

TABLE OF CONTENTS

Author's Foreword	vii
Preface	ix
Acknowledgments	xi
1. Introduction	1
1.1 Exordium	1
1.2 Historical Background	2
1.3 Technical Advances	3
1.4 Outline	5
Chapter 1 References	7
2. Theoretical Models of Nonneutral Plasma	15
2.1 Introduction	15
2.2 Kinetic Description	17
2.3 Macroscopic Fluid Description	22
2.4 Conservation Relations	26
2.5 Discrete Particle Effects	29
2.6 Gravitational Analogue	35
Chapter 2 References	35
3. Fundamental Properties of Nonneutral Plasma	39
3.1 Cold-Fluid Equilibrium Rotation	39
3.2 Single-Particle Trajectories	47
3.3 Thermal Equilibrium	52
3.4 Debye Shielding	59
3.5 Spontaneous Emission from a Test Electron	61
3.6 Strongly Coupled Nonneutral Plasma	65
Chapter 3 References	75

4. Kinetic Equilibrium and Stability Properties	79
4.1 Equilibrium Vlasov–Maxwell Equations	
for Axisymmetric Nonneutral Plasma	80
4.1.1 Axisymmetric Confinement Geometries	80
4.1.2 Nonneutral Plasma Column	84
4.1.3 Axially Confined Equilibria	88
4.2 Nonrelativistic Kinetic Equilibria	90
4.2.1 Rigid-Rotor Vlasov Equilibria	91
4.2.2 Density Inversion Theorem	97
4.2.3 Uniform-Density Plasma Column	99
4.2.4 Annular Electron Layer	102
4.3 Axially-Confined Kinetic Equilibria	109
4.3.1 Penning-Trap and Segmented Cylinder Equilibria	110
4.3.2 Mirror-Confined Electron Layer	117
4.4 Intense Relativistic Electron Beam Equilibria	122
4.5 Kinetic Stability Theorem for Nonneutral Plasma	130
4.6 Kinetic Confinement Theorem for Nonneutral Plasma	137
4.7 Electrostatic Eigenvalue Equation	143
4.8 Dispersion Relation for Body-Wave Perturbations	149
4.8.1 Electrostatic Dispersion Relation	149
4.8.2 Examples of Kinetic Waves and Instabilities	155
4.8.3 Dispersion Relation for Transverse Electromagnetic Waves	162
4.9 Dispersion Relation for Flute Perturbations	168
4.10 Kinetic Equilibrium and Stability Properties of the Modified Betatron	179
4.10.1 Introduction and Assumptions	179
4.10.2 Self-Consistent Vlasov Equilibrium	184
4.10.3 Linearized Vlasov–Maxwell Equations	195
4.10.3 Negative-Mass and Surface-Kink Instabilities	204
Chapter 4 References	212
5. Macroscopic Equilibrium and Stability Properties	221
5.1 Equilibrium Force Balance Equation	222
5.2 Examples of Macroscopic Equilibria	225
5.2.1 Nonrelativistic Nonneutral Plasma Column	226
5.2.2 Relativistic Diamagnetic Equilibria	228

Table of Contents

xv

5.2.3 Relativistic Beam-Plasma Equilibria	233
5.2.4 Bennett Pinch Equilibrium	236
5.3 Electrostatic Eigenvalue Equation	240
5.4 Dispersion Relation for Uniform-Density Plasma Column	243
5.5 Nonneutral Plasma-Filled Waveguide	248
5.5.1 Electrostatic Dispersion Relation	248
5.5.2 Trivelpiece-Gould Modes in a Pure Ion Plasma	249
5.5.3 Modified Two-Stream Instability	253
5.6 Stability Properties for Flute Perturbations	257
5.6.1 Electrostatic Dispersion Relation	257
5.6.2 Stable Oscillations	259
5.6.3 Ion Resonance Instability	260
5.7 Two-Stream Instabilities in Relativistic Beam-Plasma Systems	265
5.7.1 Electrostatic Dispersion Relation	265
5.7.2 Beam-Plasma Filled Waveguide	267
5.7.3 Thin-Beam Limit	269
5.8 Electromagnetic Filamentation Instability	271
5.8.1 Ordinary-Mode Dispersion Relation	272
5.8.2 Filamentation Instability	275
5.9 Equilibrium and Collective Oscillation Properties of Two-Dimensional Nonneutral Plasma	276
5.9.1 Two-Dimensional Disk Equilibrium	278
5.9.2 Normal Modes of Oscillation	280
Chapter 5 References	284
6. The Diocotron Instability	289
6.1 Nonrelativistic Guiding-Center Model	290
6.2 Electrostatic Stability Theorem	292
6.3 Linear Stability Properties	295
6.3.1 Electrostatic Eigenvalue Equation	295
6.3.2 Diocotron Instability for an Annular Electron Layer	297
6.3.3 Stable Oscillations for $\ell = 1$ and Arbitrary Density Profile	305
6.4 Experimental Results	306
6.5 Quasilinear Evolution	312
6.5.1 Theoretical Model	312

6.5.2 Quasilinear Kinetic Equations	315
6.5.3 Stabilization Process	319
6.6 Resonant Diocotron Instability	323
6.6.1 Instability Growth Rate	324
6.6.2 Quasilinear Stabilization Process	327
6.7 Influence of Electromagnetic and Relativistic Effects	330
Chapter 6 References	340
7. Coherent Electromagnetic Wave Generation by the Cyclotron Maser and Free Electron Laser Instabilities	345
7.1 Introduction	345
7.2 Cyclotron Maser Instability	347
7.2.1 Stability Properties for a Tenuous Electron Beam	348
7.2.2 Influence of Intense Equilibrium Self Fields	355
7.3 Cyclotron Maser Instability for an Annular Electron Beam	365
7.4 High-Power Step-Tunable Gyrotron Experiments	373
7.5 Free Electron Laser Instability	375
7.5.1 Introduction	375
7.5.2 Spontaneous Emission from a Test Electron in a Helical Wiggler Magnetic Field	377
7.5.3 Free Electron Laser Oscillator Experiments	381
7.6 Kinetic Description of the Free Electron Laser Instability	383
7.6.1 Theoretical Model	383
7.6.2 Kinetic Dispersion Relation	386
7.7 Cold-Beam Stability Properties	392
7.7.1 Linear Dispersion Relation	392
7.7.2 Conditions for Free Electron Laser Interaction	394
7.7.3 Tunable Free Electron Laser Experiments	395
7.7.4 Analysis of the Full Dispersion Relation	397
7.7.5 Compton-Regime Approximation	399
7.7.6 Raman-Regime Approximation	402
7.8 Warm-Beam Compton-Regime Stability Properties	404
7.9 Nonlinear Evolution for Multimode Excitation	412
7.10 Sideband Instability	419
7.10.1 Nonlinear Wave and Orbit Equations	420
7.10.2 Macroclump Model of the Sideband Instability	428
7.10.3 Analysis of the Sideband Instability	432

Table of Contents

xvii

7.10.4 Experimental Results	437
7.11 Harmonic Generation in a Planar Wiggler Free Electron Laser	439
7.12 High-Gain Free Electron Laser Amplifier Experiments	446
Chapter 7 References	449
8. Equilibrium and Stability Properties of Intense Nonneutral Flow in High-Power Diodes	461
8.1 Introduction	461
8.2 Child–Langmuir Flow	463
8.2.1 Nonrelativistic Planar Diode	463
8.2.2 Relativistic Planar Diode	469
8.3 Magnetically Insulated Brillouin Flow	473
8.3.1 Nonrelativistic Planar Flow	473
8.3.2 Nonrelativistic Cylindrical Flow	480
8.3.3 Relativistic Planar Flow	485
8.4 Magnetically Insulated Ion Diodes	491
8.5 Magnetron Instability for Magnetically Insulated Electron Flow	497
8.5.1 Extraordinary-Mode Eigenvalue Equation	497
8.5.2 Linear Growth Properties	503
8.6 Multiresonator Magnetron Experiments	511
8.7 Ion Resonance and Transit Time Instabilities in Magnetically Insulated Ion Diodes	515
8.8 Applied-B Diodes with Virtual Cathode	521
8.8.1 Theoretical Model and Basic Equations	523
8.8.2 Solution for Uniform-Density Electron Layer	525
8.8.3 Ion Current Enhancement at Peak Diode Power	529
Chapter 8 References	532
9. Propagation and Stability of Intense Charged Particle Beams in a Solenoidal Focusing Field	539
9.1 Introduction	539
9.2 Propagation of Intense Nonneutral Electron Beams	540
9.2.1 Envelope Equation for Beam Propagation	541
9.2.2 Space-Charge-Limiting Current	547
9.2.3 Limiting Current in an Infinitely Long Drift Space	552

9.2.4	Limiting Current in a One-Dimensional Drift Space	555
9.2.5	Laminar Flow Equilibria in an Infinitely Long Drift Space	559
9.3	Stability of Nonneutral Electron Flow in a One-Dimensional Drift Space	569
9.3.1	Review of Nonrelativistic Equilibrium Flow	570
9.3.2	Linearized Cold-Fluid–Poisson Equations	572
9.3.3	Langrangian Representation	573
9.3.4	Solution to the Eigenvalue Equation	575
9.3.5	Analysis of Stability Properties	579
9.4	Stability of Intense Nonneutral Ion and Electron Beams	583
9.4.1	Theoretical Model and Assumptions	584
9.4.2	Kapchinskij–Vladimirskij Beam Equilibrium	588
9.4.3	Linearized Vlasov–Maxwell Equations	594
9.4.4	Solution to the Eigenvalue Equation	599
9.4.5	Transverse Stability Properties in a Solenoidal Focusing Field	605
9.4.6	Transverse Stability Properties in a Quadrupole Focusing Field	610
9.5	Resistive Hose Instability for Intense Electron Beam Propagation Through a Background Plasma	615
9.5.1	Theoretical Model and Assumptions	615
9.5.2	Equilibrium Properties	618
9.5.3	Kinetic Eigenvalue Equation for $\ell = 1$ Perturbations Resistive Hose Instability for Sharp-Boundary Density Profile	623 629
9.5.5	Resistive Hose Instability for a Diffuse Density Profile	637
9.6	Resistive Sausage and Hollowing Instabilities for Intense Electron Beam Propagation Through a Background Plasma	639
9.6.1	Theoretical Model and Assumptions	640
9.6.2	Kinetic Eigenvalue Equation for Azimuthally Symmetric Perturbations	643
9.6.3	Resistive Sausage Instability ($n = 1$)	646
9.6.4	Resistive Hollowing Instability ($n = 2$)	650
	Chapter 9 References	653

10. Propagation and Stability of Intense Charged Particle	
Beams in an Alternating-Gradient Focusing Field	659
10.1 Introduction	659
10.2 Alternating-Gradient Field Configuration	662
10.3 Equations of Motion in the Paraxial Approximation	666
10.4 Orbit and Envelope Equations for a Periodic	
Quadrupole Field	669
10.4.1 Particle Orbit Equations	669
10.4.2 Beam Envelope Equations	672
10.5 Orbit and Envelope Equations for a Solenoidal	
Focusing Field	673
10.5.1 Particle Orbit Equations	673
10.5.2 Beam Envelope Equations	676
10.5.3 Beam Radius and Current for a Matched Beam	676
10.5.4 Phase Advance σ	678
10.6 Average Focusing Force and Phase Advance for a	
Periodic Quadrupole Field	680
10.6.1 Envelope Equations for Small-Amplitude	
Modulation	680
10.6.2 Phase Advance σ	682
10.6.3 Average Quadrupole Focusing Force	688
10.6.4 Beam Radius and Current for a Matched Beam	689
10.7 Hamiltonian Formulation and Relationship to	
Kapchinskij-Vladimirskij Distribution Function	690
10.7.1 Hamiltonian Formulation	691
10.7.2 Kapchinskij-Vladimirskij Distribution Function	694
10.7.3 Definition of Statistical Average and	
RMS Emittance	698
10.8 Transverse Stability of the Kapchinskij-Vladimirskij	
Distribution Function	699
10.8.1 Linearized Vlasov-Poisson Equations	699
10.8.2 Transverse Stability Properties	702
10.8.3 Generalization of the Eigenvalue Equation	
in the Low-Density Regime	707

10.9 Emittance Growth	711
10.9.1 Instability-Induced Emittance Growth	711
10.9.2 Emittance Growth Caused by Charge Nonuniformity	713
Chapter 10 References	717
Appendix A. Solution to the Eigenvalue Equation for Longitudinal Stability of the Modified Betatron	721
Appendix B. Derivation of the Extraordinary-Mode Eigenvalue Equation for Relativistic Electron Flow in Planar Geometry	725
Index	728