appl. Phys.*, vol. 80, no. 6, pp. 3196–3201, 1996.
- ¹⁵A. A. Hubble, J. E. Foster, E. V. Barnat, and B. R. Weatherford, "Laser-Collisional Induced Fluorescence Study of Electron Distributions in a Magnetic Cusp," in *33rd International Electric Propulsion Conference*, no. IEPC-2013-367, (Washington, D.C.), 2013.
- ¹⁶H. W. Drawin, "Collision and Transport Cross-Sections."
- ¹⁷H. W. Drawin, "Influence of Atom-Atom Collisions on the Collisional-Radiative Ionization and Recombination Coefficients of Hydrogen Plasmas," *Z. Phys. A*, vol. 225, no. 5, pp. 483–493, 1969.
- ¹⁸Y. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, and F. J. de Heer, "Electron-Impact Excitation and Ionization Cross sections for Ground State and Excited Helium Atoms," *Atom. Data Nucl. Data*, vol. 94, no. 4, pp. 603–622, 2008.
- ¹⁹S. S. Hodgman, R. G. Dall, L. J. Byron, K. G. H. Baldwin, S. J. Buckman, and A. G. Truscott, "Metastable Helium: A New Determination of the Longest Atomic Excited-State Lifetime," *Phys. Rev. Lett.*, vol. 103, no. 5, p. 053002, 2009.
- ²⁰H. Katori and F. Shimizu, "Lifetime Measurement of the $1s_5$ Metastable State of Argon and Krypton with a Magneto-Optical Trap," *Phys. Rev. Lett.*, vol. 70, no. 23, pp. 3545–3548, 1993.
- ²¹S. D. Baalrud, B. Longmier, and N. Hershkowitz, "Equilibrium States of Anodic Double Layers," *Plasma Sources Sci. Technol.*, vol. 18, no. 3, p. 035002, 2009.
- ²²B. Scheiner, E. V. Barnat, S. D. Baalrud, M. M. Hopkins, and B. T. Yee, "Theory and Simulation of Anode Spots in Low Pressure Plasmas," *ArXiv E-print*, 2017.
- ²³N. A. Arthur and J. E. Foster, "Increasing the Traditional Child-Langmuir Limited Current Density in Ion Thrusters through Plasma Potential Modification," in *34th International Electric Propulsion Conference*, (Hyogo-Kobe, Japan), 2015.
- ²⁴A. A. Hubble, *Experimental Assessment of Plasma Transport in Magnetic Multicusp Ion Sources*. PhD thesis, University of Michigan, Ann Arbor, MI, 2013.