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The goal of the research is to find the mechanisms in the presheath, sheath, and wall region that reflect, transmit, and absorb ion acoustic waves. Ion waves are observed to propagate from the bulk plasma into and completely through the sheath to the wall.

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Waves in Plasma Sheaths and at Boundaries: Theory and Computer Experiments

AASERT Final Report

N00014-94-1-1033
7/1/94 -9/30/97

University of California, Berkeley
Electronics Research Laboratory

Charles K. Birdsall, Principal Investigator
Keith Cartwright, Graduate Student Researcher

Office of Naval Research
9/30/97

AASERT Progress Report (7/1/96 - 9/30/97)

Keith Cartwright, Graduate Student Researcher,
Electronics Research Laboratory,
University of California, Berkeley

This is a description of the work Keith Cartwright has done as a graduate student in the last year supported by an AASERT in Professor C. K. Birdsall's Plasma Theory and Simulation Group. The four main areas of research are: (1) the reflection of ion waves from the sheath, (2) crossed-field diodes, (3) development of a PIC ion – Boltzmann electrons simulation model, and (4) the development of the OOPIC code.

1. The goal of this work is to find the mechanisms in the presheath, sheath, and wall region that reflect, transmit, and absorb ion acoustic waves. Ion waves are observed to propagate from the bulk plasma into and completely through the sheath to the wall. The sheaths used for study have been formed next to a metal wall and around a grid. These waves have a frequency less than the ion plasma frequency. Ion waves have been purposely launched as well as spontaneously generated by an ion acoustic instability. A continuous spectrum of spontaneously generated ion acoustic standing waves are observed and eigenfunctions have been measured in 1d PIC simulations.

2. In cross field diode simulations we are contrasting 2d results with 1d results already obtained in planar[1] and cylindrical[2] geometries. This investigation indicates the transverse dimension is important in delaying the onset of virtual cathode oscillations for currents above the limiting current. The work so far has been limited to the behavior of diodes at $B \simeq B_{Hull}$ and $B = 0$. The delay is only observed in the magnetized cases.

3. Kinetic simulation of plasmas in which equilibrium occurs over ion timescales poses a computational challenge due to the disparate timescales of the electron plasma frequency ($\sim 10^9$), the ion plasma frequency ($\sim 10^7$), ion transit frequency ($\sim 10^6$), and the ionization frequency ($\sim 10^7$). Hybrid electrostatic PIC algorithms are presented in which the electrons reach thermodynamic equilibrium with the ions each time step. The collision frequency, $\nu_m(v)$, can be a tabulated or fitted function. These approximations neglect effects faster than ion time-scales, decreasing the computer time used by over an order of magnitude; however, they increase the complexity of the boundary conditions and the simulation is no longer self-consistent. Theoretical ramifications

of these approximations are examined, and results are compared with full PIC simulations of undriven sheaths, ion acoustic waves, plasma display panels, and DC discharges.

4. The objectives here is to continue development the OOPIC PIC-MCC simulation program, a particle-in-cell, electromagnetic/electrostatic code which models devices ranging from high pressure discharges to vacuum electronics to microwave-beam devices. This program is written in C++, using an object-oriented design philosophy. Most of this work has been done in collaboration with Dr. John Verboncoeur. Our accomplishments are:
    (a) Improvements in the nonlinear Boltzmann electron field solver in OOPIC code. For details see Section 3. It is important to extend the usefulness of OOPIC from high frequency electromagnetic models and electron dominated electrostatic systems to the domain where low frequency ion dynamics are dominant.
    (b) A Multigrid Poisson Solve has been added.

The following is a list of abstracts of presentations made:

1. Refraction and Reflection of Ion Acoustic Solitons by Space Charge Sheath formed by a Grid *

K. L. Cartwright, and C. K. Birdsall

Experiments have shown[3,4] that ion acoustic solitons tunnel through the space charge sheath in front of a grid without time delay. They are absorbed resonantly when the spatial width of the wave is close to the characteristic gradient scale length of the sheath. The reflection and transmission coefficients found in these experiments have compared well with theory in the long wavelength limit.[5] However, to achieve this comparison, two parameters were added that were not in the original theory. These parameters allow for the absorption of wave energy by the space charge sheath. The goal of our numerical simulations, designed to reproduce the experimental results, is to uncover the mechanism of this energy loss and large speed of propagation through the sheath.

2. Hybrid PIC Acceleration Schemes for Discharges †

K. L. Cartwright, J. P. Verboncoeur, and C. K. Birdsall

Kinetic simulation of plasmas in which equilibrium occurs over ion timescales poses a computational challenge due to the disparate timescales of the electron plasma frequency ($\sim 10^9$), the ion plasma frequency ($\sim 10^7$), ion transit frequency ($\sim 10^6$), and the ionization frequency ($\sim 10^7$). Hybrid electrostatic PIC algorithms are presented in which the electrons reach thermodynamic equilibrium with the ions each time step. There are three different approximations for the electrons. First, the nonlinear Boltzmann relationship for the electrons can be applied to the bulk of a plasma. Second, there is a truncated Maxwellian which is used in undriven sheaths; this approximation truncates the electron distribution at the wall potential. Progress is shown for a method that will be used in a DC electric field. This method assumes a steady-state electron distribution function in a DC electric field, with elastic collisions between electrons and neutral gas atoms. The collision frequency, $\nu_m(v)$, can be a tabulated or fitted function; the method is implemented with a constant cross section

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*American Physical Society Division of Plasma Physics, November 1995, Denver, Co.

†IEEE International Conference on Plasma Science, May 1997, San Diego, CA.

and is planned to be implemented using Argon cross-sections. These approximations neglect effects faster than ion time-scales, decreasing the the computer time used by over an order of magnitude; however, they increase the complexity of the boundary conditions and the simulation is no longer self-consistent. Theoretical ramifications of these approximations are examined, and results are compared with full PIC simulations of undriven sheaths and preliminary comparisons of ion acoustic waves and DC discharges.

3. Refraction and Reflection of Ion Acoustic Solitons by Space Charge Sheath [‡]

K. L. Cartwright, and C. K. Birdsall

Experiments have shown,[3 4] that ion acoustic solitons tunnel through the space charge sheath in front of a grid without time delay. They are absorbed resonantly when the spatial width of the wave is close to the characteristic gradient scale length of the sheath. The reflection and transmission coefficients found in these experiments have compared well with theory in the long wavelength limit.[5] However, to achieve this comparison, two parameters were added that were not in the original theory. These parameters allow for the absorption of wave energy by the space charge sheath. The goal of our numerical simulations, designed to reproduce the experimental results, is to uncover the mechanism of this energy loss and large speed of propagation through the sheath.

4. Relaxation of Virtual Cathode Oscillations due to Transverse Effects in a Crossed–Field Diode [‡]

K. L. Cartwright, J. P. Verboncoeur, V. P. Gopinath, and C. K. Birdsall

Recent studies of cylindrical[2] and planar[1] crossed-field diodes indicate the transverse dimension plays a role in delaying the onset of virtual cathode oscillations for currents injected above the theoretical one-dimensional limiting current. For 1d and 2d planar devices, the limiting current for the magnetized ($B = B_{Hull}$) and unmagnetized diodes is examined for cold and thermal injection. A significant difference between the 1d and 2d smooth wall diodes is that the transverse direction provides an extra degree of freedom which allows the electrons to warm rapidly. The mechanism of this warming appears to be an instability in the transverse direction. The simulations show three different 'states'; laminar flow, virtual cathode oscillation and warm flow. Warm flow occurs when the electrons have a spread of energy, either due to an instability or by thermal injection, when they pass though the potential minimum. Birdsall and Bridges[6] showed that a small thermal spread (few percent) of injected electrons damps virtual cathode oscillations in a short circuited diode. This warming effect allows 'warm flow' to exist on the 2d state diagram (J/J_c versus B/B_{Hull}) which is not found on the 1d state diagram for cold emission. Parameter space is explored on these state diagrams for $B = 0$ and $B = B_{Hull}$ for J near state transitions ($J \simeq J_C$). In these PIC simulations, the particles are injected in such a way as to keep the transverse density as uniform as possible. A quiet particle injection algorithm was used so that particle noise does not warm in the transverse direction. Time centering of the velocities of the injected particles was also examined.

[‡] Sept 1996, Sendai Japan.

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