higher densities, of the order of 500 amagat, than used so far.[2] We point out that the analysis of the light-scattering spectra is complicated by the fact that at small $\omega$ an appreciable contribution to the scattering may be due to the long-range dipole-dipole interaction[8] rather than to the short-range intermolecular interaction.[2] As a first step, it would be very interesting if the predicted constructive nature of the interference could be verified experimentally.

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# EFFICIENT MODULATION COUPLING BETWEEN ELECTRON AND ION RESONANCES IN MAGNETOACTIVE PLASMAS*

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Modulation coupling between electron upper-hybrid modes and ion modes propagating nearly perpendicular to the axial magnetic field is shown to be effective in collisionless and semicollisionless regimes. A complete probeless feedback stabilization scheme based on such mode coupling is described.

We wish to report a new and efficient "modulation coupling" scheme between electron and ion resonances over a wide density range ($10^8 \lesssim n \lesssim 10^{11}$ cm$^{-3}$) and wide ion-frequency regime 1 kHz $\lesssim f_i \lesssim 200$ kHz in a magnetically confined plasma. This coupling scheme, which does not appear to depend significantly on collisional processes, permits one to excite or suppress ion resonances in plasmas "remotely" without either grids or probes while retaining the significant property of spatial selectivity. We also demonstrate that by means of such a coupling scheme, low-frequency ion instabilities in hot or rarefied plasmas can be controlled efficiently by microwave beams of relatively low power. This has important implications in controlled fusion and excitation of waves in space plasmas by ground stations. The modulation coupling in the stable regime could be relevant to modulation instabilities which are of increasing theoretical interest.

The experiments were performed in a highly ionized potassium plasma produced in a $Q$ device ($T_e \approx T_i \approx 0.2$ eV) operated in a symmetrical manner as in Fig. 1(a). In the direction perpendicular to $\vec{B}$, the electron electrostatic modes are the Bernstein modes at the upper hybrid frequency $\omega_{\rm UH}^2(r) = \omega_p^2(r) + \omega_{ce}^2$, while the ion modes are the electrostatic ion cyclotron waves and drift waves whose damping rates can be easily controlled by varying the magnetic field or the plasma density. The resonant character of upper-hybrid modes[1] and the ion cyclotron modes[2] arises from a combination of cyclotron motion and collective effects, while drift modes[3] derive their resonant behavior from the density gradient and the periodicity in the azimuthal direction. Low microwave power of the order of a few milliwatts and frequency 2-4 GHz is radiated upon the plasma column (5 cm in diameter and 80 cm in length) by waveguides located outside the chamber. The microwave is in the extraordinary mode along a direction perpendicular to the magnetic field. The microwave frequency is chosen to correspond to the upper hybrid frequency in the range of the magnetic field (1-1.5 kG) and density at which ion resonances have small damping rates. It has been demonstrated experimentally that an evanescent layer normally shields the upper hybrid resonance in the radial direction.[1] This can be overcome by either imposing a gradient in the external magnetic field or making the microwave wavelength exceed the plasma radius. We have chosen the latter because a uniform $B$ field is essential in our identification of the resonant modes. The electron resonances were identified by a forward-scattering technique[4] and by moni-

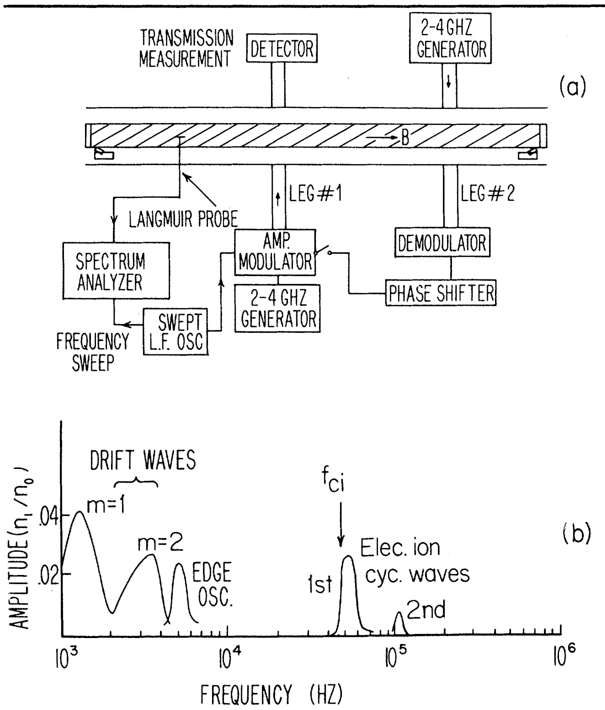


FIG. 1. (a) Experimental arrangement showing two $S$-band systems and a Langmuir probe. The amplitude modulator and the spectrum analyzer are controlled by the same low-frequency swept oscillator such that the spectrum analyzer always tracks the frequency of the ion wave being excited. (b) Amplitude response of the plasma monitored either by a negatively biased probe or from an $S$-band detection system (leg No. 2) versus the modulation frequency on the excitation $S$ band (leg No. 1); $n \approx 10^9$ cm$^{-3}$, $B = 1.25$ kG. Density gradient waves of azimuthal numbers $m = 1$, 2, an edge oscillation, and electrostatic ion cyclotron waves near $\omega_{ci}$ and $2\omega_{ci}$ are shown.

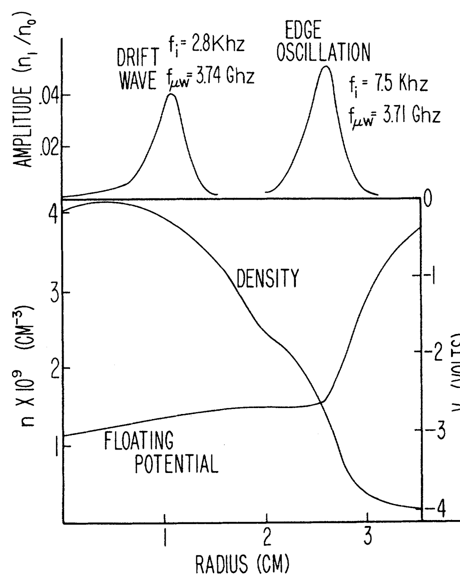


FIG. 2. Demonstration of radial selectivity of excitation of ion resonances through adjustment of incident microwave frequency. The radial positions of excited ion resonances (upper trace) are shown with reference to the density and potential profiles (lower trace). $f_{ce} = 3.70 \pm 0.005$ GHz.

toring the density with calibrated small cylindrical probe.

The ion waves are produced by modulating the incident $S$-band microwaves ($\omega \approx \omega_{UH}$) and detected by another $S$-band transmission system or a plane grid probe biased at the ion-collection region. We have found optimum plasma response occurring at the ion resonances as shown in Fig. 1(b). By measuring the azimuthal and radial propagation, the location with respect to the density gradient (Fig. 2), and the variation with the magnetic field, the ion resonances at $f < 10$ kHz were identified as density-gradient drift modes and edge oscillations,[5] while those at $f_i \approx n\omega_{ci}$ were identified as fundamental and harmonics of the electrostatic ion cyclotron modes.[2] The measured axial and perpendicular wave numbers of the fundamental mode are $k_\perp \approx 1.2$ cm$^{-1}$, $k_\parallel \approx 6 \times 10^{-2}$ cm$^{-1}$, such that $v_{i\,th} < \omega/k_\parallel < v_{e\,th}$ and the electron neutralization along $B$ is important. This coupling scheme provides an easy method of examining the ion cyclotron mode without imposing an axial current drift. The excitation of such a mode has been found difficult with a probe, possibly because of strong shielding by the electrons; the present scheme utilizes the resonant behavior of the electrons themselves to provide the electric field necessary for coupling to the ion mode.

The radial selectivity is achieved by varying the frequency of microwaves such that it corresponds to $\omega_{UH}(r)$ at the desired radius. As illustrated in Fig. 2, the drift-wave resonance occurring near the density-gradient maximum can be excited when the incident microwave $f_{\mu\omega} = f_{UH_1}$ at the location of the steepest density gradient, whereas the drift wave occurring at the edge requires $f_{\mu\omega} = f_{UH} < f_{UH_1}$ as expected since the density is lower. The ion cyclotron waves can be excited over the entire range of upper-hybrid frequencies with maximum efficiency near the maximum $f_{UH}$.

There are two important features in this experiment:

(1) An input flux as low as 0.3 mW/cm$^2$ is sufficient to excite ion waves with amplitude $n_i/n_0 \approx 5\%$. This has the same efficiency as the excitation of drift waves by a probe[6] located inside the

plasma column.

(2) Coupling is possible at the edge of the plasma where the density is typically low as well as at low central density $\approx 10^9 \text{ cm}^{-3}$ where the mean free path for electron-ion collisions is of the same order as the column length. The excitation indeed takes place in frequency and density regimes such that $\omega_{UH}\tau_{ee} \cong 10^5 \gg 1$ and $\omega_i \tau_{ei} > 1$ where $\tau_{ee}$ is the electron-electron collision time and $\tau_{ei}$ is the energy-exchange time between electrons and ions. We believe therefore that a collisionless nonlinearity could be operative in the coupling between upper-hybrid modes and ion modes via collective electric fields instead of a random collisional process.

The efficiency of the coupling can be attributed to the fact that both electron and ion modes are resonant in this magnetically confined plasma. We can examine electrons and ions by the collisionless Boltzmann equation, as appropriate for our low-density regimes:

$$\frac{\partial f_{e,i}}{\partial t} + \vec{v} \cdot \frac{\partial f_{e,i}}{\partial \vec{x}} + \frac{q}{m_{e,i}} \frac{\vec{v}}{c} \times \vec{B} \cdot \frac{\partial f_{e,i}}{\partial \vec{v}} = \frac{-q\vec{E}}{m_{e,i}} \cdot \frac{\partial f_{e,i}}{\partial \vec{v}}. \qquad (1)$$

As the extraordinary mode ($\vec{E} \perp \vec{k} \perp \vec{B}_0$) propagates radially along the increasing density gradient, its electric field $\vec{E}$ rotates toward an alignment with $\vec{k}$ in the vicinity of the upper hybrid frequency. This couples effectively to the electrostatic Bernstein mode.[1] When the free-space wavelength is large compared to the plasma radius as is true in our experiments, the coupling has been shown to be efficient in a collisionless calculation using the Boltzmann equation and the full set of Maxwell equations.[7]

Representing the modulated high-frequency field by three electrostatic modes at the upper hybrid frequencies $\omega_0$, $\omega_0 \pm \omega_m$, respectively, we can compute the second-order perturbation $f_2$. Substituting into the nonlinear Poisson equation one obtains[8]

$$E(\omega_i) = \frac{1}{\epsilon_i(\omega_i)} \left[ \frac{E(\omega_0)}{\epsilon_e(\omega_0)} M \frac{E(\omega_0 + \omega_m)}{\epsilon_e(\omega_0 + \omega_m)} + \frac{E(\omega_0)}{\epsilon_e(\omega_0)} M \frac{E(\omega_0 - \omega_m)}{\epsilon_e(\omega_0 - \omega_m)} \right]. \qquad (2)$$

Qualitatively one can see the efficient coupling as arising from the combined effects of the ion and electron resonant modes, represented by the three dielectric constants on the right-hand side of Eq. (2).

We believe the physical mechanism is as follows: First the electron, driven resonantly at $\omega_{UH}$, gains velocity and an accompanying change in its velocity distribution. The nonlinearity $\vec{E}_1 \cdot (\partial f_1 / \partial \vec{v})$, which represents a nonlinear diffusion in velocity space, brings about a charge accumulation $\int f_2 d^3v$ and an electric field at the difference frequency $\omega_m$. This electric field subsequently serves as the driving source of the ion mode at $\omega_m$. A second nonlinear term results from the plasma inhomogeneity. On account of the density gradient, the thickness of the upper-hybrid resonant layer $\Delta r$ is determined by the width of the input microwave frequency (10 kHz). The electron whose gyration orbit ($\approx 10^{-3}$ cm) is comparable to $\Delta r$ can take on a highly anharmonic motion[9] which brings about a mixing of the incident high-frequency waves.

Since we can excite ion resonances it is also possible to perturb them when they are unstable by a feedback technique.[10] Ion instabilities can be sampled either by another $S$-band microwave detection system (Fig. 2) or a probe. The instability signal is amplified, shifted in phase, and applied to modulate the microwave signal, which either suppresses or enhances the instability, depending on the phase shift of the modulation. We have found that a $m = 2$ density-gradient drift wave can be suppressed by an order of magnitude with microwave power of approximately 3 mW/cm$^2$. The distinguishing features of this feedback scheme are that no probes are required in the plasma column to detect and suppress the instability, and that the scheme appears to be effective in collisionless regimes where most fusion plasmas are.

The same coupling scheme can be used to remotely excite ion resonances in the ionosphere, the detection of which has been difficult. The layer at which such excitation takes place can be selected through the rf frequency of a ground transmitter. The detection of the excitation is similar to our forward-scattering technique with the coherent radiation from a synchronous satellite replacing the $S$-band generator.[11]

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# ANOMALOUS ALIGNMENT IN THE SMECTIC PHASE OF A LIQUID CRYSTAL OWING TO AN ELECTRIC FIELD*

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Measurements of the dielectric loss in a liquid crystal, exhibiting both nematic and smectic phases, show an ordering with the long axes of the molecules preferring a direction papallel to both dc and 5000-Hz electric fields in the nematic phase. In the smectic phase the preferred direction is parallel to a 5000-Hz electric field and perpendicular to a dc field. The observed alignment of the smectic phase in a dc field is believed to be anomalous and it is suggested that this effect may be associated with the conductivity anisotropy.

Anomalous alignment in nematic liquid crystals owing to electric fields has been observed by many workers. Recent work[1-3] employing microwave dielectric techniques has shown that the process primarily responsible for this anomalous behavior is a well-behaved process. Interfacial polarization resulting from the conductivity anisotropy of clusters of molecules was suggested[1] as a mechanism that could produce an interaction with the electric field and account for the anomalous effect. This work has recently been treated theoretically by Helfrich.[4]

In the previously mentioned nematic materials the anomalous effect involves an ordering with the long axes of the molecules preferring a direction parallel to a dc electric field and perpendicular to an ac electric field for frequencies above the audio region. Results reported here show that in a smetic phase of ethyl-$p$-[($p$-methoxybenzylidene)amino] cinnamate (hereafter referred to as EMC) the long axes of the molecules prefer a direction perpendicular to a dc electric field and parallel to a 5000-Hz electric field.

Vorlander[5] reported finding three liquid-crystalline phases in EMC, and these were later investigated by Demus and Sackmann,[6] and recently by Chistyakov, Schabischev, Jarenov, and Gusakova.[7] The work reported here involves only the nematic phase (118-140°C) and smectic phase $A$. The sample was purified by recrystallization from ethanol. An attempt to further purify by zone refining was not successful.

The experimental techniques were discussed previously.[1] Measurements of the dielectric loss in EMC at a microwave frequency of 24.5 GHz have been reported earlier.[8] The measurements of the dielectric loss in a magnetic field reported here are not identical to those reported earlier because of higher purity of the sample. Some of the effects mentioned previously[8] are now believed to be due to impurities.

Figure 1 shows measurements of the dielectric loss at a microwave frequency of 24.5 GHz as a function of temperature which were obtained by measuring the power transmitted through the sample while cooling from 120 to 110°C. When the sample was cooled in the presence of an external magnetic field of 10 000 G applied perpen-