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Electrostatic ion-cyclotron waves in a plasma with heavy negative ions

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Abstract

Results of a laboratory study of electrostatic ion-cyclotron (EIC) waves in a plasma containing K^+ (39 amu) positive ions, electrons and $C_7F_{14}^-$ (350 amu) negative ions are presented. Excitation of the fundamental and higher harmonic light and heavy ion EIC modes was observed. The presence of heavy negative ions in the plasma has a significant effect on the excitation of the light ion EIC modes. The results may be relevant to the understanding of plasma wave properties in plasmas containing negative ions, such as those found in the Earth's ionosphere, the solar system, and, in particular, near Saturn's moon Titan, where an abundance of heavy negative ion species has recently been discovered [Coates, et al., 2007. Discovery of heavy negative ions in Titan's ionosphere. Geophys. Res. Lett. 34, L22103].

Keywords: Electrostatic ion-cyclotron waves; Negative ion plasmas; Titan

1. Introduction

Electrostatic ion-cyclotron (EIC) waves were first observed in a laboratory experiment by D'Angelo and Motley (1962) and have also been observed on a rocket payload in the high latitude ionosphere in the 500-km altitude range (Mosier and Gurnett, 1969), and on the S3-3 satellite in the auroral region around 6000 km by Kintner et al. (1978). EIC waves are considered to be important in auroral plasma physics, because EIC waves accelerate the ions in the direction perpendicular to the Earth's magnetic field, and subsequently the ions are driven upward into the magnetosphere by the grad B mirror force as described by Klumpar (1979). This mechanism is considered to be the principal source of heavy, energetic (O^+) ions in the magnetosphere (see, e.g., Frank et al., 1977; Horwitz, 1982).

Magnetic field-aligned currents (FAC) have traditionally been invoked to explain the excitation of waves near the ion gyrofrequency both in the laboratory (Drummond and Rosenbluth, 1962) and in the Earth's auroral region (Kindel and Kennel, 1971). However, as pointed out by Rasmussen and Schrittwieser (1991), the excitation mechanism for EIC waves in laboratory plasmas has been the subject of ongoing debate since they were first observed. EIC waves have been produced in laboratory plasmas by drawing an electron current along the magnetic field to a small disk electrode located in the center of the plasma column. The current is driven by biasing the electrode at a potential above the plasma potential. This has led to the suggestion that the mechanism for EIC wave excitation is a two-dimensional potential relaxation instability (Sato and Hatakeyama, 1985; Hatakeyama et al., 1985; Popa et al., 1985).

The association between EIC waves and magnetic FACs in the auroral region has also been puzzling since the waves were sometimes observed even when the current (more precisely, the magnetic field-aligned electron drift speed) was below the critical threshold for excitation. Recently, however, Ganguli et al. (2002) showed that the EIC waves could grow unstable even in the absence of FAC if perpendicular velocity shear in the ion flow along the magnetic field lines was taken into account. Multiple harmonic hydrogen cyclotron waves associated with a spatial transverse gradient in the ion flow parallel to the magnetic field have been observed on the FAST satellite (Gavrishchaka et al., 2000).

Plasmas containing appreciable fractions of negative ions (formed by either direct electron attachment or

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dissociative attachment) are found in the Earth's ionosphere and mesosphere (see, e.g., Massey, 1976). The dominant negative ion in the ionosphere down to 85 km is O_2^-, with O^- the principal negative ion species above that altitude. Negative ions have also been found in the ionospheres of Mercury, the Earth's moon and Jupiter's moons, as well as in stellar atmospheres (see, Wekhof, 1981). Chaizy et al. (1991), based on measurements with the Giotto spacecraft, identified various negative ion species (O^-, OH^-, C^-, CH^- and CN^-) in coma of comet Halley near 1 AU.

The Huygens atmospheric probe has also revealed a complex, multi-species plasma environment on Titan and two special issues of Planetary and Space Science have been devoted to a presentation of the results (see Raulin et al., 2007, 2008). Borucki et al. (2006) predicted that a large reduction in the electron density during the night would occur in Titan's atmosphere due to electron attachment to very small molecular complexes. Recently, heavy negative ions, with densities up to $\sim 100\,cm^{-3}$, were discovered using the CAPS electron spectrometer on the Cassini spacecraft in Titan's ionosphere by Coates et al. (2007). On one Titan encounter (T16) at an altitude of 953 km, extremely heavy negative ions with M/q values up to 10,000 amu/q were observed. These large particles correspond to aerosols with sizes ~10–30 nm. The presence of such a complex plasma environment containing heavy negative ions should have significant effects on the excitation and dispersion properties of plasma waves in Titan's ionosphere. Intense low-frequency electric field noise extending down to the low-frequency limit of the plasma wave instrument onboard Voyager 1 was observed in Titan's wake (Ma et al., 1987). Similar electrostatic noise was observed near the space shuttle in conjunction with the release of gas from the orbiter (Shawhan et al., 1984).

In addition to naturally occurring negative ion plasmas, a number of active experiments were performed in which various electron attaching molecules were injected into the ionosphere to modify the local plasma environment (see, e.g., Bernhardt, 1984; Hunton et al., 1987; Mendillo, 1988; Ganguli et al., 1992).

Given the prevalence of negative ion plasmas in the Earth's ionosphere and in the solar system in general, it is reasonable to perform laboratory experiments and theoretical studies which investigate plasmas containing negative ions. One of the early investigations of negative ions was performed by von Goeler et al. (1966) in which a plasma containing Cs^+ and Cl^- ions was formed by surface ionization. The positive and negative ions were detected using a mass spectrometer that separated the ions according to their gyroradius. Negative ion plasmas produced by electron attachment to SF_6 was first reported by Wong et al. (1975). Hershkowitz and Intrator (1981) made important improvements to the concept introduced by Wong et al. (1975) and used their device to study beam–plasma interactions in a positive ion negative ion plasma (Intrator and Hershkowitz (1983). A detailed study of various negative ion sources was presented by Sheehan and Rynn (1988) who later showed that such sources could be used to study plasmas with adjustable levels of strong turbulence (Sheehan et al., 1993).

There have been a number of theoretical and experimental studies of EIC waves in negative ion plasmas. D'Angelo and Merlino (1986), using a three-fluid model, derived the dispersion relation for EIC waves in a plasma containing a fraction of negative ions. They showed that two modes were generally possible, one with angular frequency $\omega \gtrsim \Omega_+$ and the other with $\omega \gtrsim \Omega_-$, where $\Omega_\pm = eB/m_\pm$ is the ion cyclotron frequency, with $m_\pm$ the positive/negative ion mass and B the magnetic field strength. Sheehan (1987) was the first to report observations of EIC waves in a plasma containing negative iodine ions. The work of D'Angelo and Merlino (1986) provided the theoretical foundation for an experiment performed by our group in a plasma containing K^+ positive ions, electrons and SF_6^- negative ions (Song et al., 1989). Sato (1989, 1994) presented results of a series of experiments, performed in a Q machine, on the effects of negative ions on the characteristics of typical plasma waves and instabilities, including the EIC instability.

The conditions for excitation of EIC waves in a negative ion plasma by a magnetic field-aligned electron drift were derived by Chow and Rosenberg (1996) using kinetic theory. They showed that the critical electron drift velocity for the excitation of both the positive ion and the negative ion modes decreased as the relative density of the negative ions increased. The previous experimental and theoretical work considered only excitation of the fundamental EIC modes. Experimental and theoretical investigations of EIC wave excitation in a plasma containing negatively charged dust particles were performed by Barkan et al. (1995) and Chow and Rosenberg (1995).

In this paper we report on EIC wave experiments in a plasma containing electrons, K^+ positive ions and $C_7F_{14}^-$ (perfluoromethylcyclohexane) negative ions (350 amu). This differs from previous experimental work in a number of respects:

(1) The present experiment deals with heavy negative ions with $m_-/m_+ = 350/39 \backsimeq 9$, whereas previous experiments, using SF_6 as the electron attaching gas had $m_-/m_+ = 146/131 \sim 1$ in a cesium plasma (131 amu), or $m_-/m_+ = 146/39 = 3.7$ in a potassium plasma (39 amu).
(2) In the previous experiments, which utilized SF_6, it was not possible to exclude the possibility that both SF_6^- and SF_5^- ions were present (see, e.g., Christophorou and Olthoff, 2000), whereas in the present work only the parent negative ion is formed through the reaction $C_7F_{14} \rightarrow (C_7F_{14}^-)^* \rightarrow (C_7F_{14}^-)$ (Asundi and Craggs, 1964).
(3) In the electron energy range of the present experiments the efficiency of production of $C_7F_{14}^-$ negative ions is higher than that for SF_6^-, which means that plasmas with larger negative ion concentrations can be

produced using C_7F_{14} at lower values of the neutral gas pressure. This ensures that while substantial negative ion densities can be formed, ion neutral collisions are not a significant factor.

(4) The present experiments investigate the excitation of both the fundamental and the higher harmonic EIC modes.

In Section 2 the details of the experimental setup and methods are described. The results are presented and discussed in Section 3. A short summary and the conclusions are given in Section 4.

2. Experimental setup and methods

The experiments were performed in a single-ended Q machine device (Motley, 1975), shown schematically in Fig. 1. The plasma is formed by surface ionization of K atoms (from an atomic beam oven) that are directed onto a 6-cm diameter tantalum hot plate (~2200 K). The K^+ ions along with thermionically emitted electrons from the hot plate form a ~1-m-long plasma column, confined radially by a uniform, longitudinal magnetic field, which can be increased up to 0.5 T. The Q machine plasma is nearly full-ionized, with electron and ion temperatures $T_e \approx T_i \approx 0.2$ eV and ion densities $n_+ \sim 10^9\,cm^{-3}$. The electron temperature and plasma density are measured with planar Langmuir probes.

2.1. Negative ion plasmas

Negative ion plasmas were produced by leaking C_7F_{14} vapor into the vacuum chamber using a fine needle valve. C_7F_{14} has a relatively high-electron attachment rate for thermal electrons in the range of 0.1–0.2 eV, and thus is ideal for use in the Q machine since the electrons have energies in this range. A stable and long-lived parent negative ion $C_7F_{14}^-$ is formed by electron attachment. An illustration of the effect of adding C_7F_{14} to the plasma is given in Fig. 2, which shows two Langmuir probe current–voltage (I–V) plots before and after C_7F_{14} was leaked into the system. In this I–V plot, the electron probe current is the positive current. The upper plot was obtained when no C_7F_{14} was present. When C_7F_{14} was added, the

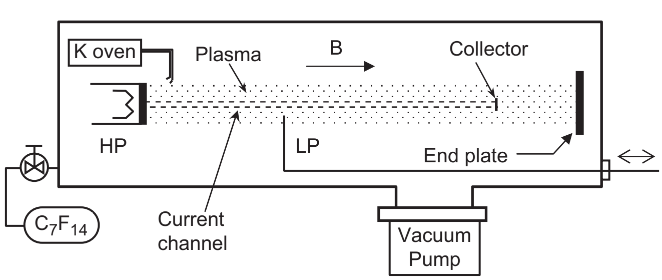

Fig. 1. Schematic of the experimental setup. The plasma source is a single-ended Q machine. EIC waves are excited by drawing an electron current to a biased collector located on the axis of the plasma column.

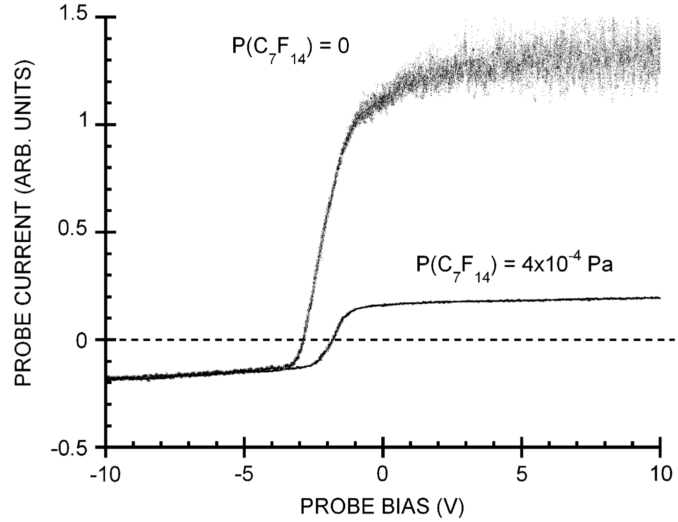

Fig. 2. Langmuir probe current–voltage characteristics in the absence of (upper) and in the presence of (lower) negative ions. The positive current in this plot corresponds to the collection of electrons. The decrease in the electron saturation current in the lower plot is due to the attachment of electrons to heavy (relatively immobile) negative ions.

electron current was significantly reduced (by about a factor of 10) as electrons became attached forming $C_7F_{14}^-$ negative ions. The negative ion contribution to the probe current is much less than the electron contribution since the thermal speed of the negative ions is much less than that of the electrons.

The parameters used to characterize negative ion plasmas are $\alpha \equiv n_-/n_+$, the fractional concentration of negative ions, or $\varepsilon \equiv n_e/n_i$, the fractional concentration of electrons, where n_j (j = i,e,−) is the density of ions, electrons and negative ions, respectively. These parameters are related through the quasineutrality condition, $n_i = n_e + n_-$, so that $\alpha + \varepsilon = 1$. In the limit in which all electrons are attached to the negative ions, $\varepsilon \to 0$. When $\varepsilon \to 0$, it is difficult to make accurate measurements of the negative ion fraction from Langmuir probe characteristics. Details of the measurements of ε (or α) in a negative ion plasma formed using SF_6 and C_7F_{14} are published elsewhere (Kim and Merlino, 2007). For later use in the interpretation of the results, we mention that for a C_7F_{14} pressure of 5×10^{-5} Pa, $\varepsilon \approx 4 \times 10^{-2} (\alpha \approx 0.96)$, while at a pressure of 5×10^{-4} Pa, $\varepsilon \approx 4 \times 10^{-3}$ Pa ($\alpha \approx 0.996$).

2.2. EIC wave excitation

The EIC waves were excited by drawing an electron current to a disk electrode (9.5-mm radius) located on the axis of the plasma column and approximately 60 cm from the hot plate. When the applied bias voltage on the collector was sufficiently high, coherent electrostatic waves were excited at a frequency about 10–20% above the ion gyrofrequency. In the absence of negative ions, the fundamental EIC mode and a few relatively weak harmonics were also excited. In most cases studied here, the waves were driven somewhat above the threshold for excitation, with wave amplitudes as large as 10–30%.

The waves were observed as fluctuations in the collector current and also as potential or density fluctuations on probes located anywhere between the hot plate and collector. The EIC waves propagated outward from the current channel with a wavevector $\vec{K}$ that was nearly perpendicular to the magnetic field. The perpendicular wavelength was typically ~a few centimeter (Song et al., 1989). The parallel wavevector, $\vec{K}_{\parallel}$, was much smaller (typically at least 10 times smaller) than the perpendicular wavevector $\vec{K}_{\perp}$. These results are consistent with the theoretical prediction that maximum wave growth occurs for $K_{\perp}/K_{\parallel}{\sim}25-50$ and $K_{\perp}\rho_i{\sim}1$, where ρ_i is the ion gyroradius. For example, with $T_i = 0.2\,\text{eV}$ and $B = 0.3\,\text{T}$, we have $\rho_i \approx 1\,\text{mm}$, so that $2\pi\rho_i \approx 6\,\text{mm}$.

3. Results and discussion

3.1. Dispersion relation from fluid theory

We begin by showing in Fig. 3 a theoretical plot of the frequency versus perpendicular wave number K_x, obtained by solving the dispersion relation obtained from the three-fluid model (D'Angelo and Merlino, 1986) for values of the parameters appropriate to the present experiment: $T_+ = T_e = 0.2\,\text{eV}$, $T \approx 0.03\,\text{eV}$, $m_-/m_+ = 350/39$ and $B = 0.3\,\text{T}$, and for several values of the percentage of negative ions, α. Two modes are possible, a low-frequency mode associated with the heavy negative ions and a higher-frequency mode associated with the light positive ions. Both the light and the heavy ion EIC mode frequencies increase with increase in α.

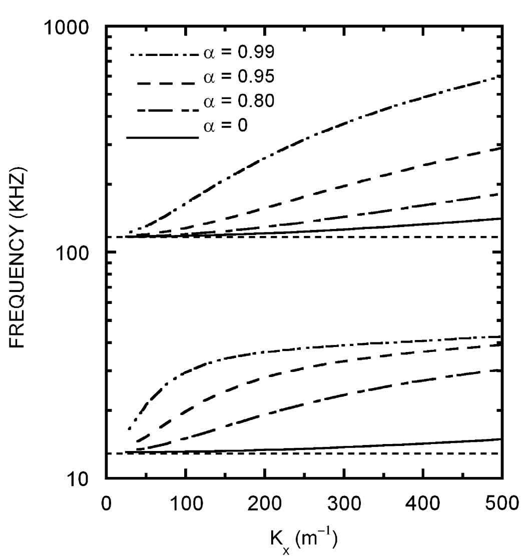

Fig. 3. Theoretical plot of the EIC mode frequencies versus perpendicular wavenumber, K_x expected in a plasma containing a fraction, α, of negative ions for several values of α, listed from top to bottom. The low-frequency modes correspond to the heavy negative ions, while the high-frequency modes are the positive ion modes. Here $B = 0.3\,\text{T}$, $T_e = T_+ = 0.2\,\text{eV}$, $T_- = 0.03\,\text{eV}$, $m_-/m_+ = 350/39$. The dashed lines are the respective cyclotron frequencies for the positive and negative ions.

3.2. EIC wave spectra

Fig. 4 shows the power spectrum of EIC waves in a plasma without C_7F_{14} and the spectrum with C_7F_{14} at a pressure of $\sim 2.7 \times 10^{-4}\,\text{Pa}$. The EIC wave spectrum without C_7F_{14} shows excitation of the fundamental at a frequency above the K^+ ion cyclotron frequency (117 kHz for $B = 0.3\,\text{T}$) and a few harmonics. When C_7F_{14} was present, additional low-frequency peaks appeared in the spectrum due to the excitation of the heavy negative ion EIC fundamental mode at 15.5 kHz, and two harmonics at 30 and 41 kHz. The negative ion cyclotron frequency in this case was 13 kHz. The K^+ EIC mode frequencies increased when the negative ions were present, in qualitative agreement with Fig. 3.

The effect of the negative ions on the excitation of higher-order harmonics of the light ion EIC modes is shown in Fig. 5. Two points are evident: (i) more harmonics were excited, and (ii) the amplitudes of the fundamental and harmonics were higher when the negative ions are present. The inset in Fig. 5 shows linear scale a histogram of the peak mode amplitudes with and without C_7F_{14}. When the negative ions were present, the amplitude of the first harmonic is comparable to that of the fundamental, while in the absence of the negative ions, only relatively weak harmonics are excited.

Under certain conditions of magnetic field and C_7F_{14} pressure, the spectrum shown in Fig. 6 was observed. In addition to the K^+ and C_7F_{14} modes, sum and difference modes with frequencies corresponding to $mf_{K^+} \pm f_{0,C_7F_{14}^-}$

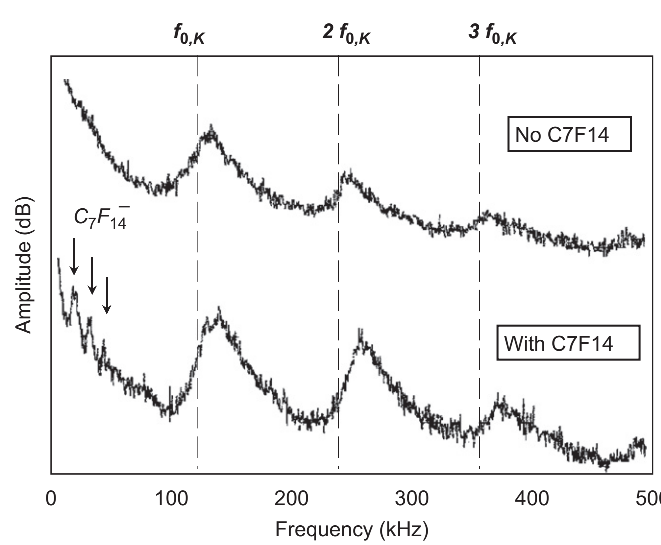

Fig. 4. Power spectra of EIC waves in plasmas without negative ions and with negative ions. The low-frequency negative ion modes are indicated by arrows. The vertical dashed lines mark the locations of the positive ion cyclotron frequency and its harmonics. The $C_7F_{14}^-$ EIC modes are indicated by arrows.

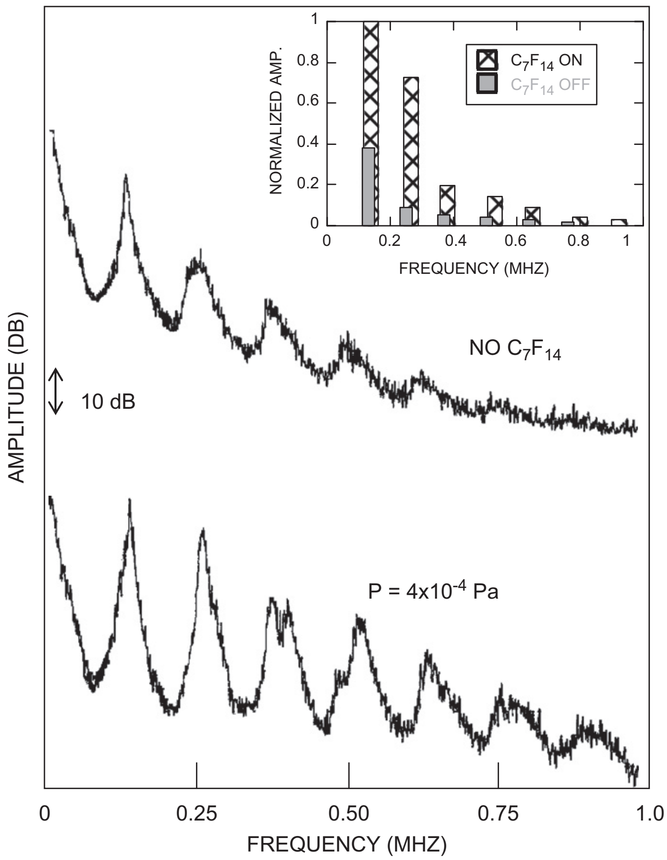

Fig. 5. EIC power spectra up to 1 MHz showing the excitation of higher harmonic EIC modes. The inset shows a histogram (linear scale) of the peak mode amplitudes with and without negative ions.

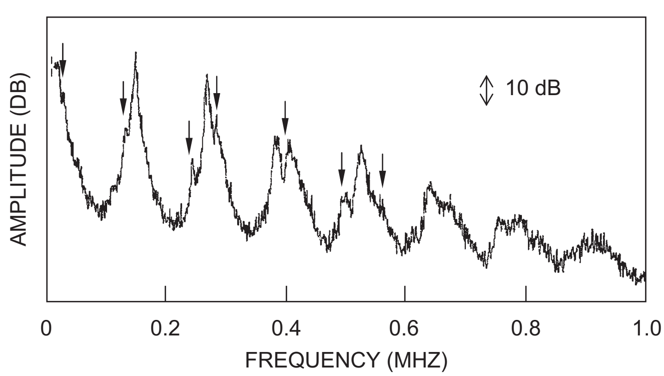

Fig. 6. Power spectrum of EIC modes, as in Fig. 5, showing additional spectral peaks originating from the sum and difference of the positive and negative ion modes.

are also present, where m is the harmonic number ($m = 1$ is the fundamental) and $f_{0,\,C_7F_{14}^-}$ is the fundamental negative ion mode. These complex spectra were usually observed when the C_7F_{14} pressure was relatively low. A similar complex spectrum of EIC modes exhibiting sum and difference peaks was also observed in a previous study of EIC waves in a plasma containing two positive ion species (Suszcynsky et al., 1988).

3.3. Magnetic field dependence

One signature of EIC waves is the increase of the frequency with increasing magnetic field strength. The frequencies of the light (K^+) and heavy ($C_7F_{14}^-$) EIC fundamental and first harmonic modes for three values of B is shown in Fig. 7. The solid lines are the positive and negative ion cyclotron frequencies, f_{K^+} and $f_{C_7F_6^-}$, and the dashed lines are $2f_{K^+}$ and $2f_{C_7F_6^-}$. The mode frequencies were always above the respective cyclotron frequencies and scaled approximately linearly with magnetic field strength. When the negative ions were present, the mode frequencies were shifted well above the gyrofrequencies. The increase of the negative (heavy) ion mode frequencies with magnetic field is shown in more detail in Fig. 8. By measuring the deviation of the frequency of the fundamental EIC mode from the cyclotron frequency, it is possible, using the results of the theory given in Fig. 3, to estimate the relative negative ion fraction, α, if the perpendicular wavelength is known. Alternately, if an independent measurement of α is available, the theoretical results can be used to estimate the perpendicular wavelength. In the present case, we know that the perpendicular wavelength is fixed by the size of the plasma column, so that $K_x \sim 100-200\,\mathrm{m}^{-1}$. Then from Fig. 3, we see that $\alpha \sim 0.85$–0.95. This estimate for α is in line with values obtained from the reduction in the electron probe current, as in Fig. 2.

3.4. Dependence of the EIC wave frequency and amplitude on C_7F_{14} pressure

The dependence of the frequencies of the fundamental positive and negative ion EIC modes on C_7F_{14} pressure is shown in Fig. 9. Over this pressure range α varied from roughly 0.8 to over 0.995. The negative ion modes did not

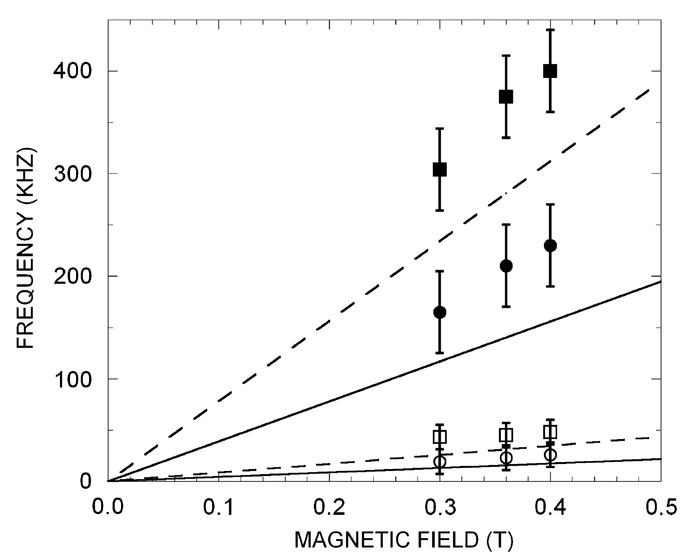

Fig. 7. EIC mode frequencies versus magnetic field strength. Open symbols refer to the negative ion modes and closed symbols the positive ion modes. The solid lines are the cyclotron frequencies, f_{c+} and f_{c-}, and the dashed lines are $2f_{c+}$ and $2f_{c-}$.

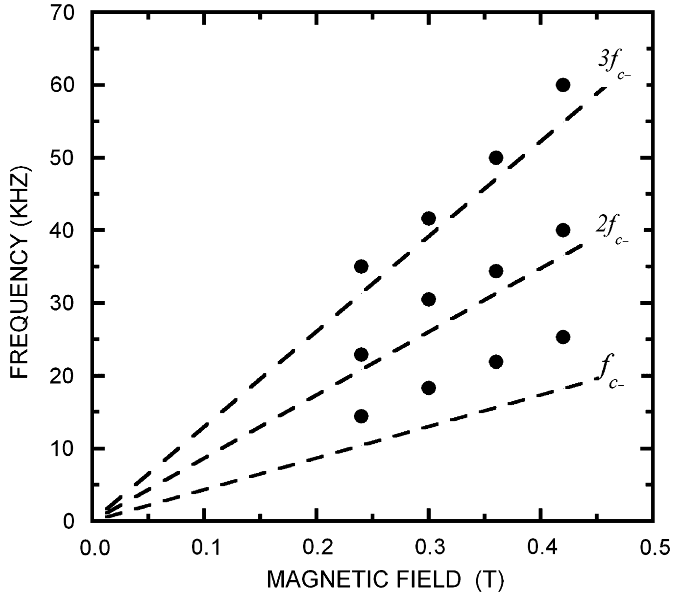

Fig. 8. Frequency versus magnetic field strength for the heavy ion (negative) EIC modes.

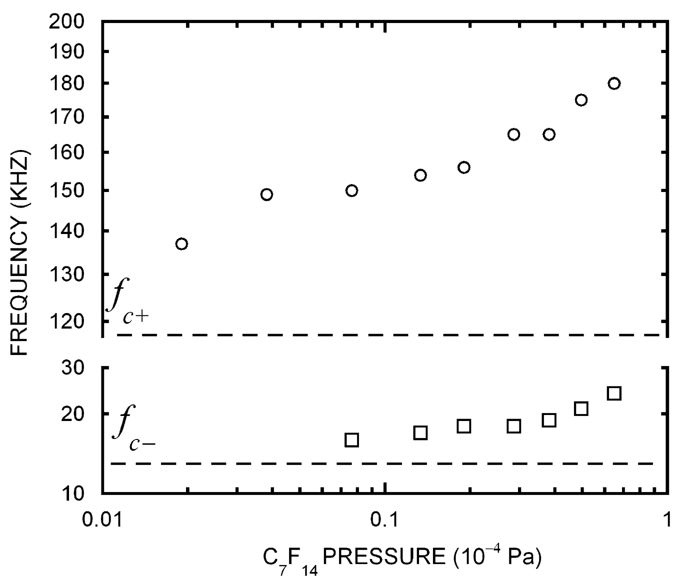

Fig. 9. Frequency versus C_7F_{14} pressure for the light and heavy ion modes.

rise above the noise level until the pressure was increased to $\sim 1.3 \times 10^{-5}$ Pa. The general trend of the frequencies to increase with α is in qualitative agreement with the theoretical results of Fig. 3.

The behavior of the positive ion EIC mode amplitude as the C_7F_{14} pressure was varied is shown in Fig. 10. In this plot the amplitudes have been normalized to the value when no C_7F_{14} was present. Initially, when a relatively small amount of C_7F_{14} was added, the normalized amplitude increased. When the C_7F_{14} pressure was increased further, the normalized amplitude decreased but remained greater than unity over a large range of

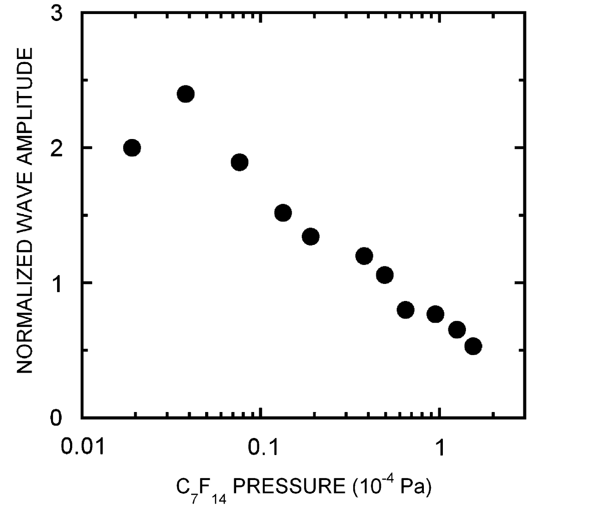

Fig. 10. Normalized wave amplitude of the positive ion EIC mode versus C_7F_{14} pressure. The amplitudes were normalized to the value obtained with no negative ions present.

C_7F_{14} pressure. The reduction of the normalized amplitude at higher pressures may be related to the fact that there were fewer electrons present to carry the current. The question of wave excitation, however, can only be properly addressed when detailed calculations starting with a full kinetic approach become available.

The effect of the negative ions on the excitation of the light ion mode was demonstrated in another way. With no C_7F_{14} present and the collector bias voltage set to 17 V, the EIC spectrum shown in Fig. 11(a) was obtained. The bias voltage was then reduced below the critical value for EIC wave excitation (in this case $V_b = -0.2$ V, which was still positive relative to the plasma potential, so that an electron current was present), and the waves disappeared, as shown in Fig. 11(b). With V_b held at -0.2 V, a small amount of C_7F_{14} was then added, and the EIC modes re-appeared, as shown in the Fig. 11(c). Obviously, the presence of negative ions lowered the threshold for wave excitation to the point that the fundamental and a few harmonics were excited. We note that if the bias on the collector was reduced to the point that no electron current was present, the EIC waves were not excited even when C_7F_{14} was present.

4. Summary and conclusions

We have investigated experimentally the excitation of EIC waves in a plasma consisting of K^+ ions, electrons and $C_7F_{14}^-$ negative ions. Two modes were excited when an electron current was drawn along the magnetic field lines to a collector located near the end of a magnetized plasma column. The frequencies of both the light (positive) ion and the heavy (negative) ion EIC modes increased with increase in α, the fraction of negative ions. The presence of the heavy negative ions increased both the number of harmonic modes excited and the intensity of all modes. The amplitude of the light ion mode first increased with

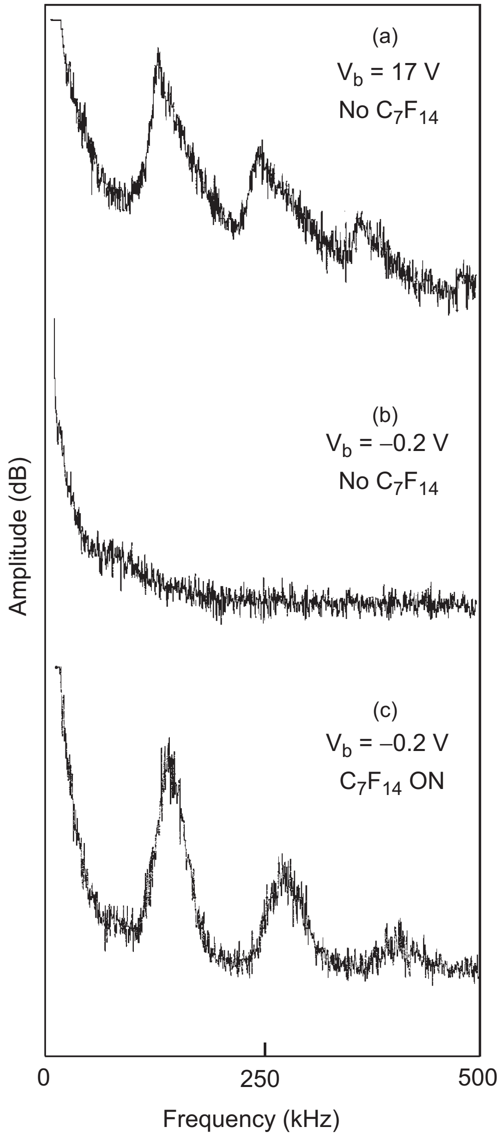

Fig. 11. Effect of C_7F_{14} on excitation of the light ion EIC modes. (a) No C_7F_{14} present, but with a sufficient collector bias voltage to excite the light ion EIC modes. (b) Disappearance of the light in EIC modes when the collector bias was below the critical value for excitation. (c) Re-appearance of the light ion EIC modes when C_7F_{14} was introduced but with the bias voltage below the critical value as in (b).

increasing α up to a point, then decreased, possibly due to the depletion of electrons forming the negative ions. The effect of the presence of negative ions on the excitation of the light ion EIC mode was clearly demonstrated (Fig. 11).

The experimental results were in general agreement with the three-fluid model of EIC waves in a negative ion plasma. This model is useful in predicting how the mode frequencies depend on the perpendicular wave number, K_x, and the negative ion concentration, α. The conditions for wave excitation, and, in particular, the excitation of higher harmonic EIC modes, however, must be properly addressed using kinetic theory.

Finally, we note that the results of such laboratory studies may be important in the interpretation of plasma wave measurements in space plasmas containing significant populations of negative ions, such as in the ionosphere of Titan.

Acknowledgements

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