I have been teaching Introductory Plasma Physics to senior undergraduates and beginning graduate students for many years, and I find the level of the presentation of material, the order that the topics are presented, and the overall length of the book to be an excellent match for my needs in a textbook.

David Hammer, Cornell University

The authors have done an excellent job in introducing the vast scope of plasma physics for basic plasma physics courses. The schematic illustrations and flow charts used are especially helpful in understanding the complexities involved in the hierarchal nature of plasmas. Mathematics is kept at just the right level for the intended readers and the descriptions of the physical processes are clear. Although this book is targeted to advanced undergraduate or beginning graduate students, it will be a good addition to the personal library of every plasma physicist.

Gurudas Ganguli, Naval Research Laboratory

This new book provides an excellent summary of the basic processes occurring in plasmas together with a comprehensive introduction to the mathematical formulation of fluid (MHD) and kinetic theory. It provides an excellent introduction to the subject suitable for senior undergraduate students or entry-level graduate students.

Richard M. Thorne, University of California at Los Angeles

## **Contents**

	Preface	page xii
1	Introduction	j
1.1	Speed, energy, and temperature	5
	Quasi-neutrality and plasma oscillations	10
	Debye shielding	13
	Example 1-1 Debye length and plasma frequency	1:
1.4	Problems	18
	References	19
2	Single-particle motion	20
2.1	Motion in a uniform B field: gyration	2
2.2	$\mathbf{E} \times \mathbf{B}$ drift	20
	Example 2-1 Hall thruster	28
2.3	Particle motion in non-uniform B fields	30
2.3.1	Gradient drift	3
2.3.2	Curvature drift	33
2.3.3	Other gradients of <b>B</b>	30
2.4	Adiabatic invariance of the magnetic moment	3′
	Example 2-2 Plasma confinement using magnetic mirrors	40
2.5	Particle motion in time-varying electric fields	42
2.5.1	Polarization drift: slowly varying E field	42
2.5.2	Particle motion in static <b>B</b> and arbitrary <b>E</b> fields	44
	Example 2-3 Cyclotron resonance	47
2.6	Summary	48
2.7	Problems	49
	References	52

vii

viii Contents

3	Kinetic theory of plasmas	<b>53</b>
3.1	Introduction	53
3.2	Comparison of properties of gases and plasmas	55
3.3	Velocity distribution function	57
	Example 3-1 Phase-space distribution function	59
3.4	The Boltzmann equation	60
3.5	The Maxwell–Boltzmann distribution	64
3.5.1	Number density	66
	Temperature	67
	Velocity in one dimension and speed	68
3.5.4	Degree of ionization: the Saha equation	71
	Example 3-2 Ionization fraction of air	72
3.5.5	Shifted Maxwellian distribution	73
	The Vlasov equation	73
	The convective derivative in physical space and in phase space	75
3.7	Equivalence of the particle equations of motion and the	
	Vlasov equation	77
	Summary	80
3.9	Problems	81
	References	83
4	Moments of the Boltzmann equation	84
4.1	Introduction	84
	The zeroth-order moment: continuity equation	86
4.2.1	Closer consideration of collisions and conservation of particles	88
	Example 4-1 Electron density in the ionosphere: day	
	versus night	89
	The first-order moment: momentum transport equation	90
4.3.1	The pressure and collision terms	95
	Example 4-2 Fluorescent lamp	97
	The second-order moment: energy transport equation	99
4.5	Systems of macroscopic equations: cold- and warm-plasma	
	models	100
	The cold-plasma model	102
	The warm-plasma model	102
	Summary	103
4.7	Problems	104
	References	105
	and the first of t	
	Multiple-fluid theory of plasmas	106
	Introduction	106
5.2	Complete set of two-fluid equations	107
	Example 5-1 Plasma discharge for IC manufacture	108

Contents

5.3	Fluid drifts perpendicular to B	110
	Parallel pressure balance	113
	Summary	114
5.6	Problems	114
	Reference	115
6	Single-fluid theory of plasmas: magnetohydrodynamics	116
6.1	Introduction	116
6.2	Single-fluid equations for a fully ionized plasma	117
	Equations of mass and charge conservation	119
6.2.2	Equation of motion	119
6.2.3	Generalized Ohm's law	120
6.3	Magnetohydrodynamics plasma model	123
6.4	Simplified MHD equations	124
6.4.1	Frozen-in magnetic flux lines	128
	Example 6-1 The solar wind	131
6.4.2	Diffusion of magnetic field lines	132
6.5	Force balance in MHD	132
6.5.1	Magnetic forces	134
	Magnetohydrostatics	138
	The $\theta$ -pinch	139
6.6.2	The cylindrical pinch	141
	Example 6-2 Tokamak	142
	Collisionless plasmas with strong magnetic field	144
	Mirror equilibrium	146
	Summary	148
6.9	Problems	149
	References	150
7	Collisions and plasma conductivity	152
	Introduction	152
	Collisions	154
	Weakly ionized plasmas	154
	Fully ionized plasmas: Coulomb collisions	155
	Specific resistivity	157
	Plasma conductivity	159
	DC conductivity	159
	Example 7-1 Ionospheric heating	162
7.3.2	AC conductivity	163
	Conductivity with ion motion	164
	Summary	165
	Problems	165
	Reference	166

x Contents

8	Plasma diffusion	167
8.1	Introduction	167
8.2	Diffusion in weakly ionized plasmas	170
8.2.1	Ambipolar diffusion in an unmagnetized plasma	170
8.2.2	Free diffusion across a magnetic field	172
8.3	Diffusion in fully ionized plasmas	174
8.4	Summary	175
8.5	Problems	176
9	Introduction to waves in plasmas	178
9.1	Introduction	178
9.2	General properties of small-amplitude waves	180
	Waves in non-magnetized plasmas	183
9.3.1	Plasma oscillations	183
9.3.2	Transverse electromagnetic waves	184
9.3.3	Electrostatic electron and ion waves	189
9.4	Problems	190
10	Waves in cold magnetized plasmas	192
	Introduction	192
	The dispersion relation	193
	Waves in magnetized plasmas	195
	Principal modes	198
	Oblique propagation at an arbitrary angle $\theta$	205
	Summary	207
	Problems	207
	References	209
11	Effects of collisions, ions, and finite temperature on waves	
	in magnetized plasmas	210
11.1	Introduction	210
11.2	Effects of collisions	210
11.3	Effects of positive ions	211
11.3.1	Parallel propagation ( $\theta = 0$ )	212
	Perpendicular propagation ( $\theta = \pi/2$ )	215
11.3.3	Oblique propagation (arbitrary $\theta$ )	216
	Hydromagnetic (MHD) waves	216
	Effects of temperature	220
	Parallel propagation ( $\theta = 0$ )	220
11.4.2	Perpendicular propagation $(\theta = \pi/2)$	222
11.5	Summary	223
11.6	Problems	223

Contents xi

12	Waves in hot plasmas	225
12.1	Introduction	225
12.2	Waves in a hot isotropic plasma	226
12.2.1	Longitudinal waves (k    E)	228
12.2.2	Transverse waves	235
12.2.3	The two-stream instability	239
12.3	Waves in a hot magnetized plasma	240
12.4	More on collisions in plasmas	244
12.4.1	The Krook collision model	246
12.5	Summary	248
12.6	Problems	249
	References	250
13	The plasma sheath and the Langmuir probe	251
	Introduction	251
13.2	Particle flux	251
13.3	Sheath characteristics	252
13.4	The Langmuir probe	257
	Problems	259
Appendix A	Derivation of the second moment of the Boltzmann equation	261
Appendix B	Useful vector relations	263
B.1	<b>Definitions and identities</b>	263
<b>B.2</b>	Relations in Cartesian coordinates	264
<b>B.3</b>	Relations in cylindrical coordinates	264
<b>B.4</b>	Relations in spherical coordinates	265
	Index	267