PHYSICAL REVIEW A VOLUME 20, NUMBER 6 DECEMBER 1979

Acoustic wave generation in a low-pressure magnetoplasma afterglow

Carl A. Ventrice
Electrical Engineering Department, Tennessee Technological University, Cookeville, Tennessee 38501

(Received 3 July 1979)

Acoustic wave generation is induced in the afterglow of a weakly ionized helium plasma by the presence of a uniform axial magnetic field. Acoustic wave oscillations are generated at a gas pressure as low as 0.04 Torr by the application of an axial magnetic field of strength equal to 75 G.

The spontaneous generation and amplification of acoustic waves in weakly ionized plasmas has been observed by numerous investigators,[1-5] and treated analytically by Ingard[6] and Ingard and Schultz.[7] Such generation can be attributed to coherent transfer of energy by means of elastic collisions between the electrons and the neutral atoms. The rate at which energy is transferred, per unit volume per second, from the electrons to the neutral gas component, is given, approximately, by the expression[8,9]:

$$R_{en} \approx \eta (U_e - U_n) N_e \bar{\nu} , \tag{1}$$

where $\eta = 2m/(m+M)$ is the fractional energy transfer of electron energy per collision; m and M are the electron and neutral particle masses, respectively; U_e and U_n are the average energy per particle of the electrons and neutrals, respectively; N_e is the electron density; and $\bar{\nu}$ is the average electron neutral collision frequency.

In the absence of an acoustic wave perturbation, all of the energy transferred to the neutral gas, by means of elastic electron-neutral collisions, appears as thermal energy. In the presence of an acoustic wave perturbation, part of this energy is coupled into the acoustic wave. If u_w represents the energy per unit volume associated with the acoustic wave and u_n the thermal energy per unit volume associated with the neutral gas, then the energy coupled into the acoustic wave per unit volume per second is[7]: $R_{en} u_w / u_n$. The rate at which energy is lost from the wave per unit volume per second is u_w / Υ_n, where Υ_n is the acoustic wave decay time.[7] The condition under which an acoustic wave perturbation can grow is

$$R_{en} u_w / u_n > u_w / \Upsilon_n . \tag{2}$$

Assuming that the electrons and neutrals obey a Maxwellian distribution, and the electron temperature T_e is much greater than the neutral gas temperature T_n, expression (2) can be written in the form:

$$(\mathrm{const})(m/M)(N_e/N_n)/(T_e/T_n) > \Upsilon_{en}/\Upsilon_n , \tag{3}$$

where $\Upsilon_{en} = 1/\bar{\nu}$ is the average electron-neutral collision time and N_n is the neutral particle density. Expression (3) is in agreement with expression (15) from Ingard and Schultz.[7]

One can see from expressions (1) and (3) that conditions become more favorable for acoustic wave generation as T_e/T_n and the neutral gas pressure p_g increase. Experimental evidence confirms this. In the experiment of Berlande *et al.*,[1] acoustic wave generation was obtained in the afterglow of helium and neon plasmas by cooling the neutral gas component down to temperatures of 77° and 4.2°K in helium and down to a temperature of 77°K in neon. Strickler and Steward,[2] operating at pressures ranging from 13.5 to 38.5 Torr, observed acoustic wave generation in modulated argon and krypton dc glow discharges.

When T_n is approximately equal to room temperature, expression (3) is difficult to satisfy for p_g less than 1 Torr. Evidence, however, of acoustic wave generation in a helium plasma afterglow has been reported by Ventrice[5] at a gas pressure as low as 0.1 Torr. In this experiment the acoustic wave generation occurred at the onset, or in the very early afterglow, and was attributed to the difference in cooling rates between the electrons and the neutral gas component. The acoustic wave was not observed directly, but the reflection of the wave off of the end walls was observed using an electrostatic probe, biased to saturation.

The present comment reports the existence of acoustic wave generation in a helium plasma afterglow at a pressure as low as $p_g = 0.04$ Torr. The experimental arrangement and procedure used was identical to that reported by Ventrice,[5] except for the application of a uniform axial magnetic field B. Measurements of ion saturation current I_s versus time were made in the afterglow over the pressure range from 0.02 to 1.0 Torr, and over the magnetic field range from 0 to 1250 G. In the absence of a magnetic field, the results were consistent with those previously reported[5]: acoustic wave generation was observed when $p_g \geq 0.1$ Torr. The leading edge of the acoustic wave oscillations appeared on the I_s versus time curves at a time which ranged from approximately 2.5 msec

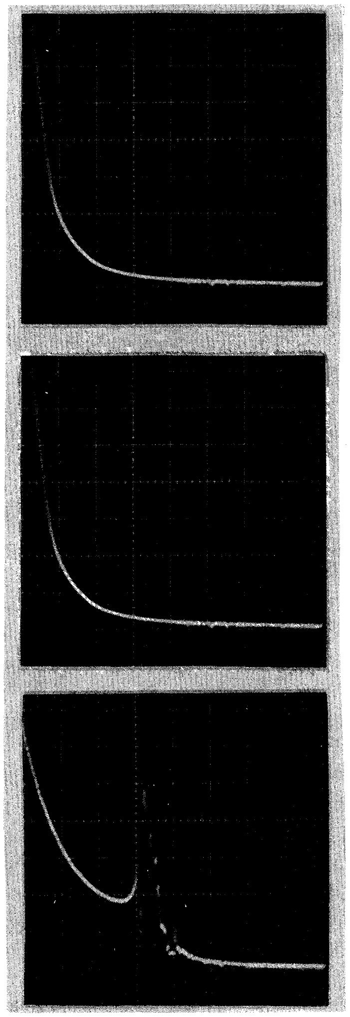

FIG. 1. Ion saturation current vs time in the afterglow of a helium plasma at $p_g = 0.04$ Torr. Upper trace: $B = 0$; center trace: $B = 75$ G; bottom trace: $B = 100$ G. Time scale begins at $t = 1$ msec and is 500 μ sec/division.

to approximately 3.2 msec. This variation can be attributed to variations in the length of the plasma column and to slight variations in the ambient temperature of the neutral gas.

When a uniform axial magnetic was applied to the plasma column, it was observed that acoustic wave generation occured at pressures below 0.1 Torr. The threshold value of B that was necessary to induce oscillations increased with decreasing pressure. A value of $B \approx 10$ G was necessary at a pressure slightly less than $p_g = 0.1$ Torr, and a value of $B = 75$ G was necessary at $p_g = 0.04$ Torr (see Fig. 1). At $p_g = 0.04$ Torr, the afterglow was observed to be quiescent for magnetic field values less than 75 G. At $B = 75$ G, the onset of oscillations appeared at $t \approx 2.6$ msec, and these oscillations were observed to grow with increasing magnetic field, becoming fully developed at $B = 100$ G. The frequency of the oscillations was observed to be approximately 10 kHz. At pressures below $p_g = 0.04$ Torr, no oscillations were observed, even for large values of B.

An insight into the phenomenon can be gained by examining the electron energy transport equation. In this equation, the significant electron energy-loss terms are the radial transport term and the collision term. The axial transport term is insignificant owing to the fact that $R \ll L$, where R is the radius of the plasma tube and L is the length. An increase in p_g gives rise to an increase in the collision loss term and a decrease in the radial loss term. This favors acoustic wave generation. On the other hand, a decrease in pressure gives rise to a decrease in the collision loss term and an increase in the radial transport term, thus making it difficult to support acoustic wave generation. It appears that both of these loss mechanisms affect acoustic wave generation. If the radial transport term predominates over the collision term (which is what happens at low values of p_g) most of the electron energy is lost at the walls by means of recombination with positive ions. Now, the application of an axial magnetic field decreases the radial transport term, and thus the rate of electron cooling. It is plausible that this decrease is sufficient to support acoustic wave generation below a gas pressure of 0.1 Torr. If the reduction in gas pressurecontinues, eventually the point is reached at which insufficient electron-neutral collisions occur to support acoustic wave generation, even in the presence of the axial magnetic field.

---

[1] J. Berlande, P. D. Goldan, and L. Goldstein, Appl. Phys. Lett. 5, 51 (1964).

[2] S. D. Strickler and A. B. Stewart, Phys. Rev. Lett. 11, 527 (1963).

[3] K. W. Gentle and U. Ingard, Appl. Phys. Lett. 5, 105 (1964).

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

[5] C. A. Ventrice, Phys. Rev. Lett. 28, 142 (1972).

[6] U. Ingard, Phys. Rev. 145, 41 (1966).

[7] U. Ingard and M. Schultz, Phys. Rev. 158, 106 (1967).

[8] I.P. Shkarofsky, T.W. Johnston, and M. P. Bachynski, *The Particle Kinetics of Plasmas* (Addison-Wesley, Reading, Mass., 1966), Chaps. I and III.

[9] M. Mitchner and C. H. Kruger, Jr., *Partially Ionized Gases* (Wiley, New York, 1973), Chaps. II and VIII.

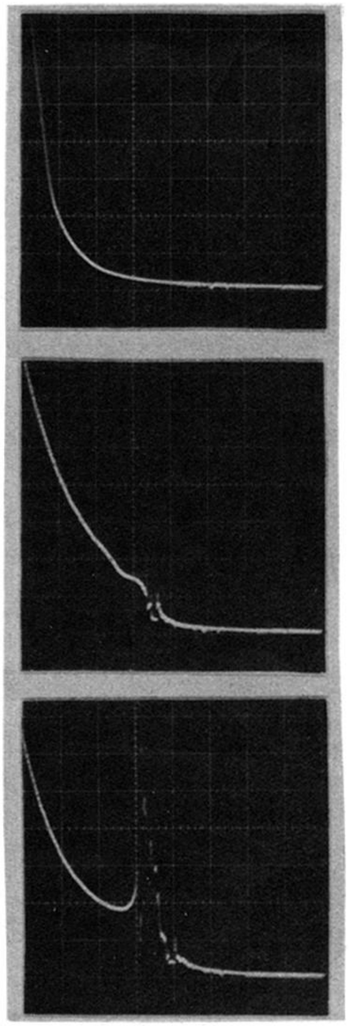

FIG. 1. Ion saturation current vs time in the afterglow of a helium plasma at $p_g = 0.04$ Torr. Upper trace: $B = 0$; center trace: $B = 75$ G; bottom trace: $B = 100$ G. Time scale begins at $t = 1$ msec and is 500 μsec/division.