PLASMA CAVITY FORMATION AND NONLINEAR FREQUENCY CONVERSION IN THE RANGE OF ION PLASMA WAVES

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In the 1970's it was intensively studied theoretically [1] and experimentally [2] that the ponderomotive force of the high frequency field played an important role for the formation of a plasma cavity. In this phenomenon the ponderomotive force is effective only to plasma electrons [3]. However, the situation is quite different if the frequency of the field becomes as low as the ion plasma frequency. Shukla [4] has theoretically shown that the "ion" ponderomotive force is effective in a low frequency ion wave such as a finite amplitude ion-acoustic wave. In his theory it is noted that the ion ponderomotive force is stronger by mass ratio M/m than the electron one. However, few experiments have been made on the direct effect of the ponderomotive force on plasmas ions in such a low frequency case so far. In this paper, we wish to report experimental results showing that the potential gradients of ion-acoustic waves, which directly affect the ion component, can cause the exclusion of plasma ions and form plasma cavities. Furthermore, the waves trapped in the cavities are shown to suffer nonlinear modulation.

Experiments were performed using a modified double plasma (MDP) device, as shown in Fig. 1 of Ref. [5]. To excite waves in the MDP device, an rf voltage was applied to the driver chamber wall just similarly to in the case of the conventional DP device. Such an rf signal excited a wave in the target plasma. Here, plasma parameters were such as plasma density n_e ~ $(2 - 5) \times 10^8$ cm^{-3}, electron temperature T_e ~ $(1.5 - 2.0)$ eV and ion temperature T_i ~ 0.1 eV. In this case, however, there were few stationary beam ions in the target plasma. Therefore, we could excite only *ion-acoustic modes* with high frequencies of 200-320 kHz in the MDP device. Measurements of plasma parameters and wave signals were made by use of a small probe movable along the axis of the device (x-axis). A small electrostatic energy analyzer

was also used to measure ion energy distributions.

First, we report experimental results on the plasma cavity formation by ion-acoustic waves. When the amplitude of an ion-acoustic wave, being externally amplitude-modulated in a sinusoidal or triangular form, was increased enough, we found that the externally formed wave packet could exclude a portion of plasma ions near its central part and form a plasma cavity at an early stage ($x \lesssim 1$ cm). At the same time, the wave itself was observed to be confined in the cavity. These features can be seen at small distances x ($\lesssim 3$ cm) in oscilloscope traces as shown in Fig. 1. The data also demonstrate that the trapped wave suffers nonlinear modulation at a low frequency at larger x ($\gtrsim 3$ cm). The nonlinear modulation of the wave was found to rapidly grow with increasing x. Furthermore, when the maximum amplitude V_{ex} of the applied rf voltage was increased, the depth of the plasma cavity was observed to increase with increasing V_{ex}. Based on these data, relations of the plasma cavity depth with the local amplitude of the rf voltage at various values of V_{ex} are shown in Fig. 2. Curves in this figure demonstrate that the plasma cavity depth ($\delta n/n)_{cav}$ always increases with increasing rf amplitude, but there exists a difference in the rate of the increase between on the upstream and downstream sides. In other words, we can find the effect of steepening at the leading edge caused by the "cavity drift". By the way, the drift velocity of the cavity can be estimated from traces as shown in Fig. 1, in which the cavity front velocity is estimated to be about 8×10^4 cm/sec. This velocity is considerably slower than the ion-acoustic one ($C_s \cong (1.6\text{-}2.0) \times 10^5$ cm/sec).
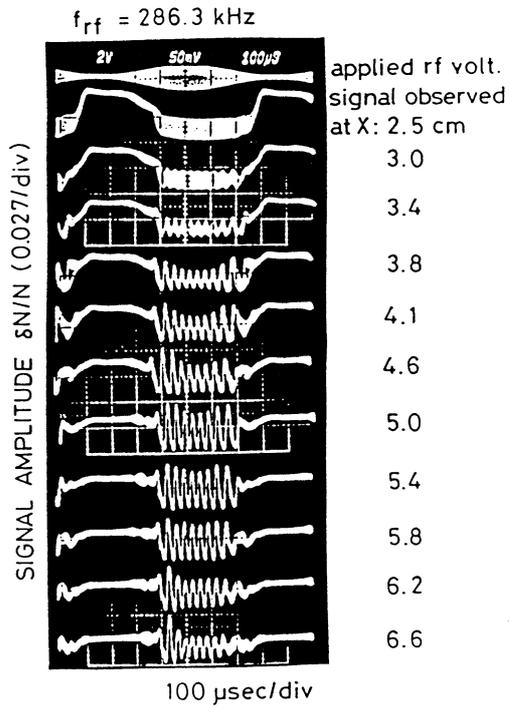
On the other hand, using a technique of time-resolved ion energy analysis, we could get a direct information on the exclusion of plasma ions from the cavity region. The ac components of ion energy distributions thus measured are shown as a function of time τ in Fig. 3(b). Here, τ means a delay time defined in Fig. 3(a). These demonstrate that only a group of plasma ions with special energies around $MC_s^2 / 2 \cong 0.5$ eV is well excluded from the cavity region and in addition, a small group of ions is piled up in front of and behind the cavity. This result suggests that the group of excluded ions corresponds to *resonant ions*. It is an important information to know the mechanism of the plasma cavity formation. Here, the dc component of the ion energy distribution is also shown at the top in Fig. 3(b).

Next, we describe on the nonlinear modulation of the waves trapped in the cavity. As seen from traces in Fig. 1., an ion-acoustic wave with a high frequency f_{rf} ($\cong$ 200-320 kHz) trapped in the cavity was observed to suffer nonlinear modulation at x ($\gtrsim$ 3 cm) and then a low frequency wave was newly generated via the wave modulation. As a result, the trapped wave was found to be replaced by another low frequency ion wave with an average frequency Δf ($\cong$ 20-40 kHz) within the cavity. The low frequency wave thus excited was observed to rapidly grow in amplitude with increasing x at x $\lesssim$ 4 cm and to slowly damp after it reached maximum at x $\sim$ 5 cm (see Fig. 4). Fig. 4 was obtained from observed frequency spectra of the evolving waves. The spectra indicate that the wave modulation yields a wave with an upper sideband frequency f_{us} as well as a wave with a low frequency Δf, showing that $f_{rf} = f_{us} - \Delta f$. On the other hand, we can get from evolving traces, as shown in Fig. 1, another information on the velocity of the low frequency wave. This datum reveals that the low frequency wave velocity is considerably slower than C_s , and it is rather closer to the ion-sound wave velocity as written in $\sqrt{T_i / M}$.
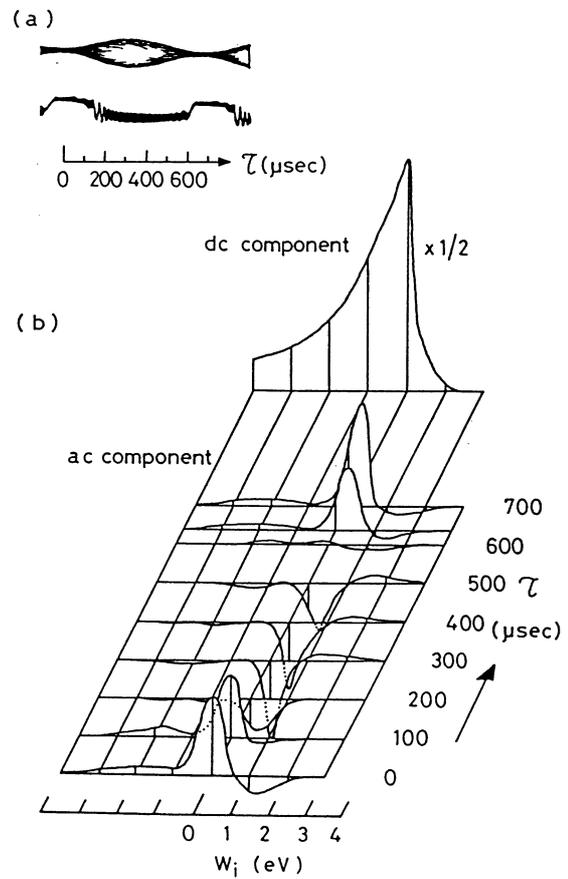
In conclusion, we have experimentally shown that an inhomogeneous ion-acoustic wave with a frequency f_{rf} $\cong$ 200-320 kHz can exclude a portion of plasma ions and form a plasma cavity. At the same time, the wave is found to be confined in the cavity. Moreover, the cavity front velocity is observed to be about (0.8 - 1.0) $\times 10^5$ cm/sec, which is considerably slower than the ion- acoustic velocity C_s [$\cong$ (1.6-2.0) $\times 10^5$ cm/sec]. In addition, using a technique of time- resolved ion energy analysis, a group of plasma ions with special energies around 0.5 eV, which corresponds to a group of resonant ions, is observed to be excluded from the cavity region. On the other hand, the ion-acoustic wave trapped in the cavity is observed to be nonlinearly modulated and create two new daughter waves with a low frequency Δf $\cong$ 20- 40 kHz and an upper sideband frequency f_{us} ($= f_{rf} + \Delta f$).

References
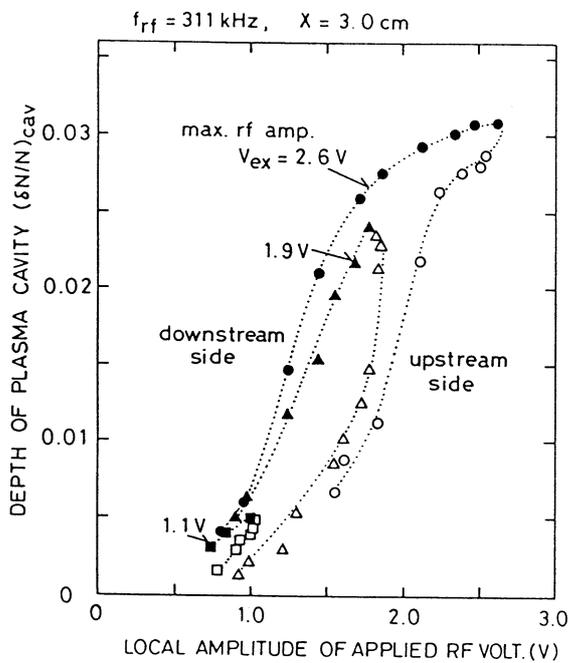
[1] K. Nishikawa et al.: Phys. Rev. Lett. **33**, 148 (1974), *etc.*

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[3] F.F. Chen: Introduction to Plasma Physics and Controlled Fusion. Plenum Press, 1984.

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$f_{rf} = 286.3$ kHz

SIGNAL AMPLITUDE $\delta N/N$ (0.027/div)

2V   50mV   100μS

applied rf volt.
signal observed
at X: 2.5 cm
3.0
3.4
3.8
4.1
4.6
5.0
5.4
5.8
6.2
6.6

100 μsec/div

[Fig.1] Oscilloscope traces of the rf signal
(top) and the density fluctuations observed
at various x (lower).

$f_{rf} = 311$ kHz,   X = 3.0 cm

DEPTH OF PLASMA CAVITY $(\delta N/N)_{cav}$

0.03
max. rf amp.
$V_{ex} = 2.6$ V

1.9 V

0.02
downstream
side
upstream
side

0.01
1.1 V

0

0   1.0   2.0   3.0
LOCAL AMPLITUDE OF APPLIED RF VOLT. (V)

[Fig.2] Relation of the cavity depth with the
local rf amplitude for each value of V $_{ex}$.

(a)

0 200 400 600 τ (μsec)

(b)

dc component   x 1/2

ac component

700
600
500 τ
400 (μsec)
300
200
100
0

0   1   2   3   4
W_i (eV)

[Fig.3] (a) Definition of time τ . (b) The ac
component of ion energy distributions ob-
served at various τ and the dc component.

WAVE POWER (rel. scale)

100
70
50
30
20

10
7
5

3
2

1

0.7

$P \propto \exp(\frac{X}{L})$ L≈0.36 cm
low freq.
wave

cavity depth
$(\delta N/N)_{cav}$

high freq. wave

$P \propto \exp(-\frac{X}{D})$
$D_1 ≈ 1.5$ cm
$D_2 ≈ 0.75$ cm

0.10
0.07
0.05

0.03
0.02

0.01

CAVITY DEPTH $(\delta N/N)_{cav}$

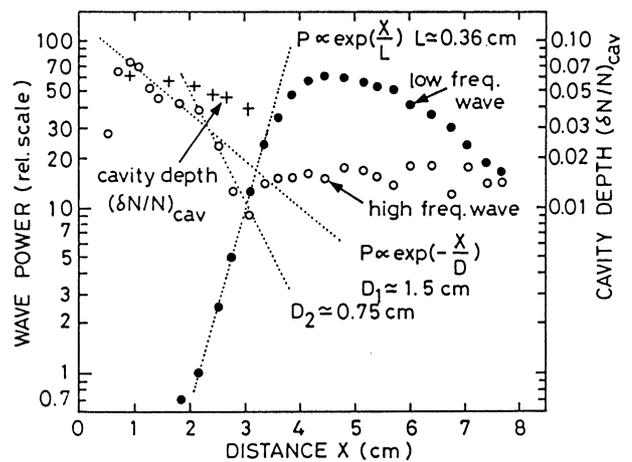0   1   2   3   4   5   6   7   8
DISTANCE X (cm)

Fig.4. Spatial variation of the wave powers
and the cavity depth (δ n/n) $_{cav}$.