XIII. SPONTANEOUS RADIOFREQUENCY EMISSION FROM HOT-ELECTRON PLASMAS*

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A. EXPERIMENTAL STUDY OF ENHANCED CYCLOTRON RADIATION FROM AN ELECTRON-CYCLOTRON RESONANCE DISCHARGE

We have continued the study of the intense instability appearing in the afterglow of a pulsed electron-cyclotron resonance discharge. As reported previously[1, 2] the instability results in enhanced radiation in the form of 1-2 μsec bursts of energy in the S-band. The radiation is observed typically a few hundred μsec after the removal of the microwave heating pulse that generates the discharge.

In this report we present a more complete study of the radiation characteristics of the instability, a detailed measurement of the magnetic field employed, and some basic characteristics of the discharge. All of the radiation and plasma measurements were made with a background gas pressure of 2×10^{-5} Torr hydrogen, a central magnetic field of 990 Gauss, and a heating frequency of 2852 MHz. As discussed in a previous report,[2] these conditions result in relatively repeatable behavior of the discharge after every microwave heating burst.

1. Radiation Characteristics

Figure XIII-1 illustrates the microwave circuit used to detect the microwave energy radiated by the discharge. The PIN diode operates as a broadband, high-power, transmit/receive switch protecting the detection diodes during the heating pulse. Both the total energy radiated in the S-band and that part capable of being transmitted through the low-Q coaxial wavemeter may be monitored simultaneously on a dual-beam oscilloscope.

We found that the majority of the bursts of instability radiation had a frequency of 2498 MHz, although smaller peaks in the spectrum were observed around this frequency and near the heating frequency, 2852 MHz. These smaller peaks were approximately 20 dB below the main radiation. It was further noted from earlier measurements that 2498 MHz and the frequencies of all of the minor peaks corresponded to resonant frequencies of the microwave cavity in the absence of the plasma. Thus the instability is

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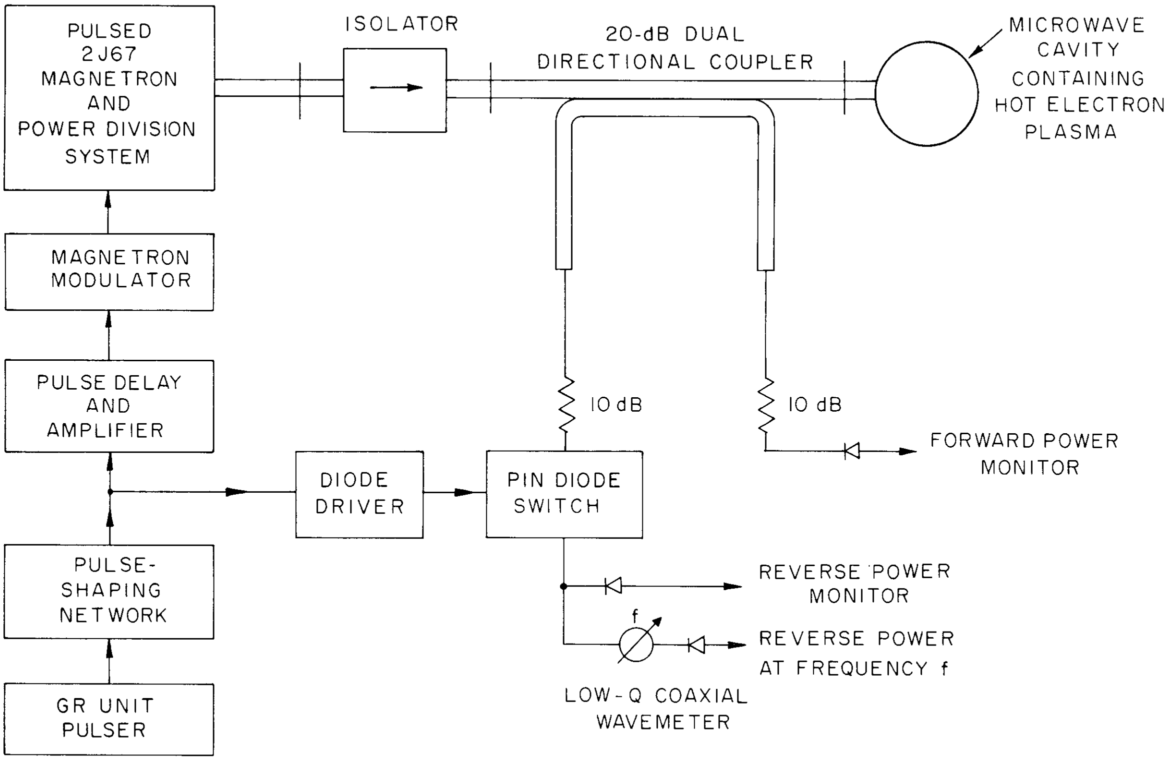

Fig. XIII-1. System for detecting microwave power radiated by the plasma in between the high-power magnetron heating pulses.

believed to result from a strong interaction of the electrons with the fields of the cavity.

A detailed study of the cavity mode was undertaken to determine why the mode at 2498 MHz was so strongly excited. Measurement of the loaded Q of the mode indicated that it was 16,650 ± 10%. This value was more than twice that of any of the neighboring modes. These measurements were made by observing the reflected power at a small coupling loop on the side wall of the cavity. An attempt was made to excite the mode from the same waveguide that was used to generate the discharge and in which the instability radiation is normally observed. Although the neighboring modes could be excited, the mode at 2498 MHz could not, thereby indicating that it is very poorly coupled to this waveguide. This accounts for the high Q_L of the mode in the presence of the open waveguide.

By exciting the cavity at 2498 MHz by means of the coupling loop and by probing the fields with conducting spheres and needles in the standard manner,[3] we found that this mode corresponded to a slightly perturbed version of the TE_{231} cylindrical cavity mode. The perturbations arise because of the presence of the open waveguide and various other diagnostic ports on the cavity walls.

2. Magnetic Field Pattern

In order to determine the contours within the cavity where the microwave heating frequency equals the local electron-cyclotron frequency and to determine the manner in which the electrons pass through these contours, a detailed study of the DC magnetic field was undertaken. Figure XIII-2 shows these results where one quadrant of the field is shown in a plane defined by the z-axis and a radius of the cavity. Also shown for reference is the outline of the cavity wall. The field lines are shown as solid lines, whereas the surfaces of constant $|B|$ are shown as broken lines. The value of $|B|$ shown in the figure is that normalized on the central field $B_o = B$ $(r = 0,\ z = 0)$. Note that the field decreases radially and increases axially, as expected in a simple mirror magnetic field. Also the maximum of the field along the axis is 3, which defines the mirror ratio of the system.

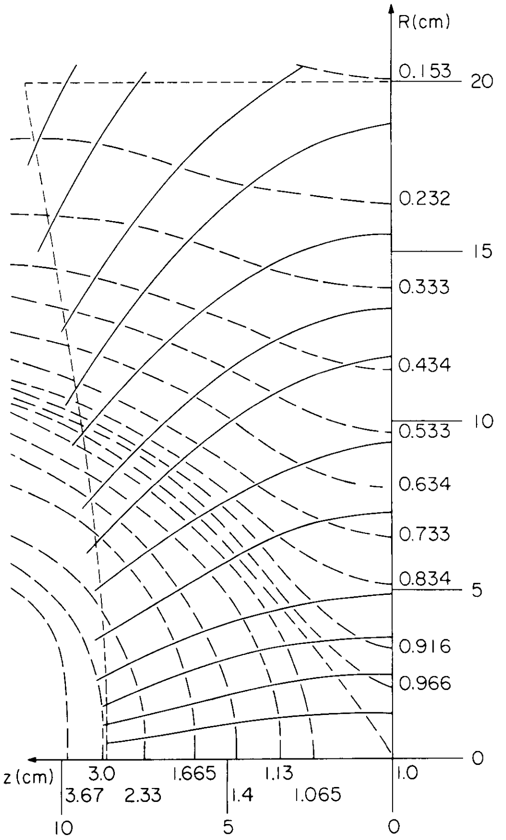

Fig. XIII-2. Magnetic field lines (solid) and surfaces of constant magnitude of magnetic field (dotted) in one quadrant of a plane defined by the system axis and any radius. [Note that the value of $|B|$ is that normalized on the contour passing through the center of the system.]

Figure XIII-3 shows the relationship between the magnet current and the value of the central field in Gauss. With the use of Figs. XIII-2 and XIII-3, the magnitude and direction of the field may be determined anywhere within the cavity, once the magnet current is known. The contour upon which the heating frequency equals the local electron-cyclotron frequency may be determined from the relation f = 2.8 MHz/Gauss.

Relating these measurements to the radiation measurements discussed above reveals that the magnetic field has a local electron-cyclotron frequency of 2498 MHz on a contour passing through the z = 0 axis at r = 3.75 cm. This value corresponds to the stated magnet current of 74 Amps. Under these conditions, the contour corresponding to the heating frequency of 2852 MHz passes through the r = 0 axis at z = 1.75 cm. Note that the TE_{231} cavity mode has a maximum of E_r at r = 4 cm and E_ϕ at r = 3.6 cm. These maximum fields occur at z = 0. Thus the TE_{231} mode in our cavity provides a strong transverse electric field resonant with the gyrating electrons at z = 0, r = 3.75 cm when the magnet current is 74 Amps.

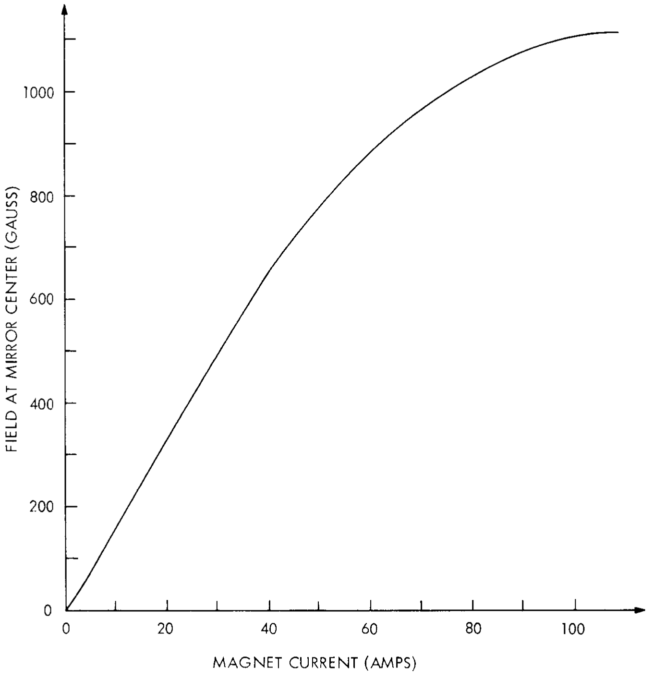

Fig. XIII-3. Relationship between the magnet current and the value of the field at the center of the system.

3. Density Measurement

The total electron density of the plasma as a function of time was determined by using the well-known fundamental mode shift technique.[4] Under the assumption that the plasma volume measurements made by Fessenden hold for our lower pressure discharge,[5] we found that the total electron density is given by

$$n = 8.87 \times 10^9 \left(\frac{\Delta f}{545}\right) \text{ per cc},$$

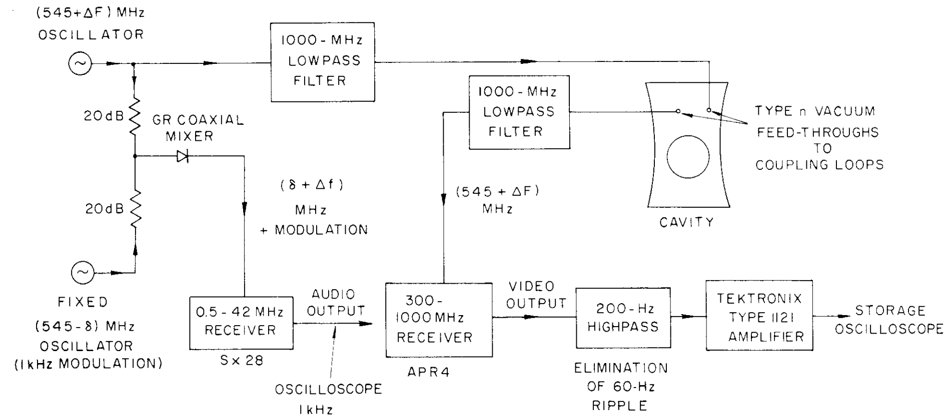

Fig. XIII-4. System for the TM_{010} mode-shift determination of the total electron density. Note that the TM_{010} resonant frequency of the empty cavity is at 545 MHz.

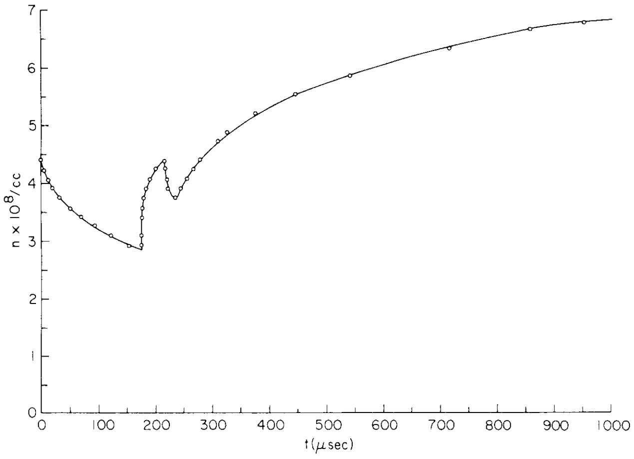

Fig. XIII-5. Total electron density as a function of time following the removal of the microwave heating energy. Discharge conditions: pressure = 2×10^{-5} Torr H_2; magnet current = 74 Amps; and heating frequency = 2852 MHz.

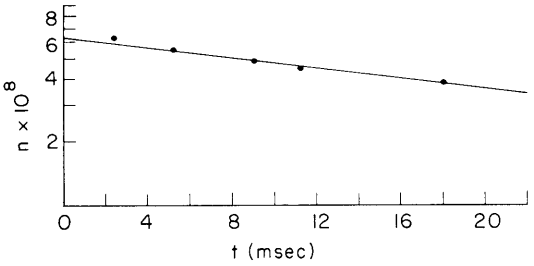

Fig. XIII-6. Long-time electron density decay if plasma is not regenerated at t = 1000 μsec.

where Δf is the shift in MHz of the TM_{010} cavity mode caused by the presence of the plasma. The empty cavity value of the TM_{010} mode frequency is 545 MHz. The circuit used to determine the mode shift is shown in Fig. XIII-4. In operation the variable oscillator is set at a frequency of $(545 + \Delta f)$ MHz. When the plasma density is such that the cavity resonance has been shifted to $(545 + \Delta f)$ MHz, a pulse of energy will be transmitted through the cavity and detected by the APR-4 receiver. The output of the receiver is displayed on an oscilloscope where the time of the burst is recorded. Because the shifts caused by our low-density plasma are less than 40 MHz, a more accurate calibration than that provided by the variable oscillator is needed. This is achieved by mixing the output of the oscillator with that of a fixed but slightly lower frequency oscillator. The difference frequency is detected by a low-frequency (0.5-42 MHz) receiver. In this manner, shifts of less than 1 MHz can easily be determined.

Figures XIII-5 and XIII-6 show the results of this measurement. Each point represents an average of 20 different measurements of the time at which the density passes through a particular value. This was necessary, because of the jitter in the time at which the instability occurred (180 ± 50 μsec). Thus, while the decay and growth rates determined from Fig. XIII-5 should be quite accurate for $0 \leq t \leq 175$ μsec and for $250 \leq t \leq 1000$ μsec, those between 175 and 250 μsec may be in question. Note, however, that the individual measurements revealed a distinct density increase followed by a decrease during this time interval. This effect is not due to the averaging process. Figure XIII-6 shows the long time decay of the plasma if it is not reheated at $t = 1000$ μsec. The time constant for this decay is 34 msec.

We are now continuing to study this instability.

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References

1. C. E. Speck and A. Bers, "Observations of Enhanced Cyclotron Radiation from an Electron-Cyclotron Resonance Discharge," Quarterly Progress Report No. 82, Research Laboratory of Electronics, M.I.T., July 15, 1966, pp. 187-189.
2. C. E. Speck, "Enhanced Cyclotron Radiation from an Electron-Cyclotron Resonance Discharge," Quarterly Progress Report No. 85, Research Laboratory of Electronics, M.I.T., April 15, 1967, pp. 219-221.
3. E. L. Ginzton, Microwave Measurements (McGraw-Hill Book Company, Inc., New York, 1957), pp. 445-452.
4. D. J. Rose and S. C. Brown, "Methods of Measuring the Properties of Ionized Gases at High Frequencies, Part III," J. Appl. Phys. 23, 1028 (1952).
5. T. J. Fessenden, "Pulsed Electron-Cyclotron Resonance Discharge Experiment," Technical Report 442, Research Laboratory of Electronics, M.I.T., Cambridge, Massachusetts, March 15, 1966, p. 33.