SECOND QUARTER PROGRESS REPORT ON
FLASHA THEORY AND SIMULATION

July 1, 1978

ERDA Contract EY-76-C-03-0034
(Project Agreement No. 128)

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THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DDC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.
Work accomplished during the Second Quarter of 1978 is reported here.

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, diffusion, transport and other phenomena in plasma. We also work on the improvement of simulation, both theoretically and practically.

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TABLE of CONTENTS

Section I
PLASMA THEORY
A. Drift Cyclotron Instability
B. * Plasmas with Field Reversal

Section II
SIMULATION
A. Quasilinear Simulation of a Mirror Machine
B. * Self-Heating of 1d Thermal Plasma
C. * One Dimensional ES1 Code for Sheaths
D. Particle Trajectories in a Cusp Field

Section III
CODE DEVELOPMENT and MAINTENANCE
A. ES1 Code
B. EML Code
C. * Electrostatic 2½d Code Development (EZOHAR)
D. ES1 + EFL Code
E. * 1½d Particle-Fluid Hybrid Model for Drift Wave Instabilities
F. RJET, PDP 11/04

Section IV
PLASMA SIMULATION TEXT

Section V
SUMMARY OF REPORTS, TALKS and PUBLICATIONS in THE PAST QUARTER

Distribution List

*Indicates ONR supported area
A. DRIFT CYCLOTRON INSTABILITY

J. K. Lee

We use the dispersion equation solver, ROOTS\textsuperscript{1}, to obtain the results of the linear theory (growth rates, etc.) as a guideline of and a comparison with future simulations of density-gradient-induced instabilities, namely, drift cyclotron (DC), drift cyclotron loss cone (DCLC), or lower hybrid drift (LHD) instabilities.

For the drift cyclotron instability, ROOTS with the local approximation provides a dispersion diagram virtually identical to Fig. 1 of Gary and Sanderson's local Vlasov theory.\textsuperscript{2} In addition to this, ROOTS provides nonlocal solutions, which will be useful in most simulations with steep density gradients. Some details will appear in the next QPR.

We found the ROOTS results in the linear local dispersion solutions to agree with Cohen \textit{et al.}\textsuperscript{3} ROOTS predicts the linear marginal stability at \( L_n/\rho_i = 5.0 \) for \( n_i/n_e = 100 \), \( \omega_{pe}/\omega_{ce} = 1 \) (where \( L_n = \frac{1}{n}\frac{dn}{dx} \) \( n(x) \) is the guiding center density, \( \rho_i \) is the ion gyroradius, \( \omega_{pe} \) and \( \omega_{ce} \) are the plasma and cyclotron frequencies of electrons).

Detailed dispersion diagrams for a choice of future simulation parameters will be given in the next QPR.

\begin{flushright}
\textsuperscript{1}M. J. Gerver, "ROOTS, A Dispersion Equation Solver", UCB/ERL Memorandum No. M77/27 (Oct. 31, 1976).
\end{flushright}
B. PLASMAS WITH FIELD REVERSAL

Douglas Harned

(1) MAGNETIC RECONNECTION

The problems of magnetic reconnection have been examined to see if an analogy can be made between the bow shock and the x-points in a field-reversed mirror configuration. The situations appear to be considerably different because of the requirement for particle flow across magnetic field lines in the reconnection. While the solar wind provides such a flow in the magnetosphere, the relatively low particle density in the regions surrounding the x-points in the field-reversed mirror suggest that reconnection will not occur at a significant rate. There is the possibility, however, that in a fusion plasma, alpha particles could provide a significant source for the reconnection process.

Additionally, some facility was developed with the particle trajectory code TIBRO-X. It would be possible with this code to investigate single particle behavior in simple reconnection schemes by replacing the gravitational force with an electric one. New models similar to the current sheet models of Speiser could be examined.

(2) STABILITY OF REVERSED-FIELD CONFIGURATIONS

An investigation has been started to analyze the stability of infinite layer (infinite in z) reversed-field configurations to modes having \( k_z = 0 \). One motivation for this study has been the recent results of simulations at Livermore and Cornell showing the instability of such configurations. The study of this instability is important for understanding the behavior of magnetic field lines in laboratory plasmas and astrophysical environments.

*This section was in Section II: Simulation in the past QPR, but should have been in Section I: Theory.


3Speiser, T. W., "Particle Trajectories in a Model Current Sheet, Based on the Open Model of the Magnetosphere, with Applications to Auroral Particles", J. of Geophysical Research 70, 1717-1728 (1965).


5Friedman, A., private communication (1978).
a cylinder. We are beginning by analyzing a slab of plasma containing a thin beam (the limit of an infinite radius cylinder). Hopefully this will provide insight into the stability of such configurations and may help determine whether the instabilities seen elsewhere are real or numerical in nature.

Section II
SIMULATION

A. QUASILINEAR SIMULATION OF A MIRROR MACHINE
Dr. Y. Matsuda with Dr. H. L. Berk (LLL)

A report is in preparation titled "Quasilinear Simulation of the Drift-Cyclotron Loss Cone Instability".

B. SELF-HEATING OF A LD THERMAL PLASMA
A. Peiravi

This project was completed this past quarter. The results were reported at Monterey (See Section V) and an ERL Report is completed, to be mailed soon.

Dr. Hirotada Abe (Dept. of Electronics, Kyoto University) has kindly called our attention to his work\(^1\) dealing with the same subject. We recommend this work to our readers.

C. ONE DIMENSIONAL ES1 CODE FOR SHEATHS
Yu-Jiuan Chen (Prof. C. K. Birdsall)

No special work to report this quarter.

D. PARTICLE TRAJECTORIES IN A CUSP FIELD
Yu-Jiuan Chen (Prof. C. K. Birdsall)

No special work to report this quarter.

Section III
CODE DEVELOPMENT AND MAINTENANCE

A. ES1 CODE
Dr. W. M. Fawley

(1) Adaptations of ES1 to use Post-Processor "ZED"

We have decided to adapt the much-used 1d electrostatic code ES1 to produce time history files that can be read and manipulated by the post-processor program ZED. ZED is normally used with the output of the 2d code ZOHAR and permits the user to investigate plasma simulation time histories of quantities such as electric potential and potential particle moments through means such as Fourier analysis and cross-correlation. It is necessary to change ES1 to run under the CHATR compiler. In the next QPR, we plan to give extensive details concerning these changes.

(2) A. B. Langdon has changed the loader for B≠O. Consult ESIREP in ES1LIB.

B. EM1 CODE
Dr. W. M. Fawley

ZED will also be set up for EM1 in the near future.

C. ELECTROSTATIC 2d CODE DEVELOPMENT (EZOHAR)
W. M. Nevins, Dr. Y. Matsuda

This work is nearly complete, as reported at Monterey (see Section V) and is being prepared for publication, with the title "A New Particle Simulation Model for a Bounded Plasma", by Nevins and Matsuda.

An initial application of the code will be given in a paper titled "Simulation of the Drift Cyclotron Instability" by Matsuda, in preparation.
A paper titled "Particle-Fluid Hybrid Codes Applied to Beam-Plasma, Ring-Plasma Instabilities" was presented at Monterey (see Section V). The abstract is as follows:

When a beam-plasma type instability is simulated using a particle code, the plasma part (which is usually 100 to 1000 times denser than the beam part) requires a lot of simulation particles; otherwise the noise from the plasma is high enough to obscure the instability itself. One example of this crucial effect can be observed in the simulation of the so-called velocity-space ring-plasma (flute-like) instability, which arises due to the interactions of energetic beam ions (a ring in velocity-space) with cooler Maxwellian plasma ions, carried out through a particle code by C. K. Birdsall et al. Upon the suggestion of A. B. Langdon, we constructed a hybrid code (the idea itself is by no means new) using a particle code (ESI) by A. B. Langdon for the simulation of beam particles and a fluid equations for the representation of the plasma component. One simple example of a fluid is an Eulerian fluid, linearized (EFL). The linearization is to be monitored but generally it is justifiable since the plasma component stays linear in many beam-plasma type interactions. Another possible fluid would be a nonlinear Lagrangian fluid (LAF) suggested by W. M. Nevins. These two fluid schemes will be discussed together with successful applications of a hybrid code combining ESI and EFL (two versions: electrostatic and electromagnetic) to the study of linear and nonlinear evolution of the above ring-plasma instability. The use of a hybrid for a beam-plasma type instability has merits of eliminating the plasma particles as well as the noise from them. For computing time on a CDC 7600 (LLL MFECG 'A' machine) the hybrid (ESI + EFL) takes about 0.14 sec per time step (= 16 usec per time step per particle) and this could be further improved through optimization.

1. STRUCTURE OF HYBRID CODES

The electrostatic hybrid (ESI + EFL) consists of ESI for the beam and EFL for the plasma. For EFL, the linearized two-fluid equations in finite-difference form is:

\[
\frac{n_{j+\frac{1}{2}}^{n+\frac{1}{2}} - n_{j+\frac{1}{2}}^{n-\frac{1}{2}}}{\Delta t} = \frac{q}{m} \left[ E_{j+\frac{1}{2}}^{n+\frac{1}{2}} + \left( \frac{v_{j+\frac{1}{2}}^{n+\frac{1}{2}} + v_{j+\frac{1}{2}}^{n-\frac{1}{2}}}{2} \times B_0 \right) \right]
\]
The leap-frog scheme is time and space centered as in Fig. 1(a). The electromagnetic hybrid code (EML + EFL) is constructed by combining
EML (relativistic and nonrelativistic electromagnetic particle code?)
with the properly modified electromagnetic version of EFL, whose leap-frog scheme shown in Fig. 1(b) is similar to the electrostatic EFL [Fig. 1(a)] except for some additional quantities kept.

II. APPLICATION OF A HYBRID CODE

The use of EM1 + EFL in simulation of an unmagnetized beam-plasma instability yields results (linear and nonlinear) almost identical with a particle code. A more important application of this code is to the above ring-plasma instability. Simulations using a hybrid code (marked x in Fig. 2) provide remarkable verification of the linear Vlasov theory (continuous curves in Fig. 2) especially when compared to particle code results (Ref. 1, marked 0 in Fig. 2). This excellent agreement extends to a wide range of plasma parameters whether electrostatic or electromagnetic.

Hybrid simulations also provide extensive information about nonlinear evolution of this instability such as beam spreading, average slowing down, and saturation level, which agrees nicely with some analytic explanations.
III. LIMITS ON THE LINEARITY OF THE FLUID PLASMA

The linearity assumption is good as long as the perturbed plasma velocities \( \mathbf{v}_i \) remain small compared to the wave phase velocity \( \mathbf{w}/k \).

Fig. 3 shows that this criterion is satisfied in many cases except for strong beam cases (e.g., \( R = n_{\text{beam}}/n_{\text{plasma}} \leq 0.1 \) to 1) near saturation times. In order to follow the nonlinearity of the fluid plasma, changing to the Lagrangian fluid (LAF) model will be discussed.

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A paper will be prepared and submitted to the Journal of Computational Physics next quarter, which will consist of the detailed code algorithm with two major applications, namely to the magnetized ring-plasma instability and to the unmagnetized beam-plasma instability [especially the off-peak saturation effects presented in the QPR II (July, 1977), pp. 5-14)].
E. l- PARTICLE-FLUID HYBRID MODEL FOR THE DRIFT-WAVE INSTABILITIES
Yu-Jiuan Chen

A simulation method is proposed for the study of the lower-hybrid-drift instability and the mirror-drift-cone instability in the sheath region. For simplicity, it is assumed that $T_e \ll T_i$, and the finite plasma beta effects (electromagnetic effects and $V_{be}$ electron orbit modification) are negligible. Moreover, primary emphasis is placed on high-frequency perturbations characterized by

$$\omega_{ci} \ll |\omega_r + i\gamma| \approx \left(\omega_{ce} \omega_{ci}\right)^{1/2} \ll \omega \approx \omega_{ce}, \quad (1)$$

$$a_i^{-2} \ll k_1^2 \approx a_e^{-2} \quad \text{and} \quad a_e^{-2} \ll L^2, \quad (2)$$

where $\omega_{cs} = |e_s|B_0/m_s c$ is the gyrofrequency, $a_s = (2T_i/m_s \omega_{ci}^2)^{1/2}$ is the local Larmor radius, and $L^{-1} = \frac{\partial n}{\partial y} y_0 / n$ is the density scale length. Therefore, we can employ the local approximation in the density gradient direction and treat electrons as a strongly magnetized fluid and ions as unmagnetized particles.

In general, the initial plasma configuration is illustrated in the slab geometry as shown in Fig. 1. We consider perturbations localized about $y = y_0$, and the local equilibrium magnetic field primarily in the $z$-direction with

$$B(x) = \hat{e}_z B_0(y_0) + \hat{e}_x B_0(y_0) \frac{y - y_0}{L_s}$$

in the vicinity of $y = y_0$, where $L_{s}^{-1} \equiv (\partial B_y / \partial y)_{y_0} / B_0(y_0)$ is the length scale characterizing the magnetic shear. The electron drift across the magnetic field $B_0 \hat{e}_z$ with the mean fluid velocity

$$v_{xe} = v_{Ee} + v_{de}, \quad (4)$$

where $v_{Ee} = c e_0 / B_0$ is the $\mathbf{E} \times \mathbf{B}$ drift velocity, $v_{de} = (T_i / m_i \omega_{ci}) \omega_e \frac{\partial n(y) n_T}{\partial y} y_0$ is the electron diamagnetic drift velocity, and $n(y) = n_0(y) e_i n_i(y)$ is the
density. For the electron fluid drifting through a stationary ion background, the electron \( \mathbf{E} \times \mathbf{B} \) drift motion and the inhomogeneities in \( n \), \( B \), and \( T_e \) provide the free energy to drive instabilities.

As \( L_s \rightarrow \infty \), i.e., no magnetic shear, a 1\( \frac{1}{2} \)d electrostatic particle fluid model (ES1 + FLUID) can be used to simulate these two kinds of instabilities in \( \mathbf{E} \times \mathbf{B} \) direction, i.e., \( x \) direction, instead of 2\( \frac{1}{2} \)d particle simulation. A 1\( \frac{1}{2} \)d magnetized electron fluid drifts with velocity \( v_x \) through a local Maxwellian 1d ion background for the lower-hybrid-drift instability, or loss cone 1d ions for the mirror-drift-cone instability. The electron \( \mathbf{E} \times \mathbf{B} \) drift and the inhomogeneities are taken care through the drift velocity \( v_x \). Since there is no boundary effect in the \( x \) direction for the slab geometry, the periodic boundary condition usually used in ES1 code is appropriate for this case (shown in Fig. 2). If the magnetic shear is considered, this model can be generalized to 2\( \frac{1}{2} \)d \((x, y, v_x, v_y, v_z)\).

Fig. 1 Slab Geometry and Coordinate System

\[ \mathbf{E} \cdot \mathbf{B} (y) + \mathbf{E} \cdot \mathbf{B} (y_0) = \frac{y - y_0}{L_s} \]

\[ v_x = v_e + v_d \]

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\(^{1}\text{D. Winske and P. C. Liewer, "Particle Simulation Studies of the Lower Hybrid Drift Instability", Phys. Fluids 21(6), pp. 1017-1025 (1978).} \)
With the exception of the Versatec controller unit described below, all necessary hardware has been installed in the UCB remote user system. The PDP 11/04 has been moved and secured into place away from the terminal rooms 119ME and 119MD where its fan noise would have interfered with mental concentration. The DZ-11A multiplexer has been installed and the 8 terminal lines run to the proper rooms.

In order to run our Versatec electrostatic printer off the PDP 11/04 directly, it was necessary to order in mid-June a PDP 11/DMA controller Model #121 from Versatec. Funds for this acquisition were requested from DOE in April and received in June 1978. An extra long 60' cable was also ordered to run from the PDP 11/04 to the Versatec unit. Delivery is expected by late August.

The software necessary to run the PDP 11/04 as a terminal concentrator still has not been delivered from Livermore. The primary difficulty appears to be the DEC's DMC11 network links not working according to specification. Consultation between LLL and DEC is in progress; until the software arrives, the UCB PDP 11/04 must sit idle.
We have initiated efforts to obtain an LBL extension phone so that we may use their tie-line to LLL. When the UC system tie-line to LLL disappeared in February, our phone bill shot up to >$1000/month. An LBL extension will cost ≤$20/month and permit constant use of the LLL computer. We have received authorization from DOE/San Francisco for the extension and hope to obtain it by mid-August.

Section IV
PLASMA SIMULATION TEXT

Revisions of Part I have been made, to be completed in September. Part II revisions are progressing well.

Section V
SUMMARY OF REPORTS, TALKS AND PUBLICATIONS IN THE PAST QUARTER

Four papers were presented at the Eighth Conference on Numerical Simulation of Plasmas at Monterey, June 28-30 (the Proceedings published up to four page abstracts), as follows:

(1) J. K. Lee and C. K. Birdsall, "Particle-Fluid Hybrid Codes Applied to Beam-Plasma, Ring-Plasma Instabilities".

(2) A. Peiravi and C. K. Birdsall, "Self-Heating of Ideal Thermal Plasmas: Comparison of Weightings; Optimal Parameter Choices".

(3) W. M. Nevins, "Diagnostics — The Business End of a Plasma Simulation Code".

(4) Y. Matsuda, W. M. Nevins and M. Gerver, "A New Particle Simulation Model for a Bounded Plasma".

Prof. C. K. Birdsall chaired one of the six oral sessions.
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