Oscillatory Behavior of Trapped Plasma Waves at the Top of a Parabolic Density Profile

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The excitation of plasma waves by resonant absorption of an electromagnetic wave is studied experimentally near the top of a parabolic density profile. The experiment shows the development of a huge density cavity ($2000\lambda_D$) inside which trapped plasma waves exhibit an oscillatory behavior, on a time scale smaller than the convection time.

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The resonant absorption of an electromagnetic wave [1] (EMW) in an inhomogeneous plasma is relevant to the physics of laser-matter interaction [2], ionospheric heating experiments [3], and microwave laboratory experiments [4]. This mechanism is described theoretically by the Zakharov equations [5] and is used as a model for turbulence in plasma physics.

Near the resonant location, where the local plasma frequency $\omega_p(x)/2\pi$ equals the incident wave frequency $\omega_0/2\pi$, an electrostatic plasma wave (EPW) is excited by an obliquely incident EMW with its electric field in the plane of incidence. In a linear density profile, the resonant growth of the EPW near the critical density is linearly saturated by the convection of that wave towards the lower-density side of the gradient. When the amplitude of the EPW is increased, nonlinear effects appear [6,7]: The ponderomotive force arising from the resonant EPW leads to low-frequency density modulations, i.e., ion-acoustic waves (IAWs), which in turn modify the EPW propagation [5].

Resonant absorption is studied experimentally in a parabolic density profile, $n_e(x)=n_M(1-x^2/l^2)$, where l is the half-width of the density profile. The critical density n_0 is defined by $\omega_0^2=n_0e^2/\varepsilon_0 m_e$ and characterized by $\beta=n_M/n_0$. When the critical density is located near the top of a parabolic profile ($\beta\sim 1$), convection is less efficient to saturate the EPW [8], so one can expect to have strong nonlinear effects. In that case, the EPW grows at the resonant location and its amplitude is supposed to be limited either by caviton collapse and burnout [9] or wave breaking [10]. We have explored, in an experiment done in the microwave range ($n_0\sim 10^{11}$ cm^{-3}), a regime of moderate incident power ($P_1\leq 600$ W) corresponding to a ratio of the energy of the incident wave (respectively EPW) of amplitude E_0 (E_p) to the thermal energy, $W_0=\varepsilon_0E_0^2/4n_0kT_e$ ($W_p=\varepsilon_0E_p^2/4n_0kT_e$), such that $W_0\leq 10^{-3}$ and $W_p\sim 10^{-1}$.

This regime is characterized by the digging of a huge ($2000\lambda_D$, λ_D is the Debye length) density cavity in which trapped EPWs exhibit an oscillatory behavior on a time scale less than the convection time. The plasma is expelled from the resonant region by the ponderomotive force associated with the EPW electric field, and the electron density on the edge of the cavity becomes larger than the critical density. The cavity is then decoupled from the driver, the EPW amplitude decreases, and the density on the edge becomes near critical. The cavity is pumped again by the EMW and a new cycle starts. This oscillatory regime is allowed by the fact that the characteristic time to build a cavity is shorter than the time to saturate the EPW by convection.

An unmagnetized argon plasma is created in a multipolar discharge [11] with the following parameters: filling pressure $P_{\rm Ar}=4\times 10^{-4}$ Torr, volume 0.8 m^3, natural density fluctuations $\delta n/n\leq 10^{-3}$, electron density $n_0\simeq 1.5\times 10^{11}$ cm^{-3}, electron temperature $T_e\simeq 4$ eV, ion neutral collision frequency $\nu_{in}\simeq 10^4$ s^{-1}, electron ion collision frequency $\nu_{ei}=6\times 10^5$ s^{-1}. A mica sheet, transverse to the discharge axis x and situated at the end of the device where EMWs are injected, insures homogeneous boundary conditions and, with a copper sheet situated at the opposite end of the device, allows density-profile adjustments. The radial gradient length is of the order of 10 m, and the half-width of the parabola, l, is of the order of 0.5 m. EMWs are launched by a horn along the x axis (left side of Fig. 1) with a frequency of 3.5 GHz (pulse

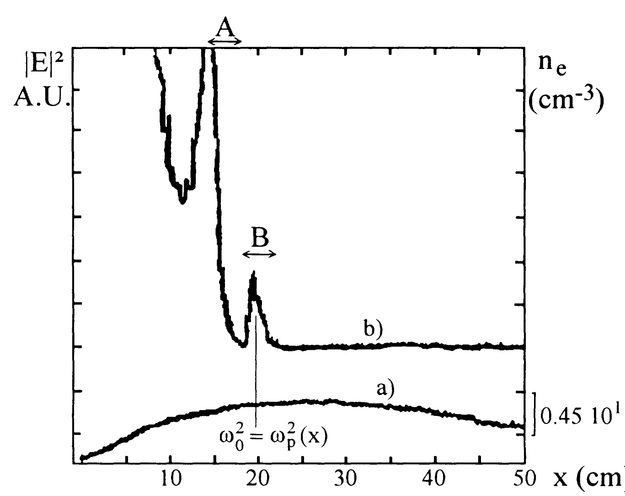

FIG. 1. (a) Unperturbed parabolic plasma density profile. (b) Envelope of the pulsed electric field as a function of distance ($P_i=600$ W). A corresponds to the region of cutoff of the EMW, and B to the region of resonance of the plasma wave.

width t_p from 0.1 to 10 μs, peak power $P_i < 2$ kW). Wave measurements are performed with two Langmuir probes.

Figure 1 shows (a) a typical longitudinal parabolic density profile and (b) the corresponding envelope of the squared electric field for an incident power of 600 W. The region of cutoff of the EM field (A) is spatially followed by the excitation of EPW around the resonant location (B).

The temporal evolution of $|E_p|^2$ in the resonant region is displayed in Fig. 2 for different values of the incident power. For weak incident power (a),(b), $|E_p|^2$ oscillates with an increasing amplitude for times greater than the convection time. When the incident power is increased, the number of peaks increases and the time of appearance of each peak is shorter. For stronger incident power, (c), the temporal evolution of $|E_p|^2$ becomes chaotic [7].

Figure 3 shows the spatial distribution of the electric field in a horizontal plane at different times and for an incident power $P_i \sim 450$ W. The incident EMWs are launched from the left, along the x axis. Figure 3(a) is a snapshot of the amplitude of the electric field in the resonant region at a time $t \approx 150$ ns after the beginning of the hf pulse. At that time, much shorter than the convection time of the EPW, the electric field is mainly electromagnetic. The extent and shape of the cutoff region (shaded area and isocontours between 20 and 2) and evanescent region result from the presence of a local parabolic density maximum in the (x,r) plane and from the radiation pattern of the EM horn used to launch the EMW. Figure 3(b) is taken at a time $t = 1.3$ μs from the beginning of the hf pulse, which corresponds roughly to the second peak in the amplitude of the EPW (Fig. 2). The cutoff region defined previously has widened and moved toward the antenna and, at the same time, maxima and minima of the electric field appear in the evanescent region. The region of the (x,r) plane in which the electric field is enhanced and goes through a maximum [Fig. 3(b), $x = -7$ cm, $r = 1$ cm] is the cross section of a density depression in which the EPW is trapped.

For the successive peaks in the amplitude of the electric field near resonance as shown in Fig. 2, the inside border of the cutoff region remains stable and the trapped electric field evolves in a pattern which reproduces Fig. 3(b) in shape but with a slightly higher amplitude for

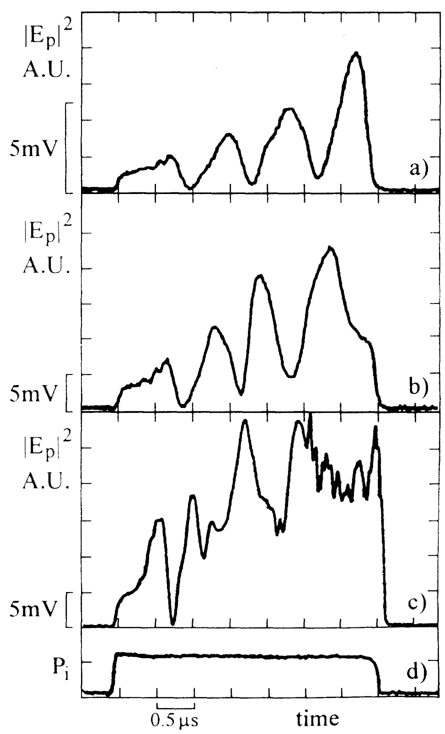

FIG. 2. Temporal evolution of the electric field in the resonant region for different incident powers; the probe is located at the initial resonant position. Pulse duration, 3.5 μs; incident power (a) $P_i = 260$ W, (b) $P_i = 380$ W, (c) $P_i = 650$ W. (d) Incident EM pulse.

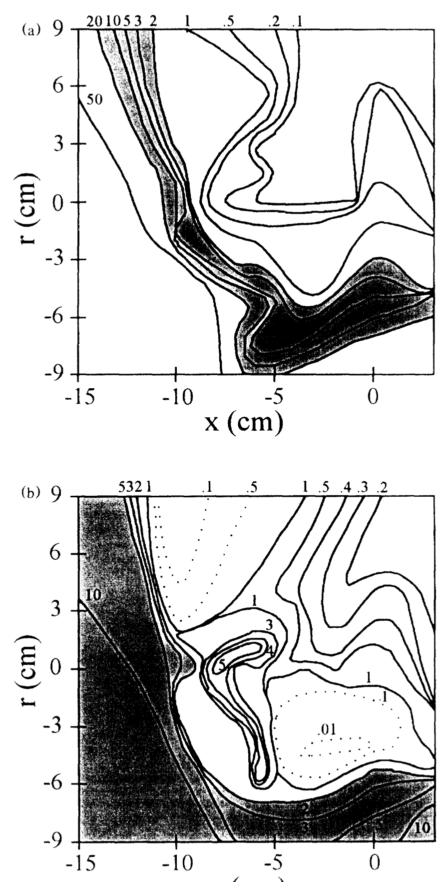

FIG. 3. Snapshots of the amplitude of the electric field in the resonant region [(x,r) plane] at different times: (a) $t \sim 150$ ns, (b) $t \sim 1.3$ μs. The shaded area indicates the cutoff region and the dotted lines are isocontours in a region where the EPW amplitude is minimum.

successive peaks. The volume on which the electric field of the EPW is trapped can be estimated from the previous measurements to have an extension $\Delta x \sim 1300\lambda_D$, $\Delta r \sim 1700\lambda_D$.

Measurements at different locations near resonance, in the volume where the EPW is trapped, show that the oscillations of the electric field are in phase. The electron saturation current of a probe located in front of the resonance exhibits, after the pulse and in the absence of hf field, the propagation of a density perturbation ($\delta n/n_0 \leq 10^{-3}$) which does not depend on the time when the hf pulse is switched off ($|E_p|^2$ maximum or minimum), and this density perturbation propagates at the IAW speed c_s (the probe signal is averaged over 16 acquisitions and the measurement of relative density perturbations of the order of 10^{-4}–10^{-3} is allowed by the coherence of these perturbations).

An estimation of characteristic times for growth and decay of the amplitude of the EPW has to be performed to get some insight on the physical processes which lead to this newly found relaxation oscillation. The growth of the amplitude of the EPW can be limited by convection of the EPW down the density gradient, by coupling of the EPW with IA perturbations, or by wave breaking.

In a parabolic density profile, the amplitude of the EPW is limited by convection to a value $E_p \sim E_d k_D l \times (4\beta)^{-1/2}$ in a time $t_{\rm conv} \sim 2(k_D l)\beta^{1/2}\omega_0^{-1}$. E_d is the value of the EMW amplitude at resonance and is obtained by solving the wave equation in a parabolic profile [8]. For our experimental conditions, this gives $E_d({\rm V/m}) \sim 2[P_i({\rm W})]^{1/2}$; the convection time is then $t_{\rm conv} \sim 0.7$ μs. The wave-breaking time near the top of the parabolic profile can be classically estimated as [12]

$$t_b = 3^{1/4}\frac{(2k_D l)^{1/2}}{W_d^{1/4}}[\beta(\beta-1)]^{-1/4}\omega_0^{-1};$$

$W_d = \varepsilon_0 E_d^2/4n_0 kT_e$ is the ratio of the energy density in the EMW at resonance to the thermal energy of the plasma. For our conditions ($\beta = 1.01$) and an incident EM power of 500 W, this leads to a wave-breaking time of 1.6 μs. The wave-breaking time is longer than the observed rise time of EPW; this discards the wave breaking of the EPW as an explanation of the relaxation. However, the convection time is of the same order as the measured rise time of the EPW.

Another time of concern is the time it takes the EPW with amplitude characterized by W_p to dig a cavity with scale length Δx and relative density perturbation $\delta n/n_0$. This time is estimated from the Zakharov equation concerning the IA perturbation [5]; this digging time is

$$t_d = \frac{\sqrt{2}}{2}\left(\frac{\delta n/n}{W_p}\right)^{1/2}\frac{\Delta x}{c_s}.$$

The values involved in this expression can be estimated from the experiment ($\Delta x \sim 3$ cm, $\delta n/n_0 \sim 10^{-4}$, $c_s = 3 \times 10^3$ ms^{-1}) and from a simulation of the Zakharov equations in a parabolic density profile which gives for our experimental conditions ($P_i \sim 500$ W) $W_p = 10^{-1}$ at $t = 0.3$ μs. The time to dig a cavity is then $t_d \approx 0.3$ μs.

From these estimates one can conclude that, during the buildup of a cavity (time scale t_d), on a time scale shorter or of the same order of the one needed to linearly saturate the EPW amplitude (time scale $t_{\rm conv}$), a local enhancement of the density on the border of the cavity arises. The density can be greater than critical, isolating the cavity from the EMW; as a consequence, the EPW is decoupled from the EMW and decays on a time scale which is the collisional time scale ($t_{\rm col} \sim 1.7$ μs). Then due to the weakening of the EPW, and the propagation of the overdensity perturbation, the density perturbation on the border of the cavity falls below critical, and the cavity is again pumped. One can note that during such cycles the cavity does not have time to relax, the characteristic relaxation time being of the order of $t_R = \Delta x/c_s$, so $t_R = 10$ μs.

In conclusion, for a plasma resonance located near the top of a parabolic density profile, as could be the case in ionospheric heating experiments or laser-matter interaction experiments, we have shown that a new mechanism can limit the amplitude of the EPW at resonance. The lowering of the convection speed of the EPW in a parabolic unmodified profile could lead to wave breaking. Instead, we found that the amplitude of the EPW is limited by its being trapped in a density depression which is decoupled from the EM driver field due to the creation of a density overshoot on its border. The numerical resolution of the Zakharov equations in a plasma with a parabolic density profile, taking into account the modification of the driver in the perturbed density profile, should reproduce our observations.

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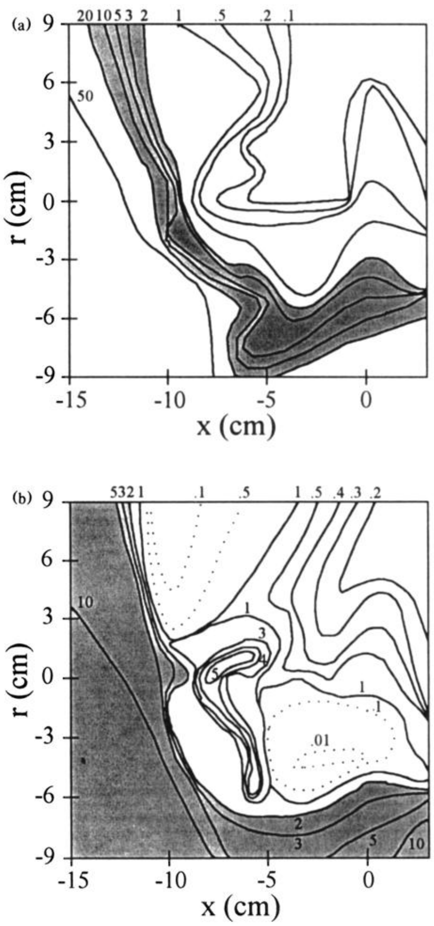

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