of helium involves the balance between the production of helium molecular ions during the afterglow and their disappearance through recombination. It should be noted in passing that under the conditions of these experiments, charged particle diffusion is expected to be negligible with respect to volume recombination.

It is generally accepted that the predominant electron volume loss mechanism in a decaying helium plasma of low charge density is recombination with helium molecular ions, the He_2^+ being formed during the afterglow. At reduced ion and electron temperatures, the associated recombination coefficient, α, is expected to increase[2] whereas the molecular-ion production rate may be decreased. Thus by cryogenically cooling the plasma, the possibility exists of obtaining, in helium, a situation in which the electron loss rate is predominantly controlled by the production of its voracious recombination partner. Temporary heating of the electron gas, with its subsequent decrease in α, would then allow a new higher steady-state concentration of He_2^+ to be approached at a rate dependent upon the neutral-atom and electron number densities. Removal of the source of heat with the attendant relaxation of T_e would, in such a situation, result in a relatively large temporary increase in the afterglow luminosity.

Such temporal variations in the relative ion concentrations could also affect the microwave absorption properties of the plasma through electron collisional excitation of low-lying rotational states of the He_2^+ molecule. Stabler[7] has indicated that the cross section for such excitation is large. Such considerations account qualitatively for the observed waveforms and their behavior as a function of "heating" pulse length. Attempts at experimental verification of the various hypotheses are in progress.

[1] L. Goldstein, J. M. Anderson, and G. L. Clark, Phys. Rev. 90, 486 (1953).

[2] C. Chen, C. Leiby, and L. Goldstein, Phys. Rev. 121, 1391 (1961).

[3] J. M. Anderson and L. Goldstein, Phys. Rev. 100, 1037 (1955).

[4] P. D. Goldan, J. H. Cahn, and L. Goldstein, Bull. Am. Phys. Soc. 9, 185 (1964).

[5] V. A. Bailey and D. F. Martyn, Phil. Mag. 18, 369 (1934).

[6] L. Goldstein, M. A. Lampert, and R. H. Geiger, Elec. Commun. 29, 243 (1952).

[7] R. C. Stabler, Phys. Rev. 131, 679 (1963).

COLLISIONLESS DAMPING OF ELECTROSTATIC PLASMA WAVES*

J. H. Malmberg and C. B. Wharton
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation, San Diego, California
(Received 6 July 1964)

It has been predicted by Landau[1] that electrostatic electron waves in a plasma of finite temperature will be damped, even in the absence of collisions. Landau's theory has been challenged on various grounds[2] and a number of experiments designed to detect the effect for electrostatic electron waves or ion acoustic waves have been reported.[3] The existence of the damping is of interest not only for its own sake, but because the method of calculation has been widely used for related problems. We report here preliminary results of an experiment designed to measure the Landau damping of electrostatic electron waves. We observe heavy damping which exhibits the expected dependence on phase velocity.

The machine which produces the plasma has been described in detail elsewhere.[4] The plasma is produced in a duoplasmatron-type hydrogen arc source and drifts from it into a long uniform magnetic field of a few hundred gauss. The entire machine is steady state. The resulting plasma has, in a typical case, a radius of 7 mm, a length of 230 cm, a density of 5×10^8 electrons/cm^3, and a temperature of 12 ± 3 eV as measured by Langmuir probes. The background pressure is 1.7×10^{-5} Torr (mostly H_2). Hence, the Debye length is about 1 mm, the electron mean free path for electron-ion collisions is of the order of 1000 meters and for electron-neutral collisions is about 40 meters. The plasma is surrounded by a stainless steel tube 3.8 cm in radius which acts as a waveguide beyond cutoff to reduce electromagnetic coupling between probes. The plasma density depends somewhat on distance from the source.

Two probes, each consisting of a 0.2-mm di-

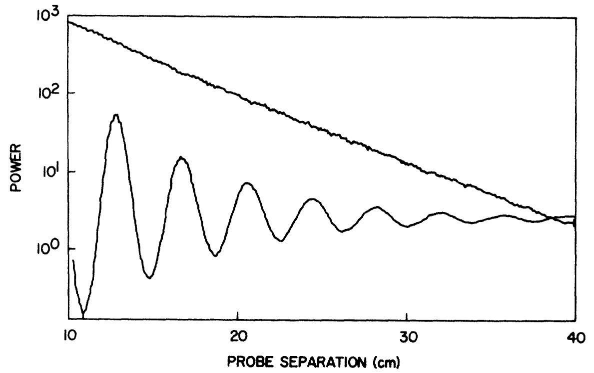

FIG. 1. Raw data. Upper curve is the logarithm of received power. Lower curve is interferometer output. Abscissa is probe separation.

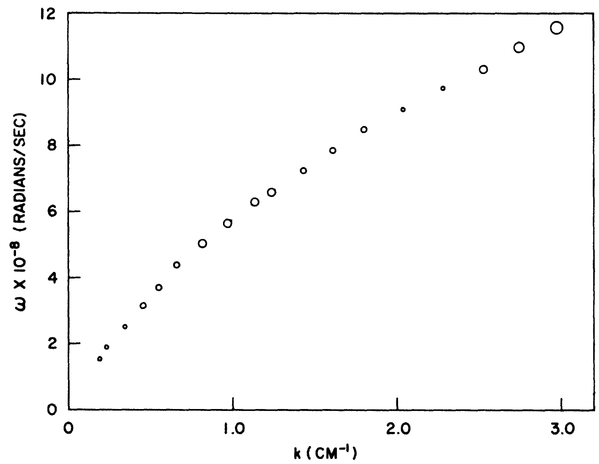

FIG. 2. Plasma-wave dispersion data. Ordinate is angular frequency. Abscissa is parallel wave number. Size of circles indicates errors.

ameter radial tungsten wire, are placed in the plasma. One probe is connected by coaxial cable to a chopped signal generator. The other probe is connected to a receiver which includes a sharp high-frequency filter, a string of broad-band amplifiers, an rf detector, a video amplifier, and a coherent detector operated at the transmitter chopping frequency. Provision is made to add a reference signal from the transmitter to the receiver rf signal, i.e., we may use the system as an interferometer. The transmitter is set at a series of fixed frequencies, and at each, the receiving probe is moved longitudinally. The position of the receiving probe, which is transduced, is applied to the x axis of an x-y recorder, and the interferometer output or the logarithm of the received power is applied to the y axis.

Typical raw data are shown in Fig. 1. The slope of the power curve is the e-folding length for power damping of the wave. In the case shown this is accurately exponential for two orders of magnitude, and in fact more, since the range is limited by the range of the logging circuit. The wave power in the plasma is of the order of 1 μW/cm^2. A 30-dB reduction in transmitter power does not change the damping length. The signal decreases smoothly as the probe is retracted radially with a half-maximum diameter about equal to that of the density profile. The distance between peaks on the interferometer curve is the wavelength, which can be determined to 3% over most of the range of the experiment. From the measured wavelengths and the transmitter frequencies we plot the dispersion relation of the waves, Fig. 2. These data have not been analyzed in detail, but the absolute magnitude and shape of the curve are approximately as expected for longitudinal electron oscillations in a strong magnetic field when the radial density distribution and finite temperature are included in the theory.[5]

In Fig. 3, the ordinate is the logarithm of damping length. The confidence limits shown indicate the uncertainty in fitting the slope of the attenuation curves. The abscissa is the square of the phase velocity, determined by multiplying the measured wavelength by transmitter frequency. This is our major experimental result. The solid curve is the theory of Landau for a Maxwellian distribution corrected approximately for the finite size of the plasma.[5] The theory predicts

$$\Lambda = \frac{\sqrt{2}}{k\sqrt{\pi}}\left[\frac{3}{x^2} + \frac{(1+3x^{-2})}{(2+ka)}\right]x^{-3}\exp(\tfrac{1}{2}x^2), \tag{1}$$

where x = phase velocity/mean thermal velocity, a = radius of the plasma, Λ = damping length for power, K = parallel wave number. The mean thermal velocity is not known with sufficient accuracy from probe measurements for use in this formula, so the theory has been normalized to the data at one point. This normalization gives a plasma electron temperature of 10.5 eV in good agreement with probe data. Data from transmission in opposite directions differ only slightly. The particles responsible for the damping have three to four and one half times the mean thermal velocity. Also $k\Lambda \gg 1$ over the range of data. This is the region in which the approximations of the theory are most accurate. The theory assumes a Maxwellian distribution function, but there is no reason to believe that the distribution function is exactly Maxwellian this far out on the tail. A high-precision comparison to the theory would

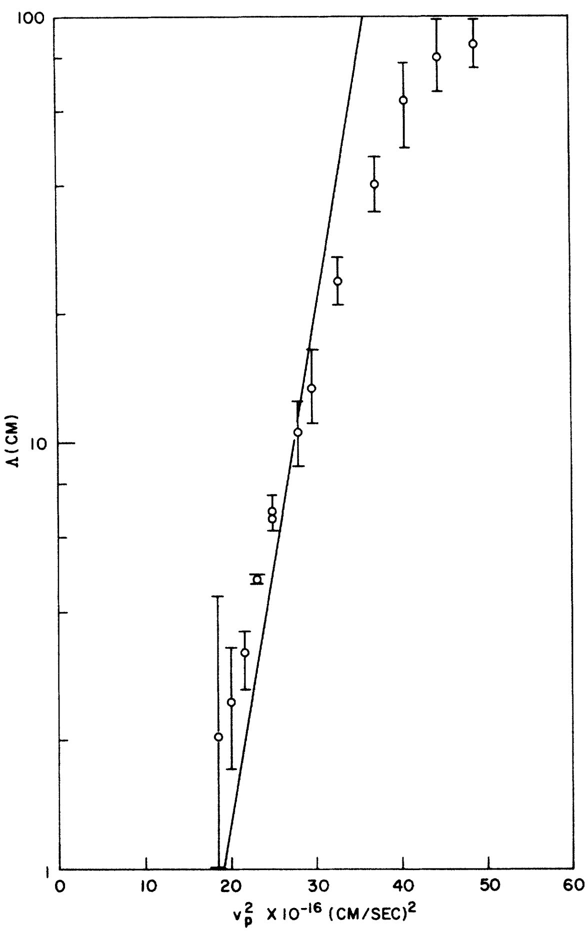

FIG. 3. Logarithm of damping length vs phase velocity squared. The solid curve is theory of Landau for a Maxwellian distribution with a temperature of 10.5 eV.

require a measurement of the slope of the tail of the distribution function.

The damping lengths observed range from 2 cm to 90 cm while the electron mean free path, which is roughly the collisional damping length, is of the order of 40 m. Damping due to currents in the boundary shield, wave scattering from irregularities in the plasma, and from wave-wave scattering from noise in the plasma have been estimated and also appear to be orders of magnitude too small to explain the result. And none of these effects are expected to give a damping with such a strong dependence on phase velocity.

The plasma is not perfectly quiescent—in part, at least, because of the noise from the arc. Since the received signal depends strongly on the slope of the tail of the distribution function, very small slope changes will amplitude modulate the received signal almost 100%. As an example, we calculate from Eq. (1) and typical experimental numbers that a 3% change in the mean thermal velocity would result in a factor of 25 change in received power. The coherent detector in the receiver integrates over such time-dependent effects. If the detected envelope of the rf is examined directly on a scope, very strong noisy modulation is observed up to frequencies of a few hundred kilocycles, i.e., the bandwidth of the rf filter in the receiver. By varying the filter frequency, we find that when the damping is heavy, the frequency of the received signal is spread over many megacycles.

We believe a likely explanation is that the damping is modulated by fluctuations of the distribution function in time. Then Fig. 3 would represent the time average of the damping produced by the plasma.

It would be highly desirable to reduce the fluctuations in the plasma and work is continuing on this line. However, the preliminary experiment clearly demonstrates heavy exponential damping of the plasma waves under conditions where collisional damping is negligible. And, assuming a reasonable plasma temperature, the magnitude of the damping and its dependence on phase velocity agree with the prediction of Landau.

It is a pleasure to acknowledge the continuing close cooperation of Dr. William E. Drummond in planning this experiment and analyzing the results. We also wish to thank Mr. C. David Moore for his contributions to the experimental work.

---

*This research was supported by the Advanced Research Projects Agency, Department of Defense, under Project DEFENDER and was monitored by the U. S. Air Force Weapons Laboratory under Contract No. AF29(601)-6366.

[1]L. Landau, J. Phys. 10, 45 (1946).

[2]H. Weitzner, Phys. Fluids 6, 1123 (1963); G. Ecker and J. Holling, Phys. Fluids 6, 70 (1963).

[3]M. J. Kofoid, to be published; M. Caulton, B. Hershenov, and F. Paschke, J. Appl. Phys. 33, 800 (1962); H. L. Stover and G. S. Kino, Bull. Am. Phys. Soc. 9, 336 (1964); J. L. Hirshfield and R. N. Dennis, Jr., Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, 1963, edited by P. Hubert (S.E.R.M.A., Paris, 1964); V. V. Dolgopolov et al., Zh. Eksperim. i Teor. Fiz. 45, 1260 (1963) [translation: Soviet Phys.—JETP 18, 866, (1964)]; A. Y. Wong, R. W. Motley, and N. D'Angelo, Phys. Rev. 133, A436 (1964).

[4]J. H. Malmberg et al., Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, 1963, edited by P. Hubert (S.E.R.M.A., Paris, 1964).

[5]W. E. Drummond, to be published.