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Observation of Superthermal Electron Beam and Cavitons in Broad Resonance Region due to Nonlinear Microwave-Plasma Interaction

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Abstract

Study of generation of superthermal electrons near the critical layer, by resonance absorption phenomenon, is extended to very high microwave power levels ($\eta = E_0^2/4\pi n_e kT_e \approx 0.5$). Successive generation of electron bunches having maximum energy about 2keV, due to nonlinear wave breaking, is observed. The energy, ε, of the electrons scales as a function of incident microwave power, P, according to $\varepsilon \propto P^{0.5}$. Spatial distribution and temporal evolution of high energy electrons reveal that they are generated near the critical layer. However, lower energy component is also generated in lower density region indicating the possibility of other electron heating mechanism. Density cavitons are observed to be generated near resonance region as well as in lower density region, temporal evolution of which, show transition from supersonic velocity regime to subsonic one.

Keywords:

resonance absorption, wave breaking, high energy electron

1. Introduction

Fast electrons, with energies well above the thermal energies, have been observed in experiments [1,2] as well as in simulations [3-5] describing the interaction of intense microwaves and laser beams with an inhomogeneous plasma. This can be attributed to the substantial intensification [6] of electric field in resonance region, where incident microwave frequency becomes equal to the local plasma frequency, due to resonance absorption of incident electromagnetic wave. For high incident power, wave breaking [7] phenomenon is the most probable candidate to account for the genration of high energy electrons as incident power is mostly absorbed resonantly [8]. It predicts electron energy scaling law as $\varepsilon \propto P^{0.5}$, wherer ε is the maximum electron energy and P is the incident radiation power.

If RF (radio frequency) field amplitude in resonance region is high enough, ponderomotive forces become important leading to caviton [9] generation. Cavitons have been observed experimentally [9,10] and numerically [4,11]. Above works do describe some physical processes behind its formaion and some effects associated with trapped RF electric field but its temporal dynamics and other related phenomena in high incident power regime is still to be uncovered.

In the present paper, we wish to present the first experimental observation of superthermal electrons near critical layer, using microwaves, to demonstrate the validity of cold wave breaking theory even when $\eta = E_0^2/4\pi nkT_e \simeq 0.5$. Superthermal electrons, having energy as high as 1.8keV are observed near the critical layer at

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250kW of incident power. The energy scaling of such electrons is measured and the results are in fairly good agreement with those predicted by the wave breaking theory. Two dimentional spatial distribution and temporal evolution of high energy electrons reveal that hot electrons are successively generated from near the critical layer as predicted in earlier simulations [5,12]. After generation of high energy (~ 2keV) electrons, low energy electrons are also observed in subcritical density region with plasma density lower than the critical density. Cavitons having velocity transition from supersonic regime to subsonic regime have also been observed in resonance region as well as in subcritical region after the generation of high energy electrons. Observed cavitons show density modification as large as $\delta n/n \simeq 35\%$, where δn and n are the density depletion and mean plasma density respectively. Generation of high energy electrons and cavitons at two different time scale in resonance and subcritical density region clearly shows that two different mechanisms are acting simultaneously.

The paper is organized as follows: Experimental arrangment is described in Sec. **2** and results are described in Sec. **3**. Section **4** discusses the results and calculates energy gaind by electrons due to nonlinear wave breaking. The paper is encapsulated in Sec. **5**.

2. Experimental Setup

The experimental arrangement is shown schematically in Fig. 1(a). Cylindrical, unmagnetized argon plasma is produced in a stainless-steel chamber of 100cm length and 32cm diameter. Outside surface of the vacuum chamber is covered, for improved plasma confinement, with line cusp arrangements, made from permanent magnets having surface magnetic field strength of 4kG. Plasma is produced by a pulsed discharge between four LaB_6 (Lanthanum Hexaboride) cathodes and the grounded chamber wall acting as ananode. Typical discharge voltage and discharge duration are 180V and 1.5msec, respectively, with the repetition rate of 10Hz. Typical plasma parameters are, $n_e \simeq 2 \times 10^{12}$cm^{-3}, $T_e \simeq 2$eV and axial density gradient scalelength, $L_z \simeq 44$cm. Argon gas pressure is adjusted to 3 ~ 5 × 10^{-3}Torr by a needle valve. Plasma density and temperature are measured by a disk probe with area of 0–96mm^2, movable along the axis and rotatable in the azimuthal plane. To get better spatial resolution and time response, disk probe is also used to measure spatial distribution and temporal evolution of high energy electrons as well as cavitons. Electrostatic energy

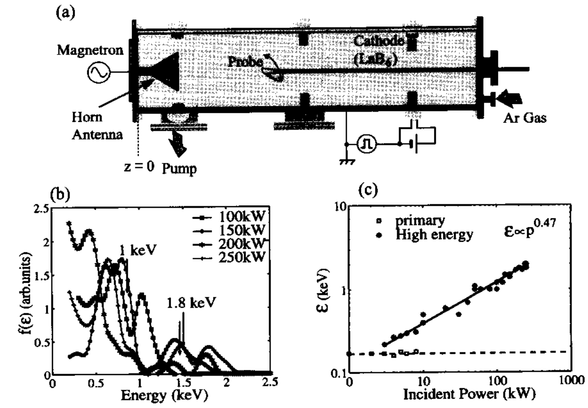

Fig. 1 (a) Experimental setup. (b) Electron energy distribution function for different incident microwave power. (c) Energy scaling law of high energy electrons.

analyzer of 23mm length and 10mm diameter, capable of measuring electron energy upto 3keV, is employed for measuring the electron energy distribution function. All three electrodes of the energy analyzer (two grids and one collector) are covered with a copper cup to shield from microwaves and other noises. Acylindrical probe with a tip of 1mm length and 0.25mm diameter is used to measure the spatial distribution of microwave field. Pulsed microwave has a central frequency, $\omega/2\pi =$ 9GHz (corresponding to cut-off density, $n_c \simeq 1 \times 10^{12}$cm^{-3}) and maxmimum power, 250kW. The pulse duration is variable from 1–3μs, full width at half maximum (FWHM), with rise and fall time of 100ns and repetition rate of 10Hz. Present experiment is performed with 1.5μs. Microwaves are launched into plasma from rectangular horn antenna, with aperture area of 14.8 × 11.7cm^2. This antenna contains a metal lens for making ray trace of incident microwave parallel to the propagation direction. Thus, the microwave can be considered as a plane wave and this has been confirmed in air without plasma. The antenna is located at lower end of the plasma density.

3. Experimental Results

When high power microwave pulse is injected into plasma, it is observed that high energy electrons are ejected from the layer close to the critical layer. The electron energy distribution function measured by the electrostatic energy analyzer is shown in Fig. 1(b) for different incident power. It is identified clearly different, with bumps in tail showing presence of superthermal beam, than that observed in earlier works [8,13] with nonthermal sholder. The scaling law of high energy electron emission as a function of incident power is obtained as shown in Fig. 1(c). It can be seen very clearly that the maximum electron energy depends on the incident microwave power as $\varepsilon \propto P^{0.47}$. This is in good agreement with that predicted by the wave breaking theory as $\varepsilon \propto P^{0.5}$ [7]. The power dependence and calculation of electron energy for present experiment will be given in the next section. The energy scaling law and the nature of the distribution function indicate that high energy electrons are produced mainly due to nonlinear wave breaking.

For getting better physical insight of mechanisms acting in the resonance region, spatial distribution of hot electrons are measured and depicted in Fig. 2(a) and (b). The dark spots in Fig. 2 indicate the loations where maximum flux of high energy electrons is observed. These locations and the one clearly visible at $r \simeq -2$cm in Fig. 2(b), move deeper (towards the higher density) in axial direction and radially outward direction respectively with increase in incident power. This is because of the deformation of plasma resonance region in a strong high frequency field [14]. Interestingly, another location can also be seen, more clearly in Fig. 2(a), around $z \simeq 37$cm and $r \simeq \pm 6$cm, where hot electrons are generated. Observation of hot electrons at two different positions motivated us to investigate their temporal evolution. Accordingly, the temporal evolution of high energy electrons at $r \simeq 6$cm is shown in Fig. 3(b). It is clearly observed that hot electron bunches are successively generated near the critical layer ($z \simeq 44$cm) for all times (40 to 540ns) during which incident microwave is present. However another bunch of electrons is observed at a later time around 180ns near $z \simeq 37$cm, as compared to that observed near resonance region, revealing that some other mechanism is also operative in the lower density region.

To explore the subcritical density region more carefully, we have measured plasma density profile at different times after microwave is launched indicating caviton with density depletion as large as $\delta n/n \simeq 35\%$ as shown in Fig. 3(d). The temporal evolution of caviton is shown in Fig. 3(c). Caviton is observed near resonance location as well as in subcritical density region, moving with supersonic speed, slowing down gradually to subsonic speeds. However caviton, observed near the resonance region, is observed to move faster than that in subcritical layer. It is also evident from Fig. 3(c) that caviton is formed after the generation of superthermal electrons in the resonance region as well as in the

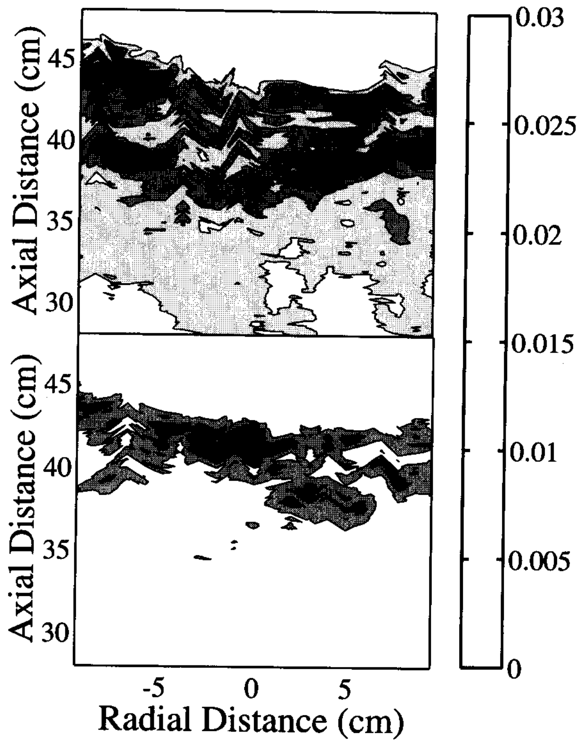

Fig. 2 Two dimentional contour map showing spatial distribution of emitted high energy electrons for incident power of (a) 250kW, (b) 50kW.

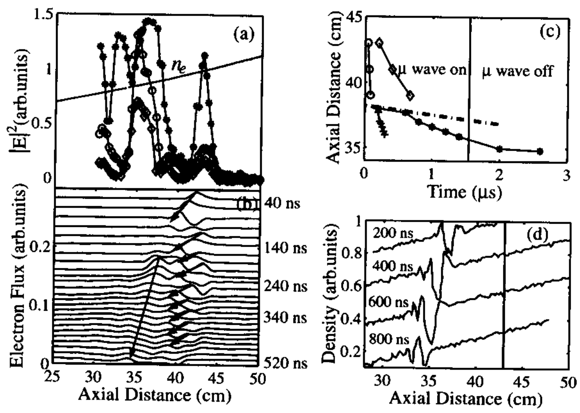

Fig. 3 Temporal evolution of high energy electrons measured by disk probe with applied bias voltage of −300V and cavitons at $r \simeq 6$cm. (a) Microwave electric field for 250kW (*), 150kW (○), 50kW (◊) and the density profile at $r \simeq 6$cm (solid line). (b) Temporal evolution of high energy electron bursts at $r \simeq 6$cm for incident power of 250kW. (c) Temporal evolution of cavitons (◊ and *) with high energy electrons (○ and +). Dotted line shows the sound velocity. (d) Typical caviton structure observed in present experiment. Solid vertical line shows the location of the critical density.

subcritical region. Figure 3(a) shows the spatial profile of microwave field in plasma at $r \simeq$ 6cm as well as plasma density in low incident power (~ 1kW). Enhanced electric field component at the resonance region can be seen clearly to increase with increase in power. Presence of large transverse electric field at $z \simeq$ 37cm in subcritical density region can play significant role modifying electron energy distribution function and generation of caviton which will be described in the next section.

4. Discussion

This section discusses foregoing results qualitatively. The observed nature of the energy distribution function and the energy scaling law as a function of the incident power, are clear evidences of wave breaking phenomenon to produce the superthermal electrons. In case of high power radiation and collisionless plasma, linear mode conversion of incident radiation to plasma wave is low efficiency process [14]. Also, it has been observed that strong density modifications decrease the effect of other phenomena like oscillating two stream and ion acoustic decay instabilities [8]. Thus, the intensified electric field in resonance region can, most probably, be limited by wave breaking. Maximum amplitude of the electric field in the resonance region is given by $E_{max} \approx E_d/S_{nonl}$ [15], where E_d, the high frequency field at resonance, connected to the vacuum field, E_0, by $E_d = E_0\phi(\tau)/(2\pi k_0 L_z)^{1/2}$ and $S_{nonl} = (eE_0/m\omega^2 L_z)^{1/2}$. Due to resonance absorption, the amplitude of the electric field at the resonance loation rises to its maximum value very rapidly. Consequently, energy conservation in the resonance region requires contraction of the resonance width. This leads to the situation where electron displacement, in one oscillation period of electric field, equals to the resonance width given by $\Delta x \approx S_{nonl}L_z$ [15] and the wave breaks ejecting high energy electron burst. One may expect that regular electron bursts (through the period) will continue until there is an appreciable energy loss due to departure of accelerated particles. If these particles leave the plasma, the field amplitude at the resonance reaches again to its maximum [5], after a time ~ $\pi/\omega S_{nonl}$, as the incident radiation still exists, a new series of bursts of accelerated particles appear leading to successive generation of high energy electron bursts as observed in the present experiment near the resonance. As the wave breaking time is very short for strong radiation [7], the bursts of high energy electrons appear earlier, in present case, than the caviton formation which occurs at the ion time scale of ion motion. One can estimate maximum energy of electrons as $\varepsilon = eE_{max}\Delta x = eE_d L_z$. For the optimum angle of incidence, using definition of E_d above formula can be written as

$$\frac{\varepsilon}{T_e} = \eta^{0.5}\left(\frac{mc^2}{T_e}\right)^{1/2}\left(\frac{L_z}{\lambda_0}\right)^{1/2}. \quad (1)$$

As $\eta \propto P$ (incident power), it can be seen that electron energy depends on incident power as $\varepsilon \propto P^{0.5}$ as predicted by the wave breaking theory. Substituting the present experimental parameters as $\eta \simeq 0.5$, $T_e \simeq$ 2eV and electron rest mass energy $mc^2 \simeq$ 512keV, one gets $\varepsilon \simeq$ 2.6keV which agrees very well with the experimentally observed maximum electron energy of 1.8keV.

Now we discuss the phenomenon responsible for the generation of high energy electrons near the region around $z \simeq$ 37cm in Fig. 3(b). Although the exact mechanism is not very well understood at present, some of the possibilities are considered. As the subcritical region, where high energy electrons are generated, is quite distant from the resonance region, possibility of parametric instability can be ignored.

We believe that the strong microwave field (transverse electric fileld) component existing at $z \simeq$ 37cm, as seen in Fig. 3(a), is responsible for nonresonant excitation of plasma waves as the density at $z \simeq$ 37cm. This possiblity can not be ignored as the plasma density at $z \simeq$ 37cm is only 15% lower than that at the resonance region. Various effects due to transverse RF field maxima have been investigated in [16,17]. Because of plasma inhomogenity, generated plasma waves will have, in general, broader wavenumber spectrum as compared to the one in the resonance region which is confined in small resonance width. Here, one can imagine electrons making "swings" from the potential wells of waves with different wavenumber gaining and loosing the energy, leading to the resultant turbulent heating (nonresonant heating) of the electrons. As the incident power is very high, the plasma wave amplitude will be sufficiently large, despite of its nonresonant excitation, to heat the electrons. Electrons are accelerated to energies at least > 300eV as temporal evolution measurements were taken by applying retarding bias of –300V.

Caviton moving with supersonic velocity has been observed previously [9]. But in the present case, we see caviton generation at two different spatial locations moving with different veloctiy. However, the one observed near the resonance layer, moves with velocity as high as 48 times greater than the sound speed.

Whereas the one observed in the subcritical layer moves initially with 8 times the sound speed slowing down gradually to sound speed. This behaviour can be attributed to the presence of hot electrons, greatly modifying the local plasma pressure resulting in enhanced "kick" to the plasma density, in turn, leading to higher velocities which ultimately slows down with decrease in its amplitude. Mechanism responsible for the generation of caviton is not clear at present but strong transverse electric field near z = 37cm can play significant role in generating strong density modifications. This behaviour has been observed in earlier works [4,16,17].

Relation among the caviton in subcritical density region, possible excitation of plasma wave and presence of high energy elecrons need more careful examination for a better clarification of the present observations. Efforts are going on to measure two dimentional spatial distribution of caviton as a function of microwave power. Above measurement can be made after different time from the microwave pulse to get the time resolved bahavior. We can also make some density fluctuation measurement and plasma wave measurements to see if some kind of decay instability exist. This may give some insight to the actual heating process.

To see another possibility, one may also make plasma potential measurements to see the extent to which it is modified due to caviton formation. These measurements will allow us to see if there are any potential structure formation responsible for the electron heating. This kind of behaviour has been seen in unpublished work in another experiment in our laboratory.

5. Conclusions

We have extended investigation of generation of high energy electrons due to nonlinear interaction of high power microwaves with inhomogeneous plasma to the regime, where the incident microwave power is as high as to make $\eta \approx 0.5$. When microwaves with peak power of 250kW are launched into inhomogeneous plasma, electrons, having maximum energy 1.8keV, are generated succesively from near the resonance region. Experimental results show that the maximum energy of electrons scales to the incident power approximately as $\varepsilon \propto P^{0.5}$ upto 250kW, showing validity of the wave breaking theory in such a high power regime. Calculation of maximum electron energy on the basis of wave breaking model shows good agreement with experimental observations. Spatial distribution and temporal evolution of the high energy electrons also show that the lower energy electrons > 300eV are generated at a later time at a different location than the resonance region. Cavitons moving with a supersonic to subsonicvelocity are observed.

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