The University of Michigan
College of Engineering
Department of Nuclear Engineering

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RECEIVED BY TIC MAY 12 1972

Progress Report

MICROINSTABILITIES IN INHOMOGENEOUS PLASMA

May 1, 1971 - January 31, 1972

Terry Kammash
ORA Project 073430

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Under Contract With:

U.S. Atomic Energy Commission
Chicago Operations Office
Contract No. AT(11-1)-1478
Argonne, Illinois

January 1972

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Introduction

Although a number of investigations were initiated this past year most of our effort was directed toward completing two investigations which had been in progress for a few years. They are:

- (1) beam-plasma interactions and instabilities in Astron, and
- (2) absolute instabilities with arbitrary propagation in mirror plasmas.

In addition we examined a problem which could be classified as a fusion reactor technology problem in which we studied the thermal efficiency of a mirror reactor with direct conversion using two fuel cycles. The results of this investigation have been incorporated in a paper soon to be published in Nuclear Fusion. A brief discussion of the important results of these investigations will be presented below.

1. Beam-Plasma Interaction and Instabilities in Astron

When a beam of charged particles traverses a plasma an interaction can occur between the beam particles and the electric field of the normal modes of the plasma. If the beam is highly energetic a transfer of energy from the beam to the normal modes of the plasma via the above mechanism can result in amplification of the waves of the plasma. This work involves the study of such a situation in the Astron system. This instability in the Astron experiments has been labeled the "hybrid" instability because it occurs at those relativistic beam cyclotron harmonics in the vicinity of the upper hybrid frequency of the background plasma.

The model used to predict the beam-plasma instability of the Astron system is as follows: A homogeneous, mono-energetic streaming relativis-

tic beam of particles propagates thru a homogeneous Maxwellian plasma perpendicular to a uniform external magnetic field. The magnetic field is assumed to have no effect on the beam particles except that it suggests considering wavelengths which are integral multiples of some characteristic dimension of the beam. This dimension has been assumed to be the cyclotron orbit radius of the beam particles in the external magnetic field. An infinite, homogeneous, linear analysis has been performed on the entire set of Maxwell equations along with appropriate particle equations, that is, relativistic fluid equations for the beam particles and Vlasov equation for the plasma particles. The normal modes of the Maxwellian plasma which exhibit the above beam-plasma interaction are the "extraordinary" modes. These are the modes which have a propagation and electric field vector in a plane perpendicular to the external magnetic field.

The resulting dispersion equation has been solved for waves with wavelengths in the beam direction as stated above and wavelengths perpendicular to the beam, which in the case of the Astron, are much less than the E-layer beam thickness in order to comply with the plane wave analysis. Choosing beam and plasma parameters appropriate to the Astron system one finds the "strongest" interaction occurring at those beam harmonics between the plasma electron cyclotron frequency and the upper hybrid frequency, and in similar locations above each subsequent plasma cyclotron harmonic. In general, at each beam harmonic, there exists unstable regions separated by stable regions in the wavelength spectrum of the normal modes. In the direction of decreasing wavelength, the first unstable region represents interaction with the first branch of the normal modes, the second region with the second branch (near second harmonic of the plasma electron cyclotron frequency) of

the normal modes, and so on. As plasma temperature is increased, these unstable regions shift to longer wavelengths thus indicating that a given harmonic could initially be unstable, then become stable as plasma temperature and density changed.

The above model has displayed qualitative and in some cases quantitative agreement with what is observed in the Astron regarding the "hybrid" instability. To indicate the direction the analytical analysis should proceed, two additional effects were studied. One is the effect of plasma electron-background neutral particle collisions. To first order, this effect showed stabilizing results for all harmonics above the plasma cyclotron frequency and destabilizing results for harmonics below the plasma cyclotron frequency after a critical density was reached. The effect on the beam-plasma mode at a given beam harmonic was found to be most pronounced when the normal mode of the plasma was coincident with that harmonic and decreased rapidly when this resonance did not exist.

Another effect studied was energy spread of the beam particles. One could analytically treat two cases: zero energy spread, which was in the base model, and "wide" energy spread. In this case, "wide" means large compared to the magnitude of the growth rate and frequency shift of the unstable mode from the beam harmonic frequency. The results indicate that energy spread of the beam particles can have a very pronounced effect on the stability of the beam-plasma interaction. It appears that harmonics below the plasma electron cyclotron frequency may be completely stabilized and that harmonics between the plasma electron frequency and the upper hybrid frequency could be quenched with sufficient energy spread.

A paper containing these results is being prepared for publication.

2. Absolute Instabilities with Arbitrary Propagation in Mirror Plasmas

We recall from previous progress reports that the aim of this investigation is to study the stability of electrostatic oscillations with arbitrary propagation relative to the confining magnetic field in mirror plasmas. Specifically we wanted to ascertain which of the known instabilities are absolute and what are the corresponding threshold densities as well as the corrective growth (or decay) rates. One dimensional analyses where propagation is limited to that along the magnetic field have been carried out by others and we compare our results with theirs.

The following systems have been analyzed for the presence of absolute instabilities: 1) Loss Cone, 2) Modified Loss Cone to include a cold ion specie, 3) Drift Loss Cone, 4) Drift Cyclotron, and 5) The Dory-Guest-Harris mode. In each case we allow for arbitrary propagation by considering two dimensions in the wave vector $\vec{k}$. We have obtained the threshold density for absolute instability, the wave numbers and the convective growth (or decay) rates for each of the above as a function of the electron temperature. We have also obtained the variation with ion temperature in the Loss Cone case. Wherever possible these results are then compared with one dimensional results.

For the Loss Cone, Drift Cone, and Drift Cyclotron Cases the density, wave numbers and growth rates do not vary appreciably for $T_e/T_{zi} < 10^{-2}$ where T_e is the electron temperature and T_{zi} is the ion temperature along the magnetic field. There is, however, some variation for larger values of T_e/T_{zi} especially in the real parallel wave number component. The parallel component of the convective growth rate decreases sharply for $T_e/T_{zi} > 10^{-2}$. In the perpendicular direction we find a convective decay rate which remains relatively constant.

The magnitude of the absolute instability threshold density for the Drift Cyclotron Case is about a factor of 55 larger than the Drift-Cone case. The Drift Cone density is about $1/2$ that of the Loss Cone. Hence, we might conclude that the temperature anisotropy is a more serious instability source than is the plasma inhomogeneity, i.e. the density gradient.

The density, wave number and convective growth (or decay) rate for the Loss Cone are much more sensitive functions of the ion temperature anisotropy. With increasing anisotropy we find that 1) the threshold density decreases; 2) the real parallel wave number increases - an indication of making the plasma short and stubby for stability; 3) the real perpendicular wave number decreases; 4) the parallel convective growth rate decreases; and 5) the perpendicular convective decay rate increases.

The one dimensional calculations of Callen (1), and Beasley and Cordey (2) indicate that the threshold density and real parallel wave number are given fairly accurately by the one-dimensional analysis when the variation with electron temperature is considered. However, for accurate values of the convective growth and decay rates, and when the ion temperature anisotropy variation is considered, one must use the two-dimensional analysis. This results from the greater dependence of the perpendicular wave number upon the ion temperature anisotropy than upon electron temperature.

The introduction of a cooler Maxwellian ion component to the hot Loss Cone ions results in a stabilizing effect on the instability at the first cyclotron harmonic. A really significant effect upon the threshold density does not occur, however, until the cold ion fraction is increased to nearly 11% of the total ion density. There is very

little change in the real wave vector components or in the parallel convective growth rate. However, the perpendicular convective decay rate decreases significantly and even becomes a growth rate, i.e., changes sign when the cold ion fraction becomes greater than 10%.

For the Dory-Guest-Harris (3) mode we have confirmed the absolute instability for the flute-like modes. Contrary to the conclusions of Tataronis and Crawford (4) we have shown that the DGH modes do not lead to an absolute instability when oblique propagation is considered.

We have carried this analysis numerically using the Derfler (5) criterion for confirming the presence of absolute instabilities in a system. This criterion lends itself more easily and quickly to numerical calculations than that of Briggs (6), and we have demonstrated the equivalence of the two in at least one example.

The results of these investigations are nearly complete and will be written up soon for publication.

3. Thermal Efficiency of Mirror Reactors with Direct Conversion.

The potential use of mirror machines with direct conversion as a fusion power reactor has been extensively studied in recent years. One measure of its viability as a power producing system is the thermal efficiency - a quantity which reflects the extent to which waste heat is rejected into the surroundings. Using an efficiency of 50% as basis for comparison we calculated the thermal efficiency of a mirror reactor with direct conversion for two fuel cycles. We show on the basis of currently available data and calculations that a D-T mirror reactor may be marginally competitive with non-fusion power plants provided Post's (7) estimates of the achievable direct conversion and injection efficiencies prove realistic. The $D-H_e^3$ mirror reactor, however, appears

less hopeful unless these efficiencies can be improved considerably or the required injection power greatly reduced by some method or other. As pointed out in the introduction these results will soon appear in an article in Nuclear Fusion.

REFERENCES

1. J. D. Callen, MIT Center for Space Research Report No. CSR T-68-3 (1968).
2. C. O. Beasley and J. G. Cordey, Plasma Physics, 10, 411 (1968).
3. R. A. Dory, G. E. Guest, and E. G. Harris, Phys. Rev. Letters, 14, 131 (1965).
4. J. A. Tataronis and F. W. Crawford, J. Plasma Physics, 4, 249 (1970).
5. H. Derfler, Phys. Rev. A, 5, 1467 (1970).
6. R. J. Briggs, Electron-Stream Interaction with Plasma, Research Monograph No. 29, MIT Press (1964).
7. R. F. Post, Proc. Int. Conf. On Nuclear Fusion Reactors, Culham, England (1969).

CONFERENCE PAPERS AND PUBLICATIONS

1. J. N. Davidson and T. Kammash, "Eckonal Approach to Drift Waves in Sheared Fields," Phys. rev. A, 4, 1260 (1971).
2. C. D. Striffler, T. Kammash, and M. Rensink, "Interaction of Relativistic Beam and Normal Modes of a Maxwellian Plasma," Bull Am. Phys. Soc. II, 16, 1271 (1971).
3. R. A. Jong and T. Kammash, "Absolute Instabilities with Arbitrary Propagation in Mirror Plasmas," Bull. Am. Phys. Soc. II, 16, 1259 (1971).
4. T. Kammash, "Charged Particle Heating of Fusion Plasmas," International Workshop on Fusion Reactor Technology, Oak Ridge, June 1971.
5. C. D. Striffler, T. Kammash, and M. Rensink, "Evolution of Unstable Bernstein Modes in Astron Plasma," Sherwood Theoretical Mtg. New York University, March 1971.