

Alexander S. Lipatov

The Hybrid Multiscale Simulation Technology

An Introduction
with Application to Astrophysical
and Laboratory Plasmas

With 124 Figures



Springer

Professor Dr. Alexander S. Lipatov

Dialogue Science – Computing Center

Russian Academy of Sciences

Vavilova St. 40, GSP-1

Moscow 117967, Russia

and

Department of Problems of Physics and Energetics

Moscow Institute of Physics and Technology

Institutsky Per. 9, Dolgoprudny

141700 Moscow Region, Russia

Library of Congress Cataloging-in-Publication Data.

Lipatov, Alexander S., 1946–.

The hybrid multiscale simulation technology: an introduction with application to astrophysical and laboratory plasmas/Alexander S. Lipatov.

p.cm. – (Scientific computation, ISSN 1434-8322)

Includes bibliographical references and index.

1. Plasma (Ionized gases)–Simulation methods. 2. Plasma astrophysics–Simulation methods. 3. Computer simulation. I. Title. II. Series.

QC718.4.L56 2002 530.4'4–dc21 2002019987

ISBN 978-3-642-07508-7 ISBN 978-3-662-05012-5 (eBook)

DOI 10.1007/978-3-662-05012-5

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

<http://www.springer.de>

© Springer-Verlag Berlin Heidelberg 2002

Originally published by Springer-Verlag Berlin Heidelberg New York in 2002.

Softcover reprint of the hardcover 1st edition 2002

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting by the author

Cover design: *design & production* GmbH, Heidelberg

Printed on acid-free paper SPIN: 10788430 55/3141/tr - 5 4 3 2 1 0

Contents

Part I. Computational Models and Numerical Methods

1. Physical Systems and Computational Models	3
1.1 Introduction	3
1.2 The Basic Steps of Computational Experiments	3
1.3 Classification of the Plasma Systems. Space and Time Scales	6
1.3.1 Solar Wind	6
1.3.2 Solar-Wind-Earth Interaction	7
1.3.3 Solar-Wind-Moon Interaction	8
1.3.4 Solar-Wind-Venus and Solar-Wind-Mars Interaction	8
1.3.5 Solar-Wind-Comet Interaction	10
1.3.6 Solar-Wind-Heliosphere Interaction	12
1.3.7 Collisionless Shocks and Neutral Current Layers	12
1.3.8 Beams and Plasma Clouds	14
1.3.9 Fusion Plasma	14
1.4 Classification of the Computational Models	16
1.4.1 Direct Solution of the Vlasov–Maxwell Equations	17
1.4.2 Water-Bag Methods	20
1.4.3 Vlasov Hybrid Simulation (VHS) Method	21
1.4.4 Conventional Particle Models	22
Summary	23
2. Particle-Mesh Models	25
2.1 Introduction	25
2.2 Hybrid Quasineutral Models	25
2.2.1 Electrostatic Model	26
2.2.2 Ampere Magnetoinductive Model	27
2.2.3 Particle-Ion–Fluid–Electron Model	29
2.2.4 Particle-Ion–Fluid–Ion–Fluid–Electron Model	36
2.2.5 Particle-Ion–Element–Fluid–Electron Model	37
2.2.6 Gyrokinetic-Ion–Fluid–Ion–Fluid–Electron Models. δF Method	37
2.2.7 Guiding-Center-Ion–Fluid–Electron Model	45
2.2.8 Particle-Electron–Fluid–Ion Model	48
2.3 Particle Nonneutral Models	49

2.3.1	Full Particle Models	50
2.3.2	Particle-Ion–Guiding-Center-Electron Model	53
2.3.3	Guiding-Center-Ion–Guiding-Center-Electron (Drift-Kinetic) Model	55
2.3.4	Particle-Electron–Immobile-Ion Model	56
2.4	Photo-ionization and Charge Exchange Processes	56
2.4.1	Hybrid Particle-Neutral-Component-Fluid- Plasma Models	56
2.4.2	Hybrid Particle-Neutral-Component-Kinetic- Plasma Models	62
	Summary	64
	Exercise	65
3.	Time Integration of the Particle Motion Equations	67
3.1	Introduction	67
3.2	Explicit Leapfrog Method	71
3.3	Implicit Method	71
3.4	Operator Splitting Method	73
3.4.1	Splitting of the Particle Motion Equations. Boris's Scheme	73
3.4.2	Analytical Time Integration. Buneman's Scheme	74
3.4.3	Time Integration with $\Omega\Delta t \gg 1$	75
3.5	Stability and Accuracy of the Leapfrog Schemes	76
3.6	Implicit Time Integration. C1 and D1 Class Schemes	78
3.6.1	C1 Class Scheme	78
3.6.2	D1 Class Scheme	79
3.7	Runge–Kutta Schemes	80
3.8	Relativistic Particle Motion Equations	81
	Summary	82
	Exercises	82
4.	Density and Current Assignment. Force Interpolation.	83
	Conservation Laws	83
4.1	Introduction	83
4.2	Cloud and Assignment Function Shapes	83
4.3	NGP, CIC and TSC Weighting	85
4.3.1	Cloud (S) and Assignment (W) Function Hierarchy	85
4.3.2	Weighting in Two- and Three-Dimensional Space	87
4.4	Force Interpolation	90
4.5	Mass, Momentum and Energy Conservation	92
4.5.1	Mass Conservation	92
4.5.2	Momentum Conservation	94
4.5.3	Energy Conservation	98
4.6	Periodic Systems. Multipole Expansion Method	102
	Summary	103

5. Time Integration of the Field and Electron Pressure Equations	105
5.1 Introduction	105
5.2 Predictor–Corrector Methods	107
5.2.1 The Upwind Method	108
5.2.2 The Leapfrog Scheme	109
5.2.3 Lax–Wendroff Scheme. Explicit Calculation of the Electric Field	111
5.2.4 Implicit Calculation of the Electric Field	114
5.3 Operator Splitting Methods	119
5.3.1 Splitting Schemes	119
5.3.2 Predictor–Corrector/Operator Splitting Scheme	120
5.4 The Transportive Property	121
5.5 High-Order Schemes	124
5.5.1 Multipoint Stencil Schemes	124
5.5.2 Differential Consequences from the Governing Equations	125
5.5.3 Compact Schemes with Spectral-Like Resolution	125
5.5.4 Advection and Diffusion Equations	131
5.5.5 Maxwell’s Equations	132
5.5.6 Filtering of Spurious Oscillations	134
5.6 Time Integration of the Equations for Electromagnetic Potentials	135
5.7 Time Integration of the Generalized Field Equations	138
5.8 Time Integration of the Electron Pressure Equation	140
Summary	140
Exercises	141
6. General Loops for Hybrid Codes. Multiscale Methods	143
6.1 Introduction	143
6.2 Examples of the Conventional Hybrid Simulation Loops	143
6.2.1 General Predictor–Corrector Loop	143
6.2.2 Implicit Time Integration of the Electromagnetic Equations	144
6.2.3 The Moment Method	145
6.2.4 The Richardson Extrapolation Method	147
6.3 Multiple-Time-Scale Methods	147
6.3.1 Electromagnetic Field Subcycling. Current Advanced Methods and Cyclic Leapfrog Schemes	148
6.3.2 Light Ion (Electron) Subcycling	151
6.3.3 Orbit Averaging	154
6.4 Multiple-Space/Time-Scale Methods	156
6.4.1 Variational Methods	157

6.4.2 Adaptive Mesh and Particle Refinement Methods	158
Summary	163
7. Particle Loading and Injection. Boundary Conditions	165
7.1 Introduction	165
7.2 Loading the Particles Inside the Computational Domain	165
7.2.1 Loading Nonuniform Distributions $f_0(\mathbf{v}), n_0(\mathbf{x})$	165
7.2.2 Loading a Maxwellian Velocity Distribution	166
7.2.3 Loading a Ring Velocity Distribution	167
7.2.4 Loading a Shell Velocity Distribution	173
7.3 Particle Injection at Boundaries	174
7.3.1 Loading a Maxwellian Velocity Distribution Flux	174
7.3.2 Loading a Ring Velocity Distribution Flux	176
7.3.3 Loading a Shell Velocity Distribution Flux	178
7.4 Charge Exchange Processes	180
7.5 Boundary Conditions for Particles and the Electromagnetic Field	181
7.5.1 Plasma–Vacuum Interface	181
7.5.2 Field Radiation and Absorption at the Boundaries	182
7.5.3 Boundary Conditions at the Conducting Wall	185
Summary	186

Part II. Applications

8. Collisionless Shock Simulation	189
8.1 Introduction	189
8.2 Collisionless Shocks Without Mass Loading	192
8.2.1 Quasiperpendicular Shocks	192
8.2.2 Oblique Shocks	198
8.2.3 Quasiparallel Shocks	202
8.3 Collisionless Shocks with Mass Loading by Heavy Ions	208
8.3.1 Quasiperpendicular Shocks	210
8.3.2 Oblique Shocks	215
8.3.3 Quasiparallel Shocks	219
8.3.4 Pickup Ion Acceleration at Shock Front. Shock Surfing	224
Summary	236
Exercises	236
9. Tangential Discontinuity Simulation	237
9.1 Introduction	237
9.2 Formulation of the Problem and Mathematical Model	238
9.3 One-Dimensional Structures	239
9.4 Two-Dimensional Structures	241

9.4.1	Magnetic Field Oriented Perpendicular to the Simulation Plane	241
9.4.2	Magnetic Field in the Simulation Plane	243
9.4.3	Analysis of the Waves at the TD and the Wave–Particle Cross-Field Transport	243
9.4.4	Dependence of the Final Thickness of TDs on Initial Conditions	246
9.4.5	Dependence of the TD Width on Anomalous Resistivity and Numerical Viscosity	247
9.4.6	The Kelvin–Helmholtz Instability at the TD	248
10.	Magnetic Field Reconnection Simulation	255
10.1	Introduction	255
10.2	Ion Tearing Instability	256
10.2.1	Formulation of the Problem and Mathematical Model	257
10.2.2	Multimode Regime	260
10.2.3	Single-Mode Regime	262
10.2.4	Explosive Regime. Ion Acceleration	264
10.3	Electron Effects on Reconnection	268
10.3.1	Effects of Electron Inertia and Electron Pressure Anisotropy	270
10.3.2	Effects of Anomalous Resistivity on Reconnection	275
	Summary	280
	Exercises	281
11.	Beam Dynamics Simulation	283
11.1	Introduction	283
11.2	Cold Beam Dynamics	284
11.2.1	One-Dimensional Models	285
11.2.2	Two-Dimensional Models	288
11.3	Mass Loading of the Supersonic Flow by Heavy Ions	291
11.3.1	One-Dimensional Models	291
11.3.2	Two-Dimensional Models	295
11.4	Finite Size Beam (Plasma Cloud) Dynamics	301
11.4.1	Generation of Low-Frequency Waves by Three-Dimensional and 2.5-Dimensional Beams in a Homogeneous Background	301
11.4.2	Interaction of the 2.5-Dimensional Beam with Tangential Discontinuities	302
	Summary	306
12.	Interaction of the Solar Wind with Astrophysical Objects 309	309
12.1	Introduction	309
12.2	Interaction of the Solar Wind with Strong Comets	309
12.2.1	Formulation of the Problem and Mathematical Model	310

XVIII Contents

12.2.2 Structure of the Region of Mass Loading by Cometary Ions	315
12.2.3 Induced Magnetosphere, Bow Wave and Magnetic Barrier	316
12.3 Interaction of the Solar Wind with Weak Comets and Related Objects	320
12.3.1 Formulation of the Problem and Mathematical Model	320
12.3.2 Interaction of the Solar Wind with Very Weak Comets	321
12.3.3 Interaction of the Solar Wind with Weak Comets	329
12.3.4 Interaction of the Solar Wind with Pluto	329
12.4 Interaction of the Solar Wind with Venus	333
12.4.1 Formulation of the Problem and Mathematical Model	333
12.4.2 Results and Conclusions	334
12.5 Interaction of the Solar Wind with the Moon	337
12.5.1 Formulation of the Problem and Mathematical Model	338
12.5.2 Method of Solution	340
12.5.3 Results and Conclusions	342
12.6 Interaction of Neutral Interstellar Atoms with the Heliosphere	344
12.6.1 Formulation of the Problem and Mathematical Model ..	344
12.6.2 Results and Conclusions	346
Summary	353
Exercises	353
13. Appendix	355
13.1 Coordinate Form of Maxwell's Equations and the Electron Pressure Equations	355
13.1.1 Cartesian Coordinates	355
13.1.2 Cylindrical Coordinates	357
13.1.3 Spherical Coordinates	358
13.2 Solving One-Dimensional Difference Equations	361
13.2.1 Three-Point Difference Equation with Nonperiodic Boundary Conditions: Forward-Elimination–Backward-Substitution Method ..	361
13.2.2 Three-Point Difference Equation with Periodic Boundary Conditions: Forward-Elimination–Backward-Substitution Method ..	362
13.2.3 Five-Point Difference Equation: Forward-Elimination–Backward-Substitution Method ..	363
14. Solutions	365
References	380
Index	401