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Microwave-generated low-frequency plasma wave excited in the periphery of the evanescent layer

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The observation of microwave-created low-frequency electrostatic waves from the evanescent layer in a pulsed plasma discharge and effects of a weak magnetic field on its propagation characteristics are reported. The creation of the electrostatic wave depends on the density variations along the direction of microwave propagation. It is observable when a part of the microwave is reflected and another part of it eventually gets absorbed in the resonance-absorption layers $(\omega=\omega_{pe})$ on two sides of the evanescent layer. The velocity of the wave is one order of magnitude higher than that of the ion-acoustic wave. Under the application of a very weak magnetic field (affecting only the electrons) perpendicular to the direction of propagation of both the excited plasma waves and the microwaves, the waves are still observable only with altered velocity and characteristics. At higher magnetic fields the electrostatic waves are completely subdued under a continuous instability independent of presence or absence of the microwaves. *© 2004 American Institute of Physics.*

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I. INTRODUCTION

Study of electromagnetic (EM) wave-plasma interaction is a subject of up-to-date technological application and interest. The resonance-absorption phenomena are one of the processes, which might occur when electromagnetic wave is incident on plasma. Efficient transfer of electromagnetic wave energy to the plasma is mostly effective by the resonance-absorption technique[1–4] due to its oblique propagation in inhomogeneous plasma. An obliquely incident electromagnetic wave reflects at a density lower than the critical density and the airy function wave profile can travel relative to this point. When an electromagnetic wave is incident in plasma, its fields tunnel through the critical density region and excite the electrostatic mode at the resonance layer (a phenomenon termed as *resonance absorption*). The electric field of the incident electromagnetic wave induces the electrons to oscillate along the density gradient at the critical density. This eventually induces ion oscillations as a result of ponderomotive force. The efficient absorption of the electromagnetic wave into the plasma can cause an electrostatic (ES) plasma wave to be created, where the microwave frequency matches with the ion plasma frequency, and its amplitude depending on the nonlinear processes (such as the density profile being modified by the ponderomotive force in the region of wave propagation, etc.) in the plasma plays an important role. Application of a weak magnetic field (of the order of a few Gauss) can magnetize these electrons taking an active part in this wave launching phenomena. Hence the effects of such a weak magnetic field on such a wave launching and propagation is also as important. However, under the application of higher magnetic field $(<20\ \mathrm{G})$ the situation is completely changed. Probably its effects on the electrons change the plasma production mechanism and instead of an airy functionlike wave, a continuous wave (similar to an instability observed in the tokamak edge plasma region[5,6]) starts to propagate, hiding all the previously observed phenomena behind.

II. EXPERIMENTAL SETUP

A schematic view of the experimental setup is given in Fig. 1. Cylindrical nonuniform Argon plasma was produced by pulse discharge (with a duration of 2 ms and 1 Hz repetition rate) in a stainless steel chamber described elsewhere.[7,8] Two modifications of the previous device[7] made during this experiment were (1) the inhomogeneous plasma excitation method and (2) the application of a magnetic field perpendicular to the direction of propagation of the microwave inside the plasma.

To create a magnetic field perpendicular to the direction of propagation of the microwave, two large (outside diameter 123 cm and inside diameter 110 cm) copper coils connected in parallel (having 170 turns in each coil with copper wire of diameter 3.2 mm) were placed in Helmholtz configuration on two sides of the plasma chamber with the planes of the coils parallel to the chamber axis. This magnetic field also was created in pulsed mode with a width of 140 ms and 1 s repetition rate in order to produce an uniform magnetic field during occurrence of each plasma pulse. The microwave pulses were also chosen to have a width of $1-2\ \mu\mathrm{s}$ with the same (1 Hz) repetition rate. By the use of a EG&G delay generator (model 9650) all these pulses were matched to occur synchronously, e.g., first the magnetic field was

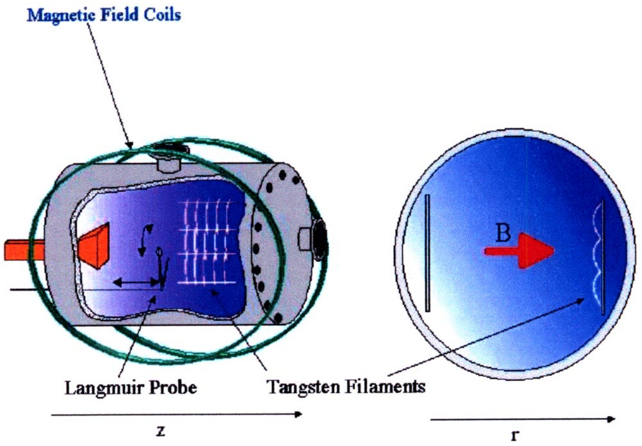

FIG. 1. (Color online). A schematic view of the experimental setup.

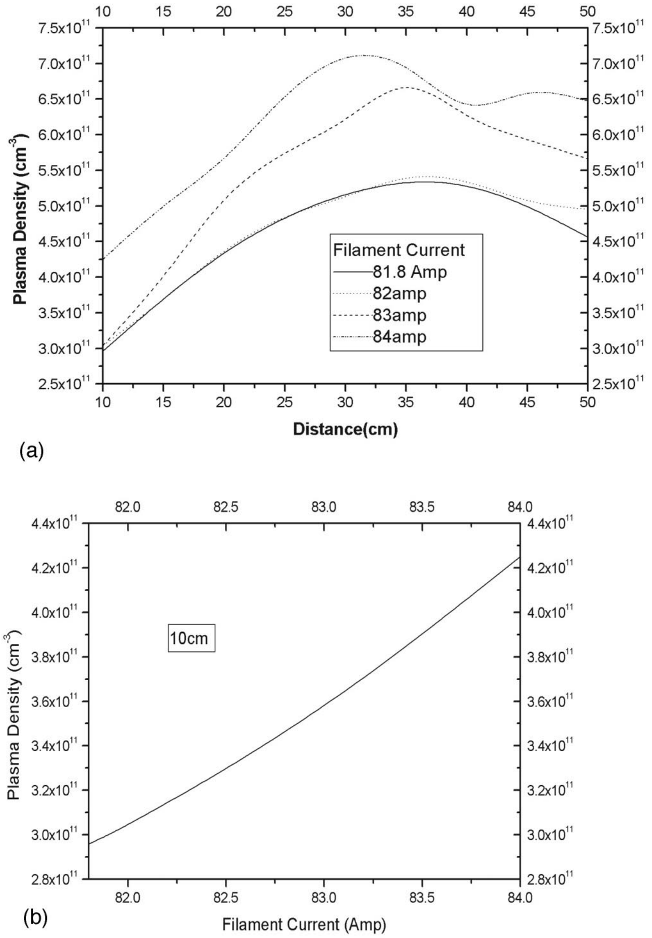

FIG. 2. (a) An example plot of density inhomogeneity structure over different distances created at different applied filament currents inside the chamber. (b) An example plot of density in homogeneity structure created at a fixed probe position (e.g., 10 cm) for different filament currents inside the chamber.

launched, and just at the middle of each magnetic field pulse the plasma pulse was launched, and again at its center the microwave pulse was created, and all with the same repetition rate of 1 Hz. In order to create a density inhomogeneity inside the cylindrical chamber, a filament structure connected in square matrices perpendicular to the microwave propagation direction was introduced. The filament source was built on a square aluminum plate floating with respect to ground and filaments were mounted with proper insulation from the plate. One more floating aluminum plate parallel to the filament-mounted plate structure having its surface normal parallel to the magnetic field was also employed in order to prevent the loss of primary electrons along the magnetic field. Prevention of primary electron loss along the magnetic field forced them to diffuse perpendicular to the magnetic field as well as to that of plasma electrons. This helped to determine that diffusion perpendicular to the magnetic field are mainly dominated by the electrons and that parallel to the magnetic field are governed by ions leading to uniform magnetic field even across the magnetic field. Without the floating plate at the end of the magnetic field lines, electrons being the lighter species would have diffused along the magnetic field lines, but ions would have diffused both across and along the magnetic field lines, their currents being close at the grounded chamber wall. This could have produced plasma in "filaments" along the magnetic field and would not have had a uniform plasma across the magnetic field. In addition, there were small magnets (4 kG each) arranged on broken line cusp arrangements all over on the outside surface of the chamber in order to achieve better plasma uniformity. A digital power supply (Hewlett Packard 6684A) with 0–40 V and 0–128 A capacity was used as the filament power supply. The plasma thus produced was found to have a density gradient inhomogeneity with a maximum density almost near the center of the axis of the chamber (e.g., typically from 25 to 35 cm position on the axis) during most measurements which depends also on the filament current employed during that set [Fig. 2(a)], and lower density regions near each end of the chamber axis (e.g., typically from 10–25 cm to 40–50 cm positions on the axis), while the microwave horn antenna used to introduce the microwave was placed near the 10 cm end of the chamber (Fig. 1). Variation of this density in homogeneity structure could easily be controlled by variation of the filament current [Fig. 2(b)]. Plane polarized microwave [electromagnetic (EM) wave] with frequency $f=2.86$ GHz and a maximum power of 10 kW irradiated from a horn antenna located at the end of one axial length of the plasma chamber were used to study microwave plasma interaction. Typical plasma parameters were: maximum plasma density 2×10^{11} cm^{-3}, electron temperature $T_e\cong 3$–5 eV, ion temperature $T_i\cong T_e/10$ in an Argon gas pressure $\cong 9.5\times10^{-4}$ Torr. Figure 2 represents the typical density gradient structure. The main diagnostic probes in this experiment are cylindrical Langmuir probes of 1 mm length and 0.5 mm diameter each made of semirigid holder cables. Probes were generally biased in the electron saturation current region especially when the density fluctuations were observed. In the absence of any magnetic field on the two Helmholtz coils external to the chamber, a narrow (1–2 μs) microwave pulse in the plasma is launched in order to form a large amplitude $(\delta n/n=32\%)$ airy-function-like wave, the amplitude of which depends on the filament currents employed to control the plasma density variation inside the chamber. Under the application of a weak magnetic field the excited electrostatic wave characteristics are modified. Presence of a weak magnetic field alters the position of maximum microwave absorption layer, which controls the existence of wave in that region. The magnetic field also contributes to the velocity as well as region of existence of such waves.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

In most of the previous experiments[7–9] the density gradient along which the microwave is allowed to propagate laid almost along its direction of propagation, i.e., the microwave was allowed to proceed from a very low plasma density side to a high-density layer. The second characteristic feature in contrast to earlier experiments[7–9] is that the microwave during this experiment was allowed to proceed from a very low plasma density side to a high-density region again to enter into a lower density region. As a result an evanescent region of the EM wave in high-density plasma was created in the middle way of its journey enclosed between two resonance absorption plane layers. It could be imagined that at the beginning of its course a part of the microwave is reflected back from the reflection layer where the microwave frequency ω is even larger than the electron plasma frequency ω_{pe}; while another part of it, depending on the plasma density structure, tunnels into the evanescent region. In the way there is the layer, where the frequency of the EM wave meets the plasma frequency and the mode conversion occurs, resulting in launching of the electrostatic plasma waves. When the microwave can tunnel through the evanescent region, it eventually approaches the resonance absorption plane on the other lower density side, and as a result excites electrostatic plasma wave again, but this plasma wave propagates in the opposite direction. This phenomenon is evident from the absorption characteristics of the microwave amplitude detected inside the plasma such as shown in Fig. 3. Typical plasma wave forms observed are represented in Figs. 4(a) and 4(b). These waves propagate from near one end of the chamber (say 10 cm position) where the microwave enters, towards the other end. When it eventually enters the denser plasma region, it slowly accelerates, resulting in a position (say, e.g., 30 cm–40 cm position) where the wave passes almost instantaneously, which we have termed as the virtual-trapped position of the wave. Ultimately, when the probe reaches a lighter density region (say, e.g., 40 cm–50 cm position) again the waveforms captured by the probe at different position start taking some time to change form instead of being instantaneous, but propagates in the other direction than they were propagating before. To represent the wave propagation in two different directions, we have plotted in two separate figures, e.g., Figs. 4(a) and 4(b) where (a) represents propagation in the lower density region (e.g., 19 cm–30 cm) with a slightly lower velocity and (b) shows the wave in the higher density region (e.g., 35 cm–43 cm) with higher velocity. Wave propagations on both sides of the evanescent region are visible only at some lower density plasma conditions. At higher filament currents, higher density plasma is produced and wave propagation is visible only at the lower density sides (10 cm–30 cm side).

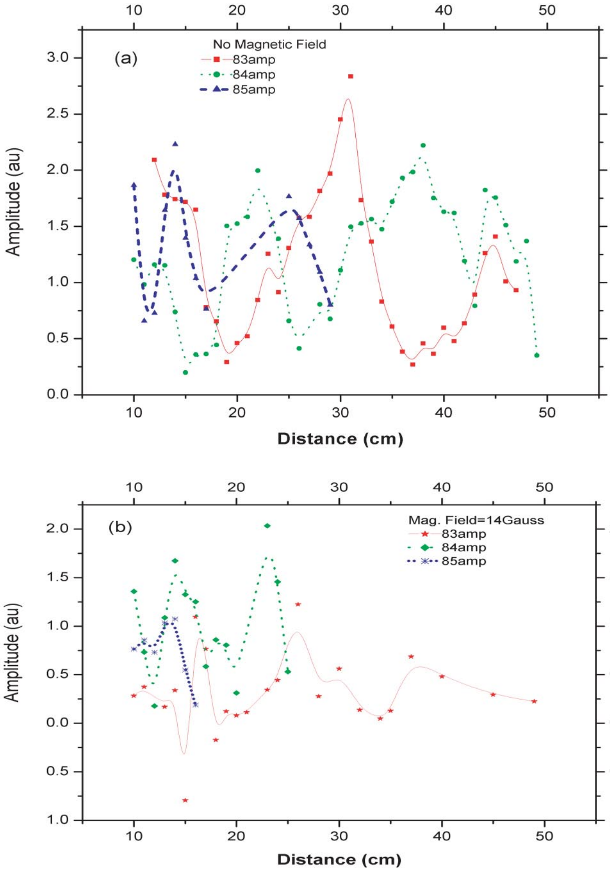

FIG. 3. (Color online). Example plot of microwave amplitude variation at different axial positions inside the plasma chamber detected by a Langmuir probe (assisted by microwave detector) (a) with no magnetic field and (b) with 14 G magnetic field for different filament currents (i.e., different plasma density structure).

We explain this wave excitation method as a result of the microwave being reflected at the resonant absorption layer, which exists on both sides of the evanescent layer. The tunneled EM wave field through this evanescent layer pushes the electrons out, resulting in some charge separation to pull out a bunch of ions. As a result, eventually a high velocity wake is formed, which ultimately transforms to ion waves but still with a velocity one order of magnitude higher than that of the ion-acoustic waves.

Similar phenomena happen on both sides of the evanescent layer. This is quite evident when we carefully look at the microwave amplitude variation detected by a probe inside the plasma (Fig. 3). At lower filament current (i.e., at low plasma density) the microwave is detectable on both sides of the evanescent layer, which means the microwave could tunnel through the evanescent layer to reach the resonance layer on the other side and excite the plasma to launch ES wave propagating in the opposite direction. Whereas at the higher filament currents, sometimes the plasma density is too high for the microwave to tunnel through the evanescent layer to reach the other side, to get reflected in the resonant absorption layer to excite the wave.

Figure 5 presents the time-position plots of the waves at different density regions with varied magnetic fields. As is clearly seen from Fig. 5, the waves travel instantly in the

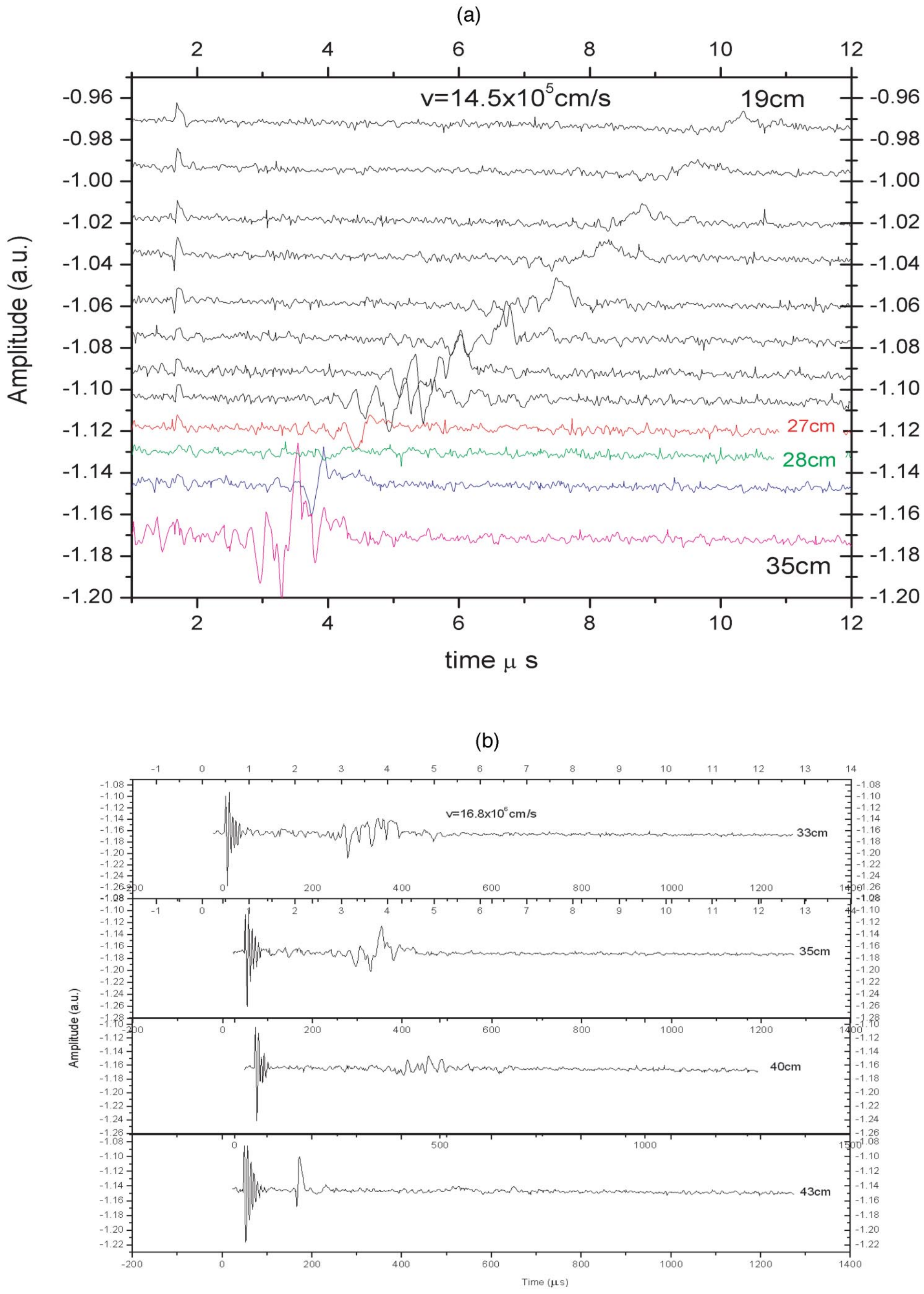

FIG. 4. (Color online). (a) An example plot of first part of the wave propagating from the resonance layer toward lower plasma density region at $B=0$. (b) Typical wave form observed propagating in a direction opposite to that of the wave in (a), over different distances in the higher plasma density region, being excited on the other side of the evanescent layer.

region, typically, in Fig. 5(c) for example. We call this phenomenon the "virtual wave trapping." This occurs only in the evanescent area. In the lower density region on both sides, the wave appears again. The wave is pseudotrapped (becomes instantaneous and takes almost no time to pass) e.g., between 27 and 41 cms position, and ultimately takes more and more time being propagated to the opposite direction at a higher velocity than the one with which it was excited on the other side of the evanescent layer, and the change of time becomes noticeable. The velocity measured here is one order of magnitude greater than the ion-acoustic velocity. Existence of such high velocity density perturbations pertains to the possibility of existence of a fast particle bunch in front of the wave. Especially the very high velocity of the excited wave suggests it to be particle bunching rather than a wave. The experiment was repeated at different plasma density distribution (controlled by filament-current variation). It was noted that the region of wave launching, its velocity distribution, and existence of reflection depends on the density distribution profile. In order to find the dependence of such wave propagation on the magnetic field, observations were recorded at three typical weak magnetic fields (e.g., 14 G, 17 G, and 20 G). Figures 3 and 5 suggest that a region of maximum microwave absorption contributes to the launching of such electrostatic waves and, since the presence of a weak magnetic field alters the position of the maximum microwave absorption layer, it controls the existence of wave in that region. The magnetic field also contributes to the veloc-

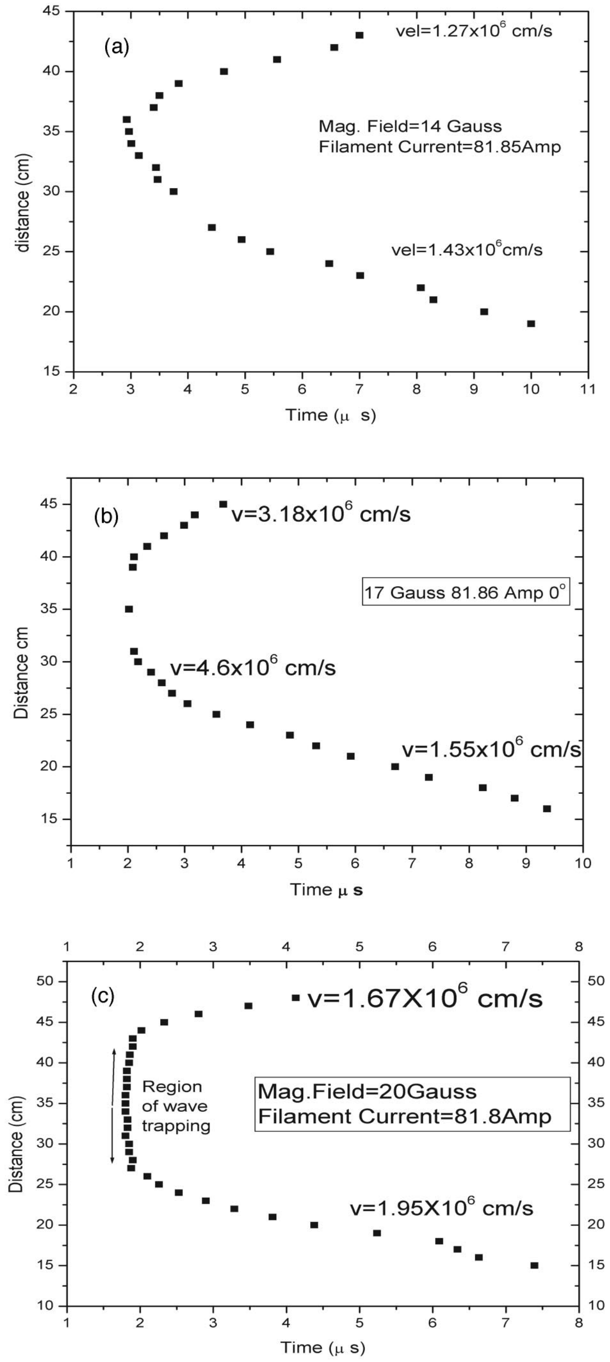

FIG. 5. Time vs distance plot showing the transformation of the wave around the resonance layer, from a lower velocity through a lower density region towards almost an instantaneous mode in the evanescent region.

ity as well as region of existence of such waves.

In Fig. 6 the velocity versus magnetic field and time is represented. The velocity changes with time and eventually to the lower value, still having higher velocity than the ion-acoustic one. On the contrary, the application of the higher magnetic field excites instability so strongly that this wave-launching phenomenon is subdued under the effects of such instability, which suggests it should be studied as a separate class of phenomena (Fig. 7).

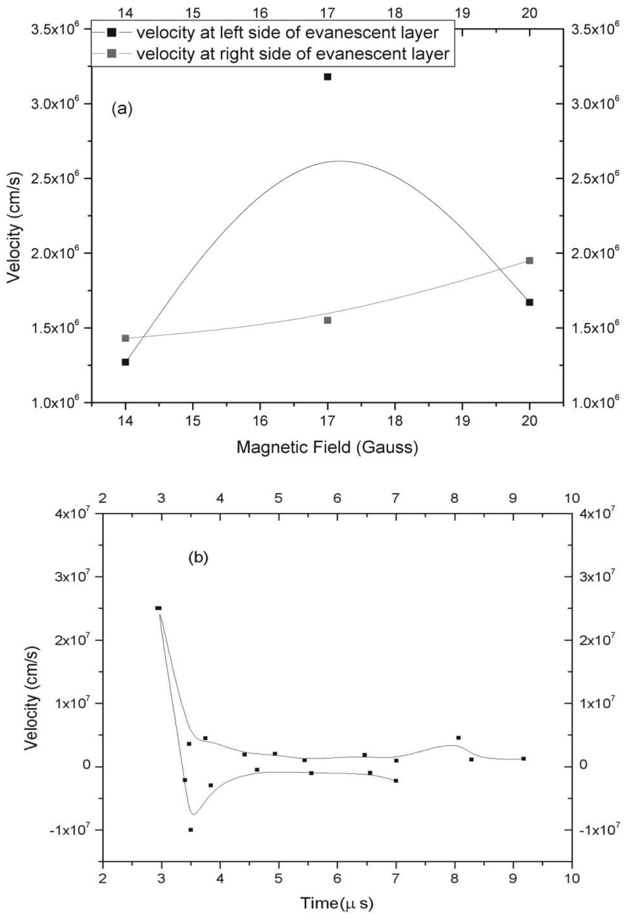

FIG. 6. (a) Variation of wave velocity with magnetic filed. (b) Representation of wave velocity variation with time, which clearly shows wave propagating in two directions with changing velocity.

The dispersion relation for the extraordinary wave propagating perpendicular to the external magnetic field is

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\cdot\frac{\omega^2-\omega_p^2}{\omega^2-\omega_h^2}, \tag{1}$$

where $\omega_h^2=\sqrt{\omega_p^2+\omega_c^2}$ is the upper hybrid frequency; $\omega_p=(n_0e^2/\in_0 m_e)^{1/2}$ the plasma frequency; and $\omega_c=|e|B/m_e$ the

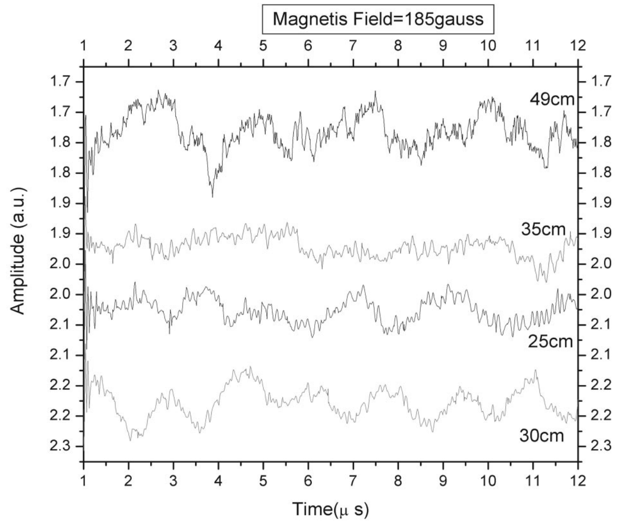

FIG. 7. An example plot of the change of the wave form to an instability obtained at stronger magnetic field (B=185 G) observed at different probe positions such as indicated in the figure. The frequency and wave form depend on the plasma density and applied magnetic field.

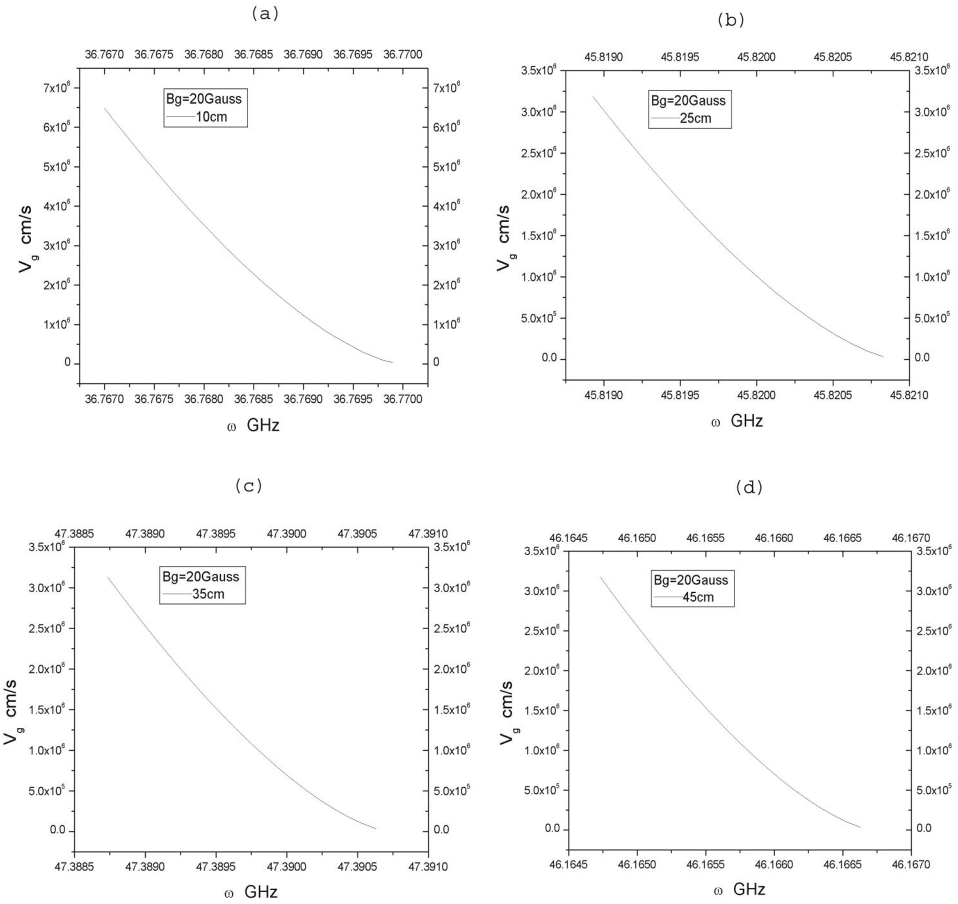

FIG. 8. Theoretical plot of group velocity V_g vs wave frequency ω.

electron cyclotron frequency. This wave can propagate for values of ω satisfying the conditions

$$\omega_L < \omega < \omega_h, \quad \omega > \omega_R,$$

where ω_L and ω_R are, respectively, the left-hand and right-hand cut-offs given by

$$\omega_R = \frac{1}{2}[\omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2}],$$

$$\omega_L = \frac{1}{2}[-\omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2}], \tag{2}$$

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\left\{1 + \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}\right\},$$

therefore

$$c^2k^2 = \omega^2 - \omega_p^2 - \omega_p^2\frac{\omega_h^2 - \omega_p^2}{\omega^2 - \omega_h^2}.$$

Differentiating this we get

$$c^2k\frac{dk}{d\omega} = \omega + \omega_p^2\omega\frac{\omega_h^2 - \omega_p^2}{\omega^2 - \omega_h^2},$$

$$c\frac{ck}{\omega}\frac{1}{v_g} = 1 + \omega_p^2\frac{(\omega_h^2 - \omega_p^2)}{(\omega^2 - \omega_p^2)^2}$$

therefore

$$v_g = c\left[1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}\right]^{1/2}\left[1 + \frac{\omega_p^2(\omega_h^2 - \omega_p^2)}{(\omega^2 - \omega_h^2)^2}\right]^{-1}. \tag{3}$$

This v_g is the group velocity of the extraordinary wave.[10] We have compared this theoretical value with the data obtained experimentally.

Experimentally the group velocity is of the order of 10^6 cm/s. We can suggest this wave to be explained by the above theory. The example plot of four graphs in Fig. 8 calculated from Eq. (3) show that the value of the group velocity is very sensitive to the selection of range of ω, which is different at different distances when plasma density varies axially. Our experimentally obtained value also occurs in this range, which leads us to suggest our experimentally observed wave to be one such candidate from similar wave group.

IV. CONCLUSION

We have observed here the electrostatic wave excitation; trapping and reflection around the resonance layer of the EM wave in an inhomogeneous weakly magnetized pulsed plasma by application of a very narrow (of the order of an ion plasma period or less) microwave pulse. The wave is observed to be propagating with velocities an order of magnitude higher than the ion-acoustic velocity. The reflected part of the wave from the resonance absorption layer having much higher velocity seems to contain contributions from the bunched fast particles such as ions.[9] The wave was found to exist even in the absence of the magnetic field. The very weak magnetic field contributes to the shifting of regions of occurrence of such phenomena. Above theoretical calculations of the dispersion relation for extraordinary wave propagating perpendicular to the external magnetic field matches with our experimental observation. Stronger magnetic field sheds such wave propagation due to the creation of a continuous wave instability existing throughout the whole plasma region with variable frequency depending on the magnetic field strength.

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