# Nonlinear excitation of ion-acoustic modes by rf waves

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We have detected a slow ion-acoustic wave propagating obliquely to the equilibrium magnetic field in a low-density, weakly ionized helium plasma produced by rf power in the linear mirror machine LISA. When an upper hybrid wave is launched perpendicular to the ambient magnetic field, we have observed that the upper hybrid wave decays parametrically into another upper hybrid wave and a slow ion-acoustic wave.

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A high-frequency electric field applied perpendicular to a dc magnetic field in a linear plasma device excites a slow ion-acoustic wave through parametric decay into an upper hybrid wave or a Bernstein wave and a lower hybrid or ion-acoustic wave [1–5]. In this paper we report the same effect occurring during electron cyclotron heating in our linear mirror machine. In our experiment we study the behavior of a radio-frequency wave launched perpendicular to the direction of the magnetic field in a helium singly ionized plasma produced in the linear mirror machine, LISA, at the Universidade Federal Fluminense. LISA is a 255-cm-long, 8.5-cm-inner-radius linear mirror device (see Fig. 1 and Table I). In the present experiment we have used helium at a pressure of $6\times10^{-5}$ Torr and a magnetic field of 875 G. The plasma is produced and heated by a 2.45-GHz microwave source with a power of 800 W injected perpendicular to the magnetic field through a side window. The electron density and the temperature were measured by a Langmuir probe to be about $4\times10^{10}$ cm$^{-3}$ and 44 eV in the central region of the plasma, respectively. More details on the machine LISA can be found elsewhere [6].

The detection of slow ion-acoustic waves was performed using two single electrostatic probes, $S_1$ and $S_2$, located along the axis of the device and separated by a distance of $\Delta z = 70$ cm. The frequency of the signal was obtained using a 485 Tektronix oscilloscope with a time scale of $t = 50$ $\mu$s/div. We measured the time of the oscillation period of the fundamental mode to be 185 $\mu$s. The parallel wave number $k_\parallel$ of these waves was measured by detecting the phase difference between the time oscillations of the signals $S_1$ and $S_2$. These signals are not sinusoidal in shape due to plasma turbulence. The probe $S_2$ is located very close to the waveguide. A typical signal is shown in Fig. 2. It can be seen that there is a time difference of 22 $\mu$s between the two maxima which corresponds to a phase angle of $\phi \cong 43°$.

To confirm the above result for $\phi$, we consider the two

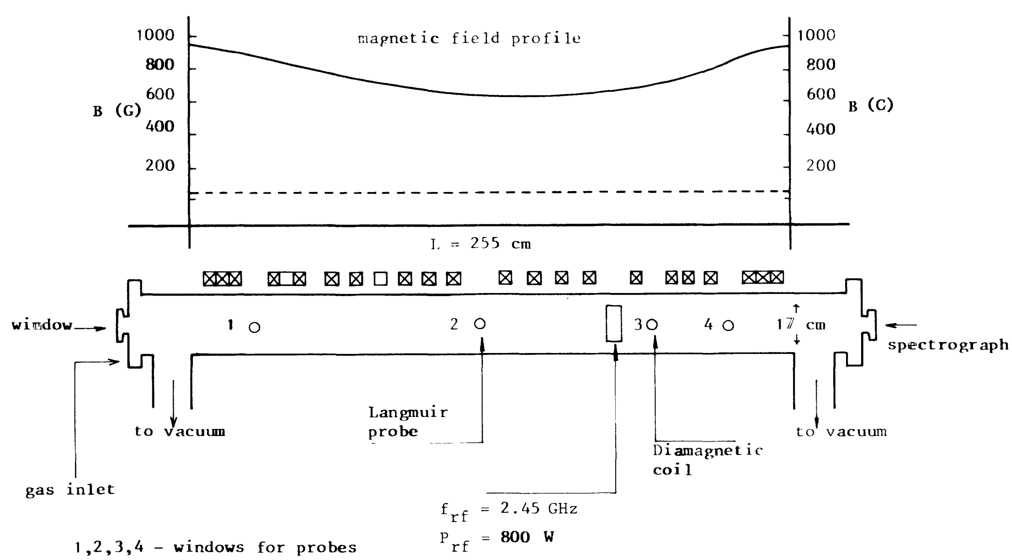


FIG. 1. LISA machine.

 

TABLE I. Summary of the basic LISA and target plasma parameters.

| | |
|---|---|
| Total length, $L$ | 255 cm |
| Inner radius, $r$ | 8.5 cm |
| Uniform magnetic field, $B$ | 10.5 kG |
| Mirror region, $B$ | 13.0 kG |
| Extension of the uniform magnetic field | 100 cm |
| Electron density, $n_e$ | $10^{10}$ cm$^{-3}$ |
| Electron temperature, $T_e$ | 80 eV |
| Ion temperature, $T_i$ | 10 eV |

signals, $S_1$ and $S_2$, which are plotted on an $x$-$y$ plane by placing $S_1$ on the $x$ axis and $S_2$ on the $y$ axis. The resulting curve is shown in Fig. 3. From this the wave number $k_\parallel$ and the phase difference between the two signals are calculated as follows: If we set $k_\parallel \Delta z = \phi$ we can write

$$x = \sin(\phi - \omega t) ,$$

$$y = -\sin(\omega t) ,$$

and we have for $y = 0$,

$$x = a = \sin\phi ,$$

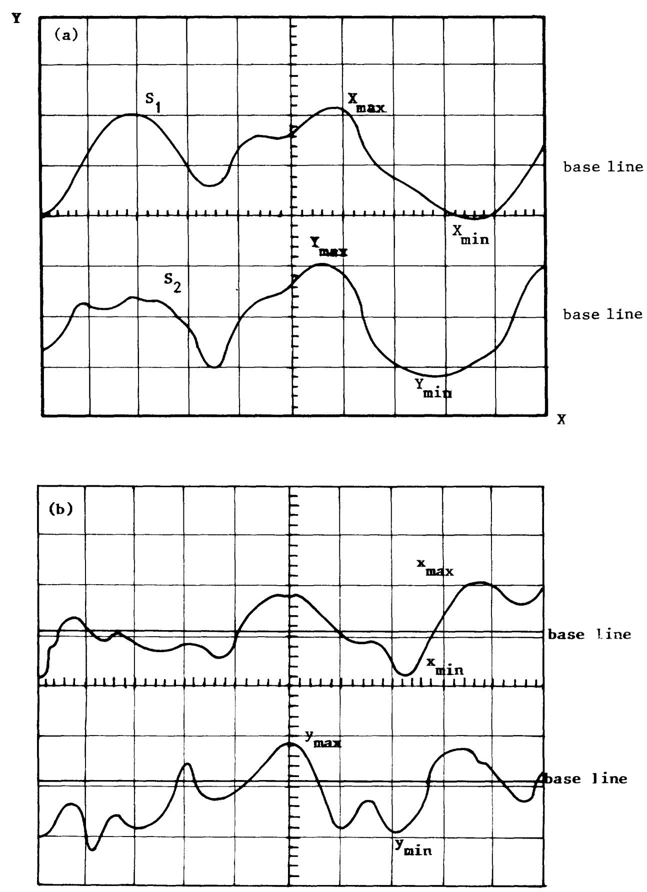


FIG. 2. Fluctuating amplitude of the low-frequency electrostatic oscillation at probes $S_1$ and $S_2$ separated along the magnetic field by a distance of 70 cm, with a time scale of $t = 50$ $\mu$s/div, for different background pressure. (a) $p = 6 \times 10^{-5}$ Torr; (b) $p = 9 \times 10^{-5}$ Torr.

$$\phi = \sin^{-1} a .$$

Taking the point $y = 0$ and $x = a$ in Fig. 3, where $a \leq 1$ is the point where the ellipse crosses the axis, we have in this case $a = 0.68$, so that the phase angle $\phi = 43°$, which agrees with our previous result.

To obtain the parallel wave number we assume that the wave propagates from the probes $S_1$ to $S_2$; we can write $k_\parallel = 0.748$ $(1/\Delta Z)$, hence $k_\parallel = 0.0107$ cm$^{-1}$. The perpendicular wave number can be estimated from $k_\perp = \pi/d = 0.18$ cm$^{-1}$, where $d$ is the LISA diameter. It fits well the value $\theta = \arctan(k_\perp / k_\parallel) = 86.6°$. When the probes were located in the same axial position, separated in the azimuthal direction, the azimuthal phase shift was not observed. From this we can estimate that the corresponding azimuthal wave number can be neglected, and this leads us to conclude that there is no plasma rotation. We assume that the phase velocity is equal to the total velocity, e.g., $v_{\text{ph}} = v_{\text{tot}}$. The measured wave frequency is $\omega_s = 34.0 \times 10^3$ rad/s. Using the appropriate quantity here, we can calculate $v_{\text{tot}} = \omega_s / k_{\text{tot}} \cong \omega_s / k_\perp$

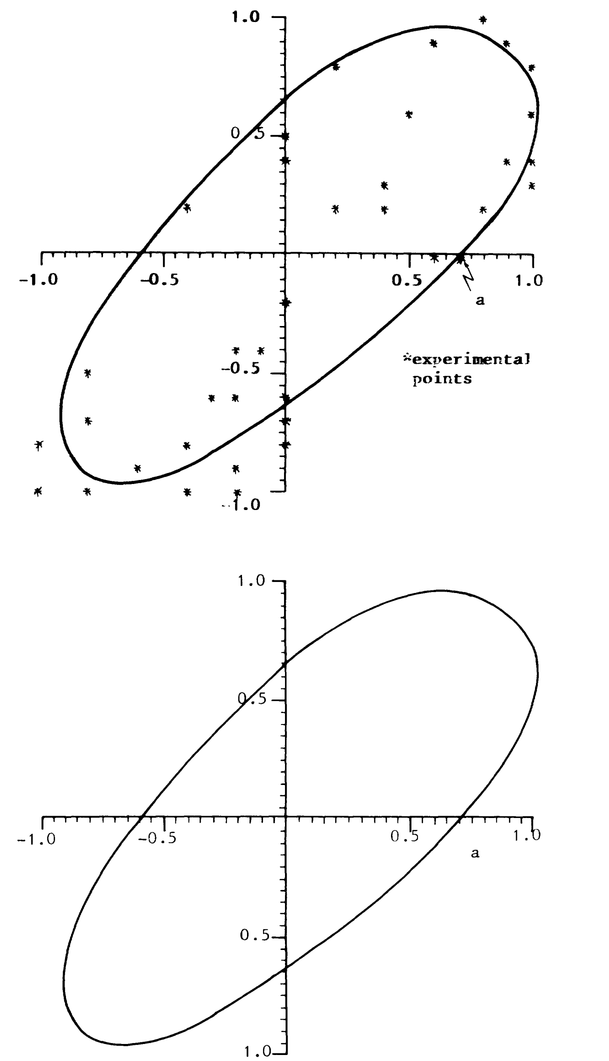


FIG. 3. Phase difference between the electrostatic probe signals.

$=34.0\times 10^3/0.18=1.9\times 10^5$ cm/s. This is a typical phase velocity for ion-acoustic waves in the LISA machine.

To obtain information about the angle of propagation we consider the following simplified dispersion relation for the ion-acoustic waves in magnetized plasmas [7]:

$$\omega^2=\frac{\omega_s^2\omega_{ci}^2\cos^2\theta}{\omega^2+\omega_{ci}^2}\ , \tag{1}$$

where $c_s=Z_i(T_e/m_i)^{1/2}$ is the ion-acoustic speed. Considering that $\omega_{ci}\gg\omega_s$, Eq. (1) is further simplified to give $v_{\rm ph}=c_s\cos\theta$. With the LISA parameters $T_e=44$ eV, $\omega_{ci}\cong 2\times 10^6$ rad/s, $\omega_s\cong 34.0\times 10^3$ rad/s, and helium ions, we have $c_s=3.3\times 10^6$ cm/s. Therefore, the experimentally obtained $\theta=\cos^{-1}(v_{\rm ph}/c_s)=86.7°$, which is close to the value obtained above (using $k_\perp\cong\pi/d$), where $v_{\rm ph}$ and $c_s$ are obtained from experimental LISA data and Eq. (1). This shows the mode propagation at a large angle to the magnetic field.

It should also be mentioned that we have varied the background magnetic field and the plasma density: For pressures of $6\times 10^{-5}$ Torr and $9\times 10^{-5}$ Torr, we obtain electron temperatures $T_e=44$ eV and $T_e=38$ eV, respectively. However, no change in the measured wave frequency was observed. We have no way to change the pump frequency in our experiment.

We interpret our observations as follows. The 2.45-GHz electromagnetic wave launched is predominantly an ordinary mode, that is, the electric field is parallel to the magnetic field. This is checked by launching microwaves into the LISA chamber without plasma and measuring components of the electric field. Now, the wave is launched at the angle of incidence between 0° and 90°, such that 70% of the power is carried by the ordinary mode. The remainder of the power is carried by the extraordinary mode. When the ordinary wave reaches the point $r=3$ cm, where $r$ is the inner plasma radius, it reaches a turning point where $\omega_{\rm rf}=\omega_{pe}$, and it is reflected. At this turning point, however, there is a linear mode conversion. Even though most of the wave energy is reflected, some energy undergoes tunneling and a Langmuir wave is excited. Nevertheless, at this turning point, $\omega_{ce}^2/\omega_{\rm rf}^2$ is slightly larger than unity so that the extraordinary wave is not reflected. As the wave propagates into the plasma, the density increases and the angle between **E** and **k** decreases until it becomes 86.7°, where it reaches the cutoff point $r=5$ cm. Note that LISA's inner radius is 8.5 cm. Beyond this point **k** becomes purely imaginary and the **E** field decays exponentially until the upper hybrid resonance point is reached. At this point $\mathbf{E}\|\mathbf{k}$ and **k** becomes real again, reappearing as a propagating wave, after tunneling through a cutoff region [8].

The excited upper hybrid wave may decay parametrically into another upper hybrid wave and an ion-acoustic wave [4,9,10]. The electric-field threshold is $E_{\rm th}=3.2$ V/cm, which corresponds to $P_{\rm th}=408$ W. The theoretical estimate of the threshold for the parametric decay of the extraordinary mode near the upper hybrid frequency yields $E_{\rm th}=3.0$ V/cm and the experimental value given by Okabayashi, Chern, and Porkolab [4] is $E_{\rm th}\cong 3.5$ V/cm, which corresponds to $P_{\rm th}=500$ W, and is in a good agreement with the experimental results obtained in this work.

In conclusion, we have shown that an ordinary mode launched perpendicular to the ambient magnetic field of the linear mirror plasma device LISA decays into an ion-acoustic wave and another upper hybrid wave.

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