Contents

1 Introduction to Plasma 1
1.1 Fourth State of Matter: Plasma 1
1.2 Brief Introduction to Plasma Physics World 3
1.3 Collective Motion: The Debye Shielding 7
1.4 Collective Motion: Plasma Oscillation 10
1.5 Conditions for Plasma Collective Motion 12
1.6 Introduction to Mathematical Models for Plasma 14
1.7 Introduction to Computer Simulation for Plasma 15
1.7.1 Computer Simulation Power and Uncertainty in Computation 16
1.7.2 Example Computer Simulation for the Debye Shielding 25
References 26

2 Plasma in Equilibrium 29
2.1 Distribution Function and Plasma 29
2.2 The Maxwell Distribution 31
2.3 Plasma Density 35
2.4 The Coulomb Collision 36
2.5 Plasma Temperature 39
2.5.1 Simulation of Temperature Relaxation 40
References 41

3 Single Particle Motion 43
3.1 Equation of Motion 43
3.2 Cyclotron Motion 44
3.3 Drift Motion 45
3.4 Magnetic Moment 50
3.5 Single Particle Simulations 52
3.6 Simulation of Electron Motion in Laser Field 55
References 57

4 Equations for Electromagnetic Field 59
4.1 The Poisson Equation 59
4.2 The Maxwell Equations 60
4.3 Potential 63
4.4 Introduction to Kinetic Particle Simulation Model for Plasma 64
4.4.1 Structure of Particle-in-Cell (PIC) Code 65
4.4.2 Field Solver 65
4.4.3 Interaction Between Field and Particles 66
4.4.4 Simulation of Electron Cloud with Laser Field 68
References 69

5 Plasma by Fluid Model 71
5.1 Basic Fluid Equations 71
5.2 Introduction to Plasma Simulation by the Euler Fluid Model 74
5.2.1 Summary of Finite Difference Method (FDM) 75
5.2.2 Example 2D Simulation for Convection 76
5.2.3 Numerical Instability and Time Step Control 80
5.2.4 Numerical Instability and Its Analysis 81
5.2.5 Example Simulation for Jet Injection 82
5.2.6 Example Simulation for Diffusion: Heat Conduction 85
5.3 Introduction to Plasma Simulation by the Lagrange Fluid Model 88
5.4 Electron Plasma Wave 93
5.5 Ion Acoustic Wave 97
5.6 Electromagnetic Wave 99
5.7 Magnetohydrodynamic Equation 101
5.8 Frozen Magnetic Flux 104
5.9 Waves in Magnetized Plasma 105
References 109

6 Plasma Treated by Distribution Function: Kinetic Model 111
6.1 The Vlasov Equation 111
6.1.1 The Klimontovich Equation 111
6.1.2 The Liouville Equation 112
6.1.3 The BBGKY Hierarchy and the Vlasov Equation 115
6.2 Equilibrium Solution 118
6.3 The Boltzmann Equation and Collision Effect 119
6.4 Moment Equations and Fluid Model 120
6.5 Dielectric Response Function for Unmagnetized Uniform Plasma 122
6.6 Plasma Oscillation and the Debye Shielding 126
6.7 Electron Plasma Wave and the Landau Damping 128
6.8 Electron Wave Propagation in Equilibrium Plasmas 129
6.9 Physical Meaning of the Landau Damping 131
6.10 Dispersion Relation for Transverse Electromagnetic Waves 133
6.11 Dispersion Relation for Magnetized Uniform Plasma 135

6.12 Waves in Magnetized Uniform Plasma 141
References 144

7 Plasma Instability 147
7.1 Two-Stream Instability 147
7.1.1 Two-Stream Instability by Fluid Model 147
7.1.2 Two-Stream Instability by Distribution Function 150
7.1.3 Example Simulation for Two-Stream Instability 152
7.2 Ion Acoustic Instability 153
7.3 Instability of Magnetized Plasma Column 154
7.3.1 Example Simulation for the Sausage and Kink Instabilities 157
7.4 Interchange Instability—The Rayleigh-Taylor instability and an Example Simulation 159
7.5 The Kelvin-Helmholtz Instability and an Example Simulation 162
7.6 Parametric Instability 165
7.7 The Weibel Instability 166
7.8 Filamentation Instability and an Example Simulation 167
7.9 Tearing Mode Instability and an Example Simulation 170
7.10 Drift Instability 173
References 175

8 Short Introduction to Nonlinear Plasma Physics 179
8.1 Solitary Wave: The Korteweg-de Vries (KdV) Equation 179
8.1.1 The Korteweg-de Vries (KdV) Equation for Ion Acoustic Wave 181
8.1.2 Property of the Korteweg-de Vries (KdV) Equation 183
8.1.3 Inverse Scattering Transform for the Korteweg-de Vries (KdV) Equation 185
8.2 The Burgers Equation and Shock Wave 186
8.3 Plasma Echo 188
8.4 A Glimpse at Turbulence 189
References 193

9 Applications of Plasmas 197
9.1 Plasma Process 197
9.2 Electron Temperature Measurement by Single-Probe Method 197
9.3 Plasma Jet 199
9.4 Nuclear Fusion 200
9.4.1 Fusion Reaction 201
9.4.2 The Lawson Criterion—To Sustain Fusion Reaction 202
9.4.3 MCF: Magnetic Confinement Fusion 203
9.4.4 ICF: Inertial Confinement Fusion 205
9.5 Laser Particle Acceleration 213
9.6 Cluster Ion Interaction with Plasma 216

9.7 Control of Plasma: Dynamic Mitigation of Plasma Instabilities and Non-uniformities 218
9.7.1 Control of Plasma: Theory 220
9.7.2 Dynamic Control of Plasma Instabilities 222
References 242

Appendix A: Additional Readings 251

Appendix B: Physical Constants and Mathematical Formulae 255

Appendix C: Complex Analysis: Summary 261

Appendix D: Derivation of Ponderomotive Force 269

Appendix E: Parallel Computing by OpenMP 271

Appendix F: Example 3D Pure Euler Fluid Code Structure 275

Appendix G: Derivation of ϵ_{xx} in Eq. (6.151) for Magnetized Uniform Plasma 287

Index 291