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Experimental evidence of parametric decay processes in the variable specific impulse magnetoplasma rocket (VASIMR) helicon plasma source

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Decay waves have been observed in the megahertz range in the helium plasma generated by the variable specific impulse magnetoplasma rocket magnetoplasma thruster. They are measured using one of the tips of a triple probe connected to a 50 Ω input of a spectrum analyzer via a dc block (a small capacitor). The maximum amplitude of all waves is in the center of the plasma and does not appear correlated to the radial electron density or temperature profiles. The waves seem to be generated close to the helicon antenna that was 91 cm “upstream” from the measuring Langmuir probe. A possible explanation is parametric decay of the large amplitude helicon wave that also generates the plasma. © 2004 American Institute of Physics. [DOI: 10.1063/1.1803579]

I. INTRODUCTION

Plasma thrusters for application to satellites are an effective alternative to chemical thruster systems and are appearing on a number of telecommunication satellites for station keeping and on scientific satellites (SMART 1 to the moon and Deep Space 1 to comet and asteroids) as a primary drive. A convenient method of controlling the trajectories of spacecraft during long flights, to Mars, for example, is to be able to change the specific impulse (essentially the exhaust velocity) and the thrust. The thruster experiment variable specific impulse magnetoplasma rocket (VASIMR), as given in Ref. 1, is aimed at this goal. Basically, it can be regarded as in the class of magnetoplasma thrusters, with the plasma being created by a high density helicon discharge operating near the lower-hybrid frequency (typically 500–1500 G) followed by an ion cyclotron heating cell (around 5000 G) and finally a magnetic expansion which is designed to accelerate the plasma and convert the perpendicular ion energy into parallel ion energy.

Since the waves that ionize the plasma are of very high amplitude, nonlinear effects may be present which could change the operational parameters of the thruster either by aiding the ionization or the heating of the ions or by hindering it by adding to turbulent cross-field diffusion and consequently producing a lower plasma density. This paper is the

investigation of instabilities in VASIMR, which has a helicon wave rf driven magnetoplasma.

Helicon plasma sources (see, for example, Ref. 2) have generated much interest in the basic and industrial plasma communities due to their ability to produce high plasma densities with a relatively low power and low frequency. They are being studied not only for use in industrial applications such as plasma processing of semiconductors and plasma thrusters but also for the understanding of basic plasma physics processes (see, for example, Refs. 1 and 3–5). Helicon (or whistler) waves are a simplified form of right hand polarized electromagnetic waves in a magnetized plasma with frequencies between the lower-hybrid and electron cyclotron frequencies. In the helicon source used in VASIMR, the frequency is relatively high at 25 MHz compared to most other helicon sources that operate at 13.56 MHz and sometimes lower. Consequently, there is a broader window of frequencies below the “pump” helicon frequency than is normally the case. As will be seen presently, this freedom allows other wave decay processes to occur that have not previously been reported with lower helicon excitation frequencies.

A resonant interaction among three waves can result in a parametric decay process which satisfies the conditions of energy conservation and momentum conservation, described by $\omega_0 = \omega_1 \pm \omega_2$ and $k_0 = k_1 \pm k_2$, respectively. For this instability to occur, the rf pump helicon wave ω_0 parametrically

drives a second lower-frequency “daughter” helicon wave ω_1 , and a lower-frequency “idler” wave ω_2 . For the present experiment, this lower frequency wave has a frequency at least five times higher than previously reported, as will be discussed below.

Parametric decay of whistler or helicon waves has been known for many decades with the first experimental evidence being taken in a strongly magnetized plasma cylinder, as given in Ref. 6, where a powerful pump whistler wave of 2.45 GHz (around the electron cyclotron frequency at 1000 G) and up to 6 kW (which also served to create the plasma of up to 10^{13} cm^{-3} in helium) decayed into another whistler and a short wavelength ion acoustic wave at around 7 MHz. The authors remark that significant heating of about 10% of both the ions and electrons accompanied the parametric decay for a pump frequency about $0.7f_{ce}$. Although the pump wave in the present experiment is 100 times lower in frequency, there are similarities between the two experiments that suggest that ion heating may also occur in VASIMR. However, it should be pointed out that the pump wave in Ref. 6 was in the microwave region, close to the electron cyclotron frequency, and consequently had a short wavelength, allowing coupling to ion acoustic waves. This is not the case for the present experiment.

Boswell and Giles, in Ref. 7, operating in a large area argon plasma at 0.5 mTorr with an applied axial magnetic field of 128 G and a measured electron density of $6 \times 10^{10} \text{ cm}^{-3}$, observed decay waves that were only seen along the group velocity resonance cones at 28 deg to the magnetic field and not elsewhere. Pump waves at 150 MHz ($0.42f_{ce}$) were transmitted from a 1 cm diameter loop antenna and received with a small floating Langmuir probe. The low-frequency ion waves had a frequency of 150 kHz and were only seen above a threshold power.

More recently, Kline *et al.* (see Refs. 8 and 9) presented experimental evidence of the parametric decay of the helicon wave into two electrostatic waves in a helicon source, thought to be a lower-hybrid wave and an ion acoustic wave. They observe a maximum amplitude of the parametrically excited wave, which can be as large as 8% of the pump wave, 1 cm from the axial center of the helicon source with frequencies in the range 400–800 kHz.

Virko, Kirichenko, and Shamrai in Ref. 10, operating in a 1 mTorr weakly magnetized argon discharge driven at 13.56 MHz, observed broadband oscillations in the low-frequency range extending up to 1 MHz. These oscillations were thought to be due to the interaction of the rf field of the helicon wave with the plasma. The excitation of these low-frequency oscillations had thresholds on input power and dc magnetic field suggesting that parametric decay was the likely phenomenon, responsible for the generation of the waves.

One of the problems in analyzing these low-frequency waves is finding the energy source that drives the wave. In the papers cited above, the waves with frequencies of hundreds of kilohertz are generally considered to be a result of a three wave parametric decay with the helicon wave being the pump. If the decay originated from the electromagnetic fields of the helicon wave, it would be reasonable to find the decay

FIG. 1. The magnetoplasma thruster prototype VASIMR.

waves having maximum amplitude in or near the center of the discharge where the helicon electric fields are maximum. However, if the electrostatic resonance cone fields, or possibly the near fields of the antenna itself drove the decay, the decay products would be expected to be maximum near the plasma boundaries. Unfortunately, near the plasma boundaries, there are commonly severe gradients in plasma density and electron temperature that are a not inconsiderable source of free energy in themselves.

Here we investigate radial and axial profiles of the basic plasma parameters, the high- and low-frequency daughter waves on the pump helicon wave and the lower-frequency idler wave and compare them with the measured plasma density and electron temperature.

II. EXPERIMENTAL DESCRIPTION

The VX-10 device incorporates three main experimental regions: helicon, ICRF acceleration and plasma exhaust. Figure 1 shows a schematic and the general form of the magnetic system used for the experiments presented here. The magnetic system consists of 3–4 liquid nitrogen cooled solenoids surrounding the stainless steel vacuum chamber. The solenoids are designated, M1, M2, M3, and M4, starting at the upstream end. Typically the magnetic field profile provides a low magnetic field strength ($<0.1 \text{ T}$) for the helicon plasma source and a high magnetic mirror (up to 1.3 T) downstream from the helicon source. The main vacuum chamber opens into a 5 m^3 chamber that was pumped with two diffusion pumps and one cryopump. The total pumping rate for hydrogen was about 6000 l/s. The chamber background pressure was kept in the low 10^{-4} Torr range during a plasma pulse. Figure 1(b) shows the temporal evolution of the gas pressure during a shot. The gas valve is opened at $t=0$ and gradually the pressure increased in the large vacuum chamber to 0.1 mTorr after about 2 s. The pressure upstream of the heli-

FIG. 2. A typical spectrum of the waves detected by the floating Langmuir probe.

con source increased dramatically when the plasma was turned on suggesting strong plasma ion pumping. The pressure under the helicon antenna was estimated to be a few milliTorr.

Referring to Fig. 1(a), gas was delivered to the upstream end of a 9 cm diameter quartz tube (length 107 cm) typically at a rate of 110 sccm via a 1000 sccm mass-flow controller. A 10 cm long double-saddle antenna was situated midway along this tube. One lead to the antenna was grounded, while the other was driven at 25 MHz at power levels of up to 3.5 kW. A 30 cm long converging Pyrex nozzle is inserted into the downstream end of the 107 cm quartz tube to reduce the tube's neutral conductance. The exit of the Pyrex gas choke was located at the maximum magnetic field strength in the system, near the center of solenoid 3; the gas choke's diameter matches the plasma diameter there. Upon exiting the gas choke, plasma flows through a second quartz tube 20 cm in length, 5 cm in diameter that serves to prevent the plasma from contacting a second antenna used in ion cyclotron heating experiments. In the VASIMR concept, the second antenna boosts the perpendicular energy of ions passing under it via the ion cyclotron resonance. The expanding magnetic field downstream of this antenna acts as a magnetic nozzle, converting the perpendicular kinetic energy acquired at the ion cyclotron resonance to parallel energy. Power was not applied to this antenna in the experiments reported here.

The Langmuir probe was located 91 cm downstream from the center of the double-saddle antenna. The probe head consists of four parallel tungsten pins, 1.0 mm in diameter and oriented perpendicular to the axis of the experiment. The pins were located at the corners of a square 4.5 mm on a side and extend 3.0 mm past the edge of a grounded cylindrical shield 16 mm in diameter and the system can be used as a "triple probe." The radial position of the probe head was set by a fine-threaded drive screw. Data for the measurements presented here were taken by coupling the electrically floating upstream pin via a small capacitor to the 50 Ω input of an analog spectrum analyzer, bandwidth 0.01–350 MHz.

III. RESULTS

The spectra measured by the floating Langmuir probe were very different to those detected in earlier experiments discussed in the Introduction. A typical spectrum taken 2.5 cm from the center of the discharge with the "standard" operating conditions of (see experimental description) is presented in Fig. 2. The pump helicon wave at 25 MHz has a clear lower sideband at 20 MHz and a low-frequency wave at 5 MHz. On the high-frequency side of the pump there is a broad peak with features appearing at 5 and 7 MHz separation from the helicon. Why this is so is not clear but it may be due to propagation effects between the antenna and the probe.

It should be remarked that the magnetic field at the helicon antenna was about 800 G but between this point and the Langmuir probe the field rises to over 5000 G and then decreases again to a few hundred gauss in the region of the Langmuir probe (see Fig. 1). Hence, any wave generated nonlinearly in the region of the antenna would have to propagate through a fairly long (compared to its wavelength) region having a varying plasma density and magnetic field.

The radial variation of the upper and lower sidebands and the low-frequency idler is shown in Fig. 3 on a log plot (on a linear plot, the waves would appear much more confined to the plasma column). Clearly, the wave amplitudes have a broad maximum in the center of the plasma that would tend to suggest that they are not driven by density gradients at the plasma's edge nor by the near fields of the antenna. The radial variation of the plasma density is shown in Fig. 4 and the radial electron temperature profile in Fig. 5.

As the gas flow is increased the gas pressure increases and consequently the ion neutral collision frequency increases. The effect on the waves is that the upper and lower helicon sideband amplitudes decrease by at least 10 dB whereas the lower-frequency idler changed little suggesting that the propagation of the waves from their source region near the helicon antenna was significantly different, with the

FIG. 3. The radial variation of the upper and lower sidebands and the idler. Note that the amplitude scale is logarithmic. The squares show the 20 MHz lower sideband, the triangles, the 32 MHz upper sideband, and the diamonds, the 5 and 7 MHz low-frequency idlers.

lower-frequency idler being less damped than the high-frequency waves.

Changing the magnetic field in the region of the helicon antenna between about 620 and 850 G did not seem to affect any of the waves, suggesting that the lower-hybrid frequency was not playing a major role in these phenomena.

Interestingly, as the power to the helicon antenna was increased from 500 to 3000 W, there was also little change in any of the wave amplitudes although there is the suggestion of a resonance in the interaction for a power of around 2 kW. The interaction appears to be saturated and the threshold is much below 500 W. Of course, the plasma density is also changing when the helicon power is varied; nevertheless it is surprising that the interaction apparently has such a low threshold.

The last run of the experimental series consisted in measuring the spectra for all waves for a period of 2 s from the time the gas valve was opened (which is essentially the same time as when the rf to the helicon antenna was switched on). This showed that the amplitudes of all waves decreased by perhaps a factor of 2 over this time.

IV. DISCUSSION

The magnetic field at the helicon antenna was about 700 G, which resulted in the rf excitation frequency being

FIG. 4. Radial variation of the plasma density.

FIG. 5. Radial variation of the electron temperature.

close to or somewhat higher than the lower-hybrid frequency. The daughter wave (the low-frequency sideband) was close to the calculated lower-hybrid frequency in the center of the discharge but the high-frequency sideband would have been always higher than the lower-hybrid frequency for the magnetic field variations (620–850 G) of this experiment. For these conditions, the helicon approximation ($E = 1/n_e J \times B$) for wave dispersion is only some percent different from the full dispersion relation and we will use it to calculate the wavelengths of the three possible waves involved in the interaction.

After some simple algebra, an expression for the wavelength of parallel propagating (electromagnetic) helicons can be expressed as

$$\lambda \sim 5 \times 10^9 (B/fn)^{1/2}.$$

Assuming that $n \sim 10^{13} \text{ cm}^{-3}$ and $B \sim 700 \text{ G}$, conditions typical near the helicon source are as follows.

- (i) For the 25 MHz pump, $\lambda \sim 8.5 \text{ cm}$, $k \sim 0.74$.
- (ii) For the 20 MHz daughter, $\lambda \sim 9.5 \text{ cm}$, $k \sim 0.66$.
- (iii) For the 5 MHz idler, $\lambda \sim 19 \text{ cm}$, $k \sim 0.33$.

Downstream from the helicon source, the magnetic field increases by almost an order of magnitude, and since there are no measurements of the electron density, the simplest approximation would be that B/n is constant. If that were the case then the wavelengths would not change appreciably. It is also possible that the density remains constant or even decreases in the increasing magnetic field; in which case, the wavelengths would increase.

If the ion inertia is taken into account then the wavelength of the idler would be somewhat longer, but, taken in the spirit of this approximation, there could be a match in the k vectors if they are not parallel to the magnetic field. As the wavelength gets longer the effect of the boundaries also needs to be taken into account and this could improve the matching.

As the experimental campaign on VASIMR was only 5 days, further measurements were not possible although wavelength measurements would have been useful. Nevertheless, the observation that the magnetic field gradients (and possibly plasma density gradients) are of the same order or smaller than the wavelengths of the propagating waves would make any measurement open to a variety of interpre-

tations. The main point to note with these experiments is that the waves had a maximum amplitude in the center of the discharge and appeared, therefore, to be electromagnetic in nature.

It is possible that low-frequency waves may contribute to the plasma production or to ion heating. The latter has been suggested by a number of groups (see the Introduction) to occur with low-frequency ion acoustic waves but the possibility of nonlinear wave conversion playing a role in plasma production has not really been investigated. To this end it is interesting to calculate the phase velocity of the waves involved in the interaction. The helicon and its upper and lower sidebands have estimated phase velocities of around $2 \times 10^8 \text{ cm s}^{-1}$ whereas the low-frequency idler has an estimated phase velocity of about half that. The velocities of the higher-frequency waves would be closer to the threshold ionization velocity for helium but the velocity of the lower-frequency idler would be deep in the Maxwellian distribution of the electrons. Some experiments have shown that waves close to the threshold ionization velocity are most effective in ionizing the plasma by trapping electrons below the threshold and moving them to velocities above the threshold (see, for example, Ref. 11). For all the waves considered here, their phase velocities are below the threshold ionization velocity for helium. It is very likely then that all the waves would be involved in directly heating the electrons but that the parametric decay would not be adding significantly to the efficiency of the ionization process.

V. CONCLUSION

Experimental evidence has been presented that shows the possible existence of a parametric decay process involv-

ing at least three helicon waves. The amplitude of all waves peaks in the center of the discharge and their estimated phase velocities are all below the threshold ionization velocity for helium. The phase velocity of the low-frequency 5 MHz idler wave is lower than the average electron thermal velocity. All waves would contribute to electron heating due to their low phase velocities but it is not likely that the existence of the parametric decay improves the ionization efficiency of the system.

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