

## Contents

### Preface XIII

<b>1</b>	<b>Fusion Research</b>	<b>1</b>
1.1	Reaction Scheme	1
1.2	Magnetic Plasma Confinement	4
1.2.1	Tokamak	5
1.2.2	Stellarator	6
1.2.3	Physics Issues of Magnetic Confinement	7
1.2.4	Plasma Heating	10
1.3	Plasma Diagnostic	11
1.3.1	Generic Arrangements	12
1.3.2	Microwave Diagnostics	15
	References	17
<b>2</b>	<b>Millimeter-Waves in Plasmas</b>	<b>19</b>
2.1	Basic Equations	20
2.2	Plasma Dielectric Tensor, General Properties	23
2.3	Dielectric Tensor from Kinetic Theory	25
2.4	Cold-Plasma Limit	29
2.5	Derivation within Fluid Description	32
2.6	Discussion of Cold-Plasma Dispersion Relations	34
2.6.1	Nonmagnetized Plasma, $\vec{B}_0 = 0$	34
2.6.2	Magnetized Plasma, Parallel Propagation, $\vec{k} \parallel \vec{B}_0$	37
2.6.3	Magnetized Plasma, Perpendicular Propagation, $\vec{k} \perp \vec{B}_0$	39
2.6.4	Slightly Oblique Propagation	41
2.7	Finite-Temperature Correction to Cold-Plasma Dielectric Tensor	42
2.7.1	Finite Larmor Radius Expansion	42
2.7.2	Warm-Plasma Approximation	44
2.7.3	Relativistic Corrections	46
2.8	Inhomogeneous Plasma	48
2.8.1	WKB Approximation	49
2.8.2	Refraction	51

2.8.3	Ray Tracing	53
2.9	Finite-Size Probing Beam	54
2.9.1	Gaussian Beam Description	54
2.10	Radiation Transfer	58
2.10.1	Transparent Plasma	58
2.10.2	Plasma Emitting and Absorbing	60
2.10.3	Multiple Chords, Imaging	61
	References	62
<b>3</b>	<b>Active Diagnostics</b>	<b>65</b>
3.1	Interferometry	65
3.1.1	Single-Chord Interferometry	68
3.1.2	Multiple Chords	69
3.2	Polarimetry	70
3.2.1	Faraday Effect	71
3.2.2	Cotton–Mouton Effect	75
3.2.3	Common Generalized Description	77
3.3	Reflectometry	83
3.3.1	Time Delay Measurement	86
3.3.2	Phase Change at Cutoff	89
3.3.3	Profile Reconstruction	92
3.3.4	Localization of Reflecting Layer	93
3.3.5	Relativistic Corrections	95
3.3.6	Influence of Density Fluctuations	95
3.4	Scattering	100
3.4.1	Single-Particle Thomson Scattering	101
3.4.2	Doppler Shift	102
3.4.3	Incoherent Scattering	104
3.4.4	Relativistic Incoherent Scattering Spectrum	106
3.4.5	Role of Density Fluctuations	108
3.4.6	Coherent Scattering	108
3.4.7	Electron and Ion Feature	110
3.4.8	Summarizing Comments	113
	References	115
<b>4</b>	<b>Passive Diagnostics</b>	<b>117</b>
4.1	Bremsstrahlung	118
4.2	Electron Cyclotron Emission	122
4.2.1	Electron Motion in a Static $\vec{B}$ -Field	122
4.2.2	Electric Field and Spectrum, Single Electron	123
4.2.3	Perpendicular Observation, Characteristic Modes	126
4.2.4	Spectrum, Electron Ensemble	128
4.2.5	Absorption Coefficient	130
4.2.6	Emission Profile	132
4.2.7	$\vec{B}_0$ -Field Varying along Sightline	135

4.2.8	Optical Depth of Most Relevant Modes	137
4.2.9	Visibility Depth and Localization	139
4.2.10	Electron Cyclotron Absorption Measurement	142
4.3	Electron Bernstein Wave Emission	143
4.3.1	Electron Bernstein Waves	144
4.3.2	Mode Conversion	146
	References	149
<b>5</b>	<b>Guided Waves</b>	<b>151</b>
5.1	Transmission Line Properties	151
5.1.1	Waves on a Lossy Transmission Line	151
5.1.2	Terminated Transmission Line	153
5.1.3	Classification of Transmission Lines	157
5.1.4	Surface Currents	160
5.2	Coaxial Transmission Line	161
5.2.1	Characteristic Properties	162
5.2.2	Losses and Limits of Coaxial Lines	162
5.3	Rectangular Waveguides	163
5.3.1	TE Waves	164
5.3.2	TM Waves	166
5.3.3	Attenuation in Rectangular Waveguides	166
5.3.4	Fundamental $TE_{10}$ Wave	167
5.4	Circular Waveguides	170
5.4.1	Fields in Circular Waveguides	171
5.4.2	TM Waves	172
5.4.3	TE Waves	173
5.4.4	Loss in Circular Waveguides	175
5.5	Multimode Waveguides	176
5.5.1	Number of Modes Propagating	176
5.5.2	Multimode Propagation	178
5.5.3	$TE_{11}$ Mode in Overmoded Circular Waveguides	179
5.6	Corrugated Circular Waveguides	182
5.6.1	Fields of Corrugated Circular Waveguides	183
5.6.2	Characteristics of $HE_{11}$ Hybrid Mode	185
5.7	Gaussian Beams	185
5.7.1	Solution of Approximate Wave Equation	185
5.7.2	Transformation of Gaussian Beams	186
5.7.3	Lenses and Curved Mirrors	191
5.7.4	Truncation of Gaussian Beams	193
5.7.5	Coupling Coefficient for Fundamental Gaussian Beams	194
5.8	Vacuum Windows	196
5.8.1	Single-Disk Window	196
5.8.2	Half-Wave Window	197
5.8.3	Thin Window	198

5.8.4	Antireflection Coating	198
	References	199
<b>6</b>	<b>Radiation Generation and Detection</b>	<b>201</b>
6.1	Signal Sources	201
6.1.1	Backward-Wave Oscillator	201
6.1.2	Solid-State Oscillators	203
6.1.2.1	Gunn Oscillator	203
6.1.2.2	IMPATT Oscillator	205
6.1.3	Multiplier Chain	206
6.2	Antennas	208
6.2.1	Basic Definitions	208
6.2.2	Antenna Temperature	211
6.2.3	Pyramidal Horn	212
6.2.4	Conical Horn	214
6.2.5	Excitation of Gaussian Beams	215
6.2.6	Antenna Arrays	217
6.3	Detection	221
6.3.1	Overview and Classification	221
6.3.2	Bolometer	223
6.3.3	Hot Electron Bolometer	225
6.3.4	Noise Equivalent Power, NEP	226
6.3.5	Schottky Diode	227
6.3.6	Schottky Diode Frequency Multiplier	229
6.3.7	Diode Direct Detector	231
6.3.8	Schottky Detector Noise	233
6.4	Heterodyne Detection	236
6.4.1	Square-Law Mixer	237
6.4.2	Diode Mixer	239
6.4.3	Two-Port Mixer	241
6.4.4	Mixer Construction	245
6.5	Thermal Noise	246
6.5.1	Noise Temperature	247
6.5.2	Noise Figure	249
6.5.3	Noise Temperature of Cascaded Systems	250
6.5.4	Mixer Noise Temperature	251
6.5.5	Noise Temperature of Heterodyne Receiver	253
6.5.6	Measurement of Noise Temperature	255
6.6	Sensitivity Limits	256
6.6.1	Shot Noise Term	256
6.6.2	Thermal Radiation Term	258
6.6.3	Influence of Bandwidth	259
6.6.4	Noise-Equivalent Power, Incoherent Detection	260
6.6.5	Noise-Equivalent Power, Coherent Detection	261
6.6.6	Minimum Detectable Temperature	263

6.7	Correlation Radiometry	264
6.7.1	Intensity Fluctuations	264
6.7.2	Cross-Correlation Function	265
6.7.3	Intensity Fluctuations and Coherence	266
6.7.4	van Cittert-Zernike Theorem	268
6.7.5	Intensity Interferometer	269
6.7.6	Accuracy of Cross-Correlation Measurements	270
6.7.7	Alternative Decorrelation	271
	References	273
<b>7</b>	<b>Components and Subsystems</b>	<b>275</b>
7.1	Two-Port Characterization	275
7.1.1	Scattering Parameters	275
7.1.2	Transmission and Reflection	278
7.1.3	Directional Coupler	281
7.1.4	Nonreciprocal Devices	283
7.2	Network-Analysis Measuring Techniques	286
7.2.1	Transmission Measurement	286
7.2.2	Reflection Measurement	287
7.2.3	Substitution Measurement	288
7.2.4	Measurements Using Noise Sources	289
7.3	Frequency- and Polarization-Selective Filters	290
7.3.1	General Definitions	291
7.3.2	Waveguide Band-Stop Filter	292
7.3.3	Band-Pass Filter in Overmoded Waveguide	293
7.3.4	Metallic Meshes	296
7.3.5	Polarization Filters	298
7.4	Phase Measurement	299
7.4.1	Phase Measurements with Analog Output	299
7.4.2	All-Digital Phase Measurement	301
7.4.3	Phase Determination by Software	303
7.5	Signal Linearity	304
7.5.1	Gain Compression	304
7.5.2	Intermodulation	305
7.6	Frequency Stability	308
7.6.1	Control Loop Components	308
7.6.2	PLL Circuits in the Millimeter-Wave Range	309
7.6.3	Comments on the Theoretical Concept	310
	References	313
<b>8</b>	<b>Architecture of Realized Millimeter-Wave Diagnostic Systems</b>	<b>315</b>
8.1	Interferometer	315
8.1.1	Comments on Wavelength	316
8.1.2	Mach-Zehnder Interferometer	318
8.1.3	Mach-Zehnder Heterodyne Interferometer	319

8.1.4	Frequency Stability	320
8.1.5	Path Length Variations	322
8.1.6	Swept Frequency Interferometer	324
8.1.7	Multichannel Interferometer	324
8.2	Polarimeter	326
8.2.1	Evolution of the Polarization State	326
8.2.2	Modulation Techniques	327
8.2.2.1	Modulation Scheme 1	327
8.2.2.2	Modulation Scheme 2	328
8.2.2.3	Modulation Scheme 3	329
8.2.3	Faraday Polarimeter	329
8.2.4	Cotton–Mouton Polarimeter	330
8.3	Reflectometer	332
8.3.1	Swept Single-Frequency System	333
8.3.2	Multifrequency Systems	337
8.3.3	Pulse Radar Technique	339
8.3.4	Ultrashort Pulse Radar	342
8.3.5	Distance Calibration and Spurious Reflections	344
8.3.6	Comments on Fluctuation Measurements	345
8.3.7	Doppler Reflectometry	346
8.3.8	Imaging Reflectometry	348
8.4	Radiometry of Electron Cyclotron Emission	349
8.4.1	General Requirements	350
8.4.2	Michelson Interferometer	352
8.4.3	Martin–Puplett Polarizing Interferometer	354
8.4.4	Grating Spectrometer	356
8.4.5	Heterodyne Radiometers	357
8.4.6	ECE Imaging	362
8.4.7	System Parameters	363
8.4.8	Calibration	366
8.5	Detection of Electron Bernstein Wave Emission	370
8.6	Coherent Scattering	373
8.7	Summarizing Comments	375
	References	378

## **Appendix A: Symbols and Constants** 381

## **Appendix B: Formulas and Calculations** 387

B.1	Functions $Q_{ij}$	387
B.2	Cold-Plasma Limit	388
B.3	FLR Approximation	388
B.4	Warm-Plasma Approximation	390
B.5	Waveguide Attenuation	391
B.6	Metallic Mesh Transmission	393
	References	393

	<b>Appendix C: Tables and Material Constants</b>	395
C.1	Waveguides, Technical Data	395
C.2	Waveguides, Theoretical Relations	396
C.3	Dielectric Materials, Electrical Data	396
C.4	Dielectric Materials, Mechanical Data	397
C.5	Dielectric Materials, Names	397
C.6	Gunn Oscillators	398
	References	398
	<b>Index</b>	401

