

Contents

LIST OF CONTRIBUTORS	v	
PREFACE	vii	
ACKNOWLEDGEMENTS	ix	
SECTION I		
INTRODUCTION		
CHAPTER 1	OVERVIEW AND SURVEY OF PLASMA PHYSICS - B.J. GREEN	3
1.1	History of Plasma Physics	3
1.2	Plasma Description	6
1.3	Plasma Properties	9
1.3.1	Radiation	9
1.3.2	Waves	10
1.3.3	Transport Theory	12
1.3.4	Macro- and Micro-instabilities	15
1.3.5	Turbulence	16
1.3.6	Computation of Plasma Behaviour	17
1.4	Particular Plasmas	17
1.4.1	Solid-state Plasma	18
1.4.2	Laser-Produced Plasma	19
1.4.3	MHD Power Generators	19
1.4.4	Sheaths	20
1.4.5	Astrophysical Plasmas	20
1.4.6	Charged Particle Beams	25
1.4.7	Plasmas of Interest for Nuclear Fusion	26
1.5	Conclusions	31
	References	32
CHAPTER 2	NUCLEAR FUSION RESEARCH - J. HUGILL	33
2.1	Motivation for Fusion Research	33
2.2	Nuclear Physics of Fusion	34
2.3	The Containment Problem	36
2.4	Magnetic Containment	38
2.5	Reactor Problems	40
2.6	Conclusions	40
	References and Additional References	41
CHAPTER 3	INTRODUCTION TO PLASMA PHYSICS - R.J. HASTIE	43
3.1	Introduction	43
3.2	Debye Screening and Neutrality	44
3.3	Coulomb Scattering	45
3.4	Plasma Conductivity	46
3.4.1	Weakly Ionized Plasma	46
3.4.2	Fully Ionized Plasma	46
3.5	Electron Runaway	47
3.6	High Frequency Response of Plasma	47
3.7	Electromagnetic Wave Propagation in a Plasma	48
3.8	Magnetic Properties	49
3.9	Equilibrium in a Magnetic Field	50
3.10	Diffusion across a Magnetic Field	51
3.11	Waves	53
	References and General References	53

SECTION II
THEORY

CHAPTER 4	MAGNETOHYDRODYNAMICS - J.J. FIELD	57
4.1	Introduction	57
4.2	The Electrodynamics of Deformable Media	58
4.3	Some Consequences of the Electrodynamical Equations	60
4.4	Fluid Equations	62
4.5	Boundary Conditions	64
4.6	Magnetostatic Equations and MHD Equilibria	65
	References	69
CHAPTER 5	PARTICLE ORBIT THEORY - R.J. HASTIE	71
5.1	Introduction	71
5.2	Motion in Constant Uniform Fields	72
5.2.1	Electric Field Only	72
5.2.2	Magnetic Field Only	72
5.2.3	Electric and Magnetic Field	74
5.2.4	Motion in a General Force Field	75
5.3	Inhomogeneous and Time Varying Fields	75
5.3.1	Time-Varying Electric Field	75
5.3.2	Time-Varying Magnetic Field: Constancy of Magnetic Moment	76
5.3.3	Space-Varying Magnetic Field	77
5.3.4	Summary	80
5.4	Adiabatic Invariants	82
5.4.1	Consequences of Non-Adiabatic Behaviour	84
5.4.2	Superadiabaticity	85
5.4.3	Invariant Series: The Higher Order Corrections	86
5.4.4	Importance of the Longitudinal Invariant J	89
5.4.5	The Flux Invariant Φ	89
	References	90
CHAPTER 6	PLASMA WAVES - J.P. DOUGHERTY	91
6.1	Introduction	91
6.2	Equations of Motion	91
6.3	Waves in an Unmagnetized Plasma	94
6.3.1	Plasma Oscillations	94
6.3.2	Transverse Waves	95
6.3.3	Effect of Pressure	98
6.4	Waves in a Cold Magnetized Plasma	99
6.4.1	The Dielectric Tensor	99
6.4.2	The Dispersion Relation	101
6.4.3	Propagation Parallel to the Magnetic Field	102
6.4.4	Propagation Perpendicular to the Magnetic Field	105
6.4.5	General Propagation	106
6.4.6	Polar Plots and the CMA Diagram	109
6.5	Magnetosonic Waves	112
6.5.1	Effect of Pressure	112
6.5.2	Waves at Low Frequency	113
6.6	Waves on Plasma Streams	114
6.6.1	The Dispersion Relation	114
6.6.2	The Two Stream Instability	116
	References	117

CHAPTER 7	KINETIC THEORY - J.J. SANDERSON	119
7.1	Introduction	119
7.2	Equations for the Distribution Functions	120
7.3	Near-Equilibrium Plasma	125
7.4	Vlasov Equation	126
7.5	Collisional Kinetic Equations	127
7.6	Fokker-Planck Equation	130
7.7	Relaxation Times	135
7.8	Landau Damping	140
7.9	Ion Acoustic Instability	147
7.10	The Bernstein Modes	149
	References	153
CHAPTER 8	TRANSPORT THEORY - E.W. LAING	155
8.1	General Information	155
8.2	Continuum Equations for a Two-Fluid Plasma	157
8.3	Qualitative Derivation of Transport Coefficients	160
8.3.1	Frictional Force R_u	161
8.3.2	Thermal Force R_T	161
8.3.3	Electron Heat Flux q_u^e	163
8.3.4	Heat Generation	163
8.3.5	Viscosity	164
8.4	Derivation of Transport Coefficients from Kinetic Theory	166
8.4.1	Solution of Kinetic Equations	167
8.4.2	The Transport Coefficients	168
8.5	The Onsager Principle	170
8.6	Single-Fluid Model	171
8.7	Transport Theory for Toroidal Systems	173
8.7.1	Collisional Diffusion (Pfirsch-Schlüter Regime)	174
8.7.2	Banana Regime	176
8.7.3	Scaling Laws	178
8.8	Drift Kinetic Equations	179
8.9	Solution of the Drift Kinetic Equation	181
8.9.1	Banana Regime	183
8.9.2	Plateau Regime	184
8.9.3	Collisional Regime	184
8.10	Experimental Tests of Transport Theory	185
8.10.1	Thetatron (Culham Theta-Pinch)	185
8.10.2	Tokamaks	187
8.10.3	Stellarators	187
	References	189
CHAPTER 9	MHD STABILITY THEORY - J.A. WESSON	191
9.1	Introduction	191
9.2	Rayleigh-Taylor Instability	193
9.2.1	Physical Description	193
9.2.2	A Simple Energy Treatment	194
9.2.3	Governing Equations	194
9.2.4	Normal Mode Method	195
9.2.5	The Equilibrium	196
9.2.6	Perturbed Equilibrium	196
9.2.7	Linearization	197
9.2.8	Fourier Transformations	197
9.2.9	Rayleigh-Taylor Instability - Two Fluids	198
9.2.10	Equations of Ideal Magnetohydrodynamics for Incompressible Fluid	200
9.2.11	MHD Rayleigh-Taylor Instability - Governing Equation	201
9.2.12	MHD Rayleigh-Taylor Instability - Two Fluids	201
9.2.13	Variation of Angle Between \mathbf{k} and \mathbf{B}	202
9.2.15	Magnetic Shear	203

CHAPTER 9 (continued)	
9.3 Energy Principle	204
9.3.1 Energy in Rayleigh-Taylor Instability	204
9.3.2 General Equations of Ideal MHD	205
9.3.3 Equilibrium	205
9.3.4 Linearized MHD Equations	206
9.3.5 Potential Energy	207
9.4 Cylindrical Pinch	208
9.4.1 Equilibrium	208
9.4.2 δW for the Cylindrical Pinch	208
9.4.3 A Sufficient Condition for Stability	209
9.4.4 Euler-Lagrange Equation for δW	210
9.4.5 Magnetic Shear and the Suydam Criterion	211
9.4.6 The General Cylindrical Case	213
9.5 Resistive Instabilities	216
9.5.1 Introduction	216
9.5.2 Resistive g -mode	219
9.5.3 Tearing Modes	220
9.6 Stability of Tokamaks	222
9.6.1 Introduction	222
9.6.2 Kink Modes	223
9.6.3 Ideal Internal Modes	226
9.6.4 Tearing Modes	227
9.7 Instabilities in Tokamaks	229
9.7.1 Mirnov Oscillations	229
9.7.2 Sawtooth Oscillations	230
9.7.3 Disruptive Instability	232
Bibliography	233
CHAPTER 10 PLASMA RADIATION - R.W.P. McWHIRTER	235
10.1 Introduction	235
10.2 Thermal Equilibria	237
10.2.1 The Concept of Temperature	237
10.2.2 Maxwellian Distribution of Particle Velocities	237
10.2.3 Saha-Boltzmann Population Distribution	238
10.2.4 Complete and Local Thermal Equilibria	239
10.2.5 The Principle of Detailed Balance	239
10.3 Ionization and Recombination Processes which Determine the State of Ionization of Impurities	239
10.3.1 Low Density Plasmas	239
10.3.2 Direct Ionization by Electron Impact	240
10.3.3 Excitation by Electron Impact	242
10.3.4 Radiative Recombination	243
10.3.5 Spontaneous Radiative Decay of an Excited Ion	244
10.3.6 Collisional-Radiative Recombination and Ionization	245
10.3.7 Dielectronic Recombination	249
10.3.8 Autoionization	251
10.4 The Steady-State Ionization Balance	252
10.5 Time-Dependent Ionization and Recombination	255
10.6 Excitation and Spectral Line Intensities	255
10.6.1 General Comments	255
10.6.2 Hydrogen and Hydrogen-Like Ions	256
10.6.3 Lithium-Like Ions	257
10.6.4 Beryllium-Like Ions	260
10.6.5 Helium-Like Ions	263
10.7 Radiation Trapping	268
10.8 The Radiated Power Loss for a Plasma in Steady-State Ionization Balance	269
References	275

	SECTION III	
	ADVANCED THEORY	277
CHAPTER 11	MICROINSTABILITIES - J.G. CORDEY	279
11.1	Introduction	279
11.2	The Drift Wave Dispersion Equation and a Physical Picture of a Drift Wave	281
11.2.1	Electron Energy Transport	282
11.2.2	Ion Energy Transport	283
11.2.3	Continuity Equation	283
11.2.4	Electron Momentum Balance along the Field Lines	283
11.2.5	The Ion Momentum Balance along the Field Lines	283
11.2.6	Quasi-Neutrality	284
11.2.7	Dispersion Equation	284
11.2.8	Physical Model	284
11.3	Dissipative Mechanisms giving Instability	286
11.3.1	Collisional Drift Instability	286
11.3.2	Collision-Free Drift Instability	286
11.3.3	Other Dissipative Mechanisms Giving Rise to Instability	288
11.4	Radial Localization and Stabilization by Shear	288
11.4.1	Weak Shear Case (ρ_{ci}/L) > (R_n/L_s)	290
11.4.2	Strong Shear Case (ρ_{ci}/L) < (R_n/L_s)	291
References		291
CHAPTER 12	PLASMA TURBULENCE - I. COOK	293
12.1	Introduction	293
12.2	Quasi-Linear Theory	297
12.3	Nonlinear Theories	299
12.3.1	Mode-Coupling Theories	299
12.3.2	Dupree-Type Theories	302
References		304
CHAPTER 13	ANOMALOUS TRANSPORT THEORY - T.E. STRINGER	305
13.1	Introduction	305
13.2	Quasilinear Theory	306
13.3	Upper Limit on the Wave Amplitude	308
13.4	Analytic Estimates of the Saturation Level	309
13.5	Physical Processes Described by Quasilinear Theory	311
13.6	Dupree-Type Theories	312
13.7	Effect of Magnetic Field Fluctuations	312
13.8	Comparison of Theory and Experiment	314
13.9	1-D Computations	315
13.10	Conclusions	317
References		318
CHAPTER 14	NONLINEAR LASER PLASMA INTERACTION THEORY - C.N. LASHMORE-DAVIES	319
14.1	Introduction	319
14.2	General Discussion of Parametric Instability	320
14.3	Qualitative Description of Parametric Instabilities in an Unmagnetised Plasma	322
14.3.1	The Parametric Decay Instability: $T=L+S$	322
14.3.2	The Two-Plasmon Decay Instability: $T=L_1+L_2$	323
14.3.3	Stimulated Brillouin Scattering: $T=T'+S$	325
14.3.4	Stimulated Raman Scattering: $T=T'+L$	325
14.4	Quantitative Description of Parametric Instabilities	326
14.5	Inhomogeneous Plasma	333
14.6	Modulational Instabilities and Four Wave Interactions	335
14.7	Filamentation	342

CHAPTER 14 (continued)		
14.8 The Langmuir Modulation Instability and Langmuir Turbulence		346
14.9 Resonance Absorption		349
14.10 Conclusion		353
References		353
Additional General References		354
SECTION IV		
EXPERIMENTAL DEVICES		
CHAPTER 15 PINCH AND TOKAMAK CONFINEMENT DEVICES - D.C. ROBINSON		357
15.1 Introduction		357
15.2 Magnetic Confinement		358
15.3 Toroidal Confinement Systems		358
15.4 Stability		362
15.5 Technology of Toroidal Confinement Systems		365
15.6 Progress in Tokamak Experiments		369
15.7 Additional Heating		373
15.8 Plasma Fuelling		376
15.9 Impurity Control		376
15.10 Screw Pinches and Belt Pinches		377
15.11 Reverse Field Pinches		378
15.12 Future Devices		380
15.13 Conclusions		381
References		382
CHAPTER 16 STELLARATOR CONFINEMENT DEVICES - D.J. LEES		385
16.1 Basic Background		385
16.2 Magnetic Topology		386
16.3 Stellarator Equilibrium		388
16.4 Stellarator Stability		389
16.5 Experiments — Historical		389
16.6 Experiments — Recent Results		392
16.7 Other Forms of Plasma Production and Heating		394
16.7.1 Wave Heating		394
16.7.2 Neutral Injection		395
16.7.3 Laser-Pellet Interactions		396
16.8 Reactor Possibilities		396
16.9 Conclusions		397
References		398
CHAPTER 17 MIRROR DEVICES - G. ROWLANDS		401
17.1 Introduction		401
17.2 Mirror Confinement		402
17.3 Mirror Instabilities and Minimum B		404
17.4 Micro-Instabilities		406
17.5 Classical Diffusion Losses		408
17.6 The Tandem Concept		409
17.7 On the Possibility of a Mirror Reactor		411
17.8 Further Reading		412
References		413
CHAPTER 18 THE NEXT GENERATION TOKAMAKS - B.J. GREEN		415
18.1 Introduction		415
18.2 The Status of Tokamak Research		417
18.3 Tokamak Subsystems — Design Considerations		421
18.3.1 Toroidal Field (TF) Coil System		421
18.3.2 The Poloidal Field (PF) System		422
18.3.3 The Vacuum Vessel		425

CHAPTER 18.3 (continued)		
18.3.4 The Additional Heating System		424
18.3.5 The Power Supply System		424
18.3.6 The Control, Monitoring and Data Acquisition System		424
18.3.7 Diagnostics		425
18.3.8 The Plasma		426
18.4 The Next Generation		428
Reference		431
CHAPTER 19 FUSION REACTOR STUDIES - R. HANCOX		433
19.1 Introduction		433
19.2 Types of Reactor Studies		433
19.3 The Objectives of Reactor Studies		435
19.4 Description of Reactor Designs		436
19.4.1 The Culham Tokamak Reactor		436
19.4.2 The Reversed Field Pinch Reactor		440
19.4.3 The Saturn Laser-Fusion Reactor		442
19.5 Assessments of Fusion Reactors		445
19.5.1 Economic Assessments		445
19.5.2 Safety and Environmental Assessments		447
19.6 Conclusion		450
References		451
SECTION V		
HEATING AND DIAGNOSTICS		
CHAPTER 20 NEUTRAL INJECTION PLASMA HEATING - R.S. HEMSWORTH		455
20.1 Introduction		455
20.2 Neutral Injection Heating		455
20.2.1 Ionization		455
20.2.2 Containment		458
20.2.3 Energy Transfer to the Plasma		460
20.2.4 Losses		460
20.3 The Neutral Injection System		461
20.3.1 Ion Generation		462
20.3.2 Ion Extraction		464
20.3.3 Neutralization		467
20.3.4 Pumping and Dumping		470
20.3.5 Beam Losses		470
20.3.6 Real Injection Systems		471
20.4 Results		473
20.5 Summary and Conclusions		473
References		475
CHAPTER 21 THE THEORY OF RADIO FREQUENCY PLASMA HEATING - P.J. FIELDING		477
21.1 Introduction		477
21.2 Non-Oscillatory and Low-Frequency Schemes		477
21.3 High-Frequency Waves — Propagation and Absorption		479
21.3.1 Geometrical Optics		479
21.3.2 Dielectric Properties of a Hot Plasma		480
21.3.3 Wave Propagation		483
21.4 Specific Heating Schemes		485
21.4.1 Electron Cyclotron Resonance Heating (ECRH)		485
21.4.2 Lower Hybrid Resonance Heating (LHRH)		491
21.4.3 Ion Cyclotron Resonance Heating		493
21.5 Conclusions		497
References		498

SECTION V (continued)

CHAPTER 22	RADIO FREQUENCY PLASMA HEATING EXPERIMENTS - A.C. RIVIERE	501
22.1	Introduction	501
22.1.1	Limits of Confinement of Energetic Ions	502
22.1.2	Plasma Power Balance	503
22.2	Transit Time Magnetic Pumping	503
22.2.1	The Method	503
22.2.2	Experimental Evidence for TTMP Heating	505
22.3	Heating in the Ion Cyclotron Range of Frequencies	508
22.3.1	The Method	508
22.3.2	The Existence of Toroidal Eigenmodes	508
22.3.3	Observation of Toroidal Eigenmodes	509
22.3.4	Strong Damping with Cyclotron Resonances in the Plasma	511
22.3.5	Results from Heating Experiments	511
22.3.6	The Future	515
22.4	Lower Hybrid Resonance Heating	516
22.4.1	The Method	516
22.4.2	Coupling with the Phased Waveguide Array or Grill	517
22.4.3	Ion and Electron Heating	519
22.4.4	Parametric Instabilities	523
22.4.5	Summary of Lower Hybrid Heating	524
22.5	Electron Cyclotron Resonance Heating	525
22.5.1	The Method	525
22.5.2	The Gyrotron Microwave Generator	526
22.5.3	Low Power Propagation Experiments	527
22.5.4	Results on Electron Heating by ECRH	529
22.6	RF Current Drive	532
22.7	Conclusions	532
	References	533
CHAPTER 23	PLASMA DIAGNOSTICS USING LASERS - G. MAGYAR	535
23.1	Introduction	535
23.2	Laser Interferometry for Electron Density Measurements	536
23.3	Thomson Scattering for Electron Temperature, Density and Ion Temperature Measurements	540
23.3.1	General Principles	540
23.3.2	Experimental Considerations	546
	References	550
CHAPTER 24	X-RAY AND PARTICLE DIAGNOSTICS - R.D. GILL	551
24.1	X-ray Continuum Measurements	551
24.2	X-ray Pinhole Techniques	555
24.2.1	The Two Foil Method	555
24.2.2	The Pinhole Method	556
24.3	Runaway Electrons	560
24.4	Neutron Diagnostic Methods	562
24.5	Ion Temperature Measurements using Charge-Exchange	564
	References	567
	Additional General References	568

SECTION VI

FURTHER TOPICS

CHAPTER 25	INERTIAL CONFINEMENT - G.J. PERT	571
25.1	Fusion in Inertially Confined Plasmas	571
25.2	Hydrodynamic Compression	573
25.3	Degeneracy	580
25.4	Rayleigh-Taylor Instability	580

CHAPTER 25 (continued)

25.5	Ablation Pressure	582
25.6	Ablation Driving Mechanisms	584
25.6.1	Lasers	584
25.6.2	Electron Beams	585
25.6.3	Ion Beams	585
25.7	Laser Compression	585
25.8	Spheres and Shells	587
25.9	Laser-Plasma Coupling	587
25.10	Profile Modification	588
25.11	Flux Limitation	589
25.11.1	Ion Acceleration	590
25.11.2	Reduction of the Ablation Pressure	591
25.11.3	Core Pre-Heat	591
25.12	Effects of Rayleigh-Taylor Instability	591
25.13	Laser Fusion-Efficiency Considerations	592
25.14	Exploding Pusher Targets	593
25.15	Ablative Compression	595
25.16	Laser Considerations	596
	References	597
CHAPTER 26	CHARGED PARTICLE BEAMS - J.D. LAWSON	599
26.1	Introduction	599
26.2	Charged Particle Optics	600
26.3	The Emittance Concept	603
26.4	The Effect of Self-Fields	605
26.5	Classes of Beam Behaviour	606
26.6	Waves on Beams, Introductory Remarks	607
26.7	Streaming Plasma	608
26.8	Two or More Streaming Plasmas	611
26.9	Beams of Finite Cross Section	613
26.10	The Effect of Arbitrary Wall Impedance	615
26.11	Landau Damping	616
26.12	Coupled Modes	616
26.13	Conclusions	617
	References	618
CHAPTER 27	ASTROPHYSICAL PLASMAS - R.J. TAYLER	619
27.1	Introduction	619
27.2	Double Extragalactic Radiosources	625
27.3	Pulsars	630
27.4	Magnetic Fields in Stars	634
27.5	The Solar Plasma	637
27.6	Conclusion	640
	References	640
CHAPTER 28	COMPUTATIONAL PLASMA PHYSICS - D. POTTER	643
28.1	Introductory Ideas on Computer Simulations	643
28.1.1	The Concept of Simulation	643
28.1.2	Some Properties of the Equations of Plasma Physics	645
28.1.3	Boundary-Value Problems	647
28.1.4	Initial-Value Problems	648
28.1.5	Numerical Stability	649
28.2	Equilibria and Transport	650
28.2.1	Equilibria as an 'Elliptic Problem'	650
28.2.2	The Convergence of Equilibrium Solutions	654
28.2.3	Diffusion Losses from Magnetic Containment	657
28.3	Dynamics of a Magnetized Fluid	660
28.3.1	Flow	660
28.3.2	The Eulerian Simulation of MHD	662
28.3.3	Lagrangian and Hybrid Methods in MHD	667

CHAPTER 28 (continued)	
28.4 Particle Methods and Phase Space	669
28.4.1 The Particle-In-Cell Method	669
28.4.2 Waterbag Methods	675
28.5 Discussion	676
References	679
DEFINITIONS	681
UNITS	683
INDEX	685