Lower-hybrid waves in a plasma with negative ions

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The low-frequency lower-hybrid (LH), ion–ion mode was investigated experimentally in a plasma consisting of K^+ positive ions, SF_6^- negative ions, and electrons. The frequency of this mode was found to increase with increasing ϵ, the relative negative ion concentration. The observations are compared with fluid calculations.

The introduction of an electronegative gas (i.e., a gas with a large electron attachment cross section, e.g., SF_6) into a plasma has made it possible to study plasmas in which the negative ion density can be much larger than the electron density.[1,2] In such a plasma, new phenomena may be expected to occur, in particular, various electrostatic wave modes are modified by the presence of negative ions, as shown theoretically,[3–5] and observed in a number of experiments.[2,6–9] In our previous work we investigated electrostatic ion-cyclotron (EIC) waves[8] and ion-acoustic (IA) waves[9] in plasmas with negative ions. The present work reports on an experimental investigation of lower-hybrid (LH) waves in a plasma with negative ions.

The theory of LH waves in a plasma with negative ions has been treated in detail elsewhere;[5] here, we will provide a summary of the theory, which will then be compared with the experimental results. Positive ions, negative ions, and electrons are treated as warm fluids which obey the equations of continuity and momentum. Charge neutrality is assumed, so that $n_+ = n_- + n_e$, where n_+, n_-, and n_e are the positive ion, negative ion, and electron density, respectively. The plasma is embedded in a static and uniform magnetic field **B** directed along the positive z axis. The continuity and momentum equations are linearized about a time-independent zeroth-order state in which the plasma is spatially uniform with densities $n_{+0} = n_0$, $n_{-0} = \epsilon n_0$ and $n_{e0} = (1-\epsilon) n_0$, no electric field is present and all fluid velocities are zero. Performing the usual linearization of the fluid equations, and taking all first-order quantities to vary as $\exp[i(Kx-\omega t)]$, the **K** vector (which is parallel to the wave electric field $\mathbf{E}_1$) having a nonzero component only along the x axis, we obtain the dispersion relation

$$\epsilon \frac{m_e}{m_+} \Omega_+^2 \Omega_e^2 + \frac{m_-}{m_+} (1-\epsilon) \Omega_+^2 \Omega_-^2 + \frac{m_e m_-}{m_+^2} \Omega_-^2 \Omega_e^2 = 0, \tag{1}$$

where $\Omega_j^2 \equiv \omega^2 - \omega_{cj}^2 - K^2 C_j^2$, with $C_j^2 = kT_j/m_j$ and $\omega_{cj} = eB/m_j$ ($j = +,-,e$). For $\epsilon = 0$ (no negative ions) Eq. (1) reduces to the usual dispersion relation for LH waves in a positive ion/electron plasma. Solutions to this dispersion relation were obtained numerically for a plasma consisting of K^+ positive ions, SF_6^- negative ions and electrons. Two modes were found, a high-frequency mode with frequencies, depending on the value of ϵ, in the range $\omega \sim (1\text{–}10)\sqrt{\omega_{c+}\omega_{ce}} \sim (10^3\text{–}10^4)\omega_{c-}$, where ω_{c-} is the negative ion cyclotron frequency, and a low-frequency mode (the ion–ion mode) with $\omega \sim (1\text{–}2)\omega_{c-}$. This paper is concerned with the latter, low-frequency mode, which, for typical Q-machine conditions has a frequency in the range of 40–100 kHz.

The experiments were performed in the Iowa single-ended Q machine (IQ-2) in which potassium neutral atoms from an atomic beam oven are contact ionized on a 6 cm diam tantalum hot plate heated by electron bombardment to $T \simeq 2300$ K. The plasma column is confined radially by a magnetic field up to 0.6 T in strength, and is terminated on a cold plate located 1.5 m from the hot plate. The plasma density, n, and electron and ion temperatures are typically $10^9\ \text{cm}^{-3} < n < 10^{10}\ \text{cm}^{-3}$ and $T_e \simeq T_{K^+} \simeq 0.2$ eV. The base pressure is $\lesssim 5 \times 10^{-7}$ Torr. Negative ions (SF_6^-) are produced by leaking variable amounts of SF_6 into the vessel at partial pressure up to $\sim 5 \times 10^{-6}$ Torr.[8] At each SF_6 partial pressure, the fractional concentration of negative ions, $\epsilon \equiv n_{SF_6^-}/n_{K^+}$, was determined by the same method as used in our earlier experiments on IA[9] and EIC[8] waves, i.e., by measuring the negative saturation current, $I_{-,s}$, to a Langmuir probe at some given SF_6 partial pressure, and $I^0_{-,s}$, the value of $I_{-,s}$ when the SF_6 pressure is zero, and using the relation $\epsilon = 1 - I_{-,s}/I^0_{-,s}$.

Low-frequency, ion–ion LH waves were launched from a 4 cm diam circular electrode inserted radially into the plasma approximately 2–3 cm from the center of the plasma column, at an axial position 50 cm from the hot plate. The normal to the plane of the electrode was oriented perpendicular to the magnetic field. For some experiments a flat strip electrode 15 cm long and 0.7 cm wide was used instead of the disk electrode. This strip was aligned along the magnetic field. A ~ 10 V peak-to-peak ac signal of variable frequency could be applied to the electrode to launch waves into the plasma with a wave vector, **K**, perpendicular to **B**. The waves could be detected on a floating, 5 cm diam Langmuir probe, movable radially with respect to the launching electrode for phase measurements.

The experiment consisted of the following: (1) SF_6 gas was leaked into the Q machine at a sufficient partial pressure to give a desired value of ϵ, the negative ion concentration. (2) The oscillating voltage of variable frequency and constant amplitude was applied to the large 4 cm diam electrode located on one side of the plasma column, and the signal observed on the (0.5 cm diam) receiving probe on the opposite side of the column as the oscillator frequency was swept past the ion–ion mode frequency. The

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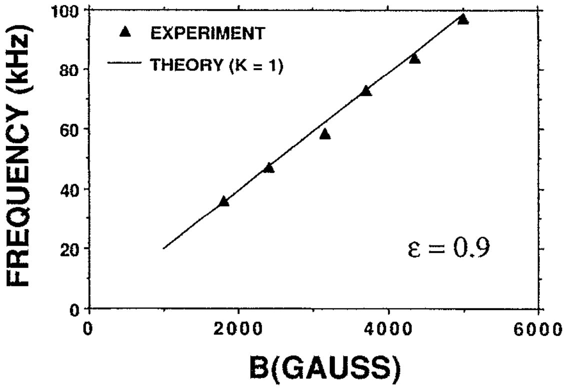

FIG. 1. Measured frequencies of the SF_6^- LH mode (ion–ion) versus magnetic-field strength, for $\epsilon=0.9$. The solid line was obtained from the fluid calculations.

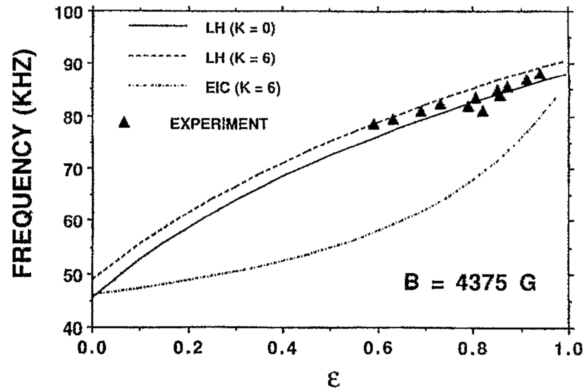

FIG. 2. Measured frequencies of the SF_6^- LH mode (ion–ion) versus ϵ, for $B=4375$ G. Upper dashed line and solid line were obtained from fluid calculations for $K=6$ cm^{-1} (dashed line) and $K=0$ (solid line). The bottom dashed line is from fluid calculations of EIC waves.

LH mode frequency was identified as that frequency at which an amplitude maximum was observed on the receiving probe. The observations were then repeated for several values of ϵ or, for a given value of ϵ, at several values of the magnetic-field strength. The results of these measurements are shown in Figs. 1 and 2. The variation of the SF_6^- (low-frequency) LH mode frequency with magnetic-field strength is shown in Fig. 1 for $\epsilon=0.9$. The solid line is the result of the fluid theory calculation (Ref. 5) for $T_+=T_-=T_e=0.2$ eV and a wave number $K(=2\pi/\lambda_\perp)=1$ cm^{-1}. In Fig. 2 the frequency of the SF_6^- LH mode is shown as a function of ϵ, for a fixed value of the magnetic field ($B=4375$ G). For $\epsilon \lesssim 0.6$ no clear resonance in the LH frequency range was found. The upper dashed line and the solid line are the result of the fluid theory calculations for wave numbers $K=0$ and $K=6$ cm^{-1}, respectively. The theoretical frequency, f, vs ϵ curves are relatively insensitive to the actual wave number. Phase measurements of the LH waves showed that the waves were propagating across the magnetic field *away* from the launching grid, with wavelengths ~ 3 cm, or $K \sim 2$ cm^{-1}. The measured frequencies seem to be in reasonable agreement with the fluid calculations. For comparison, in Fig. 2, we also show the results of a fluid theory calculation[4] for EIC waves in a plasma consisting of SF_6^-, K^+ ions and electrons.

In summary, we have experimentally investigated the low-frequency ion–ion LH mode in a plasma consisting of K^+ positive ions, SF_6^- negative ions and electrons. As the negative ion concentration increases, the frequency of this mode increases, in agreement with the dispersion relation obtained from a fluid theory.

ACKNOWLEDGMENT

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