PLASMA DYNAMICS

VII. PLASMAS AND CONTROLLED NUCLEAR FUSION*

A. Waves and Radiation

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1. ANOMALOUS CYCLOTRON RADIATION

A characteristic of anomalous cyclotron radiation in weakly ionized Ramsauer gases is its appearance in a restricted range of pressure and current.[1,2] Note that the range also depends on the microwave band that is utilized. It has been shown[1,2] that, in Xe gas, at a pressure of approximately 0.9 Torr, the maximum power appears at 100 mA discharge current for S-band frequencies (3000 MHz) and for 0.2 Torr, 600 mA in X-band (9000 MHz). In our experiments this maximum has been observed at ~400 mA in the C-band (5500 MHz) at a pressure p ~ 1.7 mm Hg in the same gas as shown in Fig. VII-1. Although the plasmas used in these experiments are produced differently

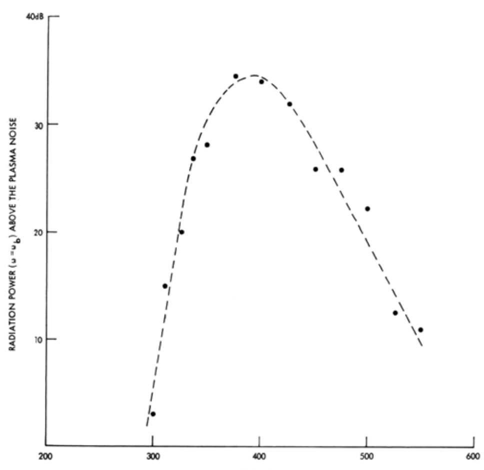

Fig. VII-1. Experimental results of the anomalous cyclotron radiation power emitted as a function of the current discharge at 1.7 mm Hg pressure.

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and are of different geometry, they are all low-voltage arc-type discharges. This leads us to believe that $\alpha^2 = \omega_p^2/\omega^2$ is an important parameter of the phenomena. Also the range of pressures, over which anomalous radiation is observed, is independent of the emitted microwave frequency, as can be seen from earlier results[1,2] and that presented in Fig. VII-2.

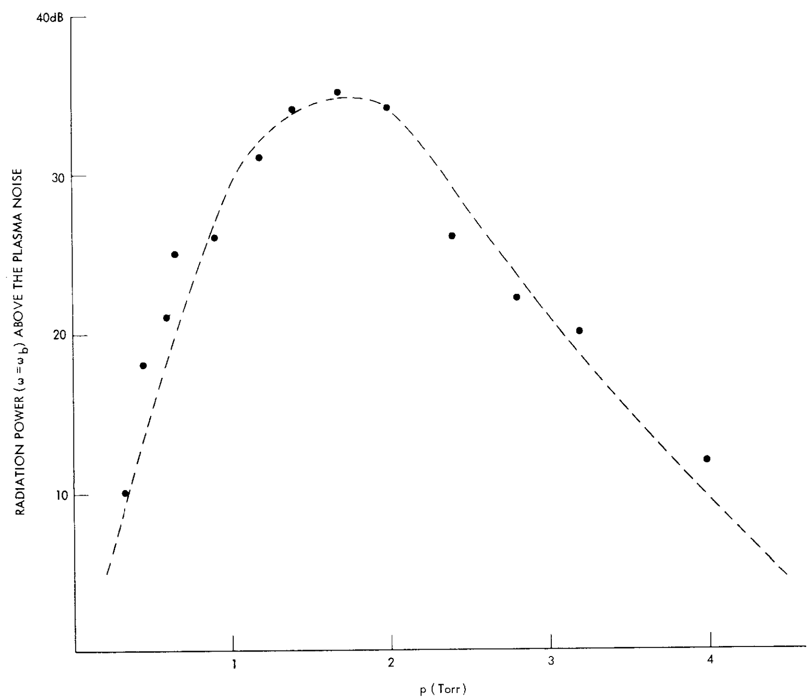

Fig. VII-2. Experimental results of the anomalous cyclotron radiation power emitted as a function of Xe gas pressure. (Discharge current = 400 mA.)

The collisional instability theory[4] in a tenuous magnetoplasma $\left(\omega_p^2 \ll \omega^2\right)$ predicts the amplification factor (attributable to the negative absorption) at $\omega = \omega_b$ is proportional to ω_p^2/ν. The conditions under which the phenomena are observed do not correspond to a tenuous plasma and hence the dispersion of the medium must be taken into account. As a consequence, there might be collective effects and we would expect to see similar phenomena associated with a hybrid frequency $\omega_H = \left(\omega_b^2 + \omega_p^2\right)^{1/2}$ (which is a resonant frequency for the extraordinary wave considered here) rather than with the cyclotron frequency. But it has been shown[5] that even for a nontenuous medium, anomalous effects caused by collisions are important only at the cyclotron frequency ω_b. This is a consequence of the strong resonant behavior of the right polarized wave conductivity, σ_r.

We have applied the results of fluctuation theory[5] to the case of negative absorption in order to calculate the total absorption $\frac{1}{\omega\epsilon_o}\left[\sigma_r|E_r|^2+\sigma_\ell|E_\ell|^2\right]$ (where E_r and E_ℓ are the right and left components of the electric field of the extraordinary wave). In Fig. VII-3 the negative absorption is maximum at the cyclotron frequency ($\beta = \omega_b/\omega = 1$) in the case

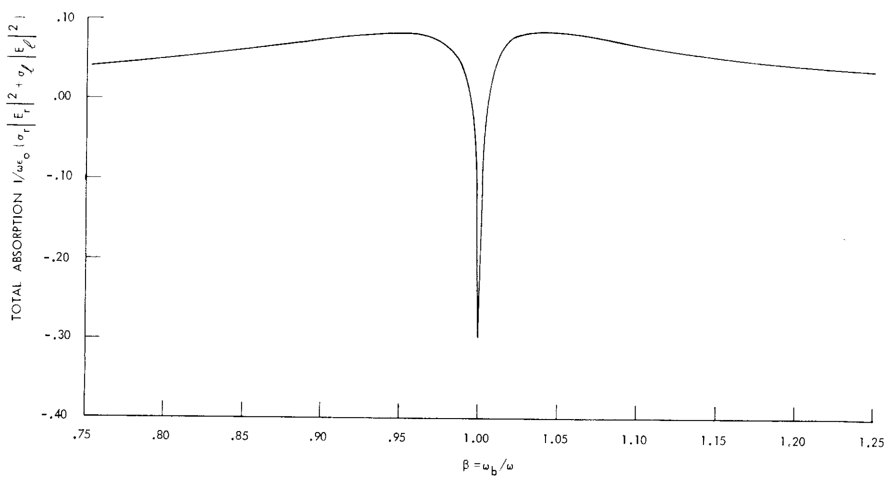

Fig. VII-3. Calculated extraordinary wave total absorption as a function of $\beta = \omega_b/\omega$ for the following Xe discharge parameters: $\alpha = \omega_p/\omega = 0.2$, $\gamma = \nu(v)/\omega = 0.1\ (v/v_T)^{4.5}$, $f = f_o v^2 e^{-v^4}$.

of a relatively dense medium ($\alpha = \omega_p/\omega = 0.2$). Figures VII-4 and VII-5 display the behavior of this maximum negative absorption when the density and the collision frequency are varied. These curves show a maximum in the amplification factor (or negative absorption) because in this calculation the positive left polarized component is taken into account. Since the emitted intensity is expected to be closely related to the amplification factor, the experimental results shown in Figs. VII-1 and VII-2 are in qualitative agreement with the theoretical predictions.

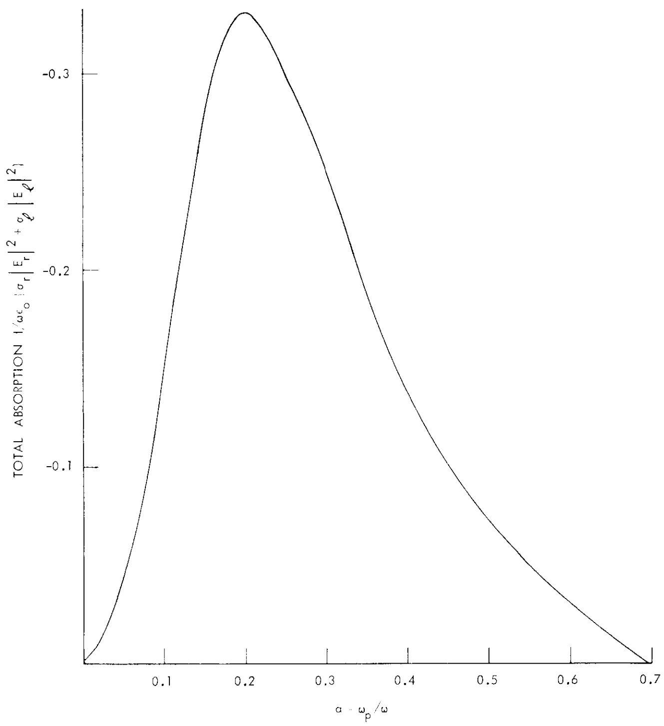

Fig. VII-4.

Theoretical variation of the extraordinary wave maximum negative absorption at $\beta = \omega_b/\omega = 1$ as a function of $\alpha = \omega_p/\omega$ (electron velocity distribution $f = f_o v^2 e^{-4}$, collision frequency $\nu(v)$ such that $\gamma = \nu(v)/\omega = 0.1\,(v/v_T)^{4.5}$).

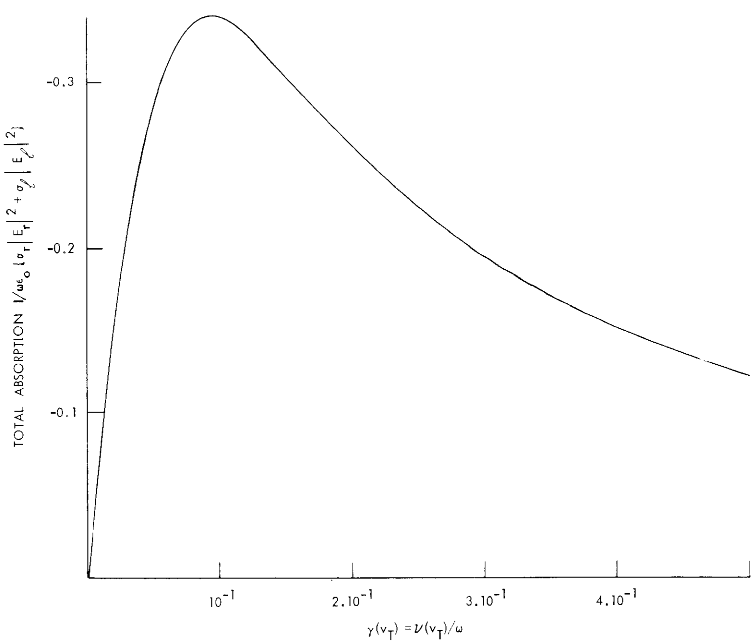

Fig. VII-5. Theoretical variation of the extraordinary wave maximum negative absorption at $\beta = \omega_b/\omega = 1$ as a function of $\gamma(v_T) = \nu(v_T)/\omega$ (electron velocity distribution $f = f_o v^2 e^{-v^4}$, $\alpha = \omega_p/\omega = 0.2$, collision frequency $\nu(v)$ such that $\gamma(v) = \nu(v)/\omega = \gamma(v_T)(v/v_T)^{4.5}$).

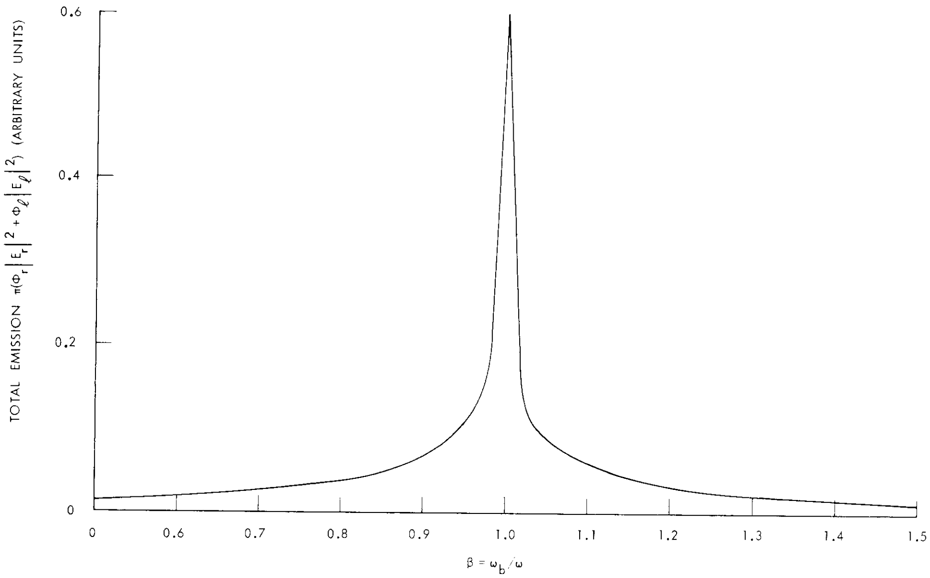

Fig. VII-6. Calculated extraordinary wave total emission as a function of $\beta = \omega_b/\omega$ for the following Xe discharge parameters: $\alpha = \frac{\omega_p}{\omega} = 0.2$; $\gamma = \frac{\nu(v)}{\omega} = 0.1\ (v/v_T)^{4.5}$, and $f = f_o\ e^{-v^4}$.

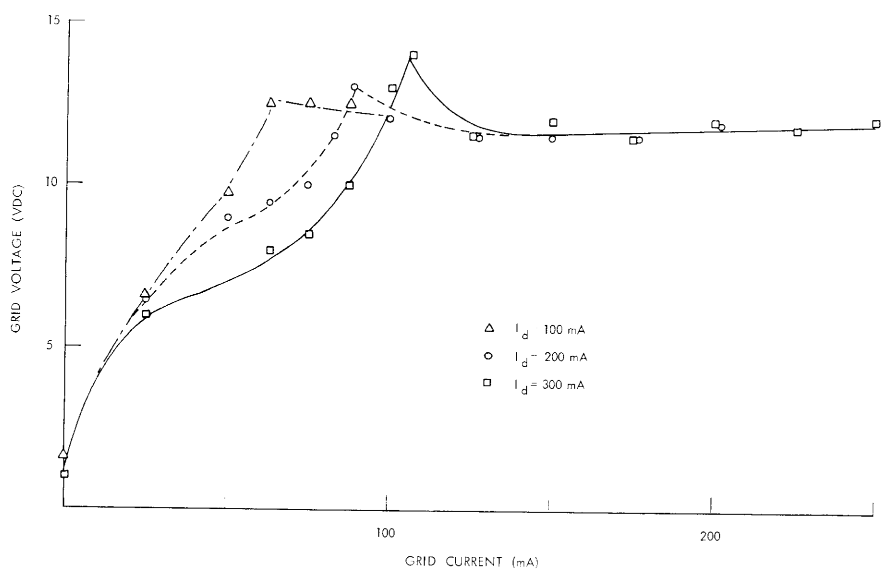

Fig. VII-7. $I_G(V_G)$ characteristics of the grid (at p = 1.7 Torr of Xe) for different anode current I_d.

The hypothesis of negative absorption has not yet been confirmed by direct measurement of the amplification. In our experiment, an amplitude-modulated microwave signal at $\omega = \omega_b$ is incident on a cavity-plasma system, and the reflected or transmitted power is synchronously detected. Variation of the detected signal as a function of the magnetic field shows only positive absorption. This has been mentioned in previous work.[1,6] It seems, therefore, that these anomalous radiation results cause us to either doubt explanations based upon negative absorption or to hypothesize that the occurrence of the phenomena is masked by the poor coupling of the radiation with the plasma. On the other hand, it must be mentioned here that a particular characteristic of the calculated emission of Xe plasma with no peak in its distribution function (that is, with positive absorption only) is a strong enhancement of the emission at $\omega = \omega_b$. Figure VII-6 shows the variation of the calculated total emission $\pi\{\phi_r |E_r|^2 + \phi_\ell |E_\ell|^2\}$, where ϕ_r and ϕ_ℓ are the right and left components of the microscopic fluctuating current correlation tensor. The enhancement of the emission is of the order of 15 dB, but cannot explain appearance of a stronger anomalous radiation peak (30 dB).

Characteristics still unexplained are the appearance of anomalous radiation in bursts correlated with low-frequency oscillations in the tube and the related

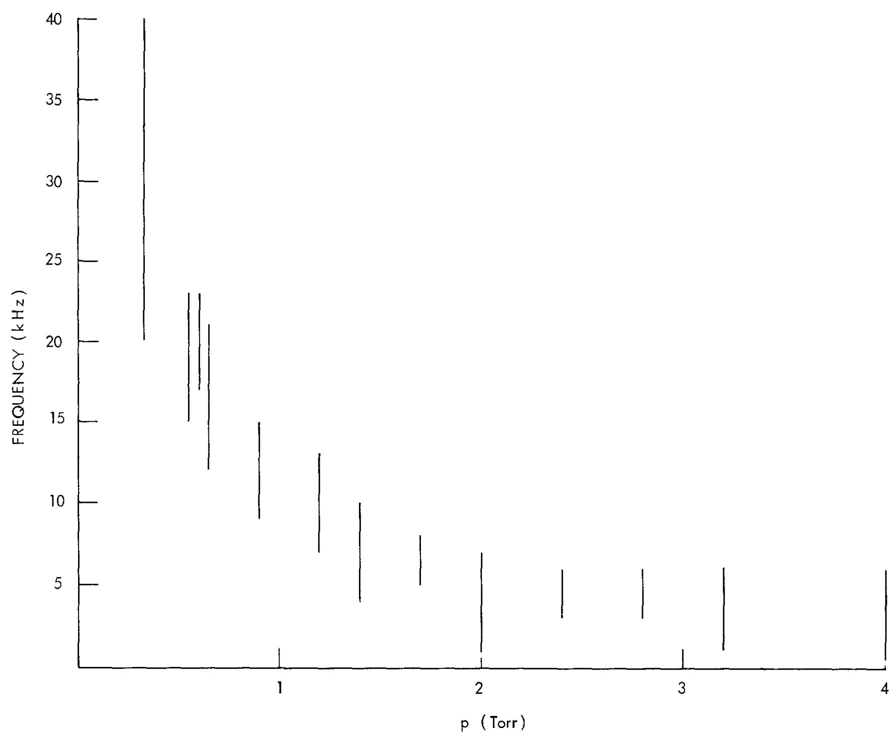

Fig. VII-8. Frequency variation of the grid oscillation as a function of gas pressure.

problem of production of a distribution function with a peak. In the early experiments[7] a round grid localized very close (1 mm) to the cathode was designed to give some of the electrons the perpendicular energy required for the creation of the peak. But different positions of the grid in the negative glow or in the positive column show the same over-all phenomena. Above a certain value of the grid current strong grid potential oscillations and anomalous microwave radiation appear, and the $V_G(I_G)$ characteristics of the grid acquire negative slope (see Fig. VII-7).

A study is being made to relate this observation of negative resistance to the observation of anomalous negative conductivity in diodes or triodes filled with gas having the Ramsauer effect.[8] Whether or not this phenomena involves ionization, relaxation oscillation, or oscillation resulting from negative resistance in Ramsauer gases cannot be ascertained. Nevertheless, the pressure of Xe gas is seen to play an important role on the resulting oscillation frequencies, as can be seen in Fig. VII-8.

These considerations permit us to proceed with the future study of anomalous radiation in two ways: (i) an experimental study of the coupling of the plasma radiation to observe negative absorption and (ii) a theoretical study of the production of an electron distribution function with a peak with the related problem of the nature of the low-frequency oscillations.

C. Oddou

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