Table of Contents

Preface

1 INTRODUCTION 1
1.1 HOW TO USE THIS BOOK . . . 1
1.2 NOMENCLATURE . . . 1
1.3 FUNDAMENTAL CONSTANTS . . . 3
1.4 UNITS AND CONVERSIONS . . . 4
1.4.1 Units *A.W. Chao* . . . 4
1.4.2 Conversions *M. Tigner* . . . 4
1.5 FUNDAMENTAL FORMULAE *A.W. Chao* . . . 5
1.5.1 Special Functions . . . 5
1.5.2 Curvilinear Coordinate Systems . . . 6
1.5.3 Electromagnetism . . . 6
1.5.4 Kinematical Relations . . . 7
1.5.5 Vector Analysis . . . 8
1.5.6 Relativity . . . 8
1.6 GLOSSARY OF ACCELERATOR TYPES . . . 8
1.6.1 Antiproton Sources *J. Peoples, J.P. Marriner* . . . 8
1.6.2 Betatron *M. Tigner* . . . 10
1.6.3 Colliders *J. Rees* . . . 11
1.6.4 Cyclotron *H. Blosser* . . . 13
1.6.5 Electrostatic Accelerator *J. Ferry* . . . 16
1.6.6 Free Electron Lasers *C. Pellegrini* . . . 17
1.6.7 High Voltage Electrodynamic Accelerators *M. Cleland* . . . 20
1.6.8 Induction Linacs *R. Bangerter* . . . 23
1.6.9 Industrial Applications of Electrostatic Accelerators *G. Norton, J.L. Duggan* . 24
1.6.10 Linear Accelerators for Electron *G.A. Loew* . . . 26
1.6.11 Livingston Chart *J. Rees* . . . 29
1.6.12 Medical Applications of Accelerators *J. Alonso* . . . 29
1.6.12.1 Radiation therapy . . . 29
1.6.12.2 Radioisotopes . . . 32
1.6.13 Microtron *P.H. Debenham* . . . 33
1.6.14 $\mu^+\mu^-$ Colliders *R. Palmer* . . . 33
1.6.14.1 Collider . . . 33
1.6.14.2 Muon Storage Ring Neutrino Factories . . . 35
1.6.15 Pulsed High Voltage Devices *J. Nation* . . . 37
1.6.16 Radio Frequency Quadrupole *J. Staples* . . . 38
1.6.17 Spallation Sources *H. Lengeler* . . . 42
1.6.18 Synchrotrons and Storage Rings *E.J.N. Wilson* . . . 44
1.6.19 Two-Beam Accelerators *A. Sessler, G. Westenskow* . . . 46
1.6.20 Wakefield Accelerators *J. Simpson* . . . 49
1.7 COMPUTER CODE LIBRARY . . . 50

2 BEAM DYNAMICS **51**
2.1 PHASE SPACE . . . 51
2.1.1 Linear Betatron Motion *D.A. Edwards, M. Syphers* . . . 51
2.1.2 Longitudinal Motion *D.A. Edwards, M. Syphers* . . . 53
2.1.3 Linear Coupled Systems *D.A. Edwards, M. Syphers* . . . 54
2.1.4 Orbital Eigen-analysis for Electron Storage Rings *J.A. Ellison, H. Mais, G. Ripken* . . . 55
2.2 OPTICS AND LATTICES . . . 57
2.2.1 Single Element Optics *K. Brown* . . . 57
2.2.2 Cylinder Model of Multipoles *M. Bassetti, C. Biscari* . . . 61
2.2.3 Lattices for Collider Storage Rings *E. Keil* . . . 62
2.2.4 Lattices for Low-Emittance Light Sources *A. Jackson* . . . 65
2.2.5 Möbius Accelerators *R. Talman* . . . 67
2.2.6 Alpha Magnet *H. Wiedemann* . . . 68
2.3 NONLINEAR DYNAMICS . . . 69
2.3.1 Hamiltonian *K. Symon* . . . 69
2.3.1.1 General case . . . 69
2.3.1.2 Transverse motion . . . 71
2.3.1.3 Longitudinal motion . . . 71
2.3.1.4 Synchrobetatron coupling . . . 72
2.3.2 Tune Dependence on Momentum and Betatron Amplitudes *D.A. Edwards, M. Syphers* . . . 73
2.3.3 Nonlinear Resonances *D.A. Edwards, M. Syphers* . . . 73
2.3.4 Synchro-Betatron Resonances *A. Piwinski* . . . 74
2.3.5 Taylor Maps *J. Irwin, A. Dragt* . . . 77
2.3.6 Lie Maps *A. Dragt* . . . 78
2.3.7 Differential Algebraic Techniques *M. Berz* . . . 84
2.3.8 Numerical Integration Methods *H. Yoshida* . . . 87
2.3.8.1 Methods of realization . . . 87
2.3.8.2 Symplectic method vs. nonsymplectic method . . . 89
2.3.9 Dynamic Aperture *J. Irwin, Y.T. Yan* . . . 89
2.3.10 Decoherence *M.A. Furman* . . . 93
2.3.11 Momentum Compaction and Phase Slip Factor *K.Y. Ng* . . . 94
2.3.12 Nonlinear Dynamics Experiments *S.Peggs* . . . 95
2.3.13 Echo *G.V. Stupakov* . . . 98
2.3.14 Transverse Beam Shaping *J. Irwin* . . . 99
2.3.15 Hénon Map and Standard Map *Y.T. Yan* . . . 100
2.4 ELECTRON GUNS AND PRE-INJECTORS *H.G. Kirk, R. Miller, D. Yeremian* . . . 101
2.4.1 Brightness . . . 101
2.4.2 DC High Voltage Guns and Bunching Systems . . . 101
2.4.2.1 Gun characteristics . . . 101
2.4.2.2 Longitudinal dynamics . . . 102
2.4.2.3 Radial dynamics . . . 102
2.4.3 RF Guns . . . 103
2.4.4 Compensation of Space-Charge Effects . . . 104
2.5 COLLECTIVE EFFECTS . . . 105
2.5.1 Collective Effects in High Energy Electron Linacs *K. Thompson, K. Yokoya* . . . 105
2.5.1.1 Single bunch effects . . . 105
2.5.1.2 Multibunch Effects . . . 107
2.5.2 Beam Loading *D. Boussard* . . . 110
2.5.2.1 Single-bunch passage in a cavity . . . 110
2.5.2.2 Cavity equivalent circuit . . . 110

2.5.2.3 Transmission of small modulations (AM and PM) through a cavity with beam loading . . . 111
2.5.2.4 Periodic beam loading at multiples of f_0 . . . 112
2.5.2.5 Rf power needed for transient beam-loading correction . . . 112
2.5.2.6 Traveling-wave cavities . . . 113
2.5.3 Space Charge Effects in Circular Accelerators *B. Zotter* . . . 114
2.5.3.1 Direct space charge effects . . . 114
2.5.3.2 Betatron frequency shifts . . . 115
2.5.4 Vlasov and Fokker-Planck Equations *B. Zotter* . . . 117
2.5.5 Potential Well Effect *B. Zotter* . . . 117
2.5.6 Single-Bunch Instabilities in Circular Accelerators *B. Zotter* . . . 119
2.5.7 Sacherer Formulae *B. Zotter* . . . 120
2.5.8 Landau Damping *A.W. Chao, B. Zotter* . . . 124
2.5.9 Touschek Effect and Intrabeam Scattering *A. Piwinski* . . . 127
2.5.10 Ion Trapping, Beam-Ion Instabilities, and Dust *F. Zimmermann* . . . 129
2.5.10.1 Ion Trapping . . . 130
2.5.10.2 Dust particles . . . 130
2.5.10.3 Single-pass ion effects in storage rings and linacs . . . 131
2.5.11 Electron-Cloud Effect *M.A. Furman* . . . 133
2.6 BEAM-BEAM EFFECTS . . . 136
2.6.1 Beam-Beam Effects in Storage Rings *K.Hirata* . . . 136
2.6.1.1 Infinitely short bunches . . . 136
2.6.1.2 Long bunches . . . 140
2.6.1.3 Dispersion at IP, crossing angle . . . 140
2.6.2 Beam-Beam Effects in Linear Colliders *P. Chen* . . . 142
2.6.2.1 Disruption with negligible beamstrahlung . . . 142
2.6.2.2 Beamstrahlung with negligible disruption . . . 143
2.6.2.3 QED and QCD backgrounds . . . 145
2.6.3 Parasitic Beam-beam Effects and Separation Schemes *J.M. Jowett* . . . 146
2.6.3.1 Separation schemes . . . 146
2.6.3.2 Long-range beam-beam effects . . . 147
2.6.4 Beam-Beam Compensation Schemes *S. Peggs* . . . 149
2.7 POLARIZATION . . . 150
2.7.1 Thomas-BMT Equation *T. Roser* . . . 150
2.7.2 Spinor Algebra *T. Roser* . . . 151
2.7.3 Spin Rotators and Siberian Snakes *T. Roser* . . . 151
2.7.4 Ring with Spin Rotators and Siberian Snakes *T. Roser* . . . 152
2.7.5 Depolarizing Resonances and Spin Flippers *T. Roser* . . . 152
2.7.6 Polarized Proton Beams and Siberian Snakes *A.D. Krisch* . . . 153
2.7.7 Radiative Polarization in Electron Storage Rings *D.P. Barber, G. Ripken* . . . 155
2.7.8 Computer Algorithms and Spin Matching *D.P. Barber, G. Ripken* . . . 159
2.7.9 Lie Algebra for Spin Motion *K. Yokoya* . . . 167
2.8 BEAM COOLING . . . 168
2.8.1 Stochastic Cooling *J. Marriner* . . . 168
2.8.1.1 Cooling rates . . . 168
2.8.1.2 Hardware . . . 170
2.8.2 Electron Cooling *F. Krienen* . . . 171
2.8.3 Laser Cooling in Storage Rings *J.S. Hangst* . . . 174
2.8.4 Ionization Cooling *D. Neuffer* . . . 178
2.8.5 Crystalline Beams *J. Wei* . . . 180

3 ELECTROMAGNETIC AND NUCLEAR INTERACTIONS 183
3.1 SYNCHROTRON RADIATION . . . 183
3.1.1 Radiation of a Point Charge *H. Wiedemann* . . . 183
3.1.2 Coherent Radiation *H. Wiedemann* . . . 184
3.1.3 Bending Magnet Radiation *H. Wiedemann* . . . 185
3.1.4 Synchrotron Radiation in Storage Rings *H. Wiedemann* . . . 187
3.1.4.1 Radiation integrals . . . 187
3.1.4.2 Radiation damping . . . 188
3.1.4.3 Quantum excitation . . . 188
3.1.4.4 Equilibrium beam emittances . . . 189
3.1.4.5 Damping wigglers . . . 189
3.1.4.6 Quantum lifetimes . . . 190
3.1.5 Undulator and Wiggler Radiation *H. Wiedemann* . . . 190
3.1.6 Other Radiation Sources *R. Carr, H. Wiedemann* . . . 192
3.1.6.1 Transition radiation . . . 192
3.1.6.2 Free electron laser . . . 193
3.1.6.3 Cherenkov radiation . . . 193
3.1.6.4 "Short" magnet and edge radiation . . . 193
3.1.6.5 Bremsstrahlung . . . 194
3.1.6.6 Coherent bremsstrahlung . . . 194
3.1.6.7 Channeling radiation . . . 194
3.1.6.8 Compton backscattering radiation . . . 195
3.1.6.9 Diffraction radiation . . . 195
3.1.6.10 Parametric radiation . . . 195
3.1.6.11 Smith-Purcell radiation . . . 196
3.2 IMPEDANCES AND WAKE FUNCTIONS . . . 196
3.2.1 Definitions and Properties of Impedances and Wake Functions *T. Suzuki* . . . 196
3.2.2 Impedance Calculation, Frequency Domain *R.L. Gluckstern, S.S. Kurennoy* . 197
3.2.3 Impedance Calculation, Time Domain *T. Weiland* . . . 201
3.2.4 Special Impedances for Lossy Smooth Pipes *A. Piwinski* . . . 205
3.2.5 Explicit Expressions of Impedances and Wake Functions *K.Y. Ng* . . . 205
3.2.6 Effective impedance *T. Suzuki* . . . 211
3.2.7 Parasitic Loss *P. Wilson, B. Zotter* . . . 212
3.2.8 Trapped Modes *S.S. Kurennoy* . . . 215
3.3 PARTICLE-MATTER INTERACTION . . . 215
3.3.1 Basic Formulae *M. Tigner, A.W. Chao* . . . 215
3.3.2 Beam and Luminosity Lifetime . . . 218
3.3.2.1 Protons *N.V. Mokhov, V.I. Balbekov* . . . 218
3.3.2.2 Electrons *M.S. Zisman* . . . 220
3.3.3 Bhabha Scattering ($e^+e^- \rightarrow e^+e^-$) *J.E. Spencer* . . . 222
3.3.4 Compton Scattering ($e^{\pm}\gamma \rightarrow e^{\pm}\gamma$) *J.E. Spencer* . . . 224
3.3.5 Limit of Focusing of Electron Beam due to Synchrotron Radiation *K. Oide* . . . 226
3.3.6 Thermal Outgassing and Beam Induced Desorption
A.G. Mathewson, O. Gröbner . . . 227
3.3.7 Ionization Processes *F. Zimmermann* . . . 231
3.3.8 Beam Induced Detector Backgrounds and Irradiation in e^+e^- Colliders
S.D. Henderson . . . 231
3.3.8.1 Sources of detector backgrounds . . . 231
3.3.8.2 Detector and IR radiation tolerance and budget . . . 234
3.3.8.3 Detector background shielding . . . 235
3.3.8.4 Detector background and radiation estimation . . . 235

3.3.9 Particle Interactions and Beam-Induced Backgrounds and Radiation *N.V. Mokhov, S.I. Striganov* . . . 237
3.3.10 Beam Collimation *P. Bryant* . . . 244
3.3.11 Atomic and Nuclear Properties of Materials . . . 247

4 OPERATIONAL CONSIDERATIONS 251
4.1 LUMINOSITY *M.A. Furman, M.S. Zisman* . . . 251
4.2 BRIGHTNESS *K.-J. Kim* . . . 255
4.2.1 Particle Beam . . . 255
4.2.2 Radiation Beam . . . 255
4.3 OPERATION OF HIGH ENERGY ELECTRON LINACS *T.O. Raubenheimer* . . . 256
4.4 OPERATION OF FINAL FOCUS SYSTEMS IN LINEAR COLLIDERS *T.O. Raubenheimer, F. Zimmermann* . . . 261
4.5 OPERATION OF CIRCULAR ACCELERATORS . . . 267
4.5.1 Error Sources and Effects *D. Rice* . . . 267
4.5.2 Orbit and Lattice Function Measurements *D. Rice* . . . 268
4.5.3 Orbit Correction *S. Krinsky* . . . 271
4.5.3.1 Global orbit correction . . . 271
4.5.3.2 Local orbit bump . . . 271
4.5.4 Measurement and Diagnosis of Coupling and Solenoid Compensation *D. Rubin* 272
4.5.4.1 Sources of transverse coupling . . . 272
4.5.4.2 Solenoids . . . 272
4.5.4.3 Coupling matrix analysis . . . 274
4.5.4.4 Measurement of coupling . . . 274
4.5.4.5 Measurement . . . 275
4.5.4.6 Solenoid compensation . . . 276
4.5.5 Modeling and Control of Storage Rings Using Orbit Measurements *J. Safranek* 277
4.5.6 Emittance Dilution Effects *M. Syphers* . . . 280
4.5.6.1 Injection mismatch . . . 280
4.5.6.2 Diffusion processes . . . 281
4.6 TEMPORAL AND SPATIAL CORRELATIONS IN BPM MEASUREMENTS *J. Irwin* 282
4.7 TRANSITION CROSSING *J. Wei* . . . 285
4.8 RF GYMNASTICS IN A SYNCHROTRON *R. Garoby* . . . 287
4.8.1 Adiabaticity . . . 287
4.8.2 Single Bunch Manipulations . . . 287
4.8.3 Multi-bunch Manipulations . . . 288
4.8.4 Debunched Beam Manipulations . . . 291
4.9 ENERGY MEASUREMENT WITH ELECTRON BEAMS *J. Seeman* . . . 292
4.10 SLOW EXTRACTION *P.J. Bryant* . . . 293

5 MECHANICAL CONSIDERATIONS 297
5.1 MECHANICAL AND THERMAL PROPERTIES OF STRUCTURAL MATERIALS *M. Kuchnir* . . . 297
5.2 MECHANICAL AND THERMAL PROPERTIES OF COMPOSITE SUPERCONDUCTORS *R.M. Scanlan* . . . 302
5.3 FABRICATION OF NIOBIUM RF STRUCTURES *T. Hays, H. Padamsee, D. Proch* . 304
5.4 THERMODYNAMIC & HYDRODYNAMIC PROPERTIES OF COOLANTS & CRYOGENS *M. McAshan* . . . 309
5.5 CREEP AND STRESS RELAXATION IN ACCELERATOR COMPONENTS *F. Markley* . . . 312
5.6 ELECTRIC AND MAGNETIC FORCES *M. Tigner* . . . 314
5.7 DEFLECTIONS AND BUCKLING *M. Tigner* . . . 315

5.8 PRACTICAL HEAT TRANSFER AND FLUID FLOW *M. McAshan, M. Tigner* . . . 317
5.9 REFRIGERATION SYSTEMS *C. Rode, R. Ganni* . . . 322
5.9.1 Refrigerators . . . 322
5.9.2 Storage and Utilities . . . 326
5.9.3 Transfer Lines . . . 327
5.10 VACUUM SYSTEMS . . . 328
5.10.1 Requirements for Vacuum Systems *N.B. Mistry, Y. Li* . . . 328
5.10.2 Units, Conversions and Some Useful Formulae *N.B. Mistry, Y. Li* . . . 329
5.10.3 Conductance and Pressure Profiles *N.B. Mistry, Y. Li* . . . 330
5.10.4 Pumping Methods *N.B. Mistry, Y. Li* . . . 332
5.10.5 Instrumentation *N.B. Mistry, Y. Li* . . . 336
5.10.6 Vacuum Chamber Design and Fabrication *N.B. Mistry, Y. Li* . . . 337
5.10.7 Special Components in the Vacuum System *N.B. Mistry, Y. Li* . . . 342
5.10.8 Ceramic Vacuum Chamber Design *H. L. Phillips* . . . 343
5.11 ALIGNMENT *R. Ruland* . . . 345
5.12 MAGNET SUPPORTS AND ALIGNMENT *G. Bowden* . . . 348
5.13 GROUND VIBRATION *C. Montag, J. Rossbach* . . . 349
5.13.1 Basics . . . 350
5.13.2 Measurements . . . 351
5.13.3 Instruments . . . 351
5.13.4 Linacs . . . 352
5.13.5 Circular Accelerators . . . 353
5.14 VIBRATION CONTROL IN ACCELERATORS
D. Mangra, R. Merl, S. Kim, S. Sharma, J. Galayda . . . 355
5.15 PROCESS CONTROL *R. Carcagno* . . . 358

6 ELECTRICAL CONSIDERATIONS **363**
6.1 PROPERTIES OF DIELECTRICS *M. Tigner* . . . 363
6.2 PROPERTIES OF CONDUCTORS, NORMAL AND SUPERCONDUCTING
R.M. Scanlan . . . 365
6.3 PROPERTIES OF FERROMAGNETIC MATERIALS *M.Tigner* . . . 369
6.4 PERMANENT MAGNET MATERIALS *R.D. Schlueter* . . . 370
6.5 PROPERTIES OF LOSSY MATERIALS *M. Tigner* . . . 371
6.6 COMMON TRANSMISSION LINES AND CAVITIES *M. Tigner* . . . 372
6.7 RF PULSE COMPRESSION *Z.D. Farkas* . . . 379
6.8 RF WINDOWS AND CAVITY COUPLING *R.M. Sundelin, H.L. Phillips* . . . 382
6.9 MULTIPACTING *D. Proch* . . . 384
6.10 POWER CONVERTERS (SUPPLIES) *H.W. Isch* . . . 387
6.11 POLYPHASE POWER CIRCUITS *M. Tigner* . . . 393
6.12 RF BREAKDOWN, FIELD EMISSION AND DARK CURRENT
G.A. Loew, J.W. Wang . . . 394
6.13 HIGH VOLTAGE TECHNIQUE *B. Goddard* . . . 396
6.14 COATING RECIPES . . . 400
6.14.1 Recipes for Coating Windows *R.M. Sundelin, H.L. Phillips* . . . 400
6.14.2 Recipes for Coating Ceramic and Metal Vacuum Chambers *S.D. Henderson* . 401
6.15 SUPERCONDUCTING WIRE AND CABLE *R.M. Scanlan* . . . 405
6.16 CAVITY MEASUREMENTS *R. Rimmer, M. Tigner* . . . 407
6.16.1 Field Maps by Perturbation Methods . . . 407
6.16.2 Q and β Determination from Input Coupler . . . 408
6.17 MAGNETIC MEASUREMENTS . . . 409
6.17.1 Accelerator Magnets *A.K. Jain, P. Wanderer* . . . 409
6.17.2 Insertion Device Measurement *S. Marks, R.D. Schlueter* . . . 415

6.18 HIGH POWER SWITCHES *M. Gundersen, G. Roth* 419

7 SUBSYSTEMS **423**
7.1 PARTICLE SOURCES 423
7.1.1 Electron Guns and Preinjectors *A.D. Yeremian, R.H. Miller* 423
7.1.2 Polarized Particle Sources 426
7.1.2.1 Photoemission sources for polarized electrons *C. Prescott, J. Clendenin* 426
7.1.2.2 Protons and heavy ions *T.B. Clegg, W. Haeberli* 428
7.1.3 Antiproton Production *G. Dugan* 429
7.1.4 H^- Ion Sources *K.N. Leung* 432
7.1.5 Positron Sources 434
7.1.5.1 Tungsten targets *S. Ecklund* 434
7.1.5.2 Conversion of undulator radiation *K. Flöttmann* 437
7.1.6 Charge State Strippers *M.A. McMahan* 439
7.1.7 Lorentz Stripping of H^- Ions *M.A. Furman* 442
7.2 CONFINEMENT AND FOCUSING 443
7.2.1 Resistive Magnets *F.E. Mills* 443
7.2.2 Consequences of Saturation of High Permeability Material *K. Halbach* 448
7.2.3 Special Topics in Magnetics *K. Halbach* 449
7.2.3.1 Orthogonal and direct analog models 449
7.2.3.2 Properties of 3-D vacuum fields integrated along a straight line . . . 450
7.2.3.3 Pole width necessary to obtain desired field quality in a 2-D magnet . 451
7.2.3.4 Eddy currents 452
7.2.3.5 Magnetic forces 453
7.2.3.6 Power dissipation in the dipole coils of a storage ring with iron poles 453
7.2.4 Cosθ Superconducting Magnets *P. Schmüser* 454
7.2.5 Superferric Magnets *A. Zeller* 460
7.2.6 Pulsed Magnets *G.H. Schröder* 464
7.2.7 Permanent Magnet Elements *K. Halbach* 470
7.2.8 Electrostatic Separators *J.J. Welch* 477
7.2.9 Electrostatic Lenses *A. Faltens* 479
7.2.10 RF Separators *H. Lengeler* 481
7.2.11 Plasma Lens *P. Chen* 484
7.2.12 Lithium Lens *G. Dugan* 487
7.2.13 Orbit Feedback Control *S. Krinsky, O. Singh* 490
7.2.14 Feedback Systems for Coupled Bunch Instabilities *J.T. Rogers* 494
7.2.15 Crystal Beam Bending *R.A. Carrigan, Jr.* 499
7.2.16 Injection and Ejection *G. Rees.* 501
7.2.17 Septum Devices *R. Keizer* 502
7.3 ACCELERATION 505
7.3.1 RF System Design for Stability *D. Boussard* 505
7.3.2 Klystron Power Amplifiers 509
7.3.2.1 Klystrons *G. Caryotakis* 509
7.3.2.2 Amplifier systems *H.D. Schwarz, M.Tigner* 511
7.3.3 Tetrode Amplifiers *J.M. Brennan* 514
7.3.4 Drift Tube Linacs *J.M. Potter* 517
7.3.5 Normal Conducting $v_p = c$ Linac Structures *G.A. Loew* 520
7.3.6 Ferrite Loaded Cavities *J.M. Brennan* 524
7.3.7 Fixed Frequency Cavities 526
7.3.7.1 Multicell cavities *W. Schnell* 526
7.3.7.2 Single cell cavities *R.A. Rimmer* 529

7.3.8 Superconducting Cavities for $v_p = c$ Linacs, Storage Rings, & Synchrotrons *D. Proch* . . . 530
7.3.9 Superconducting Cavities for $v_p < c$ Linacs *K. Shepard* . . . 537
7.3.10 Superconducting Single Cell Cavities *J. Kirchgessner* . . . 540
7.3.11 Millimeter-Wave Accelerators *D. Whittum* . . . 545
7.3.12 Plasma Accelerators *E. Esarey* . . . 548
7.4 BEAM INSTRUMENTATION AND DIAGNOSTICS . . . 551
7.4.1 Composition - Ion Beams *P. Strehl* . . . 551
7.4.2 Velocity Measurement - Ion Beams *P. Strehl* . . . 553
7.4.3 Momentum Measurement - Ion Beams *P. Strehl* . . . 553
7.4.4 Charge State - Ion Beams *P. Strehl* . . . 555
7.4.5 Beam Current Measurement *J.A. Hinkson* . . . 556
7.4.6 Beam Position Monitors *J.A. Hinkson* . . . 559
7.4.7 Measuring Longitudinal Distribution of Electron Bunches with Coherent Radiation *R. Lai, G. Schneider, A.J. Sievers* . . . 561
7.4.8 Transverse and Longitudinal Emittance Measurements *J.T. Seeman* . . . 564
7.4.9 Streak Camera *E. Rossa* . . . 566
7.4.10 Laser Wire *M. Ross* . . . 569
7.4.11 Laser Interference Methods *T. Shintake* . . . 570
7.4.12 Beam Size via Synchrotron Radiation *T. Shintake* . . . 573
7.5 IMPEDANCE DETERMINATION . . . 574
7.5.1 Bench Measurements *F. Caspers* . . . 574
7.5.2 Beam-based Characterization of Coupled Bunch Instabilities *J. Byrd* . . . 579
7.5.2.1 Passive techniques . . . 579
7.5.2.2 Active techniques . . . 580
7.5.3 Beam Transfer Functions *J.S. Berg, J. Gareyte* . . . 581
7.5.4 Schottky Spectra *J.S. Berg, J. Gareyte* . . . 585
7.5.5 Other Beam-based Methods to Measure Impedance *J. Gareyte, J.S. Berg* . . . 588
7.5.6 Direct Wakefield Measurements *J. Simpson* . . . 589
7.6 POLARIMETERS . . . 590
7.6.1 Lepton Polarimeters *M. Placidi* . . . 590
7.6.1.1 Compton polarimetry . . . 591
7.6.1.2 Møller polarimetry . . . 593
7.6.2 Proton Beam Polarimeters *T. Roser* . . . 594
7.7 CONTROLS AND TIMING *K. Rehlich* . . . 594

8 RADIATION EFFECTS AND PROTECTION 599
8.1 RADIOLOGICAL PROTECTION AT ACCELERATORS *R.H. Thomas* . . . 599
8.1.1 Brief History . . . 599
8.1.2 International Advisory Bodies: The ICRP and ICRU . . . 599
8.1.3 National Advisory Bodies: The NCRP . . . 600
8.1.4 A Brief Historical Review of the Quantities used in Radiological Protection . . . 600
8.1.5 Definitions of Current Quantities in Current Use in Radiological Protection . . . 601
8.1.6 Radiation Levels . . . 602
8.2 RADIATION SOURCES *R.H. Thomas* . . . 602
8.2.1 General Considerations . . . 602
8.2.2 Electron Interactions . . . 603
8.2.3 Proton Interactions . . . 607
8.2.4 Ion Interactions . . . 610
8.2.5 Radioactivity . . . 612
8.3 RADIATION TRANSPORT AND SHIELDING *R.H. Thomas* . . . 614
8.3.1 Specification of Shielding . . . 614

8.3.2 Radiation Transmission through Shielding . . . 615
8.3.3 Practical Accelerator Shielding . . . 617
8.3.4 Shielding Materials . . . 622
8.3.5 Ducts, Doors, Labyrinths and Tunnels . . . 624
8.4 RADIATION MEASUREMENTS AT ACCELERATORS *R.H. Thomas* . . . 625
8.4.1 General Considerations . . . 625
8.4.2 Special Considerations for Radiation Dosimetry in Accelerator Environments . 626
8.4.3 Neutron Dosimetry at Particle Accelerators . . . 626
8.4.4 Photon Dosimetry at Accelerators . . . 630
8.4.5 Universal Dose-Equivalent Instruments . . . 631
8.4.6 Personal Monitoring . . . 632
8.4.7 Environmental Monitoring . . . 633
8.5 ENVIRONMENTAL ASPECTS OF ACCELERATOR OPERATION *R.H. Thomas* . . 634
8.5.1 Environmental Impact . . . 634
8.5.2 Skyshine . . . 635
8.5.3 Radioactivity of Environmental Concern Produced by Accelerators . . . 637
8.5.4 Collective Exposure to the Population . . . 638
8.5.5 Other Products . . . 638
8.6 GLOSSARY OF TERMS USED IN RADIALOGICAL PROTECTION *R.H. Thomas* . 638
8.7 RADIATION DAMAGE THRESHOLDS *H. Schönbacher* . . . 646
8.7.1 Organic Materials . . . 646
8.7.2 Semiconductors and electronic devices . . . 649
8.7.3 Ceramics . . . 651
8.7.4 Vitreous Materials . . . 652
8.7.5 Metals . . . 653
8.7.6 Summary . . . 654
Subject Index
Author index