Plasma Adiabaticity in a Diverging Magnetic Nozzle

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A mechanism for ambipolar ion acceleration in a magnetic nozzle is proposed. The plasma is adiabatic (i.e. transfers no heat to or from its surroundings) in the diverging section of a magnetic nozzle so any energy lost by the electrons must be transferred to the ions via the electric field. Fluid theory indicates that the change in average electron energy equals the change in plasma potential. These predictions were validated by measurements in VASIMR which has experimental conditions conducive to ambipolar ion acceleration.

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Nomenclature

C = a constant
e = elementary charge
$\langle E \rangle$ = average electron energy
N = number of degrees of freedom
n_e = electron density
p_e = electron pressure
s = field aligned position
T_e = electron temperature
γ = specific heat ratio
λ_D = Debye length
ϕ = plasma potential

I. Introduction

In recent years there has been significant interest in helicon discharges in expanding magnetic fields for applications such as spacecraft propulsion[1] and plasma processing[2] as well as for studies in basic plasma science.[3–6] Helicon discharges are used to efficiently produce plasma[7] while the diverging magnetic field produces an ion beam which has the potential for producing thrust for space applications or etching in processing applications. Typical experiments involve a helicon antenna surrounding an non-conductive tube in which the plasma is created (called the source chamber) which is attached to a larger diameter conducting chamber (called the expansion chamber). The magnetic field expands from the source chamber into the expansion chamber with a corresponding drop in field strength.

In both plasma processing and propulsion the goal of the plasma source is to accelerate ions. Double layers are commonly observed in laboratory experiments, which is relevant for processing, but it is unknown whether that mechanism would apply to a helicon thruster in space. Ambipolar ion acceleration has recently been considered as an alternative mechanism that may be more relevant to the space environment.[8,9] This paper shows that experimental data are consistent with fluid theory predictions of the behavior of plasma parameters for ambipolar ion acceleration in a plasma using the adiabatic expression for pressure.

II. Ion Acceleration Mechanisms

A. Current Free Double Layers

The most commonly accepted explanation for ion acceleration in a diverging magnetic field is that a Current-Free Double Layer (CFDL) is established near the plane separating the source chamber from the expansion chamber. Although double layers can easily be formed when the plasma is carrying current, current-free double layers form even when there is no net current across the double layer.[10] A double layer is a non-neutral region consisting of two adjacent layers of opposite space-charge. The space-charge regions establish a potential drop of 1s or 10s of T_e/e's for weak and strong double layers, respectively, where T_e is the electron temperature in eV, in a region of 10s of Debye lengths.

A balance of four species makes double layer formation possible: free ions and trapped electrons originating in the source chamber and trapped ions and free electrons originating in the expansion chamber. The electron species have a Maxwellian distribution with an approximately constant electron temperature across the double layer. The electron pressure for a Maxwellian distribution is

$$p_e = n_e T_e \tag{1}$$

where n_e is the electron density. Since the electron temperature is constant, the momentum balance equation can be reduced to the Boltzmann relation

$$\phi_2 - \phi_1 = \frac{T_e}{e} \ln\left(\frac{n_{e2}}{n_{e1}}\right). \tag{2}$$

Here ϕ is the plasma potential and the subscripts 1 and 2 indicate two positions. The Boltzmann relation defines the relationship between electron density and temperature in the double layer, while, again, the electron temperature is constant.

B. Ambipolar Ion Acceleration

Probe measurements were made in the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®), a helicon generated plasma with a magnetic nozzle, to observe the expected double layer in this experiment.[9] An ion accelerating potential was observed but, surprisingly, it extended of 1000s of Debye lengths, rather than 10s, indicating that this structure was not a double layer. Instead, ambipolar electric fields established the potential structure and accelerated the ions. This phenomenon is explored in greater detail in this article.

Consider a one dimensional plasma with magnetized electrons in a magnetic nozzle. Assume that at any given point the electrons are Maxwellian, though the temperature is not constant in space. This assumption is consistent with experimental observations.[9] The ions are magnetized and follow the electric field lines. With these assumptions, the electron momentum balance equation reduces to

$$\frac{\partial p_e}{\partial s} = n_e \frac{\partial (e\phi)}{\partial s} \tag{3}$$

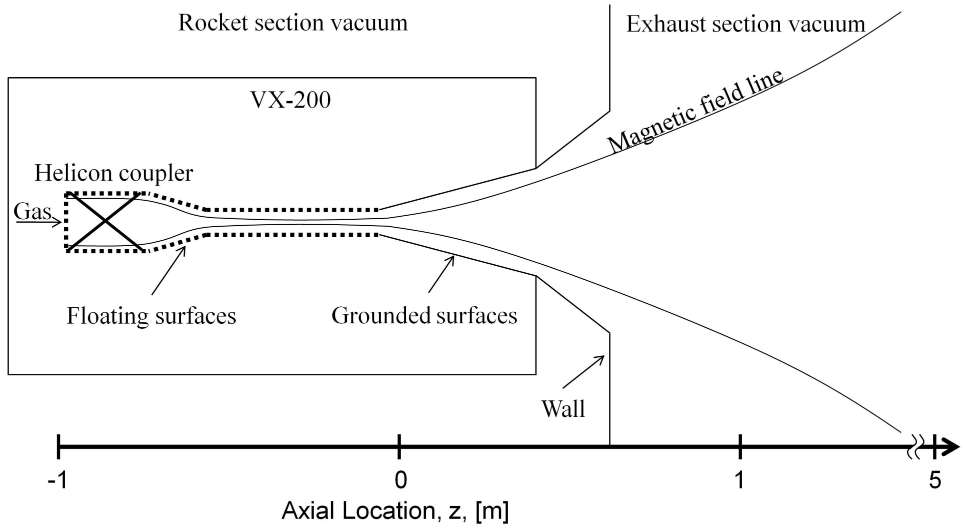

Figure 1. A schematic diagram of the experimental setup of the helicon plasma source and vacuum chamber.

where s is the field aligned position vector. Because the plasma electrons are highly magnetized with no boundary or neutral interactions and the ions are cold and simply follow the electric field lines, the plasma is adiabatic with 1 degree of freedom. The adiabatic definition of pressure is

$$p_e = C n_e^{\gamma} \tag{4}$$

where C is a constant, $\gamma = (N+2)/N$ is the ratio of specific heats, and N is the degrees of freedom. Equation 1 remains valid as well if the electrons remain Maxwellian throughout. Using Eqs. 1, 3, and 4, the change in plasma potential can be related to the change in electron temperature.

$$\frac{\partial(e\phi)}{\partial s} = \frac{3}{2}\frac{\partial T_e}{\partial s} \tag{5}$$

The average electron energy in a Maxwellian distribution is $\langle E \rangle = \frac{3}{2}T_e$, so

$$\frac{\partial(e\phi)}{\partial s} = \frac{\partial \langle E \rangle}{\partial s}. \tag{6}$$

This equation indicates that the energy lost by the electrons goes towards accelerating the ions via the electric field. The mechanism of energy transfer to ions is still unknown.

III. Experiment

Experiments on ion acceleration in a magnetic nozzle were performed in VASIMR VX-200, a prototype electrodeless plasma propulsion device for spacecraft.[9,11,12] The VASIMR device uses a helicon antenna to ionize the propellant gas to a 95% ionization fraction and heat the electrons and an ion cyclotron antenna to heat the ions. Electromagnets generated a converging/diverging magnetic nozzle to accelerate the plasma out of the device and generate thrust. For these experiments the VASIMR device was used, but only with the helicon plasma source; the ion cyclotron heating was not used. A schematic of the experiment is shown in Fig. 1.

Up to 30 kW of 6.78 MHz RF power was coupled into the plasma via the helicon antenna with a coupling efficiency of 95%. The working gas was argon with mass flow rates between 50 and 140 mg/s. The electromagnets generated a maximum magnetic field of 20,000 G in the throat of the magnetic nozzle (located at $z = 0$ in Fig. 1). All of the plasma facing components of the device were electrically floating, though the vacuum chamber was grounded. The vacuum chamber (described in detail elsewhere[9]) had a high pumping speed of 5×10^4 L/s which could establish a base pressure of 10^{-9} Torr. During operation, the neutral pressure in the chamber was up to 10^{-4} Torr, depending on the mass flow rate.

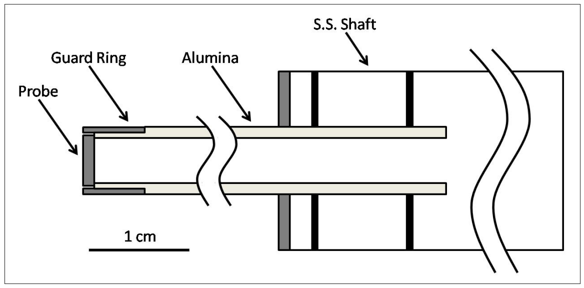

Figure 2. A schematic diagram of the planar Langmuir probe.

The plasma was diagnosed using a planar Langmuir probe, schematically depicted in Fig. 2. A stainless steel tube supported an alumina tube on which the probe was mounted, keeping the probe far enough away from the grounded stainless steel tube to prevent its influence on the measurements. The probe itself was a 6.35 mm diameter tungsten disk. A 7.5 mm outer diameter, 8 mm long tube called the guard ring fit around the tip of the probe as indicated in Fig. 2. The guard ring was electrically insulated from the probe and allowed to float, which reduced sheath expansion effects that can introduce errors in probe measurements.[13] The Langmuir probe was mounted on a two dimensional motion control table which could move the probe axially and radially, horizontally.

Langmuir probe current-voltage (I-V) traces were obtained by sweeping the bias on the probe from -40 to 40 V with a sweep rate of 80 Hz and a sampling rate of 40 kHz, which captured all features of the I-V trace from ion saturation current to electron saturation current. The traces were obtained in the diverging portion of the magnetic nozzle to within 5 cm of the throat. Further into the nozzle the energy densities were too high to safely operate the Langmuir probe. Because the probe measurements were made almost 1 m away from the helicon antenna RF fluctuations were minimal, introducing 0.2 V and 0.1 eV errors to the plasma potential and electron temperature, respectively. These variations were approximately 1% of the measured values, an acceptable uncertainty, so no RF compensation scheme was used.

The plasma potential was determined from the knee of the planar Langmuir probe I-V trace.[14] The electron temperature was calculated by fitting the semilog plot of the electron current to an line and the electron density was determined from the electron saturation current. These values are shown in Fig. 3 for a mass flow rate of 50 mg/s and helicon power of 30 kW. The plasma density, potential, and temperature all decay as the magnetic field strength decreases downstream of the throat of the magnetic nozzle. The drop in electron temperature is pronounced so Boltzmann's relation is not applicable for this experiment. Additionally, the potential drop occurs on the order of 10 cm, which is on the order of $10^4\lambda_D$, so the structure is not a double layer.

IV. Discussion

Insight can be gained by comparing the change in electron temperature to the change in plasma potential (see Fig. 4). The majority of data points fit a linear trend quite well and the line has a slope of 1.17, meaning

$$\frac{\partial(e\phi)}{\partial s} = 0.78\frac{\partial \langle E\rangle}{\partial s}. \tag{7}$$

Deviation at the higher temperatures close to the magnetic nozzle is due to uncertainty in the measurements at very high densities. Far downstream where the temperature is low the data do not fit the linear trend either. The plume is geometrically constrained where the magnetic field lines intersect the vacuum chamber walls.

The linear relationship between the electron temperature and plasma potential qualitatively matches the fluid theory prediction in Eq. 5. The scaling factor is different between theory and experiment. This difference may be due to the fact that the electron velocity distribution in the magnetic nozzle experiment is not truly Maxwellian. With an enhanced or depleted tail the expression $\langle E\rangle = \frac{3}{2}T_e$ under- or over-represents the average electron energy for the non-Maxwellian distribution. The data presented here suggest that the distribution function in the diverging section of the magnetic nozzle has a depleted high energy tail so

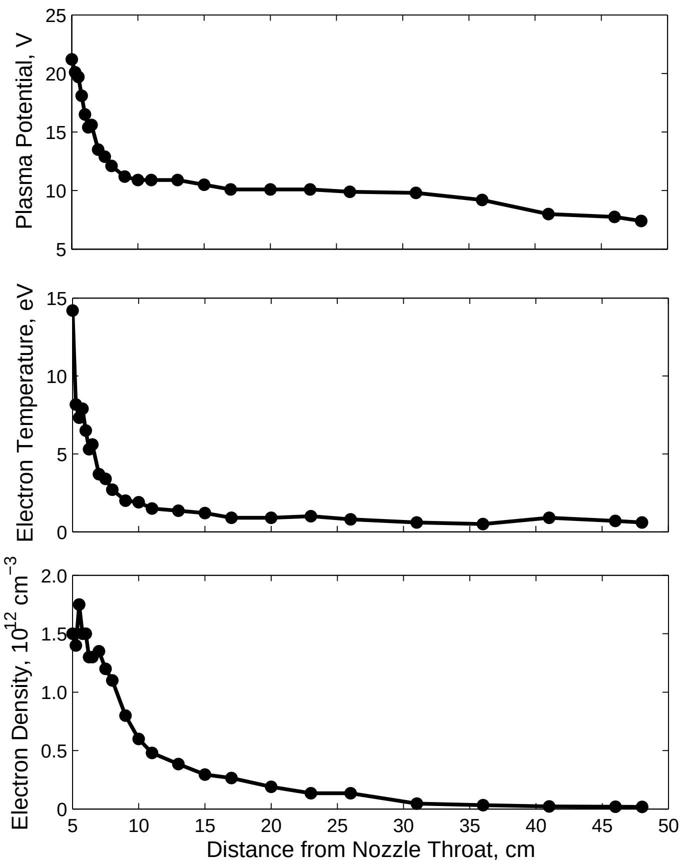

Figure 3. Plasma potential, electron temperature, and electron density as a function of distance downstream of the throat of the magnetic nozzle.

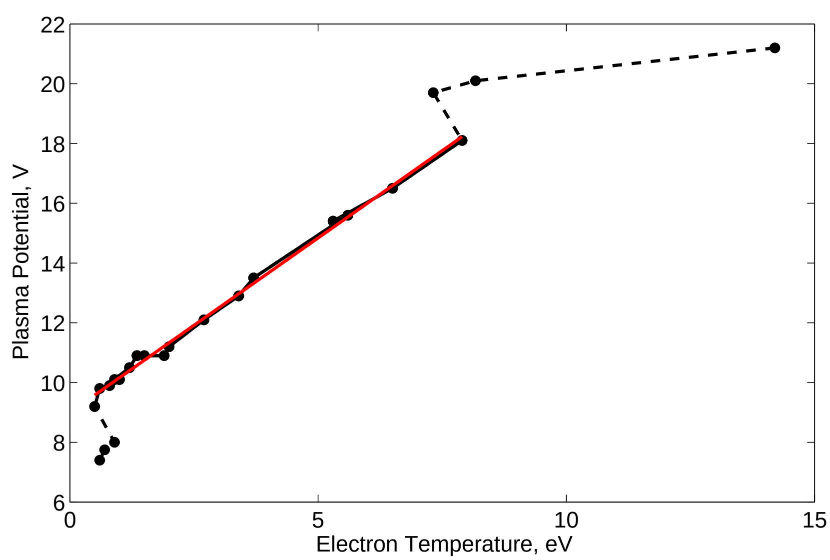

Figure 4. Plasma potential versus electron temperature in the magnetic nozzle. The red line is a linear fit and the dashed lines connect data points that were not included in the fitted data set.

$\langle E \rangle < \frac{3}{2} T_e$, assuming that T_e is determined from the bulk distribution, not the tail. Other possible causes of the discrepancy is energy losses to turbulence and instabilities in the expansion region and inelastic collisions.

A yet unknown element of this phenomenon is how the electrons lose their energy in the collisionless environment. It has been suggested energy is incrementally lost during reflections off of rarefaction waves far downstream.[8] Alternatively, a two-stream instability between the ions and electrons may be the culprit. Further investigation is necessary to fully understand ambipolar ion acceleration.

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