

IX. PHYSICAL ACOUSTICS*

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A. ACOUSTIC WAVE AMPLIFICATION

Continued work on the problem of acoustic-wave amplification in a plasma^{1,2} has led to the realization that the electron gas should be treated isothermally. The amplification mechanism, as described by Ingard,¹ is a coherent heating of the neutral gas by the electrons, which are constrained to move in phase with the neutrals and ions.³ A calculation based on the fluid equations for the three-component system yields in the isothermal-electron limit the dispersion relation

$$k = (\omega/c)(1+i/\omega\tau)^{-1/2}, \quad (1)$$

where c is the adiabatic speed of sound for the neutral gas, and τ is an amplification time. This agrees with the initial result of Ingard,²

$$k = (\omega/c)(1-i/\omega\tau)^{1/2}, \quad (2)$$

in the limit $\omega\tau \gg 1$, but not for $\omega\tau \lesssim 1$. In fact, one finds that (2) is valid only when $\text{Re } k = \omega/c$, but since τ is such a large number (10^{-2} sec $\lesssim \tau \lesssim 1$ sec), an experimental distinction between (1) and (2) would be difficult to achieve.

Acoustic losses establish a threshold condition

$$\Gamma\tau < 1 \quad (3)$$

for the observation of an amplified wave. For propagation parallel to a cylindrical boundary of radius r , one finds

$$\Gamma = (2\omega/\rho r^2)^{1/2} + (\omega/c)^2 (7\eta/3\rho) \quad (4)$$

for a monatomic gas of viscosity η and density ρ . The dispersion relation actually observed under the expected quasi-adiabatic conditions, from an expansion of (1),

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would be

$$k \approx (\omega/c) - i(1/2c\tau)(1-\Gamma\tau). \tag{5}$$

1. Lateral Acoustic Instability

Continuing work on the problem, described previously,^{4, 5} of understanding why a constricted argon discharge kinks when the current is modulated at a lateral acoustic resonant frequency has led to a simple mechanism for explaining the effect. One may estimate the ionization rate, by intuition, as

$$R = \gamma N_e (\beta + N_e) N_n \exp(-aN_n/E),$$

where N_e and N_n are the densities of electrons and neutrals, E is the electric field, and α , β , and γ are positive constants. This model has the desired properties

1. $\partial R/\partial E > 0$
2. $\partial R/\partial N_n > 0$ for $\alpha N_n/E < 1$
3. $\partial R/\partial N_n < 0$ for $\alpha N_n/E > 1$.

If the modulation is sufficient to make both properties 2 and 3 realized during separate parts of the modulation cycle, the discharge will minimize E , thereby minimizing its power dissipation, by selecting the high-gas-density region when E is large and the low-gas-density region when E is small. Thus the path known to be favorable to the

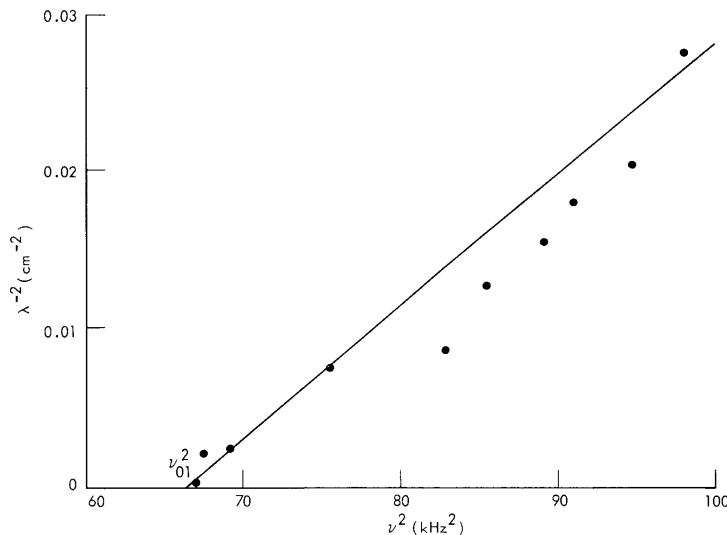


Fig. IX-1. Longitudinal structure in the mode $(nm) = (01)$, as evidenced by the lateral acoustic instability.

production of an acoustic wave is also preferred energetically in the presence of that wave. The path is stationary because the gas density and electric field at a given spatial location are periodic in time. The increase in path length serves to limit the degree of displacement.

The spatial regularity of the discharge path⁵ allows one to plot the wavelength λ against modulation frequency ν . This is done in Fig. IX-1 for the lowest mode ($n = 0$, $m = 1$), which displays through the linear relation between ν^2 and λ^{-2} the very definite excitation of a series of longitudinal modes based on the fundamental frequency ν_{01} . The line has slope c^{-2} , c being the speed of sound.

2. Acoustic Modulation of Microwave Transmission

Berlande, Goldan, and Goldstein⁶ have described an experiment in which the microwave transmission coefficient T of a decaying cryogenic helium plasma is demonstrably modulated by the sound produced by the decay of the electron temperature. An analysis now being conducted on this experiment seems to indicate that

(i) The electron temperature does not decay to the gas temperature (4.2°K), but to a temperature ($\sim 300^\circ\text{K}$) determined by the microwave signal used in making the measurement.

(ii) The initial electron density ($\sim 2 \times 10^{11} \text{ cm}^{-3}$) and temperature ($\sim 3 \times 10^4 \text{ }^\circ\text{K}$) are also unknown, so that quantitative agreement between theory and experiment can only be achieved by curve fitting.

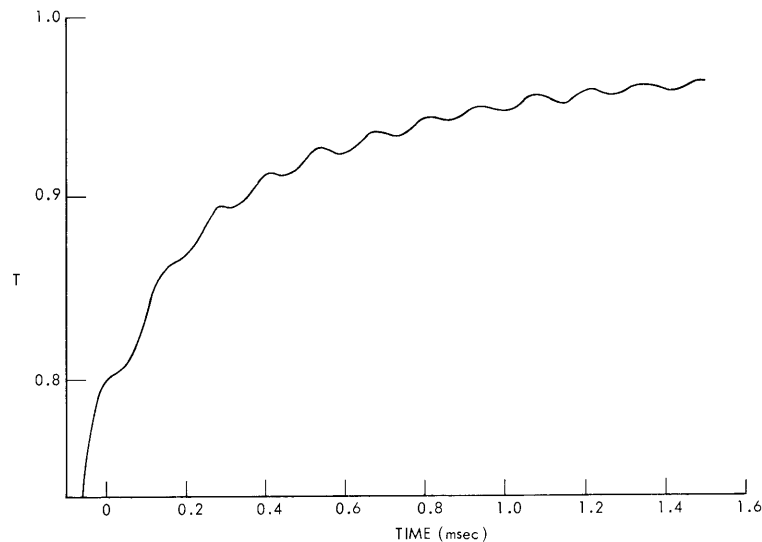


Fig. IX-2. Acoustic modulation of the microwave transmission coefficient of a decaying cryogenic plasma: theoretical plot for the parameters indicated in the text.

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(iii) The insensitivity of the acoustic amplitude to the size of the pulse generating the plasma may be due in part to an increase in gas temperature, which would defeat the purpose of raising the electron density and temperature by means of the larger pulse.

A theoretical curve with parameters as indicated in (i) and (ii) above, chosen so as to fit the experimental data, is shown in Fig. IX-2. The decay of the plasma is governed mainly by recombination rather than by diffusion. The transmission coefficient can be shown to be given approximately by

$$T = \exp\left(-\omega_p^2 \omega_c a / c \omega^2\right),$$

where a is the length of the plasma, c is the speed of light, and $\omega/2\pi$ is the microwave frequency. The plasma frequency ω_p and the collision frequency ω_c are modulated in phase with each other by the acoustic wave.

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References

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B. ERRATUM: LATERAL ACOUSTIC INSTABILITY

In Quarterly Progress Report No. 81, p. 45, Fig. VI-2, the photograph on the left-hand side marked "MODULATED" should read UNMODULATED.

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