EEDF Control Through Gas Injection Into a Plasma Plume

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Abstract

Electron Energy Distribution Function (EEDF) measurements were made in a magnetically enhanced, Inductively Coupled Plasma (ICP) with and without the introduction of an axially injected neutral jet of argon gas with a small relative flow. A lab-built RF compensated Langmuir probe (LP) along with a Hiden LP controller were used to obtain data. Results show that this counterflow of neutral gas has little effect on the EEDF.

Introduction

Ions, accelerated to high velocities, in the Low Temperature Plasma (LTP) inside Hall-effect Thrusters (HETs) are the thrust-producing constituent. With the continued push for more efficient use of propellant in HETs, time-resolved control of the EEDFs is needed. The ability to tailor the EEDF would allow electrons with energies that contribute to ionization to be increased, and those that do not have enough energy to ionize or that are involved in transient processes to be reduced. However, predictive control of the EEDFs in LTP devices remains a challenging problem in plasma physics due to the complex electromagnetic interactions taking place in the actual system that lead to the turbulent nature of these plasmas.

The goal of this research is to obtain an understanding of the physical dynamics that govern how transients and ionization are affected by changes to the EEDF. Then with that knowledge, schemes to predictably customize the EEDF in order to increase HET efficiency will be developed. As a first step in addressing this challenge, experiments are being conducted with simplified plasma sources to test various EEDF control methods. This paper discusses experiments conducted to test a neutral gas injection EEDF control scheme.

Experimental Setup

In this experiment, a 11-cm long helical antenna, constructed with 3.175-mm diameter copper tubing, was wound around a 10-cm diameter Pyrex tube so that an ICP could be obtained when gas was run through the tube. The helical antenna was water-cooled, and driven at 13.56 MHz and 500 W using an RF power supply. An L-type matching network was placed between the antenna and power supply and manually tuned so that there was zero reflected power during testing. An external magnetic field, with a peak intensity of 8 mTesla (80 Gauss), was applied to increase the intensity of the axial B-field in order to create a more

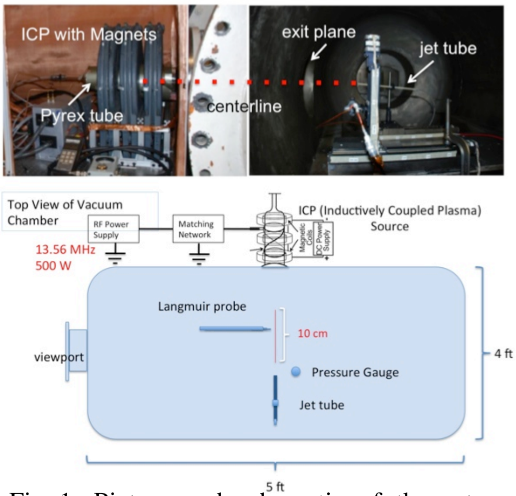


Fig 1. Picture and schematic of the setup showing the magnetically enhanced ICP, jet tube, LP and other components of the setup.

dense, blue-core plasma. The exit plane of the jet tube, with a 5.74-mm diameter, was positioned 38-cm downstream of the ICP's exit plane. Argon gas was used for both the plasma source and the jet tube with a 500 sccm flow rate for the ICP, and a 150 sccm flow rate for the neutral jet. These experiments were conducted in a vacuum chamber with a length of about 1.5-m, a diameter of 1.2-m, and a base pressure on the order of 10^{-6} Torr.

Diagnostics

Measurements were obtained using an RF compensated Langmuir Probe (LP). The tungsten probe tip was 0.13-mm in diameter, and 15-mm in length placing the probe in the OML regime for plasma densities on the order of 10^{16} m^{-3}. Since the LP is a DC diagnostic, the RF oscillations in the plasma would distort the resulting IV trace. The probe was fit with an auxiliary electrode, which had a much larger total exposed surface area relative to the probe tip. This electrode was wound around the shaft of the probe as close to the tip as possible and capacitively coupled to the probe's circuit. The capacitor was chosen so that it was large enough to be a short circuit to these fluctuations but small enough to be a broken wire to DC current. The purpose of this electrode was to obtain a stronger signal of the RF fluctuations in the probe tip region than the probe can obtain so that the first harmonic of this AC component of the LP signal could be filtered out by two chokes, with resonant frequencies of 13.56 MHz, which were placed in series with the probe tip [1].

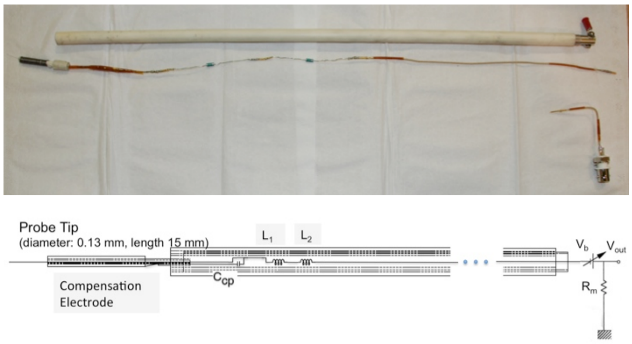


Fig 2. Picture and circuit diagram that show how the Langmuir Probe was RF compensated.

The operating pressure with and without the neutral flow was around 3-mTorr. Through the ideal gas law, this gives a background neutral density on the order of 10^{19} m^{-3}. LP data was collected in an 8-cm by 10-cm radial cross-section with a 1-cm resolution beginning 23-cm downstream of the ICP's exit plane. Twenty LP traces were obtained for each data point. The average of these traces was used to find plasma properties at each spatial location.

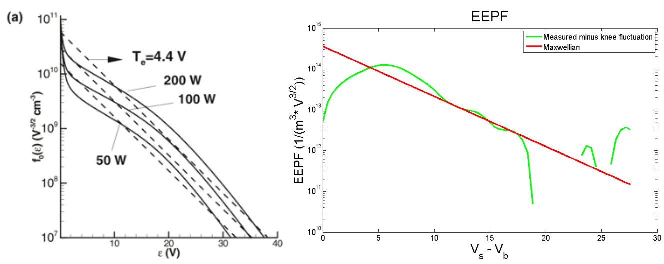
Results

Over the data collection area, the ranges and average floating and plasma potentials were very similar between the two cases. However, the average ion number density was slightly higher for the case with neutral flow and the average electron temperature was slightly lower. This was attributed to the higher neutral number density, which led to a greater electron-neutral collision cross section. Using the assumption of quasi-neutrality, the electron number density is equal to the ion number density. These densities were derived from the ion saturation current as opposed to the electron saturation current because in the I-V traces the transition between the electron retardation region and electron saturation region was not well defined, and the data shows evidence of ion reflection (ion beams). It is customary to assume quasi-neutrality and to use the ion saturation current to calculate electron number density [2].

		ICP Source Characterization	ICP Source & Neutral Flow
Floating potential (V)	Range	15.1940 - 18.2600	15.1940 - 18.2600
	Average	16.7558	16.7912
Plasma potential (V)	Range	17.8220 - 22.2020	19.1360 - 22.2020
	Average	21.1313	21.1358
Ion # density ($1*10^{16}$ m-3)	Range	2.0058 - 3.0684	2.2950 - 3.2458
	Average	2.4656	2.7552
Electron temperature (eV)	Range	3.0287 - 7.9564	3.2767 - 6.1904
	Average	5.1047	4.4847

Table 1. A comparison of the range and average values for various plasma properties between the two test scenarios.

The EEDFs calculated from the LP traces compare well to the literature. Godyak et al. conducted experiments with an inductively coupled argon discharge using a 13.56 MHz driving frequency. The plasma densities that were obtained were on the order of 10^{16} m^{-3} for operating pressures of 1-mTorr [3]. In addition, Ramamurthi et al. carried out simulations for this scenario using a one-dimensional model containing an EEDF module [4]. As seen from Fig. 3, both experimental Electron Energy Probability Functions (EEPFs) depart from a Maxwellian distribution in similar ways. Most notably, there is dearth of low energy electrons. The primary reason for this lack of thermodynamic equilibrium is the lower electron–electron collision rate in these low-pressure plasmas [5].



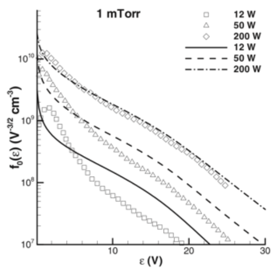


Fig 3. (top left) Comparison between Ramamurthi's simulated EEPFs and Maxwellian EEPFs. (bottom left) Comparison between this simulated data (dashes) and Godyak's experimental data (symbols). (above) EEPF 5cm downstream from ICP source in this study (without neutral jet) compared to a Maxwellian EEPF.

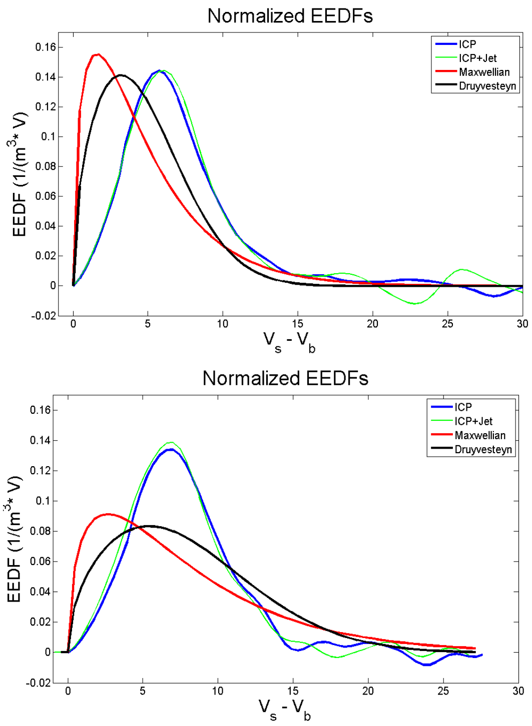


Fig 4. An EEDF comparison for the cases with and without neutral flow for two representative spatial locations in the data collecting area. Maxwellian and Druyvesteyn distributions are also shown for reference.

In comparing the EEDFs for various spatial locations in the data collecting area for the run with and without the neutral jet, the results showed there were no significant differences (Fig. 4).

Conclusion

In these experiments, there was a slight increase in the average number of low-energy electrons when the neutral jet was used. However, the introduction of this flow did not change the shape of the EEDF for various spatial points in the data collection area. Since finer control over the EEDF is being sought in order to develop effective predictive control methods to increase HET efficiency, other EEDF control methods will be investigated in subsequent work.

Future Research

A hollow cathode will be run in plume mode where the plasma exhibits an underlying periodicity similar to that inherent in HET plumes. The High-speed Dual Langmuir Probe (HDLP) system, an in-lab-built diagnostic, has been developed to obtain time-resolved plasma property measurements. For these experiments, it will be operated with a sweep rate of 20 kHz to obtain data from the cathode's argon discharge. The EEDF control method that will be tested is inert gas mixing with nitrogen. Other research has shown through simulations and experiment that when one of these gases is a small fraction of the mixture, the natural presence of its metastable states and the superelastic collisions that ensue create plateaus, holes and peaks in the EEDF [6, 7].

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