
Contents

	<i>Preface</i>	<i>page</i> ix
	<i>Conventions and Notation</i>	xii
1	Preliminary Concepts	1
	1.1 Particle (Electron) Beams	1
	1.1.1 Electron Beam Phase Space	2
	1.1.2 Beam Transport and Linear Optics	3
	1.1.3 Beam Emittance and Envelope Functions	4
	1.1.4 Beam Properties under Simple Transport	6
	1.1.5 Electron Distribution Function on Phase Space	9
	1.2 Radiation Beams	12
	1.2.1 Diffraction of Paraxial Beams	13
	1.2.2 The Paraxial Wave Equation and Energy Transport	16
	1.2.3 Phase Space Methods in Wave Optics	18
	1.2.4 Transverse Coherence	22
	1.2.5 Temporal Coherence	26
	1.2.6 Bunching and Intensity Enhancement	29
	References	31
2	Synchrotron Radiation	33
	2.1 Radiation by Relativistic Electrons	35
	2.2 The Driven Paraxial Wave Equation	37
	2.3 Bending Magnet Radiation	40
	2.4 Undulator Radiation	43
	2.4.1 Electron Trajectory and a Qualitative Discussion of Undulator Radiation	44
	2.4.2 Paraxial Analysis of Undulator Radiation	48
	2.4.3 Frequency Integrated Power	52
	2.4.4 Polarization Control	53
	2.4.5 Undulator Brightness and the Effects of the Electron Beam Distribution	56
	2.4.6 From Undulator Radiation to Free-Electron Lasers	62
	2.5 Future Directions of Synchrotron Radiation Sources	64

	2.5.1 Multi-Bend Achromat Lattices for Smaller Storage Ring Emittances	64
	2.5.2 Energy Recovery Linacs	66
	2.5.3 Superconducting Undulators	67
	2.5.4 Laser Undulator	69
	References	71
3	Basic FEL Physics	74
	3.1 Introduction	74
	3.1.1 Coherent Radiation Sources	74
	3.1.2 What Is an FEL?	76
	3.2 Electron Equations of Motion: The Pendulum Equations	78
	3.2.1 Derivation of the Equations	78
	3.2.2 Motion in Phase Space	82
	3.3 Low-Gain Regime	83
	3.3.1 Derivation of Gain	83
	3.3.2 Particle Trapping and Low-Gain Saturation	88
	3.4 High-Gain Regime	90
	3.4.1 Maxwell Equation	91
	3.4.2 FEL Equations and Energy Conservation	94
	3.4.3 Dimensionless FEL Scaling Parameter ρ	95
	3.4.4 1D Solution Using Collective Variables	97
	3.4.5 Qualitative Description of Self-Amplified Spontaneous Emission (SASE)	99
	References	102
4	1D FEL Analysis	104
	4.1 Coupled Maxwell–Klimontovich Equations for the 1D FEL	104
	4.2 Perturbative Solution for Small FEL Gain	107
	4.3 Solution via Laplace Transformation for Arbitrary FEL Gain	110
	4.3.1 Spontaneous Radiation and the Low-Gain Limit	112
	4.3.2 Exponential Growth Regime	113
	4.3.3 Temporal Fluctuation and Correlation of SASE	118
	4.4 Quasilinear Theory and Saturation	122
	4.5 Undulator Tapering after Gain Saturation	129
	4.6 Superradiance	132
	References	136
5	3D FEL Analysis	139
	5.1 Qualitative Discussion	139
	5.1.1 Diffraction and Guiding	139
	5.1.2 Beam Emittance and Focusing	142
	5.2 Electron Trajectory	143
	5.2.1 Natural Focusing in an Undulator	144

5.2.2	Betatron Motion in an External Focusing Lattice	148
5.3	3D Equations of the FEL	151
5.3.1	Maxwell Equation	151
5.3.2	3D Pendulum Equations for the Electron Motion	152
5.3.3	Coupled Maxwell–Klimontovich Equations	154
5.4	Solution in the Low-Gain Regime	156
5.4.1	Low-Gain Expression for No Transverse Focusing	160
5.5	Solution in the High-Gain Regime	162
5.5.1	Van Kampen’s Normal Mode Expansion	163
5.5.2	Dispersion Relation with Four Scaled Parameters	167
5.5.3	Gain Guiding and Transverse Coherence	168
5.5.4	Numerically Solving the Dispersion Relation	171
5.5.5	Variational Solution and Fitting Formulas	176
	References	180
6	Harmonic Generation in High-Gain FELs	182
6.1	Nonlinear Harmonic Generation	182
6.2	High-Gain Harmonic Generation	186
6.3	Echo-Enabled Harmonic Generation	189
6.4	Recent Developments in Harmonic Generation	194
	References	195
7	FEL Oscillators and Coherent Hard X-Rays	197
7.1	FEL Oscillator Principles	197
7.1.1	Power Evolution and Saturation	198
7.1.2	Qualitative Description of Longitudinal Mode Development	199
7.1.3	Longitudinal Supermodes of the FEL Oscillator	200
7.1.4	Transverse Physics of the Optical Cavity	203
7.2	X-Ray Cavity Configurations	204
7.2.1	Four-Crystal, Wavelength-Tunable XFEL Cavity	205
7.2.2	Diamond Crystals for XFEL	208
7.3	XFEL Parameters and Performance	208
7.4	X-Ray Frequency Combs from a Mode-Locked FEL Oscillator	209
7.5	A Hard X-Ray Master–Oscillator–Power Amplifier (MOPA)	212
	References	213
8	Practical Considerations and Experimental Results for High-Gain FELs	215
8.1	Undulator Tolerances and Wakefields	215
8.1.1	Undulator Errors and Tolerances	216
8.1.2	Beam Trajectory Errors	217
8.1.3	Wakefield Effects, Energy Loss, and Undulator Tapering	220
8.2	FEL Experimental Results	223
8.2.1	SASE FELs	224
8.2.2	Seeded FEL	230

8.2.3 Short-Pulse Generation	232
References	237
Appendix A Hamilton's Equations of Motion on Phase Space	240
A.1 FEL Particle Equations from Transformation Theory	242
A.2 Motion of a Test Electron in a High-Gain FEL	244
References	245
Appendix B Simulation Methods for FELs	246
B.1 The Design of FEL Simulation Codes	247
B.2 Existing FEL Codes	253
References	254
Appendix C Quantum Considerations for the FEL	255
C.1 The Quantum Formulation	255
C.2 Quantum Noise in the FEL Amplifier	259
C.3 Madey's Theorem	265
References	267
Appendix D Transverse Gradient Undulators	268
D.1 Low-Gain Analysis	271
D.2 High-Gain Analysis	276
References	278
<i>Further Reading</i>	279
<i>Index</i>	281