Contents

Pr	eface				v
Vo	olum	e 1: Cł	napte	ers 1–18	
1	Ioni	zed gase	es and	l plasmas—Historical overview, basic concepts,	
	and	applicat	tions		1
	Prea	\mathbf{mble}			1
	1.1	Introdu	uction		3
		1.1.1	Hist	orical perspective and development	4
	1.2	Ionized	l gases	and plasmas	8
		1.2.1	Plas	ma generation and occurrence	11
			(a)	Thermal ionization of a gas	12
			(b)	Impact and radiative ionization	14
			(c)	Plasmas not in TE	17
			(d)	Density and temperature of typical plasmas	18
	1.3	Plasma	a oscill	ations	20
		1.3.1	Qua	litative description	20
			(a)	Oscillations in an unbounded plasma	21
			(b)	Oscillations in a bounded plasma	22
			(c)	Nonlinear electron plasma oscillation in one-d	23
		1.3.2	Sma	ll-amplitude oscillations	24
	1.4	Charac	eteristi	c interaction lengths	27
		1.4.1	Lan	dau and Debye lengths	28
		1.4.2	Sim	ple models for Debye shielding	30
			(a)	Internal neutrality in a plasma	30
			(b)	Electron sheath at a plasma and vacuum boundary	32
		1.4.3	Posi	tional correlations in a plasma	33
			(a)	Analysis of Debye shielding and correlations	33
			(b)	Exact shielding distance; ion-ion correlations	36
			(c)	Kinetic and potential energies; the plasma parameter	37
	1.5	Collisio	onal in	teractions in a plasma	38
		1.5.1	Elec	tron-ion collisions	38
		1.5.2	Wea	kly-ionized gases and ionization degree	44
	1.6			ı of plasmas	50
	1.7	Plasma	as in n	nagnetic fields	53

		1.7.1	Dynamics in uniform \vec{B} fields	53
		1.7.2	Dynamics in slowly-varying, nonuniform \vec{B}_0	60
	1.8	Plasmas	and radiation	63
		1.8.1	Emission of radiation in low-density plasmas	63
		1.8.2	Photon-dense plasma interactions	65
	1.9	Equatio	ns describing collective dynamics	66
		1.9.1	The macroscopic, kinetic plasma equations	68
		1.9.2	Hydrodynamic model equations	70
			(a) Reduced hydrodynamic model equations	71
			(b) Classical collisional transport—Braginskii equations	75
			(c) The low-frequency and long-wavelength MHD model	
			equations	77
		D	(d) Reduced hydrodynamic models for high-frequencies	82
	1.10	•	the introductory chapters 1–4	83
	1.11	Problem		86
		P1-1	Velocity distributions and averages for a Maxwellian	86
		P1-2	Gaussian distributions	89 80
		P1-3 P1-4	Inter-charged-particle fields in a plasma	89 00
		P1-4 P1-5	Neutrality restoring fields and forces Simple derivation of the Saha Equation	90 90
		P1-5 P1-6	Oscillations in spatially bounded plasmas	90 91
		P1-7	Electron and ion density perturbations in plasma oscillations	91 91
		P1-8	Plasma sheaths and Langmuir probes	92
		P1-9	Debye shielding in a quasi-equilibrium electron-ion plasma	95
		P1-10	Characteristic quantities in some plasmas	95
		P1-11	Radiation from a gyrating charged particle in a uniform magnetic	00
			field	96
		P1-12	Pressure when f_s is a local Maxwellian	97
	1.12		ix: Plasmas in controlled fusion energy generation	98
		1.12.A	Controlled thermonuclear fusion	98
			(a) Fusion reactions of light nuclei	98
			(b) Controlled fusion reactors	98
			(c) Magnetic confinement	100
			(d) Inertial confinement	103
	Chapt	er 1. Bib	liography	106
2	Colle	ctive dv	namics in plasmas—I. Hydrodynamics and transport	109
-	Pream	• •		109
	2.1	Introdu	ction	110
	2.2		ynamic description	110
		2.2.1	Reduced hydrodynamics—validity constraints	111
		2.2.2	Conservative, reduced hydrodynamics near TE	115
	2.3		sipative hydrodynamics near TE—transport	120
		2.3.1	Transport in very weakly-ionized plasmas	123
			(a) Electrical conductivity	123
			(b) Particle diffusion	125

			(c) Thermal conductivity	100
			(d) Viscosity	$\frac{128}{129}$
		2.3.2	Elements of transport in fully-ionized plasmas	$\frac{129}{130}$
			(a) Unmagnetized plasma—Dominant transport coefficients	131
			(b) Collisional diffusion across a \vec{B}_0 -field	131
			(c) Uniformly magnetized plasma—Dominant transport	100
			coefficients	135
			(d) Toroidal (tokamak) confinement	$136 \\ 136$
		2.3.3	The Braginskii transport coefficients	$130 \\ 137$
			(a) Unmagnetized plasma $(\vec{B}_0 = 0)$	138
			(b) Strongly-magnetized plasma ($\omega_{cs}\tau_s \gg 1$)	142
			(c) Entropy balance equation	150
			(d) Classical diffusion in a strong-magnetic field	153
	2.4		is far from TE	156
		2.4.1	"Anomalous" transport	156
		2.4.2	Convective cells and Bohm diffusion	158
	2.5		ionless" collective modes	162
		2.5.1	MHD in high-temperature fully-ionized plasmas in MCF	162
		2.5.2	Mega-Gauss \vec{B} -field generated in intense laser-plasma	
	9.6	Deckl	interactions	170
	2.6	Probler P2-1		173
		P2-1 P2-2	The momentum density equation and the force density equation	173
		P <i>Z</i> -2	Conservation of ordered kinetic energy and internal heat kinetic	
		P2-3	energy Hudro demonstration (i.e. (i.e. the Mi	173
		г2-3 Р2-4	Hydrodynamic equations from the Vlasov equation	173
		P2-5	Electrical conductivity for very weakly-ionized plasmas in \vec{B}_0	174
		P2-6	Particle diffusion current density due to collisions Solution of the linear diffusion equation	174
		P2-7	Nonlinear diffusion equations	174
		P2-8	Ambipolarity of D_{\perp}	175
		P2-9	Electron conductivity and resistivity when $(\omega_{ce}\tau_e) \gg 1$	175
		P2-10	Viscosities and viscous force densities	175
		P2-11	Increasible heat generation due to viscosity, $Q_{\rm vis}^s$	176
		P2-12	Neglecting the viscous force density	$\frac{177}{177}$
		P2-13	Deriving the convective cell mode	177 177
		P2-14	Validation of single-fluid MHD models	178
	Chapt	ter 2. Bib	pliography	180
3				
J	Pream	able	namics in plasmas—II. Some basic fluid modes	181
	3.1	Introdu	ation	181
	3.2		gle-fluid MHD model	182
	0.4	3.2.1	Wave dynamics in ideal MHD	182
		J.4.1	(a) The Alfvén wave	185
			(a) The Anven wave (b) The sound wave in ideal ($\sigma = \infty$) MHD	186
			(c) The magnetoacoustic wave $(\sigma = \infty)$ MHD	190
			(~) Ino magnetoacoustic wave	191

	3.2.2	Nonlinear aspects of MHD waves	193
		(a) Nonlinear coupling of shear Alfvén and sound waves in ideal	
		MHD	194
3.3	The mu	ılti-fluid hydrodynamic model	198
	3.3.1	Cold, unmagnetized plasma and strongly magnetized electron	
		beam	199
		(a) Transverse EM (TEM) waves	201
		(b) ES electron plasma oscillations (EPO)	208
		(c) One-d electron beam waves $$	209
	3.3.2	Thermal pressure and ES waves in $B_0 = 0$	211
		(a) Electron plasma waves (EPW)	211
		(b) Ion-acoustic waves (IAW)	213
		(c) Collisional effects \dashv	215
	3.3.3	The cold, drift-free electron plasma in \vec{B}_0	218
		(a) Waves propagating parallel to \vec{B}_0	218
		(b) Waves propagating perpendicular to \vec{B}_0	224
		(c) Waves at any angle to \vec{B}_0	229
	3.3.4	Thermal pressure effects on waves in \vec{B}_0	233
		(a) The MHD regime	233
		(b) ES ion-cyclotron waves (ES-ICW)	235
		(c) ES upper-hybrid waves (ES-UHW)	237
	3.3.5	Bounded and inhomogeneous plasmas	238
		(a) Electron beam instabilities and devices	239
		(b) Resonances and plasma heating	240
		(c) The drift wave and drift wave instability	241
3.4	Probler		246
	P3-1	Finite conductivity damping of Alfvén waves	246
	P3-2	Linearization of the one-d (along \vec{B}_0) MHD equations	246
	P3-3	$(\vec{J} \times \vec{B})$ -force density in Frenet coordinates	247
	P3-4	Magnetoacoustic waves propagating perpendicular to $ec{B_0}$	249
	P3-5	Nonlinear, parametric coupling by a shear Alfvén wave pump	250
	P3-6	TEM waves in an electron-ion plasma	251
	P3-7	Plasma density measurements	251
	P3-8	Transparency of alkali metals	252
	P3-9	TEM plasma waves in the presence of collisions	252
	P3-10	Collisional absorption of laser power in a plasma	253
	P3-11	Laser-plasma heating	254
	P3-12	Collisional and collisionless skin depths	255
	P3-13	Small-amplitude one-d dynamics of an electron beam	256
	P3-14 D2 15	Electron plasma waves (EPW)	257
	P3-15 D2 16	Ion-acoustic waves (IAW)	257
	P3-16 D2 17	Fields in EPW and IAW	258
	P3-17	Electron plasma in <i>n</i> -type Silicon semiconductor	258
	P3-18 P3-19	Electron motion in a cyclotron resonance electric field	259 250
	г 9-19	Cyclotron resonance limited by collisions	259

.

 $\mathbf{5}$

		P3-20	Helicon wave in the presence of collisions	260
		P3-21	Faraday rotation in propagation parallel to \vec{B}_0	260
		P3-22	Use of O-mode in plasma density measurements	200
		P3-23	Transformation from Cartesian fields to rotating fields	261
		P3-24	Frequency at which the X-mode is circularly polarized	
		P3-25	MHD from two-fluid hydrodynamics	261
		P3-26		262
		P3-27	Quasi-neutrality in ES small-amplitude density perturbations	262
	Chan		Solving (3.254) by the method of characteristics bliography	263
	Unap	ter 5. Di	onography	264
ŀ	Colle	ective d	ynamics in plasmas—III. Collisionless kinetic effects	266
	Prear			266
	4.1	Introdu		267
	4.2	WPI in	unmagnetized, uniform plasmas	267
		4.2.1	Nonlinear aspects	269
		4.2.2	Linearized WPI—Landau dissipation	271
	4.3	WPI in	a uniform, magnetized plasma	277
		4.3.1	Nonlinear aspects for TEM waves along \vec{B}_0	277
		4.3.2	Fields on a particle's zero-order orbits in \vec{B}_0	279
		4.3.3	DSCR interaction—linear (Landau-type) dissipation for TEM	210
			waves along \vec{B}_0	285
		4.3.4	FLR effects and kinetic wave modes	200
		4.3.5	Magnetic Landau-type dissipation (MLD)	291
	4.4	Problem		294
		P4-1	Landau dissipation	294
		P4-2	Landau dissipation—an alternate, equivalent derivation	294 294
		P4-3	Weak Landau damping of EPW in a Maxwellian plasma	294 295
		P4-4	Weak Landau damping of IAW in a Maxwellian plasma	$295 \\ 295$
		P4-5	FLR effect on an ES \vec{E} -field across \vec{B}	295 296
		P4-6	Wave fields across \vec{B}_0 as seen by charged particles gyrating in \vec{B}_0	
		P4-7	Collisionless (Landau-type) cyclotron damping and wave power	296
			dissipated	297
	Chapt	er 4. Bib	bliography	297
	_			290
	Collis	sions an	d collisional transport—I. Particle collisions	299
	Prean			299
	5.1	Introdu		300
	5.2		of binary, elastic collisions	301
		5.2.1	Motion of the center of mass; relative motion	301
		5.2.2	Properties of relative motion	303
			(a) Momentum and energy conservation	303
			(b) Symmetries in elastic, binary collisions	304
			(c) The plane of relative motion	305
			(d) Impact parameter and deflection angle	306
		5.2.3	Relations between the laboratory and the center of mass	
			coordinate systems	309
			(a) Deflection and the recoil angles	309
			(b) Recoil energy of the target particle	311

	5.2.4	Interaction potentials in an ionized gas	312
		(a) Interaction between two charged particles	312
		(b) Interactions between an electron and an atom	312
		(c) Interactions between two atoms	313
	5.2.5	Calculations of deflection angles	313
		(a) Coulomb potential	313
		(b) Billiard ball type atoms	315
		(c) Attractive potentials	315
		(d) Short range atomic potentials	316
		(e) Long range potentials—small angle scattering	316
5.3	Different	tial cross-section for elastic collisions	317
	5.3.1	Definition of differential cross-section	317
		(a) Scattering by a fixed force center	317
		(b) Coherent and incoherent scattering	318
		(c) Scattering cross-section and probability: single and multiple	
		scattering	319
		(d) Elementary mean-free-path, collision time and frequency	320
	5.3.2	Cross-section and impact parameter	321
		(a) General relations	321
		(b) Scattering in a Coulomb interaction potential	321
		(c) Billiard ball type molecules	322
		(d) Differential cross-sections—center of mass and laboratory	
		frames	322
5.4	Total cr	oss-sections	323
	5.4.1	Definitions	323
		(a) Total cross-section for elastic scattering	323
		(b) Cross-sections for momentum and energy transfer	324
	5.4.2	Divergence of σ_1 for Coulomb collisions; the Debye cutoff	325
	5.4.3	The Coulomb logarithm—classical and quantum mechanical	326
	5.4.4	Effect of magnetic field on the Coulomb logorithm	327
	5.4.5	Elastic collisions of electrons and ions with neutrals	328
		(a) Polarization scattering	329
5.5		ns with neutrals—experimental results	330
	5.5.1	Experimental methods	330
		(a) Beam injected into gas	331
		(b) Colliding, low-energy beams	331
		(c) Merging, energetic beams	331
		(d) Measurement of transport coefficients	331
	5.5.2	Electron-neutral collisions	331
5.6		collisions	334
	5.6.1	Particles present in an ionized gas—energy levels	334
		(a) Energy levels of atoms	334
		(b) Molecular energy levels	335
		(c) Negative ions	338
	5.6.2	Inelastic reactions	340
		(a) Energy of reaction	340

		(b) Thresholds of reaction	340
		(c) Binary collisions. Laboratory reference system	341
	5.6.3	Principal types of inelastic collisions	342
	5.6.4	Binary, inelastic collisions	342
		(a) Total cross-section for a given reaction. Reaction rate	342
		(b) Collision cross-sections and reaction rates	346
	5.6.5	Ternary inelastic collisions	346
5.7	Proble		352
	P5-1	Homothetic trajectories	352
	P5-2	Coulomb scattering trajectory and Rutherford cross-sections	352
	P5-3	Collisions with an attractive potential $1/r^4$ —polarization	
		scattering	353
	P5-4	Small angle deflections	353
	P5-5	Cross-section for energy transfer	353
	P5-6	The method of merging energetic beams in weakly-ionized	
		plasmas	353
	P5-7	Reaction constant for two Maxwellians	354
	P5-8	Graphical relationship between inelastic and superelastic	
		cross-sections as a function of electron energy	354
5.8	Append	dix	355
	$5.8.\mathrm{A}$	Quantum mechanical definition and calculation of cross-sections	355
		(a) Scattering of a de Broglie wave by a fixed center	355
		(b) Partial waves; phase shifts	356
		(c) Remarks	357
		(d) The case of identical particles	357
		(e) Total cross-sections	358
	$5.8.\mathrm{B}$	Transport cross-sections and phase shifts	358
		(a) Expansion of $\sigma(\chi)$ in Legendre polynomials	359
		(b) Calculation of transport cross-sections	360
	$5.8.\mathrm{C}$	Spectroscopic notations	361
		(a) Atoms	361
		(b) Diatomic molecules	362
Char	oter 5. Bil	bliography	363
Coll	isions ar	nd collisional transport—II. Fully-ionized	
		nmagnetized	365
Prea			365
6.1		tion frequencies in elastic Coulomb collisions	366
	6.1.1	Classification of beam relaxations in a Maxwellian plasma	371
	6.1.2	Modified and coupled relaxation rates	375
		(a) Pitch angle scattering in $e{-i}$ collisions	375
		(b) Collisional relaxation of a current carried by fast electrons	376
6.2	Transp	ort in fully-ionized plasma	378
	6.2.1	Electrical conductivity and runaway electrons	378
		(a) Electrical conductivity	378
		(b) Runaway electrons	381
			001

		6.2.2	Transport of heat and momentum	384
			(a) Transport relaxation times	385
			(b) Summary of transport times	387
			(c) Transport in the absence of a magnetic field	388
	6.3	Probler	ns	390
		P6-1	One-d Fokker–Planck equation	390
		P6-2	Relation among relaxation rates	391
		P6-3	Estimating typical deflection and energy transfer times in a	
			fully-ionized plasma	391
		P6-4	Collisional scattering of an electron beam injected into	
			a fully-ionized plasma	392
		P6-5	Plasma heating by the injection of energetic ion beams into a	
			fully-ionized plasma	392
		P6-6	Self-heating of fusion plasmas	392
		P6-7	Fully-ionized plasma relaxation times in Tables 6.1–6.3	393
		P6-8	Beam relaxation rates in a Maxwellian plasma	393
		P6-9	e-i pitch angle scattering	393
		P6-10	Fully-ionized plasma stability of the steady states in drift	
			velocities in an electric field	394
		P6-11	Coupled, collisional evolution equations in an electric field	394
		P6-12	Perpendicular averaging the high-velocity electron's collisional	~~~
			friction	395
		P6-13	Tokamak plasma current, loop voltage resistivity, and runaway	
		1010		000
	~		electrons	396
	Chap			396 398
7		ter 6. Bi	electrons	398
7	Colli plasr	ter 6. Bi sions ar nas—U	electrons bliography	398 399
7	Colli plasr Prear	ter 6. Bi sions ar nas—U nble	electrons bliography nd collisional transport—III. Weakly-ionized nmagnetized	398 399 399
7	Colli plasm Pream 7.1	ter 6. Bi sions ar nas—U nble Introdu	electrons bliography nd collisional transport—III. Weakly-ionized nmagnetized	398 399 399 400
7	Colli plasr Prear	ter 6. Bi sions ar nas—U nble Introdu Mobilit	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized action ty and free diffusion of electrons	398 399 399 400 400
7	Colli plasm Pream 7.1	ter 6. Bi sions ar nas—U nble Introdu Mobilit 7.2.1	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized action ty and free diffusion of electrons Momentum transport equation for electrons	398 399 399 400 400 400
7	Colli plasm Pream 7.1	ter 6. Bi sions ar nas—U nble Introdu Mobilit 7.2.1 7.2.2	electrons bliography and collisional transport—III. Weakly-ionized mmagnetized action ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons	398 399 399 400 400 400 400
7	Colli plasm Pream 7.1	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3	electrons bliography and collisional transport—III. Weakly-ionized mmagnetized action ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons	398 399 399 400 400 400 401 404
7	Colli plasm Pream 7.1 7.2	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized action ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion	398 399 399 400 400 400 400 401 404
7	Colli plasn Prean 7.1 7.2 7.3	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit	electrons bliography nd collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions	398 399 399 400 400 400 401 404
7	Colli plasm Pream 7.1 7.2	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length	 398 399 399 400 400 400 401 404 404 405
7	Colli plasn Prean 7.1 7.2 7.3	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity	 398 399 399 400 400 400 401 404 404 405 409
7	Colli plasn Prean 7.1 7.2 7.3	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations	 398 399 399 400 400 400 401 404 404 405
7	Colli plasn Prean 7.1 7.2 7.3	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized nuction ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion	 398 399 399 400 400 400 401 404 404 405 409 409
7	Colli plasn 7.1 7.2 7.3 7.4	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1 7.4.2	electrons bliography and collisional transport—III. Weakly-ionized nmagnetized nuction ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion lengths	398 399 399 400 400 400 400 401 404 404 405 409 409 412
7	Colli plasn Prean 7.1 7.2 7.3	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1 7.4.2 Start-u	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized nuction ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion lengths up and maintenance of a HF discharge in a cavity	398 399 399 400 400 400 401 404 404 404 405 409 409 409 412 414
7	Colli plasn 7.1 7.2 7.3 7.4	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1 7.4.2 Start-u 7.5.1	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion lengths up and maintenance of a HF discharge in a cavity Transient regime	398 399 399 400 400 400 400 400 401 404 404 405 409 409 409 412 414 414
7	Colli plasn Prean 7.1 7.2 7.3 7.4 7.5	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1 7.4.2 Start-u 7.5.1 7.5.2	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion lengths ap and maintenance of a HF discharge in a cavity Transient regime The steady-state regime	$\begin{array}{c} 398\\ 399\\ 399\\ 400\\ 400\\ 400\\ 400\\ 401\\ 404\\ 404\\ 405\\ 409\\ 409\\ 409\\ 412\\ 414\\ 414\\ 414\\ \end{array}$
7	Colli plasn 7.1 7.2 7.3 7.4	ter 6. Bi sions an nas—U nble Introdu Mobilit 7.2.1 7.2.2 7.2.3 7.2.4 Mobilit Free di in a ca 7.4.1 7.4.2 Start-u 7.5.1 7.5.2	electrons bliography ad collisional transport—III. Weakly-ionized nmagnetized notion ty and free diffusion of electrons Momentum transport equation for electrons Mobility of electrons Free diffusion of electrons The Einstein relation. Temperature of diffusion ty and free diffusion of ions ffusion with boundary conditions. Eigenmodes and diffusion length vity General assumptions and simple model equations Evolution of an afterglow plasma. Eigenmodes and diffusion lengths up and maintenance of a HF discharge in a cavity Transient regime	398 399 399 400 400 400 400 400 401 404 404 405 409 409 409 412 414 414

	7.6.2 Ambipolar diffusion in a single ion species plasma	417
	7.6.3 Determination of the proportionality coefficient. Domain of	
	validity of the ideal ambipolar diffusion	420
7.7	Analysis of plasma columns controlled by diffusion	422
	7.7.1 General equations and similarity relations	422
	7.7.2 Explicit results for $\nu_{eo}(w_e) = \text{constant}$	424
7.8	Plasma columns in the free-fall regime	425
	7.8.1 The low pressure limit of the Schottky regime	425
	7.8.2 Free-fall regime	425
7.9	Volume recombination and attachment	427
	7.9.1 Comparison between losses by diffusion and volume	
	recombination	428
	7.9.2 Evolution of the density in a recombining plasma	429
	7.9.3 Electron attachment	430
7.10	Problems	431
	P7-1 Plasma generation by an electron beam	431
	P7-2 Positive column (simple model)	432
	P7-3 Ambipolar diffusion with several species of ions	432
7.11	Appendix	433
	7.11.A Normal modes and diffusion lengths for cylindrical and	
	rectangular cavities	433
	(a) Rectangular cavities	433
	(b) Cylindrical cavities	434
Chap	ter 7. Bibliography	437
Char	rged-particle motion in electromagnetic fields	
Prear		438
8.1	Introduction	438
8.2	Spatially-uniform and time-invariant \vec{B} -field; $\vec{E} = 0$	440
0.2	8.2.1 Nonrelativistic motion $E = 0$	441
	8.2.2 Relativistic motion	441
8.3		444
0.0	Spatially-uniform and time-invariant \vec{E} -field; $\vec{B} = 0$ 8.3.1 Nonrelativistic motion	446
	8.3.2 Relativistic motion	446
8.4		447
0.4	Magnetic, electric, gravity and gravity-like fields 8.4.1 Uniform and constant \vec{E} and \vec{B} -fields	447
		448
	(a) Nonrelativistic guiding center drift in $\vec{E} \perp \vec{B}$	449
	(b) Relativistic guiding center drift in \vec{E}_{\perp} and \vec{B} -fields	453
0 F	8.4.2 Guiding center drift in gravity-type force $\vec{F} \perp \vec{B}$	454
8.5	Slowly-varying spatially-nonuniform \vec{B} -fields; $\vec{E} = 0$	456
	8.5.1 Variations along \vec{B}	457
	(a) Axial force (see also Chapter 1, Section 1.7.2)	457
	(b) Conservation of energy and μ_M constancy	458
	8.5.2 Slow variations in \vec{B} -field perpendicular to \vec{B}	460
	8.5.3 Curvature of \vec{B} and total guiding center drift	462
	8.5.4 Exact trajectories in the Earth's dipole field	465

	8.5.5	Guiding-center drifts from the local $\nabla \vec{B}$ -dyad representation	466
		(a) Parallel gradient of \vec{B} ; local divergence or convergence of \vec{B}	467
		(b) Perpendicular gradient of \vec{B}	468
		(c) Curvature of \vec{B}	469
		(d) Shear in \vec{B}	469
8.6	Slowly-y	varying, time-dependent $ec{E}_{\perp}$ and $ec{B}$ -fields	470
	8.6.1	Polarization drift—a more detailed derivation	471
8.7		abatic motion of charged particles	473
	8.7.1	Guiding center motion in the adiabatic approximation	474
	8.7.2	Summary of guiding center equations for $v_E \sim \mathcal{O}(\varepsilon)$ and initial	
		conditions for them	480
	8.7.3	Guiding-center orbits in the Earth's dipole \vec{B} -field	482
	8.7.4	Kruskal's asymptotic formulation	482
	8.7.5	Hamiltonian formulations	483
8.8	Constan	ts of motion and confinements in time-invariant \vec{B} -fields	484
	8.8.1	Motion in axially-symmetric magnetic fields	484
	8.8.2	Guiding center motions in \vec{B} -fields for MCF plasmas	489
		(a) Particle motion and confinement in a simple mirror \vec{B} -field	489
		(b) Particle confinement in rotational transform of closed	
		\vec{B} -field lines	493
8.9	Adiabat	ic invariants	506
	8.9.1	Magnetic moment invariant	508
	8.9.2	Longitudinal (or "second") adiabatic invariant	509
	8.9.3	Flux (or "third") adiabatic invariant	513
8.10		in HF EM fields—Pondermotive effects	516
	8.10.1	Single particle in an unmagnetized $(\vec{B}_0 = 0)$ motion	516
	8.10.2	Single particle in a magnetized $(\vec{B}_0 \neq 0)$ motion	519
8.11	Problem		521
	P8-1	Free charged particles in a constant \vec{B}_0 ; collisions; collective	
	-	modes	521
	P8-2	Charged-particle motion in constant \vec{B}_0 —coordinate-	F 00
	Doo	independent description	522
	P8-3	Relativistic magnetic moment and its adiabatic invariance	522
	P8-4	Motion in constant \vec{E} -field and $\vec{B} = 0$	523
	P8-5	Guiding center drift in constant fields $\vec{E} \perp \vec{B}$	$523 \\ 524$
	P8-6	Guiding center drift in $\nabla_{\perp} B$	$\frac{524}{524}$
	P8-7	Radius of a curvature and magnetic field line geometry Motion in slowly time-varying $\vec{E} \perp \vec{B}$ fields; $\vec{B} = \text{constant}$	$524 \\ 524$
	P8-8 P8-9	Derivation of guiding-center equations to order ε	$524 \\ 525$
	го-9 P8-10	Guiding center drift-velocity perpendicular to $\vec{B}(\vec{R})$ for	020
	1 8-10	$v_E \sim \mathcal{O}(\varepsilon)$	526
	DQ 11		$520 \\ 527$
	P8-11 P8-12	Equation for guiding center velocity parallel to $\vec{B}(\vec{R}), V_{\parallel}$ Energy integral in guiding center equations	$527 \\ 527$
	P8-12 P8-13	Liouville relation in guiding center equations	527 527
		• • •	
	P8-14	Initial conditions for $V_{\parallel}\equiv ec{R}\cdot \hat{b}(ec{R})$	527

		P8-15	Rotational transform in a cylinder	529
		P8-16	Relativistic motion in the fields of a TEM wave	529
	Chap	oter 8. Bi	bliography	532
9	-	-	lrodynamics	534
	Prea			534
	9.1	Introdu		535
	9.2		from guiding-center particle dynamics	535
		9.2.1	Two-d collisionless MHD across a no-curvature magnetic field	536
			(a) Equilibrium equations	539
			(b) Slowly varying fields	539
			(c) Dynamic ideal-MHD equations	541
			(d) Constants of motion; adiabatic compression heating	542
			(e) Conservative form of equations and conservation of energy	544
		0.0.0	(f) Linear MHD stability analysis	545
		9.2.2	Rayleigh–Taylor and Kruskal–Schwarzchild instabilities	560
			(a) RTI in ICF plasmas	563
			(b) Effects of \vec{B}_0 on RTI/KSI	569
			(c) Compressibility effect on the RTI	571
		0.9.2	(d) The Kelvin–Helmholtz instability (KHI)	572
		$9.2.3 \\ 9.2.4$	The θ -pinch plasma—cylindrical and for MCF	575
		9.2.4	Three-d collisionless MHD-Chew, Goldberger and Low (CGL) theory	
				578
			(a) Fluid current density from guiding-center particle dynamics in 3-d	F 01
			(b) Confined MHD equilibria in anisotropic pressure plasmas	581
		9.2.5	Double-adiabatic CGL dynamics in uniform anisotropic plasmas	582
		5.2.0	(a) Alfvén wave perturbations along \vec{B}_0 and the "firehose"	585
			instability	586
			(b) Wave perturbations at an angle to \vec{B}_0 and the "mirror	000
			instability"	589
		9.2.6	Interchange instabilities including \vec{B} -field curvature	596
			(a) Effective gravity in curved \vec{B} -field lines	596
			(b) Instability in a simple magnetic mirror; minimum- \vec{B}	000
			stability	598
		9.2.7	The Z-pinch	602
			(a) Equilibrium	602
			(b) Linear stability/instability	605
	9.3	Single-f	fuid MHD	610
		9.3.1	Basic model equations	610
		9.3.2	Local conservation equations	612
			(a) Energy	613
			(b) Momentum	614
		9.3.3	Resistive vs. ideal MHD	615
			(a) Mass diffusion perpendicular to \vec{B}_0 —see Chapter 2,	
			Section 2.3.3 (c)	615
			(b) Magnetic field diffusion	616

		9.3.4	Ideal MHD	616
		5.0.4	(a) Plasma localized on \vec{B} -field lines	618
			(b) Magnetic flux conservation	619
			(c) Conservation of energy momentum and angular momentum	621
			(d) Magnetic helicity	622
		9.3.5	Small-amplitude dynamics-uniform plasmas	624
			(a) Linearization of model equations	625
			(b) Small-amplitude dynamic equations and natural waves	626
			(c) Small-amplitude energy conservation—stability of natural	
			waves	628
			(d) Complex Poynting equation in ideal MHD—resonances	631
			(e) Group velocity and energy velocity of stable waves	633
			(f) Dispersion relations of the natural waves	634
			(g) Small-amplitude displacement field polarizations	646
	0.4	D	(h) Weak damping of linear MHD waves e MHD instabilities	$\begin{array}{c} 648 \\ 652 \end{array}$
	$9.4 \\ 9.5$	Problem		652
	9.0	Problem P9-1	The mass-momentum equation (9.25)	656
		P9-2	Conservative equations and conservation of energy	656
		P9-3	Review of F-L tx. and space-time Green's functions	656
		P9-4	The RTI/KSI in sheared-magnetic field	659
		P9-5	Cylindrical Z-pinch equilibria	659
		P9-6	Constructing conservation equations of the MHD model	661
		P9-7	Reynolds numbers for some plasmas	662
		P9-8	F-L tx. of linearized ideal MHD equations	662
		P9-9	Proving $\vec{v}_{gr} = \vec{v}_{en}$ in ideal MHD	662
		P9-10	Spatial damping of MHD waves	663
		P9-11	Viscous to resistive damping in an Alfvén wave	664
		P9-12	Damping of magnetoacoustic waves	664
	Chapt	er 9. Bit	bliography	666
10	Drift	-free co	ld plasma, unmagnetized—Linear and nonlinear	
	electi	odynan	nics	668
	Pream	nble		668
	10.1	Introdu		669
	10.2	-	netized and drift-free, cold plasma	670
		10.2.1	The cold-plasma model equations	670
			(a) Energy, energy flow and power dissipated	672
	10.0	A 1•/	(b) Linear and nonlinear hydrodynamics	674 674
	10.3	-	ude limits for laminar ES dynamics—wavebreaking	$\begin{array}{c} 674 \\ 680 \end{array}$
		10.3.1	Traveling waves—relativistic	680
			(a) One-d, ES-field dynamics(b) Pure transverse field dynamics	681
	10.4	Linearia	zed dynamics	682
	10.4	10.4.1	Neutral, drift-free, and field-free equilibrium	682
		10.4.2	Small-amplitude perturbations	682

	10.4.3	Linear response functions for given electric fields	685
		(a) Transverse field response	685
		(b) Longitudinal field response	686
	10.4.4	Maxwell's equations for SCF	687
		(a) TEM modes	687
		(b) TEM wave reflection and transmission	690
		(c) Fields driven from an external antenna	692
		(d) LES modes	695
		(e) Validity of cold plasma linear wave descriptions	696
	10.4.5	Eigenvalue analysis of natural modes	696
	10.4.6	Small-amplitude energy conservation	698
		(a) Linear stability	699
		(b) Uniqueness of linear solutions	700
		(c) Time-average energies and complex Poynting equations	701
		(d) Orthogonality	703
		(e) Field variation equation	704
		(f) Linear electrodynamic formulation	705
10.5	Nonline	ear coupling of cold plasma waves	709
	10.5.1	Resonant Raman 3WI	711
	10.5.2	Slowly-varying amplitudes in weak coupling	713
	10.5.3	Parametric interactions	714
	10.5.4	Physical picture of the parametric instability	716
10.6	Problem	ns	718
	P10-1	Relativistic momentum conservation equation in a fluid	
		description of charged particles	718
	P10-2	The relativistic, nonlinear conservation of energy equation	719
	P10-3	Spatial harmonics in E-field near wavebreaking	719
	P10-4	Relativistic traveling waves	720
	P10-5	Accounting for elastic collisions in linear response functions	720
	P10-6	Kramers–Krönig relations for an unmagnetized, cold, and	
		drift-free plasma with collisions	721
	P10-7	Green's function for TEM fields in a cold plasma	721
	P10-8	Plasma fluid velocities induced by high-intensity lasers	722
	P10-9	TEM wave reflection and transmission at a plasma-free space	
		boundary	724
	P10-10	, p	724
	P10-11	•	726
	P10-12	5 1	728
	P10-13		728
	P10-14		
	D 46.17	density, and power density dissipated	728
	P10-15	•	729
	P10-16	Orthogonality in small-amplitude energy	729

			Complex field variation equations for cold, drift-free plasma Failure of the electrodynamic energy expression for	731
		1 10-10	dissipative media	731
		P10-19		732
		P10-20		732
		P10-21		733
		P10-22	Stable parametric 3WIs	733
		P10-23	Weak damping of waves in nonlinear 3WIs	734
	Chap		ibliography	735
11	Drift Prean		ld plasma, magnetized—I. Linearized electrodynamics	736 736
	11.1		rift-free plasma in an external magnetic field	738
		cora, a	(a) Amplitude limits for laminar dynamics	740
	11.2	Lineariz	zed dynamics for an undrifted equilibrium	740
		11.2.1	The linear susceptibility response tensor	744
			(a) Rotating coordinate fields and field polarizations	749
		11.2.2	The selfconsistent fields (SCF)	751
		11.2.3	Energy conservation relations	754
			(a) Small-amplitude energy conservation; stability and	101
			uniqueness	754
			(b) Complex Poynting equations; orthogonality and variation	101
			relations	754
			(c) Linear electrodynamic formulation	757
	11.3	Problem		760
		P11-1	Linear, ES dynamics perpendicular to \vec{B}_0	760
		P11-2	Susceptibility tensor for a cold plasma with momentum loss due	
			to elastic collisions	760
		P11-3	Singularities in the collisionless susceptibilities	760
		P11-4	Hermitian and anti-Hermitian susceptibility tensors	761
		P11-5	Properties of susceptibility tensor elements from reality of fields	761
		P11-6	Kramers–Krönig relations from causality of internal response	761
		P11-7	Kramers–Krönig relations from analyticity of $\omega \chi_{ij}(\omega)$ for $\omega_i > 0$	762
		P11-8	Cold plasma susceptibility tensor satisfying Kramers–Krönig relations	762
		P11-9	Kramers–Krönig relations from conjugate potential	102
			functions of $\omega \chi_{ij}(\omega)$	762
		P11-10		102
			field \vec{B}_0	763
		P11-11	Relation of small-amplitude conservation of energy to the	100
			nonlinear conservation of energy	763
		P11-12	Small-amplitude complex variation relation	764
		P11-13	Average power density dissipated at small amplitudes	764
		P11-14	Average power density dissipated at cyclotron resonance	764

	11.4	Append	dix: Time dispersive media	765
		11.4.A	i internet in an internet is an internet in the second sec	
			temporally dispersive medium	765
			(a) Reality of fields	766
			(b) Kramers–Krönig relations	767
			(c) Onsager relations	768
			libliography	769
12	Drift	t-free co	ld plasma, magnetized—II. Linear modes; principal waves	770
	Prear			770
	12.1		l and driven modes in a homogeneous plasma	771
		12.1.1	Dispersion relation and field polarizations of natural modes	773
			(a) Fields and their dispersion tensor	774
			(b) Dispersion relations $\vec{k}(\omega_r)$ modes	776
			(c) Polarization of natural modes	782
			(d) Energy and energy flow characteristics of waves	783
	10.0	D · · ·	(e) Natural modes in $\omega(\vec{k}_r)$	785
	12.2		al waves in an electron-ion plasma	786
		12.2.1	Waves propagating parallel to \vec{B}_0	791
			(a) The shear (or torsional) Alfvén wave	793
			(b) EMIC and whistler waves	795
			(c) Fast EM waves and Faraday rotation at HF $$	798
		12.2.2	Waves propagating perpendicularly to \vec{B}_0	799
			(a) The compressional Alfvén wave	801
			(b) LH and UH resonances in propagation	802
			(c) The Buchsbaum ion-ion hybrid resonances	805
	10.0		(d) High-frequency, fast EM waves	808
	12.3	Problem		809
		P12-1	Dispersion tensor in rotating coordinates	809
		P12-2	The dispersion tensor for transverse and longitudinal fields	809
		P12-3	Small-amplitude energy flow conservation perpendicular to \vec{B}_0	809
		P12-4	Electric field polarizations in spherical coordinates	810
		P12-5 P12-6	Natural modes for time evolution of propagating fields	810
		P12-6 P12-7	Collisional damping of Alfvén waves	811
		P12-7 P12-8	Ionic whistler waves	812
		P12-8 P12-9	UH and LH resonances in propagation	812
		P12-9 P12-10	Time average balance of energies in UH and LH resonance	812
		P12-10 P12-11	FLR effects in UH resonance The Buchsbaum IIHR	813
	Chapt		bliography	813
10				815
13	Drift.	-iree col	d plasma, magnetized—III. Waves	
	Pream		directions; nonlinear coupling	816
	13.1		propagating in orbitrary directions. 1 (to) \vec{D}	816
	13.1 13.2		propagating in arbitrary directions relative to \vec{B}_0	818
	10.2		IA diagram Phase velocity surfaces in the (a^2, a^2) shows	819
		13.2.1	Phase velocity surfaces in the (α^2, β^2) plane	822

	13.2.2	Normal mode analysis	828
	13.2.3	Dispersion relation plots	830
		(a) Propagation cutoff frequencies	831
		(b) Propagation resonance frequencies	832
		(c) Propagation dispersion for arbitrary θ	834
13.3	Alterna	te wave-surface representations	837
13.4	Accessil	pility to a LH slow wave in a plasma	840
	13.4.1	Detailed analysis of accessibility in the LHFR	843
		(a) Detailed analysis of accessibility in the LHFR	843
13.5	Asympt	otic fields from field excitations	847
	13.5.1	Initial fields of limited extent	848
		(a) One-d space; no caustics	849
		(b) Caustics	850
		(c) Three-d; no caustics	851
		(d) Two- and three-d; caustics	854
	13.5.2	Space-localized source at steady-state frequency	855
		(a) Two-d space; no caustics	856
		(b) Three-d space; no caustics	858
		(c) Two-d space and caustic	861
		(d) Three-d space and caustic	862
13.6	The Ap	pelton–Hartree dispersion relation	863
	13.6.1	The QC approximation in a neutral electron plasma	865
	13.6.2	The QP approximation in a neutral electron plasma	866
13.7	QC and	QP approximations in an electron-ion plasma	867
	13.7.1	QC and QP waves	867
	13.7.2	The QP approximation	869
	13.7.3	Polarizations in the QC and QP approximations	872
13.8	Longitu	dinal and transverse modes	873
13.9	The QE	S approximation	878
	13.9.1	QES modes	880
		(a) HF UH and Trivelpiece–Gould modes	883
		(b) Lower-hybrid waves (LHW)	884
		(c) EM corrections to ES LHWs	885
		(d) Cold plasma ES ion cyclotron (CP-ESIC) waves	885
	13.9.2	Excitation and propagation of ES modes—resonance cones	886
		d fast wave approximations	888
13.11	EHD of	helicons at an angle to $\vec{B_0}$ and their M-LD	890
13.12		-MHD regime and M-Landau damping	895
13.13		ar coupling of waves	897
13.14	Problem		905
	P13-1	Phase velocity dispersion relation	905
	P13-2	Normal mode matrix for waves in a drift-free cold plasma in \vec{B}_0	905
	P13-3	Propagation cutoff frequencies	906
	P13-4	Propagation resonance frequencies	906
	P13-5	The Appelton–Hartree dispersion relation and field polarizations \vec{r}	907
	P13-6	Energy flow in whistlers at an angle to \vec{B}_0	908

Table	of contents	xxiii
rabic	or contents	~~!!!

	P13-11	magnetosonic waves	908 909 910 910 911
Chapt		Nonlinear wave coupling in HF X-waves bliography	$\begin{array}{c} 912\\914 \end{array}$
		th thermal pressures—I. Unmagnetized plasma	916
Pream			916
	Introduc		918
14.2		del equations in unmagnetized ($\vec{B}_0 = 0$) plasmas with isotropic	
		pressure	918
14.3		eaking in the hydrodynamic model	920
14.4	Lineariz	ed dynamics	923
		(a) Neutral, drift-free, and field-free equilibrium	923
		(b) Small-amplitude perturbations	924
	14.4.1	Linear response functions for given electric fields	926
		(a) Transverse field response	926
		(b) Longitudinal field response	926
	14.4.2	Maxwell's equations for the selfconsistent fields	927
		(a) TEM modes	928
		(b) LES modes	928
	14.4.3	Energy, energy flow, and power dissipated	932
		(a) Conservation of energy	932
		(b) Small-amplitude energy conservation	934
		(c) Small-amplitude complex Poynting equation,	
		orthogonality and variation relations	936
		(d) Linear electrodynamic formulations	938
14.5	Nonlinea	ar coupling of waves	941
	14.5.1	SRBS in a thermal plasma	942
14.6	Problem	S	944
		Longitudinal susceptibility in the presence of elastic collisions	944
	P14-2	Pulse propagation in a plasma with isotropic, thermal	
		pressures	944
	P14-3	Uniqueness of linearized field solutions	945
	P14-4	Interpretation of small-amplitude energy density	945
	P14-5	Complex Poynting, orthogonality, and variation relations for a drift-free, unmagnetized $(\vec{B}_0 = 0)$ plasma with isotropic thermal	
		pressures	945
	P14-6	Comparing electrodynamic and hydrodynamic expressions for	
		densities of average energy, energy flow, and power dissipated	946
Chapte	er 14. Bil	oliography	948

15	÷		ith thermal pressures—II. Magnetized plasma	949
	Pream			949
	15.1		ized $(\vec{B}_0 \neq 0)$ drift-free plasma with thermal pressures	951
	15.2		ee plasma in \vec{B}_0 —isotropic thermal pressures	951
		15.2.1	The linear conductivity and susceptibility	952
		15.2.2	The dispersion tensor for the selfconsistent fields of the natural	~~~
			modes	956
		15.2.3	Small-amplitude conservation relations	958
		15.2.4	Natural modes	962
			(a) Principal waves along $\vec{B_0}$ $(\vec{k} \parallel \vec{B_0}, \theta = 0; \xi = 0, \zeta = 1)$	963
			(b) Principal waves across $\vec{B}_0 \ (\vec{k} \perp \vec{B}_0, \theta = \pi/2; \xi = 1, \zeta = 0)$	965
			(c) ES waves at an angle to \vec{B}_0 —modifying cold plasma slow	
			waves	967
			(d) Normal mode analysis	971
			(e) Phase velocity surfaces from normal modes	972
			(f) Dispersion relation plots for arbitrary θ	974
	15.3	Drift-fr	ee plasma in \vec{B}_0 —with anisotropic thermal pressures	981
		15.3.1	Linearized hydrodynamics for anisotropic thermal pressures	982
			(a) Homogeneous equilibrium	983
			(b) Linearized hydrodynamic equations	983
		15.3.2	Linear susceptibility tensor in perturbations of TE	985
			(a) Unmagnetized $(B_0 = 0)$ plasma	985
			(b) Magnetized $(\vec{B}_0 \neq \vec{0})$ plasma	987
		15.3.3	Dispersion relations in $\vec{B}_0 \neq 0$	991
			(a) Emphasizing (n, ξ, ζ) dependencies	991
			(b) Emphasizing $(n_{\perp}, n_{\parallel})$ dependencies	992
	15.4		ting cold plasma to kinetic dispersion relations at HF	993
		15.4.1	Transformation of the cold-plasma SX -mode to a kinetic EBW	004
		15 4 0	mode	994
		15.4.2	Thermal modifications of the Bohm–Gross and Trivelpiece–Gould	996
		15 4 9	modes Thermal we differ time of LH modes	990 998
		15.4.3	Thermal modifications of LH modes	998 1004
	155	15.4.4 Drahlar	The ES-ICW regime	1004
	15.5	Probler P15-1	Susceptibility tensor for the drift-free plasma with isotropic	1000
		r 10-1	thermal pressures in a magnetic field	1006
		P15-2	Limiting forms of the susceptibility tensor	1006
		P15-3	Isotropic thermal pressure susceptibility to first-order in	1000
		1 10-0	$(k_{\parallel}v_{Ts}/\omega)^2$ and $(k_{\perp}\rho_{Ts})^2$	1006
		P15-4	$(\kappa_{\parallel}\sigma_{Ts})^{(\omega)}$ and $(\kappa_{\perp}\rho_{Ts})^{(\omega)}$ The susceptibility tensor in rotating and transverse-longitudinal	1000
		1 10-4	field coordinates	1007
		P15-5	Normal mode wave matrix for a drift-free plasma in \vec{B}_0 with	
			isotropic thermal pressures.	1008
		P15-6	HF X-mode as modified by isotropic thermal electron pressure	1008
		P15-7	The QES dispersion relation when isotropic thermal pressure	
			effects are included	1009

		P15-8	Equation for the thermal pressure tensor	1009
		P15-9	Susceptibility tensor for anisotropic thermal pressure	
		D1F 10	perturbations	1010
		P15-10	i autoriopic	
		D15 11	thermal pressure perturbations	1010
		P15-11 P15-12	Thermal dispersion relation exhibiting $(n_{\perp}, n_{\parallel})$ dependencies Modifications in the cold-electron plasma UH propagation	1010
		D15 19	resonance due to thermal modes	1011
		P10-13	ES dispersion relation with thermal corrections for HF modes	1012
			Validity of hydrodynamic FLR description for LH modes	1012
	15.6		LH dispersion relation with EM and FLR corrections	1013
	15.0		lix: Time and space dispersive media	1014
		15.6.A	Properties of the susceptibility tensor in a spatially and	1014
			temporally dispersive medium	1014
			(a) Hermitian and anti-Hermitian tensors	1014
			(b) Properties associated with the reality of fields	1015
			(c) Onsager relations	1015
	Chan	ton 15 D	(d) Kramers–Krönig relations	1017
	Chap	ter 15. Bi	ibliography	1019
16			es, instabilities and devices	1020
	Pream			1020
	16.1	Introdu		1022
	16.2		lynamics of an electron stream	1023
		16.2.1	General, nonlinear equations	1023
	100	16.2.2	Linearized equations for small amplitude fields	1024
	16.3		and energy flow associated with the waves	1027
		16.3.1	Energy in fast and slow wave excitations	1028
		16.3.2	Small-amplitude energy density	1028
	10.4	16.3.3	Small-amplitude energy conservation equation	1030
	16.4		and unstable excitations of e-beam waves	1033
	16.5		ity in the interaction with a dissipative medium	1038
		16.5.1	Dispersion relation for the beam-resistive medium system	1038
		16.5.2	Approximate solution of the dispersion relation for weak	
		14 5 0	dissipation	1040
		16.5.3	Energy conservation in the presence of small dissipation	1043
	10.0	16.5.4	Energy flow in resistive medium amplification	1044
	16.6		teraction with a non-dissipative (reactive) medium	1045
	16.7	Problem		1048
		P16-1	Longitudinal response function	1048
		P16-2	Series expansion of kinetic energy	1049
		P16-3	Small-amplitude, kinetic energy flow density in one-d dynamics	
			of an electron stream	1050
		P16-4	Small-amplitude dynamics and conservation of energy for an	
		D16 -	inhomogeneous cold electron stream	1050
		P16-5	Boundary conditions for dipole grids in an electron beam	1051

		P16-6	Small-amplitude electron density and electric field excited by a	
			dipole grid voltage	1052
		P16-7	The Klystron amplifier	1052
		P16-8	Coupling from beam current density perturbations at a dipole	
			grid to an external system	1054
		P16-9	Eigenvalue equation for the Pierce diode instability	1054
		P16-10		1057
		P16-11	The electronic admittance (per unit area) between a pair of grids	1057
		D1010	in an electron beam, for arbitrary space charge	1057
		P16-12	The electronic admittance (per unit area of a beam) as seen across	
			a pair of grids immersed in the electron beam, in the limit of zero	1059
		D16 19	space charge Stability of <i>e</i> -beam waves with internal dissipation	1060
			Small-amplitude energy conservation with internal dissipation	1060
	Chapt		ibliography	1062
	Unap	Jei 10, D.	tonography	
17		-	stabilities in cold plasmas	1063
	Prean			1063
	17.1		ng instabilities in plasmas	1065
	17.2		ctron beam-plasma instability	1066
		17.2.1	Derivation of the dispersion relation	1066
		17.2.2	Solutions for complex $\omega(k_r)$	$\begin{array}{c} 1068 \\ 1070 \end{array}$
		17.2.3	Solutions for complex $k(\omega_r)$	1070
			(a) The plasma as a reactive medium	1070
		17.2.4	(b) Spatial amplification at real frequencies Nonlinear aspects of the instability	1071
	17.3		lities driven by currents in a plasma	1072
	17.5	17.3.1	The Pierce–Budker–Buneman instability	1073
		17.3.1 17.3.2	Nonlinear aspects	1076
	17.4		-stream instabilities	1076
		17.4.1	Counterstreaming electrons	1076
		17.4.2	Costreaming electrons with different velocities	1077
		17.4.3	Counterstreaming electrons through ions	1079
		17.4.4	Nonlinear aspects	1080
	17.5	EM ins	tabilities	1081
		17.5.1	The cold plasma, fully EM and relativistic dynamics	1081
		17.5.2	Linearized, nonrelativistic dynamics	1083
		17.5.3	The Weibel-type instability—Nonrelativistic	1084
			(a) The feedback mechanism for the instability	1088
			(b) Small-amplitude energy conservation for the Weibel	1000
			instability	1088
			(c) Nonlinear aspects of the Weibel instability	1091
		17.5.4	Relativistic dynamics and small-amplitude energy conservation	1091
			(a) Linearized dynamics and small-amplitude energy	$\begin{array}{c} 1091 \\ 1094 \end{array}$
			(b) The Weibel instability—Relativistic analysis	$1094 \\ 1095$
			(c) Waves propagating across an electron beam	1039

	17.6	Relativi	stic beam along \vec{B}_0	1097	
		17.6.1	Negative energy waves and beam-plasma interactions	1098	
			(a) Beam modes for $\vec{B}_0 = 0$ and $k_z = 0$	1098	
			(b) Negative energy EM modes in a beam along \vec{B}_0	1099	
			(c) Relativistic beam-plasma in $\vec{B}_0 = 0$ —coupling to EM waves	1103	
				1105	
	17.7	-	l-particle streams across $\vec{B_0}$	1107	
		17.7.1	LF gravitational ES instability—constant density along \vec{g}	1107	
		17.7.2	Density gradient along \vec{g} in gravitational ES instability	1110	
	17.8	Problem		1114	
		P17-1	Unstable wavenumber range for instability in the e -beam-plasma		
			interaction	1114	
		P17-2	Beam-plasma instability in a plasma density gradient along the		
			beam flow direction	1114	
		P17-3	Range of wavenumbers for the Pierce–Budker–Buneman		
			instability	1115	
		P17-4	Maximum growth rate for the Pierce–Budker–Buneman		
			instability	1115	
		P17-5	Spatial growth rate in costreaming electron beams of equal		
			densities and unequal drift velocities	1115	
		P17-6	Nonzero frequency, unstable ES mode in counterstreaming		
			electrons through ions	1116	
		P17-7	Relativistic description of one-d ES dynamics	1116	
		P17-8	The relativistic conservation of energy equation for a cold plasma	1117	
		P17-9	TEM fields with $\vec{E}_1 \perp \vec{v}_0$ in counterstreaming beams	1117	
		P17-10	Small-amplitude conservation of energy for the		
			nonrelativistic Weibel instability	1118	
		P17-11	Linearization of the relativistic momentum and kinetic energy	1118	
		P17-12	Small-amplitude, average energy densities in the relativistic	1110	
			counterstreaming system of the Weibel instability	1119	
		P17-13	Waves propagating across the drift direction of a single electron	1115	
		1 11 10	beam	1119	
		P17-14	Nonrelativistic analysis of waves propagating across an	1115	
		1 11 11	electron beam	1120	
		P17-15	Waves across an electron beam by coordinate transformation	$1120 \\ 1120$	
		P17-16	Small-amplitude, average energy density in waves across an	1120	
		1 17-10	electron beam	1101	
		P17-17		1121	
		P17-18	Susceptibility tensor for relativistic cold beam drifting along \vec{B}_0	1121	
	Chapt		<i>O</i> -mode instability analysis for counterstreaming beams along \vec{B}_0	1122	
	Unapt	er_1i , di	bliography	1123	
3	Space	e-time e	volution of linear instabilities—Absolute and convective	1124	
	Pream	ıble		1124	
	18.1	Introdue	ction	1126	
	18.2	A simple	e example of linear instability evolution	1120 1127	
	18.3	-	analysis of instability evolutions	1143	

	18.3.1	Time-asymptotic evolutions in one-d space and time	1145
	18.3.2	Absolute instabilities—Unstable normal modes	1147
		(a) Examples of absolute instabilities—Simple pinch points	
		at finite k	1153
		(b) End-point and pinch-point singularities with	
		$\vec{k} \rightarrow \infty$ —Essential singularities in $I(z, \omega)$	1157
		(c) Absolute instability in more complex systems	1161
	18.3.3	Convective instabilities—spatial amplification	1165
		(a) Examples of convective instabilities	1169
	18.3.4	Propagating waves in an unstable medium	1171
18.4	Asympt	otic pulse shapes of unstable evolutions	1173
	18.4.1	Nonrelativistic pulse evolutions	1173
	18.4.2	Relativistic pulse evolutions	1177
	18.4.3	Pulse edge evolutions	1179
	18.4.4	Examples of unstable, time-asymptotic pulse shapes	1179
18.5	Problen	as	1184
	P18-1	Green's function for the p.d.e. (18.1)	1184
	P18-2	Branch-cut integrals in (18.27)	1184
	P18-3	Residues in simple and double poles	1185
	P18-4	Taylor series of D near (k_0, ω_0)	1186
	P18-5	Merging on two k_u or two k_ℓ roots of $k(\omega_L)$	1186
	P18-6	Absolute instability in counter-streaming electron beams	1187
	P18-7	Absolute instability in the coupled-mode/tachyon dispersion	
		relation	1187
	P18-8	A BWO-type dispersion relation gives absolute instability	1188
	P18-9	Mappings in the stability/instability analysis for (18.90)	1189
	P18-10	Green's function for the cold e -beam plasma instability	1190
	P18-11	Simple dispersion relations with essential singularity in its	
		associated Green's function inverse transform	1193
	P18-12	Convective instability in the system with dispersion	
		relation (18.90)	1194
	P18-13	Stability analysis for costreaming electron beams	1194
	P18-14	v i 0	
		of waves	1195
		Pure waves in the convectively unstable coupling of modes	1195
	P18-16		1195
	P18-17	Pulse-edge characteristic for the EM-Weibel,	
	D 4 6 4 6	counterstreaming instability	1196
	P18-18	Asymptotic pulse shapes for unstable, coupled-mode	110-
	D10.10	interactions (18.87) and (18.125)	1197
	P18-19	Asymptotic pulse shape for the cold beam-plasma instability	1197
CI	P18-20	5 1 1 1	1198
Chapt	Chapter 18. Bibliography 119		

Vo	olumo	e 2: C ł	hapters 19–33			
19	19 Electrodynamics of linear modes—Conservation relations and					
	perturbation theory					
	Prear	mble		$\frac{1200}{1200}$		
	19.1	Introdu	uction	1202		
	19.2	One-d	ES dynamics	1203		
		19.2.1	Conservation of average densities of energy and energy flow	1206		
			(a) Natural modes	1208		
			(b) Some examples	1209		
		19.2.2	Conservation of average densities of momentum and momentum			
			flow	1210		
			(a) Natural modes and wave action density	1211		
			(b) Some examples	1212		
	19.3		d and fully EM dynamics	1213		
		19.3.1	Slowly-varying amplitudes and weak dissipation	1215		
		19.3.2	Conservation of average densities of energy and energy flow	1218		
			(a) Natural modes	1219		
		10.0.0	(b) Quasi-electrostatic (QES) and pure ES waves	1220		
		19.3.3	Conservation of average densities of momentum and momentum			
			flow	1222		
		10.0.4	(a) Normal modes and wave action density	1223		
	10.4	19.3.4	Angular momentum and torques; rotating circular medium	1224		
	19.4		nergy and momentum for systems in relative motion at any			
			it velocity	1225		
		19.4.1	Transformations of coordinates and fields—summary	1226		
		19.4.2	Energy-momentum tensor transformation	1228		
	19.5	19.4.3 Logar	Transformation of coupled-mode equations	1230		
	19.0 19.6		nedia and adjoint systems	1230		
	19.0	19.6.1	ic perturbation of modes—slowly-varying amplitudes	1232		
		19.0.1 19.6.2	One-d ES dynamics	1233		
		19.0.2 19.6.3	Three-d and fully EM dynamics—amplitudes and polarizations	1234		
	19.7	Problen	Perturbation and coupling of modes	1237		
	10.1	P19-1		1241		
		1 15-1	Energy and energy flow densities in one-d ES hydrodynamics with thermal pressures	10.41		
		P19-2	Small-amplitude energy (Poynting) equation	1241		
		P19-3	Small-amplitude energy (1 Synting) equation	1241		
		P19-4	Average power density dissipated	1241		
		P19-5	Slowly-varying expansions in 3-d space and time	1241		
		P19-6	Identifying the average small-amplitude energy density and its	1242		
			conservation equation	1242		
		P19-7	Conservation of average wave energy density	$\frac{1242}{1242}$		
		P19-8	Identifying the average small-amplitude momentum density and	1242		
			its conservation equation	1244		