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

Progress Report

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ABSTRACT

The research is directed toward the development and testing of new numerical methods for particle and fluid simulation of plasmas, and their application to physical problems of current significance to Magnetic Fusion Energy. During the past year, research on the project has been concerned with the following specific problems:

- (i) Numerical simulations of one and two dimensional Langmuir turbulence.
- (ii) Extension of the long-time-scale particle simulation method to include weak collisional effects and cyclotron waves.
- (iii) Development of a computer simulation method to study ion ring stability.
- (iv) Development of a simulation method for wave phenomena in toroidal plasmas in the drift-kinetic approximation.

RESEARCH ACCOMPLISHED SINCE LAST RENEWAL

(i) Computer simulation of strong Langmuir turbulence

(Part A of Technical Scope)

Computer simulations of the generation and collapse of Langmuir solitons in one and two dimensions have been continued in cooperation with the Laboratory of Plasma Studies at Cornell University. Soliton generation in one dimension by parametric instability with weak pump field (normalized amplitudes $\eta \approx 0.1$ to 0.2) has been studied using both particle and fluid simulations. Two dimensional simulations were done with a fluid code developed earlier in the program and improved to allow its application to larger problems without requiring the use of peripheral storage devices. For small pump fields ($\eta < 0.25$) a coherent rather than turbulent soliton structure is found in one dimension, and the saturation spectrum fits the law $\cosh^{-2}(k/k_0)$ better than any particular power law. The situation in two dimensions is notably different because solitons are continuously created and annihilated by collapse and Landau damping. These simulations are presented in two papers "Numerical Simulations of One-Dimensional Solitons" and "Numerical Study of Two-Dimensional Generation and Collapse of Langmuir Solitons" by N. R. Pereira, R. N. Sudan and J. Denavit. The first paper has been accepted for publication in The Physics of Fluids; the second paper is in the final stages of preparation.

(ii) Long-time-scale particle simulation methods

The development of long-time-scale particle simulation methods has been continued. These methods allow particle simulations with time steps Δt much longer than the electron plasma period, $\Delta t \gg \omega_e^{-1}$, and much longer than the transit time of a particle across a wavelength, $\Delta t \gg (kv_e)^{-1}$ (ω_e : electron plasma frequency, k : wave number, v_e : electron thermal speed). Such methods will be

particularly useful to examine resonant particle effects in plasmas with an energetic population of density n_E much smaller than the cold plasma density n_0 . During the past year the algorithm has been extended to include (a) weak collisional effects and (b) cyclotron waves in one dimension, which require a four-dimensional phase space. A number of new test problems have been solved, including nonlinear cyclotron damping of a large-amplitude whistler wave, cyclotron instability of a beam and correlation in phase of resonant particles by a whistler wave propagating along a non-uniform magnetic field. These methods are presented in the paper "Long-Time-Scale Simulation of Resonant Particle Effects in Langmuir and Cyclotron Waves" by C. E. Rathmann, J. Vomvoridis and J. Denavit, now in preparation to be submitted to the Journal of Computational Physics.

(iii) Computer study of the stability of ion rings

(Part C of Technical Scope)

A new computational study of the stability of proton rings was started in cooperation with the Laboratory of Plasma Studies at Cornell University. In the initial (least sophisticated) code presently being developed, the ambient plasma contributes only to charge neutralization. Beam protons are represented by rotating, ring-shaped particles with variable radii and axial positions. To allow stability studies related to kinks and other deformations, the particles are also given first-order perturbations $\sum_m \xi_m \exp(i\ell\varphi)$ where φ is the azimuthal angle and ℓ is integer. A numerical code has been written for this algorithm and is now at the initial testing stage.

(iv) Numerical solutions of the drift-kinetic equation in toroidal plasmas

A numerical method is being developed in cooperation with the Oak Ridge National Laboratory to study long-wavelength phenomena in toroidal plasmas. In its present form, the method is limited to the local flux-surface approximation and uses a simplified collision model. The collisional drift-kinetic equation is used with the distribution function expanded as

$$f = \sum f_{\ell n}(\theta, \zeta) \psi_{\ell n}(v, \alpha)$$

where $\psi_{\ell n}$ denotes orthogonal velocity space functions, v is the particle speed, α the pitch angle and $f_{\ell n}$ are spatially dependent amplitudes (see H. K. Meier et al, ORNL/TM-5314, March 1976). The internal electric field is evaluated from the quasi-neutrality condition $\nabla_{\perp} \cdot \mathbf{J} = 0$, expressed in terms of the amplitudes $f_{\ell n}$. The code has been tested on problems involving electron trapping (without the internal fields) and on simple wave propagation problems. A paper entitled "Simulation of Wave Phenomena in Toroidal Plasmas in the Drift-Kinetic Approximation" by C. E. Rathmann and J. Denavit will be presented on this subject at the San Francisco meeting of the Division of Plasma Physics of APS.

To allow sufficient time to be devoted to the development of this method, further studies of collisional effects on turbulent heating of electrons (see part B of Technical Scope) have been postponed until the next renewal period.

PERSONNEL

During the present period (1 February 1976 to 31 January 1977) research on the project is carried out by the following personnel:

1. Principal investigator:

Professor J. Denavit, 15% of time from 1 February 1976 to 15 June 1976
16 September 1976 to 31 January 1977
Full time from 1 September 1976 to 15 September 1976

2. Research Associate:

Dr. Carl E. Rathmann, full time from 1 June 1976 to 31 August 1976

3. Research Assistants:

John Vomvoridis, full time from 1 September 1976 to 31 January 1977

S. L. Wu, full time from 16 June 1976 to 15 December 1976

LIST OF PUBLICATIONS

(Table I)

1) Publications submitted or in preparation during the past year

<u>Title</u>	<u>Authors</u>	<u>Journal/Status</u>	<u>Percent ERDA Support</u> (under present contract)
"Numerical Simulation of One-Dimensional Langmuir Solitons"	N. R. Pereira R. N. Sudan and J. Denavit	Accepted by <u>The Physics of Fluids</u>	33%
"Numerical Study of Two-Dimensional Generation and Collapse of Langmuir Solitons"	N. R. Pereira R. N. Sudan and J. Denavit	To be submitted to <u>The Physics of Fluids</u>	33%
"Long-Time-Scale Simulations of Resonant Particle Effects in Langmuir and Cyclotron Waves"	C. E. Rathmann J. Vomvoridis and J. Denavit	To be submitted to <u>Journal of Computational Physics</u>	50%

2) Publications submitted during previous years

"Collisional Effects on Electron Heating Due to Parametric Instability"	J. Denavit	Published in <u>The Physics of Fluids</u> 19, 972 (1976)	33%
"Numerical Simulation Methods for Collisional and Turbulent Heating in Plasmas"	C. E. Rathmann	Ph.D. Dissertation Northwestern Univ. (August 1975)	50%
"A Long-Time-Step Particle-Pushing Algorithm"	C. E. Rathmann and J. Denavit	Proc. 7-th Conf. Num. Sim. of Plasmas (Courant Inst. June 1975)	50%
"Whistler Sideband Instability"	J. Denavit and R. N. Sudan	Published in <u>The Physics of Fluids</u> 18, 575 (1975)	25%

Table I (continued)

<u>Title</u>	<u>Authors</u>	<u>Journal/Status</u>	<u>Percent ERDA Support</u> (under present contract)
"Effect of Phase-Correlated Electrons on Whistler Wavepacket Propagation"	J. Denavit and R. N. Sudan	Published in <u>The Physics of Fluids</u> <u>18</u> , 1533 (1975)	25%
"Simulation of Collisional Effects in Plasmas"	C. E. Rathmann and J. Denavit	Published in <u>Journal of Computational Physics</u> <u>18</u> , 165 (1975)	50%
"Two-Dimensional Stability of Langmuir Solitons"	J. Denavit, N. R. Pereira and R. N. Sudan	Published in <u>Physical Review Letters</u> <u>33</u> , 1435 (1975)	33%
"Theory of Triggered VLF Emissions from the Magnetosphere"	R. N. Sudan and J. Denavit	Published in <u>Physics Today</u> , Vol. 12, Dec. 1973	25%
"Discrete Particle Effects in Whistler Simulation"	J. Denavit	Published in <u>Journal of Computational Physics</u> <u>15</u> , 449 (1974)	50%