and three-photon transitions of the same molecular state becomes feasible. As in simultaneously recorded one- and two-photon spectra[14] of NO ($A^2\Sigma^+$) Doppler-free two- and three-photon absorption will provide a new method to obtain valuable spectroscopic information such as, for example, separations between two- and three-photon absorption lines which originate from λ-type doubling.

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Observation of Anomalous Resistivity Caused by Ion Acoustic Turbulence

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The dc resistivity caused by ion acoustic turbulence in plasmas is measured and effective collision frequencies of electrons are obtained from the resistivity as a function of electron drift velocity. These experimental results can be explained by using the theoretical model of Horton *et al.*, in which the nonlinear ion Landau damping dominates the turbulence spectrum.

Observation of anomalous electrical resistivity caused by ion acoustic turbulence in plasmas has been reported by many authors.[1-6] Collective electric fields associated with the ion acoustic instability[7] provide an effective high collision rate for electrons which, experimentally, appears as anomalously high electrical resistivity. Therefore, measurements of turbulence spectrum are very important for explaining the effective high collision rate since it would give more detailed information of the turbulence. However, the relationship between the effective collision frequency and the turbulence spectrum has not been investigated experimentally in detail so far. We wish to report here that the anomalous resistivity caused by the current-driven ion acoustic instability was observed in a large-diameter plasma and the dependence of the effective collision frequency on the electron drift velocity can be explained by using the theoretical results which have been derived by Horton and co-workers.[8,9]

The experiments were performed using the plasma box,[10] whose diameter and length were 70 cm and 34 cm, respectively. The plasma was produced by discharges between the tungsten filaments and the chamber wall with permanent magnets. The density and temperature of the electrons were measured by a Langmuir probe and an electron energy analyzer, and were found to be homogeneous across the box. The electron density n_e was varied from 10^9 to 5×10^{10} cm^{-3} by changing the emission currents of the filaments. The electron temperature T_e was in the range 1–3 eV. The pressure of the argon gas was varied from 5×10^{-5} to 5×10^{-4} Torr. The temperature ratio T_e/T_i, which was obtained by taking the dispersion relation of the test ion acoustic wave without instabilities, was found to be from 10 to 15.

The current-driven ion acoustic instability was excited by drifting the electrons in the plasma. The drift motion of the electrons was caused[11,12] by the dc electric field between two grids, G_1 and G_2 (5 cm in diameter), which were relatively coarse in order to avoid disturbance to the plasma (size of mesh ≫ Debye length). The potential V_g (0–250 V) was applied to the grid G_1. Although V_g was relatively large, electron beams, which may be produced by the grids, were not observed. The unstable waves were detected by the grids and the probes, and analyzed by a spectrum analyzed.

The electric field E was observed by measuring the floating potential on two thin probes (0.1 mm in diameter) spaced 1 cm apart, which were placed at the center between two grids. A directional rotating probe[5] (5 mm in diameter) located in the plasma between the two grids was used to measure the electron drift velocity v_d. Thus, we can determine the electrical resistivity ρ experimentally by using $\rho = E/en_e v_d$.

When the grid potential V_g exceeds a critical value (~10 V), the ion acoustic waves have been observed in the plasma between the two grids G_1 and G_2. On increasing V_g, v_d increased up to $0.15v_e[v_e=(T_e/m)^{1/2}]$ and the fluctuation level of the waves did up to 15%. At the same time, the peak of the power spectrum shifted towards the low frequencies. This means that wave energy is transferred into the low frequencies, which is due to some nonlinear process.[8,9,13] We show a typical example of the final power spectrum in Fig. 1, where the current fluctuation was about 6% and the distance, L, between the two grids was 7 cm. Figure 1 shows that the power spectrum is proportional to ω^{-1} around the peak of the spectrum and decreases more rapidly than ω^{-1} in the high frequencies.

For the case where the nonlinear ion Landau damping dominates the stationary wave spectrum, Horton and co-workers[8,9] have obtained a modified Kadomtsev spectrum[13] by a renormalized theory, including a modification of an electron distribution due to the feedback effect of the turbulent waves. In order to compare our experimental results with their theory, we obtained the ω spectrum from the k spectrum given by the theory, using the relation[13] $p(\omega)\propto k^2I(k)/(d\omega/dk)$ as well as the dispersion relation,[14] and plotted the spectrum found by Horton *et al.*[8,9] as the dashed line in Fig. 1, indicating a good agreement. In this case, the theoretical curve was chosen so as to fit the experimental results around the peak. Thus, one can say that in the present experiment the nonlinear ion Landau damping plays an important role in the establishment of the turbulence spectrum.

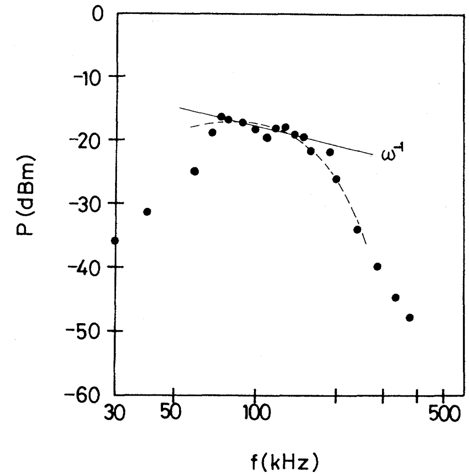

FIG. 1. Example of the frequency dependence of the power spectrum, where $v_g = 218$, $f_{pi}\simeq 2.2$ MHz and $v_d/v_e\simeq 0.1$. The neutral pressure is 10^{-4} Torr. The dashed curve is the spectrum of Horton *et al.*

We measured the resistivity in the plasma with the ion acoustic turbulence described above and obtained the effective collision frequency ν from the relation $\rho = m\nu/n_e e^2$. An example of our measurements for different plasma densities as a function of v_d/v_e is shown in Fig. 2, where T_e = 1 eV and the pressure was 2×10^{-4} Torr. As seen from Fig. 2, ν/ω_{pe} increases with increasing v_d/v_e and for $v_d/v_e \gtrsim 0.09$, $\nu/\omega_{pe}\propto v_d/v_e$. For $v_d/v_e\lesssim 0.05$, the electron drift velocity seems to be about constant.

The lowest collision frequency in Fig. 2 is already a factor of 30 larger than the classical value ν_c, as observed elsewhere.[5] In this case we took the length of the plasma box as a mean free path since the mean free path for electron-neutral collisions was much larger than the size of the plasma.

In order to interpret the experiment quantitatively, we calculated the effective collision frequency numerically as a function of electron drift velocity by using the effective collision frequency derived by Horton *et al.* According to them, the effective collision frequency $\nu_{\rm eff}$ is given as follows[8]:

$$\nu_{\rm eff}=\frac{15\pi}{64}\left(\frac{\pi}{2}\right)^{1/2}\frac{T_e}{T_i}\frac{v_d}{v_e}\omega_{pe}\int_{x_{\rm min}}^{1}dx[\delta\ln(1/x)-2(\pi\nu_{\rm eff}/\omega_{pe})^{1/2}(x^{-1/2}-1)],$$

where $x_{\rm min}$ is determined by

$$\delta\ln(x_{\rm min}^{-1})-2(\pi\nu_{\rm eff}/\omega_{pe})^{1/2}(x_{\rm min}^{-1/2}-1)=0.$$

In the above equations, $\delta=1+\gamma^i/\gamma^e$, where γ^i and γ^e are the damping rate for the ions and the linear growth rate for the electrons, respectively. By solving the above coupled equations, we obtain $\nu_{\rm eff}$ in terms of v_d/v_e. The result for $T_e/T_i=15$ is shown[15] as the dashed line in Fig. 2. In estimating δ, we neglected the contribution of the high-energy tail of the ions, which has been observed in most cases of turbulent heating experiments.[16] The theoretical curve in Fig. 2 demonstrates that (1) $v_d\approx$ const. for $v_d/v_e\lesssim 0.05$ and (2) $\nu_{\rm eff}/\omega_{pe}\propto v_d/v_e$ for $v_d/v_e\gtrsim 0.09$. Sagdeev and Galeev[17] have derived the relation $\nu_{\rm eff}\propto v_d$ from the Kadomtsev spectrum. Thus, as seen from Fig. 2, the experimental results agree with the theoretical ones in value as well as in tendency. Therefore, we can conclude from these discussions that the effective high collision frequency observed here has been caused by the ion acoustic turbulence, in which nonlinear ion Landau damping is the dominant process.

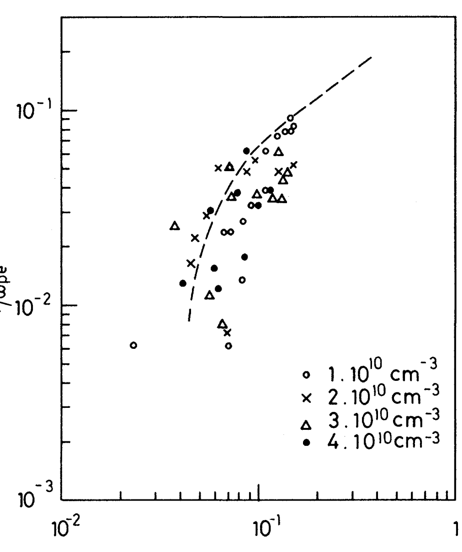

FIG. 2. The effective collision frequency of the electrons as a function of v_d/v_e at a pressure of 2×10^{-4} Torr, where $T_e=1$ eV and $L=10$ cm. The dashed line represents the theoretical values.

If a power law on the ω spectrum is given, we could estimate experimentally a wave energy, W/n_eT_e, normalized by a thermal energy. As seen in Fig. 1, in our case most of the wave energy is concentrated around the low-frequency region, where the spectrum is peaked, so that roughly we can assume that $p(\omega)\propto\omega^{-1}$. Then, we have $W/n_eT_e\approx 0.24$ for $v_d/v_e=0.1$. On the other hand, Choi and Horton[8] have derived an equation for the wave energy as well. Theoretically, we have $W/n_eT_e\approx 0.22$, which indicates a good agreement.

In this type of experiments it would be essential that the electric field is measured to a high degree of accuracy. The method used here may not be the best one. From the agreement between the experiment and the theory, however, we might as well conclude that this method still gives some useful information to us.

In summary, the ion acoustic turbulence was excited by the current-driven ion acoustic instability in a large-diameter plasma. The turbulence spectrum agrees with that predicted by Horton *et al.* We obtained the effective collision frequency of the electrons caused by such turbulence by measuring the electron drift velocity and the electric field independently. To interpret the experimental results, the effective collision frequency was calculated by using the theory of Horton *et al.* We found that in the presence of the ion acoustic turbulence, in which the nonlinear ion Landau damping dominates, the collision frequency increases as v_d in large electron drift velocities and $v_d\approx$ const. in small electron drift velocities.

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Measurement of Density Modification of Laser-Fusion Plasmas

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Density profile of the glass-microballoon plasma irradiated by Nd laser with intensity of 10^{16} W/cm^2 was measured by newly developed microscopic interferography. The existence of strong density modification by intense radiation pressure was clearly indicated.

The hydrodynamic behavior of laser-produced plasmas is essentially important for laser fusion research, because absorption mechanisms of laser light depend on the density profile of the plasma. Recent theoretical and computational investigations[1-5] show that the density gradient near the critical density ($n_c = 10^{21}$ cm^{-3} for Nd laser) is dramatically steepened by intense radiation pressure.[6] Because of the density steepening, the resonant absorption[7,8] becomes an effective absorption mechanism while the efficiency of the parametric instability and the classical absorption are reduced. There have been a number of experimental studies[9-13] on the density profile of laser-produced plasmas. Density cavities produced by the radiation pressure were observed in in recent experiments using CO_2 laser ($\lambda = 10.6$ μm).[12,13] We have reported the existence of the density modification by Nd laser ($\lambda = 1.06$ μm) with an indirect method, that is, spectrum measurement of backscattered light.[14]

In this Letter, we present the observation of the density profile of the plasma irradiated by Nd laser with an intensity of 10^{16} W/cm^2 and infer the existence of the strong density modification.

The glass laser "Gekko II," two-beam system[15] was used to irradiate a glass-microballoon target, the diameter of which was 50–58 μm. The oscillator was a yttrium aluminum garnet laser, mode locked by a saturable dye, which was followed by nine rod-type amplifiers. The diameter of the final rod was 80 mm. The output energy was typically 15 J per beam and the pulse duration was 30 psec full width at half-maximum. The prepulse energy was minimized by two saturable dye cells in the early stage of the amplifiers. The energy of the prepulse was less than 20 μJ. The amplified spontaneous emission was below 1 mJ. The soft aperture and the vacuum spatial filters were used to get a clean beam. The f number of the focusing lens was 1.2. The typical focusable power was 10 J in 50 μm diam.