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Experimental Observation of Plasma Electron Pressure

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In a magnetically supported plasma column the mechanical force parallel to the magnetic field exerted on an electrically floating balance has been measured over the range of 2 to 40 dyn. This measured force agrees with the force computed from the experimentally measured plasma electron density and the electron temperature. The large range of agreement between this measured force and the computed force implies that in this apparatus, at least, the plasma pressure is due to the electrons and it can be measured directly.

INTRODUCTION

IN a plasma with the electrons considerably hotter than the ions, the electrons theoretically produce a thermal electron pressure.[1] The thermal pressure of the electron gas is quite analogous to the pressure of the hot molecules in an ordinary gas. An experimental measurement of the thermal electron pressure is interesting because it demonstrates that the plasma electrons behave somewhat as an ordinary gas, and because it gives the product of the plasma electron temperature and density. Indirect experimental evidence for the existence of thermal electron pressure is obtained from the observation of ionic sound waves.[2,3] In these waves, first predicted by Tonks and Langmuir,[4] the plasma electron pressure provides the restoring force.[5] In this present work, the plasma electron pressure is measured directly by a simple mechanical method.

EXPERIMENTAL PROCEDURE

The apparatus is shown in Fig. 1. Electrons from a heated tantalum cathode were pulled through a perforated anode. Under proper conditions of gas pressure and other parameters, a dense column of plasma extended beyond the anode and parallel to the magnetic field. For measuring plasma force the column was terminated at its anticathode end by a sensitive torsion balance. The moving arm of the torsion balance was electrically insulated by a quartz fiber which also supplied the restoring torque. It was damped by an aluminum disc at its pivot. The range of the balance was 8 to 50 dyn with an error of ±0.5 dyn at full scale. The torsion balance could be removed and the column terminated on an electrically insulated electrode.

The basic assumption in this work is that the force exerted by the end of a magnetically supported plasma column is due only to the plasma electrons. The magnitude of the force on the balance is $F=An_ekT_e$. Here, F is in dynes, A is the cross-sectional area of the plasma column in cm^2, n_e is the number of electrons per cm^3, k is Boltzmann's constant in ergs per °K, and T_e is the electron temperature in °K. A rough calculation shows that the force due to the incident electron beam from the cathode should be 100 times less than the force from the plasma electrons. Forces due to ion and electron streaming should not be present because the plasma column is field free on the average—the cathode and anode of the plasma column are both at the same end. Electrostatic forces between the balance and the rest of the apparatus were calculated to be 10^3 times less than the smallest observed plasma force. The force exerted by the end of the plasma column is due to momentum transmitted along the column, which must be conserved. Thus, the force deflecting the balance does not depend

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

[1] L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956), Sec. 2.2.

[2] I. Alexeff and R. V. Neidigh, Bull. Am. Phys. Soc. **6**, 309 (1961); Phys. Rev. Letters, **7**, 223 (1961); Thermonuclear Division Semiannual Report, January 31, 1961, Oak Ridge National Laboratory ORNL-3104 (unpublished), pp. 31–45.

[3] R. W. Revans, Phys. Rev. **44**, 798 (1933); F. W. Crawford, Phys. Rev. Letters **6**, 663 (1961).

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

[5] L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956), Sec. 4.3.

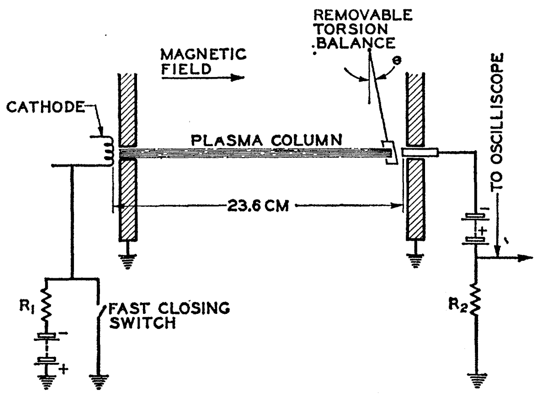

FIG. 1. The experimental apparatus. Argon and helium were studied because they are monatomic and differ greatly in mass. The plasma column was 23.6 cm long from cathode to anticathode and about 0.65 cm in diameter. The magnetic field was 3000G. For argon, the gas pressure was 6×10^{-4} torr, the cathode voltage was about 60 V, and the cathode current varied from about 0.1 to 2.0 A. Roughly, only about a tenth of the cathode current penetrated through the hole in the anode to the plasma. For helium, the values were 4.5×10^{-3} torr, 230 V, and 0.25 A, respectively.

on whether the electrons actually reach the balance, or are repelled by sheath phenomena—the balance always measures the pressure in the column.

The first two quantities needed for computing the plasma force were measured together as the product An_e, the number of electrons per linear cm along the plasma column. The method of measurement is locally called the "plasma sweeper."[6] The torsion balance was removed from the plasma column, and the column was terminated on an electrode connected to ground through a battery and a resistor. The battery voltage was so chosen that the electrode drew no net current. Effectively, the end of the plasma column was still electrically floating. The total electron charge in the plasma column was measured by shorting the cathode to ground with a fast closing switch (mercury-wetted contact relay, Durakool Cat. No. BF-74, making time, 2 μsec). Grounding the cathode has two effects. The electron stream from the cathode ceases, so no new plasma is made; and an electric field is produced across the sheath at the end of the plasma column. This electric field "sweeps out" the charge in the column.

The plasma sweeper appears to collect half the electron charge in the plasma column. This conclusion is obtained directly from the following model of the decaying column. The applied sweeping voltage is assumed not to penetrate the plasma column, but to appear only across a thin sheath at the negative anticathode electrode. Under this assumption, ions drift in equal numbers to both ends of the plasma column and escape. Electrons, however, are repelled by the negative anticathode sheath and escape only at the cathode. A series of experiments indicate that the above model of the decaying plasma column is valid and that the plasma sweeper collects half the total electron charge.[6] Dividing the total electron charge by the charge of one electron and the length of the plasma column yields the number of electrons per cm, An_e. The conventional Langmuir-probe method of measuring electron density did not work, as the required electron current saturation could not be found.

The electron temperature was measured using ionic sound waves. The conventional Langmuir probe gave temperatures which agreed within a factor of 2 with the ionic sound-wave values, but often produced complex characteristic curves which could not be analyzed. The ionic sound-wave method seemed more reliable.[7] Electron temperatures may be measured by ionic sound waves in this apparatus because the apparatus is a self-excited ionic sound-wave oscillator. A standing ionic sound wave appeared along the plasma column, parallel to the magnetic field.[2] The fundamental mode of oscillation, which is usually present, has a wavelength equal to twice the plasma column length. The frequency of the oscillating plasma column is given by

$$f=\frac{1}{2L}\left(\frac{3kT_e}{m_i}\right)^{\frac{1}{2}},$$

where f is the frequency in cycles per second, L is the length of the plasma column in cm, k is Boltzmann's constant in ergs per °K, T_e is the electron temperature in °K, and m_i is the ion mass in grams. The frequency can easily be observed on an oscilloscope connected to the electrode at the anticathode end. As L, k, and m_i are known, one solves for the electron temperature T_e.

The mechanical pressure exerted by the ionic sound waves on the torsion balance must be small compared to the thermal electron pressure, because the sound-wave equations are only valid for small amplitudes. In particular, if a periodic perturbation were transporting momentum per unit area and unit time comparable to the thermal pressure, the disturbance would degenerate into a series of shock fronts.[8] In any case, the experimental force measurements generally lie below the computed values, which suggests that no extra sound wave force is present.

RESULTS

The results of the experiment are shown in Fig. 2. The vertical error bars represent the drift between a force measurement at the beginning of a run and one at the end. A diagonal line means that only one force

[6] I. Alexeff and R. V. Neidigh, presented at the Symposium on Engineering Aspects of Magnetohydrodynamics, University of Rochester, March 28–29, 1962 (to be published).

[7] I. Alexeff and R. V. Neidigh, Thermonuclear Division Progress Report, Oak Ridge National Laboratory, ORNL-3239 (unpublished), p. 27–28; I. Alexeff and R. V. Neidigh, Gaseous Electronics Conference, Schenectady, New York, 1961 [Bull. Am. Phys. Soc. 7, 133 (1952)].

[8] Lord Rayleigh, *The Theory of Sound* (Dover Publications, Inc., New York, 1956), Sec 251, 253, 245.

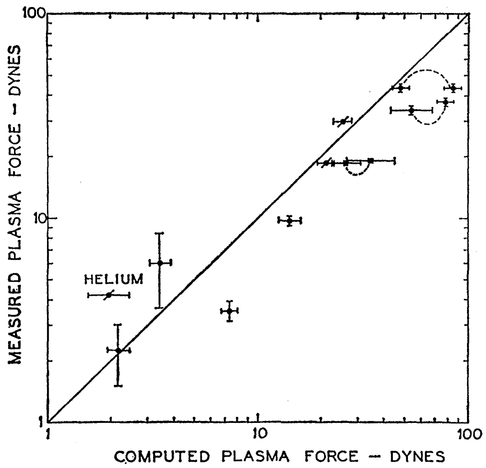

FIG. 2. Measured vs computed plasma force. The diagonal line represents equality between the measured and computed forces. All unlabeled points are for argon.

measurement was made. The horizontal error bars correspond to the known errors in measuring the quantities An_e and T_e. Two other sources of error are not included in the error bars. First, when the torsion balance was used, the plasma column was shortened slightly. This shortening changed the arc voltage and current, but by less than 5% in most cases. Second, unpredictable drifts occur in the data as shown by the pairs of points joined by dashed lines. Each pair represents two runs made in immediate succession. This drift might be due to pressure changes near the arc. Pressure monitoring was out of the magnetic field in the vacuum manifold.

CONCLUSIONS

The experiment appears to demonstrate the existence of a plasma electron pressure of magnitude $n_e k T_e$ in this apparatus. The experimental value of the plasma electron force as measured on a delicate balance agrees with the value as computed from measurements of the electron density by a novel but simple technique and the electron temperature by standing ionic sound waves. The pure physical significance of this work is a demonstration that a plasma behaves somewhat as an ordinary gas by exerting a mechanical pressure. The applied physical significance is that the pressure measurement gives the product of the electron temperature and the electron density.