COLLISIONLESS ION-WAVE PROPAGATION AND THE DETERMINATION OF THE COMPRESSION COEFFICIENT OF PLASMA ELECTRONS*

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In the propagation of ionic sound waves in collisionless plasmas, the wave velocity V is given by $V=(\gamma kT_e)^{1/2}m_i^{-1/2}$. Here, k is Boltzmann's constant, T_e the electron temperature, and m_i the ion mass. We have investigated γ, the adiabatic compression coefficient of the electron gas. The value of γ can be 1, 5/3, or 3. The values 1 and 3 should hold for collisionless waves if the waves are isothermal or adiabatic, respectively,[1,2] and the value 5/3 should hold for collision-dominated adiabatic waves. However, the subtleties of collisionless waves are such as to make an experimental study of γ desirable.

The most clear-cut experiments on collisionless waves have been done by Wong, Motley, and D'Angelo.[3] However, their experiments were made in a cesium machine, where the ion temperature T_i and the electron temperature T_e were approximately equal, and the waves were strongly damped. Other experiments[4] have studied the waves under less desirable conditions in which the plasma had too much electron scattering from background gas for clear-cut collisionless waves to occur, magnetic fields were present, boundary effects at the walls of the plasma vessel possibly occurred, and streaming of electrons relative to ions was present. In this experiment, the plasma is formed under conditions such that it is collisionless, no external magnetic field is present, the effects of the walls are negligible, $T_e \gg T_i$, and there is negligible streaming of electrons relative to ions. As noted in Table I, the mean-free paths of the plasma electrons are comparable to the 20-cm diameter of the plasma container. In addition, the plasma is remarkably quiescent, as will be discussed under the topic of electron-temperature measurements.

The experimental apparatus is shown in Fig. 1. Plasma is formed in the simple source, and drifts into the main volume to form a density of about 10^9 cm^{-3}. The plasma source can be quiescent[5] if the voltage and current of the plasma source are adjusted carefully. Ion waves are generated at the transmitting probe by perturbing its voltage with a step function, pulse, or burst of sine waves. The waves are detected by observing the modulation of ion current to the receiving probe. Direct electrostatic coupling between the transmitting and receiving circuits also produces a signal, which is separated from the weaker ion-wave signal by time of flight, as shown in Fig. 2. The time-of-flight technique allows one to perform the velocity

Table I. Properties of plasmas.

Gas	T_e (eV)	$V_{\text{expt.}}\times10^{-5}$ (cm/sec)	$\gamma_{\text{expt.}}$	$N_e\times10^{-9}$ (cm^{-3})	$P\times10^3$ (Torr)	Electron mean-free path (cm)
			Quiescent plasmas			
He[a]	9.63	15.1	0.94	0.38	2.5	20
Ne	0.91	2.05	0.94	3.8	13.0	15
A	0.64	1.26	1.00	2.4	2.8	70
Kr	0.84	0.90	0.81	4.4	2.1	95
Xe	0.79	0.79	1.03	11.0	1.4	140
			Noisy plasmas			
Ne	1.62	2.25	0.63	4.0	12.8	16
A	1.38	1.57	0.72	2.6	2.8	70
Kr	1.08	1.13	0.99	2.3	1.5	135
Xe	1.43	0.94	0.82	6.5	1.4	145

[a] Electrostatic trapping and good thermalization of the plasma electrons was not observed.

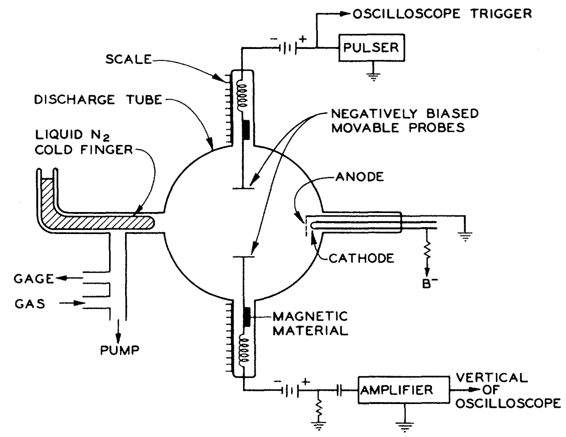

FIG. 1. Schematic of experimental apparatus. The plasma source is simply a coarse wire cage (anode) enclosing a hot tungsten cathode. The background pressure is about 10^{-6} Torr, the operating pressure being about 10^{-3} Torr. A high-pass filter placed between the receiving probe and the oscilloscope removes low-frequency noise originating in the power line.

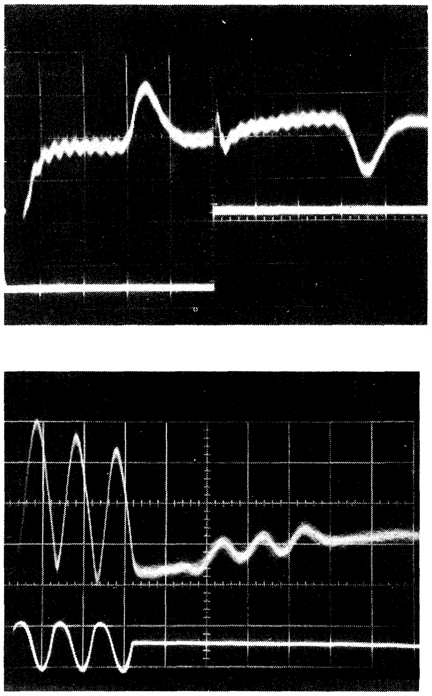

FIG. 2. Ion-wave signals generated by a step function (top) and a burst of sine waves (bottom). In the upper figure, a positive-voltage step is placed on the transmitting probe at zero time (lower trace) and a positive change in the receiving potential is observed at 60 μsec (upper trace). A negative-voltage step placed on the transmitting probe at 100 μsec results in a negative change in the receiving potential at 160 μsec. The time scale is 20 μsec per large division, and the plasma is formed of xenon. (The upper trace is inverted relative to the lower.) In the lower figure, a burst of sine waves is placed on the transmitting probe at zero time (lower trace). The receiving probe detects first an electrostatically coupled signal from the transmitting probe (upper trace, larger burst of sine waves), and later an ion-wave signal (upper trace, smaller burst of sine waves). The time scale is 10 μsec per large division, and the plasma is formed of xenon.

measurements before reflections from the walls can interfere, although under the experimental conditions discussed here, no reflections have been observed.[6] Our preliminary measurements and basic experimental techniques have been discussed elsewhere.[6,7]

Typical experimental data for pulses are plotted in Fig. 3. The slope of each curve is the experimental velocity for the plasma concerned. The failure of each curve to pass through the origin apparently represents the very rapid propagation of the signal through sheaths covering the transmitting and the receiving electrodes. The effect of plasma drift to the container wall was evaluated by observing the Doppler shift in ion-wave velocity for waves propagating from the center of the container to the wall, relative to waves propagating in the opposite direction. The maximum plasma drift rate was about 10% of the wave velocity. Since the transmitting and receiving electrodes are normally symmetrically placed about the center of the container, the plasma drift influences the ion-wave velocity only to second order and can be neglected. The plasma drift velocity also allows one to infer that the ions are at approximately room temperature. Calculations show that there should be negligible slowdown of the waves due to ion-neutral collisions.[8] For these calculations, the high-frequency content of a pulse was computed from the observed rise time. Dispersion effects[1,2] are not expected, as we have found that the waves do not propagate in the theoretically predicted dispersive region near the ion-plasma frequency.[9]

The basic problem in comparing the theoretical ion-wave velocity with the experimental velocity has been in obtaining reliable measurements of the electron temperature, T_e. We found that in all the gases studied except helium, the bulk of the electrons are trapped electrostatically in a potential well a few volts more positive than anode potential. These

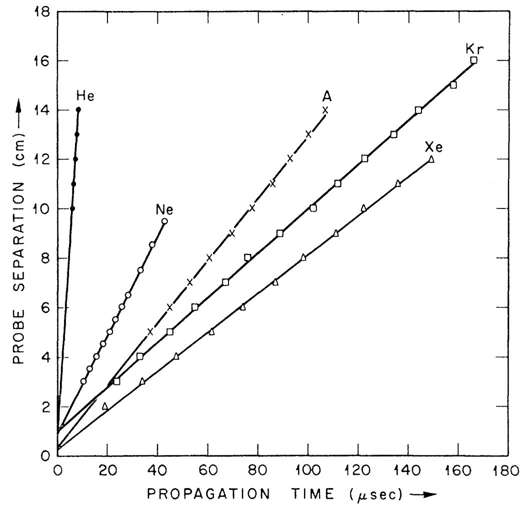

FIG. 3. Some velocity measurements for helium, neon, argon, krypton, and xenon plasmas. These curves represent the data noted in Table I. Vertically is plotted the probe separation, and horizontally the time, measured from the time of pulsing, required for the leading edge of a pulse to appear on the receiving probe.

trapped electrons apparently thermalize at the very slow rate given by collision processes,[10] probably becuase the plasma is remarkably noise-free. Consequently, Langmuir probes used to measure the electron temperature must be quite small in area or else they drain away the trapped electrons so rapidly that the equilibrium energy distribution is distorted. In our plasma volume of 12 liters at a density of about 10^9 cm^{-3}, a cylindrical wire probe having an area of 0.06 cm^2 apparently gives reliable results.

The experimental results are listed in Table I and show that under the given conditions of operation, the value of γ best corresponds to 1. Thus, the ion waves appear to propagate with collisionless, isothermal compression taking place in the electron gas. The data refer to the velocity of the leading edge of ion-wave pulses, and so correspond to the signal velocity[11] in the plasma. We have shown experimentally that the pulse velocity is identical to the phase velocity, V, by a comprehensive series of measurements using sine-wave bursts. The data also show that adjusting the plasma source to be noisy leads to an increase in the plasma electron temperature with a corresponding increase in the ion-wave velocity.

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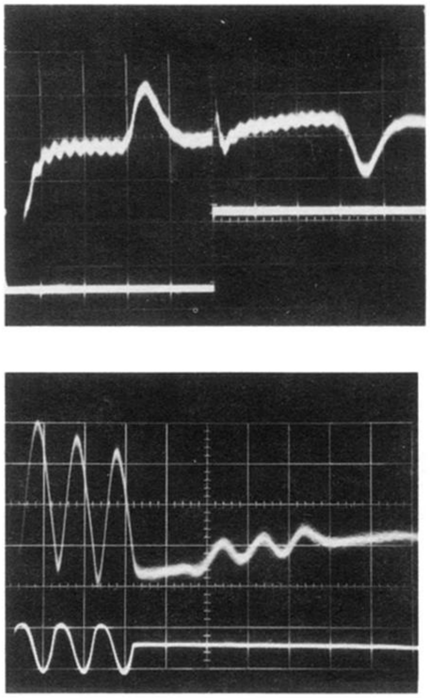

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