Presented at the First Topical Conference on RF Plasma Heating,
Lubbock, Texas, July 6-8, 1972

Conf-720705--2

Measurement of Effective Collision
Frequency in RF Heating through
Parametric Instabilities

T. K. Chu and H. W. Mendel
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

Enhanced absorption of an em-wave near ω_{pe} was observed
coincident with the onset of parametric decay instability, in
a Q-device plasma. The effective collision frequency

$$\nu_{eff} = \nu_{ei} (E/E_{cr})^2.$$

RECEIVED BY TIC
AUG 31 1972

Recent results on heating of ionospheric and laboratory plasmas by intense electromagnetic waves near the plasma frequency have focussed interest on parametric instabilities, which are expected to produce enhanced resistivity at the driving frequency due to enhanced momentum transfer from electrons to ions by wave-particle interactions in addition to binary particle collisions. Although extensive theoretical work on parametric instabilities¹ has been reported and numerical simulation² has indicated concomittant, enhanced plasma heating, the causal, direct relation between well identified parametric instability, enhanced resistivity and plasma heating has not been demonstrated conclusively in prior experiments.^{3,4}

The parametric decay instability is destabilized when the electron drift velocity due to an rf electric field at ω_{pe} approaches $\sim 0.05 v_{the}$.

The incident em-wave decays into two electrostatic waves. Enhanced absorption arises because the instability extracts energy from the pump field which is then transferred to the particles.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

RECEIVED BY TIC
AUG 31 1972

The principal result of the present work is the measurement of such enhanced absorption, and the resulting plasma heating, coincident with destabilization of the parametric ion acoustic decay instability. This result is based on: 1) the observed reduction of the transmission coefficient (ratio of transmitted to absorbed microwave power), and of the Q (i.e., increase in plasma dissipation), of a resonant cavity containing the plasma, when the pump field is increased above a threshold, 2) the simultaneous onset of the well identified instability, and 3) plasma heating, measured as increase in electron temperature, also coincident with instability onset. The measured dependences of instability threshold on plasma density and excitation electric-field-strength agree with those predicted by linear, infinite plasma theory. Finally, in the unstable regime, the dependence of pump field E on absorbed power is $P_{\text{abs}} \propto E^4$ and the effective collision frequency $\nu_{\text{eff}} \propto E^2$, in agreement with recent theoretical predictions.²

The experiments were performed on the Princeton Q-1⁶ thermally ionized potassium plasma, 126 cm long and 3 cm in diameter, with $T_i \geq T_e \approx T_{\text{ionizer}} = 2800^\circ\text{K}$. The neutral pressure is below 2×10^{-7} torr, so that collisions with neutrals are negligible. Two resonant cavities, operating in the TM_{010} and TM_{020} modes, were used to excite the instability at two different densities. The rf electric field is aligned parallel to the external magnetic field. Chokes at the cavity ends allow plasma to pass, but prevent microwave power losses. $\omega_{\text{ce}}/\omega_{\text{pe}} \approx 6$, $\omega_{\text{ci}} \approx \omega_{\text{pi}}$ and the collisionless skin depth $c/\omega (\omega_{\text{pe}}^2/\omega^2 - 1)^{-1/2} \gtrsim r_{\text{plasma}}$, so that wave penetration is assured. Thus, the plasma is expected to introduce only a small perturbation to the cavity field, which is substantiated by direct probe measurements. To have available a range of frequencies and hence densities, grids immersed in the plasma were also used to generate the destabilizing field.

Identification of the parametric instability is based on the following

agreements of experiment with theory: 1) the frequencies obey the sum rule $\omega_{\text{pump}} = \omega_{\text{pe}} + \omega_{\text{acoustic}}$; 2) for grid-launched waves the wave numbers obey the sum rule, $k_{\text{pump}} = k_{\text{pe}} + k_{\text{acoustic}}$ (in the cavity k 's cannot be measured, due to the small wavelengths at the cavity frequency and the perturbation problems with axially moveable probes in the axial-electric-field); and 3) the measured onset field agrees with that predicted by infinite-plasma theory. In addition, this identification is substantiated by the following supporting evidence: 1) the radial extent of the instability is comparable to the radial density distribution, consistent with the structure of the radial eigenmodes expected to occur in a strongly magnetized plasma column; 2) instability can only be excited at frequencies below or close to the plasma frequency of the maximum density as expected from the dispersion relation of the ω_{pe} waves; 3) the total power of the instability at saturation is comparable to that of the pump field, as observed also in computer experiments;² and 4) the intensity of the high frequency ω_{pe} wave is much higher than that of the ion acoustic wave near ω_{pi} , in agreement with predictions.² We note that the purely growing mode has not been observed in the present experiment.

The cavity simultaneously serves as diagnostics and supplies the destabilizing pump field. In the stable regime, when the cavity field is below threshold Q can be measured by the sweep method, $Q = f/\Delta f$ (Δf = halfwidth of resonance curve), since the implicit assumption that the dissipation (or Q) is independent of (sweep or pump) field strength and frequency is valid. Earlier work⁴ on anomalous microwave absorption also utilized the (pump) frequency-sweep Q measurement in the anomalous absorption regime (direct observation of instability was not achieved). Since both amplitude and frequency of the pump, i.e., the cavity field, are varying throughout the Q measurement, instability amplitude, effective collision frequency and hence Q are not constant and the frequency

sweep method cannot produce correct Q-values (although the numbers so obtained trend in the right direction). In addition, for sweep times comparable to instability growth times, the (apparent) growth rates become a function of the sweep rate, and measured onset pump fields for fast sweep are too high, by an amount depending on the sweep rate.

In the present work, the cavity Q in the unstable regime was measured by a method which makes use of transmitted and absorbed powers at constant pump frequency and amplitude, i.e., at constant effective collision frequency, during the measurement. The cavity power balance gives:

$$P_{\text{inc}} - P_{\text{refl}} = P_{\text{abs}} = P_{\text{tr}} + P_{\text{Cu}} + P_{\text{coll}} + P_{\text{instab}} = cE^2/Q_{\text{unstab}} \quad (1)$$

where the power losses on the right side are those due to transmission, cavity copper-wall resistance, plasma collisions, and instability, and c can be calculated from geometry and frequency of the cavity. Observing that the transmitted power is uniquely determined by E, whether the plasma is stable or unstable, we obtain, using (2),

$$Q_{\text{unstab}} = cE^2/P_{\text{abs}} = c c_1 P_{\text{tr}}/P_{\text{abs}}, \quad (2)$$

where c_1 can be determined⁸ in the stable state.

Measured $1/Q$ (inversely proportional to the transmission coefficient), electron-plasma wave amplitudes and electron temperatures are shown in Fig. 1 vs absorbed power, with ω_{pe} evaluated for center density. For empty and plasma-filled cavities with $\omega/\omega_{pe} \geq 1.3$, and for $\omega/\omega_{pe} < 1$ below threshold, Q is nearly constant as power is increased. Above threshold, Q decreases rapidly with increasing absorbed power. These Q changes are comparable to, but smaller than, those of Ref. 4, and threshold values are lower, as expected due to the recognition of the effects of the sweep method. We note that the error in the

measurement of absolute density may be 40%.

Simultaneous with onset of enhanced dissipation, the instability destabilizes at ω_{pe} and ω_{pi} and both amplitudes increase with increasing absorbed power. The electric field at onset is in good agreement with linear, infinite plasma theory, assuming electron-ion collisional damping for the electron plasma wave and Landau damping for the ion acoustic wave. We note that according to theory⁹, the present Q-device plasma must be considered a homogeneous plasma, since radial density scale length and mean free path are comparable, a result which is consistent with our measurement: the onset value agrees with that of homogeneous theory. Electron heating resulting from the power absorbed by the instability is shown in Fig. 1b. The electron temperature was determined from a d.c. conductivity measurement; the local temperature increase is expected to be higher.

For P_{abs} vs E , below threshold good agreement between experiment and theory, with collision frequency according to Dawson-Oberman,¹⁰ is found, Fig. 2. Above threshold an effective collision frequency ν_{eff} can be assumed which depends on pump (or instability) amplitude. Recent theoretical results based on non-linear ion Landau damping indicate $\nu_{eff} \propto E^2$, in agreement with the experimental results $\nu_{eff} \approx \nu_{ei} (E/E_c)^2$, although the requirements of low-pump field energy ($E^2/4nkT \ll \omega_{pi}/\omega_{pe}$) and $\nu_e \ll \omega_{pi}$ are not well met in the experiment. In addition, the highest attained experimental value of $\nu_d/\nu_{th} = (eE/m\omega)/\nu_{th} \approx 0.15$ does not allow a check of numerical simulation results² for $\nu_d/\nu_{th} \geq 1$, where it was shown that ν_{eff} is independent of E .

Several important considerations arise from this work. Firstly, the present results confirm predictions of the linear and nonlinear theories of the parametric instability for an infinite homogeneous plasma. Secondly, the instability can be excited over a wide range of frequencies due to the dispersion relation for plasma waves in a finite size plasma. Thirdly, since

instability can be destabilized at very low pump intensities (at onset, drift over thermal energy ~ 5%), parametric effects may play a significant role in many rf heating methods. To sum up, this work presents conclusive evidence for the existence of a dissipation mechanism for electromagnetic waves not based on particle-particle collisions but on wave-particle interactions, which can lead to power absorption much larger than the dissipation due to classical rf heating.

We acknowledge valuable discussions with Drs. K. Bol, W. Kruer, F. Perkins, M. Porkolab, and E. Valeo, and Mr. J. Flick.

This work was jointly supported by U. S. Atomic Energy Commission Contract AT(11-1)-3073 and by the Advanced Research Projects Agency under Contract No. F30602-72-C-0053.

REFERENCES

- ¹D. F. Du Bois and M. V. Goldman, Phys. Rev. Lett. 14, 544 (1965) and Phys. Rev. 164, 207 (1967); V. P. Silin, Zh. Eksp. Teor. Fiz. 48, 1679 (1965) [Sov. Phys.--JETP 21, 1127 (1965)]; and Zh. Eksp. Teor. Fiz. 51, 1842 (1966) [Sov. Phys.--JETP 24, 1242 (1967)]; K. Nishikawa, J. Phys. Soc. Japan 24, 916 (1968); and 24, 1152 (1968); J. R. Sanmartin, Phys. Fluids 13, 1533 (1970); J. M. Dawson and W. L. Kruer, Phys. Fluids 12, 2586 (1969).
- ²W. L. Kruer, P. K. Kaw, J. M. Dawson, and C. Oberman, Phys. Rev. Lett. 24, 987 (1970).
- ³I. A. Gekker and O. V. Sizukhin, ZhETF Pis. Red. (JETP Lett. 9, 243 (1969)); H. P. Eubank, Phys. fluids 14, 2551 (1971); W. F. Utlaut and R. Cohen, Science 174, 245 (1971); A. Y. Wong and R. J. Taylor, Phys. Rev. Lett. 27, 644 (1971); R. Stenzel and A. Y. Wong, Phys. Rev. Lett. 28, 274 (1972); W. E. Gordon, R. Showen, and H. C. Carlson, J. Geophys. Res. 76, 7808 (1971).
- ⁴H. Dreicer, C. Ingraham, and D. Henderson, Phys. Rev. Lett. 26, 1616 (1971).
- ⁵E. Valeo, C. Oberman, and F. W. Perkins, Phys. Rev. Lett. 28, 340 (1972); D. F. Du Bois and M. V. Goldman, Phys. Rev. Lett. 28, 218 (1972).
- ⁶N. Rynn, Rev. Sci. Instr. 35, 40 (1964).
- ⁷E. L. Ginzton, Microwave Measurements (McGraw-Hill, New York (1957), p. 404.
- ⁸The measured temperature increase due to classical heating is small and does not affect classical power losses appreciably.
- ⁹F. W. Perkins and J. Flick, Phys. Fluids 14, 2012 (1971).
- ¹⁰J. M. Dawson and C. Oberman, Phys. Fluids 5, 517 (1962) and 6, 394 (1963).

FIGURE CAPTIONS

Fig. 1. Measured cavity $1/Q$ values, T/T_0 , and instability (lower sideband) amplitude vs absorbed power. Electron temperature determined from dc conductivity; measured T_0 is equal to the plate temperature, 2800°K .

Fig. 2. Measured pump field vs absorbed power, x , cavity without plasma; o, cavity with plasmas. a. empty cavity, indicating $P \propto E^2$; b. calculated from a and classical plasma dissipation (Ref. 10); c. obtained by using an effective collision frequency $\nu_{\text{eff}} \propto E^2$; measured $E_{\text{onset}} \approx 12 \text{ V/cm}$, theoretical $E_{\text{onset}} \approx 8 \text{ V/cm}$.