Contents

Foreword *x*
Preface *xi*
About the Authors *xiv*
Acknowledgments *xvi*
Acronyms *xvii*
About the Companion Website *xix*

1 Introduction to Charged Particle Beams *1*
1.1 History of Particle Accelerators and the Chronological Milestones *6*
1.2 Maxwell's Equations *9*
1.2.1 Maxwell's First Equation: Gauss's Law for Electricity *10*
1.2.2 Maxwell's Second Equation: Gauss's Law for Magnetism *10*
1.2.3 Maxwell's Third Equation: Faraday's Law of Electromagnetic Induction *10*
1.2.4 Maxwell's Fourth Equation: Ampère's Law with Maxwell's Addition *11*
1.3 Electrostatic Accelerators *11*
1.3.1 Cockcroft–Walton Accelerator *11*
1.3.2 Tandem Accelerators *14*
1.4 Cyclotrons *18*
1.5 Synchrotrons *21*
1.6 Synchrocyclotron *23*
1.7 Betatron *25*
1.8 Particle Colliders *26*
1.8.1 Microtron *27*
1.9 FFAG Accelerators *28*
1.10 Wakefield Accelerators *30*
1.10.1 Laser Wakefield Acceleration *30*
1.10.2 Beam Wakefield Acceleration *34*
1.11 Radiation Physics *36*
1.12 Beam Conceptual Visualization *39*
1.13 Numerical Problems *40*

2 Ion Sources *43*
2.1 ECR Ion Sources *44*
2.1.1 Electron Energy Distribution Function *47*
2.1.2 Magnetic Confinement by a Mirror Field *47*
2.1.3 Modes of ECR Cavity and Plasma Frequency *49*
2.1.4 Plasma Potential *50*
2.1.5 Geller Scaling Laws *51*
2.2 SNICS Ion Source *52*
2.3 Duoplasmatron *54*
2.4 Electron Beam Ion Source *55*
2.5 Penning Ion Sources *57*
2.6 Laser Ion Sources *59*
2.7 Vacuum Arc Ion Source *61*
2.8 Numerical Problems *61*

3 Beam Optics *63*
3.1 Phase Space and Liouville's Theorem *64*
3.2 Emittance and Acceptance *66*
3.3 Brightness *68*
3.4 Luminosity *69*
3.5 Matrix Formalism *71*
3.5.1 Significance of Transfer Matrix Elements *75*
3.6 Equation of Motion in a Co-moving Coordinate System *76*
3.7 Hill's Equation and Twiss Parameters Formalism *79*
3.8 Horizontal and Vertical Root Mean Square Beam Sizes in Accelerators *84*
3.9 Betatron Phase Advance and Tune *86*
3.10 Chromaticity *89*
3.11 RMS Emittance *91*
3.12 Space Charge Effects on Ion Beam *93*
3.13 Numerical Problems *96*

4 Motion in Magnetostatic Devices *99*
4.1 Magnetostatic Devices *99*
4.1.1 Motion of a Charged Particle in a Magnetic Field *100*
4.2 Ampere's Law for Magnet Design *101*
4.3 Equation of Motion in a Co-moving Coordinate System *101*
4.4 Drift *104*
4.5 Dipole Magnets *106*
4.5.1 Radial and Vertical Motion Inside Dipole Magnets *106*
4.6 Design of Dipole Magnets *110*
4.6.1 Steps for Designing a Dipole Magnet *113*
4.6.2 Edge Effects in a Dipole Magnet *114*
4.7 Quadrupole Magnets *116*
4.7.1 Design of Quadrupole Magnets *118*
4.8 Beam Rotation Matrix *120*

"ftoc_PrintPDF" — 2025/8/4 — 14:45 — page vii — #3

4.9 Solenoid Magnets *120*
4.9.1 Focal Length of Solenoid Magnet *123*
4.9.2 Design of Solenoid Magnets *126*
4.10 Sextupole Magnets *128*
4.11 Magnetostatic Steerer/Deflector *130*
4.12 Wien Filter *132*
4.13 Achromatic Magnets *134*
4.13.1 Two Dipoles Bending in Same Directions *135*
4.13.2 Two Dipoles Bending in Opposite Directions *135*
4.14 Septum and Kicker Magnets *136*
4.15 Glaser Lens *137*
4.16 Undulators *141*
4.17 Wigglers *145*
4.18 Numerical Problems *148*

5 Electrostatic Devices *151*
5.1 Motion of a Charged Particle in an Electric Field *151*
5.2 Electrostatic Dipole *152*
5.2.1 Radial and Vertical Motion Inside an Electric Field *153*
5.3 Electrostatic Quadrupole *155*
5.4 Electrostatic Thin Lens and Einzel Lens *158*
5.5 Electrostatic Steerer/Deflector *165*
5.6 Electrostatic Accelerating Tube *165*
5.7 Electrostatic Septum *169*
5.8 Numerical Problems *170*

6 Radio Frequency Devices *171*
6.1 Longitudinal Beam Dynamics *172*
6.2 Pillbox Cavity *175*
6.3 Traveling Wave Structures *175*
6.4 Standing Wave Structures *176*
6.4.1 RF Devices *178*
6.4.2 Earnshaw's Theorem *179*
6.4.3 Motion of a Charged Particle in an RF Field *180*
6.5 Phase Stability in LINACs *181*
6.6 Radial Impulse and Deflection in an RF Gap *186*
6.7 RF Chopper *188*
6.8 RF Buncher *189*
6.9 RF Acceleration *190*
6.9.1 Wideroe Structure *191*
6.9.2 Sloan–Lawrence Structure *191*
6.9.3 Alvarez Structure *191*
6.10 Quarter-wave and Half-wave Resonators *193*
6.11 Radio Frequency Quadrupole *195*

"ftoc_PrintPDF" — 2025/8/4 — 14:45 — page viii — #4

6.12 Drift Tube LINACS *197*
6.13 Numerical Problems *199*

7 Beam Diagnostics *201*
7.1 Faraday Cups *203*
7.2 Beam Profile Monitor *204*
7.3 Beam Position Monitors *204*
7.4 Beam Current Transformers *207*
7.5 Capacitive Pick-up Probes *208*
7.6 Fast Faraday Cups *209*
7.7 Phase Detector Cavity *212*
7.8 Transverse Beam Emittance by Quadrupole Magnet Scan *214*
7.9 Longitudinal Beam Emittance by Buncher Scan *215*
7.9.1 Bunch Length Measurements *216*
7.10 Energy Spread Measurements *217*
7.11 Ion Bunch Width Using Detectors *217*
7.12 Numerical Problems *219*

8 Vacuum Devices *221*
8.1 Basics of Vacuum Technology *222*
8.1.1 Units in Vacuum *222*
8.1.2 Ideal Gas Law *224*
8.1.3 Mean Free Path, Knudsen Number, Reynolds Number, Coefficient of Viscosity *226*
8.1.4 Conductance, Pumping Speed, Throughput, and Outgassing in Vacuum Systems *229*
8.2 Vacuum Accessories and Subcomponents *231*
8.2.1 Fast Valves *231*
8.2.2 Vacuum Bellows *232*
8.2.3 Rubber Gaskets *232*
8.2.4 Metallic Gaskets *233*
8.2.5 Vacuum Flanges and Adapters *233*
8.3 Vacuum Pumps *234*
8.3.1 Oil-sealed Rotary Vane Pumps *235*
8.3.2 Turbomolecular Pump *235*
8.3.3 Ion Pump *236*
8.3.4 Getter Pump *236*
8.3.5 Diaphragm Pump *236*
8.3.6 Roots Blower *237*
8.3.7 Scroll Pump *237*
8.3.8 Screw Vacuum Pumps *237*
8.3.9 Cryopump or Sorption Pump *238*
8.3.10 Diffusion Pump *238*

"ftoc_PrintPDF" — 2025/8/4 — 14:45 — page ix — #5

8.4 Vacuum Gauges *238*
8.4.1 Pirani Gauge *239*
8.4.2 Capacitance Manometer *239*
8.4.3 Thermocouple Gauge *240*
8.4.4 Cold Cathode Ionization Gauge *240*
8.4.5 McLeod Gauge *240*
8.4.6 Penning Gauge *240*
8.4.7 Bayard–Alpert Gauge *241*
8.4.8 Bourdon Gauge *241*
8.5 Helium Leak Detector: Mathematical Principles *241*
8.5.1 Steps for Leak Detection *242*
8.6 Numerical Problems *243*

Appendix A: Field-induced Breakdown in Accelerator Technologies *245*
Paschen's Law for the Breakdown Voltage of Gases *247*
Appendix B: Panofsky–Wenzel Theorem in Accelerator Physics *249*
Appendix C: Child–Langmuir Law and Richardson's Law *253*
Appendix D: Larmor's Formula and Its Importance in Accelerator Physics *255*
Appendix E: Stefan–Boltzmann Law and Its Applications in Particle Accelerators *257*
Bibliography *259*
Index *263*