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FREQUENCY UP-SHIFTS OBSERVED IN MICROWAVE—PLASMA INTERACTION

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Abstract

Frequency up-shifts and some higher frequency components have been observed in the interaction of a high power microwave (f_0=9GHz) with an unmagnetized inhomogeneous argon plasma. The relationship of the frequency up-shift with incident microwave power, plasma density and strength of electric field have also been investigated. The induced frequency up-shift is considered to be related to a rapidly expanding plasma which is created by the ponderomotive force of a strong standing wave.

I. Introduction

Recently, the frequency up-shift (blue shift) has been studied in laser plasma interaction and plasma wake field accelerator [1,2]. Frequency up-shifts in laser–plasma interaction have been observed in recent experiments by Wood et al. and Savage et al [3,4].

The first observation of the frequency up-shift in the microwave-plasma interaction without any ionization front has been reported [5,6]. In this paper, we demonstrate that when a high power microwave is injected into a underdense plasma a frequency up-shift around 2MHz and some other higher frequency components from 2 to 8MHz have been observed.

II. Experimental Arrangement

In the present experiments, a cylindrical, unmagnetized argon plasma column was created by a pulsed discharge between two directly heated LaB_6 cathodes in a vacuum chamber (32cm in diameter, 60cm in length) as shown in Fig.1.

A typical plasma discharge pulse duration is t_w=2ms with a repetition rate of 10 Hz. The typical plasma parameters are: maximum electron density $n_0 \leq 1.2\times10^{12}\text{cm}^{-3}$ and electron temperature $T_e \simeq 3 \sim 5$eV. The estimated electron-ion collision frequency is $\nu_{ei} \simeq 4.5 \times 10^6\text{sec}^{-1}$, and ion neutral collision frequency is $\nu_{in} \simeq 10^5\text{sec}^{-1}$. Within the experimental region of concern, a parabolic density, $n_0 = n_{max}[1-(z-z_0)^2/L_z^2]$, is observed in the z direction. Here L_z is the half-width of the density profile along the chamber axix, n_{max} is the maximum plasma density during the experiment and z_0 is the position of the maximum density layer, while in the radial direction there is a quite weak linear density gradient. In the present experiments, the L_z is around 25cm and L_r, the gradient length in radial direction, is around 300cm.

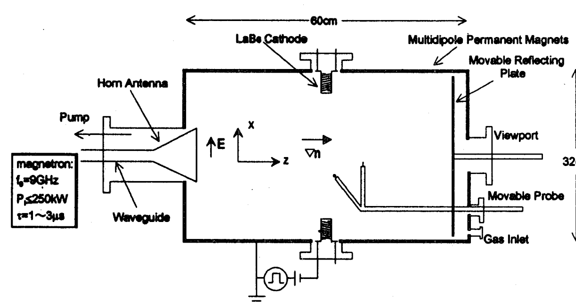

Fig.1 Experimental set-up.

Pulsed microwave (f_0=9GHz) with a rise-time of $\tau_r \approx$ 100ns, maximum power of 250kW and a typical pulse width of $\tau \simeq 3\mu$s is irradiated synchronously with the discharge pulse through a rectangular horn antenna (aperture area= $13.5 \times 10.5\text{cm}^2$) from the lower density side of the plasma along the chamber axis (z direction). The ratio of the electric field energy to the plasma energy is $\varepsilon_0 E_0^2/4n_cKT_e \approx 0.1$, where E_0 is the amplitude of the electric field of the incident microwave, $n_c = 1.0 \times 10^{12}\text{cm}^{-3}$ is the plasma density of critical layer and K is Boltzmann's constant. Because the pulse width of the microwave is short enough for the ionization or plasma heating, these effects can safely be neglected. The plasma density perturbation and rf signal in the plasma are detected by a plane Langmuir probe and a cylindrical probe, respectively.

III. Experimental Results

The frequency spectra of rf signals are observed along the center axis of the chamber. A typical example of the frequency spectra of microwave pulses is shown in Fig.2. These frequency spectra are observed inside the plasma at z=11cm where plasma density $n_0=0.5n_c$ with two different incident powers. Here z is a distance from the horn antenna aperture. The dashed and solid lines represent the spectra of rf signals of 37 and 250kW, respectively. It can be seen that the up-shift is 2.5MHz when P_i is 250kW, but is 0.5MHz when P_i is decreased to 37kW.

The relationship between the upper frequency components and the incident power is plotted in Fig.3. We found that as the incident power of the microwave P_i is increased from 0 to 250kW, the frequency up-shift (f_1) and the higher frequency components (f_m, m=2, 3) can only been observed when P_i is higher than 7.9kW, i.e. the threshold power for the present phenomenon is around 7.9kW. This result is the same as that we obtained before [5,6].

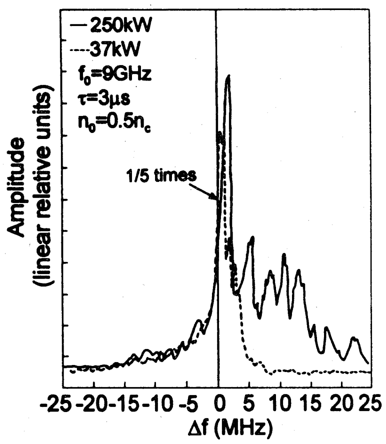

Fig.2 Frequency spectra of microwave for different incident power.

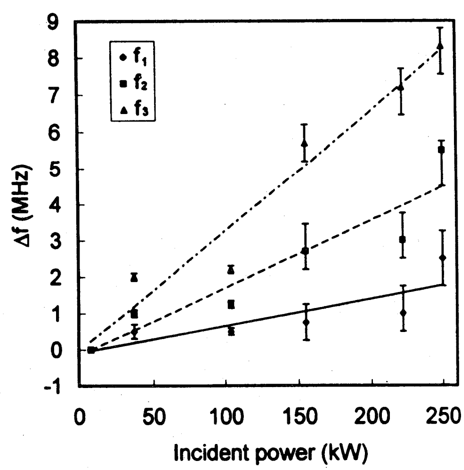

Fig.3 Frequency up-shift and higher frequency components vs. incident power.

The relationship between the frequency up-shift and plasma density has also been investigated. Figure 4 shows the dependence of the frequency on plasma density. It can be seen that when the plasma density n_0 is increased from 0 to $0.9n_c$ ($n_c = 1\times10^{12}\mathrm{cm}^{-3}$) the up-shifted frequency increases from 0 to 2MHz, and the higher frequency components increase from 0 to about 8MHz proportionally to the plasma density.

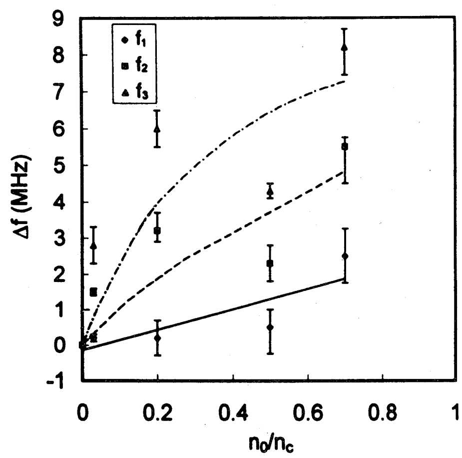

Fig.4 Frequency up-shift and higher frequency components vs. plasma density.

As mentioned in Ref[5,6], the up-shifts are due to moving plasmas which are created by the ponderomotive force of the incident wave. So, the frequency up-shifts should have a relation to the strength of the electric field of the incident wave. In order to verify it, a moveable reflecting plate is put near the end wall of the chamber (z_r=0cm) for investigating the dependence of frequency spectra on the intensity of the electric field. The the electric field intensity of the incident wave $|E|^2$ and frequency spectra are observed at a fix point z=11cm while the reflecting plate is moved from z_r=0 to 9cm with a step Δz=0.4cm.

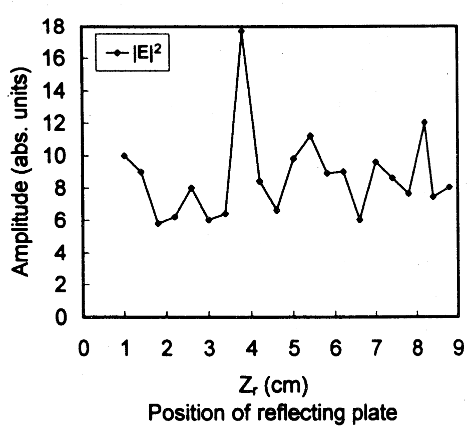

Fig.5(a) Electric field intensity vs. reflecting position.

The electric field intensity $|E|^2$, frequency up-shifts and higher frequency copmonents observed as a function of reflecting position are shown in Fig.5(a) and Fig.5(b). It is obvious that the frequency up-shifts and higher frequency components have been observed at which the electric field intensity is strong.

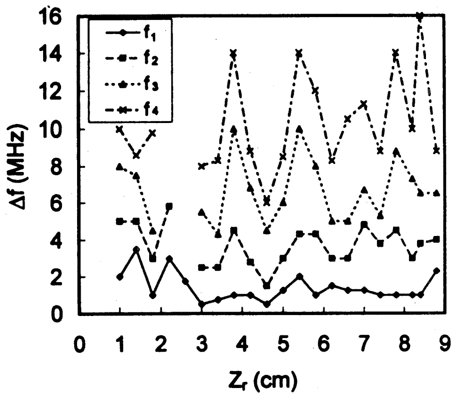

Fig.5(b) Higher frequencies f_m (m=1,2,3,4) vs. reflecting position.

IV. Discussion

Frequency up-shifts have been verified experimentally in the interaction of high power microwave and plasma. As shown above, the observed up-shifted frequency and higher frequency components depend not only on the incident power of the microwave and the plasma density but also on the strength of electric field. According to Refs.[5,6], the frequency up-shifts are due to moving plasmas arising from ponderomotive force and the velocity of the expanding plasma can be written as

$$v \approx \left[\frac{2P_i}{clA} \frac{\omega_p^2}{\omega_0^2} - K(T_i + T_e)\nabla n_0 \right] \tau/(m_i n_0), \quad (1)$$

where A is the irradiation area of the microwave, c is speed of light in vacuum and m_i is ion mass. T_i and T_e are ion temperature and electron temperature, respectively. If we take P_i= 250kW, f_0=9GHz, T_e = 3eV, A= 5×10^{-3}m^2, τ=3 μs, $l = 8 \times 10^{-3}$ m, the velocity of the expanding plasma is estimated to be $v \approx 7.5 \times 10^6$ cm/s. When the incident wave encounters such a moving plasma, a part of it is reflected by the plasma, and the rest transmmits through the moving plasma. In the frame of the moving plasma (the prime frame) the frequency of the incident wave is $\omega_0' = \gamma(1+\beta)\omega_0$, where $\gamma = (1-\beta^2)^{-1/2}$, $\beta = v/c$. Performing an inverse Lorentz transformation to get back to the lab frame, the wave frequency for the reflected wave is

$$\omega_r = \gamma^2(1+\beta)^2\omega_0^2 \quad . \quad (2)$$

while for the transmitted wave, it is found that

$$\omega_t = \gamma^2(1+\beta) \left[1 - \beta \left(1 - \frac{\omega_p^2}{\omega_0^2\gamma^2(1+\beta)^2} \right)^{\frac{1}{2}} \right] \omega_0, \quad (3)$$

Substituting $v = 7.5 \times 10^6$ cm/s (experimental result) into Eq.(2), the frequency up-shift of the reflected wave is $\triangle f_r = \frac{2\beta f_0}{1-\beta} \approx 4$(MHz), and for the transmitted wave, the frequency up-shifted is $\triangle f_t = \frac{\beta f_0}{1-\beta} \approx 2.1$(MHz). These results are in good agreement with the experimental results. Since the up-shifted frequency signal interacts with the moving plasmas several times within one pulse duration of the incident wave, higher frequency components could be observed in the experiments.

V. Conclusion

In summary, the frequency up-shift around $1 \sim 2$MHz and some other higher frequency components in the range of 2MHz to 8MHz have been demenstrated again experimentally in the interaction of microwave (f_0=9GHz, P_i=250kW) with underdense plasma. It has been predicated theoretically that a frequency up-shift may occur when an electromagnetic wave interacts with an underdense ionization front [7]. This mechanism is verified by our experiments of microwave-plasma interaction when there is no ionization front. It means not only an underdense ionization front but also a moving underdense plasma can be used to up-shift the frequency of a microwave radiation. In the present case, because a strong standing wave is established in the chamber, the plasma is expanded rapidly by the collective ponderomotive force arising from the electric field gradient of the standing wave. The reflected and transmitted waves interact with the moving plasmas, and the frequency is up-shifted due to the Doppler effect.

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