Contents

1. Introduction 1
1.1 Short Historical Overview 1
1.2 Particle Accelerator Systems 5
1.2.1 Basic Components of Accelerator Facilities 5
1.2.2 Applications of Particle Accelerators 8
1.3 Basic Definitions and Formulas 9
1.3.1 Units and Dimensions 9
1.3.2 Basic Relativistic Formalism 12
1.3.3 Particle Collisions at High Energies 15
1.4 Basic Principles of Particle-Beam Dynamics 17
1.4.1 Stability of a Charged-Particle Beam 20
Problems 21

2. Linear Accelerators 25
2.1 Principles of Linear Accelerators 25
2.1.1 Charged Particles in Electric Fields 25
2.1.2 Electrostatic Accelerators 27
2.1.3 Induction Linear Accelerator 30
2.2 Acceleration by rf Fields 31
2.2.1 Basic Principle of Linear Accelerators 31
2.2.2 Waveguides for High Frequency EM Waves 33
2.3 Preinjector Beam Preparation 47
2.3.1 Prebuncher 47
2.3.2 Beam Chopper 49
Problems 50

3. Circular Accelerators 53
3.1 Betatron 54
3.2 Weak Focusing 58
3.3 Adiabatic Damping 60
3.4 Acceleration by rf Fields 62
3.4.1 Microtron 63
3.4.2 Cyclotron 65
3.4.3 Synchro Cyclotron 67
3.4.4 Isochron Cyclotron 68

3.5 Synchrotron 69
3.5.1 Storage Ring 71
3.6 Summary of Characteristic Parameters 72
Problems 73

4. Charged Particles in Electromagnetic Fields 75
4.1 The Lorentz Force 75
4.2 Coordinate System 76
4.3 Fundamentals of Charged Particle Beam Optics 81
4.3.1 Particle Beam Guidance 81
4.3.2 Particle Beam Focusing 84
4.4 Multipole Field Expansion 88
4.4.1 Laplace Equation 88
4.4.2 Magnetic Field Equations 91
4.5 Multipole Fields for Beam Transport Systems 92
4.6 Multipole Field Patterns and Pole Profiles 97
4.7 Equations of Motion in Charged Particle Beam Dynamics 100
4.8 General Solution of the Equations of Motion 103
4.8.1 Linear Unperturbed Equation of Motion 104
4.8.2 Wronskian 106
4.8.3 Perturbation Terms 107
4.8.4 Dispersion Function 109
4.9 Building Blocks for Beam Transport Lines 110
4.9.1 General Focusing Properties 110
4.9.2 Chromatic Properties 112
4.9.3 Achromatic Lattices 112
4.9.4 Isochronous Systems 113
Problems 116

5. Linear Beam Dynamics 118
5.1 Linear Beam Transport Systems 119
5.1.1 Nomenclature 120
5.2 Matrix Formalism in Linear Beam Dynamics 121
5.2.1 Driftspace 123
5.2.2 Quadrupole Magnet 123
5.2.3 Thin Lens Approximation 125
5.2.4 Quadrupole End Field Effects 127
5.2.5 Quadrupole Design Concepts 131
5.3 Focusing in Bending Magnets 137
5.3.1 Sector Magnets 138
5.3.2 Wedge Magnets 143
5.3.3 Rectangular Magnet 145
5.4 Particle Beams and Phase Space 147
5.4.1 Beam Emittance 147
5.4.2 Liouville's Theorem 149

5.4.3 Transformation in Phase Space 152
5.4.4 Measurement of the Beam Emittance 157
5.5 Betatron Functions 159
5.5.1 Beam Envelope 162
5.5.2 Beam Dynamics in Terms of Betatron Functions 162
5.5.3 Beam Dynamics in Normalized Coordinates 164
5.6 Dispersive Systems 168
5.6.1 Analytical Solution 168
5.6.2 (3 × 3)-Transformation Matrices 170
5.6.3 Linear Achromat 171
5.6.4 Spectrometer 174
5.7 Path Length and Momentum Compaction 178
Problems 180

6. Periodic Focusing Systems 184
6.1 FODO Lattice 185
6.1.1 Scaling of FODO Parameters 186
6.2 Betatron Motion in Periodic Structures 190
6.2.1 Stability Criterion 190
6.2.2 General FODO Lattice 192
6.3 Beam Dynamics in Periodic Closed Lattices 196
6.3.1 Hill's Equation 196
6.3.2 Periodic Betatron Functions 199
6.4 Periodic Dispersion Function 202
6.4.1 Scaling of the Dispersion in a FODO Lattice ... 202
6.4.2 General Solution for the Periodic Dispersion 205
6.5 Periodic Lattices in Circular Accelerators 210
6.5.1 Synchrotron Lattice 210
6.5.2 Phase Space Matching 212
6.5.3 Dispersion Matching 213
6.5.4 Magnet Free Insertions 215
6.5.5 Low Beta Insertions 218
6.5.6 Example of a Colliding Beam Storage Ring 219
Problems 221

7. Perturbations in Beam Dynamics 225
7.1 Magnet Alignment Errors 226
7.2 Dipole Field Perturbations 228
7.2.1 Existence of Equilibrium Orbits 229
7.2.2 Closed Orbit Distortion 231
7.2.3 Closed Orbit Correction 238
7.3 Quadrupole Field Perturbations 240
7.3.1 Betatron Tune Shift 240
7.3.2 Resonances and Stop Band Width 243
7.3.3 Perturbation of Betatron Functions 246

7.4 Resonance Theory 248
7.4.1 Resonance Conditions 249
7.4.2 Coupling Resonances 253
7.4.3 Resonance Diagram 254
7.5 Chromatic Effects in a Circular Accelerator 255
7.5.1 Chromaticity 256
7.5.2 Chromaticity Correction 260
Problems 262

8. Charged Particle Acceleration 265
8.1 Longitudinal Particle Motion 266
8.1.1 Longitudinal Phase Space Dynamics 267
8.1.2 Equation of Motion in Phase Space 271
8.1.3 Phase Stability 277
8.1.4 Acceleration of Charged Particles 282
8.2 Longitudinal Phase Space Parameters 285
8.2.1 Separatrix Parameters 285
8.2.2 Momentum Acceptance 287
8.2.3 Bunch Length 290
8.2.4 Longitudinal Beam Emittance 292
8.2.5 Phase Space Matching 293
Problems 297

9. Synchrotron Radiation 300
9.1 Physics of Synchrotron Radiation 302
9.1.1 Coulomb Regime 302
9.1.2 Radiation Regime 303
9.1.3 Spatial Distribution of Synchrotron Radiation 306
9.1.4 Radiation Power 307
9.1.5 Synchrotron Radiation Spectrum 311
9.1.6 Photon Beam Divergence 315
9.2 Coherent Radiation 317
9.2.1 Temporal Coherent Synchrotron Radiation 318
9.2.2 Spatially Coherent Synchrotron Radiation 320
9.2.3 Spectral Brightness 324
9.2.4 Matching 325
9.3 Insertion Devices 326
9.3.1 Bending Magnet Radiation 326
9.3.2 Wave Length Shifter 327
9.3.3 Wiggler Magnet Radiation 327
9.3.4 Undulator Radiation 330
9.4 Back Scattered Photons 333
9.4.1 Radiation Intensity 333
Problems 335

10. Particle Beam Parameters 337
10.1 Definition of Beam Parameters 337
10.1.1 Beam Energy 337
10.1.2 Time Structure 338
10.1.3 Beam Current 338
10.1.4 Beam Dimensions 339
10.2 Damping 341
10.2.1 Robinson Criterion 342
10.3 Particle Distribution in Phase Space 348
10.3.1 Equilibrium Phase Space 349
10.3.2 Transverse Beam Parameters 355
10.4 Variation of the Equilibrium Beam Emittance 358
10.4.1 Beam Emittance and Wiggler Magnets 358
10.4.2 Damping Wigglers 360
10.5 Variation of the Damping Distribution 363
10.5.1 Damping Partition and rf Frequency 363
10.5.2 Robinson Wiggler 365
10.5.3 Damping Partition and Synchrotron Oscillation . 365
10.5.4 Can We Eliminate the Beam Energy Spread? ... 366
Problems 368

11. Beam Life Time 370
11.1 Beam Lifetime and Vacuum 371
11.1.1 Elastic Scattering 372
11.1.2 Inelastic Scattering 378
11.2 Ultra High Vacuum System 380
11.2.1 Thermal Gas Desorption 381
11.2.2 Synchrotron Radiation Induced Desorption 381
Problems 383

12. Collective Phenomena 384
12.1 Linear Space-Charge Effects 384
12.1.1 Self Field for Particle Beams 385
12.1.2 Forces from Space-Charge Fields 387
12.2 Beam–Beam Effect 388
12.3 Wake Fields 390
12.3.1 Parasitic Mode Losses and Impedances 391
12.4 Beam Instabilities 396
Problems 401

13. Beam Emittance and Lattice Design 402
13.1 Equilibrium Beam Emittance in Storage Rings 403
13.2 Beam Emittance in Periodic Lattices 407
13.2.1 The Double Bend Achromat Lattice (DBA) 407
13.2.2 The Triple Bend Achromat Lattice (TBA) 410

13.2.3 The Triplet Achromat Lattice (TAL) 410
13.2.4 The FODO Lattice 413
13.3 Optimum Emittance for Colliding Beam Storage Rings . 416
Problems 417

Appendices

A. Suggested Reading 419

B. Bibliography 424

References 427

Author Index 437

Subject Index 441