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EXCITATION OF LOWER HYBRID OSCILLATIONS AT UPPER HYBRID RESONANCE BY MICROWAVES

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Parametric excitation of plasma waves has been of considerable interest.[1-3] In the absence of a dc magnetic field, a nonlinear coupling process has been observed[1] between two basic collective modes, the electron plasma wave and the ion acoustic waves. There are also several theories[2] related to the parametric excitation of plasma oscillations by means of transverse electromagnetic radiation. In the presence of a dc magnetic field, the excitation of Alfvén waves by a small low-frequency oscillation has been studied theoretically.[3]

In this paper we report the possible observation of lower hybrid oscillations excited by microwaves in the presence of a dc magnetic field. The crucial point is that the parametric coupling is observed only when the microwave frequency f_0 satisfies the condition of upper hybrid resonance, $f_0^2=f_{ce}^2+f_{pe}^2$, where f_{pe} and f_{ce} are the electron plasma frequency and the electron cyclotron frequency, respectively. Figure 1 shows the radiation pattern of microwaves for fixed receiving frequency 4100 MHz as a function of the dc magnetic field. The radiation is in the extraordinary mode for propagation at right angles to the magnetic field. The emission peaks move toward the lower magnetic field region as the current is increased. Further increase of the current yields the second-harmonic radiation at $f_{ce}/f_0=0.5$. The characteristics of the upper hybrid resonance have been well explained by Bernstein's longitudinal mode.[4,5]

In the present experiment the magnetic field

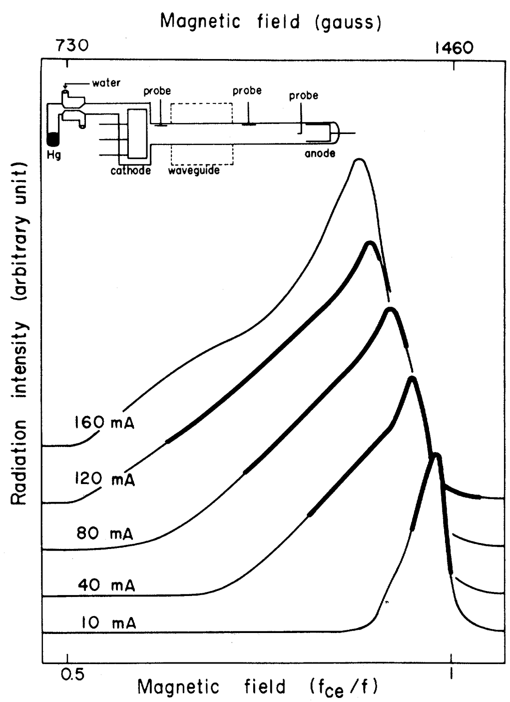

FIG. 1. Microwave radiation (in relative unit) in an extraordinary mode at 4100 MHz from a plasma column of mercury vapor as a function of magnetic field with discharge current as a parameter. The curves for current are displaced for display purposes. The bold line indicates the region where the low-frequency oscillations are excited by the external microwave irradiation. Plasma is produced in mercury vapor at 3.4×10^{-3} Torr. The discharge tube is inserted in a waveguide (TE_{10}) with the electric field parallel to the tube axis.

is homogeneous to about 5% over the experimental region and is variable up to 1500 G. The pressure of mercury vapor ($\simeq 10^{-3}$ Torr) is controlled by cooling the mercury reservoir. Several discharge tubes with different inner diameters (10, 12.6, and 26.4 mm diam) are examined. In each tube the distance between the oxide cathode (30 mm diam) and the anode is 20 cm. Electron densities are typically in the range of 10^9 to 10^{11} cm^{-3} and electron temperatures in the range of 4 eV. Since the plasma is weakly ionized the electron-neutral collisions are dominant and the collision frequency is about 70 MHz.

In the experiment, a relatively high-power microwave signal of frequency $f_0 = 4100$ MHz in TE_{10} mode is beamed in the extraordinary mode at a cylindrical plasma column inserted into a waveguide (Fig. 1). In order to avoid passing the primary microwave signal into the spectrum analyzer, the signal is made to interfere with the signal divided from the same source by properly adjusting an attenuator and a phase shifter, and is canceled out. Because of the irradiation, strong excitation of the upper hybrid oscillation as well as the electron cyclotron harmonic structure are observed. When the magnetic field is swept into the region of the upper hybrid resonance and when the incident microwave power is increased above a threshold level ($\simeq$100 mW), the plasma is found to emit coherent radiation at two additional frequencies f_0+f^* and f_0-f^* as shown in Fig. 2(c). For the incident microwave power there is an upper limit ($\simeq$2 W) as well as the threshold ($\simeq$100 mW). The electric field associated with the threshold power is about 2 V/cm. The absorption rate is measured to be about 60 to 70% at the upper hybrid resonance. It must be emphasized that no microwave discharge is seen in the tube due to the irradiation.

At the same time, when the two additional frequencies ($f_0 \pm f^*$) are observed, low-frequency oscillations of frequency f^*, ranging from 12 to 300 kHz, are also detected by a probe inserted in the plasma column. The difference frequency f^* coincides with the frequency of the simultaneously excited low-frequency oscillations as shown in Fig. 2. No essential difference is found between the signals received by the probes in the anode side and in the cathode side. The fluctuations in the probe currents are displayed on a low-frequency spectrum analyzer as shown in Figs. 2(a) and (b). These

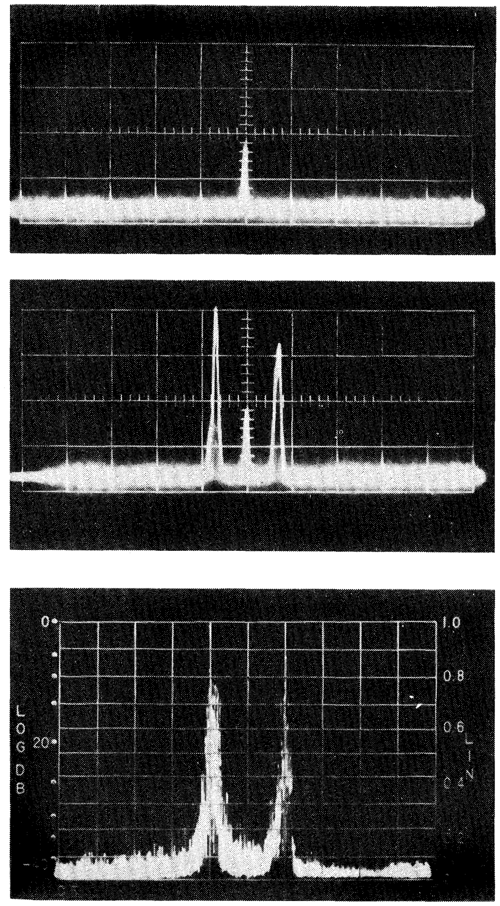

FIG. 2. Spectral components of parametrically excited oscillations in a plasma column (26.4 mm in inner diam) with 60 mA discharge current under the magnetic field (1350 G). (a) Fluctuations received by a probe on a low-frequency spectrum analyzer for the microwave power below threshold. The pip at the center is a zero-frequency marker. (b) Excited low-frequency oscillations, with dispersion 50 kHz/cm, when the microwave power is increased above threshold; incident power 2 W (field strength 10 V/cm). The coherent low-frequency spectrum, 35 kHz, is observed. (c) Display of a microwave spectrum analyzer with dispersion 35 kHz/cm. The incident microwave signal (4.1 GHz) with a power ($\simeq$2 W) above threshold is canceled by interference. After a parametric interaction in the plasma, the incident microwave frequency f_0 is observed being accompanied with two additional frequencies, $f_0 \pm f^*$(35 kHz).

low-frequency oscillations are not detected without the microwave irradiation as seen in Fig. 2(a). The amplitude of the oscillations is larger toward the waveguide within which the oscillations are excited. There is a phase difference between the low-frequency signal received by the probe close to the anode and that close to the waveguide. However, no systematic relation between the frequency and the phase shift has been found.

The frequency f^* of the low-frequency oscillations increases with the magnetic field intensity and the electron density. It is normalized as $(f_{ci}/f^*)^2$ to be studied as a function of $(f_{pi}/f^*)^2$ in the Clemmow-Mullaly-Allis diagram,[6] where f_{ci} and f_{pi} are the ion-cyclotron frequency and the ion-plasma frequency, respectively. In Fig. 3 $(f_{ci}/f^*)^2$ is plotted against the current density, which is obtained from the discharge current divided by the tube cross section. Though it is difficult to determine the accurate electron density of plasma in a magnetic field, one can estimate[7] it from the position of the upper-hybrid resonance. The current density of 100 mA/cm^2 is found to correspond to an electron density of about 10^9 electron/cm^3. The linear relation between $(f_{ci}/f^*)^2$ and the current density in Fig. 3 seems to indicate that the excited low-frequency signals are due to lower hybrid oscillations. It will be hard to explain why it is possible to have the lower hybrid oscillations in a plasma where the ion-cyclotron radius is comparable with the tube radius.

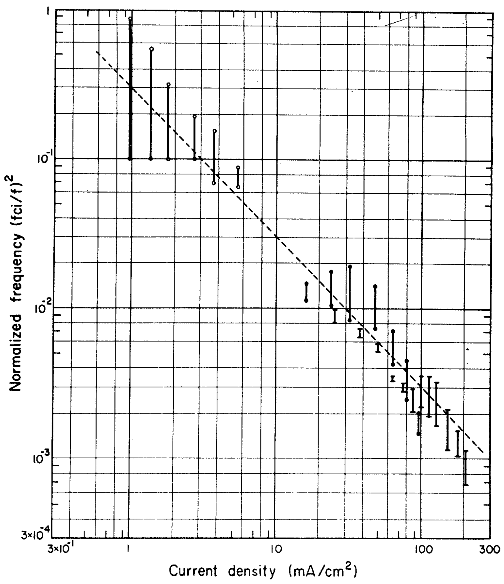

FIG. 3. Plot of normalized frequency $(f_{ci}/f^*)^2$ against the current density. The current density 100 mA/cm^2 corresponds to about 10^9 e/cm^3. Three discharge tubes with different tube diameters are used, as designated by different shapes on the ends of the experimental bars: open circles for 26.4 mm, closed circles for 12.6 mm, and cross bars for 10 mm, in inner diameter. The dashed line indicates $(f_{ci}/f^*)^2 + (f_{pi}/f^*)^2 = 1$, where f_{pi} and f_{ci} are the ion-cyclotron frequency and the ion-plasma frequency, respectively.

In a discharge tube with a tube diameter of 12.6 mm, the low frequency f^* increases almost linearly with the discharge current, $f^* \simeq 1.5I$ (kHz), where I is the total discharge current in mA. Such a strong dependence on the electron density would also eliminate the possibility of ion acoustic waves being excited in a dc magnetic field. The possibility of exciting Alfvén waves should be excluded as well, since f^* is an increasing function of the plasma density.

In summary, we have described low-frequency oscillations excited by microwaves at the upper hybrid resonance in the presence of a dc magnetic field. The frequency f^* increases with the electron density and satisfies a simple relation, $(f_{ci}/f^*)^2 + (f_{pi}/f^*)^2 = 1$, which is known as the lower hybrid resonance. Since there is a threshold power for exciting the oscillations, it is expected that the lower hybrid mode in plasmas is coupled with the Bernstein mode at the upper hybrid resonance through a strong nonlinear process.

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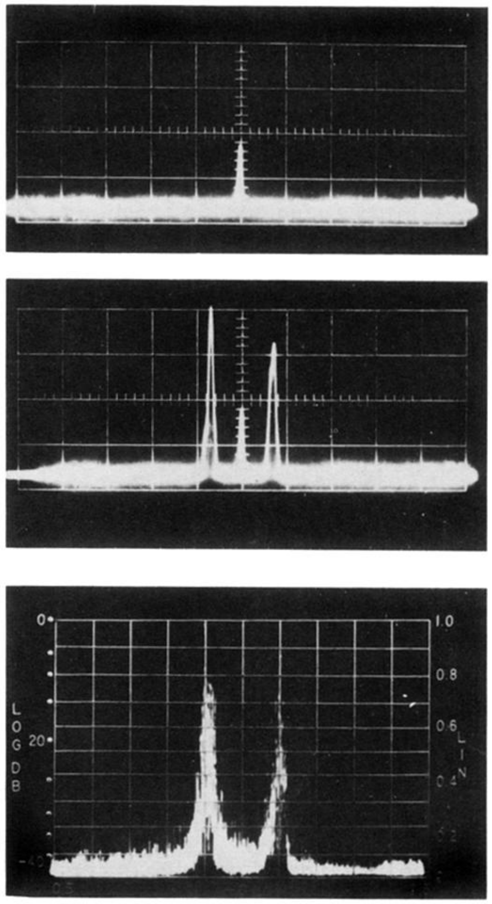

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