LOCKHEED MARTIN ENERGY RESEARCH LIBRARIES
3 4456 0515941 3

2

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

ORNL-4089
UC-20 – Controlled Thermonuclear Processes

SOUND WAVES IN PLASMAS – A BASIC PHENOMENON AND A SIMPLE DIAGNOSTIC TOOL

Wm. Denver Jones

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.
UCN-7969
(3 3-67)

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

Printed in the United States of America. Available from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-4089

Contract No. W-7405-eng-26

THERMONUCLEAR DIVISION

SOUND WAVES IN PLASMAS – A BASIC PHENOMENON AND A SIMPLE DIAGNOSTIC TOOL

Wm. Denver Jones

JULY 1967

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

LOCKHEED MARTIN ENERGY RESEARCH LIBRARIES
3 4456 0515941 3

SOUND WAVES IN PLASMAS – A BASIC PHENOMENON AND A SIMPLE DIAGNOSTIC TOOL

Wm. Denver Jones

ABSTRACT

This report deals primarily with the experimental aspects of ionic sound waves. A brief history and discussion is given of some of the more important ionic-sound-wave work. The experiments at the Oak Ridge National Laboratory are discussed in some detail. Note is made of the plasma diagnostic capabilities of these waves.

The following is the content of an invited talk given by the author at the Southeastern Section Meeting of The American Physical Society, December 1–3, 1966, at Vanderbilt University, Nashville, Tennessee. The present report arises from the need for an official manuscript suitable for distribution to individuals and institutions requesting copies of the talk.

Ionic sound waves, or as they are sometimes called, ion acoustic waves, are low-frequency, longitudinal density oscillations in a plasma. They can be either propagating waves or standing waves. An ionic sound wave in a plasma is similar to an ordinary sound wave in a gas. Like ordinary sound, an ionic sound wave is a longitudinal wave with the momentum due to the mass density of the medium and the restoring force due to thermal pressure. Since ions are several thousand times as heavy as electrons, the ions make up most of the mass density of the plasma medium and thus supply most of the momentum of the wave. On the other hand, for most of the experiments which will be discussed, the electrons are hotter and consequently supply most of the restoring force of the wave. The velocity thus depends on the temperature of the electrons but on the mass of the ions.

The experimental studies of ionic sound waves can be classed in two broad categories – those involving standing waves and those involving propagating waves. All of the early work was done on standing ionic sound waves, whereas most of the later and present-day work involves propagating waves.

The earliest work in this field is thought to be the prediction of these waves in ordinary discharge-tube plasma by Tonks and Langmuir in 1929.[1] Both the name "ionic sound waves" and the dispersion relation shown in Eq. (1) appear in this paper:

---

[1]L. Tonks and I. Langmuir, *Phys. Rev.* **33**, 195 (1929).

$$\nu = \left[\frac{4\pi n e^2}{m_i(4\pi^2 + \lambda^2/\lambda_D^2)} \right]^{1/2} , \tag{1}$$

where

$$\lambda_D = \left(\frac{kT_e}{4\pi n e^2} \right)^{1/2} \equiv \text{Debye distance.}$$

Here n is electron density, m_i is ionic mass, λ is wavelength, e is the charge on an electron, T_e is electron temperature, and λ_D is the plasma Debye distance. In this paper the authors also described some experimental work; however, their observations do not clearly show the predicted dispersion relation. For the case of $\lambda >> 2\pi\lambda_D$, which is the usual case for ionic-sound-wave experiments, the dispersion relation reduces to the following equation:

$$\nu = \frac{1}{\lambda}\sqrt{\frac{\gamma k T_e}{m_i}}, \quad \text{or} \quad v = \nu\lambda = \sqrt{\frac{\gamma k T_e}{m_i}} , \tag{2}$$

where γ, the compression coefficient of the electron gas, has been inserted to make the equation hold for conditions more general than those considered by Tonks and Langmuir. Equation (2), which is a good approximation only when $T_e >> T_i$, shows explicitly the velocity dependence on electron temperature but on ionic mass, as noted before. For the case where the electron and ion temperatures are comparable, which they are not for normal discharge plasmas, the wave velocity can be shown (by modifying the treatment by Fried and Gould,[2] for example) to be given by the following expression:

$$v = \sqrt{\frac{kT_e + 3kT_i}{m_i}} , \tag{3}$$

where T_i is the temperature of the plasma ions.

The first clear-cut observation of ionic sound waves was made in 1933 by R. W. Revans.[3] In both spherical and cylindrical mercury discharge-tube plasmas, he was able to show unambiguously the presence of radial standing ionic sound waves. Figure 1 shows the type of data obtained by Revans when he moved a positively biased probe across the diameter of a spherical tube. The pattern of the standing waves and their wavelengths could be determined quite accurately by observing the maxima and minima of the dc electron current to the positive probe as a function of position of the probe. Utilizing this technique, he could pick out not only the fundamental frequency, but by properly adjusting the discharge parameters he could preferentially excite several harmonics.

Although ionic sound waves must surely have been present in many experiments and must have baffled many experimenters in the intervening years, apparently after Revans' experiments in

---

[2]B. D. Fried and R. W. Gould, *Phys. Fluids* **4**, 139 (1961).

[3]R. W. Revans, *Phys. Rev.* **44**, 798 (1933).

ORNL DWG. 67-2144

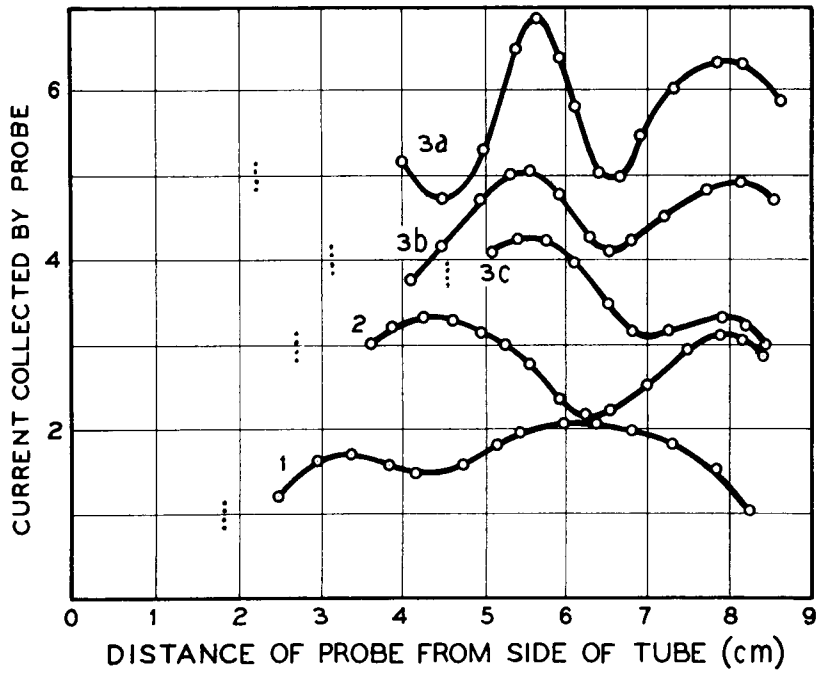

Fig. 1. Variation of Electron Current to a Positively Biased Probe in a Spherical Discharge Tube as a Function of Probe Position, by Revans.[3] The dotted lines indicate the position of the filament. From the maxima and minima of the current, the wavelengths of standing radial ionic sound waves could be determined.

1933 this plasma phenomenon went unrecognized for almost 30 years. It was not until 1961, when Alexeff and Neidigh at Oak Ridge National Laboratory observed and correctly identified standing ionic sound waves in a reflex-discharge plasma column, that the next literature appeared on these waves.[4] Figure 2 shows their apparatus. The plasma column was formed between the hot cathode and the reflecting anticathode. Note that the plasma column was supported by a magnetic field parallel to the column. Whereas the standing waves which had been observed by Revans were always radial standing waves, the ones observed in the column shown here were longitudinal standing waves. The oscillations produced in the plasma by these waves could be observed either by electrostatic probes placed in the plasma or by photomultiplier tubes monitoring the light from the plasma. Typical oscillations are shown in the multitrace oscillograms in Fig. 3. These photos show the fundamental and first overtone, which could be excited separately by proper adjustment of the discharge parameters in a xenon plasma column 23 cm long. The theoretically expected dispersion relation for ionic sound waves is as follows:

---

[4]I. Alexeff and R. V. Neidigh, *Phys. Rev.* **129**, 516 (1963).

ORNL-LR-DWG 69140

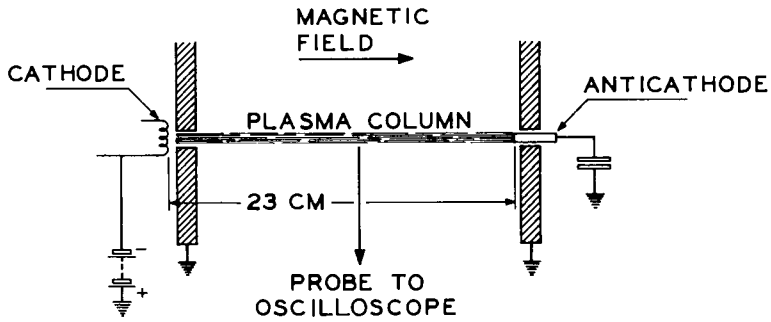

Fig. 2. Apparatus for Producing the Magnetically Supported Plasma Column in Which Alexeff and Neidigh[4] Observed Standing Longitudinal Ionic Sound Waves.

$$\nu = \frac{1}{\lambda}\left[\frac{\gamma k T_e}{m_i}\right]^{1/2}, \tag{4}$$

where ν and λ are the frequency and wavelength, respectively, of the wave. For a standing wave, λ should be limited by the dimensions of the plasma. Over a large range of plasma column length, Alexeff and Neidigh were able to show that the fundamental wavelength was equal to twice the length of the column. This is shown in Fig. 4, where frequency is plotted as a function of the reciprocal of the plasma column length. The superimposed straight line shows the dependence theoretically expected. The note regarding the possible resonance is not of interest in the present discussion. Alexeff and Neidigh were also able to verify the inverse square-root dependence of the frequency on ionic mass. This is shown in Fig. 5, which shows frequency variation with ionic mass for two different column lengths. The two superimposed straight lines again show the expected theoretical dependence. Though T_e could not be varied in a systematic manner, the dispersion relation was accurately obeyed for the different values of T_e which were observed for the different gases used.

Concurrent with some of the experiments of Alexeff and Neidigh on ion acoustic waves, other people were becoming interested in ionic sound waves, both experimentally and theoretically. Burton Fried and Roy Gould published a comprehensive theoretical paper on ionic sound waves in 1961, treating the phenomenon from both the hydrodynamic and the Vlasov-formalism viewpoints.[2] In this paper the phenomenon of Landau damping of ionic sound waves was discussed at length.

During this same time F. W. Crawford at Stanford was making experimental observations of plasma oscillations in cylindrical discharges and was interpreting these observations in terms of

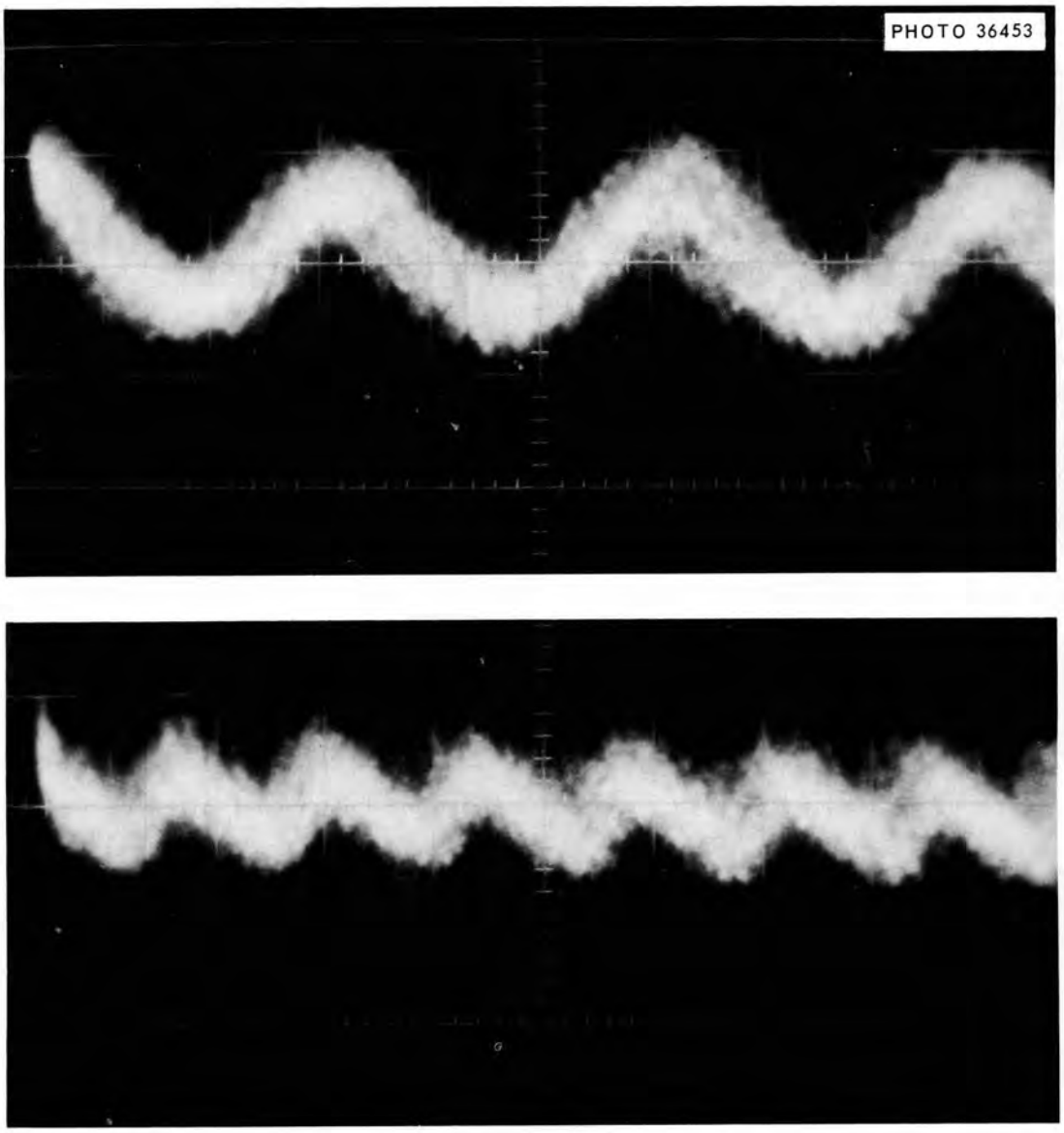

Fig. 3. Fundamental and First Overtone of Standing Ionic Sound Waves Observed by Alexeff and Neidigh[4] in the Plasma Column Shown in Fig. 2. Xenon plasma; 20 μsec/cm.

standing radial ionic sound waves.[5] Figure 6 shows a diagram of the apparatus used by Crawford, as well as typical rf signals picked up on a ring detector outside the tube. Note that no magnetic field was used. Over a wide range of tube diameters, the observed frequencies were found to be related in the manner predicted for radial standing waves. During this time, also, Consoli, Le Gardeur, and Slama in France were making observations of longitudinal standing waves in a cylindrical reflex discharge plasma supported by a variable magnetic field.[6] Although the results reported verbally make it appear that their observations were very detailed and methodically carried out, unfortunately, the amount of data published in this short note was sparse.

Thus far, only *standing* ionic sound waves have been discussed. Probably the first successful experiments to be done with *propagating* ionic sound waves were reported by some Japanese workers, Hatta and Sato, in 1961.[7] These workers derived, using hydrodynamic theory, a dispersion relation for ionic sound waves which takes into account the effect of collisions between ions and neutrals in the plasma. The dispersion relation found predicts that not only should the waves be damped by ion-neutral collisions but that they should also be slowed down. Hatta and Sato were able to experimentally verify both of these predictions using propagating ionic sound waves

[5]F. W. Crawford, *Phys. Rev. Letters* **6**, 663 (1961).

[6]T. Consoli, R. Le Gardeur, and L. Slama, *Compt. Rend.* **253**, 1923 (1961).

[7]Y. Hatta and N. Sato, *Proc. Intern. Conf. Ionization Phenomena Gases, 5th Conf., Munich, 1961*, vol. I, p. 478, 1962.

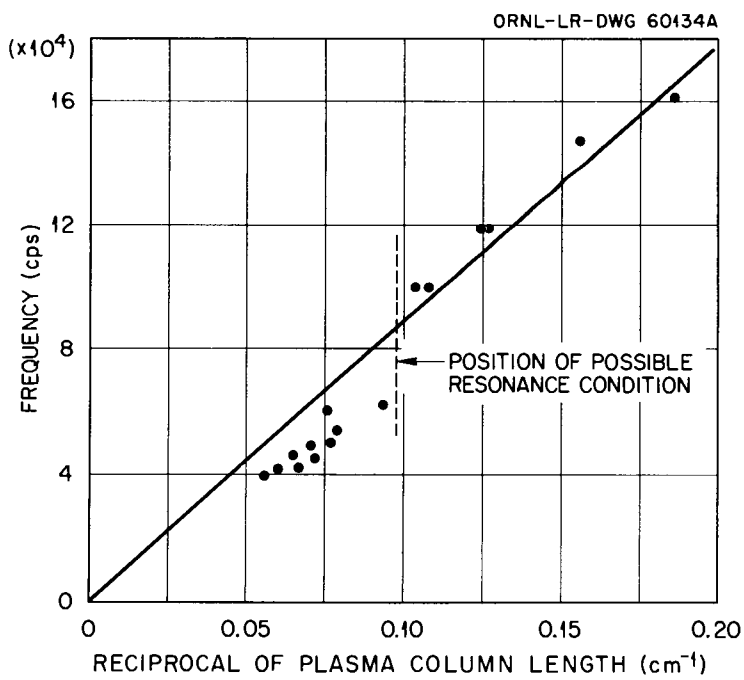

Fig. 4. Ionic Sound Wave Frequency Dependence on Plasma Column Length, as Observed by Alexeff and Neidigh.[4] An argon plasma was used.

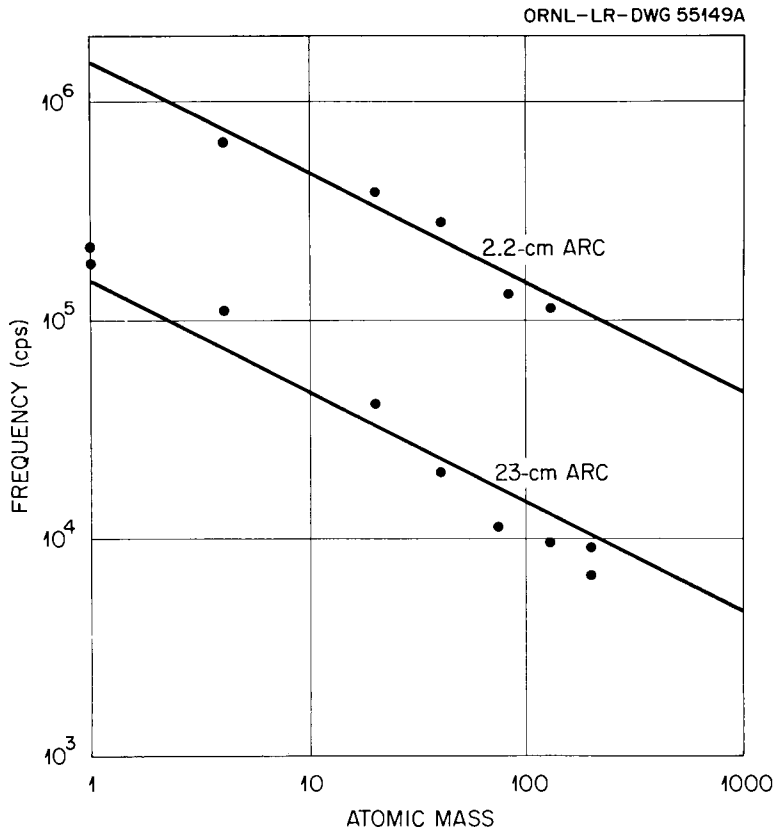

Fig. 5. Frequency Dependence of Ionic Sound Waves on Ionic Mass for Waves in a Plasma Column, as Observed by Alexeff and Neidigh.[4]

generated by superimposing a sinusoidally varying potential on a floating mesh grid sticking into the plasma.

Following the experiments of Hatta and Sato, there was a flurry of experiments attempting to study ionic sound wave propagation in cylindrical discharge-tube-type plasmas. Prominent among these experiments were those of Crawford and Self at Stanford[8] and of Barrett and Little in England. [9] These workers, however, found results which were much less clear-cut than those reported by Hatta and Sato.[7] Using a somewhat different technique of excitation, these workers found several different types of waves to be generated simultaneously. Despite the valiant theoretical efforts of such people as Pekarek in Czechoslovakia[10] and L. C. Woods in England,[11]

---

[8]F. W. Crawford and S. A. Self, *Compt. Rend. Conf. Intern. Phénomènes Ionisation Gaz, 6e, Paris, 1963*, ed. by P. Hubert and E. Cremieu-Alcan, vol. III, p. 129, SERMA, Paris, 1963.

[9]P. J. Barrett and P. F. Little, *Phys. Rev. Letters* **14**, 356 (1965).

[10]L. Pekarek, *Compt. Rend. Conf. Intern. Phénomènes Ionisation Gaz, 6e, Paris, 1963*, ed. by P. Hubert, vol. 2, p. 133, SERMA, Paris, 1964.

[11]L. C. Woods, *J. Fluid Mech.* **23**, 315 (1965).

ORNL DWG. 67-2142

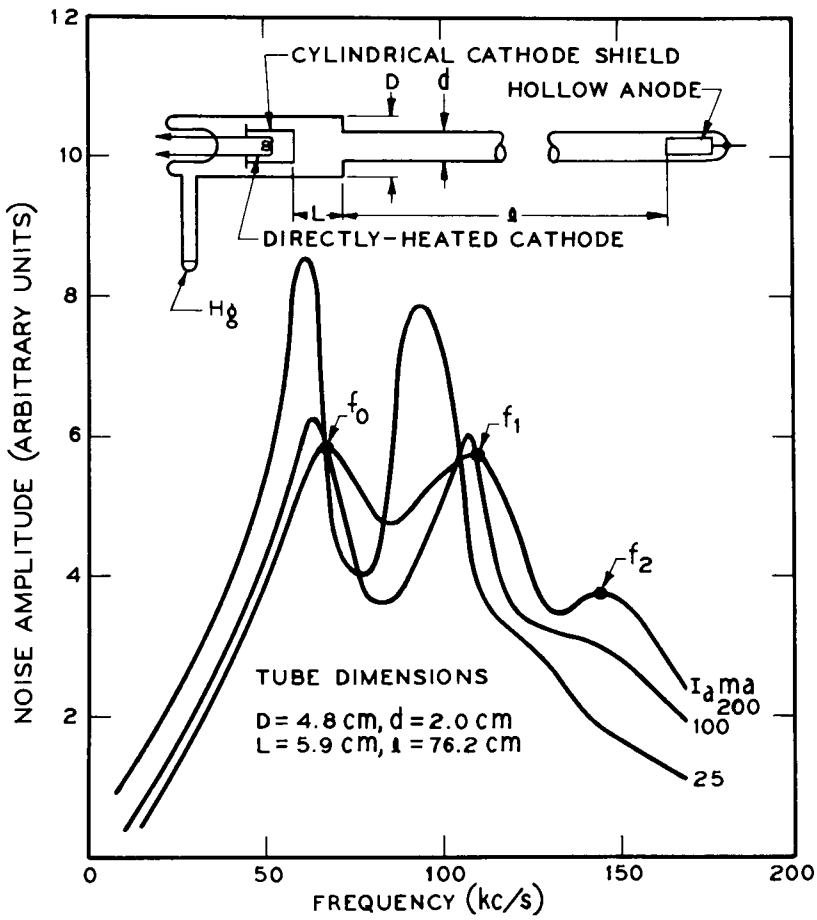

Fig. 6. Experimental Discharge Tube Used by Crawford,[5] and Typical Spectra of Low-Frequency Fluctuations Interpreted as Standing Radial Ionic Sound Waves.

taking into account such things as two-stream instabilities, wall losses, ionization rates, etc., many of the observations made in these experiments have not yet been satisfactorily explained.

Somewhat more clear-cut results have been achieved by experimenters using diffusion-type plasma columns supported by magnetic fields. For example, Bardet and Consoli of France were able to demonstrate the inverse square-root dependence of the propagation velocity on ionic mass.[12] At Princeton University, Wong, Motley, and D'Angelo were able to make a quantitative measurement of the Landau damping of ionic sound waves in magnetically supported plasma columns generated from alkali metal vapors.[13] Figure 7 shows the Princeton machine. A hot plate at one end of the machine is exposed to a beam of either cesium vapor or potassium vapor gen-

[12]R. Bardet and T. Consoli, *Phys. Letters* **16**, 117 (1965).

[13]A. Y. Wong, N. D'Angelo, and R. W. Motley, *Phys. Rev. Letters* **9**, 415 (1962).

erated in a hot oven below. On contact, the vapor is ionized and the resulting plasma diffuses out along the supporting axial magnetic field to form a column of plasma. In both cesium and potassium plasma columns, these workers found excellent agreement between experimental observations and the predictions of the theory of Landau damping. In addition to the damping work, these authors made phase velocity measurements. In agreement with theory, they found the phase velocity to be dispersionless and to be independent of ion density. These workers were also able to measure plasma drift velocity along magnetic field lines by propagating ionic sound waves in the direction of plasma drift and against the direction of plasma drift and observing the Doppler shift in the wave velocity. Recently Wong was able to show theoretically why it is easier to do meaningful experiments in plasma columns which are supported by strong magnetic fields by showing that the plasma boundary effects become unimportant if the ion Larmor radius is much smaller than the plasma radius.[14] This is a much less stringent condition than one might a priori have expected, which is that the ion acoustic wavelength itself would have to be much smaller than the plasma radius.

All of the experiments involving propagating ionic sound waves which have been discussed thus far have been done in cylindrical geometry. As already indicated, unless strong supporting

[14]A. Y. Wong, *Phys. Fluids* **9**, 1261 (1966).

ORNL DWG. 67-2143

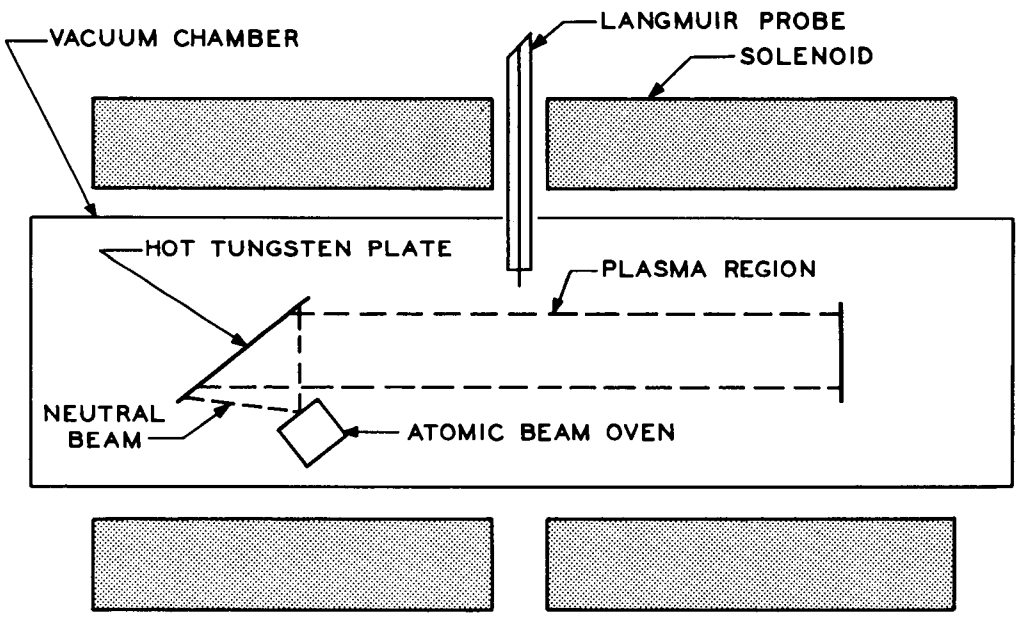

Fig. 7. Experimental Device Used by Wong, Motley, and D'Angelo[13] to Generate Alkali Plasma Columns for the Study of Propagating Ionic Sound Waves.

magnetic fields are employed, this can lead to complicating plasma boundary effects as well as to strong damping due to heavy plasma loss to the walls. Also, in none of these experiments was the velocity measured directly. The standard procedure was to look for phase shifts between the generating signal and the detected one. Because the plasma is a good conductor, this technique can encounter severe difficulties due to coupling between transmitter and receiver probes.

In an effort to circumvent both the plasma boundary problem and the problems associated with phase-shift measurement, at Oak Ridge for the past three years our measurements have been made in spherically shaped plasmas using a so-called time-of-flight technique. The scheme is to locate the ionic-sound-wave experiment in the interior region of a volume of plasma large enough so that the measurement of interest is over before the wave has had time to propagate to the surface of the plasma and experience boundary effects. The time-of-flight technique simply means that we turn off the driving signal at the ion wave source before the ion wave has had time to propagate to the detector, so that only the ionic sound wave signal is present at the detector at the time of measurement. Measuring the time elapsing between the generation time and the detection time gives a measure of the velocity of propagation of the wave between the two probes, whose physical separation is known. For the remainder of the report, a brief discussion of some of the Oak Ridge experiments will be given. Many of these experiments have been discussed in detail elsewhere,[15] but some of them are current experiments still in the preliminary stages of development.

Figure 8 shows the apparatus we typically use. The measurements are made in a spherical glass discharge tube some 20 cm in diameter. We use plasmas made from the rare gases – Xe, Kr, A, Ne, and He. The anode-cathode assembly, seen on the right-hand side of the tube, provides a source of energetic electrons, which, by way of ionizing collisions with the background gas atoms, generate the plasma.

The ionic sound waves are propagated between the two negatively biased probes. If a surface such as one of these probes is biased negatively with respect to the plasma, the probe will then repel the electrons in the plasma but will attract the positive ions. The result is that right next to the probe surface there is a region having more ions than electrons, or, in other words, the probes are surrounded by positive ion sheaths. The upper probe is used as a source of ionic sound waves, while the lower probe is used as a detector. The pulser unit shown is used to generate time variations in the potential on the emitter probe to produce the ion waves.

The negatively biased detector probe is connected to ground through a small resistor, so that it draws an ion current from its sheath. If the sheath structure is changed by an ion density perturbation such as an ionic sound wave, this event will be evidenced as a change in the ion current to the probe.

You will note that the emitter and detector probes are arranged so that they can be moved to change the spacing between them, without having to enter the discharge tube. This is accom-

---

[15]W. D. Jones and I. Alexeff, *Proc. Intern. Conf. Phenomena Ionized Gases, 7th Conf., Belgrade, 1965*, ed. by B. Perovic and D. Tosic, vol. II, p. 330, Gradevinska Knjiga Publishing House, Belgrade, 1966.

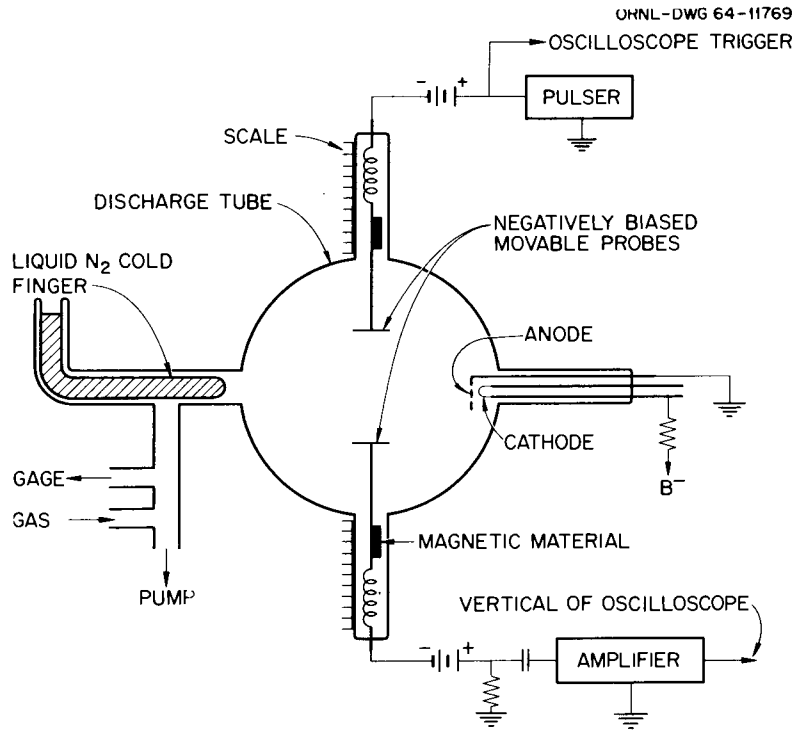

Fig. 8. Apparatus Typically Used at Oak Ridge for Studying the Properties of Propagating Ionic Sound Waves.

plished by simply attaching a piece of magnetic material such as an iron bolt to each one, so that they can then be easily moved by an external bar magnet, for example. The constant source of gas and the vacuum pump system allow the gas in the discharge tube to be continually renewed, thus preventing buildup of impurities. The cold trap further reduces the impurity level in the system and is an essential feature of the apparatus. Not shown in the figure are two probes, one of which is a Langmuir probe allowing us to measure the electron temperature of the plasma and the other an incandescent probe[16] allowing us to vary the electron temperature.

Figure 9 shows some typical ionic-sound-wave data, using both step-function voltages and sine-wave voltages on the emitter probe. The lower traces in each photo show the driving signals, while the upper traces show the received signals. The time elapsing between the generation of the waves and the first detection of the wave is taken to be the propagation time of the waves. Note the large directly coupled signals, whose presence is what makes it necessary to use the time-of-flight technique.

---

[16] I. Alexeff and W. D. Jones, *Appl. Phys. Letters* **9**, 77 (1966).

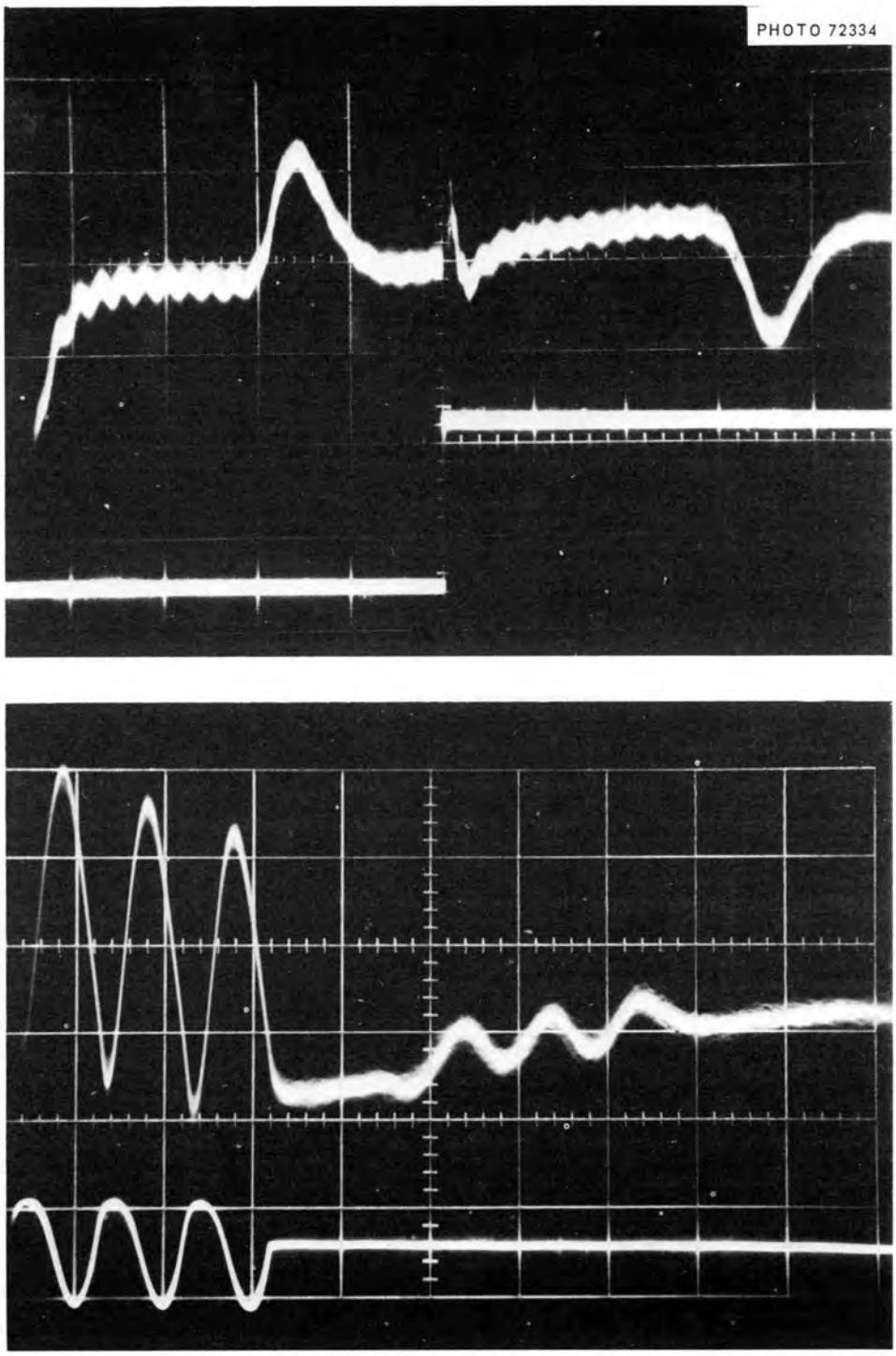

Fig. 9. Typical Time-of-Flight Ionic-Sound-Wave Data, Using Both Step-Function Voltages and Sine-Wave Voltage Bursts on the Transmitter Probe. The lower traces in each photo show the driving signals, while the upper traces show the received signals.

If the spacing between the emitter and detector probes is varied and the propagation time for each spacing is measured, data such as are shown in Fig. 10 are obtained. Note that these points show very little scatter from a straight line, attesting to the general stability of the experiment. The velocity of the ionic sound wave is given by the slope of the straight line and for this case is about 10^5 cm/sec. Generally, velocities obtained in this manner agree quite closely with those predicted theoretically using Eq. (2). From this figure we see another interesting feature, and that is that if we extrapolate the straight line, zero propagation time does not correspond to zero probe spacing. The discrepancy is of the order of 1 cm. We interpret this distance to be a measure of the thickness of the ion sheaths on the emitter and detector probes. Thus, from this simple experiment we not only measure the wave velocity, but we also learn something about plasma sheaths.

We have done many simple experiments to investigate the basic properties of these waves. For example, one of the first experiments which we did was simply to verify the inverse square-root dependence of the velocity on ionic mass. The ion mass was varied over a range of better than 30 to 1 by propagating ionic sound waves in all the rare-gas plasmas. Figure 11 shows the dependence of the velocity on ion mass. Again we have plotted probe separation vs propagation time, so that the slope of each line gives the propagation velocity. Except for the helium plasma,

ORNL-DWG 65-7674

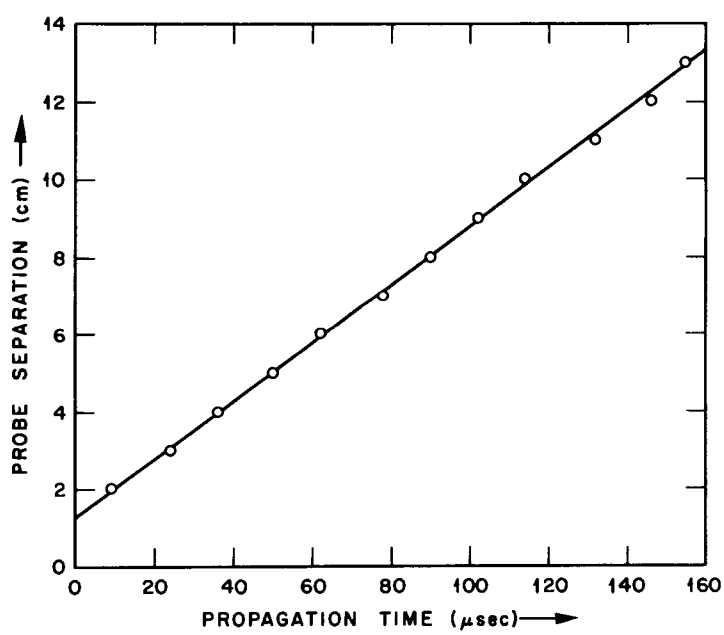

Fig. 10. Typical Time-of-Flight Data for Ionic Sound Wave Propagation in a Xenon Plasma, Using Pulses. Time is measured from the beginning of the driving pulse to the leading edge of the response signal. The slope of the line of best fit gives the average velocity of the waves.

ORNL DWG. 65-7153

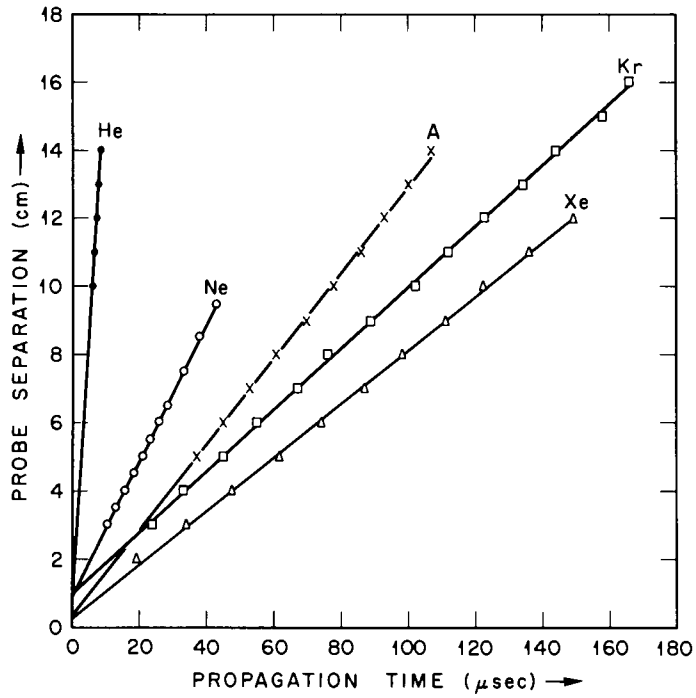

Fig. 11. Ionic-Sound-Wave Data, Using Pulses, Showing the Dependence of Wave Velocity on Ionic Mass. For the four heaviest gases the electron temperature was about 1 eV, whereas for helium it was about 9 eV.

the electron temperatures of all the plasmas were approximately the same, so that the observed variation is due only to the variation of the ion mass and agrees quite well with theory.

It was not until we learned a few months ago how to vary the electron temperature over wide ranges in a controllable manner[16] that we have been able to systematically check the velocity dependence on electron temperature. Figure 12 shows some data which we have just recently obtained. On the vertical is plotted wave velocity and on the horizontal is plotted electron temperature. We also have superimposed two theoretical curves on the plot. The lower theoretical curve assumes a zero ion temperature. This curve fits the data quite well at the higher temperatures – which is where we normally operate – but obviously begins to deviate at the lower temperatures. The upper theoretical curve takes into consideration that at the lower electron temperatures the thermal pressure of the ions is becoming comparable with the electron thermal pressure and should therefore contribute significantly to the restoring force acting on the waves. Assuming an ion temperature of 1/30 eV leads to good agreement between experiment and theory over the entire range of electron temperature. It should be emphasized that the observed agreement is both quantitative and qualitative, there being no adjustable parameters in these equations other than T_i. Thus we feel that not only have we observed the proper dependence of the wave velocity on elec-

tron temperature but in the process have found a fairly accurate means for determining the ion temperature.

In the comparisons between experiment and theory which have been made so far, it has been implicitly assumed that $\gamma = 1$. Theoretically, γ can be 1, 5/3, or 3. The values of 1 and 3 should hold for collisionless waves if the waves are isothermal or adiabatic respectively. The value of 5/3 should hold for collision-dominated adiabatic waves. To obtain an experimental value for the adiabatic compression coefficient of the electron gas, we used the known values of m_i along with the experimentally measured values of velocity and electron temperature and simply solved for γ in Eq. (2). The experiments seem to indicate quite clearly that γ is indeed near 1.[17] Thus, the ion waves appear to propagate with collisionless, isothermal compression taking place in the electron gas.

We have demonstrated both constructive and destructive interference effects with ionic sound waves. This is most easily done by using two ion wave sources and one detector, or in other words, an "ion wave interferometer." By properly phasing the driving signals on the two emitter

[17] I. Alexeff and W. D. Jones, *Phys. Rev. Letters* **15**, 286 (1965).

ORNL DWG. 66-13026

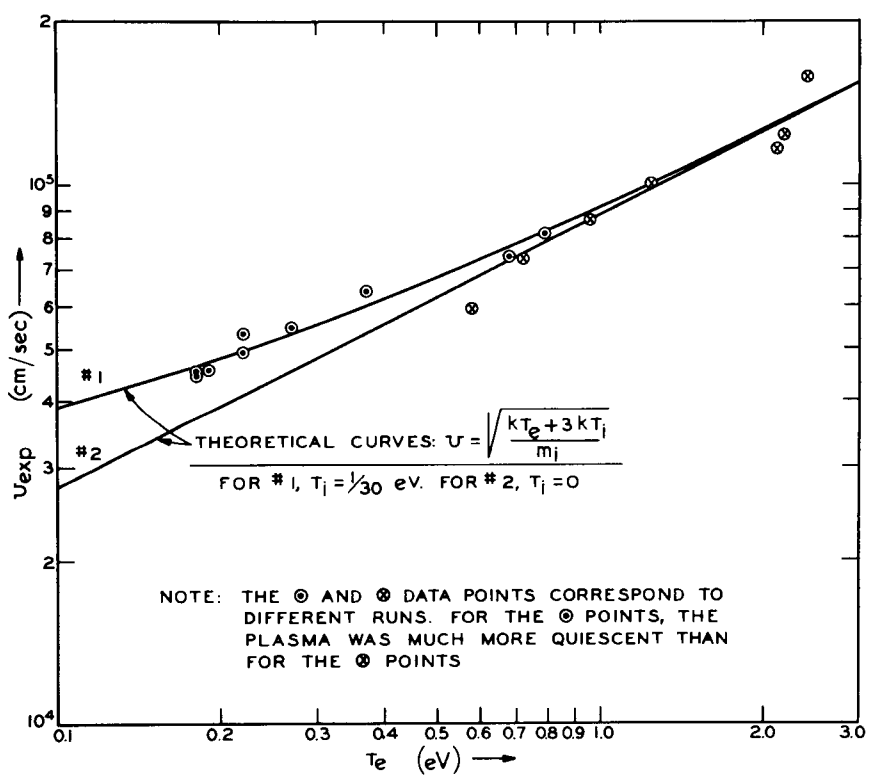

Fig. 12. Ionic Sound Wave Velocity in a Xenon Plasma as a Function of Electron Temperature. At the lower electron temperatures the effect of the ion temperature becomes visible.

probes, for example, the two ion waves can be made to arrive at the detector probes with any relative phase desired, thus leading to interference effects. Figure 13 shows an example of destructive interference. The two bottom traces in each photo show two step-function voltages of opposite polarity used to generate the two ion waves, while the top trace is the detector response to the two signals. When the two generating voltages are well separated in time, the ion wave signals do not interfere; however, as they get closer and closer, the interference becomes more and more complete and then goes away again as soon as the signals are separated again. It is

PHOTO 69117

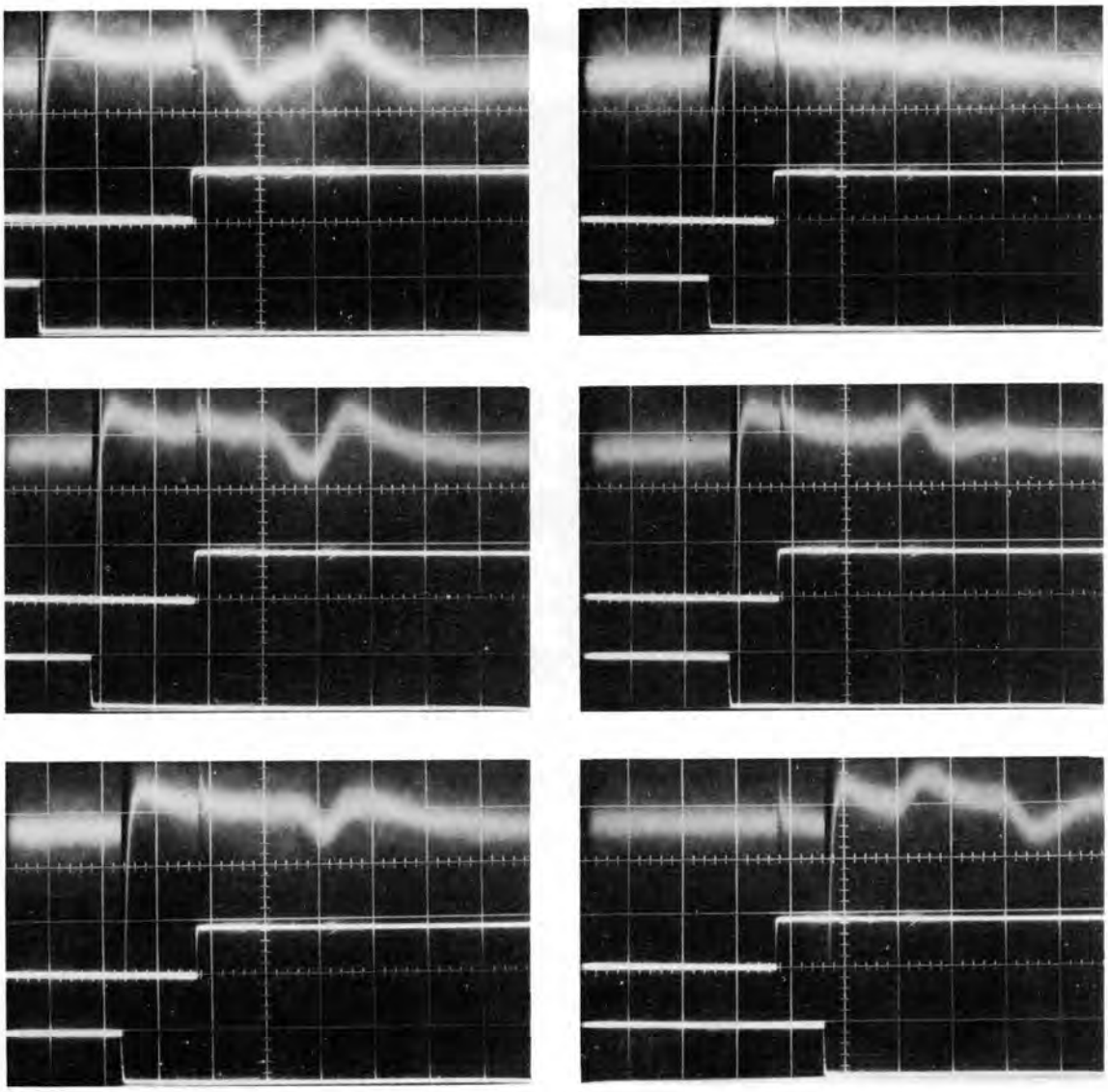

Fig. 13. Destructive Interference of Two Ionic Sound Waves in a Xenon Plasma. For each photo, the uppermost trace shows the detector signal; the central trace shows a positive voltage step applied to one emitter probe at a point constant in time, relative to the time of oscilloscope triggering; the lowermost trace shows a negative voltage step applied to the other emitter at a variable point in time. Note the progressive interference, with essentially complete destructive interference shown in the upper right-hand photo.

noted that maximum interference occurs, not when the two emitter probes are pulsed simultaneously, but rather when one was pulsed somewhat before the other. This is because, in this particular experiment, the two probes were not located equidistant from the detector, so that in order for the two signals to arrive at the same time, the probe farther away had to be pulsed first. As might be expected, if, instead of putting steps of opposite polarity on the two emitters, one puts voltage steps of the same polarity, then constructive interference is observed rather than destructive interference.

Ionic sound waves are easily focused. To demonstrate this property, we used a large concave emitter probe and moved a detector probe radially in and out of the optical focus of the concave emitter. Figure 14 shows how the amplitude of the ion wave signal to the detector varied with the radial position of the detector. The data show quite clearly that the waves are focused by the concave emitter.

That ionic sound waves propagate in a direct line-of-sight manner is easily demonstrated. A metal plate just slightly larger in diameter than the detector probe was arranged so that it could be rotated between the emitter and the detector, thus "shadowing" the detector. Figure 15 shows the amplitude of the detected signal both with and without the metal plate between emitter and detector. The metal plate blocks the waves.

Theoretically,[7] ion acoustic waves are expected to be exponentially damped by background neutral gas. This gas damping occurs because collisions between the ions involved in the wave motion and the background gas atoms rob the ions of their coherent wave motion. Experimentally, we have been able to measure this damping and from it to calculate values of background gas pressure in good agreement with those measured by more conventional means.

We have been able to measure the drift velocity of the ions in our plasma, and hence to calculate approximately the ion temperature, by using a velocity Doppler shift technique. The technique involves simply propagating ion waves alternately in and against the direction of the drifting plasma; the difference in the experimentally observed velocities is, then, just twice the ion drift velocity. Typical data are seen in Fig. 16. The upper curve, showing the faster velocity, is for wave propagation from a probe in the center of the sphere to a probe located near the wall of the tube, that is, in the direction of plasma drifting to the wall. The lower curve is for propagation in the opposite direction. The plasma drift velocity is usually about one-tenth of the wave velocity, giving an ion temperature of about 1/30 eV.

We have tried to see reflections of ionic sound waves at the plasma boundaries. We have looked for reflections from the glass walls of the discharge tube as well as from biased and unbiased metal walls inserted into the plasma. Figure 17 shows a typical arrangement used with a spherical tube. The emitter and detector probes are located approximately at conjugate foci of the reflecting surface. This arrangement should virtually eliminate any $1/r^2$ decrease in the ion wave signals. Thus far, we have been unable to see any evidence for reflections. In light of the fact that standing ionic sound waves do occur in many plasmas, implying reflection of the waves at the boundaries, our failure to observe reflections is not completely understood. Recently, theoretical

ORNL-DWG 65-3506

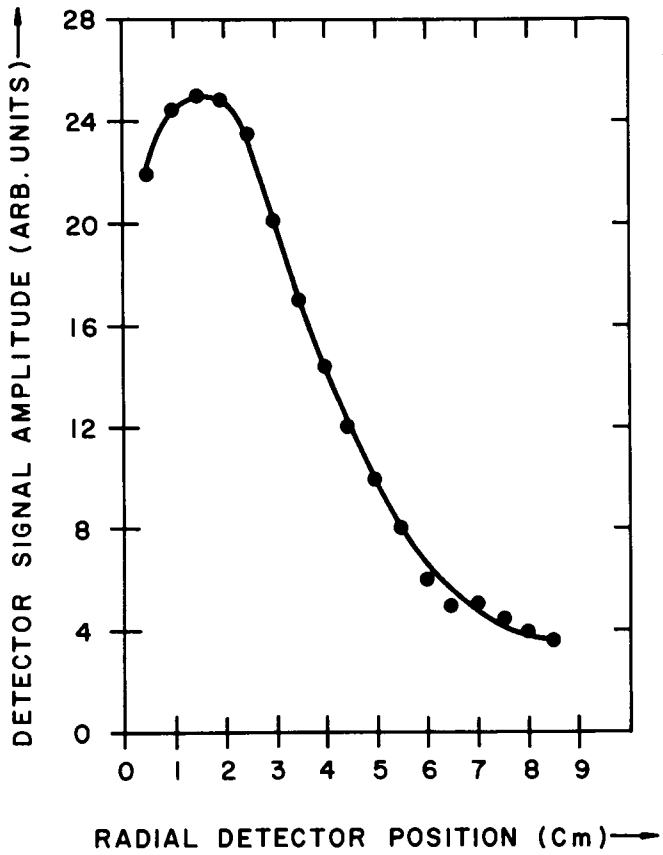

Fig. 14. Focusing of Ionic Sound Waves by Means of an Emitter Probe Having a Concave Surface.

work by some Italian workers – Bertotti, Brambilla, and Sestero – links the presence or absence of reflections to the type of plasma sheath insulating the main plasma from solid surfaces in contact with the plasma.[18] Although our negative results are in agreement with the predictions of the theory, it is not obvious that all of the standing wave experiments support the theory.

Some of the more interesting experiments which we have done have been some recent preliminary experiments involving Landau damping. In our normal discharge plasmas, the average thermal velocity of the electrons is some three orders of magnitude greater than the ion wave velocity, whereas the thermal velocity of the ions is about an order of magnitude lower, so that normally we

[18]B. Bertotti, M. Brambilla, and A. Sestero, *Phys. Fluids* **9**, 1428 (1966).

expect no Landau damping. We have used two techniques to bring about Landau damping. The first is to lower the electron temperature so that the wave velocity begins to approach the average ion thermal velocity.[19] The second is to increase the number of ions in the plasma having velocities near the ion wave velocity.[20] Figure 18 is a plot showing how, for a fixed separation of the emitter and detector probes, the detected wave amplitude decreases as the wave velocity is decreased by lowering the electron temperature. The relatively slight damping occurring at the higher electron temperatures is not completely understood; however, we are fairly confident that the extremely heavy damping setting in at about 0.3 eV is due to Landau damping. The agreement between experiment and theory is partly quantitative and partly qualitative. The theory quantitatively predicts the value of T_e at which the "break" in the damping occurs as well as the rate of the damping, once it begins; however, the apparent agreement with the absolute magnitude of the damping results from normalizing the theoretical curve to one of the experimental points.

The second technique for studying Landau damping takes advantage of the fact that the ion temperature of our plasma is always near room temperature, regardless of what gas we use to form

[19] I. Alexeff, W. D. Jones, and M. G. Payne, *Bull. Am. Phys. Soc.* 11, 843 (1966).

[20] I. Alexeff, W. D. Jones, and D. Montgomery, paper 3R-10 at the Eighth Annual Meeting of the Plasma Physics Division of The American Physical Society, Nov. 2–5, 1966, Boston, Mass. (to be published in the Proceedings).

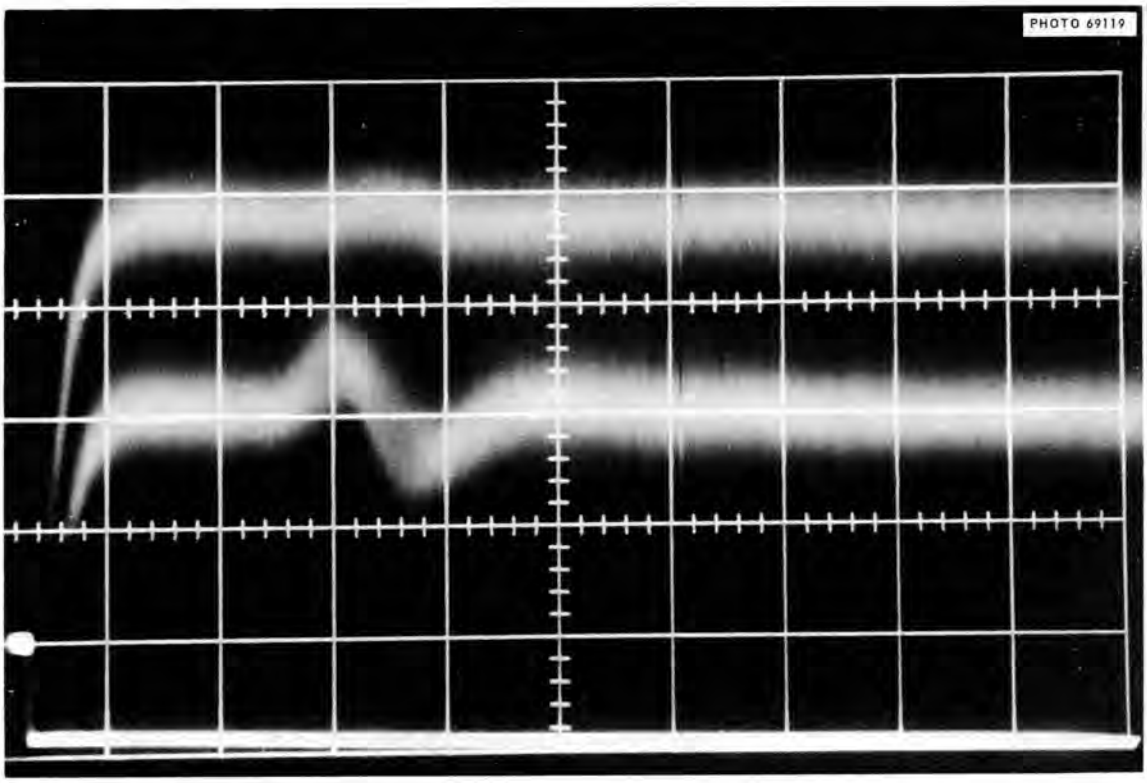

Fig. 15. Rectilinear Propagation of Ionic Sound Waves in a Xenon Plasma. The upper and lower traces show the relative amplitudes of ionic sound waves detected with and without, respectively, a metal plate obstructing the line of sight between emitter and detector.

ORNL-DWG 65-2698

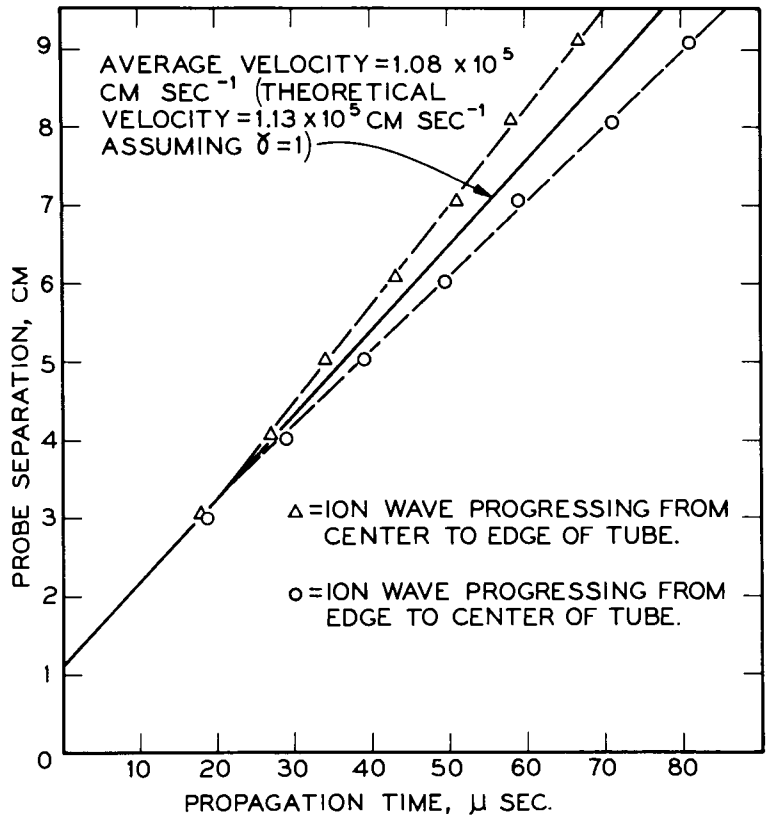

Fig. 16. Doppler Shifting of Ionic Sound Wave Velocity Due to Plasma Drift. The uppermost and lowermost curves are for ion wave propagation in and against, respectively, the direction of the plasma drift to the wall of the discharge tube. The amount of shift provides an estimate of the ion temperature.

the plasma. This means, of course, that the lighter the mass of the ion, the larger its thermal velocity. If one does a few calculations one finds that, fortuitously, the thermal velocity of a helium ion is almost exactly equal to the velocity of an ion acoustic wave in a xenon plasma. Thus, in the second technique we start with a pure xenon plasma; after the ion waves are propagating, we introduce a small number of helium ions into the plasma to lead to the Landau damping. Figure 19 shows some typical preliminary results. The top oscillogram is for wave propagation in a pure xenon plasma. The second one is for a very small fraction of helium ions present. The third oscillogram, showing maximum damping, resulted when only 2% of the plasma was helium ions. In agreement with a theory developed for a two-ion-species plasma, if a sizable fraction of the plasma is made up of helium ions, then the speed of the ion wave increases and the Landau damping goes away. These effects are seen in the bottom photo, where the propagation time is seen to decrease and the amplitude to increase. This second technique is superior to the first technique in several ways, one of the most important being that the bulk properties of the plasma, such as electron temperature, remain essentially unchanged at all times.

These Landau damping experiments have two advantages over those of Wong *et al.* at Princeton.[13] The first is that we are observing the effect without an externally imposed magnetic field. The second is that we can very accurately control the amount of Landau damping, whereas in the Princeton experiments the ratio of ion temperature to electron temperature – and consequently the rate of damping – was rather rigidly fixed by the inherent properties of the plasma machine itself and thus could not be varied much.

Before summarizing, let me mention one further experiment which we and others have performed with apparently some incompatibility in the results. Simple theory predicts an upper frequency cutoff above which ionic sound waves will not propagate. A somewhat more complex theory by Gould indicates that maybe propagation is possible above this critical frequency.[21] In experiments done both by us at Oak Ridge[15] and in Japan by Tanaca *et al.*,[22] cessation of wave propagation has been observed always somewhat below the predicted critical frequency; however, G. M. Sessler at Bell Telephone apparently has seen ion wave propagation *above* the predicted cutoff frequency.[23] The resolution of these seemingly incompatible results remains to be made.

---

[21]R. W. Gould, *Phys. Rev.* **136**, A991 (1964).

[22]H. Tanaca, M. Koganei, and A. Hirose, *Phys. Rev. Letters* **16**, 1079 (1966).

[23]G. M. Sessler, *Phys. Rev. Letters* **17**, 243 (1966).

ORNL-DWG 65-4602

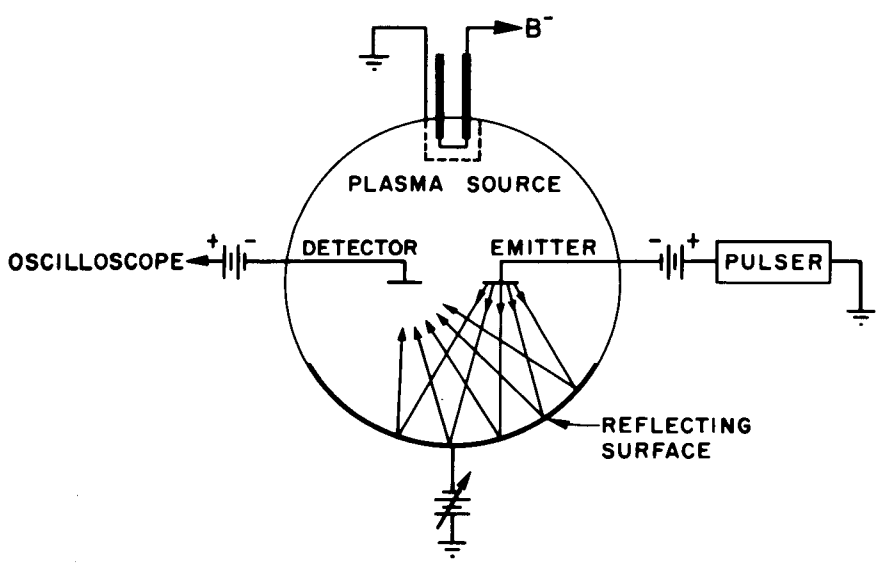

Fig. 17. Typical Arrangement Used to Look for Reflection of Ionic Sound Waves. The emitter and detector probes are located approximately at conjugate foci of the reflecting surface, thus eliminating any $1/r^2$ (geometrical) decrease in signal strength.

ORNL DWG. 66-13056

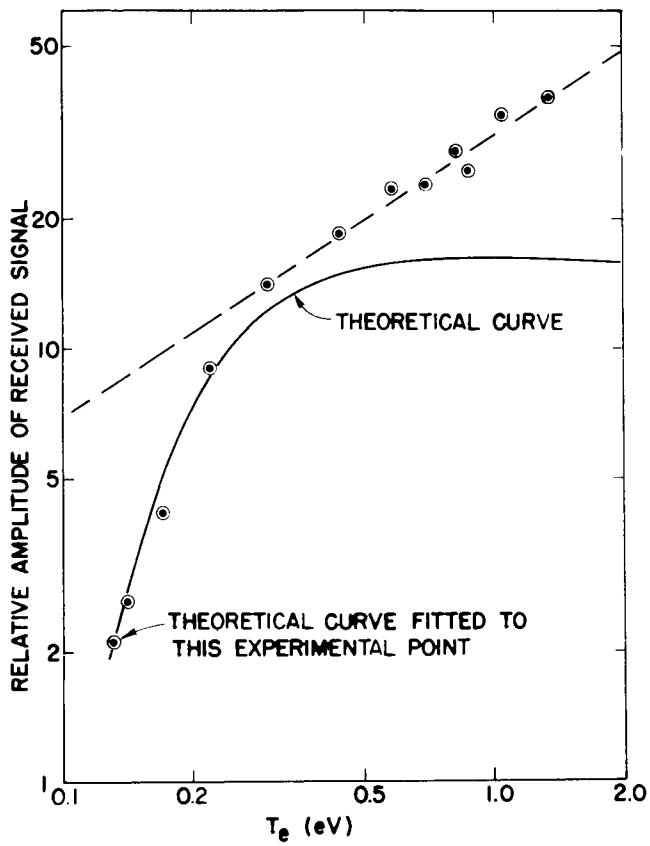

Fig. 18. The Experimentally Observed Variation in Wave Amplitude as a Function of Electron Temperature. Note that the theoretical curve correctly predicts the severe damping at low electron temperatures as well as the change of slope at approximately 0.3 eV. The theoretical curve does not predict the slow variation of amplitude with electron temperature at the highest temperature values. 40-kHz sine-wave bursts were used.

In summary, ionic sound waves seem to be an almost universal plasma phenomenon, both as observed experimentally and as predicted theoretically. While many of the experimental results are well understood and have provided welcome confirmation of basic plasma theory, some of the observations are still not completely resolved. These waves can be very useful as a diagnostic tool for studying plasmas, with the full realization of their potential in magnetically supported plasmas probably still to be realized. One interesting aspect of ionic-sound-wave experiments is that most, if not all, can be done with simple inexpensive apparatus available in most laboratories, and therefore can be readily adapted to student-type academic experiments.

ORNL DWG. 66-13027

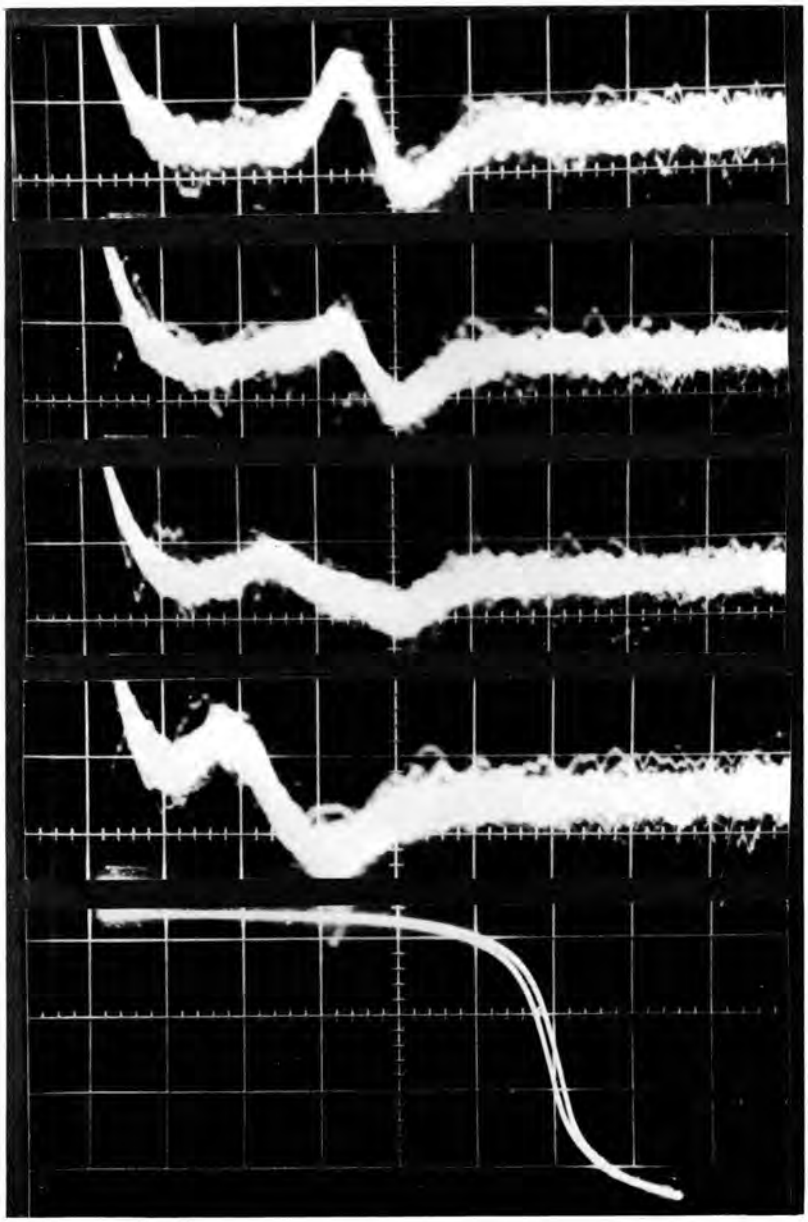

Fig. 19. Damping of Ionic Sound Waves in a Xenon Plasma by the Addition of a Helium Contaminant. Top trace: No He; 2nd trace: slight trace of He, with damping beginning to appear; 3rd trace: about 2% He ions present, with maximum damping occurring; bottom trace: still more He. The wave speeds up (appears at shorter times), and the damping decreases. Time scale is 20 μsec/large division. A Langmuir probe curve was taken for each ion-wave picture, the curve beneath the ion-wave traces being an example.

ORNL-4089
UC-20 – Controlled Thermonuclear Processes

INTERNAL DISTRIBUTION

1. Biology Library
2-4. Central Research Library
5-6. ORNL – Y-12 Technical Library
Document Reference Section
7-26. Laboratory Records Department
27. Laboratory Records, ORNL R.C.
28. G. Guest
29-178. W. D. Jones
179. H. W. Joy
180. C. E. Larson
181. H. G. MacPherson
182-183. R. B. Parker
184. M. J. Skinner
185. M. R. Skidmore
186. A. H. Snell
187. R. F. Stratton
188. A. M. Weinberg
189. O. C. Yonts
190. Abraham Bers (consultant)
191. P. B. Burt (consultant)
192. Owen Eldridge (consultant)
193. J. W. Flowers (consultant)
194. H. Grad (consultant)
195. E. G. Harris (consultant)
196. V. W. Hughes (consultant)
197. E. W. McDaniel (consultant)
198. D. Montgomery (consultant)
199. C. E. Nielsen (consultant)
200. J. M. Reynolds (consultant)
201. H. E. Rorschach (consultant)
202. D. J. Rose (consultant)
203. R. Sugihara (consultant)
204. T. H. Stix (consultant)
205. G. M. Haas (consultant)
206. H. S. Robertson (consultant)

EXTERNAL DISTRIBUTION

207. P. L. Auer, College of Engineering, Cornell University, Ithaca, N.Y.
208. L. M. Branscomb, Joint Institute, Laboratory of Astrophysics, Boulder, Colo.
209. S. C. Brown, Massachusetts Institute of Technology, Cambridge, Mass. 02139
210. S. J. Buchsbaum, Bell Telephone Laboratories, Murray Hill, N.J. 67971
211. O. Buneman, Stanford Electronics Laboratories, Stanford, Calif. 94305
212. F. W. Crawford, Stanford Electronics Laboratories, Stanford, Calif. 94305
213. J. E. Drummond, Boeing Scientific Research Laboratories, Headquarters Office Boeing Company, P.O. Box 3981, Seattle, Washington 98124
214. W. E. Drummond, Department of Physics, University of Texas, Austin, Texas 78712
215. W. A. Fowler, Calif. Inst. Technology, 1201 E. Calif. Blvd., Pasadena, Calif. 91109
216. H. P. Furth, Lawrence Radiation Laboratory, University of Calif., Berkeley, Calif. 94551
217. M. B. Gottlieb, Princeton University, Princeton, New Jersey 08540
218. J. G. Hirschberg, Dept. of Physics, Univ. of Miami, Coral Gables, Fla., 33124
219. D. W. Kerst, Univ. of Wisconsin, Madison, Wisconsin 53706
220. A. C. Kolb, Radiation Division, Code 7470, USN Res. Lab., Washington, D.C. 20234
221. H. W. Lewis, Physics Dept., Univ. of California, Santa Barbara, Calif. 93106
222. J. A. Phillips, Los Alamos Scientific Laboratory, Box 1663, Los Alamos, N.M. 87544
223. Albert Simon, Dept. of Mechanical & Aerospace Sciences, U. Rochester, Rochester, N.Y.
224. L. D. Smullin, Massachusetts Institute of Technology, Cambridge, Mass. 02139
225. R. F. Post, Lawrence Radiation Laboratory, P.O. Box 808, Livermore, Calif. 94551
226. M. N. Rosenbluth, University of California, La Jolla, California
227. R. F. Taschek, Los Alamos Scientific Laboratory, Box 1663, Los Alamos, N.M. 87544

228. J. L. Tuck, Los Alamos Scientific Laboratory, Box 1663, Los Alamos, N.M., 87544
229. C. M. Van Atta, Lawrence Radiation Laboratory, Livermore, Calif. 94551
230-231. Research and Development Division, AEC, ORO (1 copy each to H. M. Roth and R. B. Martin)
232-234. Controlled Thermonuclear Research Branch, AEC Washington (1 copy each to A. S. Bishop, S. O. Dean and B. J. Eastlund)
235. J. A. Swartout, 270 Park Avenue, New York 17, New York
236. J. R. Roth, NASA Lewis Research Center, Cleveland, Ohio
237–498. Given distribution as shown in TID-4500 under Controlled Thermonuclear Processes Category (25 copies – CFSTI)