CONTENTS

Preface		xi
CHAPTER 1 INTRODUCTION TO PLASMA PHYSICS		1
	Part One Plasma Concepts and Terminology	3
1.1	Equilibrium and Metaequilibrium	3
	Debye Length	3
1.3	Plasma Parameter	4
1.4	Distribution Function	5
1.5	Temperature and Other Moments of the Distribution Function	6
1.6	Magnetic Pressure	7
1.7	Particle Drifts	7
	Plasma Frequency	9
	Waves in Plasmas	9
	Landau Damping	12
	Plasma Stability and Controlled Thermonuclear Fusion	12
	Shock Waves and Solitary Waves	16
	Collisions	18
	Diffusion and Bohm Diffusion	20
1.15	Plasma Radiation	23
	Part Two Plasma Production	25
1.16	The Low-pressure Cold-cathode Discharge	27
1.17	The Thermionic-arc Discharge	27
	Plasma Guns	30
	Alkali Metal Vapor Plasma—Q Machines	33
	RF-produced Plasmas	33
	Dense-plasma Focus	37
	The Solar Plasma	39
1.23	Laser-produced Plasmas	39
	Part Three Measurement of Plasma Properties	41
1.24	Current and Voltage Measurements in Plasmas	42
	Plasma Probes	45
	Other Methods of Measurement of Plasma Properties	50 54
References		

vi contents

CHAP	TER 2 THERMODYNAMICS AND STATISTICAL MECHANICS OF EQUILIBRIUM PLASMAS	55
2.1	The Plasma Parameter	57
2.2	Gibbs Distribution and Correlation Functions	58
2.3	Two-particle Correlations in an Equilibrium Plasma	60
2.4	Free Energy of a Plasma	63
2.5	Equation of State of a Plasma	65
2.6	The Plasma as a Fluid	66
2.7	The Ideal Plasma	67
2.8	Potential of a Test Particle in a Plasma	68
2.9	Other Examples of the Plasma as a Fluid	70
2.10	Coulomb Energy of a Plasma Discussion	74
2.11 Refere		76 77
-		
	PTER 3 MACROSCOPIC PROPERTIES OF PLASMAS	78
3.1	The Distribution Function and the Liouville Equation	79
3.2	Macroscopic Variables of a Plasma	82
3.3	Macroscopic Equations for a Plasma; Fluid Equations	84
3.4 3.5	Two-fluid Plasma Theory One-fluid Plasma Theory; Magnetohydrodynamics	88 89
3.5 3.6	Approximations Commonly Used in One-fluid Theory	92 92
3.7	Simplified One-fluid Equations and the MHD Equation	95
3.8	Properties of the Plasma Described by the One-fluid and MHD Models	98
3.9	Dynamic Properties of a Plasma Described by the One-fluid and MHD Plasma	20
••••	Theories	104
3.10	Double-adiabatic Theory	118
3.11	The Dynamic Pinch	123
Refere	nces	128
CHAF	TER 4 WAVES IN THE FLUID PLASMA	129
4.1	Dielectric Constant of a Field-free Fluid Plasma ($\mathbf{E}_0 = \mathbf{B}_0 = 0$)	130
4.2	Plasma Oscillations	133
4.3	Plasma Oscillations in a One-dimensional Drifting Plasma	136
4.4	Space-charge Waves in a Warm Plasma	143
4.5	Plane Waves in a Cold Plasma	147
4.6	Microwave Transmission Method of Measuring Plasma Properties	153
4.7	Plasma-column Resonances	157
4.8	Space-charge Waves in Finite Plasmas	167
4.9	Dielectric Constant of a Cold Magnetized Plasma ($\mathbf{E}_0 = 0, \mathbf{B}_0 = B_0 \hat{\mathbf{z}}$)	178
4.10	Waves that Propagate Parallel to the Magnetic Field in a Cold Magnetized Plasm $(\mathbf{E}_0 = 0, \mathbf{B}_0 = B_0 \hat{\mathbf{z}})$	ia 182
4.11	Waves that Propagate Perpendicular to the Magnetic Field in a Cold Magnetized Plasma ($\mathbf{E}_0 = 0, \mathbf{B}_0 = B_0 \hat{\mathbf{z}}$)	196
4.12	Wave Frequencies in Typical Plasmas	200
4.13	Space-charge Waves in Cold Finite Plasmas in a Finite Magnetic Field	202
4.14	Low-frequency Drift Waves in Nonuniform Plasmas	206
Refere		213
CHAI	PTER 5 STABILITY OF THE FLUID PLASMA	215
	Part One The Plasma Stability Problem	215
5.1	The Equilibrium Problem	217
5.2	Classification of Plasma Instabilities	218

1

References

7.7 Properties of the Vlasov Equation

7.8 Properties of the Kinetic Equation to Order g

5.3 5.4	Methods of Stability Analysis Regions of Stability	220 221
	Part Two Stability of Unconfined Plasma from Macroscopic Fluid Equations	221
5.5	Two-stream Instabilities of Space-charge Waves	222
5.6	Fire-hose Instability of an Alfvén Wave	228
	Part Three Stability of Magnetically Confined Plasma from Macroscopic Fluid	
	Equations	229
5.7 5.8	Stability of the Fluid Plasma Supported against Gravity by a Magnetic Fluid Stability of Magnetically Confined Fluid Plasma from Thermodynamic	230
5.8	Considerations; Interchange Instability	233
5.9	Macroscopic Equations for the Study of the Hydrodynamic Stability of Magneti-	
	cally Confined Plasmas	241
5.10	Stability of the Fluid Plasma Supported against Gravity by a Magnetic-field:	246
E 11	Normal-mode Analysis	246 251
5.11 5.12	Energy Principle Stability of a Plane Plasma-Magnetic Field Interface: Energy Principle Analysis	257
5.12	Stability of Self-confined Plasma (B_{θ} Only): Energy Principle Analysis	261
5.14	Stabilizing Influence of Line Tying	263
	Part Four Stability Theory and Controlled Thermonuclear Fusion Research	265
5.15	Open Plasma-confinement Experiments	267
5.16	Closed Plasma-confinement Experiments	275
5.17	Other Plasma-confinement Experiments	281
Refere		285
CHAF	TER 6 TRANSPORT PHENOMENA IN PLASMA	287
6.1	Binary Coulomb Collisions	289
6.2	Deflection of a Charged Particle by Multiple Coulomb Collisions	291
6.3	Fokker-Planck Theory for Transport in a Fully Ionized Plasma	295
6.4	Relaxation Times in a Fully Ionized Plasma	301
6.5	Transport Properties of a Fully Ionized Plasma Boltzmann Transport Equation and the Lorentz Model for a Weakly Ionized	307
6.6	Plasma	311
6.7	Modified Boltzmann Equation	315
6.8	Transport Coefficients in a Weakly Ionized Plasma	318
6.9	Ambipolar Diffusion	321
6.10	Transport Properties of a Weakly Ionized Plasma in a Steady and Homogeneous	
	Magnetic Field	327
6.11	Ambipolar Diffusion of a Weakly Ionized Plasma across a Magnetic Field	333
6.12	MHD Power Generators	340
Refere		347
CHA	PTER 7 KINETIC EQUATIONS FOR A PLASMA	349
7.1	The Microscopic Equations for a Many-body System	350
7.2	The Statistical Equations for a Many-body System	351
7.3	Statistical Equations for a Coulomb Plasma	355
7.4		357 358
7.5	Kinetic Equation in Zero Order—The Vlasov Equation	359
7.6	Kinetic Equation in First Order	200

359 360

366 367

viii CONTENTS

CHAP	TER 8 THE VLASOV THEORY OF PLASMA WAVES	368
8.1	The Vlasov Equations	368
8.2	The Linearized Vlasov Equations	369
8.3	Solution of the Linearized Vlasov Equations for Electrostatic Perturbations	
	of a Field-free Plasma Equilibrium	371
8.4	Time-asymptotic Solutions for $\phi_k(t)$	375
8.5	Simplified Derivation for Electrostatic Waves in a Plasma	381
8.6	The Vlasov Theory of Langmuir Waves, Ion-sound Waves, and Landau Damping	
	$(\mathbf{E}_0 = \mathbf{B}_0 = 0)$	383
8.7	Perturbed Distribution Function for Plasma Waves	391
8.8	The Dispersion Relation for Waves in a General Plasma Equilibrium	395
8.9	The Vlasov Theory of Small-amplitude Waves in a Field-free Plasma Equilibrium-	
	Electrostatic and Electromagnetic Waves $[\mathbf{E}_0 = \mathbf{B}_0 = 0, f_0 = f_0(v^2)]$	398
8.10	The Vlasov Theory of Small-amplitude Waves in a Uniformly Magnetized	
	Plasma $[\mathbf{B}_0 = B_0 \hat{\mathbf{z}}, \mathbf{E}_0 = 0, f_{\alpha 0} = f_{\alpha 0}(v_{\perp}^2, v_{\parallel})]$	402
8.11	The Vlasov Theory of Waves in Cold Magnetized Plasma	407
8.12	Waves That Propagate Perpendicular to the Equilibrium Magnetic Field in a	
	Hot Magnetized Plasma ($\mathbf{E}_0 = 0$, $\mathbf{B}_0 = \hat{\mathbf{z}} B_0$)—Electromagnetic Waves and the	
	Bernstein Modes	407
8.13	Waves That Propagate Parallel to the Equilibrium Magnetic Field in a Magnetized	
	Hot Plasma—Electrostatic and Electromagnetic Waves ($\mathbf{E}_0 = 0, \mathbf{B}_0 = \hat{\mathbf{z}} B_0$)	414
8.14	Electromagnetic Waves Propagating at an Arbitrary Angle with Respect to the	
	Equilibrium Magnetic Field in a Magnetized Hot Plasma ($\mathbf{E}_0 = 0, \mathbf{B}_0 = \hat{\mathbf{z}} B_0$)	417
8.15	Waves in an Inhomogeneous Magnetized Hot Plasma $[\mathbf{E}_0 = 0, \mathbf{B}_0 = \hat{\mathbf{z}} B_0(x),$	
	$n_0 = n_0(x)]$	418
8.16	Low-frequency Electrostatic Waves in an Inhomogeneous Magnetized Plasma	427
8.17	Nonlinear Electrostatic Waves (BGK Waves)	432
8.18	Fluid Waves vs. Vlasov Waves	437
8.19	Summary of Wavelike Vlasov States	439
Refere	ences	441
CHAI	PTER 9 THE VLASOV THEORY OF PLASMA STABILITY	442
9.1	Introduction	442
9.2	Stability of Monotone-decreasing Distribution; The Newcomb-Gardner Theorem	445
9.3	Stability of Multipeaked Distributions—The Two-stream Instability	449
9.4	Stability of Multipeaked Distribution in Warm Plasmas-Gentle-bump Instability	458
9.5	Mechanism of the Two-stream Instability	463
9.6	The Nyquist Method and the Penrose Criterion for Stability	464
9.7	Ion-acoustic Instability	476
9.8	Applications of Two-stream-instability Theory	478
9.9	Instabilities in Anisotropic Plasmas	482
9.10	Electromagnetic Pinching Instabilities	483
9.11	Discussion of Pinching Instabilities	494
9.12	• • •	495
9.13	-	497
	Other Instability Mechanisms	505
	Thermodynamic Bounds on Field Levels and Growth Rates in Unstable Plasma	506
Refere		511
CHAI	PTER 10 THE NONLINEAR VLASOV THEORY OF PLASMA WAVES	
	AND INSTABILITIES	512
10.1	The Need for a Nonlinear Theory of Plasmas	512

10.4 10.5 10.6 10.7 10.8	Conservat Landau D The Gent Quasilinea Electron 7 Plasma W Nonlinear	ar Equations for Changes in a Plasma Distribution tion of Particles, Momentum, and Energy in Quasilinear Theory Damping in Quasilinear Theory le-bump Instability in Quasilinear Theory ar Theory of the Two-stream Instability Trapping in a Single Plasma Wave Yave Echoes Wave-particle Interactions (Weak Turbulence)	514 518 520 527 532 536 539 549 554
СНАР	TER 11	FLUCTUATIONS, CORRELATIONS, AND RADIATION	556
11.5 11.6 11.7 11.8 11.9	Electric F Electric F Drag on a Electroma Scattering Emission Blackbody Cyclotrom Test Sour Kinetic E	of a Moving Test Charge ield Fluctuations in a Plasma ield Fluctuations in a Nonmaxwellian Plasma a Test Particle; Emission of Electrostatic Waves genetic Fluctuations and Radiation of Incoherent Radiation from a Plasma Density Fluctuations of Radiation from a Plasma; Kirchhoff's Law y Radiation from and in a Plasma (Synchrotron) Radiation from a Plasma in a Magnetic Field ce Theory of Radiation from a Plasma quations Including Collisional Relaxation of a Plasma	557 563 568 570 573 575 588 590 592 595 599 605
5		PARTICLE MOTION	607
		ations of Motion	
I.1 I.2 I.3 I.4 I.5	Particle M Particle M Particle M Small-am	Action in Static Homogeneous Electric and Magnetic Fields Action in Slowly Varying Homogeneous Electric and Magnetic Fields Action in a Static Homogeneous Magnetic Field and a Rapidly Varying, plitude, Electric Field $[\mathbf{B}_0 \neq 0, \mathbf{E}(t) \neq 0]$ Motion in a Homogeneous Large-amplitude Plane Electromagnetic	608 608 613 615
	Adiabatic	Aotion in Static Inhomogeneous Magnetic Fields Invariants roperties from Orbit Theory	618 621 627 628
Referen	nces		630
	NDIX II	SUMMARY OF SOME PROPERTIES OF VECTORS AND TENSORS, SOME INTEGRAL THEOREMS, AND CURVILINEAR COORDINATES	631
APPEN	NDIX III	SYSTEMS OF UNITS, CONVERSION FACTORS, AND FREQUENTLY USED SYMBOLS	644
III.1 III.2 III.3		of Units on Factors and Physical Constants y used Symbols	644 647 647
APPEN	NDIX IV	SELECTED ADDITIONAL READINGS FOR THE ADVANCED STUDENT	654
IV.1 IV.2 IV.3 IV.4	Transport	hock Waves	654 655 655 656

X CONTENTS

IV.5	Computer Techniques in Plasma Physics	656
1V.6	Normal Modes of a Plasma and Landau Damping	657
IV.7	Plasma Equilibrium	657
IV.8	Plasma Oscillations and Stability	658
IV.9	Solid State Plasmas	659
IV.10	Applications of Plasma Physics to Space Physics	659
Name Index		661
Subject Index		666