# XV. SPONTANEOUS RADIOFREQUENCY EMISSION FROM HOT-ELECTRON PLASMAS[*]

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## A. OBSERVATION OF ENHANCED CYCLOTRON RADIATION FROM AN ELECTRON-CYCLOTRON RESONANCE DISCHARGE

We report the results of a preliminary investigation of the enhanced cyclotron radiation observed in the afterglow of our experimental electron-cyclotron discharge apparatus.[1] A low-density ($\sim 10^8$/cc) plasma is produced by RF breakdown of low-pressure hydrogen gas in a cylindrical microwave cavity. The plasma is confined by a mirror magnetic field (mirror ratio = 3) of such value that the exciting RF frequency equals the local electron-cyclotron frequency at certain points within the cavity. Excitation at the cyclotron frequency produces a hot-electron plasma with observed energies around 20-40 keV. The radiofrequency source is a magnetron producing 1-$\mu$sec pulses at $\sim 3$ kMc. The source is operated with repetition rate of 1 kc, and at power levels of $\sim 100$ kW peak (100 watts average). A more complete description of the apparatus and the plasma that it produces has been reported previously.[1] In all of the observations reported here, the excitation frequency is 2.85 kMc, and the background pressure of hydrogen is $2 \times 10^{-5}$ Torr.

Typical plots of the microwave emissions from the plasma are illustrated in Fig. XV-1 for a magnetic field at the center of the cavity of 1100 Gauss. The exciting microwave pulses occur at the extreme right and left ends of the traces and are barely visible. In each of the sequences of Fig. XV-1, the bottom trace is a plot of microwave power developed across a coupling loop on the cavity wall and detected by a microwave diode. The top trace is a plot of detected microwave power that has been passed by a radar transmit/receive switch located in the S-band waveguide which connects the magnetron to the cavity. This switch is a narrow-band device which in these measurements is tuned to the exciting frequency. Thus the plasma is seen to spontaneously emit pulses of microwave energy at or near the exciting frequency during the afterglow period. Figure XV-2 is an expanded view of the early part of the afterglow, and illustrates the facts that the signal across the coupling loop and that across the T/R tube are correlated in time. Thus we conclude that the power measured at the coupling loop also results from microwave emissions at or near the applied frequency.
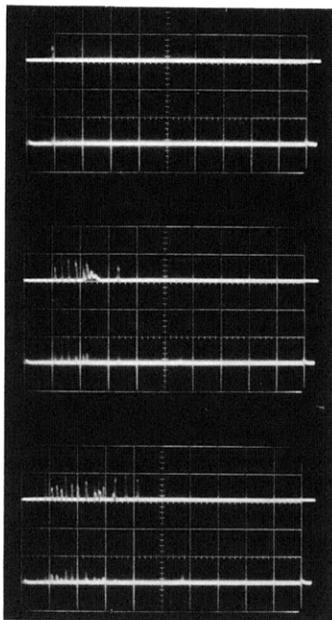
**Fig. XV-1.**

Characteristics of the observed microwave pulses during the afterglow of these different excitation pulses. Time = 100 μsec/div. Top: Signal at transmit/receive switch. Bottom: Signal at coupling loop.
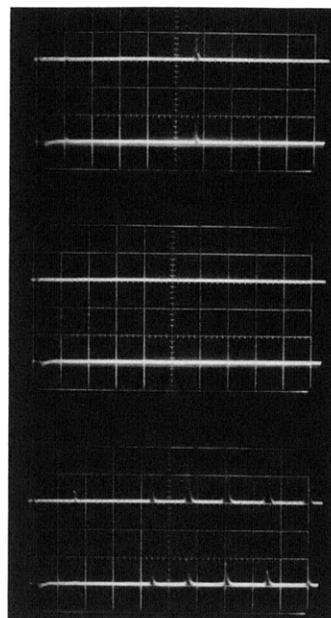


**Fig. XV-2.**

Observed microwave pulses during the early part of the afterglow. Time = 20 μsec/div. Top: Signal at transmit/receive switch. Bottom: Signal at coupling loop.

**Fig. XV-3.**

Correlation between the diamagnetic signal and the observed pulses of radiation when the central magnetic field is 1100 Gauss. Time = 50 μsec/div. Top: Diamagnetic signal. Bottom: Signal at coupling loop.
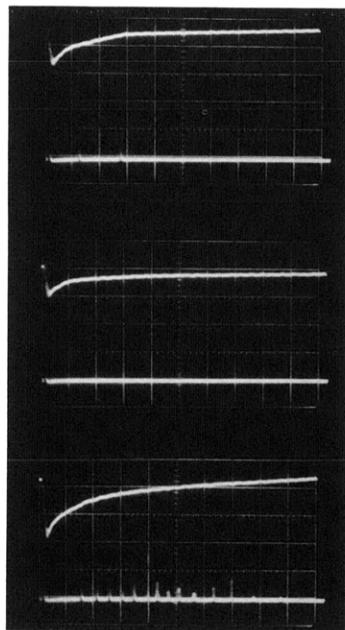


**Fig. XV-4.**

Correlation between the diamagnetic signal and the observed pulses of radiation when the central magnetic field is 1300 Gauss. Time = 50 μsec/div. Top: Diamagnetic signal. Bottom: Signal at coupling loop.
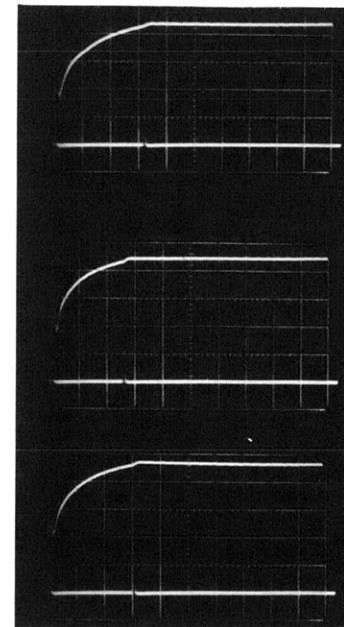
In Fig. XV-3 the bottom trace is again the power detected across the coupling loop while the top trace is the diamagnetic signal. This signal which is proportional to the energy density of the plasma is seen to decay quite smoothly, even in the presence of the strong emission of microwaves. This behavior is radically changed if the magnetic field is increased. In Fig. XV-4 the field has been increased to approximately 1300 Gauss at the center. Now, at the instant when the emitted microwave pulse is observed, the diamagnetic signal suddenly drops to zero, thereby indicating that the hot electrons have been lost from the plasma.

No correlation between the visible light radiated by the plasma and the emission of microwave pulses has been observed. This might indicate that the cold electrons are not involved in the instability mechanism.

These preliminary observations suggest that there are two types of instabilities. The first type results in enhanced cyclotron radiation in the form of several pulses of radiofrequency energy in the afterglow. The diamagnetic signal decays smoothly during these pulses. The second type occurs at higher magnetic fields, and is characterized by a single pulse of microwave energy and a sudden loss of the diamagnetic signal. This second type is obviously dependent upon the hot electrons in the plasma.

We are continuing a detailed study of the properties of the plasma and the observed radiation in order to formulate a model for the instabilities.

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### References

1. T. J. Fessenden, "Electron-Cyclotron Resonance Discharge," Quarterly Progress Report No. 73, Research Laboratory of Electronics, M. I. T., April 15, 1964, pp. 72-80.

## B. INSTABILITIES IN THE EXTRAORDINARY WAVES ACROSS THE MAGNETIC FIELD

In this report we formulate the small-signal energy expression for the extraordinary wave that was reported last quarter.[1] In general, the total small-signal energy in a plasma is given[2] by

$$\left\langle w(\omega, \overline{k}) \right\rangle = \left[ \frac{1}{4} \mu_0 |\overline{H}|^2 + \frac{1}{4} \epsilon_0 \overline{E}^* \cdot \frac{\partial}{\partial \omega} (\omega \overline{\overline{K}}) \cdot \overline{E} \right]_{D(\omega, k) = 0},$$

(1)

where $\overline{H}$ and $\overline{E}$ are the small-signal magnetic and electric fields, respectively, and the expression is evaluated only for those real $\omega$ and real $k$ that satisfy the dispersion relation, $D(\omega, k) = 0$. In terms of the elements of the dielectric tensor $\overline{\overline{K}}$, it is found that the existence of free waves propagating in the x-direction requires

$$
\begin{bmatrix}
\dfrac{\omega^2}{c^2} K_{xx} & \dfrac{\omega^2}{c^2} K_{xy} & 0 \\
-\dfrac{\omega^2}{c^2} K_{xy} & \dfrac{\omega^2}{c^2} K_{yy} - k^2 & 0 \\
0 & 0 & \dfrac{\omega^2}{c^2} K_{zz} - k^2
\end{bmatrix}
\cdot
\begin{Bmatrix}
E_x \\ E_y \\ E_z
\end{Bmatrix}
= 0.
\tag{2}
$$

For the extraordinary wave $E_z = 0$, from which it follows that for nonzero $\underline{\underline{E}}$,

$$
\underline{E}_y = -\frac{K_{xx}}{K_{xy}} \underline{E}_x
\tag{3}
$$

and

$$
\frac{k^2 c^2}{\omega^2} = \frac{K_{xy}^2}{K_{xx}} + K_{yy}.
\tag{4}
$$

Furthermore, Maxwell's equations require

$$
\underline{\overline{H}} = \underline{H}_z \overline{i}_z = \frac{k\underline{E}_y}{\omega \mu_o} \overline{i}_z.
\tag{5}
$$

Evaluation of Eq. 1 with the use of Eqs. 3, 4, and 5 results in

$$
\frac{<w>}{\epsilon_o/4} = \left| \underline{E}_y \right|^2 \left[ 2K_{yy} + \omega \frac{\partial K_{yy}}{\partial \omega} + \omega \frac{\partial K_{xx}}{\partial \omega} \frac{\left| K_{xy} \right|^2}{K_{xx}^2} \right]
\tag{6}
$$

or

$$
\frac{<w>}{\epsilon_o/4} = \left| \underline{E}_x \right|^2 \left[ 2K_{yy} + \omega \frac{\partial K_{yy}}{\partial \omega} + \omega \frac{\partial K_{xx}}{\partial \omega} \frac{\left| K_{xy} \right|^2}{K_{xx}^2} \right] \frac{K_{xx}^2}{\left| K_{xy} \right|^2}.
\tag{7}
$$

Here, we have made use of the fact that $K_{xx}$ is pure real and $K_{xy}$ is pure imaginary for real $\omega$ and $k$. Combining Eqs. 6 and 7 yields

$$
\frac{<w>}{\epsilon_o \left| \underline{\underline{E}} \right|^2 / 4} = \frac{\dfrac{K_{xx}^2}{\left| K_{xy} \right|^2} \left[ 2K_{yy} + \omega \dfrac{\partial K_{yy}}{\partial \omega} \right] + \omega \dfrac{\partial K_{xx}}{\partial \omega}}{1 + \dfrac{K_{xx}^2}{\left| K_{xy} \right|^2}}.
\tag{8}
$$

This is the expression for the time-averaged small-signal energy which is to be evaluated along those portions of the dispersion relation which both have real $\omega$ and k.

The sign of this expression has been determined for the waves reported last quarter so as to determine the positive (passive) and negative (active) energy branches of the dispersion diagram. The results are indicated in Figs. XII-2 and XII-3 of the previous report[1] as (+) for positive and (-) for negative energy branches. The unstable regions in those figures can now be interpreted as arising from the coupling between the active and passive wave branches.

A. Bers, C. E. Speck

## References

1. A. Bers and C. E. Speck, "Instabilities in the Extraordinary Waves across the Magnetic Field," Quarterly Progress Report No. 81, Research Laboratory of Electronics, M. I. T., April 15, 1966, pp. 133-137.

2. W. P. Allis, S. J. Buchsbaum, and A. Bers, Waves in Anisotropic Plasmas (The M. I. T. Press, Cambridge, Mass., 1963).