

Contents

1	Nature of Plasma	1
1.1	Introduction	1
1.2	Charge Neutrality and Landau Damping	3
1.3	Fusion Core Plasma	5
	References	9
2	Orbit of Charged Particles in Various Magnetic Configuration . . .	11
2.1	Orbit of Charged Particles	11
2.1.1	Cyclotron Motion	11
2.1.2	Drift Velocity of Guiding Center	12
2.1.3	Polarization Drift	16
2.1.4	Pondromotive Force	17
2.2	Scalar Potential and Vector Potential	19
2.3	Magnetic Mirror	21
2.4	Toroidal System	23
2.4.1	Magnetic Flux Function	23
2.4.2	Hamiltonian Equation of Motion	24
2.4.3	Particle Orbit in Axially Symmetric System	27
2.4.4	Drift of Guiding Center in Toroidal Field	28
2.4.5	Effect of Longitudinal Electric Field on Banana Orbit	32
2.4.6	Precession of Trapped Particle	33
2.4.7	Orbit of Guiding Center and Magnetic Surface	38
2.5	Coulomb Collision and Neutral Beam Injection	40
2.5.1	Coulomb Collision	40
2.5.2	Neutral Beam Injection	45
2.5.3	Resistivity, Runaway Electron, Dreicer Field	46
2.6	Variety of Time and Space Scales in Plasmas	47
	References	49

3	Magnetohydrodynamics	51
3.1	Magnetohydrodynamic Equations for Two Fluids	51
3.2	Magnetohydrodynamic Equations for One Fluid	54
3.3	Simplified Magnetohydrodynamic Equations	56
3.4	Magnetoacoustic Wave	59
4	Equilibrium	63
4.1	Pressure Equilibrium	63
4.2	Grad–Shafranov Equilibrium Equation	65
4.3	Exact Solution of Grad–Shafranov Equation	67
4.4	Tokamak Equilibrium	70
4.5	Upper Limit of Beta Ratio	77
4.6	Pfirsch Schluter Current	78
4.7	Virial Theorem	81
	References	83
5	Confinement of Plasma (Ideal Cases)	85
5.1	Collisional Diffusion (Classical Diffusion)	87
5.1.1	Magnetohydrodynamic Treatment	87
5.1.2	A Particle Model	90
5.2	Neoclassical Diffusion of Electrons in Tokamak	91
5.3	Bootstrap Current	93
	References	96
6	Magnetohydrodynamic Instabilities	97
6.1	Interchange Instabilities	98
6.1.1	Interchange Instability	98
6.1.2	Stability Criterion for Interchange Instability	102
6.2	Formulation of Magnetohydrodynamic Instabilities	105
6.2.1	Linearization of Magnetohydrodynamic Equations	105
6.2.2	Rayleigh–Taylor (Interchange) Instability	109
6.3	Instabilities of Cylindrical Plasma with Sharp Boundary	110
6.4	Energy Principle	115
6.5	Instabilities of Diffuse Boundary Configurations	118
6.5.1	Energy Integral of Plasma with Diffuse Boundary	118
6.5.2	Suydam’s Criterion	123
6.5.3	Tokamak Configuration	124
6.6	Hain Lust Magnetohydrodynamic Equation	126
6.7	Ballooning Instability	128
6.8	η_i Mode Due to Density and Temperature Gradient	133
	References	135
7	Resistive Instabilities	137
7.1	Tearing Instability	138
7.2	Neoclassical Tearing Mode	144
7.3	Resistive Drift Instability	151

7.4	Resistive Wall Mode	155
	References	160
8	Boltzmann's Equation	163
8.1	Phase Space and Distribution Function	163
8.2	Boltzmann's Equation and Vlasov's Equation	164
8.3	Fokker-Planck Collision Term	167
8.4	Quasi Linear Theory of Evolution in Distribution Function	171
	References	173
9	Waves in Cold Plasmas	175
9.1	Dispersion Equation of Waves in Cold Plasma	176
9.2	Properties of Waves	180
9.2.1	Polarization and Particle Motion	180
9.2.2	Cutoff and Resonance	181
9.3	Waves in Two Components Plasma	182
9.4	Various Waves	185
9.4.1	Alfvén Wave	185
9.4.2	Ion Cyclotron Wave and Fast Wave	188
9.4.3	Lower Hybrid Resonance	189
9.4.4	Upper Hybrid Resonance	191
9.4.5	Electron Cyclotron Wave (Whistler Wave)	191
9.5	Conditions for Electrostatic Waves	193
	References	194
10	Waves in Hot Plasmas	195
10.1	Landau Damping and Cyclotron Damping	195
10.1.1	Landau Damping (Amplification)	195
10.1.2	Transit-Time Damping	199
10.1.3	Cyclotron Damping	200
10.2	Formulation of Dispersion Relation in Hot Plasma	202
10.3	Solution of Linearized Vlasov Equation	205
10.4	Dielectric Tensor of Hot Plasma	207
10.5	Dielectric Tensor of bi-Maxwellian Plasma	210
10.6	Plasma Dispersion Function	212
10.7	Dispersion Relation of Electrostatic Wave	215
10.8	Dispersion Relation of Electrostatic Wave in Inhomogeneous Plasma	217
10.9	Velocity Space Instabilities	222
10.9.1	Drift Instability (Collisionless)	222
10.9.2	Ion Temperature Gradient Instability	223
10.9.3	Various Velocity Space Instabilities	223
	References	223

11	Wave Heatings and Non-Inductive Current Drives	225
11.1	Energy Flow	226
11.2	Ray Tracing	230
11.3	Dielectric Tensor of Hot Plasma, Wave Absorption	232
11.4	Wave Heating in Ion Cyclotron Range of Frequency	237
11.5	Lower Hybrid Wave Heating	241
11.6	Electron Cyclotron Heating	244
11.7	Lower Hybrid Current Drive	247
11.8	Electron Cyclotron Current Drive	252
11.9	Neutral Beam Current Drive	254
	References	258
12	Instabilities Driven by Energetic Particles	259
12.1	Fishbone Instability	259
12.1.1	Formulation	259
12.1.2	MHD Potential Energy	260
12.1.3	Kinetic Integral of Hot Component	263
12.1.4	Growth Rate of Fishbone Instability	266
12.2	Toroidal Alfvén Eigenmode	269
12.2.1	Toroidicity Induced Alfvén Eigenmode	269
12.2.2	Instability of TAE Driven by Energetic Particles	274
12.2.3	Various Alfvén Modes	282
	References	283
13	Plasma Transport by Turbulence	285
13.1	Fluctuation Loss, Bohm, GyroBohm Diffusion	285
13.2	Loss by Magnetic Fluctuation	291
13.3	Dimensional Analysis of Transport	292
13.4	Analysis by Computer Simulations	298
13.4.1	Gyrokinetic Particle Model	299
13.4.2	Full Orbit Particle Model	303
13.5	Zonal Flow	307
13.5.1	Hasegawa–Mima Equation for Drift Turbulence	307
13.5.2	Generation of Zonal Flow	316
13.5.3	Geodesic Acoustic Mode (GAM)	320
13.5.4	Zonal Flow in ETG Turbulence	322
	References	324
14	Development of Fusion Researches	327
	References	335
15	Tokamak	337
15.1	Tokamak Devices	337
15.2	Stability of Equilibrium Plasma Position	341
15.3	MHD Stability and Density Limit	346
15.4	Beta Limit of Elongated Plasma	348

15.5	Impurity Control, Scrape-Off Layer and Divertor	351
15.6	Confinement Scaling of L Mode	357
15.7	H Mode and Improved Confinement Modes	359
15.8	Steady-State Operation	367
15.9	Design of ITER (International Tokamak Experimental Reactor)	370
15.10	Trials to Innovative Tokamaks	382
15.10.1	Spherical Tokamak	382
15.10.2	Trials to Innovative Tokamak Reactors	384
	References	385
16	Reversed Field Pinch	389
16.1	Reversed Field Pinch Configuration	389
16.2	Taylor's Relaxation Theory	390
16.3	Relaxation Process	393
16.4	Confinement of RFP	397
	References	401
17	Stellarator	403
17.1	Helical Field	403
17.2	Stellarator Devices	407
17.3	Neoclassical Diffusion in Helical Field	410
17.4	Confinement of Stellarator	414
17.5	Quasi-symmetric Stellarator System	417
17.6	Conceptual Design of Stellarator Reactor	420
	References	421
18	Open End System	423
18.1	Confinement Times in Mirror and Cusp	423
18.2	Confinement Experiments with Mirrors	425
18.3	Instabilities in Mirror Systems	426
18.4	Tandem Mirrors	429
18.4.1	Theory	429
18.4.2	Experiments	432
	References	437
19	Inertial Confinement	439
19.1	Pellet Gain	439
19.2	Implosion	444
19.3	MHD Instabilities	448
19.4	Fast Ignition	450
	References	453

Appendix A: Derivation of MHD Equations of Motion	455
Appendix B: Energy Integral of Axisymmetric Toroidal System	461
Appendix C: Quasi-Symmetric Stellarators	473
Appendix D: Physical Constants, Plasma Parameters and Mathematical Formula	483
Curriculum Vitae in Sentence of Kenro Miyamoto	489
Index	491