A REVIEW OF EXPERIMENTS ON CROSS-FIELD PLASMA INSTABILITIES

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ABSTRACT

If electrons drift relative to ions across a magnetic field, three types of electrostatic cross-field instability can occur at frequencies much greater than the ion cyclotron frequency. These have been predicted to cause particle heating and perhaps anomalous diffusion. The experiments on each type are described. The main observations include linear and nonlinear wave properties, together with the ion heating associated with the two low frequency modes.

Keywords: cross-field instability, turbulence, electron cyclotron, modified two-stream, ion acoustic, ion heating

1. INTRODUCTION

A wide variety of waves can occur in a plasma, especially when a magnetic field is present. They can be electromagnetic or electrostatic; they can involve only the electrons (at the higher frequencies) or electrons and ions together (at the lower frequencies); and some of them depend strongly on their direction of propagation $\theta$ relative to the magnetic field, especially when $\theta$ is almost 90°. Such variety stems from the presence of three types of restoring force ($-\nabla p$, $qE$ and $qv \times B$) rather than the single type ($-\nabla p$) that occurs in a neutral gas.

In this article we shall be concerned with a small group of plasma waves called Cross-field Instabilities. This name can embrace a slightly wider group, including the Universal Drift Instability driven by $\nabla p \times \vec{B}$, but in its more limited sense it refers to the three electrostatic types that can arise when:

(i) There is relative drift between electrons and ions across a magnetic field;
(ii) The electrons are magnetized but not the ions;
(iii) The wave vector $\vec{k}$ is almost perpendicular to $\vec{B}$.

The relative drift velocity can be achieved either by direct injection of an ion beam across $\vec{B}$, with the beam radius of curvature much greater than typical wavelengths, or by $\vec{E} \times \vec{B}$ drift of the electrons (but not the ions), or in the form of a diamagnetic drift.

The three types of instability are known as the Electron Cyclotron Drift (ECD) type, the Modified Two Stream (MTS) and the Cross-
field Ion Acoustic (CIA). Their relevance to the anomalous diffusion of plasma was the subject of much discussion in the early 1970's and their linear properties were summarized by Lashmore-Davies and Martin.1

2. ELECTRON CYCLOTRON DRIFT INSTABILITY

The Electron Cyclotron Drift instability occurs at a frequency just above the electron cyclotron frequency $\Omega_e (= eB/m_e)$ and, in the rest frame of the electrons, it is simply an electron Bernstein wave, driven unstable by the ion drift. The first (and only?) experiment on the ECD was performed by Ripin & Stenzel2 using an almost exactly parallel 1 keV hydrogen ion beam (divergence angle ~ 1°) which travelled across a 40 gauss magnetic field and ionized the background hydrogen gas. An important feature of their experiment was the extractor-grid system comprising three grids as shown in Fig. 1. The hole size and spacing of the grid plates were carefully designed for the required "ion optics", and the beam could be de-focussed by varying the voltage $V_F$ of the second grid, thus switching off the instability. Such control enables one to switch on and observe the temporal growth rate. The experiment requires a sufficiently large beam speed ($v_b \sim c_e$, the electron thermal speed ) and beam density ($n_b > 0.3 n_e$), and sufficiently small $k_i/k_e$. Computer simulation of the ECD3 shows that it heats the electrons rapidly and may be responsible for the turbulence and anomalously large plasma resistivity observed in certain collisionless shock experiments.4 The electron heating observed by Ripin & Stenzel2 is relatively small but there is a sufficient temperature gradient, they suggest, to reduce the effective length for coherent growth, thereby limiting the final ECD amplitude.

3. MODIFIED TWO STREAM INSTABILITY

The Modified Two Stream type, MTS, has also been called the Lower Hybrid Beam Plasma instability because it occurs at about the lower hybrid frequency,

$$\omega_{\text{ LH}} = \omega_{\text{ pl}}(1 + \frac{\omega_{\text{ pe}}^2}{\Omega_e})^{-1/2},$$

as seen in the rest frame of the ions. Like the ECD it is driven unstable by the relative drift of the ion and electron populations. Such drift constitutes free energy of the particle system, which feeds into the growing waves. As early as 1967, Ashby and Paton5 noted that a burst of plasma from a Pierce gun, fired axially into a current-carrying solenoid, rapidly developed a fairly broad range of turbulence centred on $\omega \sim \omega_{\text{ pl}}$ (ion plasma frequency), with $k_z \sim 0.1 k_e$. They interpreted this as MTS turbulence, driven by the diamagnetic drift of the ions. However, the comparatively large value of $k_r/k_e$ suggests that this was not the MTS but the cross-field ion acoustic instability described below. The first clear observation of the MTS appears to be that of R. Chang6 who was able to control $k_y$ by the use of a phased-array of modulated ion beams, thereby ensuring the MTS requirement that $k_y/k_e \sim \sqrt{m_e/m_i}$. He found fairly good agreement

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Fig.1. ECD experiment.2
between observed and predicted frequency and growth rate. It appears that the only other experiments on the MTS were those performed by Yamada and Owens\textsuperscript{7} and Yamada and Seiler\textsuperscript{8} in a Q-machine.

The first of these dealt with the generation of an MTS by the $\vec{E} \times \vec{B}$ electron drift occurring in the edge region of an axial electron beam. With the electron beam pulsed on and off, the parallel and perpendicular ion temperatures were measured as functions of time by boxcar sampling of the ion current to a small Faraday cup (to obtain the I–V curve at a given time after switch-on). As shown in Fig. 4, the parallel ion temperature hardly increased when the MTS appeared, but the perpendicular (azimuthal) ion temperature increased by nearly an order of magnitude. Furthermore, the heating rate was shown to be proportional to the MTS energy density, in accordance with the quasi-linear theory of wave–particle interaction. In Yamada's second experiment the MTS is generated by a spiralling ion beam which exhibits anomalous slowing in the strongly nonlinear stages of the instability, together with a transition from the quasilinear to the particle-trapping regime.

Computer simulation experiments show that MTS turbulence heats both electrons and ions efficiently; more than 30\% of the beam energy can be converted into plasma thermal energy.\textsuperscript{9} A further simulation experiment deals with the acceleration of electrons by MTS turbulence. Figure 5 contains data from a rocket experiment, together with a computed curve, privately communicated by J.M. Dawson to Bingham et al.\textsuperscript{10}

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**Fig.2.** Chang's MTS experiment.\textsuperscript{6}

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**Fig.3.** Yamada's MTS experiment.\textsuperscript{7}

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**Fig.4.** Pulsed operation. From top, mesh bias, instability amplitude, and perpendicular (closed circles, $T_{i\perp}$) and parallel (open circles, $T_{i\|}$) ion temperatures are plotted vs time. $B = 4$ kG.\textsuperscript{7}
4. CROSS-FIELD ION ACOUSTIC INSTABILITY

The Crossfield Ion Acoustic instability, CIA, propagates as the slow mode of the ion beam at a phase velocity \( \omega/k = v_b-c_a \), where \( c_a \) is the ion acoustic velocity, \( \sqrt{KT_e/m_i} \). This was first reported by Barrett and Taylor\(^{11} \) and then Barrett et al\(^{12} \) and Virko and Kirichenko.\(^{13} \) They all operated with \( v_b \) several times larger than \( c_a \), \( B<1000 \) and \( n_e \sim 10^8 \) to \( 10^9 \) cm\(^{-3} \). Measurements of \( v_b-(\omega/k) \) as a function of \( T_e \) confirm that the instability is ion acoustic. The spatial growth rate is accounted for in terms of inverse Landau damping by resonant electrons.\(^{14} \)

Some of the quasilinear and nonlinear behaviour of the CIA is described below.

A related ion acoustic instability was reported by Hirose et al,\(^{15} \) driven by \( \nabla T_e \times \vec{B} \) in a pulsed toroidal plasma. Also, ion acoustic waves near the lower hybrid frequency (\( \Omega, \Omega_H \)) driven by \( \nabla p \times \vec{B} \) and/or \( \vec{E} \times \vec{B} \) electron drift, have been observed recently in high-beta plasmas by Stenzel\(^{16} \) and Barrett and Popov.\(^{17} \)

The significance of the CIA is that (i) its threshold beam velocity is comparatively low (\( \sim 2c_a \)), as in the case of the MTS; (ii) it can occur over a comparatively wide range of \( k_n/k \) (\(< v_b/c_a \)), and (iii) it can produce substantial heating of the ions together with some heating of the electrons. We turn now to a more detailed account of CIA experiments performed in the DP device shown in Fig. 6. Typical waveforms of excited waves are given in Fig. 7.

4.1. NONLINEAR FREQUENCY SPECTRUM \( S(f) \)

The CIA shows spatial growth over a relatively wide spectrum. As the waves propagate they mix and produce an increasingly wide spectrum of wave–wave products, as shown in Fig. 8. Waves of frequency \( f_1 \) and \( f_2 \) are launched and generate an increasing number of harmonics and other product waves according to the frequency relation

\[
f = m f_{p0} = n |f_p - f_q| \quad (n, m = 0,1,2,...).
\]

It is found that the envelope of the spectral peaks in Fig. 8 has the same shape as the underlying broad spectrum of noise. This
suggests that the broadening of the noise spectrum proceeds by wave–wave interaction.\textsuperscript{18} Similar broadening is shown in Fig. 9 where the successively increasing noise levels are obtained by increasing the electron emission in the target chamber.

4.2. WAVE NUMBER SPECTRUM $S(k)$ (three dimensional)

The distribution of CIA wave energy over all directions in $k$–space can be expressed in the form of the wave number spectrum $S(k)$. With $k_z/k$ set at some typical value, say 0.02, one can calculate a pattern of growth rate contour lines in the $k_x k_y$ plane, such as that shown in Fig. 10. The wave energy propagates largely within a cone that is flattened (since the CIA requires $k_y/k \ll 1$) and has a half–angle $\theta_c$ given by\textsuperscript{19}

$$\sin \theta_c = \frac{c_e}{V_b} \frac{n_e}{n_i}$$

Experimentally the wave number spectrum of CIA noise has been investigated by applying digital correlation techniques to the fluctuating signals received by a 4–probe array. Figure 11 shows such an array, together with a typical isosurface enclosing that volume in $k$–space in which $S(k)$ exceeds 30% of its maximum value.

4.3. ANISOTROPY IN $S(k)$ – OBLIQUE TURBULENCE

When a non-conducting layer accumulates on the walls of the plasma chamber the CIA turbulence changes: the wave energy then propagates obliquely to the ion beam direction.\textsuperscript{20} Similarly oblique propagation has been reported

Fig. 7. Damped and growing ion acoustic waves in DP device.

Fig. 8. Wave spectrum with two launched waves $\omega_1$ and $\omega_2$ at two distances along the beam: Dotted line – linear instability growth band. Dashed line – envelope of observed nonlinear wave spectrum.\textsuperscript{18}

Fig. 9. Noise spectra at different electron emission levels.\textsuperscript{18}
in the case of turbulence in a collisionless shock wave experiment by Machalek and Nielsen. Both experiments have a particle drift \( \mathbf{v} \) across a magnetic field \( \mathbf{B} \) and in both cases it is found that \( \mathbf{k}_{\text{max}} \), the wave vector of maximum wave energy, is not parallel to \( \mathbf{v} \) but is rotated through an angle \( \alpha \) towards the \( -\mathbf{j} \times \mathbf{B} \) direction. From laser scattering experiments Machalek and Nielsen found \( \alpha \approx 25^\circ \). This was later explained in terms of the viscous drag by the turbulence on the drifting electrons. Such a model can account partially for the linear relationship between \( \tan \alpha \) and the normalized noise energy density in CIA turbulence, observed by Greaves, see Fig. 12. However, the obliqueness is perhaps better explained by the presence of an axial electric field \( E_x \) which would create a vertical electron drift \( \mathbf{v}_{dy} = \mathbf{E}_x \times \mathbf{B}_z \) of the order of the ion acoustic speed \( c_s \) (too small to be measured directly). The field \( E_x \sim 10 \text{ V/m} \) is present whether the chamber wall is clean or has a non-conducting layer. However, in the non-conducting case a much smaller electron emission current from the filaments is needed to sustain the plasma because the electrons are much better contained and survive for many transit periods, i.e. long enough to affect the CIA noise. The growth rate contours are then no longer symmetrical about the \( x \)-axis (as in Fig. 10) but are shifted towards the \( -\mathbf{v}_{dy} \) direction and become concentrated near the Mach cone angle, as in Fig. 13.

Likewise the observed \( S(\mathbf{k}) \) isosurface in Fig. 14 is strongly oblique when \( \mathbf{v}_{dy} \sim c_s \). Furthermore, comparison of Figs. 10 and 13 shows that obliqueness implies a reduced range of \( k_x \) and therefore a narrower frequency spectrum, as observed.

### 4.4. ION HEATING BY CIA TURBULENCE

When the wave number spectrum \( S(\mathbf{k}) \)
is non-isotropic, as in Figs. 10 and 11, one expects the stochastic heating of the ions and electrons (by the fluctuating electric fields) also to be non-isotropic. Furthermore, with electrons constrained by the magnetic field, their heating is mainly parallel to the field by the small $E_z$ components, whereas the ion heating is mainly perpendicular to the field, by the larger and components.\(^8\)

We consider the ion heating by CIA turbulence, measured with electrostatic energy analyzers. Using a conventional analyzer, orientated to receive the ion beam directly, the spatial development of the ion beam distribution function is obtained; see Fig. 15(b).\(^18\) Figure 15(a) is included to show that there is negligible ion heating in the absence of CIA turbulence (with $B = 0$). By employing a directional energy analyzer, Greaves\(^22\) mapped out the collected ion current as a function of the angle of the analyzer axis, from which $T_y \parallel (\mathbf{L} \mathbf{B})$ and $T_x \perp (\mathbf{B})$ could be calculated. Figure 16 shows that $T_y$ is an order of magnitude larger than $T_x$ at the largest value of $B$, i.e. at the highest turbulence level.

From $f(V)$ curves such as those in Fig. 15(b) Greaves and Barrett\(^23\) obtained the spatial rate of increase of the beam energy halfwidth (which is related to the axial temperature $T_y$) as
a function of the total noise energy density $\Psi$; see Fig. 17. At intermediate values of $\Psi$ they found rough agreement with the quasilinear prediction $\delta T_i/\delta x \propto \Psi \tau_c$ where the autocorrelation time $\tau_c$ turned out to be almost independent of $\Psi$ at intermediate and strong turbulence. (The large $\tau_c$ observed at low $\Psi$ may account for the reduced slope of the graphs in this region). The data in Fig. 17(b) show a change of slope at the highest values of $\Psi$, consistent with the onset of the trapping of beam ions by the electrostatic potential fluctuations, i.e. when the trapping time becomes as short as $\tau_c$, which occurs here when the average fluctuation level $\langle n \rangle/n$ is about 10%.

5. CONCLUSION

In this paper we have considered the main results of experiments on the three types of crossfield instability. Most have been performed with an ion beam passing through a stationary plasma or electron population. However crossfield instabilities have been generated by $\vec{E} \times \vec{B}$ or diamagnetic drift of one...

![Fig.15. Spatial development of ion beam distribution function (a) with $B = 0$ and (b) with $B = 30$ G; $V_b = 50$ eV.](image)

![Fig.16. Parallel and perpendicular ion temperature versus magnetic field.](image)

![Fig.17. Ion beam heating rate versus total noise energy density at (a) medium turbulence and (b) high turbulence.](image)
of the charged species relative to the other, which is a not infrequent situation in laboratory and space plasmas. Present experimental research on the CIA is concerned with turbulence–driven particle transport\textsuperscript{24} and the turbulence associated with $\mathbf{E} \times \mathbf{B}$ electron drift.\textsuperscript{17,25}

REFERENCES