

Observation of ion wave streamers and low frequency sheath instability by the resonant absorption due to nonlinear interaction of microwave-plasma

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Unmagnetized, inhomogeneous laboratory plasma irradiated by an oblique p -polarized microwave with pulse length $0.2\text{--}1.5\ \mu\text{s}$ and power $P = 1\text{--}2\ \text{kW}$ is studied. The incident electromagnetic wave is linearly converted into an electrostatic plasma wave when the incident wave frequency ω_0 is equal to the local plasma frequency ω_p . The localized linear enhancement of the driven oscillating field can lead to nonlinear phenomena driven by the ponderomotive force, which expels electrons from the resonance region, and the resulting ambipolar electrostatic fields also expel the ions, creating density cavities at the resonance region. Expelled ions tend to form an ion bunch and accelerate up to energies greater than $10\ kT_e$. After all these processes are achieved, it has been observed in the experiment that the density cavity develops as ion wave streamers and propagate both up and down the density gradient from the resonant layer. It is observed that the downward streamer velocity V_{down} and upward streamer velocity V_{up} have the relation as $V_{\text{down}} > C_s > V_{\text{up}}$. Another physical phenomenon, called the low frequency sheath instability, in the plasma sheath area created by the accelerated ion bunch near the resonant region, is also observed in the experiment. © 2004 American Institute of Physics. [DOI: 10.1063/1.1639910]

I. INTRODUCTION

Resonant absorption of an electromagnetic wave in an unmagnetized, inhomogeneous laboratory plasma is relevant to the physics of laser plasma interaction¹ and to radio wave propagation in the ionosphere.² The microwave plasma interaction is one of the electromagnetic wave interaction with plasma. Many new phenomena have been explored by microwave plasma interaction experiments.^{3–11} Resonant absorption occurs when a plane p -polarized electromagnetic (EM) wave is incident obliquely in an unmagnetized, inhomogeneous plasma. The incident EM wave reflects at a density determined by the relation $\omega_p(z) = \omega_0 \cos \theta$, where ω_0 is the incident wave frequency and θ is the angle of incidence defined as the angle between the propagation vector $\mathbf{k}$ of the incident microwave and the direction of the density gradient scale length L_z of the plasma. The evanescent field of the EM wave can penetrate to the higher density region, called the critical density region, when $\omega_p = \omega_0$ and resonantly excites a large electrostatic plasma wave.^{12,13} For the case of a cold plasma with a linear density profile $n_e(z) = n_0(1 + z/L_z)$, the solution of the electromagnetic wave is given by the Airy function in the underdense plasma column, while considering in the absence of collisions, the electric field becomes infinite in the critical density layer.¹² The amplitude of the enhanced electric field in the resonance region is limited by various processes like the collisional effect,^{12,14} plasma wave convection,^{6,15,16} and nonlinear effects such as wave breaking.^{3,6,17,18}

High energy electrons have been observed in many laboratory experiments using microwaves. The incident power

level in the nonlinear excitation is described via the cold wave breaking phenomena for the production of high energy electrons. Many experiments have demonstrated that the high energy suprathermal electrons generated by high power microwave absorption near critical layer by the conversion of microwave energy into particle energy can be explained by the cold wave breaking mechanism.^{3,5,11} Another physical phenomenon to eject particles from the resonance region is that when the resonant electric field goes to a sufficiently high level, the associated ponderomotive force pushes the trapped electrons in the wave toward the outside and, as a consequence, these suprathermal electrons can pull the ions from the critical density layer by the ambipolar Coulomb force and drive a suprathermal ion bunch.^{10,17,19–21} In the present experiment, it is also observed that a self-consistent ambipolar force pulls out the ion bunch from the resonance region and this ion bunch can travel through the underdense plasma. The energy of this accelerated ion bunch is observed $\geq 10\ kT_e$. Following these processes, density cavities develop as ion wave streamers with density modification propagate both up and down the density gradient from the resonance layer, which has been clearly observed in our experiment. In the present paper, we present experimental observation of ion wave streamers in the underdense plasma area with velocity higher than the ion acoustic velocity and in the overdense plasma area with velocity lower than the ion acoustic velocity. A low frequency sheath instability is also observed in the plasma sheath area created by energetic ion bunches accelerated from the resonance region.

This paper is organized as follows: experimental setup is

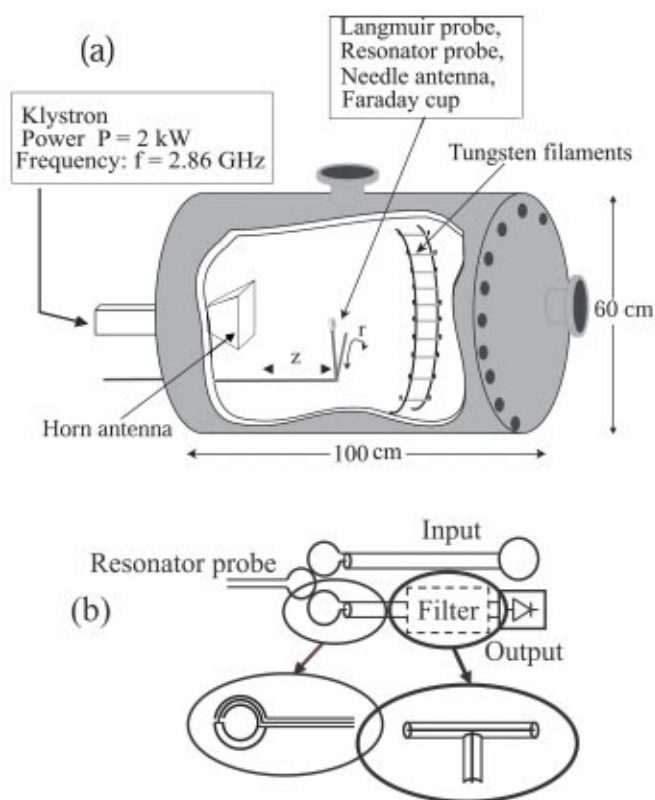


FIG. 1. Schematic drawing of the experimental arrangements: (a) main arrangements of the experiment, (b) microwave resonator probe.

described in Sec. II, results and discussions in Sec. III. Finally, Sec. IV concludes the paper.

II. EXPERIMENTAL ARRANGEMENTS

A schematic drawing of the experimental arrangements is shown in Fig. 1. A cylindrical, unmagnetized, nonuniform, argon plasma is produced in a stainless steel chamber of 100 cm length and 60 cm diameter. The outside surface of the vacuum chamber is covered with line cusp arrangements for improved plasma confinement, made from permanent magnetic bars. Plasma is produced by the pulsed discharge with applied voltage (60 V) between tungsten filament arrangements as the cathode (heating current up to 95 A) and grounding chamber wall as the anode with discharge duration 2 ms and repetition rate 10 Hz. Tungsten filaments are connected to a frame made by two stainless steel rings. The vacuum chamber is initially evacuated to a pressure (ionization gauge meter reading) $p \approx 2.5 \times 10^{-6}$ Torr and after filling with argon gas, the chamber pressure (gauge meter reading) is adjusted to $p \approx 8 \times 10^{-4}$ Torr. Plasma density as well as the density perturbation are measured by two disc shaped (1-mm-diam) Langmuir probes, one facing toward the resonant region and the other facing oppositely from the resonant region. A microwave resonator probe²² shown in Fig. 1(b) is also used to measure the plasma density. A U-shaped quarter wavelength resonator probe is coupled by two loop antennas in this device. An insulated needle antenna with a tip 2 mm length and 0.25 mm diameter is used to measure the spatial distribution of microwave field in the plasma. A Faraday cup

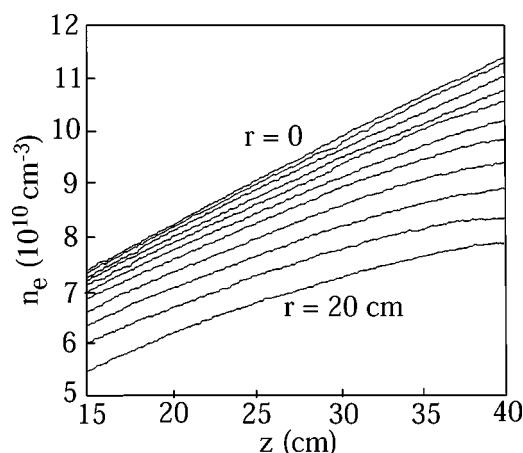


FIG. 2. Spatial density profiles inside the plasma chamber in the absence of incident microwaves. Each line separates $r=2$ cm between neighboring lines.

protected by a ceramic-cover and estimated collimating angle 16° is used in order to detect the energetic ion flux. The energy analyzer has two grids in front of its collector; the outer one (inner diameter 8.5 mm) is left at floating potential in order to reduce disturbances of analyzer on the ambient plasma, and the inner one is biased negatively in order to reflect plasma electrons. The distance between the outer grid and the collector is about 14.75 mm. All diagnostic tools are movable in the axial z direction and rotatable in the radial r direction by a low power dc motor system, where $z=0$ locates the point on the face of horn antenna and $r=0$ locates the point on the chamber axis.

A p -polarized microwave pulse with frequency $f = \omega_0/2\pi = 2.86$ GHz (corresponding critical plasma density $n_c = 1 \times 10^{11} \text{ cm}^{-3}$ for resonance absorption) and maximum power 2 kW is launched into plasma from a rectangular horn antenna located at lower plasma density side. The horn antenna has a metallic lens in order to minimize diverging output radiation angle for creating p -polarized microwave-plasma interaction. The width of the microwave pulse is maintained from 0.2 to 1.5 μs full width at half maximum with a repetition rate of 10 Hz. To prevent the maximum reflection of the launched electromagnetic wave from the chamber walls, which could make an unnecessary disturbance in the microwave-plasma interaction, we have put metallic-wool inside the chamber walls to absorb the electromagnetic wave. To create the interaction of microwave with inhomogeneous plasma, the horn antenna and the filaments are separated by placing them at the two ends of the plasma chamber, as shown in Fig. 1(a). The axial increase of plasma density is created in the direction from the horn antenna to filaments and the radial increase is created from the cylindrical chamber wall to the chamber axis. The feature of the inhomogeneous plasma is depicted in the results in Fig. 2.

III. RESULTS AND DISCUSSIONS

When high power microwaves are launched in the inhomogeneous plasma, the component of the electric field parallel to the density gradient tunnels up to the resonant region,

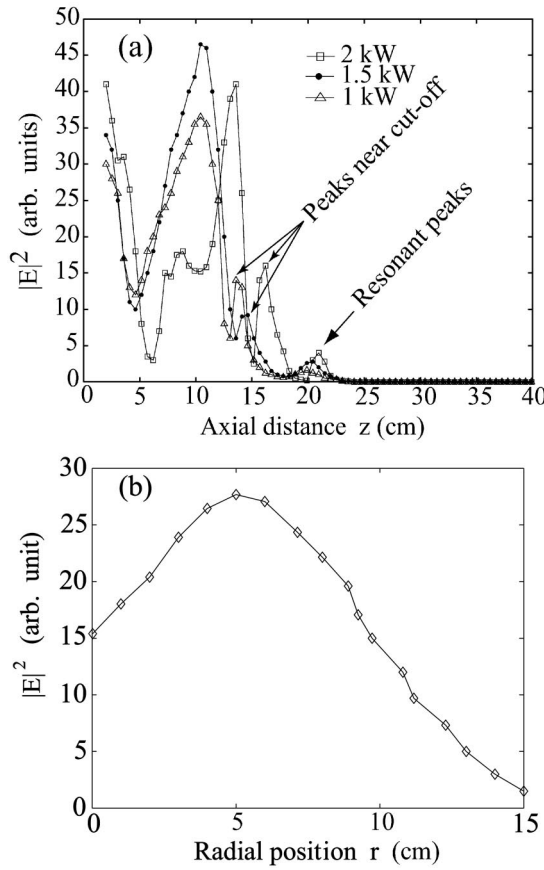


FIG. 3. Microwave profiles inside the plasma: (a) axial profiles of microwave electric fields at $r \approx 5$ cm taken in different incident powers, (b) amplitude profile of resonant peaks in different r positions for the microwave power 2 kW.

where the local plasma frequency approximately equals the incident microwave frequency. To show the feature of inhomogeneous plasma inside the chamber, a typical example of plasma density profiles is shown in Fig. 2. This figure shows the spatial density profiles in the absence of incident microwaves. A nonuniform plasma density is observed of the order of 10^{10} – 10^{11} cm^{-3} . It should be mentioned that the density profile shown in Fig. 2 just represents the picture of inhomogeneous plasma inside the chamber. The critical layer described by Fig. 3 is detected by a separate density parameter taken at a separate time which is not directly connected to the density parameter depicted in Fig. 2. The typical density gradient scale length in the axial (z) direction and radial (r) direction is observed to be $L_z \approx 68$ cm and $L_r \approx 52$ cm, respectively. Electron temperature $T_e \approx 3$ eV and ion temperature $T_i \approx 0.5$ eV are observed to be approximately identical throughout the main part of the plasma volume, where the experiments are performed. However, when a narrow p -polarized microwave pulse with a frequency ω_0 is irradiated obliquely in an inhomogeneous plasma, the resonance absorption occurs at the critical density layer where $\omega_0 = \omega_p$. The resonant layer is detected by taking the spatial profile of microwave field inside the plasma, as shown in Fig. 3 by using a needle antenna coupled to a crystal detector. Figure 3(a) displays the axial profiles of microwave field

for different powers 2.0, 1.5, and 1.0 kW, respectively, at $r \approx 5$ cm. One can observe the cut-off layers of the incident microwaves and resonant electric fields at different microwave powers. A comparatively higher resonant field is observed for the power 2 kW at the axial position $z \approx 21$ cm, which is the position where the plasma density becomes critical ($\approx 1 \times 10^{11}$ cm^{-3}). It is seen that the incident microwave radiation vanishes beyond $z \approx 21$ cm where the plasma becomes overdense. Figure 3(b) shows the radial distribution of amplitude profile of the resonant electric field. Note that the maximal resonant field intensity occurs at $r \approx 5$ cm and it decreases in the regions of $r < 5$ cm and $r > 5$ cm. From Figs. 3(a) and 3(b) one can conclude that the maximum resonant field intensity for incident power 2 kW is observed at $z \approx 21$ cm and $r \approx 5$ cm in the present experiment. Using the above experimental results, one can obtain the angle of incidence by the following method.¹¹ When a p -polarized electromagnetic wave with $k_0 L_z \gg 1$ is incident on a plasma slab with linear density profile $n_e(z) = n_0(1 + z/L_z)$ at an incidence angle θ , the incident ray trajectories are assumed to be parabolic. The component of the group velocity in the radial (r) direction is constant. For a given microwave launch point z_l and the reflection (turning) point $z_T = L_z \cos^2 \theta$, the radial deflection is proportional to the transit time τ from the point z_l to the point z_T . Thus one can calculate τ by the following term:

$$\tau = \int_{z_l}^{z_T} \frac{dz}{c \sqrt{1 - \omega_p^2/\omega_0^2}},$$

which gives

$$\begin{aligned} \tau c &= \int_{z_l}^{L_z \cos^2 \theta} \left[1 - \frac{z}{L_z} - \sin^2 \theta \right]^{-1/2} dz \Rightarrow \tau c \\ &= 2L_z \left(\cos^2 \theta - \frac{z_l}{L_z} \right)^{1/2}. \end{aligned} \quad (1)$$

Substituting $r = \tau c \sin \theta$, we have

$$\frac{r^2}{(2L_z \sin \theta)^2} = \cos^2 \theta - \frac{z_l}{L_z}, \quad (2)$$

which gives the solution expressed by

$$2 \cos^2 \theta = 1 + \frac{z_l}{L_z} \pm \left[\left(1 - \frac{z_l}{L_z} \right)^2 - \left(\frac{r}{L_z} \right)^2 \right]^{1/2}. \quad (3)$$

There are two roots of $\cos \theta$ in Eq. (3). With measured values $z_l = 2$ cm, $L_z = 68$ cm, $r = 5$ cm, and considering the plus sign one can obtain $\theta = 2.14^\circ$ and for minus sign $\theta \approx 80^\circ$. Out of two roots, we can accept a reasonable value of $\theta \approx 2.14^\circ$. One can calculate the angle of incidence by a different method⁶ given by the formula $\theta \approx \sin^{-1} \{ [(D/d)/L_z]^{1/2} \}$, where $d \approx (L_z/k_0^2)^{1/3}$ and D the distance between the resonant point and the first Airy peak from the resonant point. Using the value $D = 4.73$ cm measured from Fig. 3(a) for incident EM wave 2 kW, one can calculate $\theta \approx 6.3^\circ$. However, both of the values of θ calculated by different methods have the optimal range of angle of incidence which can support our process to locate the maximum resonant point.

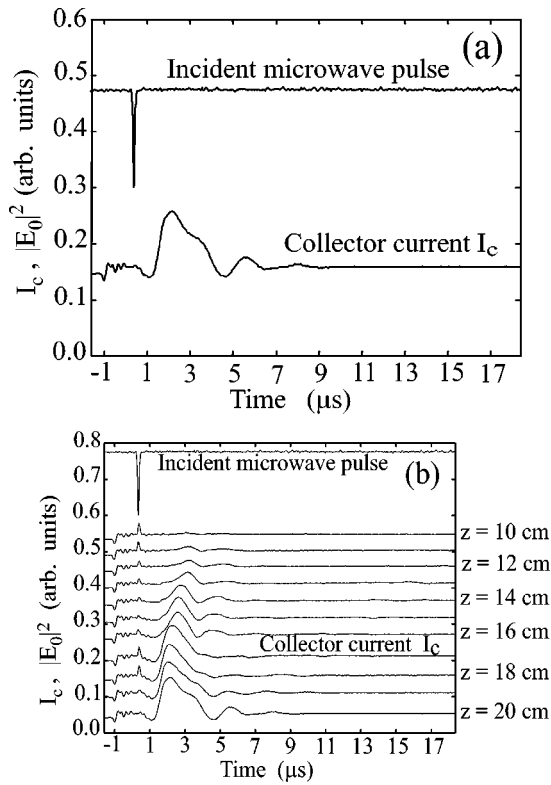


FIG. 4. Observation of ion bunches by using a Faraday cup: (a) time profile of the ion current observed in the collector (bottom trace) and the incident microwave pulse (top trace), (b) time profiles of the ion current in different axial positions (bottom traces) and the incident microwave pulse (top trace).

When a short pulsed microwave is irradiated obliquely in an inhomogeneous plasma, the incident electromagnetic waves linearly convert into electrostatic plasma waves. If the incident microwave power is sufficiently high, the localized linear enhancement of the driven oscillating field can lead to a nonlinear phenomena driven by the ponderomotive force

$$F = -\frac{\nabla \langle E^2 \rangle}{8\pi}.$$

The ponderomotive force expels electrons from the resonance region, resulting in leaving a bunch of ions around the neighborhood of the critical surface layer, and finally this bunch of ions can be accelerated by the created ambipolar Coulomb force from the resonant layer.^{10,17,19–21,23} One can observe in the typical oscillogram shown in Fig. 4 that the resonant absorption of a short microwave pulse produces a bunch of accelerated ions. The bottom trace of Fig. 4(a) shows the typical result of an ion bunch which is generated after shut-off of the incident microwave pulse. It should be mentioned that all time measurements in the experiment follow at $t = 0$ when microwave pulse radiation is started-on. The top traces of Figs. 4(a) and 4(b) show the incident microwave pulse detected by a needle antenna and bottom traces show the collector currents produced by the ion bunch detected by an energy analyzer (Faraday cup) in the underdense plasma region. Here the pulse duration of the incident microwave is $0.27 \mu\text{s}$ and the resonant point in the measurements is observed at $z \approx 21 \text{ cm}$ and $r \approx 5 \text{ cm}$. Further collec-

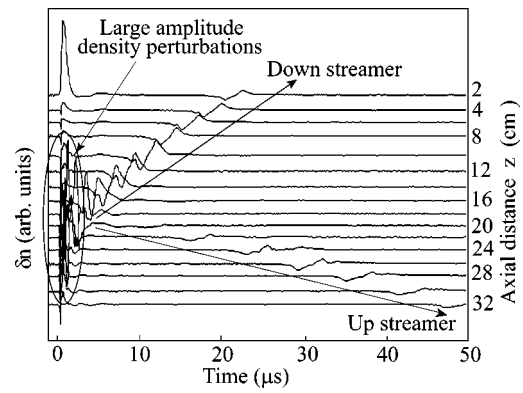


FIG. 5. Large amplitude density perturbations near the resonant region (inside the elliptical marker) and wave streamers (along the arrow markers) propagating up and down the density gradient at a fixed radial position $r \approx 5 \text{ cm}$.

tor currents are detected in different axial positions ($z = 20\text{--}10 \text{ cm}$) at $r \approx 5 \text{ cm}$, as shown in Fig. 4(b). It shows that an ion bunch gradually disappears when it moves from the resonant layer to underdense plasma region. The observed energy of this ion bunch is greater than $10 kT_e$ close to the resonant region. When this high energy ion bunch penetrates into the plasma, it excites large amplitude density perturbations which are observed very close to the resonant region. The observed large amplitude density perturbations are depicted inside the elliptical marker in Fig. 5. After these processes are achieved the created density perturbations turn into ion wave streamers and propagate both up and down the density gradient from the resonant layer, as shown in Fig. 5 by arrow markers. The measurements of Fig. 5 are taken by the Langmuir probe facing toward the resonant region. It is observed that the propagation of the ion wave streamer starts after penetrating the ion bunch out of the resonance region. Here the term ion wave streamer is used for the density perturbations propagating both up and down the density gradient on the order of ion acoustic speed but not exactly at the ion acoustic speed. It has been observed that the velocity of the downward streamer is greater than the ion acoustic speed, while the upward streamer is less than the ion acoustic speed. In the present experiment, the observed velocity of downward streamer $V_{\text{down}} \approx 4.5 \times 10^5 \text{ cm/s}$ has a good coincidence to our earlier paper on ion wave wakefields.²¹ The velocity of the upward streamer is observed $V_{\text{up}} \approx 1.5 \times 10^5 \text{ cm/s}$. From our experimental parameters the calculated ion acoustic speed is $C_s \approx 2.7 \times 10^5 \text{ cm/s}$. One can observe that the velocity of the streamers has the relation as $V_{\text{down}} > C_s > V_{\text{up}}$. From the above values $V_{\text{down}} \approx 1.7 C_s \text{ cm/s}$ and $V_{\text{up}} \approx 0.6 C_s \text{ cm/s}$ have been identified. Now we wish to look at how much influence can be created by the ambient plasma flow velocity to the observed streamers flow. If we assume that the plasma flow occurs from the area of the higher density side toward the lower density side, then the next relationship will be assumed by the Doppler effect; $V_{\text{down}} = C_s + V_{\text{flow}}$, $V_{\text{up}} = C_s - V_{\text{flow}}$, where V_{flow} is the ambient plasma flow velocity. From the above Doppler relations, $C_s = (V_{\text{down}} + V_{\text{up}})/2$ and $V_{\text{flow}} = (V_{\text{down}} - V_{\text{up}})/2$ are given. Thus, $C_s = 3.0 \times 10^5 \text{ cm/s}$ and $V_{\text{flow}} = 1.5 \times 10^5 \text{ cm/s}$ are ob-

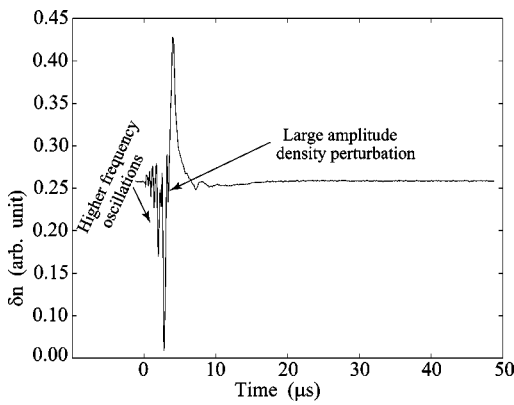


FIG. 6. Large amplitude density perturbation and comparatively higher frequency oscillations incorporated in the gross density perturbation observed near the resonant region.

tained. Here one can see that $V_{\text{flow}} = 1.5 \times 10^5$ cm/s gives too large a quantity, which can hamper the neutral plasma conception considerably, and the calculated value $V_{\text{flow}} = V_{\text{up}}$ violates our experimental observation of upper streamer flow, because V_{up} and V_{flow} travel oppositely to each other. As a consequence we would not observe any streamer flow to the upper density side from the resonant layer. Now we wish to calculate the plasma flow velocity by a different method. By assuming the ambipolar plasma flow with the density gradient, the flow velocity could be estimated by $V_{\text{flow}} = D_a n_0^{-1} (\partial n_0 / \partial z) = D_a / L_z$. With measured value $L_z = 68$ cm and critical plasma density $n_c = 1 \times 10^{11}$ cm $^{-3}$, the plasma flow velocity yields $V_{\text{flow}} \approx 1.9 \times 10^4 < V_{\text{up}}$ cm/s, which shows a reasonable value. Even this calculated ambient plasma flow velocity satisfies the existence of streamer which travels through the upper density region from the resonant plasma in this experiment. Therefore, the flow velocity calculated by the Doppler effect creates a controversy and challenges our observed result of the existence of streamer to the upper density region.

Let us now observe a single line trace corresponding to large amplitude density perturbations shown inside the elliptical marker in Fig. 5 by using an enlarged graphic. It has been shown in Fig. 6 by a typical oscillogram observed very close to the resonant layer. The density perturbation is detected by a disc Langmuir probe facing toward the resonant region and biased at the electron saturation current. We can easily distinguish two different phenomena observed in Fig. 6: the large amplitude density perturbation and comparatively higher frequency low amplitude oscillations incorporated in the large density perturbation. As we mentioned above, the large amplitude density perturbation is excited when the high energy ion bunch penetrates into the plasma. Let us now discuss the part of oscillations shown in Fig. 6. The oscillations may occur due to the sheath instability.^{24,25} The characteristic frequency of the oscillations ($f_{\text{low}} \approx 1.8 \sim 2$ MHz) is observed below the ion plasma frequency. These oscillations are described as a low frequency sheath-plasma instability. The instability occurs only when the disc Langmuir probe is facing toward the resonant region and is biased at the electron saturation current. That is, it occurs

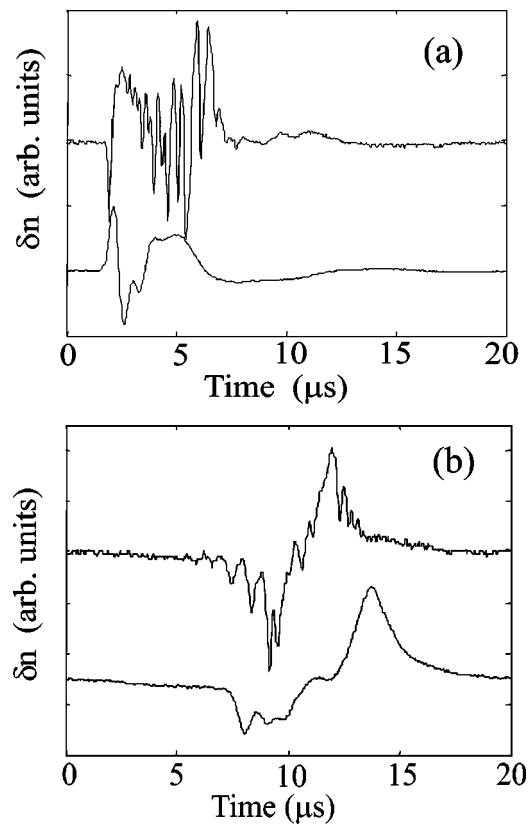


FIG. 7. Density perturbation observed by Langmuir probe (top trace) and microwave resonator probe (bottom trace): (a) perturbation detected very close to the resonant layer where the instability is observed, (b) perturbation detected far from the resonant layer where the ion wave streamer is observed.

when the probe is irradiated by accelerated ions produced during the resonant absorption. In the present experiment, the high-energy ion component has been produced by the resonant absorption of strong microwaves pushed out by the ponderomotive force which was already mentioned above. The ambipolar field produces ion acceleration, the confirmation of which in our experimental observations is shown in Fig. 4. The oscillations have not been observed at the ion saturation current as well as when the disc Langmuir probe is facing oppositely from the resonant region. We believe that the oscillations in the electron saturation current are due to the sheath instability. To illustrate the characteristics of these oscillations we have measured plasma density perturbations by the microwave resonator probe and compared the results with Langmuir probe measurements, as shown in Fig. 7. The vacuum resonance frequency of the microwave resonator is $f_0 = 4.88$ GHz and its quality factor $Q \approx 170$. A quarter wavelength filter rejects a large amplitude pick-up through the pump microwave at $f_{\text{pump}} = 2.86$ GHz. The probe is tuned to the slope of the resonance characteristics, thus the change of the resonance frequency caused by the density perturbations would be proportional to the plasma density variation. In Fig. 7 top traces show the density perturbations measured by the Langmuir probe and bottom traces the density perturbations measured by the microwave resonator probe. One can clearly notice the difference between the two results: the Langmuir probe signals show [in Fig. 7(a)] the

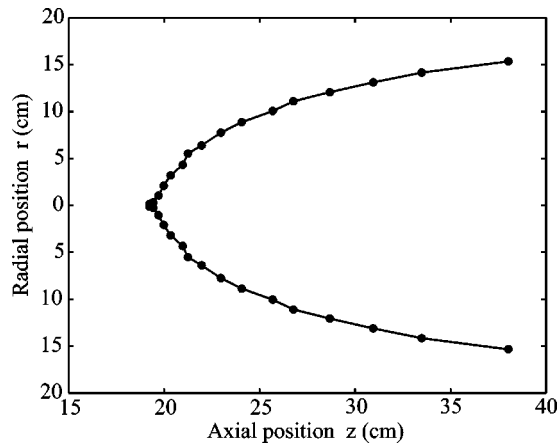


FIG. 8. Spatial profile of resonant points observed with both axial (z) and radial (r) variation.

existence of the higher frequency oscillations, while the resonator probe does not show them. But far from the resonant region [in Fig. 7(b)] when the sheath instability disappears, the density perturbations measured by both the Langmuir probe and the resonator probe are almost similar. The observed phenomena taken by both the Langmuir probe and the resonator probe tell us that the higher frequency oscillations in the electron saturation current are not due to the plasma density fluctuations but are related to the sheath instability. The observed higher frequency oscillations of the electron saturation current take place when an energetic ion beam component comes into the sheath area of the biased probe. It does not represent the macro plasma density perturbations. It is an instability created by high energy ion flux, which is shot out by the nonlinear ponderomotive force developed in the resonant plasma region. We wish to suggest a simple physical model of the observed instability.²⁶ Consider a positively biased (at U_0) probe immersed into plasma with an ion beam having energy eU_b . If $U_0 > U_b$, the beam is reflected inside the electron-rich sheath. Near the reflection point its density greatly increases and diminishes, consequently, the total negative space charge of the sheath. As a result, an overshoot of the electron saturation current occurs due to the fact that the plasma ions do not evacuate instantaneously (recall that $V_b \gg C_s$ from the present experimental data). The duration of the overshoot corresponds to the time ($t_s \approx r_s / C_s \approx 0.11 \mu\text{s}$) taken by plasma ions to move with the sound speed ($C_s \approx 2.7 \times 10^5 \text{ cm/s}$) across the sheath region ($r_s \approx 5\lambda_D \approx 0.3 \text{ mm}$). Before plasma ions can move, the positive probe potential strongly penetrates into the plasma and in turn influences the ion beam. While the beam front has propagated toward the probe through potential-free plasma, the subsequent part of the beam propagates into the sheath through a decelerating potential. Hence, the ion beam disruption occurs due to the time-of-flight effect, and the beam density inside the sheath decreases leading the sheath back to its initial unperturbed state. However, the detailed analysis of the observed instability is explained in our separate paper.²⁶

In the present paper, we mentioned that the strongest resonant point has been observed at $z \approx 21 \text{ cm}$ and $r \approx 5 \text{ cm}$. It is mentioned that the density profiles of our cy-

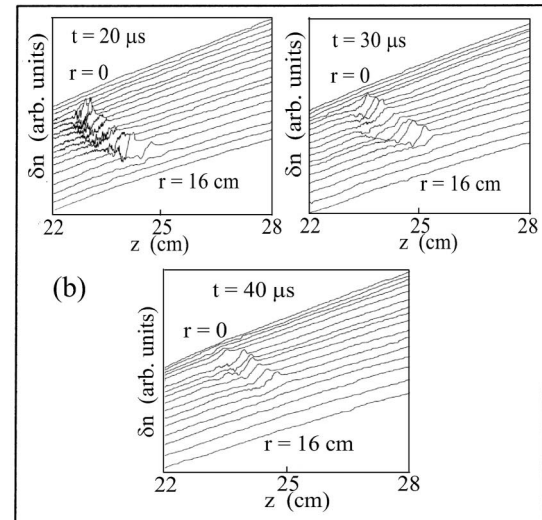
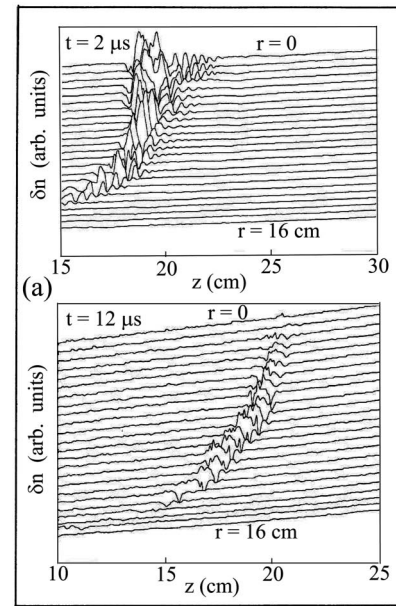


FIG. 9. Spatial profiles of streamers observed with both axial (z) and radial (r) variation: (a) streamers propagating down the density gradient, (b) streamers propagating up the density gradient.

lindrical plasma chamber are both axially and radially inhomogeneous (shown in Fig. 2). The incident microwaves, which are irradiated in various angles other than the strongest resonant point, create resonant interaction at different positions, where the plasma density satisfies as critical density parameter. It is observed that the resonant points occurred in the chamber by axial and radial variation, as shown in Fig. 8 in a two-dimensional view, which contains a parabolic form. The resonant points in Fig. 8 are detected by taking the spatial profile of the resonant electric field by using the needle antenna. Therefore, one can observe typical examples of the streamers in two, dimensional (axial and radial) variation, as shown in Fig. 9. The measurements in Fig. 9 are taken by using the disc Langmuir probe. It should be mentioned here that it is not possible to record all the results in a single day, which is described in the experiment.

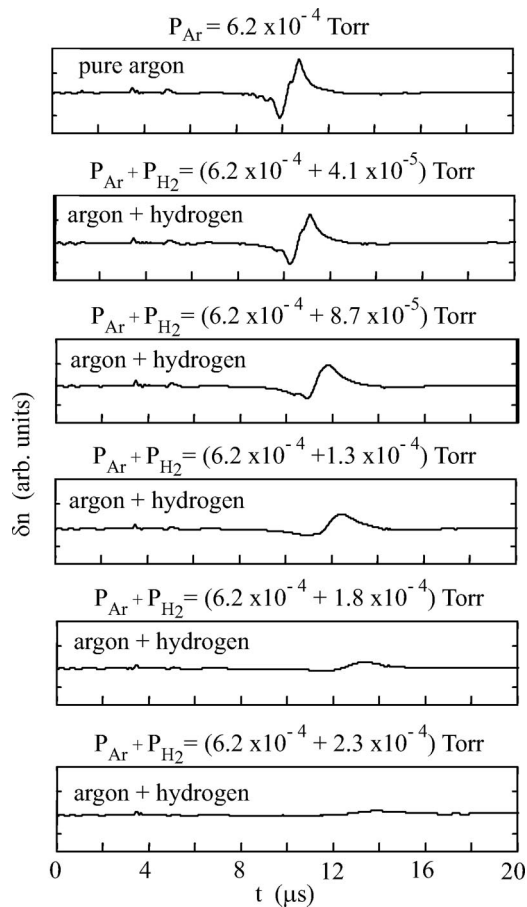


FIG. 10. Ion Landau damping of the downward streamer as shown by the wave form.

Every time we tried to keep the plasma parameters in the same condition to create the strongest resonant at reference point $(z, r) \approx (21, 5)$, but it is very difficult to keep plasma parameters exactly in the same condition in different times. So, there may be some labeling problems with the results shown in Fig. 9, because the strongest resonant point may be slightly superseded by a different point from the point $(z, r) \approx (21, 5)$. Further we have tried to show the streamers clearly by increasing the amplitude of the oscillogram where the actual amplitudes of the streamers are very low. Figure 9(a) shows the spatial (r, z) profiles of ion wave streamers propagating down the density gradient observed at time $t = 2$ and $12 \mu\text{s}$ and Fig. 9(b) shows the ion wave streamers propagating up the density gradient observed at $t = 20, 30$, and $40 \mu\text{s}$.

The measurements presented above have been performed in pure argon gas. In order to study the nature of the observed wave streamers we have also performed a set of experiments by using the mixture of argon gas with some amount of hydrogen. The addition of hydrogen ions does not change noticeably the electron temperature, but it causes ion Landau damping of the ion-acoustic mode through its interaction with the light ions.^{27–29} Figure 10 displays oscillogram of the downward streamer for different pressures of hydrogen gas. The top trace in Fig. 10 shows the largest amplitude when it is excited only by pure argon gas at the

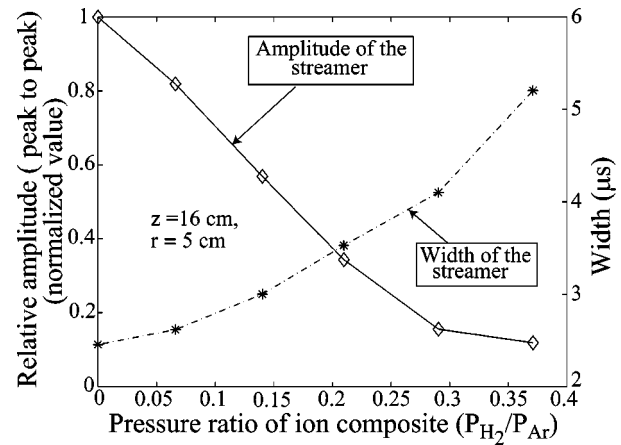


FIG. 11. Gradual decrease of amplitude of the streamer (solid line with diamond ($\diamond$) markers) and gradual increase of width broadening of the streamer (dashed-dotted line with asterisk (*) markers).

pressure of $P_{\text{Ar}} = 6.2 \times 10^{-4}$ Torr. The bottom five traces in Fig. 10 show the gradual decrease of amplitude of the streamer with the addition of more and more lighter hydrogen atoms to the argon by the increasing sequence of pressure $P_{\text{H}_2} = 4.1 \times 10^{-5}$ Torr, $P_{\text{H}_2} = 8.7 \times 10^{-5}$ Torr, $P_{\text{H}_2} = 1.3 \times 10^{-4}$ Torr, $P_{\text{H}_2} = 1.8 \times 10^{-4}$ Torr, and $P_{\text{H}_2} = 2.3 \times 10^{-4}$ Torr, respectively. We also recognize that the increase of hydrogen creates the gradual increase of width broadening of the streamer pulse. Let us notice that we have maintained the same plasma density during these measurements, i.e., all streamers in Fig. 10 are observed at the same distance from the resonant absorption layer. Thus the observed difference in the streamer behavior should be caused by its ion Landau damping. These results prove that the streamer represents a kind of nonlinear ion acoustic wave and not a bunch of accelerated ions. To insert two sorts of gases in the vacuum chamber, we used separate inlets for each sort of gas. Figure 11 shows the graph of the damping, as well as the change of the width of the streamer as a function of hydrogen partial pressure. The solid line with diamond ($\diamond$) markers in Fig. 11 shows the gradual decrease of amplitude and the dashed-dotted line with asterisk (*) markers shows the gradual broadening of the streamer wave form with respect to the hydrogen–argon pressure ratio $(P_{\text{H}_2}/P_{\text{Ar}})$. The amplitude and width broadening are calculated from the waveform of Fig. 10. One can observe from Figs. 10 and 11 that the maximum damping occurs when the hydrogen–argon pressure ratio of ion composite $(P_{\text{H}_2}/P_{\text{Ar}})$ reaches to greater than 30%.

IV. CONCLUSIONS

We have observed the ion wave streamer formation and propagation in an unmagnetized, inhomogeneous laboratory plasma irradiated by oblique p -polarized microwaves with pulse length $0.2\text{--}1.5 \mu\text{s}$ and power $P = 1\text{--}2$ kW. Due to the fundamental physics of the microwave–plasma interaction, the nonlinear ponderomotive force at the resonant region can sweep out electrons and the ambipolar force then can also pull out ions from that region. After shot-up of the ion bunch

from the resonant region, the generation of ion wave streamers has been observed. This streamer can travel downward and upward the density gradient. The velocity of the downward streamer $V_{\text{down}} = 4.5 \times 10^5$ cm/s is greater than the ion acoustic velocity ($C_s = 2.7 \times 10^5$ cm/s) and the velocity of the upward streamer $V_{\text{up}} = 1.5 \times 10^5$ cm/s is less than the ion acoustic velocity. Another physical aspect of the low frequency sheath-plasma instability is observed near the resonant region. This instability appears due to the energetic ions generated from the resonant layer.

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