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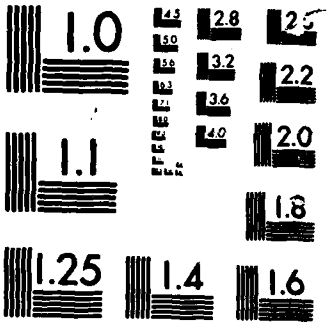

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FINAL REPORT

to the

OFFICE OF NAVAL RESEARCH

on

Grant N00014-84-C-0255

Acceleration of Ions and Electrons by Wave-Particle Interactions

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Co-Principal Investigator

Funding Period: April 1, 1984 - March 31, 1985

UNIVERSITY OF MARYLAND

CONTENTS

I. HIGHLIGHTS OF RESEARCH ACTIVITIES DURING 1984-1985

This report summarizes the research activites carried out at the Institute for Physical Science and Technology, University of Maryland, under the auspices of the Office of Naval Research Contract N00014-84-C-0255 from April 1, 1984, to March 31, 1985. We are pleased to report that significant progress has continued in the study. Five theoretical and numerical investigations of these processes with applications to space physics and laboratory plasmas have been published. The ONR contract was acknowledged appropriately. Dr. Gaffey chaired two sessions at the Spring 1984 Meeting of the American Geophysical Union, and Professor Wu gave an invited talk at the 26th Annual Meeting of the Division of Plasma Physics of the American Physical Society. Professor Wu has been recently elected a Fellow of the American Physical Society and Dr. Gaffey was elected a Member of the New York Academy of Sciences.

A. Overview

The ~~research~~ program ~~is devoted to~~ study~~ing~~ed instabilities resulting from energetic ion beams streaming across a magnetic field, or other nonequilibrium features, such as temperature anisotropy or a loss-cone distribution function, and to calculating the emission of radiation at the fundamental and harmonics of the cyclotron frequency and at the second harmonic of the plasma frequency.

The program ~~is divided~~ into five tasks.

1. Effect of electron thermal anisotropy on the kinetic cross-field streaming instability.

2. Applications of kinetic cross-field streaming instabilities to laboratory experiments.

3. Electromagnetic electron-cyclotron instability excited by energetic electrons with a loss-cone distribution.

4. Induced emission of electromagnetic radiation near the second harmonic of the plasma frequency. and

5. Calculation of spontaneous cyclotron emissivity using the complete relativistic resonance condition.

B. Summary of Research Accomplishments

We now summarize the research results achieved. Detailed reports on each problem are given in the published papers.

1. **Effect of electron thermal anisotropy on the kinetic cross-field streaming instability** (S. T. Tsai, M. Tanaka, J. D. Gaffey, Jr., E. H. da Jornada, C. S. Wu, and L. F. Ziebell, J. Plasma Phys. 32, 159, 1984).

We have investigated both numerically and analytically the kinetic cross-field streaming instability, which is excited by a relative electron-ion cross-field drift and enhanced by an electron temperature anisotropy $T_{e\perp} > T_{e\parallel}$. This investigation is motivated by the research on collisionless shock waves and applied to the earth's bow shock.[1,2] The unstable waves have been shown to be obliquely propagating whistlers, and the instability is not suppressed by electromagnetic effects when the drift velocity V_0 exceeds the Alfvén velocity v_A and the plasma parameter β is of order unity. The effect of increasing V_0/v_A is to shift the direction of propagation more nearly parallel to the magnetic field. The effect of increasing the electron temperature ratio $T_{e\perp}/T_{e\parallel}$ is to increase the growth rate and to shift the direction of propagation more nearly perpendicular to the magnetic field. The mode has mixed electrostatic and electromagnetic polarization. However, for $\beta \sim 1$ and for nearly perpendicular propagation, the mode is predominantly electrostatic; whereas, for more oblique propagation, the electromagnetic and electrostatic components are nearly equal. Finally, for small β, the mode becomes the well-known modified two-stream instability.[3]

In summary, we have studied the plasma instability resulting from a cross-field drift and an electron temperature anisotropy, $T_{e\perp}/T_{e\parallel} > 1$. We find that both effects significantly affect the instability. In particular, the present study has led to the following major conclusions:

a. A relative electron-ion cross-field drift can cause instability, even if $V_0/v_A > 1$.

b. An electron temperature anisotropy $T_{e\perp}/T_{e\parallel} > 1$ significantly enhances the peak growth rate.

c. The unstable waves have both electrostatic and electromagnetic components in general. For $\beta \sim 1$ and nearly parallel propagation, the electrostatic and electromagnetic components are comparable and the polarization is mixed.

d. The instability is highly kinetic for high $\beta \sim 1$. From numerical solutions of the dispersion equation, we find that

$$\frac{\omega_r}{k_\parallel v_{e\parallel}} \lesssim 1 \qquad \text{and} \qquad \frac{|\omega_r - k_\perp v_0|}{k v_i} \gtrsim 1$$

over the entire range of angles of propagation. Moreover, electromagnetic effects, high-order electron cyclotron harmonics, and ion terms all affect the dispersion equation significantly and, therefore, it is difficult to treat the dispersion equation accurately by analytic techniques.

2. **Applications of kinetic cross-field streaming instabilities to laboratory experiments** (E. H. da Jornada, J. D. Gaffey, Jr., and D. Winske, Phys. Fluids 28, 611, 1985).

In a recent paper,[4] we have investigated the kinetic cross-field streaming instability,[1] which is excited by an ion drift across the magnetic field and electron temperature anisotropy, $T_{e\perp} > T_{e\parallel}$. We have found that the usual low-β modified two-stream instability[5] is modified by finite-β effects[1] and enhanced by the electron temperature anisotropy.[4] Quasilinear theory predicts, and computer simulations have verified, that this instability results in significant heating of the electrons and ions.[6]

We have extended the theory of cross-field streaming instabilities to the parameter regime of the Tandem Mirror Experiment (TMX) with neutral beam injection.[7] The cross-field ion drift, as well as the electron thermal anisotropy, provides the free-energy for several instabilities. Three instabilities have been found to occur: an obliquely propagating electromagnetic, lower-hybrid instability (EMLHI), an obliquely propagating ion-ion streaming instability (IISI), and a nearly perpendicular propagating, modified two-stream instability (MTSI). The latter two modes (IISI and MTSI) are electrostatic and their real frequencies are insensitive to the electron temperature anisotropy. The EMLHI and MTSI are the low-β limits of the kinetic cross-field streaming instability.[4] The major conclusions of our study are:

a. The EMLHI is highly kinetic for small values of the drift velocity V_0.

b. The IISI has the largest growth rate when the ratio of the drift to the background ion thermal velocity $V_0/v_{i0} \lesssim 4$.

c. The MTSI has the largest growth rate when $V_0/v_{i0} \gtrsim 4$.

d. Thus, for the present conditions in TMX, the IISI has the largest growth rate; however, when more energetic neutral beams become available, the MTSI may become the dominant instability.

3. **Electromagnetic electron-cyclotron instability excited by energetic electrons with a loss-cone distribution** (H. K. Wong, C. S. Wu, and J. D. Gaffey, Jr., Phys. Fluids 28, 2751, 1985).

An electromagnetic electron-cyclotron instability associated with a loss-cone distribution of energetic electrons has recently been investigated extensively by the space physics community[8-12] as a source mechanism of the auroral kilometric radiation (AKR).[13-21] It has also been suggested that this instability may occur in some laboratory experiments, such as TMX and EBT. A special case of the electron-cyclotron instability excited by a loss-cone distribution of energetic electrons has been studied recently.[22] The analysis is restricted to the special case of radiation propagating parallel to the applied magnetic field ($k_\perp = 0$) and, moreover, emphasis is placed on the limit $k_\parallel \rightarrow 0$. We have generalized the theory to treat an arbitrary direction of propagation and, in addition, a background of cold electrons is included. The major conclusions of our study are:

a. The electron-cyclotron instablity can occur at all angles of propagation for a wide range of parameters.

b. In general, the instability for nearly perpendicular propagation is more serious than that for parallel propagation.

c. The peak of the growth rate, maximized over k, increases with temperature T, and for large T occurs at finite k, rather than at $k = 0$.

d. The range of unstable values of ω_e/Ω_e broadens as T increases.

e. The instability can be suppressed by the presence of a sufficiently large population of cold electrons if T is not too high.

Recent observations[23] indicate that this instability does occur in TMX.

4. **Induced emission of electromagnetic radiation near the second harmonic of the plasma frequency** (C. S. Wu, G. C. Zhou. amd J. D. Gaffey, Jr., Phys. Fluids 28, 846, 1985).

The loss-cone cyclotron instability has recently been extended to the case of electrons with a hollow-beam distribution.[24,25] The study was motivated by the idea that the mechanism may also be applicable to the theories of some solar radio emission processes. However, the discussion in Refs. 24 and 25 is limited to cases in which the plasma frequency ω_e is comparable to the electron-cyclotron frequency Ω_e. In many important astrophysical problems, the radiation processes occur in regions where $\omega_e^2 \gg \Omega_e^2$. For example, in the source region of type II and III solar radio bursts, it is usually believed that $\omega_e^2 \gg \Omega_e^2$. Thus, it is necessary to extend the treatment of the electron-cyclotron instability to the high-density, weak-magnetic-field regime. We have re-examined the hollow-beam excited instability with $\omega_e^2 \gg \Omega_e^2$ for this reason. The major conclusions of our study are:

a. The presence of a hollow-beam of moderately relativistic electrons can amplify unpolarized electromagnetic waves with frequencies near twice the plasma frequency.

b. As the electron energy increases, the real frequency, corresponding to the peak of the maximum growth rate, shifts to values higher than $2\omega_e$.

c. The principal source of the free-energy which drives the instability is the ring feature of the distribution, rather than the beam.

5. **Calculation of spontaneous cyclotron emissivity using the complete relativistic resonance condition** (H. P. Freund, C. S. Wu, and J. D. Gaffey, Jr., Phys. Fluids 27, 1396, 1984).

General expression for the emissivity of cyclotron radiation from high-temperature plasmas including collective effects have been derived and discussed in two recent articles by Freund and Wu[26] and by Audenaerde[27] (relevant bibliographies concerning earlier publications are cited in these articles). Although sufficient generality has been retained in these results, practical evaluations of these expresions are, however, difficult. As a result, emissivity has been discussed in two distinct regimes: (1) $N \cos \theta \gg \bar{v}/c$ and (2) $N \cos \theta \ll \bar{v}/c$, where N is the index refraction of the radiation, θ is the angle between the wavevector and the ambient magnetic field, $\bar{v}$ denotes a characteristic velocity of the electrons, and c is the speed of light. In the first regime, the Doppler effect prevails over the relativistic effect in the wave-particle resonance condition and vice versa for the second regime. It is evident that when the refractive index is close to unity the later regime only occurs in the very small range of θ (i.e., $\theta \simeq 90°$) for weakly relativistic electron energies ($\lesssim$ 10 keV). Obviously the aforementioned approximations become invalid in the intermediate regime where $N \cos \theta \simeq \bar{v}/c$. The range of θ which defines the intermediate regime increases with electron energy, and results in a serious limitation of the previous calculations.[26,27]

Spurred by efforts to explain the auroral kilometric radiation,[28] considerable progress has been made in treating the general resonance condition, and in obtaining general expressions for the growth rates of the escape modes (ordinary and extraordinary) in the presence of a population of suprathermal electrons with a loss-cone distribution function.[8,11,13,15-18,24,25] The success of these efforts provides the motivation for the present work in which we extend the previous[26,27] work on the emissivity to treat arbitrary angles of propagation with no approximation imposed on the resonance condition. In this work we specifically consider the emissions of the escape modes due to energetic electrons with a loss-cone distribution. The applications of the results of our calculation to the study of both the auroral kilometric radiation and to magnetic mirror machine experiments, however, will be presented in separate articles.

In summary, the spontaneous cyclotron emissivity has been calculated using the complete relativistic resonance condition. Unlike prior calculations of synchrotron radiation;[26,27] the result is valid over the entire angular range of propagation without regard to the bulk energy of the electron population. We are specifically interested in the evaluation of the radiation spectrum from an energetic population of trapped electrons having a loss-cone distribution in a low-density plasma. The major conclusions of our study are:

a. In such a plasma (i.e., $\omega_e < \Omega_e$), a relatively high radiation intensity is found in the X-mode at frequencies just above cutoff due to the fundamental gyroresonance which, since this is an escape mode, can readily propagate out of the plasma.

b. While cyclotron damping due to the background plasma can be expected to be negligible for sufficiently low-bulk temperatures of background plasma, amplification of the radiation can occur due to the anisotropic nature of the suprathermal electron distribution. The detailed nature of this instability has been amply discussed in the literature dealing with auroral kilometric radiation.[8,11,13,15-18]

c. While the overall level of spontaneous synchrotron radiation is greatest for the X-mode above cutoff, the detailed angular spectrum is more complex. In particular, the X-mode radiation intensity at the higher gyroharmonics actually exceeds that near the fundamental $\left(\omega \gtrsim \Omega_e \, , \, \omega \gtrsim \omega_{x0} \right)$ for angles of propagation nearly perpendicular to the ambient magnetic field.

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II. LIST OF PUBLICATIONS, PRESENTATIONS AND HONORS

A. Papers Published in Refereed Journals

1. Calculation of the spontaneous cyclotron emissivity using the complete relativistic resonance condition, H. P. Freund, C. S. Wu, and J. D. Gaffey, Jr., *Phys. Fluids*, *27*, 1396 (1984).[1]

2. Effect of electron thermal anisotropy on the kinetic cross-field streaming instability, S. T. Tsai, M. Tanaka, J. D. Gaffey, Jr., E. H. da Jornada, C. S. Wu, and L. F. Ziebell, *J. Plasma Phys.*, *32*, 159 (1984).[2]

3. Instabilities excited by an energetic ion beam and electron temperature anisotropy in tandem mirrors, E. H. da Jornada, J. D. Gaffey, Jr., and D. Winske, *Phys. Fluids* *28*, 611 (1985).[2]

4. Induced emission of radiation near $2\omega_e$ by a synchrotron-maser instability, C. S. Wu, G. C. Zhou, and J. D. Gaffey, Jr., *Phys. Fluids* *28*, 846 (1985).[1]

5. Electron-cyclotron maser instability caused by hot electrons, H. K. Wong, C. S. Wu, and J. D. Gaffey, Jr., *Phys. Fluids*. *28*, 2751 (1985).[3]

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[1] NASA.

[2] NASA and CNPq.

[3] NASA and NRC.

B. Papers Presented at Scientific Society Conferences

1. Electron-cyclotron maser instability in magnetic mirror machines, H. K. Wong, J. D. Gaffey, Jr., and C. S. Wu, Proc. 1984 Sherwood Theory Meeting, Annual Controlled Fusion Theory Conf., Incline Village, NV, USA (Apr., 1984).

2. Instabilities excited by an energetic ion beam and electron temperature anisotropy in tandem mirrors, J. D. Gaffey, Jr., E. H. da Jornada, and D. Winske, Proc. 1984 Sherwood Theory Meeting, Annual Controlled Fusion Theory Conf., Incline Village, NV, USA (Apr., 1984).

3. Instabilities due to transmitted and reflected ions in the quasiperpendicular bow shock, J. D. Gaffey, Jr., E. H. da Jornada, and D. Winske, EOS Trans. Am. Geophys. Union 65, 270 (1984).

4. Emission of radiation near $2\omega_e$ by a synchrotron-maser instability, C. S. Wu, G. C. Zhou, and J. D. Gaffey, Jr., Bull. Am. Phys. Soc. 29, 1196 (1984).

5. Instabilities driven by cross-field ion drift and electron temperature anisotropy in the quasiperpendicular bow shock, E. H. da Jornada, D. Winske, and J. D. Gaffey, Jr., EOS, Trans. Am. Geophys. Soc. 65, 1073 (1984).

6. Electron-cyclotron maser instability in TMX-U, J. D. Gaffey, Jr., C. S. Wu, R. F. Ellis, R. A. James, and H. K. Wong, Bull. Am. Phys. Soc. 30, 1435 (1985).

7. Excitation of electromagnetic waves by a moderately relativistic hollow beam of electrons, B. R. Shi, C. S. Wu, J. D. Gaffey, Jr., and G. C. Zhou, Bull. Am. Phys. Soc. 30, 1471 (1985).

8. Effect of an electrostatic instability on the synchrotron-maser process, S. Kainer, X. W. Hu, J. D. Gaffey, Jr., and C. S. Wu, Bull. Am. Phys. Soc. 30, 1511 (1985).

C. Invited Presentations at Scientific Society Conferences

Cyclotron-Maser Instabilities: Auroral Kilometric Radiation (AKR) and Other Applications; C. S. Wu, invited talk presented at the 26th Annual Meeting of the Division of Plasma Physics of the American Physical Society held in Boston, MA, October 29 - November 2, 1984!

D. Honors

Professor C. S. Wu was elected a Fellow of the American Physical Society in October, 1984.

Dr. J. D. Gaffey, Jr., was elected a Member of the New York Academy of Sciences.

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