XVII. SPONTANEOUS RADIOFREQUENCY EMISSION FROM HOT-ELECTRON PLASMAS*

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A. IDENTIFICATION OF A HIGH-FREQUENCY MICROINSTABILITY

We have previously reported[1] the observation of an instability in the afterglow of our pulsed electron-cyclotron resonance discharge characterized by enhanced electron-cyclotron radiation. In order to obtain a model upon which to base a detailed experimental investigation of this instability, we have undertaken a study of its basic characteristics. These characteristics were determined from observations made in our discharge and from similar observations made in several other experiments throughout the country. The characteristics have then been compared with various proposed theoretical explanations of the phenomenon.

Table XVII-1 presents a comparison of a number of experiments exhibiting instabilities in which enhanced radiation near the electron-cyclotron frequency is observed (Stuffed Cusp,[2] Physics Test Facility,[3] Table Top,[4] and M. I. T. Pulsed Discharge[1]). It should be noted that, while the various plasmas are confined by different types of magnetic field and are generated in different ways, their basic parameters are quite similar. Although it is not stated in Table XVII-1, all four of these experiments exhibit increased loss of plasma along the field lines during the instability. The main conclusion that should be drawn from Table XVII-1 is that the microinstability in question is characteristic of hot-electron plasmas with plasma frequency much less than the electron-cyclotron frequency confined in open-ended magnetic field systems. In the light of the universality of the phenomenon, it appears that this end-loss instability may be a limiting factor in the containment of energetic plasmas in such fields.

In terms of the observations made in these experiments, the basic characteristics of the instability have been listed in Table XVII-2. The first two entries are the main macroscopic effects that are distinctive of the instability. First, enhanced radiation at the electron-cyclotron frequency is observed. It occurs in the form of bursts of several microseconds duration, with peak powers exceeding several hundred watts. Cyclotron harmonic radiation has also been observed coincidentally with these bursts. Second, accompanying this radiation is enhanced loss of plasma along the magnetic field

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Table XVII-1. Comparison of experiments exhibiting enhanced electron-cyclotron radiation.

EXPERIMENT	MAGNETIC FIELD	PRESSURE	$v_\perp/c$	$f_{pe}(\text{hot})/f_{ce}$	FREQUENCY OF INSTABILITY RADIATION
STUFFED CUSP PULSED ECRD LRL, LIVERMORE	STUFFED CUSP (MINIMUM-B) $f_{ce} = 9$ Gc	5×10^{-6} D_2	0.1	0.1	$\sim f_{ce}$ $\sim 2f_{ce}$
PHYSICS TEST FACILITY CW ECRD ORNL, OAK RIDGE	MIRROR $f_{ce} = 10.6$ Gc	$2-5\times10^{-5}$ H_2	0.2	0.3	$\sim f_{ce}/2$
TABLE TOP INJECTION AND COMPRESSION LRL, LIVERMORE	COMBINED MIRROR AND IOFFE BARS (MINIMUM-B) $f_{ce} = 9$ Gc	—	0.2	0.1	$\sim f_{ce}$
PULSED ECRD MIT	MIRROR $f_{ce} = 3$ Gc	$1-3\times10^{-5}$ H_2	0.1	0.1	$\sim f_{ce}$ $\sim 2f_{ce}$

lines. This is to be contrasted with the enhanced loss across the field lines associated with the magnetohydrodynamic interchange instability. The third entry indicates the

Table XVII-2. Characteristics of the microinstability.

1) SINGLE OR MULTIPLE BURSTS OF INTENSE RADIATION AT THE ELECTRON CYCLOTRON FREQUENCY.

2) RESULT IN ENHANCED LOSS OF PLASMA. BURSTS OF PLASMA EJECTED ALONG THE MAGNETIC FIELD LINES.

3) OCCUR IN ENERGETIC ELECTRON PLASMAS ($v \sim 0.1\ c$) AT DENSITIES SUCH THAT $f_{pe}(\text{HOT})/f_{ce} \cong 0.1$.

main plasma parameters that characterize the instability. First, the electrons are energetic, having velocities of the order of one-tenth the speed of light. Second, the hot-electron densities are such that the ratio of the hot-electron plasma frequency to the electron-cyclotron frequency is of the order of one tenth.

Turning specifically to the appearance of the microinstability in our experiment, it is first important to understand the time behavior of the plasma. As Fessenden previously noted,[5] at high background pressures (greater than 1.5×10^{-5} Torr H_2) the plasma is stable. The time behavior of the plasma in this regime is shown schematically in Fig. XVII-1. The important aspects of this behavior are that the hot-electron density ($T_H \sim 20$ keV) is a maximum at the end of the heating pulse, whereas the cold-electron density ($T_c \sim 10$ eV) is initially zero and must rise by ionization of the background gas. At lower background pressures the instability appears in the form of intense bursts of

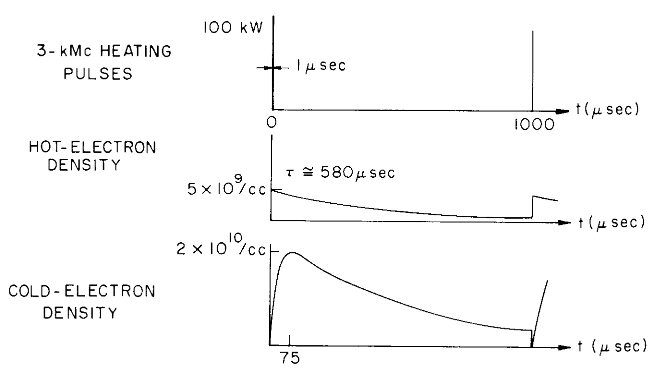

Fig. XVII-1. Stable operation of pulsed electron-cyclotron resonance discharge. (Pressure 2×10^{-4} Torr H_2.)

Table XVII-3. Comparison of instability theories with experiment.

INSTABILITY	EXPECTED INSTABILITY RADIATION	INSTABILITY CRITERION	EXPERIMENTAL OBSERVATIONS
HARRIS	ELECTROSTATIC AT f_{ce}	$(f_{pe}/f_{ce}) > 1$ $T_{\|\|}/T_{\perp} < 1/2$	$(f_{pe}/f_{ce}) \cong 0.1$
LOSS CONE ($k_{\|\|} = 0$) DORY, GUEST AND HARRIS	ELECTROSTATIC AT $\sim 3/2\ f_{ce}$	$(f_{pe}/f_{ce}) \gtrsim 2.7$	$(f_{pe}/f_{ce}) \cong 0.1$ $f \cong f_{ce}$
LOSS CONE ($k_{\|\|} \neq 0$) CRAWFORD AND TATARONIS	ELECTROSTATIC AT $\sim 1/2\ f_{ce}$	$(f_{pe}/f_{ce}) \gtrsim 0.6$	$(f_{pe}/f_{ce}) \cong 0.1$ $f \cong f_{ce}$
RELATIVISTIC FAST WAVE BERS AND SPECK	ELECTROMAGNETIC AT f_{ce}	$(f_{pe}/f_{ce}) < 0.13$ FOR $v_{\perp}/c = 0.1$	$(f_{pe}/f_{ce}) \cong 0.1 < 0.13$
CYCLOTRON DOUBLE HALL ET AL.	ELECTROSTATIC AT f_{ce}	$(f_{pe}/f_{ce})^2 >$ $(2\pi/L)\ (2/qc)\ (T_{\|\|c}/T_{\perp n})^{1/2}$ HERE FOR $(f_{pe}/f_{ce}) > .02$	$(f_{pe}/f_{ce}) \cong 0.1 > 0.02$

microwave radiation. These occur often after a delay of several hundred microseconds from the end of the heating pulse. The manner in which the plasma decays before the onset of the instability will be important when trying to understand these long delay times.

A short list of theories predicting radiation near the electron cyclotron frequency has been compiled in Table XVII-3, wherein the resulting instability conditions have been compared with the observations in our experiment. The first three theories (Harris,[6] Loss Cone ($k_{11} = 0$),[7,8] Loss Cone ($k_{11} \neq 0$)[9,10]) all require densities that are too high for these mechanisms to explain the radiation in our experiment. Both of the two remaining theories, however, offer a possible explanation.

The Relativistic Fast-Wave[11] theory predicts radiation at the electron-cyclotron frequency when $f_{pe}(\text{hot})/f_{ce} < 0.13$ (for electron velocities equal to one-tenth the speed of light). In terms of the time evolution of the hot-electron density in Fig. XVII-1, a possible explanation of the observed time delay before the onset of the instability is the requirement that the hot-electron density must decay to such a value that $f_{pe}/f_{ce} = 0.13$. This is not inconsistent with the estimated densities at the time of occurrence of the radiation.

The Cyclotron Double[12] instability requires the presence of a cold-electron component. As stated in Table XVII-3, this instability criterion contains the factor q_c, which is the cold-electron fraction of the total density. Note that for $q_c = 0$, infinite total density would be required before the instability could occur. Again, in terms of the time evolution of the cold density shown in Fig. XVII-1, a possible explanation of the observed time delay would be the requirement that the cold density must build up to a high enough value that the instability criterion is satisfied.

The Relativistic Fast Wave theory and the Cyclotron Double theory offer two different explanations of the microinstability observed in our experiment. Measurements made in the stable high-pressure region of operation, and preliminary measurements in the unstable region, indicate that either mechanism could be a possible explanation. We are, at present, undertaking a detailed investigation of the time evolution of the parameters of the plasma in the unstable region in order to determine which, if either, of the two theories properly accounts for the instability.

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