Study of the Current-Driven Ion-Acoustic Instability Using CO_2-Laser Scattering

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The saturated state of the current-driven ion-acoustic instability in a He positive-column plasma is studied using CO_2-laser scattering and heterodyne detection. It is found that small concentrations of hydrogen present in the positive-column plasma play a crucial role in saturating the instability. The measured angular extent and level of saturation of the turbulence are found to be consistent with "resonance-broadening"—enhanced ion Landau damping by 1 to 4% H^+ impurity ions.

The current-driven ion-acoustic instability presents a simple physical situation where the drifted electron distribution feeds energy into the ion-acoustic wave modes by inverse Landau damping. An experimental study of this instability provides a well-defined test of theories of the saturation of plasma turbulence. The most unstable waves in the turbulent spectrum have relatively short wavelengths $2\pi/K$ such that $K\lambda_{De}$ is approximately 0.6 (where λ_{De} is the electron Debye wavelength).[1,2] For these short wavelengths electrostatic-probe measurements, which have been used previously to study this instability, are difficult to interpret. We present a study of the saturated state of the ion-acoustic instability in a positive-column plasma using CO_2-laser scattering as a nonperturbative diagnostic technique.[3] The positive-column discharge is chosen for this study since it supports a uniform electric field necessary to cause the electron distribution to drift in order to excite the instability. The saturated state of the turbulent spectrum is studied over a wide range of parameters. It is found that the level of saturation depends crucially on small amounts of hydrogen (at levels of 10^{-4} of the neutral-He pressure) which are present in typical nonbakable vacuum systems. The saturated state of the instability is found to be well described by resonance-broadening theory[4,5] applied to the H^+ impurity ions. Finally the scattering techniques described here hold promise of application to a wide range of plasma problems in high-temperature plasmas where probes cannot be used.

The plasma is the "positive column" portion of a discharge in He gas, with the pressure p ranging from 0.01 to 0.15 Torr, flowing at a rate of 0.7 Torr liter/sec in a 7.5-cm-i.d. water-cooled Pyrex tube.[6] The vacuum system is pumped with a liquid-nitrogen trapped oil diffusion pump. The discharge current is varied between 1 and 8 A. The indirectly heated W cathode is impregnated with BaO and located 140 cm from a water-cooled Cu anode. The current I in the positive column determines the plasma density and hence the electron and ion plasma frequencies ω_{pe} and ω_{pi}. The neutral-gas pressure determines the electron drift velocity v_D and the electron and ion collision frequencies ν_{in} and ν_{en}. The electron temperature T_e ranges from 4 to 6 eV, and the He-ion temperature $T_{i\mathrm{He}}$ is believed to be less than $T_e/40$. The range of parameters studied are v_D/v_e from 0.10 to 0.18 [v_e is the electron thermal velocity $(T_e/m_e)^{1/2}$] and ν_{in}/ω_{pi} from 2×10^{-2} to 5×10^{-3}. The effect of electron-neutral collisions is small with ν_{en}/Kv_e less than 0.03.

The output of a single-mode, 400-W, cw CO_2 laser with a wavelength of 1.06×10^{-3} cm traverses the discharge 105 cm from the cathode in a direction perpendicular to the plasma current. The unstable ion-acoustic waves typically have wavelengths from 0.03 to 0.2 cm. Thus the Bragg-scattered CO_2-laser radiation is oriented at a small angle φ of approximately 10^{-2} rad with respect to the incident laser beam. Scattering occurs for ion-acoustic waves whose wave vectors $\vec{K}$ are oriented in the plane nearly perpendicular to the direction of the incident laser beam. In this plane we denote by θ the angle between $\vec{K}$ and the plasma current $\vec{I}$. By measuring the orientation of the scattered light with respect to that of the incident laser beam, θ and φ are measured which determine, respectively, the direction and magnitude of $\vec{K}$. The detector is a

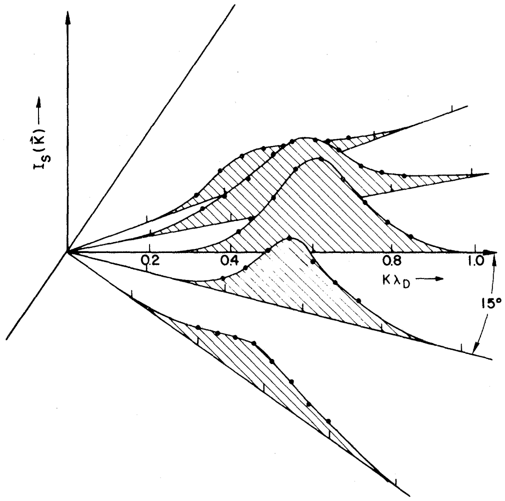

FIG. 1. The heterodyne photocurrent $I_s(\vec K)$ (which is proportional to the electron density modulation $n_{\vec K}$) as a function of the direction θ and magnitude K of the plasma wave vector. Data are shown for values of θ of − 30°, − 15°, 0°, 15°, and 30°.

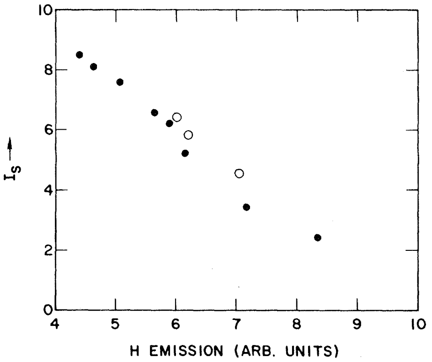

FIG. 2. The heterodyne photocurrent I_s as a function of the observed emission of visible radiation at 6523 Å from neutral hydrogen. Solid and open circles indicate data taken when the neutral-H concentration was, respectively, increased and decreased.

Ge:Cu photoconductor; it has frequency response to 1 GHz and is flat over the range of measured frequencies (10–30 MHz). The heterodyne photocurrent, produced in the detector by the beat of the local oscillator beam (formed by attenuating the main laser beam) and the scattered radiation, is frequency analyzed. The absolute level of the fluctuations is determined from the frequency response of the detector and the measured heterodyne efficiency.

In Fig. 1 we show the amplitude of the heterodyne photocurrent $I_s(\vec K)$ (which is proportional to the electron density modulation $n_{\vec K}$)[7] as a function of wave-vector magnitude K and direction θ. The pressure is 0.04 Torr and the discharge current is 3.8 A. The resolution is limited by the finite angular extent of the incident and scattered beams. Deconvolution of the data allows a resolution $\delta K\lambda_{De}$ of ± 0.05 and $\delta\theta$ of ± 3°. The largest-amplitude wave is observed with $K\lambda_{De}$ ranging from 0.6 to 0.8 (depending on I and p) and in the direction for which θ is zero.

It was found that impurities can make an order-of-magnitude change in the saturated level of the turbulence when, for instance, a part of the vacuum system is "outgassed." Since a small percentage of impurity ions would produce negligible collision damping in comparison to the damping due to He-ion–neutral collisions, hydrogen-ion Landau damping was suspected (i.e., H is the only abundant impurity lighter than He; its small mass leads to more H^+ ions with velocities of the order of the ion-acoustic phase velocity and thus to more effective Landau damping). The dominant role of H ions in determining the saturated turbulent level was verified by correlating the measured emission of visible radiation from neutral H in the plasma at 6563 Å with the measured saturation level of the turbulence. In order to study the effect of H systematically, H was introduced into the discharge while the light-scattering signal was monitored. The results are shown in Fig. 2 for a discharge current of 2.0 A and a pressure of 0.14 Torr. The wave amplitudes are found to vary inversely with the H emission. In Fig. 2 the increase in H emission from 4.4 to 8.4 units corresponds to an increase in neutral-H pressure of 2×10^{-5} Torr. The residual background initially present before the addition of H corresponds to 4.4 units in Fig. 2. It was verified that the H does not enter the system from the He supply tank, by using the vapor from boiling liquid He. Since impurities containing H (e.g., hydrocarbons and water) are common in nonbakable vacuum systems, a partial pressure of atomic H of the order of 10^{-5} Torr in the discharge is quite reasonable. Before taking the data described below, we minimized the concentration of H impurities in the system by discharge cleaning at low pressures.

Shown in Fig. 3 as a function of v_D/v_e are data for $\Delta\theta$ which is the angle θ at which $|n_{\vec K}|^2$ falls to $1/e$ of its value at $\theta = 0°$, for ΔK which is the increment in K over which $|n_{\vec K}|^2$ falls by $1/e$ of its value at the peak K, and for

$$W/nT_e = \sum_{\vec K} |n_{\vec K}/n|^2 (1 + K^2\lambda_{De}^2) \qquad (1)$$

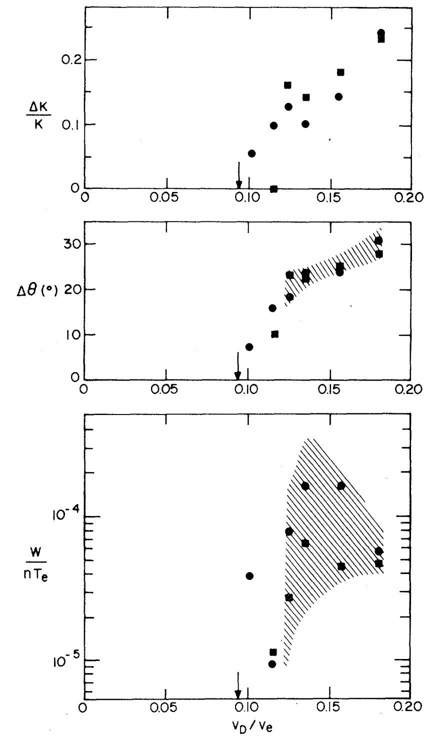

FIG. 3. The total fluctuation energy W/nT_e, the spread in angle $\Delta\theta$, and the spread in the magnitude of the unstable wave vectors $\Delta K/K$ as a function of v_D/v_e. Circles and squares indicate, respectively, higher and lower values of discharge current. The values of v_D/v_e are 0.072, 0.082, 0.088, 0.095, 0.11, and 0.13. The corresponding values of current are 1.8 A, 2.8 and 1.55 A, 4.8 and 2.3 A, 5.8 and 2.8 A, 6.8 and 3.8 A, and 6.8 and 4.8 A. The predictions of resonance-broadening theory are indicated by the shaded areas.

which is the ratio of the total wave energy to the thermal energy of the electrons with density n. At a given value of v_D/v_e (i.e., a fixed pressure) are shown the results for different densities (i.e., different currents). A threshold in v_D/v_e is observed below which there is no instability. Above this value of v_D/v_e the extent of the turbulence in θ and K is observed to increase rapidly. For all data, the wave phase velocity ω/K agrees within ± 10% of the predictions of linear theory for the ion-acoustic dispersion relation. This places an upper limit of 6% on the concentration of H^+ impurity ions.

We now wish to consider the mechanism by which the instability is saturated. Considering first the possible saturation mechanisms involving the electrons, the measured angular extent of the turbulence rules out saturation by electron trapping (previously suggested as a saturation mechanism for this instability),[1] since the correlation time of an electron with the wave potential $2\pi/Kv_e\Delta\theta$ is short compared to both ν_{en}^{-1} and the electron bounce time. The data in Fig. 2 indicate the crucial role played by H^+ ions. Calculations indicate that nonlinear ion Landau damping saturates at a much higher level than that which is observed.[8] On the other hand the predictions of ion-resonance-broadening theory applied to the H^+ impurity ions agree with our measurements.

Sleeper, Weinstock, and Bezzerides[4] have derived an analytic expression for the saturation of a wave mode with wave vector $\vec{K}$ propagating at an angle θ with respect to the plasma current. The theory assumes a narrow, peaked spectrum in $|\vec{K}|$. We have modified this theory to include the effects of ion-neutral collisions and resonance broadening on the H^+ impurity ions. Denoting by c_H the ratio of H^+-ion to He^+-ion density and by T_{iH} the H^+-ion temperature, we find a self-consistent equation for the turbulent wave amplitudes of the form

$$\left(\frac{v_D\cos\theta-\omega/K}{v_e}\right)-\frac{(2/\pi)^{1/2}\nu_{in}}{\omega\zeta^2}-\frac{c_H\zeta(T_e/T_{iH})^{3/2}}{2[1+1.25W^{1/2}(\theta)]}\exp\left\{-\tfrac{1}{8}\left(\zeta^2\frac{T_e}{T_{iH}}[1+W^{1/2}(\theta)]^{-1}\right)\right\}=0, \tag{2}$$

where

$$W(\theta)=\frac{\omega_{pi}^2}{\omega^2}\int\frac{K^2\,dK}{(2\pi)^2}\,\frac{\mathcal{E}_{\vec{K}}}{\pi nT_{iH}}. \tag{3}$$

The parameter ζ is $(\omega/K)(m_{He}/T_e)^{1/2}$ and $\mathcal{E}_{\vec{K}}$ is the field fluctuation energy in mode $\vec{K}$. We neglect the He-ion Landau damping since T_{iHe} is expected to be sufficiently small to make this effect negligible. In Eq. (2) the first term corresponds to inverse Landau damping which is balanced by the effects of the neutral collisions (the second term) and the resonance broadening of H^+-ion Landau damping (contained in the third term). The effects of c_H on the wave phase velocity ω/K are taken into account. We fitted the measured values of W/nT_e and $\Delta\theta$ by varying c_H and T_{iH} and using the measured values of $K\lambda_{De}$, T_e, p, v_D/v_e, and n. The predictions of the theory for W/nT_e and $\Delta\theta$ are shown by the shaded areas in Fig. 3. This range of theoretical values takes into account an experimental uncertainty of ± 10% in the measured parameters. The ratio T_e/T_{iH} is found to be 30 ± 4 and c_H ranges from

1.5% at 0.145 Torr to 4% at 0.03 Torr. These values of c_H multiplied by the plasma density are found to be proportional to the observed H emission as a function of pressure which indicates experimentally that c_H varies in the assumed manner. The arrows in Fig. 3 at the value of v_D/v_e of 0.094 mark the onset of the instability as predicted by the theory for a value of c_H of 1.5%. This prediction agrees well with the experimentally observed threshold. The predicted values of W/nT_e and $\Delta\theta$ near threshold are very sensitive to all parameters so that no reliable predictions are available for $v_D/v_e < 0.12$. The theory[3] does not predict the spectral shape of the turbulent spectrum. We have detailed data on this aspect of the saturation which requires further theoretical consideration.

In conclusion, we have studied in detail the saturated state of the current-driven ion-acoustic instability in a positive-column plasma and find that the saturation of the turbulent state is due to a 1 to 4% H^+-ion concentration present in this experiment and probably in all previous experiments which also used nonbakable vacuum systems. Ion-resonance-broadening theory applied to the H^+ impurity ions appears to be the most plausible mechanism to describe the measured properties of the saturated state of the instability. We are presently building a high-vacuum system with which to study the instability without a background concentration of H^+ ions.

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Energy Deposition in Laser-Heated Plasmas

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The number and energy distribution of suprathermal electrons produced in a laser-heated plasma can be quantitatively obtained directly from the experimental x-ray spectrum with only the assumption that the fast electrons lose energy by bremsstrahlung and electron-electron collisions. The result is independent of the spatial and temporal distribution of electron density and temperature.

The x-ray spectra from laser-irradiated plasmas typically shows an athermal component which cannot be attributed to the radiation from a plasma with a well-defined temperature and hence Maxwellian electron distribution. The hard radiation is believed to be due to energetic electrons produced by resonant absorption, or by laser-plasma instabilities. The correlation between the observed x-ray spectrum and the athermal electron population is usually made by the use of computer models which incorporate various models of the absorption process. In this note I show that a simple direct correlation exists which allows essentially model-independent determination of the fast electron distribution and also direct determination of the energy deposited in fast electrons. I base my analysis on the simple and reasonable assumption that electrons produced in the absorption process, with initial energies well above the temperature of the bulk population, lose energy by radiation and by collisional exchange with the much colder thermal electrons, that collisions among the suprathermal electrons can be ignored, and that the fast-electron density is much less than the thermal-electron density.

The radiation emitted into all solid angles by a