Microwave Interferometry (90 GHz) for Hall Thruster Plume Density Characterization

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A phase-bridge microwave interferometer operating at a frequency of 90 GHz (3mm wavelength) is currently under development at the Air Force Research Laboratory (AFRL) at Edwards AFB, California. The motivation for developing this diagnostic is the capability to take time resolved plasma density measurements with higher spatial resolution than other interferometers typically operating at 30 GHz. This interferometer has demonstrated preliminary electron density measurements in the plume of a 200 W Hall thruster. The interferometer has been modified to overcome initial difficulties encountered during the preliminary testing. The modifications include the ability to perform remote and automated calibrations as well as an aluminum enclosure to shield the interferometer from the Hall thruster plume. With these modifications, it will be possible to make unambiguous electron density measurements of the thruster plume as well as to rapidly and automatically calibrate the interferometer to eliminate the effects of signal drift. Due to the versatility of the diagnostic, it is also anticipated that it will be applied to Hall thrusters and large scale pulsed plasma sources under development.

I. Introduction

When investigating the physical nature of Hall thruster operation, it is often important to characterize the plasma density distribution of the plume. Measuring the electron density reveals the topography and temporal fluctuations of the plume and, when combined with other measurements such as ion velocity, can be used to estimate thruster performance and the degree of interaction with the host spacecraft.

Electron densities are commonly measured using Langmuir and similar electrostatic probes; however, these probes must be physically present in the plume during measurements. The presence of these probes in the plume is known to affect the plasma. It has been demonstrated that the presence of such probes in the plume can affect the discharge current of a Hall thruster by 10 to 50 percent [1]. The intrusive nature of these probes makes them undesirable for obtaining unambiguous electron density measurements.

Microwave interferometry provides a method for measuring electron density that is both non-intrusive and easily interpreted. No part of the interferometer is required to be present in the plume. As such, direct effects on the plasma are avoided. Furthermore, the interferometer can easily measure time resolved electron densities. These advantages are offset to some degree by the complication that the interferometer can only directly measure the line averaged electron density across the test leg. Mathematical techniques such as

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14. ABSTRACT **A phase-bridge microwave interferometer operating at a frequency of 90 GHz (3mm wavelength) is currently under development at the Air Force Research Laboratory (AFRL) at Edwards AFB, California. The motivation for developing this diagnostic is the capability to take time resolved plasma density measurements with higher spatial resolution than other interferometers typically operating at 30 GHz. This interferometer has demonstrated preliminary electron density measurements in the plume of a 200 W Hall thruster. The interferometer has been modified to overcome initial difficulties encountered during the preliminary testing. The modifications include the ability to perform remote and automated calibrations as well as an aluminum enclosure to shield the interferometer from the Hall thruster plume. With these modifications, it will be possible to make unambiguous electron density measurements of the thruster plume as well as to rapidly and automatically calibrate the interferometer to eliminate the effects of signal drift. Due to the versatility of the diagnostic, it is also anticipated that it will be applied to Hall thrusters and large scale pulsed plasma sources under development.**					
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‘onion peeling’ and Abel inversions can be used to produce spatially resolved data from a number of measurements across the plume, especially for cylindrically symmetric flows.

AFRL and Stanford University are developing a 90 GHz microwave phase-bridge interferometer capable of measuring linearly averaged electron (plasma) densities. This interferometer is unique in that it is entirely within the vacuum chamber during operation. Use of the interferometer within the test facility removes sources of interference that are generally present in other interferometers, such as optical access ports and adverse chamber effects such as reflections, etc.

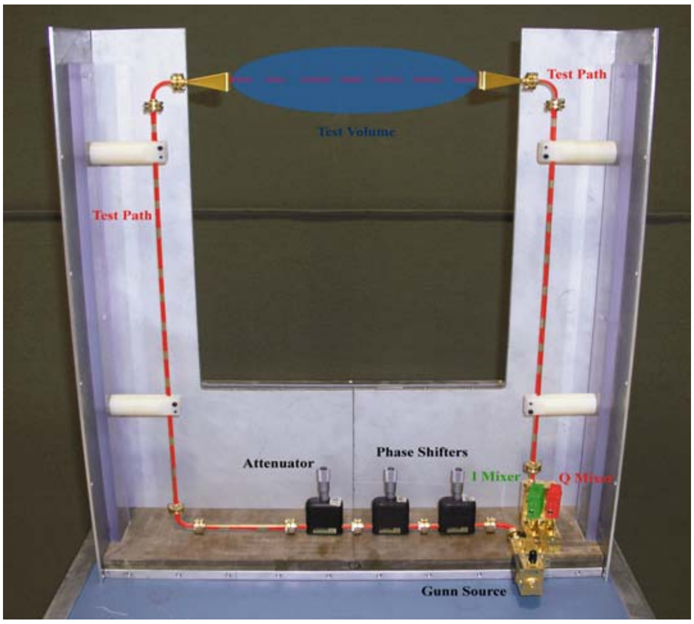

Figure 1. Picture of the interferometer with the test path (red) and test space (blue) marked. Note manual micrometers on phase shifters and attenuator.

In addition, a 3 mm wavelength will produce measurements with a higher spatial resolution than other interferometers typically operating at 30 GHz [2].

Preliminary measurements have been recorded using this interferometer to examine the near-field plume densities of a 200 W Hall thruster [3]. A number of difficulties were encountered during these measurements, manifested as signal drifts. These drifts can be separated into two general classes based on time scale. The first consists of a continuous variation of the signal baseline over periods of tens of minutes. The second consists of abrupt changes in signal which occur at random intervals, on the order of minutes.

In the preliminary assessment of the 200 W Hall thruster near plume plasma density measurements, these signal drifts required that the data interpretation be somewhat qualitative. The lack of a reliable calibration and periodic, seemingly random, abrupt shifts in the signal baseline required considerable human effort when interpreting the data.

The mechanisms responsible for these signal drifts are not completely understood. The first slow baseline shift is presumably due to thermal drifts in the system which produced temporal uncertainties in the calibration. It is also believed that the thruster is producing electromagnetic interference (EMI) that affects the operation of the interferometer within the vacuum chamber. The EMI produced by the thruster may be responsible for the abrupt changes in the signal.

The goal of this paper is to modify the AFRL/Stanford University 90 GHz microwave interferometer and determine the extent to which we can eliminate these sources of measurement uncertainty. This work will present efforts toward that goal as well as some preliminary operational data.

II. Theory of Operation

A brief description of the operation of the AFRL/Stanford University interferometer is provided below. A more complete description is available elsewhere [3].

The microwave interferometer shown in Figure 1 measures electron density using two identical 90 GHz (3 mm wavelength) microwave signals originating from a Gunn oscillation source. These signals are propagated through the interferometer using gold plated waveguides and components.

One of the signal paths is internal to the interferometer and is unimpeded by outside forces; this is the reference signal. The second path, the test path, is directed via waveguides across an open test volume 30cm wide using pyramidal gain horns. These horns are essentially antennas that allow the 90GHz test branch to cross the open space with minimal loss of signal. It is through this open space that plasma can be introduced to the test signal.

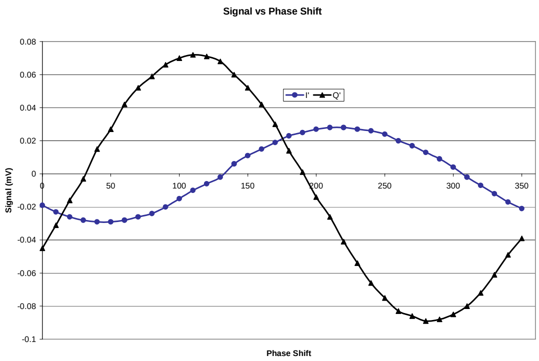

Figure 2. Sinusoidal calibration waves generated during an interferometer calibration. Note the phase shift between signals reflects the 90 degree shift built into the system.

The interferometer has the added capability of expanding this open area based on the size of the plasma to be measured. The enclosure shield, and support structure for the interferometer can be expanded. The interferometer itself can be expanded by adding more sections of wave guide with minimal loss. This provides us with the capability to lengthen the open test area to any length required.

Significant electron densities such as those present in a Hall thruster plume impede the velocity of the test signal; it is this effect that provides the basis for electron density measurements. Both test and reference signals are recombined at two separate diode mixers that convert microwave oscillations into easily measurable DC voltage signals.

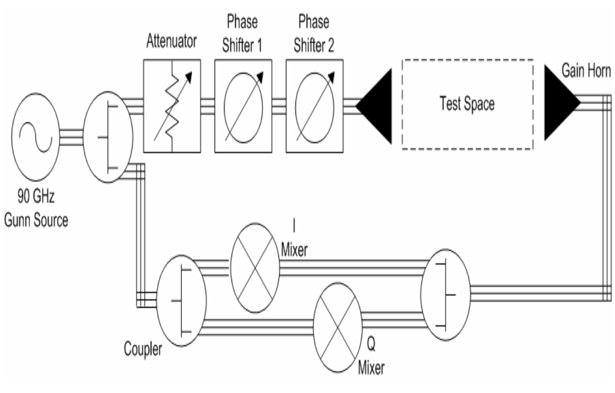

Figure 3. Logical diagram illustrating interferometer system.

The DC output of these two mixers can be described by the following equations:

$$I = I_0 + \alpha_I \frac{A_1 A_2}{2} \cos \Delta\phi$$

$$Q = Q_0 + \alpha_Q \frac{A_1 A_2}{2} \sin \Delta\phi$$

Where *I* and *Q* are the signals from the two mixers, I_0 and Q_0 are the DC signal offsets, A_1 and A_2 are the reference and test amplitudes, α_1 and α_2 are the intrinsic sensitivities of the mixers. In these equations, $\Delta\phi$ represents the phase shift between the test and reference branches of the interferometer.

It is the difference between the *I* and *Q* signals that indicates the amount of electrical impedance the test signal (*Q*) witnessed compared to the un-impeded reference signal (*I*). Thus phase shift ($\Delta\phi$) can be correlated to the electron densities encountered.

Also present in this system are two phase shifters and an attenuator required for calibration. The phase shifters provide 0-360° phase shift in the test branch. The attenuator allows for the calibration of the signal reduction of the test leg through the plasma.

Additionally, one section of waveguide in the system is twisted to produce a 90° offset between the test and reference branch. Thus when applying varying phase shifts and recording the relative signals, two sinusoidal oscillations that are offset 90° from one another are obtained.

Figure 2 shows the sinusoidal waves recorded during a calibration in which the phase shifters were used to apply a 360° phase shift in 10° increments. Voltages from both mixers are recorded at each interval. Graphing these two waves as a function of one another produces a calibration circle representative of a 360° phase shift. See Figure 4.

To acquire electron densities, a relationship must be established between densities and the recorded phase shift. The line averaged electron density encountered by the test branch can be described as a function of phase shift by the following equation.

$$\bar{n}_e = \frac{4\pi\, m_e\, \varepsilon_o\, c^2}{e^2\, \lambda_o\, \ell}\, \Delta\phi$$

The term m_e represents the electron mass, e is the electron charge, c is the speed of light, λ_0 is the microwave wavelength, ε_0 is the open space permittivity, and ℓ is the plasma column width. Using this formula, line averaged electron density may be calculated as a function of measured phase shift.

III. Experimental Apparatus

In our previous measurements, the interferometer was mounted to a rigid, magnetic steel frame. Although structurally sound, the ferromagnetic structure is believed to have adversely affected the operation of the Gunn oscillator. The Gunn oscillator specifications recommend that it not be operated in the vicinity of ferrous materials. Following the initial operation of the interferometer, the oscillator failed and was returned to the manufacturer for repair. Proximity to the ferrous structure is believed to have contributed to this failure.

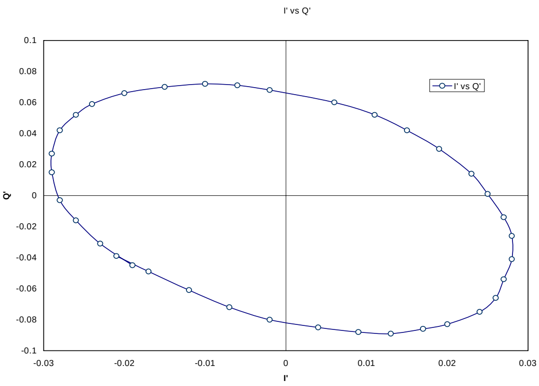

Figure 4. Smith circle generated from waveforms shown in Figure 2. Note data is not perfectly circular due to differing sensitivity of the mixers.

In addition, the open frame mounting of the interferometer left the system components exposed to the plasma produced by the Hall thruster. Although the thruster plume did not directly impinge on the interferometer, the divergent portion of the plume did contact the instrument. This exposed the interferometer to radiative heating and electrical contact with the plasma. The radiative heating is likely responsible for the long term, slow (likely thermal) signal baseline drift seen in the preliminary 200 W Hall thruster tests. It is also possible the plasma provides inadvertent electrical contacts between various components within the instrument.

In addition, a Hall thruster is not truly a steady state device. The main discharge is an unsteady plasma with a well documented 10-20 kHz AC component over a usually predominant DC component [4]. However, the discharge plasma is known to change modes from this typical operation and enter a mode where the anode discharge is dominated by the AC component with a significant increase in EMI emissions. In this case, the thruster discharge is literally turning itself off and on at approximately 20 kHz. It is believed that these variations in thruster operation periodically occur on time scales similar to the abrupt shifts in the baseline interferometry measurements. It is therefore possible that thruster EMI is at least a contributing factor to this behavior.

As originally constructed, calibration is carried out by hand through use of two manually operated phase shifters and an attenuator. This results in a slow and laborious process that can only be completed with the vacuum test facility open to the laboratory.

In an attempt to reduce the plasma influence on the measurement, an aluminum housing has been designed and constructed. Figure 5 shows a diagram of the probe housing. The housing encloses and shields the majority of the interferometer components from the plasma. This protects the more sensitive parts (e.g. mixers, Gunn oscillator diode, etc.) from adverse EMI and thermal variations as well as any affect of direct plasma impingement. Three ports in the housing provide wiring access as well as clearance for transmit and receive horns of the test branch of the microwave signal. It is anticipated that the housing will reduce the long-term drift by eliminating plume contact with the interferometer. The housing should also provide a degree of protection from EMI and eliminate most contact between the interferometer components and the plasma.

Another source of thermal drift is the temperature of the interferometer components, specifically the Gunn oscillator and the mixing diodes. Temperature variations will affect interferometer operation by either shifting the frequency of the generated microwaves (Gunn oscillator), or affecting the phase shift measurements (mixing diodes). Maintaining these components at a constant temperature within the vacuum chamber is a challenge.

By isolating the interferometer components from the plume, it is anticipated that the interferometer will thermally stabilize quickly. Although the aluminum housing will provide a convenient passive heat sink, it may not prove to be sufficient. Provisions for active cooling of several of the more sensitive active components (oscillator, and the two mixers) have been made using a circulating fluid refrigeration system with CPU heat exchangers mounted to the active interferometer components. Alternatively, the introduction of small actively controlled heater elements to improve frequency stabilization of the Gunn oscillator diode has also been considered.

Even if the long-term drift is not completely eliminated, improvements in the calibration procedure may mitigate this issue. Calibration consists of varying 2 phase shifters and an attenuator mounted in series along the test branch of the system. Applying incremental changes in phase shift and attenuation take the interferometer through the full measurement range. As originally constructed and initially tested, calibration is performed manually using micrometers to increment the phase shifters and attenuator. Typically, manual calibration requires an hour, or longer. In addition to introducing human error, manual calibrations also require depressurizing and opening the vacuum chamber. Therefore in the preliminary configuration, it was not possible to produce a timely calibration. For example, AFRL Chamber 6 requires approximately 8 hours to warm the cryogenic pumps to temperature above the laboratory dew point, and an additional 8 hours to return the chamber to operational. During this time period, the instrument calibration is known to shift.

The ideal situation is to calibrate the interferometer *in situ* immediately before firing the thruster and gathering plasma density data. To address these issues, the calibration process has been automated so that the interferometer may now be calibrated without breaking vacuum.

Automated calibration is made possible through the use of 3 Thor Labs

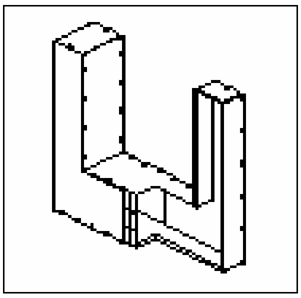

Figure 5. Cut-away diagram of the aluminum plume shielding enclosure. Note: microwave transmission ports are not present on this diagram.

Inc. Z600 servo motor actuators. These motors are specifically designed to replace the micrometers currently used in the 2 phase shifters and attenuator. The motors are controlled remotely using a National Instruments™ MID-7654 servo power motor drive unit. A specially written LabView program has reduced calibration time to less than 5 minutes. The application of this automated calibration scheme has produced greater precision and repeatability by removing the human element. As an added benefit, methodologies to improve the accuracy of the calibration by calibrating the phase shifters during the calibration of the interferometer and not relying on the factory calibration of the phase shifters as was done previously have been incorporated. Prompt calibrations performed within the evacuated vacuum chamber should eliminate the calibration uncertainties that limited the utility of the preliminary data.

V. Future Work

This system will be used to characterize the plasmas of laboratory Hall thrusters as well as new and experimental thrusters such as the Field Reversed Configuration Plasma Thruster (FRCPT) [5]. In pulsed plasmas, such as the FRCPT and others, the ability of the microwave interferometer to measure plasma densities with microsecond timescales will prove invaluable.

It is the versatility of this system that makes it so desirable. The interferometer system is compact and extremely mobile and is easily aligned. The system may be expanded by the use of additional waveguide segments to fit most plasma geometries with ease. This system can be adapted to measure a wide variety of propulsion related plasmas.

VI. Conclusions

The opportunity this interferometer presents for the accurate, *in situ* characterization of plasmas is unprecedented. The 90 GHz microwave interferometer provides the ability to take plasma density measurements in a non-intrusive manner contained entirely in the test chamber. This system has already been used in a preliminary fashion to characterize the plume of a 200 W Hall thruster, and has produced results that suffered only from thermal drifts and other uncertainties in the system. It is believed that these uncertainties may be reduced to a negligible level as a result of system improvements detailed in this paper.

VII. Acknowledgements

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