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14. ABSTRACT

Results of two complementary methods of measuring the near field plasma densities of a 200W Busek X3 Hall thruster are presented. Both a Faraday probe and microwave interferometery system are used to examine the density distribution of the thruster plasma at regular spatial intervals. Both experiments are performed in situ under the same conditions. The resulting density distributions obtained from both experiments are presented. Advantages and uncertainties of both methods are presented, as well as how comparison between the two data sets can account for the uncertainties of each method alone.

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Complementary Density Measurements for the 200W Busek Hall Thruster (Pre-Print)

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Results of two complementary methods of measuring the near field plasma densities of a 200W Busek X3 Hall thruster are presented. Both a Faraday probe and microwave interferometery system are used to examine the density distribution of the thruster plasma at regular spatial intervals. Both experiments are performed in situ under the same conditions. The resulting density distributions obtained from both experiments are presented. Advantages and uncertainties of both methods are presented, as well as how comparison between the two data sets can account for the uncertainties of each method alone.

Nomenclature

θ	=	phase angle
Φ	=	flux density
e	=	electron charge
c	=	speed of light
m_e	=	electron mass
E_0	=	free-space permittivity
n_i	=	Ion density per cubic meter
$\overline{n}_e$	=	linearly averaged electron density per cubic meter
λ	=	wavelength
L	=	test volume length
q	=	electrical charge
V	=	ion velocity

I. Introduction

The Busek 200 Watt Hall thruster (BHT-200) is scheduled to be the first American manufactured Hall thruster in orbit. It will soon provide orbit keeping thrust for the TacSat-2 satellite scheduled to launch in late 2006. Investigating the operational characteristics of this thruster better aids future design methodology and understanding of how these thrusters operate in orbit. One of the chief characteristics of interest for plasma based thrusters is the distribution of charged particles throughout the plume. Measuring the distribution of particles that make up the plume allows us a quantifiable measurement of the plume profile. To further examine the plasma density of this thruster, two methods and their respective results are presented. Microwave interferometery provides a non-intrusive method for measuring the density of the plume though only across an integrated test vector. Faraday probe measurements in conjunction with ion velocities allow us to measure densities at specific points in the plume of the thruster, though at the same time affecting that plume by their presence.

Both experiments yield density measurements, but it is their respective certainties that make them of interest for comparison on the same thruster. Comparing results from these two experiments allows the researcher a unique opportunity to better characterize the density of the plasma through two independent methods.

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II. Theory of Operation

Interferometery

Interferometery provides a non-intrusive alternative to electrostatic probes when measuring densities. The Interferometer used for the measurements presented is a phase-bridge system operating at a wavelength of 3.3mm (90GHz). The interferometer provides a differential phase measurement between two generated signals, one of which passes through the test path and incident plasma, while the other is transmitted internally and is unaffected by the plasma.

A microwave signal (~17dBm) is generated by a Gunn oscillator, and transmitted via rectangular channel. Immediately after being generated the signal is split into two branches, here after referred to as the test branch (*I*) and the reference branch (*Q*). The *I* branch is transmitted through two phase shifters capable of applying 360 degrees of combined phase shift to the signal. These devices are used to calibration the interferometer before taking data. The *I* branch is then transmitted across the test volume through a pyramidal gain antenna. The test volume, an open space 30 centimeters long, is were the *I* branch interacts with the thruster plasma. Free electrons present in the plasma retard the transmission of the *I* signal thereby applying a small phase shift. The *I* branch is then collected at another pyramidal antenna, split once again, and provides "RF" input power for two biasable mixers. The *Q* branch is transmitted directly, split, and provides "LO" input power to the mixers. It should be noted that there is a component implemented 90 degree phase difference between the two "LO" power inputs. Figure 1 shows a functional diagram of the interferometer and its constituent components.

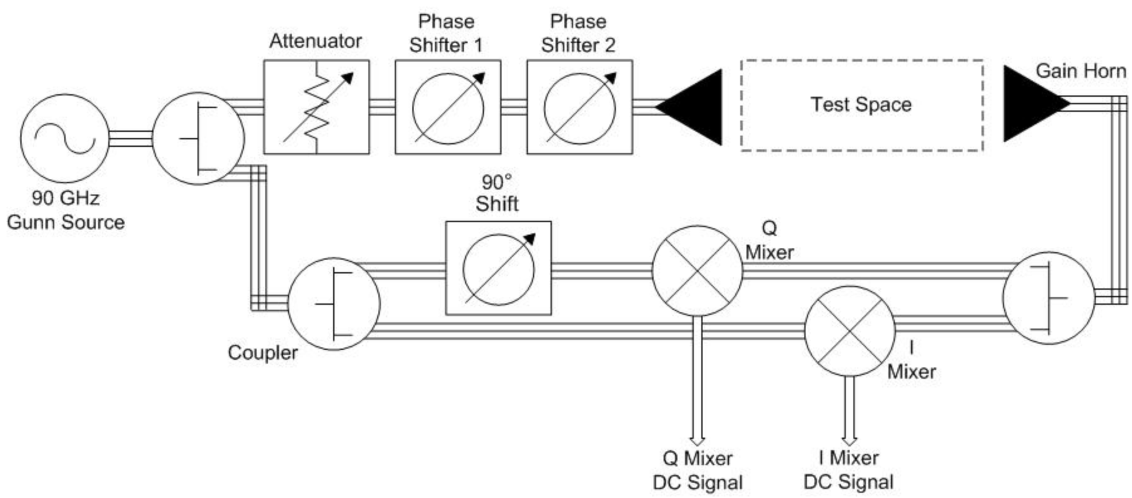

Figure 1. Functional diagram of the of interferometery system.

Each of the two biasable mixers output a voltage signal that is proportional to the difference in phase shift between the "RF" and "LO" power inputs. The resulting voltages can be used to calculate the amount of phase shift between the *I* and *Q* signals. This relationship between the electron density of the plasma and the amount of phase shift applied to the *I* Signal can be quantified by the following equation:

$$\overline{n}_e \ell = \frac{4\pi\, m_e\, \varepsilon_o\, c^2}{e^2\, \lambda_o}\, \Delta\phi \qquad (1)$$

It should be noted that the above equation generates a total electron density across the test volume of 30 centimeters. The signal can be averaged to yield particles per cubic centimeter, though there is some ambiguity when making this calculation. Averaging over the entire test volume produces an electron number per cubic meter but is ambiguous because the density distribution is not uniform throughout the test volume.

In order to verify the interferometer is functioning properly, 360 degrees of phase shift is applied to the *I* signal in small increments before each scan. The *I* and *Q* outputs of the interferometer oscillate as the shift is applied as can be seen in Figure 2. Because one of the mixers "LO" inputs is shifted 90 degrees with respect to the other, sine and cosine type waveforms are generated. The data shown in Figure 3 represents the full range of phase shift that can be applied to the interferometer. After this functional test an initial test point is taken (I_0, Q_0) that represents the baseline calibration measurement without plasma present. Each data point taken while the plasma is present (I, Q) can be correlated to a phase shift based on (I_0, Q_0). Figure 3 features data sampled from a calibration and 4 centimeter radial scan. From Equation 1 the phase difference between (I_0, Q_0) and (I, Q) is proportional to the electron number density.

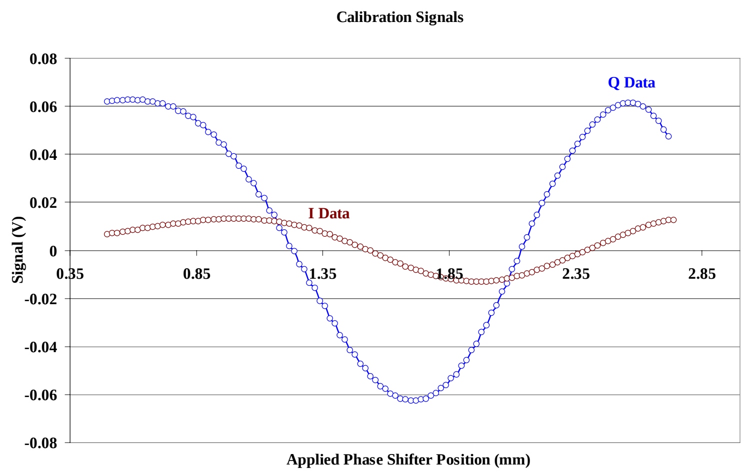

Figure 2. *I* and *Q* oscillation as phase shifters are applied.

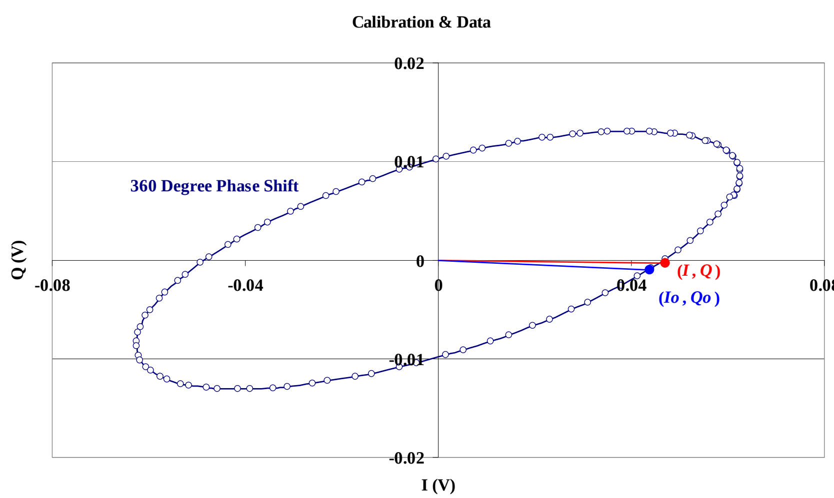

Figure 3. Calibration with initial point (*Io*, *Qo*) and test point (*I*, *Q*).

Faraday Probes & Ion Velocity

Faraday probes offer an advantage over interferometery due to their simplicity of design and spatial resolution. The Faraday probe collects a measurement of current density per surface area of the collector. In order to calculate particle density measurements however Faraday probe data must be combined with ion velocities. Current density and particle velocity measurements allow us to calculate density according to the following equation:

$$n_i = \frac{\Phi}{qV} \tag{2}$$

The Faraday probe used to collect data presented in this paper is a simple "miniature" faraday probe consisting of a single conductive rod insulated along its length by a non conductive tube. The collector is the planar surface of one end of the rod oriented perpendicular to the thruster centerline. The collector is electrically isolated from the chamber and is set at a negative electrical potential when testing (-30 volts for the tests presented here). This negative potential repels free electrons present in the plume while simultaneously collecting ions that are moving away from the thruster. Due to the probes design only ions that are traveling at an angle roughly perpendicular to the thruster exit plane and probe face are collected.

III. Apparatus

Test Facilities & Thruster Operation

Density measurements presented for the BHT-200 were performed in Chamber 6 at the Air Force Research Laboratory (AFRL) Electric Propulsion Laboratory at Edwards AFB California. Chamber 6 is a stainless steel high vacuum chamber with a 1.8 meter inner diameter and 3 meter interior length. Four single stage cryogenic panels provide a pumping speed of 32K liters of xenon per second. Typical pressure during thruster operation is approximately 1-5 microTorr.

For these tests the BHT-200 was mounted to a three axis stage capable of moving the thruster 30 centimeters along each axis. Flexible propellant lines enable the thruster to be moved during operation. The thruster is positioned to be centered in line with both experiments and such that the thruster exit plane is located 15cm from the test vector. All of the data presented in this paper were taken while the thruster operated at nominal conditions:

Discharge Voltage: 250 V
Magnet Current: 1 A
Heater Current: 3 A
Keeper Current: 500 mA
Cathode Flow: 1 SCCM
Anode Flow: 50 SCCM

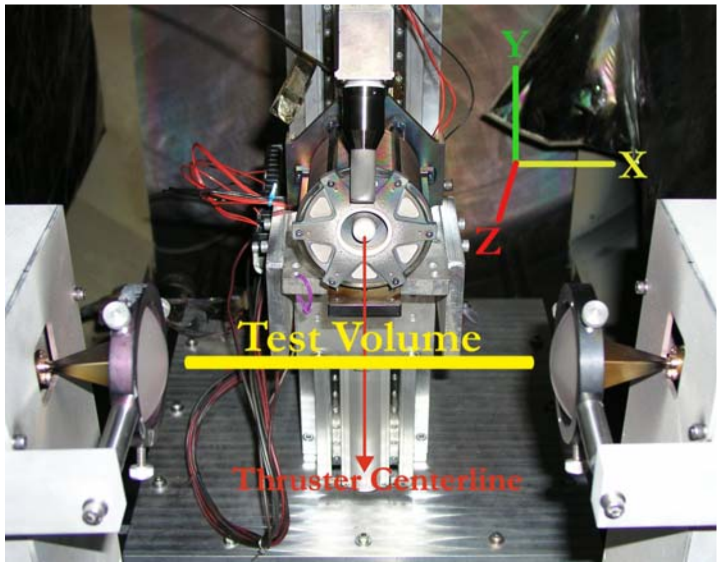

Figure 4. Thruster with stages & orientation.

Interferometery

To protect the interferometer from adverse affects associated with a hall thruster plume the entire system is encased in an aluminum housing. This grounded housing shields the interferometer from both thermal effects and electromagnetic disturbances caused by the plasma. The housing also has the added effect of shielding the interferometer from erosion caused by prolonged contact with the Hall thruster plasma.

As discussed in previous papers (Cappelli[1]) the active components of interferometer suffer from thermal drift in vacuum. Operating in atmosphere the interferometer baseline signal will stabilize after a short amount of time. In vacuum however convective cooling ceases and the interferometer will continue to heat and drift over time. Previous measurements taken with this interferometer have shown that this drift compromises the accuracy of the resulting data. To combat this problem a glycol based active cooling system has been installed on the interferometer to thermally stabilize components such as the Gunn and biasable mixers.

Voltage measurements for the I and Q interferometer channels are recorded using a National Instruments 16 bit 6036E I/O PCI card in conjunction with a BNC-2110 breakout board. Voltages were recorded by taking a differential “floating source” measurement. Taking measurements in this way eliminated electrical noise associated from the three axis stage motors.

Faraday Probes

The Faraday probe used for these experiments is a very simple design. The collector is a molybdenum rod 2.28 millimeters in diameter. The rod is insulated along its length by a 3.28mm diameter alumina tube with an inner diameter that matches that of the molybdenum rod. Faraday probe current measurements are recorded using a 24 bit Agilent 34401A digital multi-meter. Bias voltage for the probe is supplied with a Sorenson 75-5 power supply. Probe electrical configuration is illustrated in Figure 5.

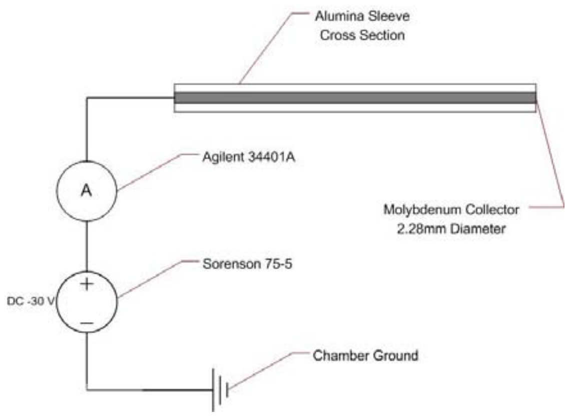

Figure 5. Probe design and electrical configuration.

IV. Experimental Results

The data for both experiments was taken at regularly spaced intervals with respect to the thruster exit plane to generate a profile of the plume. The final data sets presented consist of radial scans taken at decreasing axial distances from the thruster face, Figure 6 illustrates a portion of the 4 centimeter scan. Interferometery scans were taken from 4 to 13 centimeters away from the exit plane at 1 centimeter increments. Faraday probe scans were taken at the same locations however additional scans were taken at 3 and 14 centimeters away from the thruster face. Each scan consisted of fifty two data points taken from 13 centimeters below to 13 above the thruster centerline in 0.5 centimeter increments.

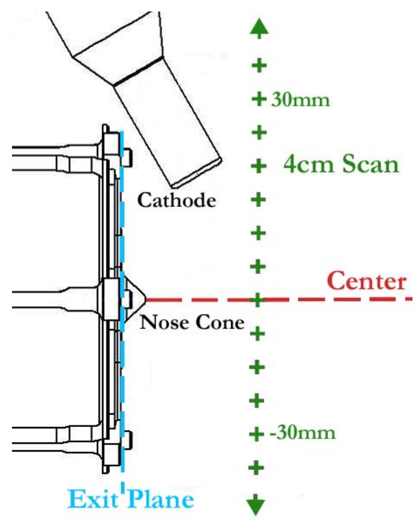

Figure 6. Test Orientation.

Interferometery

The resulting data from the interferometer as seen in Figure 7 revealed a typical plume profile associated with a Hall thruster. Density peaks at or within 5 millimeters of thruster centerline and decreases rapidly as the radial test distance is increased in either direction. The greatest density measured for the entire plume profile was $3x10^{16}$ (particles / m^3) which occurred at an axial distance of 4 centimeters, 5 millimeters below thruster centerline. Subsequent scans at larger radial distances show the density diminishing.

These measurements also reveal the interferometer to be a highly sensitive experiment. As seen in Figure 7, radial scans at axial positions 4 to 6 centimeters show significant perturbations immediately above the centerline that are not consistent with a thruster plume. It is believed these perturbations are attributed to the presence of the cathode which is physically located at a radial distance of 3 centimeters from the center line and an axial distance of 3 centimeters from the exit plane. It is believed measurements taken with any proximity to the cathode, specifically measurements closer than 4 centimeters from the exit plane, are greatly affected. Even as far away as 6 centimeters there is a noticeable disruption that can be attributed to the cathode.

The asymmetry indicated by this data is of particular significance. It is noticeable that the plume profile is not symmetric about the centerline as might be expected. Each radial scan the peaks slightly (approximately 5mm) below thruster centerline. Averaging all 10 radial scans and integrating the data between radial positions -20 and 20 millimeters (to take a uniform sample and avoid possible cathode perturbations) we find that there is a greater signal concentration below the center line than above (Figure 8). The total density measured between the centerline and -20 millimeters is approximately 33% greater than the total density measured from the center to +20 millimeters. This asymmetry is an interesting facet of the data and implies that the cathode jet or another outside effect is distorting the plume.

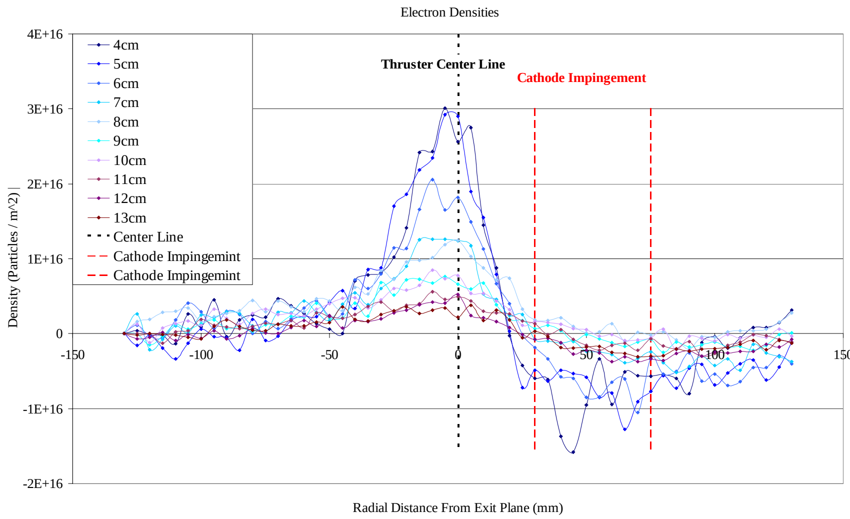

Figure 7. Interferometer test data.

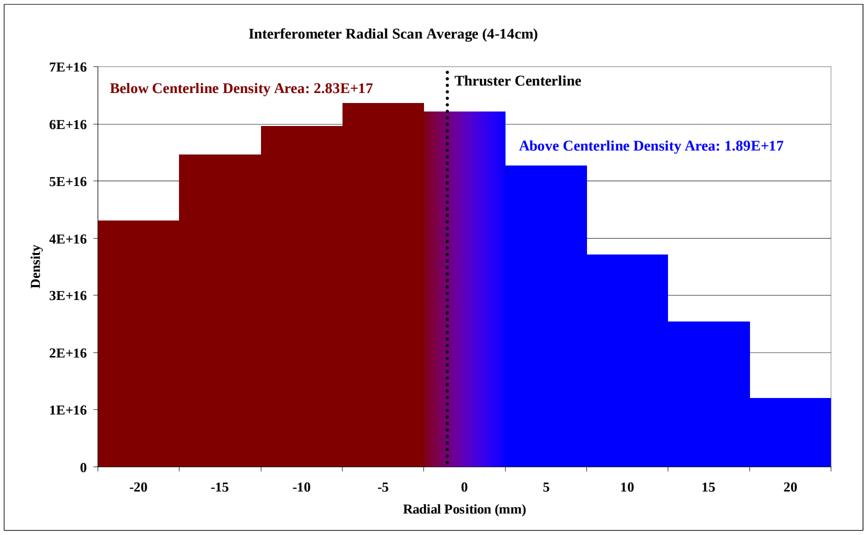

Figure 8. Interferometer averaged test data.

Faraday Probes & Ion Velocity

Current densities measured with the Faraday probe were combined with ion velocity measurements. It has been shown by (Hargus[2]) that the ion velocities for particles exiting the thruster converge to a velocity of 1.72×10^4 (m/s) 2 centimeters from the exit plane. Current densities combined with the velocity measurements as per equation *2* yield particle density measurements per unit volume. The final data set revealed a very clear profile of the plume (Figure 9). The maximum density measured by this experiment was 2.2×10^{17} (particles / m^3) on thruster centerline, 3 centimeters away from the exit plane. The peak density measured 4 centimeters from the exit plane was 1.7×10^{17} (particles / m^3).

Unlike the interferometer the Faraday probe was totally unaffected by the presence of the cathode. During the 3 centimeter radial scan the probe face comes within 1-2 millimeters of the cathode (the cathode does not extend exactly 3cm from the exit plane as previously pictured) and show no perturbation in signal at all. The data is smooth and shows no significant disturbances as with the interferometer.

The plume is again shown to be slightly asymmetric. There is a slight shift of the density signal to the left of Figure 10. Average all the radial scans and calculating the integral we see the density signal is again concentrated slightly below the thruster centerline (Figure 10). The total density measured below the centerline is approximately 11% greater than that measured above. Again this would imply, though to a much lesser degree, that the plume is being distorted.

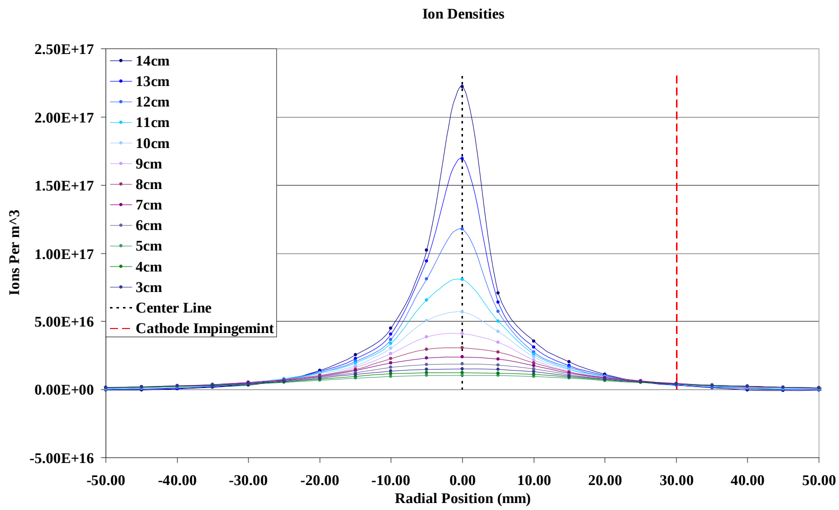

Figure 9. Faraday probe test data.

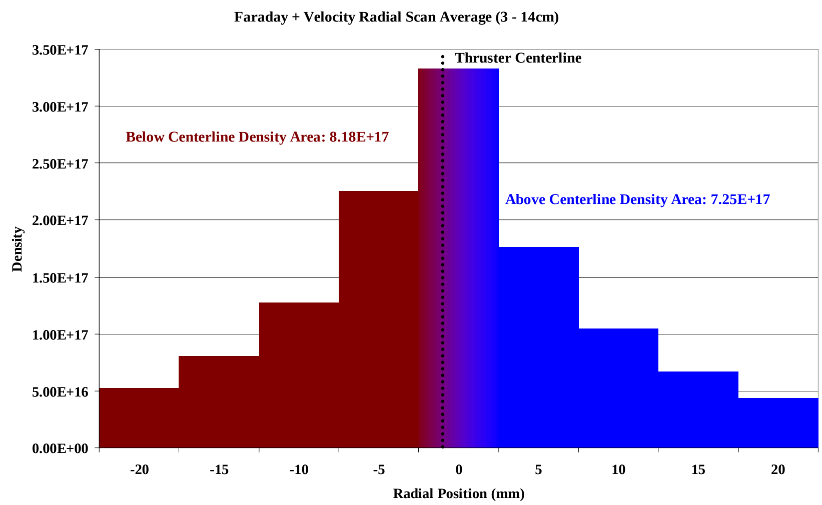

Figure 10. Faraday averaged test data.

V. Conclusions

Both methods of obtaining particle densities for the plume were successful and agreed to within an order of magnitude (4cm Scan Peak, Interferometery: $3\text{x}10^{16}$ (particles/m^3) versus Faraday: $1.7\text{x}10^{17}$ (particles / m^3)). For some measurements one order of magnitude discrepancy would be disastrous but it must be remembered we are measuring the number of electrons and ions scattered over a total test volume of roughly 300 cm^3.

These two experiments are said to be complementary because they are both plasma diagnostics with robust features in opposite aspects. The interferometer has proven to be much more sensitive to outside influences than the Faraday probe. This sensitivity proves to be a liability when taking data near thruster structures, but appears to capture to a greater degree the asymmetry previously discussed. The Faraday probe measurements were extremely stable and unaffected by proximity to the cathode but were also less sensitive to the asymmetry of the plume. To what degree the plume is asymmetric (Faraday Probe: 11%, Interferometer: 30%) may be somewhere between what these two different diagnostics measured, but it is believed these two diagnostics have established upper and lower bounds for this effect.

The complementary aspects of these two experiments continue in their basic theory. The interferometer takes measurements without disturbing the plume, but is a more complicated calculation, and suffers from some ambiguity. The Faraday probe is very simple and straightforward both to implement and interpret, but the probe has an effect on the plume when present. The data indicates that both methods are acceptable measures of particle density. There are some situations were probes may be problematic to place in a plasma as with Field Reverse Configuration plasma devices (FRCs) and similar thrusters were the plasma is enclosed. In this case interferometery could provide the means. There could also be plasmas were the sensitivity of the interferometer could greatly affect the measurements, or could be too large for the interferometer to accommodate. Faraday probes can measure a plasma of any size provide there is sufficient access and allowable motion. It is left to the researchers discrimination as to which is a more applicable mean to obtain density measurements.

VI. Future Work

In the near future both experiments will be used to examine the plume of a Busek 600 Watt Hall thruster. Measurements collected through two separate methods have validated the interferometers ability to reliably measure densities. The interferometer will also be used to examine an FRC generated plasma. Analysis will be expanded upon for all of these measurements by applying an Abel inversion to interpolate a three dimensional profile of the plasmas.

VII. Acknowledgements

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VIII. References

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