Contents

Preface to the Second Edition XI

Preface to the First Edition XIII

- **1** Introduction 1
- 1.1 Linear Accelerators: Historical Perspective 2
- 1.2 Linac Structures 6
- 1.3 Linac Beam Dynamics 10
- 1.4 Multiparticle Effects 12
- 1.5 Applications of Modern RF Linacs 13
- 1.6 Accelerator-Physics
- Units, Unit Conversions, and Physical Constants 15
- 1.7 Useful Relativistic Mechanics Relationships 16
- 1.8 Maxwell's Equations 17
- 1.9 Conducting Walls 19
- 1.10 Group Velocity and Energy Velocity 20
- 1.11 Coaxial Resonator 22
- 1.12 Transverse-Magnetic Mode of a Circular Cylindrical Cavity 24

۷

- 1.13 Cylindrical Resonator Transverse-Magnetic Modes 26
 - Cylindrical Resonator Transverse Electric Modes 27
 - References 30

2 RF Acceleration in Linacs 32

- 2.1 Particle Acceleration in an RF Field 32
- 2.2 Energy Gain on Axis in an RF Gap 33
- 2.3 Longitudinal Electric Field as a Fourier Integral 36
- 2.4 Transit-Time-Factor Models 39
- 2.5 Power and Acceleration Efficiency Figures of Merit 42
- 2.6 Cavity Design Issues 44
- 2.7 Frequency Scaling of Cavity Parameters 46
- 2.8 Linac Economics 47 References 52

RF Linear Accelerators. 2nd, completely revised and enlarged edition.

Thomas P. Wangler

1.14

Copyright © 2008 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim ISBN: 978-3-527-40680-7

VI	Contents

3	Periodic Accelerating Structures 53
3.1	Synchronous Acceleration and Periodic Structures 53
3.2	Floquet Theorem and Space Harmonics 54
3.3	General Description of Periodic Structures 57
3.4	Equivalent Circuit Model for Periodic Structures 59
3.5	Periodic Array of Low-Pass Filters 61
3.6	Periodic Array of Electrically Coupled Circuits 62
3.7	Periodic Array of Magnetically Coupled Circuits 63
3.8	Periodic Array of Cavities with Resonant Coupling Element 64
3.9	Measurement of Dispersion Curves in Periodic Structures 65
3.10	Traveling-Wave Linac Structures 68
3.11	Analysis of the Periodic Iris-Loaded Waveguide 69
3.12	Constant-Impedance Traveling-Wave Structure 72
3.13	Constant-Gradient Structure 74
3.14 3.15	Characteristics of Normal Modes for Particle Acceleration 76 Physics
	Regimes of Traveling-Wave and Standing-Wave Structures 79
	References 81
4	Standard Linac Structures 83
4.1	Independent-Cavity Linacs 83
4.2	Wideröe Linac 87
4.3	H-Mode Structures 89
4.4	Alvarez Drift-Tube Linac 91
4.5	Design of Drift-Tube Linacs 96
4.6	Coupled-Cavity Linacs 98
4.7	Three Coupled Oscillators 99
4.8	Perturbation
	Theory and Effects of Resonant-Frequency Errors 101
4.9	Effects from Ohmic Power Dissipation 103
4.10	General Problem of $N + 1$ Coupled Oscillators 105
4.11	Biperiodic Structures for Linacs 108
4.12	Design of Coupled-Cavity Linacs 111
4.13	Intercell Coupling Constant 114
4.14	Decoupling of Cavities Connected by a Beam Pipe 116
4.15	Resonant Coupling 117
4.16	Accelerating Structures for Superconducting Linacs 121
	$\lambda/4$ Superconducting Structures 121
	$\lambda/2$ Superconducting Structures 121
	TM Superconducting Structures 122
	RF Properties and
	Scaling Laws for TM and $\lambda/2$ Superconducting Structures 125 Shunt
	Impedance for TM and $\lambda/2$ Superconducting Structures127Stored Energy for TM and $\lambda/2$ Superconducting Structures129

Contents VII

Scaling Formulas for $\lambda/4$ Superconducting Structures 131 References 133

- 5 Microwave Topics for Linacs 135
- 5.1 Shunt Resonant Circuit Model 135
- 5.2 Theory of Resonant Cavities 137
- 5.3 Coupling to Cavities 138
- 5.4 Equivalent Circuit for a Resonant-Cavity System 139
- 5.5 Equivalent Circuit for a Cavity Coupled to two Waveguides 144
- 5.6 Transient Behavior of a Resonant-Cavity System 146
- 5.7 Wave Description of a Waveguide-to-Cavity Coupling 148
- 5.8 Microwave Power Systems for Linacs 156
- 5.9 Multipacting 159
- 5.10 Electron Field Emission 162
- 5.11 RF Electric Breakdown: Kilpatrick Criterion 163
- 5.12 Adiabatic Invariant of an Oscillator 164
- 5.13 Slater Perturbation Theorem 165
- 5.14 Quasistatic Approximation 167
- 5.15 Panofsky–Wenzel Theorem 168 References 173

6 Longitudinal Particle Dynamics 175

- 6.1 Longitudinal Focusing 175
- 6.2 Difference
 - Equations of Longitudinal Motion for Standing-Wave Linacs 177
- 6.3 Differential Equations of Longitudinal Motion 178
- 6.4 Longitudinal Motion when Acceleration Rate is Small 178
- 6.5 Hamiltonian and Liouville's Theorem 182
- 6.6 Small Amplitude Oscillations 186
- 6.7 Adiabatic Phase Damping 187
- 6.8 Longitudinal
 - Dynamics of Ion Beams in Coupled-Cavity Linacs 189
- 6.9 Longitudinal Dynamics in Independent-Cavity Ion Linacs 1906.10 Longitudinal
- Dynamics of Low-Energy Beams Injected into a v = c Linac 192 6.11 Rf Bunching 194
- 6.12 Longitudinal Beam Dynamics in H-Mode Linac Structures 196 References 199

7 Transverse Particle Dynamics 201

- 7.1 Transverse RF Focusing and Defocusing 201
- 7.2 Radial Impulse from a Synchronous Traveling Wave 203
- 7.3 Radial Impulse near the Axis in an Accelerating Gap 204
- 7.4 Including Electrostatic Focusing in the Gap 207
- 7.5 Coordinate Transformation through an Accelerating Gap 208

VIII Contents

7.6 Quadrupole Focusing in a Linac 209 Transfer-Matrix Solution of Hill's Equation 7.7 211 7.8 Phase-Amplitude Form of Solution to Hill's Equation 7.9 Transfer Matrix through One Period 214 7.10 Thin-Lens FODO Periodic Lattice 215 7.11 Transverse Stability Plot in a Linac 217 Effects of Random Quadrupole Misalignment Errors 7.12 7.13 Ellipse Transformations 221 7.14 Beam Matching 222 Current-Independent Beam Matching 7.15 224 7.16 Solenoid Focusing 225 7.17 Smooth Approximation to Linac Periodic Focusing 226 7.18 Radial Motion for Unfocused Relativistic Beams 227 References 230 Radiofrequency Quadrupole Linac 8 232 8.1 Principles of Operation 232 General Potential Function 236 8.2 8.3 Two-Term Potential Function Description 238 Electric Fields 8.4 240

213

218

- Synchronous Acceleration 8.5
- 241 8.6 Longitudinal Dynamics 242
- 8.7 Transverse Dynamics 243
- Adiabatic Bunching in the RFQ 8.8 245
- Four-Vane Cavity 8.9 248
- Lumped-Circuit Model of Four-Vane Cavity 8.10 249
- 8.11 Four-Vane Cavity Eigenmodes 251
- 8.12 Transmission-Line Model of Quadrupole Spectrum 254
- 8.13 Radial-Matching Section 260
- RFQ Transition Cell 8.14 265
- 8.15 Beam Ellipses in an RFQ 271
- 8.16 Tuning for the Desired Field Distribution in an RFQ 273
- 8.17 Four-Rod Cavity 274
- Four Vane with Windows RFQ 8.18 276 References 280

9 Multiparticle Dynamics with Space Charge 282

- 9.1 Beam Quality, Phase Space, and Emittance 283
- RMS Emittance 285 9.2
- 9.3 Transverse and Longitudinal Emittance 287
- 9.4 Emittance Conventions 288
- 9.5 Space-Charge Dynamics 289
- Practical Methods for Numerical Space-Charge Calculations 9.6 292
- 9.7 RMS Envelope Equation with Space Charge 296
- Continuous Elliptical Beams 9.8 297

Contents IX

352

- 9.9 Three-Dimensional Ellipsoidal Bunched Beams 299
- 9.10 Beam Dynamics Including Linear Space-Charge Field 300
- 9.11 Beam-Current Limits from Space Charge 302
- 9.12 Overview of Emittance Growth from Space Charge 303
- 9.13 Emittance Growth for rms Matched Beams 306
- 9.14 Model of Space-Charge-Induced Emittance Growth in a Linac 314
- 9.15 Emittance Growth for rms Mismatched Beams 316
- 9.16 Space-Charge Instabilities
- in RF Linacs from Periodic Focusing: Structure Resonances 3189.17 Longitudinal-Transverse Coupling
- and Space-Charge Instabilities for Anisotropic Linac Beams 3199.18 Beam Loss and Beam Halo 325
- 9.19 Los Alamos Beam Halo Experiment 329
- 9.20 Scaling of Emittance Growth and Halo 331
- 9.21 Longitudinal
 - Beam Dynamics Constraint on the Accelerating Gradient 332 References 338

10 Beam Loading 341

- 10.1 Fundamental Beam-Loading Theorem 342
- 10.2 The Single-Bunch Loss Parameter 344
- 10.3 Energy Loss to Higher-Order Cavity Modes 344
- 10.4 Beam Loading in the Accelerating Mode 345
- Equations Describing a Beam-Loaded Cavity 10.5 347 General Results 348 Optimum Detuning 350 Extreme Beam-Loaded Limit 351 Numerical Example of a Beam-Loaded Cavity 351 Example of a Heavily Beam - Loaded Superconducting Cavity with Bunches Injected on the Crest of the Accelerating Wave 10.6 Generator Power when the Beam Current is Less than Design Value 352 10.7 Transient Turn-On of a Beam-Loaded Cavity 354
- References 360

Wakefields 361

- 11.1 Image Force for Line Charge in Round Pipe 362
- 11.2 Fields from
 - a Relativistic Point Charge and Introduction to Wakefields 364
- 11.3 Wake Potential from a Relativistic Point Charge 367
- 11.4 Wake Potentials in Cylindrically Symmetric Structures 368
- 11.5 Scaling of Wake Potentials with Frequency 370
- 11.6 Bunch Wake Potentials for an Arbitrary Charge Distribution 371
- 11.7 Loss Parameters for a Particular Charge Distribution 376
- 11.8 Bunch Loss Parameters for a Gaussian Distribution 377
- 11.9 Beam-Coupling Impedance 378

X Contents

- 11.10 Longitudinal- and Transverse-Impedance Definitions 380
- 11.11 Impedance and Wake Potential for a Single Cavity Mode 381
- 11.12 Short-Range Wakefields-Parasitic Losses 383
- 11.13 Short-Range Wakefields: Energy Spread 383
- 11.14 Short-Range
- Wakefields: Compensation of Longitudinal Wake Effect 384
- 11.15 Short-Range Wakefields: Single-Bunch Beam Breakup 384
- 11.16 Short-Range Wakefields: BNS Damping of Beam Breakup 386
- 11.17 Long-Range Wakefields and Multibunch Beam Breakup 389
- 11.18 Multipass BBU in Recirculating Electron Linacs 397
 - References 402

12 Special Structures and Techniques 405

- 12.1 Alternating-Phase Focusing 405
- 12.2 Accelerating Structures Using Electric Focusing 406
- 12.3 Coupled-Cavity Drift-Tube Linac 410
- 12.4 Beam Funneling 411
- 12.5 RF Pulse Compression 413
- 12.6 Superconducting RF Linacs 414 Brief History 415 Introduction
- to the Physics and Technology of RF Superconductivity 416 12.7 Examples of Operating Superconducting Linacs 419 Atlas 419 CEBAF 419
 - Spallation Neutron Source 421
- 12.8 Future Superconducting Linac Facilities 423 International Linear Collider 423 Next-Generation Rare Isotope Facility 426 Free-Electron Lasers 427 References 430

Index 433