

Contents to Volume 1

Conductorart by Claus Grupen (drawing) XX

Preface XXI

List of Contributors XXIII

1	Fundamentals 1
1.1	Superconductivity 1
1.1.1	Basic Properties and Parameters of Superconductors 1 <i>Reinhold Kleiner</i>
1.1.1.1	Superconducting Transition and Loss of DC Resistance 1
1.1.1.2	Ideal Diamagnetism, Flux Quantization, and Critical Fields 6
1.1.1.3	The Origin of Flux Quantization, London Penetration Depth and Ginzburg–Landau Coherence Length 10
1.1.1.4	Critical Currents 16 References 25
1.1.2	Review on Superconducting Materials 26 <i>Roland Hott, Reinhold Kleiner, Thomas Wolf, and Gertrud Zwicknagl</i>
1.1.2.1	Introduction 26
1.1.2.2	Cuprate High-Temperature Superconductors 29
1.1.2.3	Other Oxide Superconductors 33
1.1.2.4	Iron-Based Superconductors 35
1.1.2.5	Heavy Fermion Superconductors 36
1.1.2.6	Organic and Other Carbon-Based Superconductors 40
1.1.2.7	Borides and Borocarbides 42 References 44
1.2	Main Related Effects 49
1.2.1	Proximity Effect 49 <i>Mikhail Belogolovskii</i>
1.2.1.1	Introduction 49

1.2.1.2	Metal–Insulator Contact	51
1.2.1.3	Normal Metal–Superconductor Contact	54
1.2.1.4	Ferromagnetic Metal–Superconductor Contact	57
1.2.1.5	New Perspectives and New Challenges	61
1.2.1.6	Summary	62
	References	63
1.2.2	Tunneling and Superconductivity	66
	<i>Steven T. Ruggiero</i>	
1.2.2.1	Introduction	66
1.2.2.2	Normal/Insulator/Normal Tunnel Junctions	66
1.2.2.3	Normal/Insulator/Superconducting Tunnel Junctions	67
1.2.2.4	Superconductor/Insulator/Superconducting Tunnel Junctions	68
1.2.2.5	Superconducting Quantum Interference Devices (SQUIDs)	71
1.2.2.6	Phonon Structure	72
1.2.2.7	Geometrical Resonances	73
1.2.2.8	Scanning Tunneling Microscopy	73
1.2.2.9	Charging Effects	73
	References	74
1.2.3	Flux Pinning	76
	<i>Stuart C. Wimbush</i>	
1.2.3.1	Introduction	76
1.2.3.2	Flux Lines, Flux Motion, and Dissipation	76
1.2.3.3	Sources of Flux Pinning	78
1.2.3.4	Flux Pinning in Technological Superconductors	81
1.2.3.5	Experimental Determination of Pinning Forces	83
1.2.3.6	Regimes of Flux Motion	85
1.2.3.7	Limitations on Core Pinning Efficacy	85
1.2.3.8	Magnetic Pinning of Flux Lines	87
1.2.3.9	Flux Pinning Anisotropy	88
1.2.3.10	Maximum Entropy Treatment of Flux Pinning	89
	References	90
1.2.4	AC Losses and Numerical Modeling of Superconductors	93
	<i>Francesco Grilli and Frederic Sirois</i>	
1.2.4.1	Introduction	93
1.2.4.2	General Features of AC Loss Characteristics	93
1.2.4.3	Measuring AC Losses	95
1.2.4.3.1	Transport Losses	95
1.2.4.3.2	Magnetization Losses	96
1.2.4.3.3	Combination of Transport and Magnetization AC Losses	98
1.2.4.4	Computing AC Losses	98
1.2.4.4.1	Analytical Computation	98

1.2.4.4.2	Numerical Computation	99
	References	102
2	Superconducting Materials	105
2.1	Low-Temperature Superconductors	105
2.1.1	Metals, Alloys, and Intermetallic Compounds	105
	<i>Helmut Krauth and Klaus Schlenga</i>	
2.1.1.1	Introduction	105
2.1.1.2	Type I and Type II Superconductor Elements and High-Field Alloys	106
2.1.1.2.1	Fundamental Superconductor Properties	106
2.1.1.2.2	Elemental Superconductors and Their Applications	107
2.1.1.2.3	The Effect of Alloying	108
2.1.1.3	Superconducting Intermetallic Compounds	109
2.1.1.4	Pinning in Hard Type II Superconductors	110
2.1.1.5	Design Principles of Technical Conductors	112
2.1.1.5.1	Electromagnetic Considerations	112
2.1.1.5.2	Mechanical Properties	115
2.1.1.5.3	Co-Workability and Compatibility of Wire Components	115
2.1.1.5.4	Cost Aspects	116
2.1.1.6	Wire Manufacturing Routes and Properties	116
2.1.1.6.1	NbTi Wires	116
2.1.1.6.2	Nb ₃ Sn	120
2.1.1.7	Built-Up and Cabled Conductors	126
2.1.1.7.1	Wire-in-Channel (WiC)	126
2.1.1.7.2	Cabled Conductors	127
2.1.1.8	Concluding Remarks	127
	Acknowledgments	127
	References	128
2.1.2	Magnesium Diboride	129
	<i>Davide Nardelli, Ilaria Pallecchi, and Matteo Tropeano</i>	
2.1.2.1	Introduction	129
2.1.2.2	Intrinsic and Extrinsic Properties of MgB ₂	130
2.1.2.3	Sample Preparation	139
2.1.2.3.1	MgB ₂ Phase Diagram and Polycrystals Synthesis	139
2.1.2.3.2	MgB ₂ Single Crystals	142
2.1.2.3.3	MgB ₂ Thin Films	142
2.1.2.4	Applications of MgB ₂	143
2.1.2.4.1	Wires and Tapes	143
2.1.2.4.2	Electronic Applications	146
2.1.2.5	Summary and Outlook	147
	References	148

- 2.2 High-Temperature Superconductors 152
- 2.2.1 Cuprate High-Temperature Superconductors 152
Roland Hott and Thomas Wolf
- 2.2.1.1 Introduction 152
- 2.2.1.2 Structural Aspects 152
- 2.2.1.3 Metallurgical Aspects 153
- 2.2.1.4 Structure and T_c 156
- 2.2.1.5 Superconductive Coupling 158
References 163
- 2.2.2 Iron-Based Superconductors: Materials Aspects for Applications 166
Ilaria Pallecchi and Marina Putti
- 2.2.2.1 Introduction 166
- 2.2.2.2 General Aspects of Fe-Based Superconductors 166
- 2.2.2.3 Material Preparation 169
- 2.2.2.4 Superconducting Properties 171
- 2.2.2.4.1 Critical Temperature T_c 171
- 2.2.2.4.2 Critical Fields and Characteristic Lengths 172
- 2.2.2.4.3 Critical Current Density J_c 175
- 2.2.2.5 Critical Current Pinning 177
- 2.2.2.6 Grain Boundaries 178
- 2.2.2.7 Wires and Tapes 180
- 2.2.2.8 Coated Conductors 184
- 2.2.2.9 Electronic Applications 185
- 2.2.2.10 Summary 187
References 188
- 3 Technology, Preparation, and Characterization 193**
- 3.1 Bulk Materials 193
- 3.1.1 Preparation of Bulk and Textured Superconductors 193
Frank N. Werfel
- 3.1.1.1 Introduction 193
- 3.1.1.2 Melt Processed REBCO 195
- 3.1.1.2.1 Process Steps 195
- 3.1.1.2.2 Melt Processing Thermodynamics 197
- 3.1.1.2.3 Powder Compacting 199
- 3.1.1.2.4 Texture Process 199
- 3.1.1.2.5 Single Grain Fabrication 202
- 3.1.1.2.6 Mechanical Properties 206
- 3.1.1.2.7 Doping Strategy 207
- 3.1.1.3 Characterization 208
- 3.1.1.3.1 Electromagnetic Force 208
- 3.1.1.3.2 Magnetization and Field Mapping Technique of Bulk Superconductors 211
- 3.1.1.3.3 Trapped Field Magnetic Flux Density 214
- 3.1.1.3.4 Multiseeded Bulk Characterization 215
- 3.1.1.3.5 Comparison of the REBCO Bulk Materials 216
References 219
- 3.1.2 Single crystal growth of the high temperature superconducting cuprates 222
Andreas Erb
- 3.1.2.1 General Problems in the Crystal Growth of the High T_c Cuprate Superconductors 222
- 3.1.2.2 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, $\text{YBa}_2\text{Cu}_4\text{O}_8$, and $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (RE, Rare Earth Element) 222
- 3.1.2.3 The 214-Compounds $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$, $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$, and $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$ 225
- 3.1.2.4 Conclusions 230
References 230
- 3.1.3 Properties of Bulk Materials 231
Günter Fuchs, Gernot Krabbes, and Wolf-Rüdiger Candors
- 3.1.3.1 Irreversibility Fields of Bulk High- T_c Superconductors 231
- 3.1.3.2 Vortex Matter Phase Diagram of Bulk YBCO in an Extended Field Range up to 40 T 232
- 3.1.3.3 Critical Current Density 235
- 3.1.3.4 Flux Creep in Bulk YBCO 238
- 3.1.3.4.1 Flux Creep in HTS 238
- 3.1.3.4.2 Reduction of Flux Creep 240
- 3.1.3.5 Selected Properties of Bulk YBCO 241
- 3.1.3.5.1 Mechanical Properties 241
- 3.1.3.5.2 Thermodynamic and Thermal Properties 242
References 245
- 3.2 Thin Films and Multilayers 247
- 3.2.1 Thin Film Deposition 247
Roger Wördenweber
- 3.2.1.1 Introduction 247
- 3.2.1.1.1 Material Requirements 250
- 3.2.1.1.2 Substrate Requirements 252
- 3.2.1.2 Deposition Techniques 256
- 3.2.1.2.1 PVD Techniques 257
- 3.2.1.2.2 CVD Technologies 267
- 3.2.1.2.3 CSD Techniques 268

- 3.2.1.3 HTS Film Growth and Characterization 269
- 3.2.1.3.1 Nucleation and Phase Formation 270
- 3.2.1.3.2 Heteroepitaxial Growth, Stress, and Defects 273
- 3.2.1.4 Concluding Remarks 276
- Acknowledgment 277
- References 277
- 3.3 Josephson Junctions and Circuits 281
- 3.3.1 LTS Josephson Junctions and Circuits 281
- Hans-Georg Meyer, Ludwig Fritzsche, Solveig Anders, Matthias Schmelz, Jürgen Kunert, and Gregor Oelsner*
- 3.3.1.1 Introduction 281
- 3.3.1.2 Junction Characterization 283
- 3.3.1.3 Nb–Al/AIO_x–Nb Junction Technology 284
- 3.3.1.3.1 General Aspects 284
- 3.3.1.3.2 Basic Processes of the Nb–Al/AIO_x–Nb Technology 289
- 3.3.1.4 Circuits, Applications, and Resulting Requirements for Josephson Junctions 295
- 3.3.1.4.1 Josephson Voltage Standard 295
- 3.3.1.4.2 Superconducting Tunnel Junction 295
- 3.3.1.4.3 SIS Mixer 296
- 3.3.1.4.4 SQUID 296
- 3.3.1.4.5 Qubit 297
- 3.3.1.4.6 Mixed-Signal Circuit 297
- 3.3.1.4.7 RSFQ Digital Electronics 298
- References 298
- 3.3.2 HTS Josephson Junctions 306
- Keiichi Tanabe*
- 3.3.2.1 Introduction 306
- 3.3.2.2 Various Types of Junctions 307
- 3.3.2.3 Grain-Boundary Junctions 308
- 3.3.2.3.1 Bicrystal Junctions 308
- 3.3.2.3.2 Step-Edge Junctions 313
- 3.3.2.4 Ramp-Edge Junctions 317
- 3.3.2.5 Other Types of Junctions 322
- 3.3.2.6 Summary and Outlook 323
- References 324
- 3.4 Wires and Tapes 328
- 3.4.1 Powder-in-Tube Superconducting Wires: Fabrication, Properties, Applications, and Challenges 328
- Tengming Shen, Jianyi Jiang, and Eric Hellstrom*
- 3.4.1.1 Overview of Powder-in-Tube (PIT) Superconducting Wires 328
- 3.4.1.1.1 Introduction 328
- 3.4.1.1.2 General Comments about PIT Wire Manufacture 329
- 3.4.1.2 Manufacturing, Heat Treatment, and Superconducting Performance of PIT Wires 330
- 3.4.1.2.1 Bi₂Sr₂CaCu₂O_x (Bi-2212) Round Wire 330
- 3.4.1.2.2 (Bi,Pb)₂Sr₂Ca₂Cu₃O_x (Bi-2223) Tapes 336
- 3.4.1.2.3 Nb₃Sn 338
- 3.4.1.2.4 MgB₂ 340
- 3.4.1.2.5 Iron-Based Superconductors (FBS) 341
- 3.4.1.3 Strain Sensitivity of PIT Superconductor Wires 345
- 3.4.1.4 Successful Applications Using PIT Wires, Remaining Challenges, and PIT Wires in the Future 347
- Acknowledgments 348
- References 348
- 3.4.2 YBCO-Coated Conductors 355
- Mariappan Parans Paranthaman, Tolga Aytug, Liliana Stan, Quanxi Jia, and Claudia Cantoni*
- 3.4.2.1 Introduction 355
- 3.4.2.2 RABiTS and IBAD Technology 355
- 3.4.2.3 Simplified IBAD MgO Template Based on Chemical Solution Processed Al₂O₃ 358
- 3.4.2.4 Current Status of 2G HTS Wires 363
- 3.4.2.5 Future Outlook 363
- Acknowledgments 364
- References 364
- 3.5 Cooling 366
- 3.5.1 Fluid Cooling 366
- Luca Bottura and Cesar Luongo*
- 3.5.1.1 Introduction 366
- 3.5.1.2 Bath Cooling 368
- 3.5.1.2.1 Principle 368
- 3.5.1.2.2 Heat Removal in a Bath 369
- 3.5.1.2.3 Heat Transfer from a Solid Surface to a Bath 371
- 3.5.1.3 Internal Cooling 374
- 3.5.1.3.1 Heat Removal from an Internally Cooled Loop 375
- 3.5.1.3.2 Mass Flow and Circulator Mechanisms 376
- 3.5.1.3.3 Heat Transfer in Internal Flows 377
- 3.5.1.3.4 Helium Expulsion 379
- 3.5.1.3.5 HeII Cooling 379
- References 381

- 3.5.2 Cryocoolers 383
Gunter Kaiser and Gunar Schroeder
- 3.5.2.1 Motivation 383
- 3.5.2.1.1 The Principle of “Invisible” Cryogenics 383
- 3.5.2.1.2 Pros and Cons 383
- 3.5.2.2 Classical Cryocoolers 384
- 3.5.2.2.1 Stirling Cryocoolers 384
- 3.5.2.2.2 Gifford–McMahon Cryocoolers 386
- 3.5.2.3 Special Types of Cryocoolers 387
- 3.5.2.3.1 Pulse Tube Cryocoolers 387
- 3.5.2.3.2 Mixture Joule–Thomson Cryocoolers 391
- References 392
- 3.5.3 “Cryogen-Free” Cooling 393
Gunter Kaiser and Andreas Kade
- 3.5.3.1 Motivation and Basic Configuration 393
- 3.5.3.1.1 Motivation 393
- 3.5.3.1.2 Basic Configuration 393
- 3.5.3.2 Heat Transfer Systems 393
- 3.5.3.2.1 Heat Conduction 393
- 3.5.3.2.2 Thermosiphon 394
- 3.5.3.2.3 Two-Phase Tubes 395
- 3.5.3.2.4 Heat Pipes 396
- 3.5.3.2.5 Circulations 397
- 3.5.3.3 Thermal Interceptors 399
- 3.5.3.3.1 Mechanically Actuated Switches 399
- 3.5.3.3.2 Thermal Dilatation Switches 399
- 3.5.3.3.3 Gas Gap Switches 401
- References 401
- 4 Superconducting Magnets 403**
- 4.1 Bulk Superconducting Magnets for Bearings and Levitation 403
John R. Hull
- 4.1.1 Introduction 403
- 4.1.2 Understanding Levitation with Bulk Superconductors 405
- 4.1.2.1 Simplified Model: Double-Image Dipole 405
- 4.1.2.2 Magnetomechanical Stiffness 406
- 4.1.2.3 More Advanced Models 407
- 4.1.3 Rotational Loss 407
- 4.1.3.1 Hysteresis Loss 408
- 4.1.3.2 High-Speed Loss 410
- 4.1.4 A Rotor Dynamic Issue 411
- 4.1.5 Practical Bearing Considerations 412
- 4.1.6 Applications 415
References 416
- 4.2 Fundamentals of Superconducting Magnets 418
Martin N. Wilson
- 4.2.1 Windings to Produce Different Field Shapes 418
- 4.2.2 Current Supply 420
- 4.2.3 Load Lines, Degradation, and Training 422
- 4.2.4 Cryogenic Stabilization 423
- 4.2.5 Mechanical Disturbances and Minimum Quench Energy 426
- 4.2.6 Screening Currents and the Critical State Model 429
- 4.2.7 Magnetization and Flux Jumping 431
- 4.2.8 Filamentary Wires and Cables 434
- 4.2.9 AC Losses 440
- 4.2.10 Quenching and Protection 442
References 447
- 4.3 Magnets for Particle Accelerators and Colliders 448
Luca Bottura and Lucio Rossi
- 4.3.1 Introduction 448
- 4.3.2 Accelerators, Colliders, and Role of Superconducting Magnets 448
- 4.3.2.1 Magnet Functions and Type 448
- 4.3.2.2 Transverse Fields 451
- 4.3.2.3 Dipoles and Relation to Beam Energy 452
- 4.3.2.4 Quadrupoles and Focusing 453
- 4.3.2.5 Higher Order Multipoles 454
- 4.3.3 Magnetic Design 455
- 4.3.3.1 General 455
- 4.3.3.2 Current Density 456
- 4.3.3.3 Field Shape 458
- 4.3.3.4 $\cos \theta$ Coil 459
- 4.3.3.5 Other Coil Shapes: Block, Canted, Super-Ferric, Transmission line 463
- 4.3.4 Mechanical Design 467
- 4.3.4.1 Collars and $\cos \theta$ 467
- 4.3.4.2 Bladders and Keys 469
- 4.3.5 Margins, Stability, Training, and Protection 471
- 4.3.5.1 Margins and Stability 471
- 4.3.5.2 Training 472
- 4.3.5.3 Protection 475
- 4.3.6 Field Quality 478
- 4.3.7 Fast-Cycled Synchrotrons 482
Acknowledgments 484
References 484

- 4.4 Superconducting Detector Magnets for Particle Physics 487
Michael A. Green
 - 4.4.1 The Development of Detector Solenoids 487
 - 4.4.1.1 Early Superconducting Detector Magnets 487
 - 4.4.1.2 Low Mass Thin Detector Magnets 488
 - 4.4.2 LHC Detector Magnets for the ATLAS, CMS, and ALICE Experiments 489
 - 4.4.2.1 Magnets for the ATLAS Detector 491
 - 4.4.2.1.1 The ATLAS Central Solenoid 491
 - 4.4.2.1.2 The ATLAS Endcap Toroids 492
 - 4.4.2.1.3 The ATLAS Barrel Toroid 492
 - 4.4.2.2 The CMS Detector Magnet 493
 - 4.4.3 The Future of Detector Magnets for Particle Physics 496
 - 4.4.4 The Defining Parameters for Thin Solenoids 498
 - 4.4.5 Thin Detector Solenoid Design Criteria 500
 - 4.4.6 Magnet Power Supply and Coil Quench Protection 505
 - 4.4.6.1 Quench Protection Dump Resistor 506
 - 4.4.6.2 The Role of Quench Back 507
 - 4.4.7 Design Criteria for the Ends of a Detector Solenoid 509
 - 4.4.7.1 Cold Mass Support System 509
 - 4.4.7.2 The Solenoid Support Structure, the Cryogenic Heat Sink 511
 - 4.4.7.3 Coil Electrical Connections and Leads to the Outside World 511
 - 4.4.8 Cryogenic Cooling of a Detector Magnet 512
 - 4.4.8.1 Forced Two-Phase Flow Circuits 512
 - 4.4.8.2 Two-Phase Cooling Using Natural Convection 515
 - 4.4.8.3 High-Temperature Superconducting (HTS) Leads 517
 - 4.4.8.4 Detector Magnets Cooled and Cooled Down with Small Cooler 517
- 4.5 Magnets for NMR and MRI 523
Yukikazu Iwasa and Seungyong Hahn
 - 4.5.1 Introduction to NMR and MRI Magnets 523
 - 4.5.1.1 NMR and MRI 523
 - 4.5.1.2 Spatial Field Homogeneity 524
 - 4.5.1.3 Temporal Stability 524
 - 4.5.1.3.1 Persistent Mode 524
 - 4.5.1.3.2 Driven Mode 525
 - 4.5.1.4 General Coil Configurations of NMR and MRI Magnets 525
 - 4.5.2 Specific Design Issues for NMR and MRI Magnets 526
 - 4.5.2.1 Superconductor 526
 - 4.5.2.2 Stability of Adiabatic Magnets 527
 - 4.5.2.3 Stress Analysis – Electromagnetic, Thermal, Winding 529
 - 4.5.2.3.1 Electromagnetic 530
 - 4.5.2.3.2 Thermal 530
 - 4.5.2.3.3 Winding 530
 - 4.5.2.4 Solenoidal Field 530
 - 4.5.2.4.1 Harmonic Analysis 531
 - 4.5.2.5 Field Mapping and Shimming 531
 - 4.5.2.5.1 Active Shimming 531
 - 4.5.2.5.2 Passive Shimming 533
 - 4.5.2.6 Field Shielding 533
 - 4.5.2.6.1 Active Shielding 533
 - 4.5.2.6.2 Passive Shielding 534
 - 4.5.2.7 Safety 534
 - 4.5.3 Status (2013) of NMR and MRI Magnets 534
 - 4.5.3.1 Solid-State and Solution NMR 534
 - 4.5.3.1.1 LTS Magnets (400–1000 MHz) 535
 - 4.5.3.1.2 LTS/HTS Magnets (> 1 GHz) 535
 - 4.5.3.2 Medical Diagnostic MRI Magnet 536
 - 4.5.3.2.1 Whole Body 536
 - 4.5.3.2.2 Extremity 537
 - 4.5.3.2.3 Functional 537
 - 4.5.3.2.4 Research 537
 - 4.5.4 HTS Applications to NMR and MRI Magnets 539
 - 4.5.4.1 Annulus NMR 539
 - 4.5.4.2 Liquid Helium (LHe)-Free 539
 - 4.5.4.2.1 MgB₂ MRI 539
 - 4.5.4.3 No-Insulation Winding Technique 539
 - 4.5.4.4 HTS Shim Coils 540
 - 4.5.4.5 All-HTS 4.26 GHz (100 T) NMR Magnets 540
 - 4.5.5 Conclusions 540
 - References 541
 - 4.6 Superconducting Magnets for Fusion 544
Jean-Luc Duchateau
 - 4.6.1 Introduction to Fusion and Superconductivity 544
 - 4.6.2 ITER 546
 - 4.6.2.1 Introduction 546
 - 4.6.2.2 The ITER Magnet System 547
 - 4.6.2.3 Main Dimensioning Aspects of ITER 548
 - 4.6.2.4 The ITER TF System 550
 - 4.6.2.5 The ITER Model Coils 551
 - 4.6.3 Cable in Conduit Conductors (CICC) 552
 - 4.6.3.1 Introduction 552
 - 4.6.3.2 Stability of Cable in Conduit Conductors 554
 - 4.6.3.3 Current Densities in Cable in Conduit Conductor 557
 - 4.6.4 Quench Protection and Quench Detection in Fusion Magnets 557
 - 4.6.4.1 Specific Solution of Quench Protection for Fusion Magnets 557
 - 4.6.4.2 High Voltages in Fusion Magnets During FSD and in Operation 559

- 4.6.4.2.1 Normal Operation 560
- 4.6.4.2.2 Quality Control During Coil Production 561
- 4.6.4.3 The Quench Protection Circuit (QPC) 561
- 4.6.4.4 Quench Detection 562
 - 4.6.4.4.1 Mitigation of the Inductive Part of the Voltage 562
 - 4.6.4.4.2 The Main Parameters of the Quench Detection 563
 - 4.6.4.4.3 Quench Propagation in CICC 565
- 4.6.5 Prospective about Future Fusion Reactors: DEMO 565
 - 4.6.5.1 Which Superconducting Material for DEMO? 566
- 4.6.6 Conclusion 567
 - References 568
- 4.7 High-Temperature Superconducting (HTS) Magnets 569
 - Swarn Singh Kalsi*
 - 4.7.1 Introduction 569
 - 4.7.2 High-Field Magnets 569
 - 4.7.3 Low-Field Magnets 573
 - 4.7.3.1 Magnetic Separation 573
 - 4.7.3.2 Crystal Growth 575
 - 4.7.3.3 Induction Heating 576
 - 4.7.3.4 Accelerator and Synchrotron Magnets 579
 - 4.7.4 Outlook 580
 - References 580
- 4.8 Magnetic Levitation and Transportation 583
 - John R. Hull*
 - 4.8.1 Introduction 583
 - 4.8.2 Magnetic Levitation: Principles and Methods 583
 - 4.8.2.1 Magnetic Forces 583
 - 4.8.2.2 Static Stability 584
 - 4.8.2.3 Magnetic Biasing 584
 - 4.8.2.4 Electromagnetic Suspension 585
 - 4.8.2.5 AC Levitation 586
 - 4.8.2.6 Electrodynamic Levitation 588
 - 4.8.2.7 Levitation by Tuned Resonators 591
 - 4.8.2.8 Magnitude of Levitation Pressure 591
 - 4.8.2.9 HTS/PM Levitation 592
 - 4.8.2.10 Propulsion 592
 - 4.8.3 Maglev Ground Transport 592
 - 4.8.3.1 History 592
 - 4.8.3.2 System Technical Considerations 595
 - 4.8.3.3 Guideway Design 596
 - 4.8.3.4 Cryostats and Vehicle Design 597
 - 4.8.4 Clean-Room Application 597

- 4.8.5 Air and Space Launch 598
 - References 599