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PARAMETRIC INSTABILITIES
AND ANOMALOUS ABSORPTION

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A Survey of Experiments on Parametric * Instabilities and Anomalous Absorption

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ABSTRACT

In rf heating experiments the possibility of parametric instabilities must be recognized. The experimental evidence for the occurrence of parametric instabilities and associated anomalous absorption and/or heating will be surveyed. The experiments performed in the past few years can be divided according to geometry as follows:

- (1) Excitation by grids (including probes and capacitor plates).
- (2) Cavity excitation.
- (3) Microwave irradiation from waveguides.

The advantages and disadvantages of these techniques will be compared by discussing specific laboratory experiments. The evidence of anomalous absorption and heating, as being due to parametric instabilities, will be discussed.

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1. INTRODUCTION

In this lecture we shall attempt to summarize the status of experimental work on parametric instabilities and anomalous absorption associated with such instabilities. Because of the vast growth of this subject, we will give only a rather rudimentary survey and concentrate on the most recent work. In particular, we shall not cover here the extensive research that has been done on mode-mode coupling. Rather, an attempt will be made to concentrate on those experiments where (i) the "pump" is essentially an "electromagnetic" wave; i.e., its wavelength is much longer than that of the decay waves. (ii) The purpose of study is directed toward the possibility of anomalous absorption and/or heating. This work can best be surveyed either from the point of view of the geometry of the experimental setup, or from a distinction based on the modes involved in the instabilities. We shall employ a bit of both classifications here, as well as a historical approach.

2. DISCUSSION OF EXPERIMENTS

In Table I we attempted to make a survey of some of the experimental results in the last three years. Some of the work listed here has either not been published yet, or has been published only very recently. Hence, our understanding of the results of these experiments could be rather poor and we assume responsibility for any mis-quotations.

In the first column of Table I we list the experimental geometries and in the second column the authors of the experiments are listed. Then we classify their experiments according to the direction of the electric field relative to the dc magnetic field, and then the main results of the experiments are listed. In particular, the important questions concern the measurements of the thresholds, the spectrum, the pump frequencies, the decay waves, and whether anomalous absorption and heating have been observed.

One of the first experiments to demonstrate anomalous absorption was that done by Gekker and Sizukhin.¹ The experimental setup is shown in Fig. 1. Plasma was injected into a circular waveguide from one end, and high power microwave energy was injected from the other end, with frequency $\omega < \omega_{pe}$. It was found that, while at low powers most of the energy was reflected, above some threshold the reflection was greatly reduced (see figure of reflection coefficient). It was concluded that "anomalous" absorption occurred. The threshold $v_D/v_{th} \approx 0.1$ observed was approximately an order of magnitude larger than that predicted by theory. In addition, a time variation of the absorption coefficient was observed. In this experiment no detailed measurement of spectrum, local electric field, etc. was made. Similar experiments were performed also by Batanov, et al.,^{2,3} and Sergeichev, et al.,⁵ who placed the waveguide in a dc magnetic field. These authors measured strong heating; i.e., the appearance of energetic particles, at time scales orders of magnitude faster than that accountable by ordinary collisional absorption.

We should also mention the results of Demirkhanov, et al., who observed parametric instability and heating due to a modulated current in the plasma.⁴

Eubank⁶ later performed a series of experiments in which x-band microwave power was beamed onto a magnetically confined plasma column. The setup is shown in Fig. 2. He found that as the reflection was reduced, decay spectrum appeared in the plasma, as shown in Fig. 3. At the same time a diamagnetic loop placed around the plasma column showed increase in the perpendicular energy content of the plasma. A gridded probe at the end of the device showed parallel energy increases by 10 - 15 eV. After changing polarization, roughly comparable results were found both for the ordinary and the extraordinary modes. The thresholds, which were an order of magnitude too high, were attributed to density gradient effects. However, the microwave wavelength was comparable with the plasma size in this experiment, which causes problems in interpreting thresholds. Furthermore, additional ionization due to the x-band microwave power made more detailed conclusions difficult.

A number of authors used cavities for exciting parametric instabilities and for studying anomalous absorption. The experimental setup of Dreicer, et al.⁷ is shown in Fig. 1(b). In a similar setup, typical results obtained by Chu and Hendel¹² are shown in Figs. 4 and 5. These figures show instability onset as deduced from the cavity Q measurements (where $P_{\text{abs}} = P_{\text{inc}} - P_{\text{ref}} = cE^2/Q$ and $E^2 = P_{\text{trans}}/c$). By monitoring the reflected and transmitted power, it is possible to determine the "lossiness" of the

cavity and hence the onset of instability. Figure 4 shows the increase of plasma rf resistivity, increase of "temperature" as determined from conductivity measurements, and growth of noise spectrum (picked up by a probe from within the cavity). In Fig. 5 the electric field is plotted as a function of absorbed power. It is found that in the unstable regime $P_{\text{abs}} \propto E^4$, and hence in the high frequency resistivity, ν is found to be $\nu \propto E^2$. This relationship is found to agree with the theoretical predictions of Oberman and Valeo, and Dubois and Goldman.

The experiments of Chang and Porkolab,¹⁰ and Stencel and Wong¹¹ have been performed in a "grid" geometry, i.e., the rf fields are applied between grids immersed in the plasma, or between a long wire probe and the metal chamber wall. This geometry allows probing of the plasma with rf probes which can be moved in various directions in the region of decay. Thus, the wave numbers can be determined quantitatively and hence the waves identified. For a definite identification of the decay processes, this was found to be a crucial measurement in a number of recent experiments.^{13,14} In addition, with special rf probes the local electric fields can be measured, and hence the threshold fields and growth rates can also be measured.

From the work of Chang and Porkolab in Fig. 6 we show some wavelength measurements of Bernstein waves.¹⁰ More recently, Grek and Porkolab¹³ have obtained further results in the parametric decay of the extraordinary mode into Bernstein waves and ion acoustic waves and/or lower hybrid waves. In these experiments the pump field has been applied in the accessible regime either

near the upper hybrid frequency or the second harmonic of the cyclotron frequency. At the same time, intense heating of the plasma was observed, together with anomalous absorption of the applied rf fields. We believe these results might explain the recently observed strong rf heating in the TM-3 Tokamak.¹⁵

Finally, let us discuss briefly some experiments by Porkolab and Arunasalam,¹⁴ (see Fig. 7) in which a study has been made of plasma produced by a slow wave structure (such as has been used first by Lisitano and coworkers).¹⁶ It is found that strong parametric decay occurs at frequencies such that $\omega < \omega_{ce}$. The instability is due to the decay of either a long wavelength electron plasma wave (at low densities), or a whistler wave (at high densities, i.e., $n_0 > 2 \times 10^{12} \text{ cm}^{-3}$). The electron plasma wave decays into a similar short wavelength wave, and an ion acoustic wave. The whistler may decay into either an electron plasma wave and an ion acoustic wave, or into a second whistler wave and an ion acoustic wave.^{17,18} The wave numbers have been measured with interferometry, and the decay processes were identified. Using a second coil, additional heating has also been measured. Utilizing a fast rise time, 6 kW S-band rf source, with pulse lengths from 0.4 to 10 μsec , anomalous heating of both electrons and ions is observed. The distribution functions of both electrons and ions have been measured. Approximately 10% of both species are heated by one to two orders of magnitude above the cold plasma temperature, in times of the order of a microsecond. Nearly complete absorption of the applied rf power is observed. We shall show several slides demonstrating anomalous heating processes in these

experiments. We should also mention that a good nonresonant plasma source can be made by injecting rf from a waveguide at an angle to the $\vec{B}$ -field at frequencies below the electron cyclotron frequency. Again, parametric instability is observed to be responsible for such plasma production.¹⁴

3. DISCUSSION OF THE RESULTS

Let us now summarize some of the results presented in this lecture. In Table II we list some of the waves which have been observed to decay parametrically. We see that essentially all the electromagnetic modes with frequencies above the ion plasma frequency may be used for parametric heating of a plasma. Waves with frequencies near the lower hybrid^{19,20} and below may also produce similar phenomena, although the situation here is more complicated (i.e., mode-mode coupling, cross-field currents, etc., make the understanding of these experiments more difficult). In Fig. 8 (after Ref. 17) we show how some of these results may be applied to heat toroidal devices, such as tokamaks. Note that the shaded triangle, which is inaccessible for the extraordinary mode, is accessible for whistler waves and electron plasma waves.

In summary, it is clear from Table I that not any one geometry has proved the best to verify all aspects of parametric instabilities. In particular, the waveguide experiments offered some of the first evidence of anomalous absorption (and/or reduced reflection). The advantage of this geometry is the possibility of using large powers for heating, wavelengths less than the

density gradient scale length, and direct applicability to high frequency heating of fusion plasmas, ionospheric experiments,⁸ and laser fusion projects.

The cavity experiments have the advantage of controlled electric field geometry, as long as one is near threshold so that pump depletion is not significant. Thus this geometry proved useful for a quantitative measurement of the anomalous resistivity in the regime of weak turbulence. The disadvantage of this system is the difficulty with which the plasma can be probed in the region of interaction (i.e., wavelength measurements have not been possible and local electric field measurements are difficult).

The grid system is highly versatile in that probing of the plasma region is easy, thus wavelength measurements can be done readily. Although the control of electric field pattern is more difficult, in some cases it has been measured by double probes. Thus, this geometry offers the possibility of local measurement of pump depletion. Perhaps the main disadvantage of this system is that the grids are in contact with the plasma, and thus in the case of long wavelength waves reflections may occur. Hence, care must be exercised in determining thresholds. The slow-wave structures and capacitor-type arrangements offer possibilities of exciting interesting "body" waves, such as whistlers, electron plasma waves, etc. They may also provide some practical geometries to heat fusion plasmas to high temperatures. More work remains to be done to optimize such coil structures.

Thus, in conclusion we may state that parametric instabilities occur in almost any configuration in the presence of medium strength (or strong) high frequency field in a plasma. In particular, the thresholds of such instabilities correspond to rf drift velocities of a few percent of the electron thermal velocity in most experiments. The anomalous absorption and/or heating of plasmas has also been observed in a number of cases, and in many cases the simultaneous presence of a parametric instability and/or decay spectrum has also been observed. In some cases weak turbulence theory has been successful to explain saturation.

It must be pointed out, however, that a number of questions remain, some of which include the following: (a) Different saturation mechanisms may occur for different modes and these will have to be studied. (b) The nature of heating must be further studied, i.e., an important question is what part of the distribution function is heated under different circumstances. (c) The mechanisms of ion heating must be dealt with. (d) Saturation in strong fields, i.e., $V_d/V_{te} > 1$ remains to be studied. (e) The question of "anomalous" reflection, i.e., Raman back-scatter, etc., and the effect of density gradients, will have to be studied. Thus, in the next few years we may expect intensive work in many laboratories to answer some of these questions.

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TABLE I. SUMMARY

GEOMETRY	GROUP	POL.	THRESH.	SPECTR.	PUMP	DECAY WAVES	ANOM. ABS.	HEATING
WAVEGUIDE	GEKKER SIZUKHIN	$B = 0$	(?)	NO	$\omega \approx \omega_{pe}$	NO	YES	NO
	BATANOV	$E \perp B$	NO	NO	$\omega \lesssim \omega_{ce}$	NO	NO	YES
	EUBANK	$E \parallel B$ $E \perp B$	(?)	YES	$\omega \lesssim \omega_{pe}$ $\omega \gtrsim \omega_{ce}$	NO	YES	YES
CAVITY	DREICER INGRAHAM	$E \parallel B$	YES	(?)	$\omega \approx \omega_{pe}$	NO	YES	YES
	CHU HENDEL	$E \parallel B$	YES	YES	$\omega \approx \omega_{pe}$	NO	YES	YES
	STENCEL WONG	$B = 0$	YES	YES	$\omega \approx \omega_{pe}$	YES	NO	NO
GRID	CHANG PORKOLAB	$E \perp B$	YES	YES	$\omega > \omega_{ce}$	YES	NO	NO
	GREK PORKOLAB	$E \perp B$	YES	YES	$\omega \approx n\omega_{ce}$ $\omega \approx \omega_{UH}$	YES	YES	YES
	PORKOLAB ARUNASALAM	$E \nabla B$	?	YES	$\omega \lesssim \omega_{ce}$	YES	YES	YES
SLOW-WAVE ST.	DEMIRKHOV ET AL.	$E \nabla B$	NO	YES	$\omega \approx \frac{k_y}{k} \omega_{pe}$	(?)	NO	YES
CAPACITOR	HOOKE ET AL.	$E \nabla B$	YES	YES	$\omega \approx \frac{k_{ }}{k} \omega_{pe}$	YES	NO	YES
DISCHARGE T. IN WAVEGUIDE	STERN IZOAR	$B = 0$	(?)	YES	$\omega \approx \omega_{pe}$	(?)	NO	NO
TOKAMAK	DOVIN, ET AL.	-	-	?	MAGNETOSONIC WAVE		YES	NO

TABLE II. TYPES OF WAVES INTERACTING

PUMP WAVE	SIDE BANDS	ION MODE	OBSERVATION
ORDINARY MODE $E \parallel B, \quad \omega \approx \omega_{pe}$	ELECTRON PLASMA	ION ACOUSTIC	YES
EXTRAORDINARY MODE $E \perp B, \quad \omega > \omega_{ce}$	CHW (UPPER HYBRID), BERNSTEIN)	ION ACOUSTIC, LOWER HYBRID	YES YES
WHISTLER MODE $E \nparallel B, \quad \omega \leq \omega_{ce}$	WHISTLER ELECTRON PLASMA	ION ACOUSTIC ION ACOUSTIC	YES YES
ELECTRON PLASMA WAVE $\omega \neq \omega_{pe}, \quad \omega \neq \omega_{ce}$ ($E \nparallel B$)	ELECTRON PLASMA	ION ACOUSTIC	YES
CHW (BERNSTEIN) Δ ($\omega \approx n\omega_{ce}, E \perp B$) Δ	CHW	ION ACOUSTIC LOWER HYBRID	YES

For 100V/cm, $V_E/V_{th} = \frac{eE}{m\omega} / V_{th} \approx 0.1$

(b)

723374

Fig. 1. (a) Experimental setup of Gekker and Sizukhin.
(b) Typical arrangement of cavity measurements of anomalous absorption (after Dreicer et al.).

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Fig. 2. Experimental setup of Eubank.

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Fig. 3. Typical experimental results of Eubank. (a) Reflection coefficient for incident microwave power, for $\omega < \omega_{pe}$ and $\omega > \omega_{pe}$. (b) Observed oscillation spectrum in argon with 6000 W incident rf power.

723160

Fig. 4. Results of the cavity experiment of Chu and Hendel.

723180

Fig. 5. Measurements of the cavity Q of Chu and Hendel.

723373

Fig. 6. Decay spectrum and wavelength measurements in the experiments of Chang and Porkolab. (a) Spectrum of the ion acoustic waves (above threshold). (b) Spectrum of the high-frequency waves. $\omega_{ce}/2\pi = 148$ MHz, $\omega_0/\omega_{ce} = 2.41$ (above threshold). The arrow shows the pump frequency and its location in the dispersion curve. (c) Dispersion curve of cyclotron harmonic waves. The shaded regions show regions where parametric instability has been observed. Interferometer traces of waves above threshold. (d) Ion acoustic wave, $\omega_A/2\pi = 3.2$ MHz, $k_\perp \approx 20$ cm⁻¹ (at $r \approx 1.5$ cm); (e) lower side band, $\omega_L/2\pi = 354.8$ MHz, $k_\perp \approx 18$ cm⁻¹, $k_\perp r_{ce} \approx 2.2$; (f) upper side band, $\omega_U/2\pi = 361.2$ MHz, $k_\perp \approx 21$ cm⁻¹, $k_\perp r_{ce} \approx 2.5$.

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Fig. 7. Setup for the parametric decay of whistler waves in the experiments of Porkolab and Arunasalam.

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Fig. 8. Accessibility for the extraordinary mode in a torus. An approximate sketch of accessibility for the extraordinary mode of propagation in a toroidal device. n_0 is the assumed plasma density as a function of radius, EP refer to electron plasma waves (shown by crosses) and CHW refer to cyclotron harmonic waves (shown by dots). $\Omega = \omega_c$ in the text. The shaded regions show inaccessible regimes. $\omega_p^2/\omega_c^2 \approx 1$.

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