Contents

1 Basic Concepts 1

1.1 Introduction . . . 1
1.2 Magnet Types . . . 2
1.3 Pictures . . . 2
1.4 Conventions . . . 6
1.5 The Field from a Line Current (Biot-Savart law) . . . 6
1.6 Magnetic Force on a Line Current . . . 7
1.6.1 MKS Units . . . 7
1.6.2 Force Directions . . . 8
1.6.3 Dipole Magnet . . . 8
1.6.4 Quadrupole Magnet . . . 8
1.6.5 Sextupole Magnet . . . 9
1.6.6 Corrector Magnets . . . 10
1.6.7 Specialized Magnets . . . 11
1.6.8 More Polarity . . . 14
1.6.9 Alternate Polarity Convention . . . 15
1.7 Chapter Closure . . . 15
1.8 Problems . . . 17

2 Solutions of the Magnet Equations 19

2.1 Introduction . . . 19
2.2 Maxwell's Magnet Equations . . . 19
2.2.1 Continuity . . . 19
2.2.2 Units . . . 20
2.3 The Function of a Complex Variable . . . 20
2.4 The Two-Dimensional Fields . . . 21
2.4.1 Fields from the Two-Dimensional Function of a Complex Variable . . . 22
2.5 Two Dimensional Fields in a Vacuum . . . 22
2.5.1 Multipoles . . . 22
2.5.2 Laplace's Equation . . . 23
2.5.3 Solutions to Laplace's Equation . . . 23

2.6 Two-Dimensional Vector and Scalar Potentials 24
2.6.1 Magnetic Fields from the Two-Dimensional Potentials 24
2.7 A Particular Function of the Complex Variable, $F = C_n z^n$ 25
2.7.1 Ideal Two-Dimensional Multipole Magnets 26
2.7.2 Two-Dimensional Flux Lines and Poles 26
2.7.3 Pole Contours 30
2.7.4 Complex Extrapolation 30
2.8 Magnetic Fields Using the Function of the Complex Variable 31
2.8.1 n=1, the Dipole Magnet 32
2.8.2 n=2, the Quadrupole Magnet 32
2.8.3 n=3, the Sextupole Magnet 33
2.9 Multipole Errors 34
2.9.1 The Error Spectrum 34
2.9.2 "Allowed" or Systematic Multipole Errors 34
2.9.3 Multipole Field Errors 36
2.10 Simple Conformal Maps 37
2.10.1 Mapping Functions 37
2.10.2 Quadrupole to Dipole Map 38
2.10.3 Dipole to Quadrupole Map 38
2.10.4 Sextupole to Dipole Map 38
2.10.5 Dipole to Sextupole Map 39
2.10.6 Gradient Magnet to Dipole Map 39
2.10.7 Dipole to Gradient Magnet Map 40
2.11 Chapter Closure 40
2.12 Problems 41

3 Pole Tip Design **43**
3.1 Understanding the Dipole Magnet 43
3.1.1 The Orthogonal Analog Model 43
3.1.2 The Orthogonal Analog Model and the Quadrupole 46
3.1.3 The "H" Dipole Geometry 48
3.1.4 H-Magnet Uniformity 50
3.2 Understanding the Quadrupole Magnet 53
3.2.1 Quadrupole Uniformity 53
3.3 Understanding the Gradient Magnet 56
3.3.1 Gradient Magnet Uniformity 56
3.4 Mapping an Existing Gradient Magnet Design 60
3.4.1 Baseline Optimized Pole 62
3.4.2 New Unoptimized Pole 63
3.4.3 Baseline Mapped Pole 63
3.4.4 New Mapped Unoptimized Pole 63
3.4.5 Scaling and Shifting 64

3.4.6 Center Expansion 65
3.4.7 Mapping Back into the Quadrupole Space 67
3.5 Chapter Closure 67
3.6 Problems 70

4 Perturbations **73**
4.1 Introduction 73
4.2 Algorithms and Tables 74
4.2.1 Quadrupole Pole Error Coefficients, N=2 74
4.2.2 Sextupole Pole Error Pole Error Coefficients, N=3 75
4.2.3 Computing Error Multipoles 75
4.3 Two Piece Quadrupole 77
4.3.1 Magnet Assymetry 78
4.3.2 Differences in Lengths of the Upper and Lower Halves 80
4.3.3 Sorting 83
4.3.4 Two Piece Quadrupole Errors 83
4.3.5 Tolerances (Examples of Computations) 84
4.3.6 Alignment Error 85
4.3.7 Excitation Error 87
4.3.8 Random Multipole Error 87
4.4 Sextupole Trim Windings 89
4.4.1 Orthogonality 90
4.4.2 Horizontal Steering Trim 90
4.4.3 Vertical Steering and Skew Quadrupole Trim 91
4.4.4 Trim Excitations 93
4.5 Chapter Closure 94
4.6 Problems 96

5 Magnetic Excitation and Coil Design **97**
5.1 Introduction 97
5.2 Maxwell's Inhomogeneous Equation 97
5.2.1 Continuity 98
5.3 Magnet Excitations 99
5.3.1 Magnet Efficiency 99
5.3.2 Dipole Magnets 100
5.3.3 Quadrupole Magnet 106
5.3.4 Sextupole Magnet 108
5.4 Coil Design 109
5.4.1 Coil Power 110
5.5 Coil Cooling 113
5.5.1 Pressure Drop 113
5.5.2 Flow Velocity 114

5.5.3 Units . . . 115
5.5.4 Coil Cooling . . . 119
5.5.5 Calculations . . . 120
5.5.6 Sensitivities . . . 121
5.6 Chapter Closure . . . 126
5.7 Problems . . . 128

6 POISSON 131
6.1 Elements of the Family of Codes . . . 133
6.2 Documentation . . . 134
6.3 Problem Flow . . . 134
6.4 AutoMesh . . . 136
6.4.1 Boundary Conditions and Constraints . . . 136
6.4.2 Geometry . . . 139
6.4.3 Setting Up and Testing the Geometry . . . 141
6.5 Symmetries . . . 141
6.5.1 Example - Collins or Figure Eight Quadrupole . . . 142
6.5.2 Coil Geometry . . . 143
6.5.3 Yoke Geometry . . . 145
6.6 The Vector Potential Boundary Condition . . . 146
6.6.1 Simple Dipole . . . 147
6.6.2 The Simple Dipole with Vector Potential Boundary Conditions . . . 147
6.6.3 The Vector Potential Boundary Condition for Optimizing the Quadrupole Pole . . . 153
6.6.4 Other Applications of the Vector Potential Boundary Conditions . . . 164
6.7 Chapter Closure . . . 165
6.8 Problems . . . 169

7 Stored Energy, Magnetic Forces and Dynamic Effects 171
7.1 Force on Coils . . . 171
7.2 Force on a Pole . . . 173
7.2.1 Units . . . 173
7.2.2 A Reference Point . . . 174
7.3 Magnet Stored Energy . . . 174
7.3.1 Inductance . . . 175
7.4 Eddy Currents . . . 177
7.4.1 Field Attenuation due to Eddy Currents in a Semi-infinite Conductive Horizontal Plate . . . 178
7.4.2 Field Attenuation due to Eddy Currents in a Pair of Semi-infinite Conductive Vertical Plates . . . 182

7.4.3 Field Attenuation due to Eddy Currents in a Closed Rectangular Chamber . . . 183
7.4.4 Field Amplification . . . 184
7.5 Chapter Closure . . . 191
7.6 Problems . . . 192

8 Magnetic Measurements **195**
8.1 The Vector Potential . . . 196
8.1.1 Fourier Analysis . . . 198
8.2 Output Voltage . . . 200
8.3 The Compensated Coil . . . 201
8.3.1 The Quadrupole Coil . . . 203
8.3.2 The Dipole Coil . . . 203
8.3.3 The Sextupole Coil . . . 204
8.4 "Spilldown" and Magnetic Center . . . 204
8.4.1 Quadrupole Magnetic Center . . . 206
8.4.2 Sextupole Magnetic Center . . . 207
8.5 Rotating Coil Magnetic Measurements . . . 208
8.5.1 The Measurement System . . . 209
8.6 Fourier Analysis . . . 211
8.6.1 Uncompensated Signal . . . 212
8.6.2 Compensated Signal . . . 213
8.6.3 Expressions for the Integrated Multipole Fields . . . 213
8.6.4 Excitation and Transfer Function . . . 214
8.6.5 Relative Phases . . . 215
8.6.6 Units . . . 216
8.7 Measurements and Output . . . 216
8.7.1 Measurement Plan . . . 216
8.7.2 Raw Data Output . . . 217
8.7.3 Bucking Ratio . . . 217
8.7.4 Normalized Multipole Errors . . . 218
8.7.5 Error Spectrum Normalized to the Required Good Field Radius . . . 219
8.7.6 Magnetic Center . . . 219
8.8 Measurement Output . . . 220
8.8.1 Tabular Output . . . 221
8.9 Analog Output (Iso-Error Plots) . . . 221
8.10 Chapter Closure . . . 224
8.11 Problems . . . 225

9 Magnet Yoke Design and Fabrication **229**
9.1 Introduction . . . 229
9.2 Saturation . . . 229
9.3 Two Dimensional Design . . . 231
9.4 Three Dimensional Design . . . 232
9.4.1 Dipole Fringe Field . . . 232
9.4.2 Quadrupole Fringe Field . . . 234
9.5 Solid Iron or Steel Laminations . . . 238
9.5.1 Reproducibility and Symmetry . . . 238
9.5.2 Solid Iron Cores . . . 238
9.5.3 Laminated Steel Cores . . . 239
9.5.4 Economics . . . 240
9.5.5 Laminated Yoke Fabrication . . . 241
9.6 Yoke Assembly/Fabrication Techniques . . . 242
9.6.1 Gluing . . . 244
9.6.2 Welded Laminated Yokes . . . 251
9.6.3 Mechanically Assembled Laminated Yokes . . . 253
9.7 Core Grounding . . . 261
9.8 Chapter Closure . . . 261
9.9 Chapter Appendix . . . 264

10 Magnet Coil Fabrication **267**
10.1 Introduction . . . 267
10.1.1 Conductor Size and Turn to Turn Insulation . . . 267
10.1.2 Coil Winding . . . 268
10.1.3 Coil Potting (Encapsulation) . . . 271
10.2 Coil Failures . . . 278
10.2.1 Specifications . . . 278
10.2.2 Measurements and Tests . . . 279
10.3 Chapter Closure . . . 284

11 Magnet Assembly **285**
11.1 Introduction . . . 285
11.2 Coil Supports and Bussing . . . 285
11.2.1 Bussing . . . 286
11.2.2 Magnet Tests . . . 293
11.3 Chapter Closure . . . 295

12 Magnet Installation and Alignment **297**
12.1 Introduction . . . 297
12.2 Magnet Support . . . 298
12.2.1 Predetermined Alignment . . . 298
12.2.2 Generic Fiducialization . . . 299

12.2.3 Adjusted Alignment 300
12.2.4 Adjustable Struts 303
12.2.5 Adjustable Support Blocks 306
12.2.6 Pedigreed Fiducialization 308
12.3 Chapter Closure 310

Solutions **313**

References **327**

Index **329**