ABSTRACT


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 plasmas. We also work on the improvement of simulation, both theoretically and practically. Our focus has been more and more on the plasma edge (the "sheath), interactions with boundaries, leading to simulations of whole devices.

I. INTRODUCTION

Modern simulations have benefited greatly by improvements in numerical techniques, programming, and, of course, by much faster computers. Currently there are codes in use which are multidimensional, electromagnetic, and relativistic; these codes use realistic (close to laboratory and space) boundary conditions, with particle injection and collection. Many of the techniques for particle simulation were developed for fusion plasma applications, following both electrons and ions, with some attention to boundaries. In addition, there are now many applications to electron devices, such as klystrons, magnetrons, traveling-wave tubes, gyrotrons, accelerators, free electron lasers, and vircators; some of these codes are very large, say typically of 40,000 lines, usually run by groups of professionals. Applications to space plasmas are growing rapidly.

The beauty and quality of many-particle simulations comes from a combination of properties, such as:

(a) working from first principles, using the Newton-Lorentz equation of motion to move particles, using Maxwell's equations to solve for the fields;
(b) fields, potentials, currents and densities as functions of time and space (t,x); in addition, particle simulations can provide velocity distributions at (x,t) as well as Fourier decompositions in (x,t);
(c) being fully nonlinear, that is, not restricted to relatively small amplitudes (although well used to verify linear theory), hence capable of following growth in (x,t) from linear through large amplitudes (e.g., saturation of amplifiers or instabilities);
(d) complete accounting for spatial anisotropies and inhomogeneities;
(e) ability to employ real boundaries with emission, absorption, reflection, surface charges and currents;
(f) addition of Monte Carlo collisions between the charged particles and the neutrals, allowing self-consistent simulations of gas discharges (RF, DC, ECR, etc.)

* Also done under the titles "Plasma Instabilities and Nonequilibrium Processes" and "Plasma-Sheath-Surface Dynamics" ONR Contract No. N00014-85-K-0809
Simulations are used to complement both theory and experiment, and to stand on their own. In the former, simulations are widely used by theoreticians in verifying linear and nonlinear theory, adding feedback for improvement in theory; simulations are useful to experimentalists in complementing explanations that they have obtained from their observations. In addition, simulations have proven very useful as a tool for exploration into new parameters, ahead of doing the comparable theory or experiments. Simulations have also been a tool for discovery, trying out new ideas, or (very importantly!) recognizing new and unexpected behavior. For example, we can say a great deal now about RF discharges, such as $J\ E$ time and space resolved for electrons and ions, to show where the power goes as pressure changes, etc. The lesson is that particle simulations are both an asset to theory and experiment and have a role of their own.

II. SPECIFIC RESULTS

We have reported our results in Quarterly Progress Reports for many years. The sum total of these QPR's and journal publications over the July, 1985, to December 1989 period of ONR support is about five inches thick. We have chosen to provide a list of the titles of articles, reports and talks, with some comments on the publications of our group (16 articles, 24 reports, 64 talks, 1 workshop). ONR provides on the order of half the support of the group; that is, there is joint support for many of the published results. Our report is by year, highlighting work supported primarily by ONR.

1985

The Lawson article is unique, showing how to integrate the Vlasov equation in $f(x,v,t)$ when $f$ has steep edge in $(x,v)$ space. This is done by adding in a fake $f$ to make total $f$ smooth, but then ignoring the fake $f$ in the potential solver. Comparisons with full particle dynamics are very good.

The Crystal-Kuhn article on the Pierce Diode is one of a series on such, adding more physics than done elsewhere (more to come).

Various talks presented our initial results on simulating bounded plasmas (whole devices).

1986

The Kuhn and Horhager work is from our occasional colleague S. Kuhn (Innsbruck) but part of our series on the Pierce Diode. Here, the interest is in stability as affected by $R, L, C$ elements in the external circuit. This is echoed in the Crystal and Kuhn talk.

The Theilhaber and Birdsall talk is the initial presentation of our 2d studies of surface waves in magnetized plasma sheaths, a milestone. (See 1989)

The Workshop was set up to draw attention to "bounded plasmas" per se, (as opposed to the plasma bulk, away from real boundaries). The response was excellent, with very good exchange of information.

1987

Kim's double layer article was a very neat, compact treatment, again part of a series of articles and simulations.

Lawson's "bounded plasma" report is the best exposition yet of such simulations, finally published in 1989.

The Theilhaber reports and talks are more introduction to the magnetized sheath in 2d.
Again, more Pierce Diode reports.

The Schwager talks are our early fully bounded source sheath and collector sheath simulations, with excellent checks with analytic results.

1988

Finally, the Theilhaber Kelvin-Helmholtz instability and vortex theory and simulation report is out, in detail.

The Schwager reports on the two sheaths are also out.

Birdsall receives the first IEEE Plasma Science and Applications Award and presents a talk on serendipity.

The first presentation of our RF discharge results is made by Morey et al. (at APS/DPP) displaying what is to become our PIC-MCC codes, adding Monte-Carlo collisions between charged particles and neutrals, a milestone in simulating weakly ionized gases (which means most laboratory and industrial plasmas).

1989

The Kelvin-Helmholtz instability in the magnetized sheath is now published in November Physics of Fluids, showing vertex formation and subsequent Bohm diffusion. This milestone had earlier presentations.

Again, more presentations were made on our RF discharge results now showing considerable detail of interest to the plasma-assisted materials processing community (e.g. semiconductor etching, deposition and sputtering). The Alves et al. talk was the first simulation on asymmetric-electrode-RF discharges, coming very close to the analytic model of our colleague Professor M. A. Lieberman.
Our group began a transition into bounded plasma problems in 1981. Our new objective is to understand the dynamics of plasma sheaths at walls in terms of equilibrium, stability and transport. We also study other large potentials in plasmas, such as double layers and thermal barriers. The list here reflects the transition, a learning experience, starting with reports and talks, maturing into journal articles. Major support comes from DOE and ONR, plus help from Varian Associates-MICRO and Hughes.

Statement "A" per telecon Dr. Charles Roberson. ONR/Code 1112AI

VHG 3/4/91
Book


Journal Articles


Reports


Talks, Conference Proceedings

*Sherwood Theory Conference*, April 15-17, 1985, University of Wisconsin, Madison, Wisconsin:


*Eleventh International Conference on Numerical Simulation of Plasma*, Montreal, Quebec, Canada, 25-27 June 1985:

(1) C.K. Birdsall, W.S. Lawson, T. Crystal, S. Kuhn, N. Otani, I. Roth, and A.B. Langdon, "Problems of Bounded Particle Simulations and First Generation Solutions."

(2) B.I. Cohen, M.E. Stewart, and C.K. Birdsall, "Direct Implicit Particle Simulation of Tandem Mirror."
17th International Conference on Phenomena in Ionized Gases, Budapest, July 1985:


INTOR Specialists' Meeting On Impurity Control, IAEA Headquarters, Vienna, Austria:

C.K. Birdsall, "Boundary Conditions; Matching Plasma-Sheath-Wall." (invited paper)

Talks, Poster Papers

APS/Division of Plasma Physics Annual Meeting, Nov 4-8, 1985, San Diego, CA:

(1) B.I. Cohen, M.E. Stewart, R.P. Freis (LLNL), L.A. Strugala, and C.K. Birdsall, "Direct Implicit Particle Simulation of Tandem Mirrors."


Journal Articles


ERL Reports


William S. Lawson, "Limits of Linear Response of a Vlasov Distribution," University of California, Berkeley, Memorandum No. UCB/ERL M86/44, June 3, 1986


Talks, Poster Papers


APS Division of Plasma Physics Twenty-Eighth Annual Meeting, November 3-7, 1986, Baltimore, MD:


T.L. Crystal and S. Kuhn, "Pierce Diode Instability Simulations with External Inductance and Resistance."
S.E. Parker, C.K. Birdsall, and K. Theilhaber, "Electrostatic Effects on Confinement Outside the Separatrix of Field Reversed Configurations."

R.J. Procassini, C.K. Birdsall, and B.I. Cohen (LLNL), "Direct Implicit Particle Simulation of Tandem Mirrors."

K. Theilhaber and C.K. Birdsall, "Structure of the Crossed-Field Sheath." (with short movie)

Talks


Minicourse


Workshop

Bounded-Plasma Physics Workshop, University of California, Berkeley, September 22-23, 1986. See schedule following.
Schedule of BPPW Presentations
Monday 22 September 1986

8:30 Registration and parking arrangements.
Coffee, tea, orange juice and rolls.

9:00 C.K. Birdsall (chairman). Welcoming address and general information.
   C.K. Birdsall, (2)T.L. Crystal, P.C. Gray, S. Kuhn, and (1)Wm.S. Lawson Introduction to
   PDW1 and Q-machine simulation; presentation of "The Movie".

   C.K. Birdsall, (1)T.L. Crystal, P.C. Gray, P. Krumm, (2)S. Kuhn, Wm.S. Lawson, M.
   Oertl, and N. Schupfer. Trapped-electron effects on negative-bias d.c. states of a col-
   lisionless single-emitter plasma device: theory, simulation, and experiment.

10:30 Coffee and posters of preceding talks.

   S. Parker. Electrostatic potentials due to nonuniform magnetic fields.
   D.Hewett (LLNL).
   Electromagnetic boundary conditions for implicit codes.

12:15 Lunch in Kerr Campus dining hall Building 10 (the great hall). Posters.

1:30 K.S. Theilhaber (chairman)
   (1)T.L. Crystal, M. Hörhager, (2)S. Kuhn, and (3)Wm.S. Lawson.
   Theory and simulation of Pierce diode dynamics:
   Linear and nonlinear features, plus nontrivial external circuit effects.

   C.K. Birdsall and P.C. Gray.
   Small-amplitude impedance Z(ω) of a floating single-emitter plasma device.

2:30 Coffee and posters.

3:30 C.K. Birdsall, B.I. Cohen, and (1)R. Procassini.
   Efficient incorporation of Coulomb collisions in bounded-plasma simulations.

   L.A. Schwager. Transport in the plasma sheath region near a wall.

   S. Kuhn. Integral-equation approaches to bounded-plasma physics.

5:00 Coffee and posters.

6:30 Dinner in executive dining room Building 10, Kerr Campus.
Schedule of BPPW Presentations
Tuesday 23 September 1986

8:30 Coffee, tea, orange juice and rolls.

9:00 T.L. Crystal (chairman).
   (1) C.K. Birdsall, and K.S. Theilhaber.
   Source-sheath ion acceleration

   P.C. Gray, (2) Wm.S. Lawson and (1) R.D. Pierce.

10:30 Coffee and posters of preceding talks.

   (1) A. Wendt, M.A. Lieberman and H. Meuth.
   Theory of nonuniform plasma in a planar magnetron discharge

   (1) J. Helmer and K. Doniger.
   Ion diagnostics in a planar magnetron discharge.

12:15 Lunch
   Posters.

1:30 S. Kuhn (chairman)
   (1) T. Intrator (Wisconsin).
   Some comments from experiments.

   Stochastic electron heating in the sheaths of an RF discharge.

   O. Buneman (Stanford).
   Matching plasma radiation to free-space in spherical geometry using spherical harmonics (outward radiation only).

2:30 Coffee and posters.

3:30 O. Buneman (Stanford).
   How to use a plasma boundary condition stated as Z(0) in plasma simulation.

   Panel discussion. M.A. Lieberman (chairman).
   Concluding remarks from the steering committee...short!...and open discussion.
   Where are we, where do we want to go, and what should we do next?
   → Should we have another BPPW in 1988?

Authors listed alphabetically
   (1), (2) means talks split
Journal Articles


ERL Reports


Talks, Conference Proceedings

At U.S./Japan Seminar: Effects of Electric Fields on Magnetic Confinement, January 22-24, 1987, University of California, Los Angeles:


At Sherwood Controlled Fusion Theory Conference. April 6-8, 1987, San Diego, California:
K. Theilhaber, "Transport Induced by a Crossed-Field Sheath."

Richard J. Procassini and Charles K. Birdsall, "Performance and Optimization of Direct Implicit Time Integration Schemes for Use in Electrostatic Particle Simulation Codes."

Lou Ann Schwager, "Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and Ion Reflection at the Bounding Surface."

*At IEEE International Conference on Plasma Science, June 1-3, 1987, Arlington, Va.:*

K. Theilhaber and C. K. Birdsall, "Large Electric Fields in a Magnetized Plasma Sheath; Long-lived Vortices."


*At 12th Conference on Numerical Simulation of Plasmas, September 21-23, 1987, San Francisco, California:*


S.E. Parker, "Numerical Error in Electron Orbits with Large ωpe dt."


W.S. Lawson and T.L. Crystal, "Artificial Cooling Due to Quiet Injection in Particle Simulation of a Bounded Plasma."

*Talks presented at US-Japan Workshop on Plasma Modeling with MHD and Particle Simulations, September 25-26, 1987, Napa, California. (Professor C.K. Birdsall was host, USA organizer):*

A. Friedman, C.K. Birdsall, S.E. Parker, S.L. Ray, "Multi-Scale Particle Simulations."


*Invited Talk*

*At APS Division of Plasma Physics Twenty-Ninth Annual Meeting, November 2-6, 1987, San Diego, California:*

K. Theilhaber, "Vortex Formation and Transport to the Wall in a Crossed-Field Sheath."

*Talks, Poster Papers*

*Poster Papers at APS Division of Plasma Physics Twenty-Ninth Annual Meeting, November 2-6, 1987, San Diego, California:*
C. K. Birdsall, K. S. Theilhaber, and S. Kuhn, "Ion Acceleration in a Plasma Source Sheath."


Journal Articles


ERL Reports


Talks, Conference Proceedings

ICRF/Edge Physics Workshop, March 30-April 1, 1988, Boulder, Colorado.

W. S. Lawson and C. K. Birdsall, "Undriven Plasma Wall Interaction Simulations, Showing Turbulence with and without an Initial Vacuum Gap."

W. S. Lawson and C. K. Birdsall, "Antenna Driven Plasma Wall Interaction Simulation, Showing Local Turbulence and About 3 Times Larger Flux to the Wall."


C.K. Birdsall, "Serendipity is no accident, even in plasma research", Plasma Science and Applications Award acceptance address.

W. S. Lawson, M. A. Lieberman, and C. K. Birdsall, "Electron Dynamics of RF Driven Parallel Plane Reactor."


S.E. Parker, "A Proposed Particle-In-Cell Method for Modeling Small Angle Coulomb Collisions in Plasmas."

C.K. Birdsall, "Computer simulation of Plasma Response Near an RF Antenna."

J.J. Morey, R.W. Boswell, and C.K. Birdsall, "Particle Simulation of a Low Pressure RF Discharge."
Talk


Invited Talks (in Japan)


C.K. Birdsall, "Source and collector sheaths in a bounded plasma device," (Co-author L.A. Schwager) and "The magnetized plasma sheath interacting self-consistently with an absorbing wall; Kelvin-Helmholtz instability growth with saturation as a dynamic steady state, producing Bohm diffusion," (Co-author K. Theillaber), December 8, 1988, Inst. of Plasma Physics, Nagoya University, Japan. (The latter also presented at Hiroshima University a week later.)

Journal Articles


ERL Reports

J. Verboncoeur, "ES1 Reference Manual" (which is distributed with our PC disk, which is not included here - but free for the asking)


 Talks, Conference Proceedings

At Sherwood Theory Conference, San Antonio, Texas, April 3-5, 1989:

W.S. Lawson and C.K. Birdsall, "Simulation of RF driven plasma edge."


At 13th Conference on Numerical Simulation of Plasmas, Santa Fe, NM, September 17-20, 1989

IJ. Morey, J.P. Verboncoeur, and V. Vahedi, "Bounded Plasma Device Simulation with PDWI, Including: External RLC Circuit, DC and RF Drive, and Collisional Processes."

IJ. Morey, and C.K. Birdsall, "The Traveling-Wave-Tube Code IBC."


S.E. Parker, A. Friedman S.L. Ray, and C.K. Birdsall, "Multi-Scale Particle Simulation of Bounded Plasmas."

S.E. Parker, "A Particle-In-Cell Method for Modeling Small Angle Coulomb Collisions in Plasmas."


Talks, Poster Papers

At APS/Gaseous Electronics Conference Annual Meeting, Palo Alto, CA, October 17-20, 1989

IJ. Morey, V. Vahedi, J.P. Verboncoeur, and M.A. Lieberman, "Particle Simulation Code for Modeling Processing Plasmas."

M.V. Alves, V. Vahedi, and C.K. Birdsall, "Cylindrical Simulations for RF Discharges and Plasma Immersion Ion Implantation."


S.E. Parker, and R.J. Procassini, "Large Space and Time Scale Particle Simulation of Bounded Plasmas with a 'Logical Sheath'."


IJ. Morey, V. Vahedi, and J. Verboncoeur, "Particle Simulation Code for Modeling Processing Plasmas."
Journal Articles


S.E. Parker, and C.K. Birdsall, "Numerical Error in Electron Orbits with Large \( \omega_{ce} \Delta t \)," accepted by *J. Comp. Physics*, April 1990.


ERL Reports


Conference Proceedings, Poster Papers

Sherwood Fusion Theory Conference, Williamsburg, VA, April 23-25, 1990:
Live demonstration in Plasma Visualization evening session 7-11pm April 24 of our bounded plasma PC codes. applications. (by Birdsall, Vahedi)

Microwave Power Tube Conference, Monterey, CA, May 7-9, 1990:
I.J. Morey, and C.K. Birdsall, "Traveling-Wave Tube Simulation; the IBC Code."

1990 IEEE International Conference on Plasma Science, Oakland, CA, May 21-23, 1990:
M.V. Alves, M.A. Lieberman, V. Vahedi, C.K. Birdsall, "Sheath Voltage Ratio For Asymmetric RF Discharges."
J.P. Verboncoeur, V. Vahedi, M.A. Lieberman, C.K. Birdsall, "Work Done And Energy Balance in RF Discharges."
V. Vahedi, M.A. Lieberman, M.A. Alves, J.P. Verboncoeur, C.K. Birdsall, "Collisional Model For Plasma Immersion Ion Implantation."

V. Vahedi, M.A. Lieberman, M.A. Alves, J.P. Verboncoeur, and C.K. Birdsall, "A One Dimensional Collisional Model For Plasma Immersion Ion Implantation."

43rd Annual Gaseous Electronics Conference, Urbana-Champaign, IL, October 16-19, 1990.
C.K. Birdsall, "Particle-In-Cell Combined with Monte Carlo Collisions-In Living Color." (Invited talk)
J.P. Verboncoeur, V. Vahedi, and C.K. Birdsall, "Power Deposition in Parallel Plate Discharges."

APS/Division of Plasma Physics, Cincinnati, OH, November 12-16, 1990.
S.E. Parker, and C.K. Birdsall, "Particle Transport due to Kelvin-Helmholtz Vortices and Small Scale Turbulence."


Course


Invited Talks


C.K. Birdsall, "Interactive Plasma Computer Experiments; Plasma Device Simulations on PC's and Workstations," June 1, 1990 Naval Post Graduate School, Monterey, CA.