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ANNUAL PROGRESS REPORT, FOR 1990
PLASMA THEORY AND SIMULATION GROUP

Professor C.K. Birdsall

January 1 to December 31, 1990

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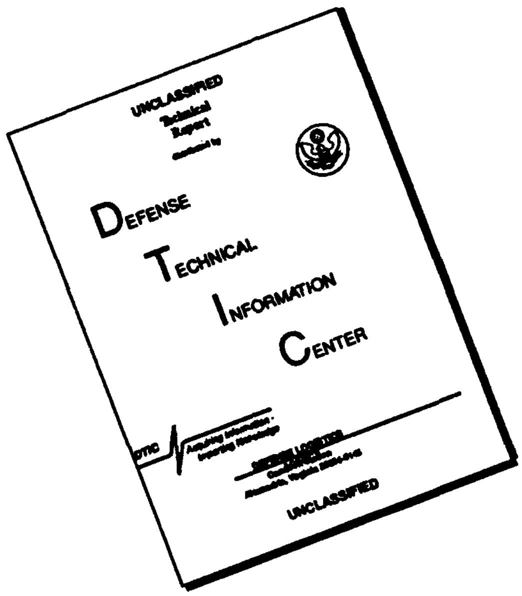

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18. SUPPLEMENTARY NOTES

Our group uses theory and simulation as tools in order to increase the understanding of plasma instabilties, heating, transport, plasma-wall interactions, and large potentials in plasma. We also work on the improvement of simulation both theoretically and practically.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Research in plasma theory and simulation, plasma-wall interactions, large potentials in plasmas, bounded plasmas

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a brief progress report, covering our research in general plasma theory and simulation, plasma-wall physics theory and simulation, and code development. Reports written in this period are included with this mailing. A publications list plus abstracts for two major meetings are included.

ANNUAL PROGRESS REPORT 1990
PLASMA THEORY AND SIMULATION GROUP

January 1 to December 31, 1990

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, transport, plasma-wall interactions, and large potentials in plasmas. We also work on the improvement of simulation, both theoretically and practically.

Our staff is:

Professor C.K. Birdsall	191M	Cory Hall	643-6631
Principal Investigator			
Dr. Scott Parker (May-August)	199MD	Cory Hall	642-1297
Dr. Xueqiao Xu (August on)	187M	Cory Hall	642-3477
Dr. A. Tarditi (from Genoa, Italy, NATO Fellow, October on)			
Post-doctorates			
Mr. Scott Parker (Ph.D. completed April)	199MD	Cory Hall	642-1297
Mr. Richard Procassini (Ph.D. completed April)	199MD	Cory Hall	642-1297
Mr. Vahid Vahedi	199MD	Cory Hall	642-1297
Mr. John Verboncoeur	199MD	Cory Hall	642-1297
Mr. Henry Heikkinen	199MD	Cory Hall	642-1297
Mr. Frank Tsung	199MD	Cory Hall	642-1297
Mr. Ed Chao	199MD	Cory Hall	642-1297
Research Assistants(students)			

M. Virginia Alves (from Brazil, until July)
Prof. Jan Trulsen (from Tromso, Norway, April-July)
Prof. S. Kuhn (from Innsbruck, Austria, August)
Dr. M.J. Gerver (from SatConTech, MA, two weeks, August)
Visitors

Our advisers are:

Dr. Ilan Roth	304	SSL	642-1327
Physicist, Space Science Lab, UCB			
Dr. Bruce Cohen	L630	LLNL	422-9823
Dr. Alex Friedman	L630	LLNL	422-0827
Dr. A. Bruce Langdon	L472	LLNL	422-5444
Physicists, Lawrence Livermore Natl. Lab			

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ANNUAL PROGRESS REPORT 1990

January 1 to December 31, 1990

Our research for 1990 has been widely reported, as given by the listing following, of 16 Journal Articles, 3 ERL Reports, 4 Talks, and 12 Poster Papers.

Abstracts are attached for some of the talks.

Sent along with this Report are reprints of Journal Articles and the ERL Reports.

Our prior mode was to publish Quaterly Progress Reports; these then became Semi-Annual Reports, which ended in 1988. In 1989, we began publishing Annual Progress Reports. While QPR's were excellent exercises in reporting, they required an immense effort; in today's research climate, such effort is not available.

We trust that our reporting is still usefull.

C.K. Birdsall
Principal Investigator

Publications for 1990

Journal Articles

M. Surendra, D.B. Graves, and I.J. Morey, "Electron Heating in Low- Pressure RF Glow Discharges," *Appl. Phys. Lett.*, **56**, pp. 1022-1024, March 12, 1990.

Lou Ann Schwager and C.K. Birdsall, "Collector and Source Sheaths of a Finite Ion Temperature Plasma," *Phys. Fluids B*2, pp. 1057-1068, May 1990.

M.J. Gerver, S.E. Parker, and K. Theilhaber, "Analytic Solutions and Particle Simulations of Cross-Field Plasma Sheaths," *Phys. Fluids B*2 pp. 1069-1082, May 1990.

I.J. Morey and C.K. Birdsall, "Traveling Wave-Tube Simulation: the IBC Code," *IEEE Trans. Plasma Sciences.*, pp. 482-489, June 1990.

J.K. Lee and C.K. Birdsall, "Particle Simulation of Drift Cyclotron Instability", *Japanese Journal of Applied Physics*, Part 1, **29**, pp. 2126-2134, October 1990.

R.J. Procassini, C.K. Birdsall, B.I. Cohen, "Particle Simulation of Collisional Transport in a Diverted Scrape-off Layer. Part I-The High-Recycling Regime,"*Nucl. Fusion.* **30** pp. 2329-2347, November 1990

R.J. Procassini, C.K. Birdsall, E.C. Morse, "A Fully-Kinetic, Self-Consistent Particle Simulation Model of the Collisionless Plasma-Sheath Region," *Phys. Fluids B*2 pp. 3191-3205, December 1990.

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

A. Friedman, S.E. Parker, S.L. Ray, and C.K. Birdsall, "Multi-Scale Particle-In-Cell Plasma Simulation," accepted by *J. Comp. Physics.*

S.E. Parker, A. Friedman, S.L. Ray, and C.K. Birdsall, "Bounded Multi-Scale Plasma Simulation: Application to Sheath Problems," accepted by *J. Comp. Physics.*

N.F. Otani, J-S Kim, C.K. Birdsall, B.I. Cohen, W. Nevins, N. Maron, "Elimination of Velocity Space Rings-and-Spokes Instabilities in Magnetized Electrostatic Particle Simulations of Plasmas," accepted by *J. Comp. Physics.*

S.E. Parker, R.J. Procassini, C.K. Birdsall, B.I. Cohen, "A Suitable Boundary Condition for Bounded Plasma Simulation without Sheath Resolution," accepted by *J. Comp. Physics.*

V. Vahedi, M.A. Lieberman, M.V. Alves, J.P. Verboncoeur, and C.K. Birdsall, "A One Dimensional Collisional Model for Plasma Immersion Ion Implantation," accepted by *J. Appl. Physics.*

M.V. Alves, M.A. Lieberman, V. Vahedi, and C.K. Birdsall, "Sheath Voltage Ratio for Asymmetric RF Discharges," accepted by *J. Appl. Physics.*

J.P. Verboncoeur, M.V. Alves, and V. Vahedi, "Simultaneous Potential and Circuit Solution for Bounded Plasma Particle Simulation Codes," submitted to *J. Comp. Physics* June 1990.

T.L. Crystal, P.C. Gray, W.S. Lawson, C.K. Birdsall, S. Kuhn, "Trapped Electron Effects on Time-Independent Negative-Bias States of a Collisionless Single-Emitter Plasma Device: Theory and Simulation," to appear in *Physics of Fluids* **B**, January 1991.

ERL Reports

M.V. Alves, M.A. Lieberman, V. Vahedi, and C.K. Birdsall, "Sheath Voltage Ratio for Asymmetric RF Discharges," Memo. No. UCB/ERL M90/56, June 21, 1990.

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," Memo. No. UCB/ERL M90/60, July 9, 1990.

J.P. Verboncoeur and V. Vahedi, "PDP1: Plasma Device Planar 1 Dimensional Bounded Electrostatic Code. Reference Manual," August 1990.

Conference Proceedings, Poster Papers

Sherwood Fusion Theory Conference, Williamsburg, VA, April 23-25, 1990:

R.J. Procassini, and C.K. Birdsall, "Particle Simulations of Transport in a Diverted Tokamak Scrape-Off Layer: The High-Recycling Regime."

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:

R.J. Procassini, C.K. Birdsall, B.I. Cohen, "Particle Simulations of Transport in a High-Recycling Divertor Scrape-Off Layer."

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, "A Collisional Model For Plasma Immersion Ion Implantation."

Workshop on High-Density Plasma Techniques and Processes for Integrated Circuit Fabrication, Burlingame, CA, September 11-12, 1990.

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."

V. Vahedi, J.P. Verboncoeur, M.A. Alves, and C.K. Birdsall, "Plasma Processing Via Computer Simulation."

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."

US-Japan Workshop on "Advanced Computer Simulation Techniques Applied to Plasmas and Fusion," UCLA, September 26-28, 1990.

V. Vahedi, J.P. Verboncoeur, M. Surendra, and C.K. Birdsall, "A Monte-Carlo Collision Model for the Particle-in-Cell Method."

Course

M.A. Lieberman and C.K. Birdsall, "Low Pressure Plasma Discharges Used in Semiconductor Processing", UC Extension, San Francisco, CA, May 23-25 1990, and Oxford, England, July 9-11, 1990.

Invited Talks

C.K. Birdsall, "Interactive Plasma Computer Experiments; Plasma Device Simulations on PC's and Workstations," January 16, 1990 at Naval Research Laboratory, Washington, D.C.

C.K. Birdsall, "Magnetized plasma sheath, with Kelvin-Helmholtz instability, vortices, Bohm-like diffusion", and "Computer experiments with bounded collisional plasmas on fast PC's, March 26-27, 1990, at University of Wisconsin, Madison, Wisconsin.

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

C.K. Birdsall, "Particle-In-Cell Combined with Monte Carlo Collisions In Living Color:, October 16-19, 1990, at the 43rd Annual Gaseous Electronics Conference, Urbana-Champaign, Illinois.

Presented at Sherwood Fusion Theory Conference
Williamsburg, VA, April 23-25, 1990

Particle Simulations Of Transport In A Diverted Tokamak Scrape-Off Layer: The High-Recycling Regime*

Richard J. Procassini and Charles K. Birdsall

Electronics Research Laboratory
University of California
Berkeley, CA 94720

Bruce I. Cohen

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Livermore, CA 94550

The transport of particles and energy through a tokamak scrape-off layer (SOL) is studied via the particle simulaton code DIPSI (Direct Implicit Plasma Surface Interactions). This code combines direct-implicit particle-in-cell (PIC) techniques with Monte Carlo models for Coulomb collisions, and charged/neutral atomic physics interactions. The fully-kinetic guiding-center PIC code provides a self-consistent solution of the electrostatic potential profile in one spatial dimension (along the open field lines in the SOL) and two velocity components $(v_{\parallel}, v_{\perp})$.

The Monte Carlo, binary-particle Coulomb collision model conserves both the momentum and kinetic energy of the interacting particles. The full range of Coulomb collisional processes (e-e, e-i and i-i) are included. Recycled neutral particles are treated in an *ad hoc* manner: the density is assumed to decay exponentially with increasing distance from the divertor plate (the e-folding length is taken to be the average mean-free path to ionization) and the temperature of the neutrals is prescribed by the user. The neutral particles interact with the background plasma via charge-exchange events with ions and impact ionization events arising from electron/neutral collisions.

This model is used to determine the effect of charged/neutral interactions on the transport properties of a tokamak SOL plasma. The prescribed neutral particle density will span a wide range of recycling fractions. Values of the presheath and collector sheath potential drops, plasma temperature, flow velocity and parallel heat fluxes as a function of charged/neutral collisionality will be presented.

We will also discuss the possibility of extending this model to include the effects of sputtered impurity particles, which could be evolved as a second ionic species. This would allow one to determine the effect of sputtered impurities on the potential profile (and ultimately, the transport of particles and energy) in the plasma-sheath region.

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* Work performed for the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

Presented at IEEE International Conference on Plasma Science
Oakland, CA
May 21-23, 1990

2P1-4

Particle Simulations of Transport in a High-Recycling Divertor Scrape-Off Layer*

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The transport of particles and energy through a tokamak scrape-off layer (SOL) is studied via the particle simulaton code DIPSI (Direct Implicit Plasma Surface Interactions). This code combines direct-implicit particle-in-cell (PIC) techniques with Monte Carlo models for Coulomb collisions and charged/neutral atomic physics interactions. The fully-kinetic guiding-center PIC code provides a self-consistent solution of the electrostatic potential profile in one spatial dimension (along the open field lines in the SOL) and two velocity components $(v_{\parallel}, v_{\perp})$.

The Monte Carlo, binary-particle Coulomb collision model conserves both the momentum and kinetic energy of the interacting particles. The full range of Coulomb collisional processes (e-e, e-i and i-i) are included. Recycled neutral particles are treated in an *ad hoc* manner: the density is assumed to decay exponentially with increasing distance from the divertor plate (the e-folding length is taken to be the average mean-free path to ionization) and the temperature of the neutrals is prescribed by the user. The neutral particles interact with the background plasma via charge-exchange events with ions and impact ionization events arising from electron/neutral collisions.

This model is used to determine the effect of charged/neutral interactions on the transport properties of a tokamak SOL plasma. The prescribed neutral particle density will span a wide range of recycling fractions. Values of the presheath and collector sheath potential drops, plasma temperature, flow velocity and parallel heat fluxes as a function of charged/neutral collisionality will be presented.

Extensions of this model which include the effects of sputtered impurity particles will also be discussed. The sputtered particles may be evolved as a second ionic species. This will allow one to determine the effect of sputtered impurities on the potential profile (and ultimately, the transport of particles and energy) in the plasma-sheath region.

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* Work performed for the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

4P1-9

SHEATH VOLTAGE RATIO FOR ASYMMETRIC RF DISCHARGES[1]

M. V. Alves[2], M. A. Lieberman,
V. Vahedi and C. K. Birdsall
University of California
Berkeley, CA 94720

Spherical and cylindrical many-particle models are being used to simulate RF discharges in which the RF powered and the grounded electrodes have different areas. This asymmetry determines the magnitude of the self-bias voltage V_s (the ion bombarding energy) at the powered electrode, which is a critical process parameter. Recent analytical models for the sheath voltage ratio including the effect of the floating potential have been developed[3 4] that agree with some experimental results. One dimensional (radial) spherical shell models have also been developed[5], incorporating various assumptions for the sheath and the glow discharges, leading to a scaling which is in agreement with some measurements. We have simulated the spherical model with a non uniform ionization and the results agree with the theory. The cylindrical simulation shows that the floating potential plays an important role. The simulation results will be given graphically as the sheath voltage ratio versus area ratio, and will be compared with the theory. The simulation codes are PDC1 (cylindrical) and PDS1 (spherical) which utilize particle-in-cell techniques plus Monte-Carlo simulation of electron-neutral (elastic, excitation and ionization) and ion-neutral (scattering and charge-exchange) collisions[6 7].

---

1. This work is supported in part by ONR contract N00014-90-J-1198.

2. M. V. Alves, visiting from INPE-Brazil, supported partially by CAPES-Ministry of Education, Brazil.

3. M. A. Lieberman, to appear in *J. Vac. Sci. Technol. A*, (1990)

4. A. M. Pointu, *Appl. Phys. Lett.*, 50:1047, (1987)

5. M. A. Lieberman, *J. Appl. Phys.*, 65:4186, (1989)

6. M. V. Alves, V. Vahedi and C. K. Birdsall, *Bull. APS*, 34:2028, (1989) (Abstract)

7. Codes available from Industrial Liaison Program, EECS Dept., UC Berkeley.

Presented at IEEE International Conference on Plasma Science
Oakland, CA
May 21-23, 1990

4P1-10

WORK DONE AND ENERGY BALANCE IN RF DISCHARGES[1]

J. P. Verboncoeur and V. Vahedi
M. A. Lieberman, and C. K. Birdsall
University of California
Berkeley, CA 94720

The fields applied to a parallel plate RF discharge do work on the plasma particles (deposit energy) non-uniformly in space and time at a rate given by $\mathbf{J} \cdot \mathbf{E}$. Similarly, energy is lost by the plasma particles when they strike the electrodes or collide with neutrals or radiate. We are currently characterizing the work done and the losses as a function of time and space in a manner similar to that of Vender and Boswell[2] self-consistently. We compare these results to discharge models and other simulations. The simulation code is PDP1 which utilizes particle-in-cell techniques plus Monte-Carlo simulation of electron-neutral (elastic, excitation and ionization) and ion-neutral (scattering and charge-exchange) collisions[3,4]. The code can simulate different environments with various gases and various pressures commonly used in RF discharges needed in plasma processing.

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1. This work is supported in part by ONR contract N00014-90-J-1198

2. D. Vender and R. W. Boswell, *Measurements of Power Dissipation in a RF Plasma Simulation*. Report ANU-PRL-PP88/8, Plasma Research Laboratory, Australian National University, Canberra (1988).

3. I. J. Morey, V. Vahedi and J. Verboncoeur, *Particle Simulation Code for Modeling Processing Plasmas*, Bull. APS, 34:2028, (1989) (Abstract)

4. Codes available from Industrial Liaison Program, EECS Dept., UC Berkeley.

4P1-11

A COLLISIONAL MODEL FOR PLASMA IMMERSION ION IMPLANTATION[1]

V. Vahedi, M. A. Lieberman,
M. V. Alves[2], J. P. Verboncoeur,
and C. K. Birdsall
University of California
Berkeley, CA 94720

In plasma immersion ion implantation, a target is immersed in a plasma and a series of negative short pulses are applied to it to implant the ions. A new analytical model is being developed for the high pressure regimes in which the motion of the ions is highly collisional. The model provides values for ion flux, average ion velocity at the target, and sheath edge motion as a function of time. The model suggests that the transient ion flux at the target scales with:

$$J_c = \sqrt{2}\, e u_0 n_0 (1 + \omega_0 t)^{-\frac{3}{4}}$$

where ω_0 and u_0 are characteristic frequency and velocity of the ions in the sheath, n_0 is the density, and t is the time. These values are being compared with those obtained from simulation and show good agreement. A review will also be given (for comparison) of the earlier work done at low pressures, where the motion of ions in the sheath is collisionless[3], also showing good agreement between analysis and simulation[4]. The simulation code is PDP1 which utilizes particle-in-cell techniques plus Monte-Carlo simulation of electron-neutral (elastic, excitation and ionization) and ion-neutral (scattering and charge-exchange) collisions[5].

---

1. This work is supported in part by ONR contract N00014-90-J-1198

2. M. V. Alves, visiting from INPE-Brazil, supported partially by CAPES-Ministry of Education, Brazil.

3. M. A. Lieberman, *J. Appl. Phys.*, 66:2926, (1989)

4. I. J. Morey, V. Vahedi and J. Verboncoeur, *Particle Simulation Code for Modeling Processing Plasmas*, Bull. APS, 34:2028, (1989) (Abstract)

5. Codes available from Industrial Liaison Program, EECS Dept., UC Berkeley.

APS/Division of Plasma Physics
Cincinnati, OH
November 12-16, 1990

Particle Transport due to Kelvin-Helmholtz Vortices and Small Scale Turbulence* S. E. PARKER AND C. K. BIRDSALL, *University of California, Berkeley*—In simulations of the cross-field plasma sheath, which has **B** parallel to an absorbing wall and $v_{\|} = k_{\|} = 0$, we have found that the $\mathbf{E} \times \mathbf{B}$ drift velocity shear produces the Kelvin-Helmholtz instability which saturates to large scale drifting vortices ($\frac{e\phi}{T_i} \approx -2$, diameter $\approx$ 5-15ρ_i), with subsequent Bohm-like diffusion.[1] In addition to the circular vortex flow, there is a smaller amplitude, small scale turbulent spectrum ($\frac{e\phi}{T_i} \ll 1$, $k\rho_i \sim 1$ and $\omega \sim \omega_{ci}$). We have now modeled the vortex as a Gaussian potential well and the small scale turbulence as perturbing plane waves traveling parallel to the wall. With no waves present, $\mathbf{E} \times \mathbf{B}$ drifting test electrons stay on the equipotential lines. The addition of one wave leads to stochastic motion and loss of particles. Use of many waves of a given spectrum will also be presented, as well as ties between rate of transport and wave(s) amplitude. Our objective is to understand how the K-H vortices provide a mechanism for enhanced transport.

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*This work supported by DoE contract No. DE-FG03-86ER53220 and ONR contract N00014-85-K-0809.

[1]K. Theilhaber and C. K. Birdsall, *Phys. Fluids B* 1, 2241, Parts I and II, (1989).

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