MASTER

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NUMERICAL SIMULATIONS OF PLASMAS
WITH SMOOTHING IN PHASE SPACE
AND FILTERING IN TIME

Progress Report

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ABSTRACT

Research under the present contract AT(11-1)-2200 was initiated on February 1, 1972 and renewed on February 1, 1973. The program is supported jointly by the U.S. Atomic Energy Commission and the Office of Naval Research (Physics Branch), each agency contributing approximately \$22,000 yearly during the present period.

As stated in the original proposal, the research is directed toward the development of new numerical methods for plasma simulation and their application to physical problems of current interest to Controlled Thermonuclear Research.

During the past year, research on the project has been concerned with the following problems:

1. Analysis of numerical effects in particle simulation of whistler wave propagation.
2. Theoretical and numerical studies of triggered emissions from electrons correlated in phase by a large-amplitude whistler wave.
3. Development of long-time-step algorithms.
4. Anomalous absorption of radiation in weakly collisional plasmas.

RESEARCH ACCOMPLISHED SINCE LAST RENEWAL

During the past year, research on the project has been concerned with the following problems:

1. Analysis of Numerical Effects in Particle Simulation of Whistler Wave Propagation. Numerical effects due to the initial discrete loading of particles in phase space, which do not exist in real plasmas can lead to misinterpretations of computer simulation results. These effects, which are particularly noticeable in the simulation of low-amplitude wave phenomena, have been studied analytically and numerically. The results of this study have been presented at the 6th Conference on Numerical Simulation of Plasmas held at Berkeley July 18-20, 1973. Papers relating to this study and to the algorithm used in the code have been submitted for publication.
2. Applications to Triggered Emissions. The study of the effect of trapped electrons on the nonlinear evolution of whistler wave-trains has been continued in cooperation with Professor Sudan. Theoretical results supported by computer simulations have shown that electrons correlated in phase during their transit through a triggering wavetrain can emit new waves by a whistler sideband instability with frequencies related to the local magnetic field intensity. The effects of a loss-cone instability and particle diffusion into the loss cone has been considered in details. Preliminary results of this study have been included in a paper to be published this fall in Physics Today and more complete publications are now in preparation.
3. Long-Time Step Algorithms. The development of a time-filtering algorithms (Part B of the original proposal) has been initiated during the past three months. Such algorithms which would follow the low-frequency motion of the

particles, while smoothing out high frequency components of the field, have potential application in the numerical simulation of phenomena involving ion waves on a long time scale. An implicit algorithm has been developed and its convergence and stability have been proven analytically. A test program is presently being written by Mr. Carl Rathmann to confirm these analytical results.

4. Anomalous Absorption of Radiation in Weakly Collisional Plasmas. An analysis of the effect of weak collisions on the turbulent absorption of radiation by plasmas has been started in cooperation with the Laser Fusion Theory group at Lawrence Livermore Laboratory. The simulation method with periodic smoothing in phase space can be easily adapted to include weak collisions by incorporating a collision operator into the smoothing operation. This modification was made on a collisionless code developed earlier and a summary of the results of initial computations on parametric heating is given in Appendix A.

PUBLICATIONS

The research carried out under the present AEC contract resulted in the following articles:

- 1) "Theory of Triggered VLF Emissions from the Magnetosphere" by R. N. Sudan and J. Denavit. To be published in Physics Today, Fall 1973.
- 2) "Numerical Simulation of Whistler Wave Propagation" by J. Denavit. Presented at the 6th Conference of Numerical Simulation of Plasmas, Berkeley, July 18-20, 1973. Submitted for publication to Journal of Computational Physics. (AEC Technical Report C00-2200-3).
- 3) "Periodic Band Matrix Solution," by W. P. Gibbons. Submitted for publication to Communications of the Association for Computing Machinery. (AEC Technical Report C00-2200-4).

PERSONNEL AND TIME ALLOTMENT

During the present period, research on the project is carried out by the following personnel:

1. Principal Investigator: Professor J. Denavit

10% time from 1 February 1973 to 15 June 1973

15 September 1973 to 31 January 1974

2. Research Associate: Dr. B. L. Bogema

Full time from 16 February 1973 to 31 August 1973

3. Research Assistants: John Vomvouridis

Full time from 15 September 1973 to 31 December 1973

Carl E. Rathmann

Half-time from 1 October 1973 to 31 December 1973

APPENDIX A

ANOMALOUS ABSORPTION OF RADIATION IN WEAKLY COLLISIONAL PLASMAS

Computer simulations have shown that a collisionless plasma can absorb energy from radiation through a turbulent heating mechanism*. The energy of the incoming radiation is first converted into plasma waves by the ion decay and oscillating two-stream instabilities. The plasma waves in turn accelerate particles by Landau damping or trapping and this process converts the wave energy into particle kinetic energy. It is found, however, that the absorbed energy appears in the form of high-energy electrons rather than in the desirable heating of the main body of the distribution function.

The purpose of the present study is to consider the weak collisional regime, which is of interest in controlled fusion and ionospheric modification experiments**. In this regime the dominant heating mechanism remains turbulence, caused by instabilities, but collisional damping of the plasma waves may now channel a significant amount of the absorbed energy into main body heating rather than suprathermal tails.

A numerical simulation method is used with periodic smoothing in phase space and a one-dimensional collision operator of the form

$$\left(\frac{\partial f}{\partial t}\right)_c = \frac{\partial}{\partial v} \left[v v f + a^2 \frac{\partial}{\partial v} (v f) \right] .$$

Here the velocity dependent collision frequency $\nu(v)$ may be specified to simulate the desired collisional effects and a^2 is specified by energy conservation.

Initial computations have been made with a large pump field exciting strong turbulent motions and electron trapping. The results shown in Figs. 1, 2, and 3 are comparisons between a collisionless plasma and a plasma with a velocity-

*"Anomalous Absorption of Intense Radiation" by W. L. Kruer and J. M. Dawson, in "Laser Interaction and Related Plasma Phenomena" edited by H. J. Schwarz and H. Hora (Plenum Press, 1972).

**"Parametric Instabilities and Ionospheric Modification" by F. W. Perkins, C. Oberman and E. J. Valeo, Plasma Physics Laboratory report AP69, Princeton, University, 1973.

independent collision frequency $\nu = 0.003 \omega_p$. The ratio of the oscillating velocity to the thermal velocity is $v_{osc}/v_{th} = 0.5$ and the pump frequency is $\omega_{osc} = 1.04 \omega_{pe}$. The ion to electron mass ratio is $M/m = 100$ and the temperature ratio is $T_e/T_i = 30$. Fig. 1 shows the evolution of the electrostatic energy. In both the collisionless and collisional cases the instabilities cause this energy to exponentrate until it reaches a saturation level at $t \approx 300 \omega_p^{-1}$. Fig. 2 shows the total energy and thus describes the energy absorbed by the plasma. Up to $t \approx 300 \omega_p^{-1}$ very little energy is absorbed in either case, showing that direct energy absorption by collisional effects is not significant. For $t > 300 \omega_p^{-1}$ the plasma is strongly turbulent and significant energy absorption takes place in both cases. Fig. 3 shows the distribution functions after the plasma energy has increased approximately a factor of five. We observe here the presence of high-energy tails in the collisionless case, while a considerable amount of main body heating is evident in the collisional case.

Further runs carried out with $\nu(v) \sim v^{-3}$, corresponding to Coulomb interaction, do not show such favorable heating of the main body of the distribution function as shown in Fig. 3. However, in the weakly turbulent regime corresponding to $v_{osc}/v_{th} \sim 0.1$, theoretical considerations suggest that collisional damping, may prevent the formation of suprathermal tails, even in the case of Coulomb interactions. Further numerical simulations with parameters approaching the weakly turbulent regime would therefore be of significant interest.

Figure 1

Figure 2

Figure 3