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1973 J. Phys. A: Math. Nucl. Gen. 6 L24

(http://iopscience.iop.org/0301-0015/6/3/003)

J. Phys. A: Math., Nucl. Gen., Vol. 6, March 1973. Printed in Great Britain. © 1973

LETTER TO THE EDITOR

Plasma heating effects in the presence of a parametric decay instability

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MS received 3 January 1973

Abstract. Experimental results are presented which show that, above a certain threshold value, a large-amplitude electron Bernstein wave can decay into another Bernstein wave plus a low frequency (LF) ion cyclotron wave. At increased incident wave amplitudes, a whole spectrum of LF ion waves appeared, with frequencies extending up to the ion plasma frequency. Simultaneous, with the excitation of this spectrum of ion waves, measurement of both ion and electron temperatures indicated increases in value up to 2·5 times their initial values.

Recently, there has been increasing interest in the anomalous absorption of high frequency (HF) radiation and the probable plasma heating that might ensue from the enhanced fluctuation levels resulting from the excitation of parametric decay instabilities in a plasma. In fact, enhanced resistivity and heating effects have been observed in a number of laboratory (Eubank 1971, Driecer *et al* 1971, Chu and Hendel 1972), ionospheric (Wong and Taylor 1971), and numerical plasmas (Kruer *et al* 1970, Carlile 1972). In particular, an interesting case is that in which a monochromatic HF electromagnetic wave incident on a plasma induces a large-amplitude electron wave in the plasma, and this by nonlinear coupling of the HF electric fields to low frequency (LF) density oscillations transfers energy to an electron wave at a lower frequency and an ion decay instability at a low frequency. It has been suggested that this transfer of energy to the ions might result in ion heating in the plasma (Keen and Fletcher 1971). This paper reports the situation in which the incident HF electric field induces in the plasma a large-amplitude Bernstein mode at a frequency ω_0 close to the electron cyclotron resonance (ECR) frequency ω_{ce}, and the nonlinear coupling transfers energy to another Bernstein mode at a lower frequency ω_1, plus a low frequency mode ω_2. Previous experiments at lower magnetic fields (Keen and Fletcher 1971, Chang *et al* 1972) have shown that the low frequency mode was an ion sound wave, whereas in these experiments, at higher fields, the ion mode is an ion cyclotron wave, $\omega_2 = \omega_{ci}$. From the conservation of energy and momentum in the decay process, the following relationships between the frequencies $\omega(k)$ and wavenumbers k, must be satisfied:

$$\omega_0(k_0) = \omega_1(k_1)+\omega_2(k_2) \quad (1)$$

$$\boldsymbol{k}_0 = \boldsymbol{k}_1+\boldsymbol{k}_2. \quad (2)$$

This single-mode decay process occurs when the incident EM wave just exceeds a certain threshold power value. However, if this threshold power value is greatly exceeded, many low frequency ion modes extending up to the ion plasma frequency ω_{pi} are observed. Under these conditions, substantial plasma heating results and both the electron temperature T_e, and the ion temperature T_i, have been measured.

Plasma was produced by a helical transmission line, operating in the S band microwave range. This plasma production region was separated from the main experimental region and thus enabled the pressure of the neutrals (H_2, He, Ne, or Ar) in the experimental region to be maintained at less than 10^{-5} Torr. The resulting plasma in the experimental region had a peak density in the range 5×10^{10}–3×10^{11} cm^{-3}, $T_e \simeq 3$–7 eV, and $T_i \simeq 0{\cdot}5$–$1{\cdot}0$ eV depending upon the neutral gas used and the input power to the source. However, most of the experiments described here were performed in a neon plasma. The plasma column was about 1·5 m long, and was contained in a longitudinal magnetic field which could be varied in the range 0·3–3·0 kG (homogeneity < 0·5%). The plasma density n, and electron temperature T_e were measured using a floating double probe. The electron temperature and its energy distribution function were further checked using a double-differentiated single probe curve technique and a gridded electron energy analyser. All of these gave consistent results for T_e. The ion temperature T_i was measured using a gridded ion energy analyser, and an ion sensitive probe (Katsumata and Okazaki 1967).

The HF electromagnetic waves were coupled to the plasma in the experimental region from a cylindrical slot-line cavity device surrounding the plasma column operated at a constant frequency of 2·45 GHz. It was found that this device was useful for propagating Bernstein waves in the plasma (Keen and Fletcher 1971). Alternatively, a small aerial probe was employed as a transmitter, and at small powers, the linear wave dispersion diagram was checked using an interferometric technique, as previously. The HF and LF spectra were detected on small probe aerials which could be moved radially in the plasma, and the output was displayed directly on a spectrum analyser.

In these experiments, the HF signal at frequency $\omega_0 (= 2{\cdot}45$ GHz) was fed to the slot-line cavity or transmitting probe, and if the magnetic field was varied such that $\omega_0 \gtrsim \omega_{ce}$, Bernstein waves were propagrated across the magnetic field. At low input powers the HF spectrum near ω_0 indicated a single frequency at ω_0. However, above a certain threshold power value (~ 5–8 W), there were found to be two additional frequencies (near ω_0), at $(\omega_0-\omega_{ci})$ and $(\omega_0+\omega_{ci})$. The signal at $(\omega_0+\omega_{ci})$ was at least an order of magnitude in level below the one at $(\omega_0-\omega_{ci})$. The corresponding low frequency spectrum showed the presence of a single mode at ω_{ci} in the plasma. These frequency spectra showed that equation (1) was satisfied in the wave decay process. Figure 1(*a*) shows the amplitude of this low frequency component in a neon plasma as a function of magnetic field for an input power just above threshold. It is seen that the instability at ω_{ci} is only obtained in the field region where the HF input signal excites large-amplitude Bernstein waves in the plasma (at $\omega_0 \gtrsim \omega_{ce}$), since at higher field values no instability is observed. The identification of the LF instability as an ion cyclotron wave is based upon results such as those in figure 1(*b*), where the instability frequency ω_I is plotted as a function of field B and for comparison the full line $\omega = \omega_{ci}$ is drawn. Good agreement is obtained in this case. Further evidence has been obtained by performing similar experiments at different frequencies and with other gases (H_2, He, and Ar), and these results will be published elsewhere.

Equation (2) could not be checked directly. The wavenumber $\boldsymbol{k}_0$ was measured at small amplitude using the aerial launched waves, but the wavenumber $\boldsymbol{k}_1$ of the HF signal at ω_1 could not be measured. This was due to the presence of the large-amplitude signal at ω_0 completely swamping the signal at ω_1 and this rendered its spatial variation undetectable. However, in view of the fact that equation (1) is satisfied, and that the measured threshold field agrees with that predicted theoretically by Tzoar

(1969), it is inferred that the observed LF instability is the ion cyclotron instability decay wave induced by the large-amplitude Bernstein mode.

If the input power level is increased above threshold value (P_{th}) the decay instability amplitude increases gradually. However, at powers between about 2 and 3

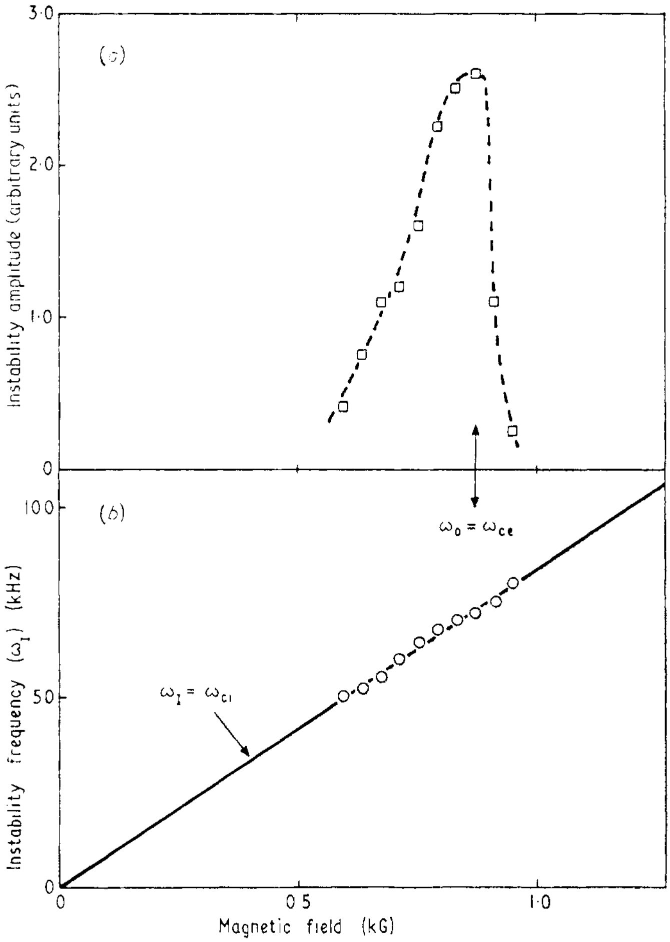

Figure 1. (*a*) Induced LF instability amplitude as a function of magnetic field; and (*b*) its frequency ω_I as a function of magnetic field.

times P_{th} the single mode begins to saturate and other modes and harmonics appear in the LF spectrum. These frequencies appear also in the upper and lower sidebands of the HF spectrum. Further increase of the input power at ω_0, causes a whole 'turbulent-like' spectrum of LF waves to appear stretching from ω_{ci} right up to the ion plasma frequency ω_{pi}. The corresponding HF spectrum shows this range of frequencies in the upper and lower sidebands. The value of ω_{pi} ($= 4\pi ne^2/M$) has been checked in various plasmas (H_2, He, Ne and Ar) and by varying the density of the plasma, as previously (Keen and Fletcher 1971).

Under the conditions in which the input power at ω_0 has been increased up to 20–25 times P_{th}, the electron distribution function and T_e have been measured at distances of 10–25 cm away from the exciting structure. In the neon plasma, at zero input power, $T_{e0} \simeq 5{\cdot}5$ eV and the distribution function was maxwellian. The situation which existed at high powers ($P = 120$ W) is shown in figure 2(*b*). Here the measured T_e is plotted against the magnetic field B. It is seen that at magnetic field values

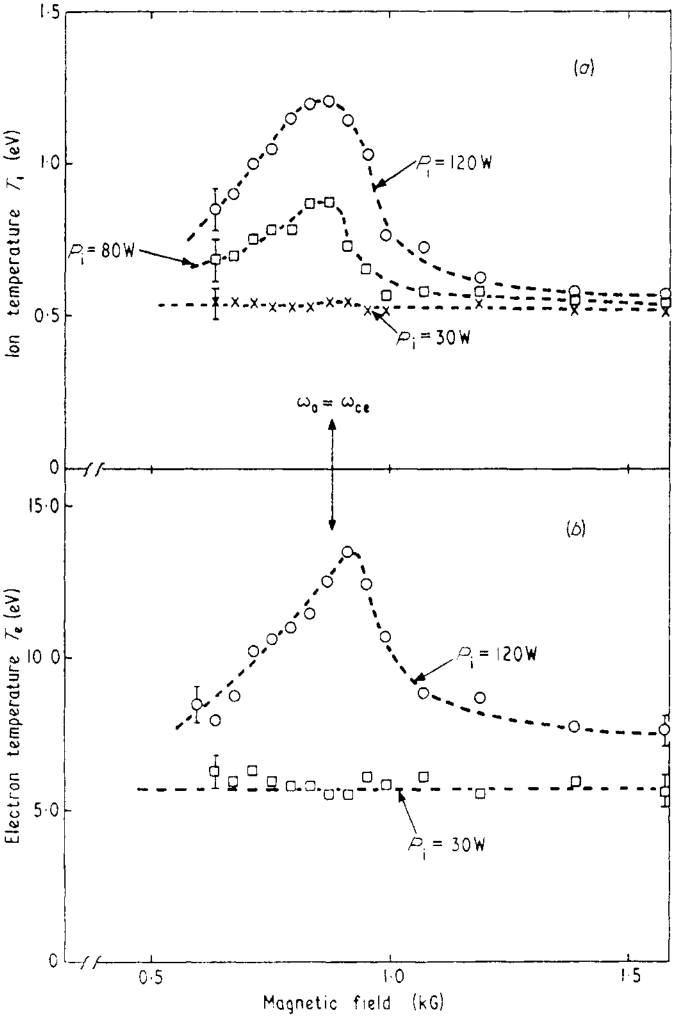

Figure 2. (*a*) Ion temperature as a function of magnetic field taken at input powers P_i, of 30, 80 and 120 W; and (*b*) electron temperature as a function of magnetic field measured at input powers of 30 and 120 W.

where Bernstein waves are excited in the plasma, and thus the decay instability occurs ($\omega_0 \ngtr \omega_{ce}$), increases in T_e occur with values up to 13·5 eV. However, at higher magnetic field values no parametric instabilities are observed, and the increase is much less, showing values of $T_e < 8$ eV. The electron distribution function measured at the same time indicated an approximate maxwellian distribution, although at values of B near $\omega_0 = \omega_{ce}$, signs of a high energy tail to the function were observed. Also shown in figure 2(*b*) ,is a plot of T_e against magnetic field B taken at an input power of 30 W. In this case it is seen that the rise in electron temperature is relatively small at all field values.

The optimum increase in T_e occurred near $\omega_0 = \omega_{ce}$, so at this value of magnetic field ($B = 0{\cdot}87$ kG), T_e was measured as a function of input power P_i. (T_e/T_{e0}) is shown plotted against P_i in figure 3(*a*). It is seen that at low powers there is little

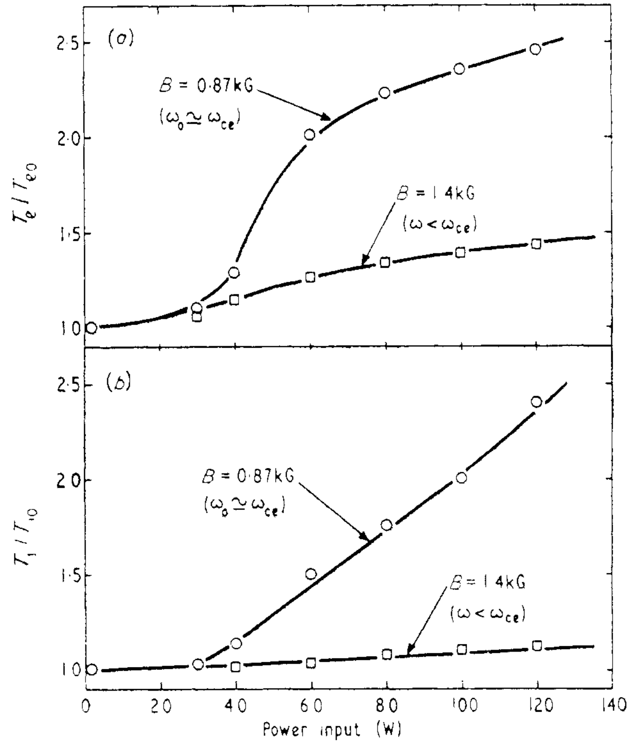

Figure 3. (*a*) Reduced electron temperature (T_e/T_{e0}) and (*b*) reduced ion temperature (T_i/T_{i0}) as a function of power input taken in constant magnetic fields of 0·87 and 1·4 kG.

effect on T_e, and even at power inputs up to about 20 W ($P_{th} \sim$ 5–6 W), T_e rises are hardly noticeable. However, at $P_i > 20$ W, where a more 'turbulent-like' LF spectrum is apparent, T_e begins to rise fairly abruptly, and then settles to values of $T_e/T_{e0} \simeq$ 2–2·5, at values up to $P_i = 120$ W. Also, shown for comparison in figure 3(*a*), is a plot of (T_e/T_{e0}) against P_i taken at a magnetic field $B = 1{\cdot}4$ kG where $\omega_0 < \omega_{ce}$ and no parametric instabilities are excited. It is seen that heating effects in this situation are much less apparent.

Simultaneously, measurements of the ion energy distribution function and T_i were taken. Some results are shown in figure 2(*a*) which indicate the variation of T_i with magnetic field B, at three different HF power inputs (120, 80 and 30 W). It is seen that T_i increases in the field region ($B < 0{\cdot}87$ kG), where $\omega_0 > \omega_{ce}$, and where the LF parametric instability is excited. Increases in value from $T_i = 0{\cdot}5$ eV up to $T_i = 1{\cdot}2$ eV have been observed, and the energy distribution indicated a maxwellian distribution. Similarly, T_i has been measured as a function of input power P_i at the magnetic field ($B = 0{\cdot}87$ kG) near $\omega_0 = \omega_{ce}$, and this is shown in figure 3(*b*) plotted as (T_i/T_{i0}) against P_i. Again, it is seen that there is little effect in ion heating until input powers in excess of 30 W are used. This is the region in which the 'turbulent-like' LF spectrum occurs in the plasma. At higher power values, T_i/T_{i0} increases to values of about 2·5 at $P_i = 120$ W. In comparison, the change in T_i is negligible at all power levels, in the field $B = 1·4$ kG.

Unfortunately, no theoretical predictions have been made for the decay of Bernstein waves into LF ion modes except those of Tzoar (1969). In this case predicted threshold field values agree reasonably with measured values. However, numerical computations have been performed on the anomalous heating of a one-dimensional plasma by a large-amplitude, long-wavelength electric field oscillating near the plasma frequency ω_{pe} (Kruer *et al* 1970). It was found, that a large-amplitude pump field near ω_{pe} excited a decay instability in the plasma at the ion frequency as well as the plasma oscillations. At a sufficiently high HF input power ($\omega_0 \simeq \omega_{pe}$), these ion fluctuations reached a certain large level and then the plasma began to heat efficiently according to an anomalous resitivity. Qualitatively, similar effects have been observed in this experiment, except that the HF waves are Bernstein waves, and the LF ion waves are ion cyclotron waves. Moreover, in this experiment the ion–electron collision frequency ν_{ie} is so small that direct transfer of energy from the heated electrons to the ions by binary collisions would be insufficient to account for the ion heating.

Hence, it is concluded that the enhanced transfer of energy from the HF pump field to the electrons and ions is due to enhanced wave–particle interaction associated with the development of the parametric decay instability in this highly nonlinear regime. Therefore, it appears that the plasma heating is directly associated with the presence of the parametric decay instability in the plasma, and that this technique suggests a useful method of electron and ion heating, since the plasma is an extremely efficient absorber of radiation in the frequency range near ω_{ce}.

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