

Contents

1. Introduction	1
1.1 Advantages of FELs Over Quantum Lasers	3
1.2 Principle of FEL Operation	4
1.3 Suggested Bibliography	11
2. One-Dimensional Theory of the FEL Amplifier	13
2.1 Linear Mode of Operation	15
2.1.1 Effective Hamiltonian	15
2.1.2 Self-Consistent Equations	18
2.1.3 Solution of the Initial-Value Problem by the Laplace Technique	22
2.1.4 General Solution of the Initial-Value Problem	38
2.1.5 Linear Theory of the FEL Amplifier with a Planar Undulator	41
2.2 Saturation Effects	48
2.2.1 Self-Consistent Equations	49
2.2.2 Numerical Simulation Algorithm	51
2.2.3 Power Balance	51
2.2.4 Saturation in the High-Gain FEL Amplifier	52
2.2.5 Space Charge Effects	59
2.2.6 Energy Spread Effects	61
2.2.7 FEL Amplifier with a Planar Undulator	63
2.3 FEL Amplifier with Tapered Undulator	65
2.3.1 Low-Efficiency Approximation	66
2.3.2 The High-Efficiency FEL Amplifier	76
2.3.3 Some Generalizations	79
2.4 Concluding Remarks	82
2.5 Suggested Bibliography	86
3. One-Dimensional Theory of the FEL Oscillator	87
3.1 Small-Signal Gain	89
3.1.1 Basic Relations	89
3.1.2 Cold Electron Beam	91
3.1.3 Gaussian Energy Spread	92

VIII Contents

3.1.4	Space Charge Effects	94
3.2	Saturation Effects in the FEL Oscillator	96
3.2.1	Self-Consistent Equations	97
3.2.2	Nonlinear Simulation Algorithm	98
3.2.3	Resonator Losses and Efficiency Optimization	99
3.2.4	Space Charge and FEL Efficiency	104
3.2.5	Energy Spread and FEL Efficiency	106
3.2.6	Some Generalizations	107
3.3	FEL Oscillator with Nonuniform Undulator	111
3.3.1	Basic Equations	113
3.3.2	Optical Klystron	118
3.3.3	FEL Oscillator with a Prebuncher and a Tapered Main Undulator	126
3.4	Start-Up from Shot Noise in the FEL Oscillator	134
3.4.1	Basic Equations	135
3.4.2	General Results	139
3.4.3	Operation Below Threshold	144
3.4.4	Operation Above Threshold	146
3.5	Concluding Remarks	149
3.6	Suggested Bibliography	152
4.	Diffraction Effects in the FEL Amplifier	155
4.1	Self-Consistent Equations	159
4.2	Power Balance	164
4.3	Linear Theory of the FEL Amplifier with a Sheet Electron Beam	168
4.3.1	Eigenvalue Problem for a Stepped Profile	170
4.3.2	Analysis of the Beam Radiation Modes	178
4.3.3	Initial-Value Problem for a Stepped Profile	187
4.3.4	Epstein Profile	194
4.3.5	Parabolic Profile	205
4.3.6	Arbitrary Gradient Profile	209
4.4	Linear Theory of the FEL Amplifier with an Axisymmetric Electron Beam	214
4.4.1	Eigenvalue Problem for a Stepped Profile	214
4.4.2	Analysis of the Solutions	216
4.4.3	Initial-Value Problem for a Stepped Profile	225
4.4.4	Parabolic Profile	234
4.4.5	Arbitrary Gradient Profile	238
4.4.6	Numerical Solution of Initial-Value Problem	243
4.5	Nonlinear Mode of Operation	245
4.5.1	Nonlinear Simulation Algorithm	246
4.5.2	Some Results of Numerical Simulations	248
4.5.3	Planar Undulator	258
4.6	Concluding Remarks	259

4.7 Suggested Bibliography	261
5. Waveguide FELs.....	263
5.1 Self-Consistent Equations.....	265
5.1.1 Integro-Differential Equation for the Field	266
5.1.2 Integro-Differential Equation for the Beam Modulation	268
5.2 Power Balance	272
5.3 Beam Radiation Modes in a Circular Waveguide.....	276
5.3.1 Stepped Profile of Electron Beam.....	278
5.3.2 Parabolic Profile	303
5.3.3 Arbitrary Gradient Profile	307
5.4 Initial-Value Problem	309
5.4.1 Analytical Solution	309
5.4.2 Effective Potential for a Circular Waveguide	320
5.4.3 Numerical Solution	328
5.5 Nonlinear Mode of Operation	330
5.6 Rectangular Waveguide	340
5.7 Wall Resistance Effects.....	342
5.8 Concluding Remarks	350
5.9 Suggested Bibliography	351
6. FEL Amplifier Start-up from Shot Noise.....	353
6.1 Shot Noise in the Electron Beam	357
6.2 One-Dimensional Theory of SASE FEL	360
6.2.1 Analytical Description of the Linear Regime	360
6.2.2 Numerical Simulation Algorithm	380
6.2.3 Numerical Simulations of the Main Characteristics of a SASE FEL	385
6.3 Three-Dimensional Simulations of SASE FEL	402
6.3.1 Numerical Simulation Algorithm	402
6.3.2 Transverse Coherence	407
6.4 SASE FEL: Experiment and Theory	414
6.4.1 Region of Physical Parameters	415
6.4.2 Numerical Analysis of the Experiment	419
6.5 Suggested Bibliography	424
Appendices	425
A.1 The Extended Hamiltonian Formalism	425
A.2 Longitudinal Space Charge Field of a Modulated Electron Beam with Finite Transverse Size	428
A.3 Green's Function for a Homogeneous Waveguide.....	429
A.4 Eigenfunctions of a Passive Circular Waveguide	435
A.5 Calculation of the Sums in (5.119)	437
A.6 List of Symbols	441

X Contents

Suggested Further Reading	449
References	453
Index	457