

Dynamic of ion density perturbations observed in a microwave-plasma interaction

Md. Kamal-Al-Hassan^{a)}*Department of Physics, Dhaka University of Engineering and Technology, Gazipur 1700, Bangladesh*

Hiroaki Ito, Noboru Yugami, and Yasushi Nishida

Energy and Environmental Science, Graduate School of Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya, Tochigi 321-8585, Japan

(Received 23 May 2005; accepted 29 September 2005; published online 22 November 2005)

The dynamical behavior of ion density perturbations propagated at low-frequency wave nature is experimentally observed in microwave-plasma interaction. An unmagnetized, inhomogeneous laboratory plasma irradiated by an obliquely incident microwave with maximum power $P = 10$ kW and pulse width approximately ion plasma period ($\tau_{pi} \approx 2\pi/\omega_{pi}$) is studied. The p -polarized electric-field component of the interacted microwave of frequency ω_0 leads to a nonlinear phenomenon driven by the ponderomotive force by the process of resonance absorption at the critical layer where $\omega_0 = \omega_p$ is satisfied. The nonlinear ion density perturbations are created from the resonant layer and propagated to an underdense plasma as an electrostatic wave nature. © 2005 American Institute of Physics. [DOI: 10.1063/1.2126815]

I. INTRODUCTION

Resonance absorption due to microwave-plasma interaction in an inhomogeneous laboratory plasma carries a great importance in relevant topics of laser-pellet experiments,¹ laser plasma interaction,² and active interaction with the ionosphere by radio waves.^{3,4} Resonance 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,^{5,6} where local plasma frequency equals the incident microwave frequency. High-energy suprathermal electrons can be generated by high-power microwave absorption near the critical layer by the conversion of microwave energy into particle energy.⁷⁻⁹ High-energy ions can also be generated by the phenomenon of nonlinear growth of local electric field in the resonance region, which creates a ponderomotive force. This ponderomotive force pushes the trapped electrons in the wave toward the outside and, as a consequence, these suprathermal electrons can pull ions from the critical density layer by the ambipolar Coulomb force and drive a suprathermal ion bunch.¹⁰⁻¹⁶

We have previously demonstrated some experimental results described as ion wake field,¹⁴ ion wave streamer,¹⁶ and instability¹⁵ by the phenomenon of resonance absorption of microwave-plasma interaction. In the results of those articles, when it was stated about the density perturbations, all perturbations were observed by a Langmuir probe biased by

positive voltage in order to collect electron current. In the present paper we have focused on the results about ion density perturbations collected by the Langmuir probe biased by negative voltage in order to collect ion current. These ion density perturbations also move with the velocity of the order of ion wave regime stated in the experiment. The self-consistent ambipolar force pulls out the ion bunch from the resonant region and this ion bunch can travel through the underdense plasma. The typical ion bunches have been detected with an energy of 30–58 eV and explained in the previous results.^{14,16} The energy of an ion bunch depends on the incident microwave power and pulse width. Higher power and lower pulse width of microwave create higher energy of the ion bunch, while lower power and higher pulse width create lower energy of the ion bunch. In the results of this article, we have used microwave power about 7 kW and pulse width near about $\tau_{pi} \approx 2\pi/\omega_{pi}$. Pulse width $\tau_{pi} \approx 95$ ns is calculated by our critical plasma density parameter $n_c = 1 \times 10^{11} \text{ cm}^{-3}$. The parameter $\tau_{pi} = 2\pi/\omega_{pi}$ is actually important for creating ion bunches in the region of critical layer. These ion bunches create ion density modifications and propagate as low-frequency wave nature down the density gradient from the resonant layer, which have been described in the experiment.

This paper is organized as follows: experimental setup is described in Sec. II, results and discussions in Sec. III, and conclusions in Sec. IV.

II. EXPERIMENTAL SETUP

The setup of the experiment is schematically shown in Fig. 1. A cylindrical, unmagnetized, inhomogeneous argon plasma is produced in a stainless-steel chamber of 100 cm length and 60 cm diameter. For better plasma confinement the outside surface of the vacuum chamber is covered with line cusp arrangements made from permanent magnetic bars.

^{a)}Electronic mail: dmkahassan@gmail.com

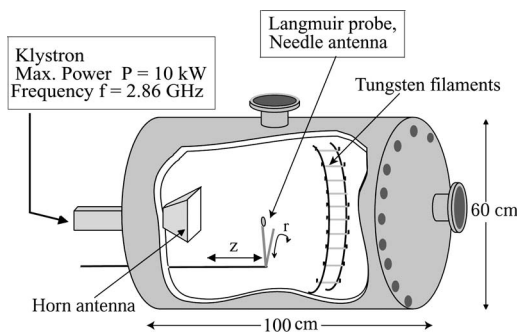
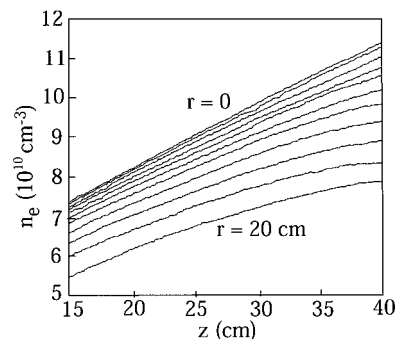


FIG. 1. Experimental arrangements.

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 a discharge duration of 2 ms and repetition rate of 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 perturbations are measured by two disk-shaped (1-mm-diam) Langmuir probes, one facing toward the resonant region and the other facing oppositely from the resonant region. A needle antenna with a tip of 2 mm length and 0.25 mm diameter, coupled to a crystal detector, is used in order to have spatial distribution of microwave field intensity peaks in the plasma. The needle antenna is insulated by a ceramic coating to prevent the crystal detector from damaging due to high current. 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 the 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 10 kW is launched into plasma from a rectangular horn antenna located at the 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 of the order of ion plasma period ($\tau_{pi} \approx 2\pi/\omega_{pi}$) 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 of microwave-plasma interaction, we have put metallic wools inside the chamber walls to absorb the electromagnetic wave. To create the interaction of microwave with an inhomogeneous plasma, the horn antenna and the filaments are separated by placing them at the two ends of the plasma chamber, as it is shown in Fig. 1. The axial increase of plasma density is created in the direction from the horn antenna to the 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.

FIG. 2. Undisturbed inhomogeneous plasma density profiles in the absence of incident microwave. Each line separates $r=2$ cm between the neighboring lines.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the feature of undisturbed inhomogeneous plasma inside the chamber. Spatial density profiles in this figure are measured by the Langmuir probe in the absence of incident microwaves. A nonuniform plasma density is observed of the order of 10^{10} – 10^{11} cm^{-3} . The typical density gradient scale lengths in the axial (z) direction and radial (r) direction are 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 operated.

When high-power microwaves are launched in the inhomogeneous plasma with an inclined angle θ , the incident EM wave reflects at a density determined by the relation $n_e \approx n_c \cos^2 \theta$, and the electric-field component of the p -polarized microwave, which is ultimately parallel to the density gradient at the reflection layer, tunnels up to the resonant region where $\omega_0 = \omega_p$ is satisfied. The resonant layer is detected by taking the spatial profile of microwave field inside the plasma shown in Fig. 3(a) by using a needle antenna coupled to a crystal detector. Figure 3(a) displays the axial profile of the microwave field at radial position $r \approx 4.8$ cm where the maximum resonant field is detected. The power and pulse width of the microwave are used, 7 kW and 98 ns, respectively. Comparing Fig. 3(a) with the theoretical pattern of Airy function as it is shown in Fig. 3(b), one can find the resonant electric field at the axial position $z \approx 17.25$ cm, which is the position where the plasma density becomes a critical one. It should be mentioned that the microwave field pattern drawn from the experimental data shown in Fig. 3(a) must be differed from the well-known Airy function due to complicated geometry of the plasma chamber. Since our plasma is both axially and radially inhomogeneous, indeed, the observed standing-wave pattern is formed as a result of multiple wave reflection from cut-off (reflection) plasma layers as well as walls of the vacuum chamber. It is seen in Fig. 3(a) that the microwave radiation vanishes beyond $z \approx 17.25$ cm where the plasma density becomes greater than the critical density. Please notice that the critical plasma density parameter in the experiment is $n_c = 1 \times 10^{11} \text{ cm}^{-3}$ for resonant absorption. Figure 3(a) shows the critical layer at $z = 17.25$ cm, which the plasma density may not be matched

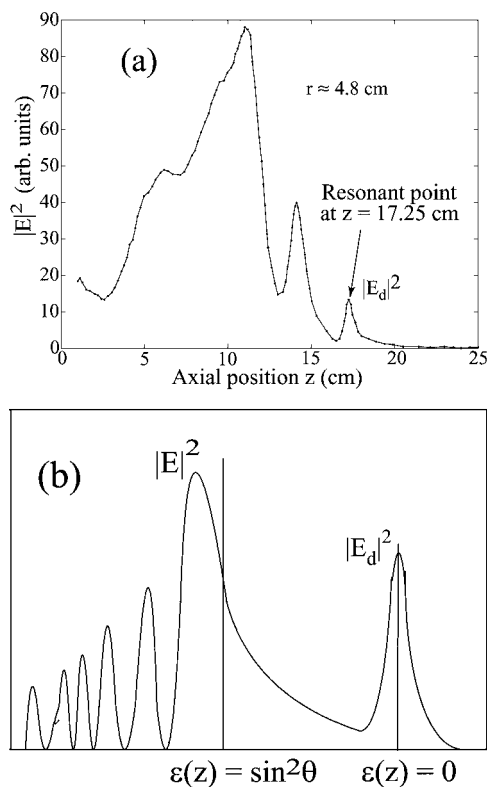


FIG. 3. Microwave profiles inside the plasma: (a) Axial profiles of microwave electric fields drawn by experimental data at radial position $r \approx 4.8$ cm. (b) Theoretical pattern of Airy function.

in the same position in Fig. 2. The results are shown by Figs. 2 and 3(a) depicted in separate density parameters produced at separate times. Practically same plasma density would not be created in the same position in chamber operated in different days and times. The density profile shown in Fig. 2 just represents the picture of an inhomogeneous plasma inside the chamber.

In this paper, we are particularly interested to show the dynamical behavior of ion plasma density perturbations after irradiating the microwave inside the plasma chamber. Figure 4 shows the ion density perturbations after resonance absorption of high-power short pulse microwave in the plasma. The

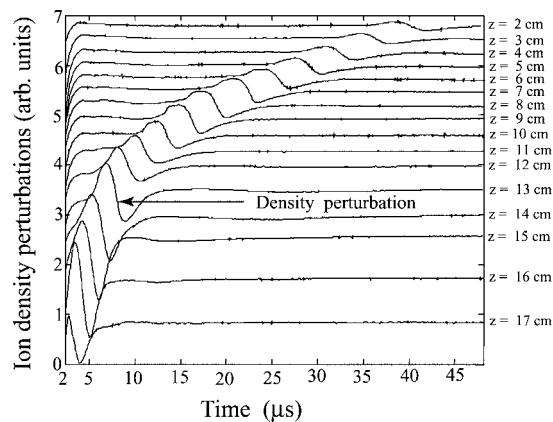


FIG. 4. Ion density perturbations measured by a Langmuir probe. The probe is biased by negative voltage in order to collect ion current.

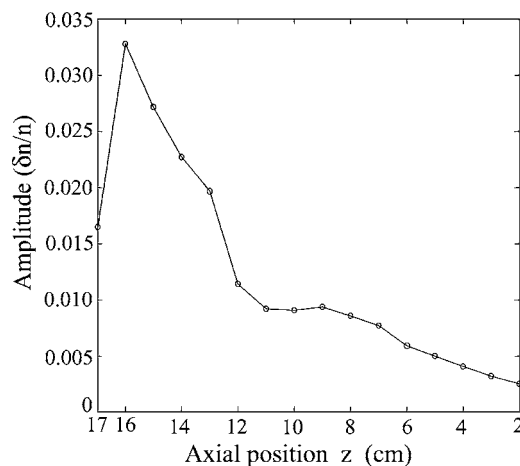


FIG. 5. Amplitude of the density perturbations in different points of the axial position z .

density perturbations are measured in the region of underdense plasma by Langmuir probe biased by -55 V. It is observed that the ion density perturbation patterns are almost the same if the Langmuir probe is facing towards and opposite to the resonant layer. Figure 4 shows that a density perturbation is highly nonlinear near the resonant region and the nonlinearity gradually goes to linear mode as it is moved away from the resonant region. Figure 5 shows the amplitude of the density perturbations in different points of the axial position z . Here the amplitude is defined as $\delta n/n$, and δn is defined by the pick-to-pick difference following the perturbations of Fig. 4. The maximum amplitude of ion density perturbation is observed about 3.3%. On the contrary, the maximum amplitude of electron-density perturbations observed was about 40% in the experiment stated in our previous article.^{14,16} The observed ratio of maximum ion density to electron-density perturbation is about $\delta n_i/\delta n_e = 0.0825$.

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 nonlinear phenomenon driven by the ponderomotive force $F_p = -(\omega_p^2/\omega^2) \nabla \langle \epsilon_0 E_d^2 \rangle / 2$. The ponderomotive force expels electrons from the resonant 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.^{10–16} The energy of these ion bunches has typically been observed, 30–58 eV,^{14,16} close to the resonant region. When this high-energy ion bunch penetrates into the plasma, it excites ion density perturbations in the underdense plasma column.

It is observed that these ion density perturbations, created near the critical plasma region, travel through the lower plasma density column. Figure 6 represents the phase velocity of the density perturbations. The phase velocity is higher near the resonant layer where the density perturbations are highly nonlinear. The amplitude as well as the velocity decreases gradually when the density perturbation travels away

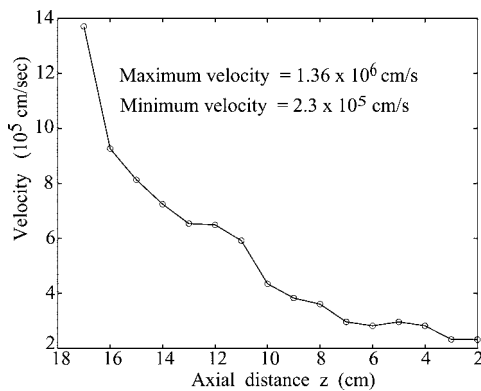


FIG. 6. Velocity of ion density perturbations.

from the resonant layer, and very far from the resonant region the density perturbation disappears. Figure 6 shows that the maximum velocity observed is 1.36×10^6 cm/s which is larger than the ion acoustic velocity and it slows down to a velocity of 2.3×10^5 cm/s. It should be mentioned that using our plasma parameter the ion acoustic velocity is measured about $v_s \approx 2.5 \times 10^5$ cm/s.

IV. CONCLUSIONS

We have detected ion plasma density perturbations and propagation by the resonance absorption process in a laboratory plasma. The resonance absorption process is established by a high-power short-pulsed microwave with a pulse duration of the order of $\tau_{pi} \approx 2\pi/\omega_{pi}$, incident obliquely in an unmagnetized, inhomogeneous plasma. The amplitude and velocity of the density perturbations are comparatively higher near the resonant region. The initial velocity, for example, 1.36×10^6 cm/s detected near the resonant layer, is higher than the ion sound speed. The amplitude as well as the velocity of density perturbations gradually decrease when

they move away from the critical density region. The minimum velocity of ion density perturbations detected is 2.3×10^5 cm/s in this experiment, which is approximately equal to the ion sound speed.

ACKNOWLEDGMENTS

One of the authors (M.K.A.H) is indebted to the support given by Dhaka University of Engineering and Technology, Bangladesh. A part of the present work is supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Sports and Culture, Science and Technology, Japan.

- ¹J. F. Kephart, R. P. Godwin, and G. H. McCall, *Appl. Phys. Lett.* **25**, 108 (1974).
- ²C. E. Max, *Laser Plasma Interaction*, edited by R. Balian and J. C. Adam (North-Holland, Amsterdam, 1982), Chap. 2, pp. 317, 323.
- ³A. Y. Wong and J. Y. Taylor, *Phys. Rev. Lett.* **27**, 644 (1971).
- ⁴B. Thide, H. Kopka, and P. S. Stubbe, *Phys. Rev. Lett.* **49**, 1561 (1982).
- ⁵V. L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasma*, 2nd ed. (Pergamon, New York, 1970).
- ⁶J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, *Phys. Rev. Lett.* **28**, 795 (1972).
- ⁷Y. Lee, Y. Nishida, N. C. Luhmann Jr., S. P. Obenschain, B. Gu, M. Rhodes, J. R. Albritton, and E. A. Williams, *Phys. Rev. Lett.* **48**, 319 (1982).
- ⁸Y. Nishida, M. Yoshizumi, and R. Sugihara, *Phys. Fluids* **28**, 1574 (1985).
- ⁹C. Rajyaguru, T. Fuji, H. Ito, N. Yugami, and Y. Nishida, *Phys. Rev. E* **64**, 016403 (2001).
- ¹⁰P. Koch and J. Albritton, *Phys. Rev. Lett.* **32**, 1420 (1974).
- ¹¹A. Y. Wong and R. L. Stenzel, *Phys. Rev. Lett.* **34**, 727 (1975).
- ¹²N. Yugami, S. Kusaka, and Y. Nishida, *Phys. Rev. E* **49**, 2276 (1994).
- ¹³N. Yugami, S. Kusaka, Y. Nishida, B. Cros, and G. Matthieussent, *Plasma Phys. Controlled Fusion* **38**, 751 (1996).
- ¹⁴M. Kamal-Al-Hassan, M. Starodubtsev, H. Ito, N. Yugami, and Y. Nishida, *Phys. Rev. E* **68**, 036404 (2003).
- ¹⁵M. Starodubtsev, M. Kamal-Al-Hassan, H. Ito, N. Yugami, and Y. Nishida, *Phys. Rev. Lett.* **92**, 045003 (2004).
- ¹⁶M. Kamal-Al-Hassan, M. Starodubtsev, H. Ito, N. Yugami, and Y. Nishida, *Phys. Plasmas* **11**, 836 (2004).