CONTENTS

| CHAPTER 1 SUPERCONDUCTING MAGNET TECHNOLOGY | | | | | • | . 1 |
|--|---|---|---|---|---|-----|
| 1.1 Introductory Remarks | | | | | | . 1 |
| 1.2 Superconductivity | | | | | | . 3 |
| 1.3 Magnet-Grade Superconductors | | | | | | . 6 |
| 1.4 Magnet Design | | | | | | . 7 |
| 1.5 Class 1 and Class 2 Superconducting Magnets | | | | | | . 9 |
| 1.6 The Format of the Book | | | • | • | | . 9 |
| CHAPTER 2 ELECTROMAGNETIC FIELDS | | | | | | 11 |
| 2.1 Introduction | | | | | | 11 |
| 2.2 Maxwell's Equations | | | | | | 11 |
| 2.3 Quasi-Static Case | | | | | | 14 |
| 2.4 Poynting Vector | | | | | | 15 |
| 2.5 Field Solutions from the Scalar Potentials | | | | | | 16 |
| Problem 2.1: Magnetized sphere in a uniform field | | | | | | 19 |
| Problem 2.2: Type I superconducting rod in a uniform field . | | | | | | 23 |
| Problem 2.3: Magnetic shielding with a spherical shell | | | | | | 26 |
| Problem 2.4: Shielding with a cylindrical shell | | | | | | 32 |
| Problem 2.5: The field far from a cluster of four dipoles | | | | | | 34 |
| Problem 2.6: Induction heating of a cylindrical shell | | | | | | 36 |
| Induction heating—Part 1 (Field) | | | | | | 37 |
| Induction heating—Part 2 (Power Dissipation) | | | | | | |
| Problem 2.7: Eddy-current loss in a metallic strip | | | | | | 43 |
| Lamination to Reduce Eddy-Current Loss | ٠ | • | • | • | • | 44 |
| CHAPTER 3 MAGNETS, FIELDS, AND FORCES | | | | | • | 45 |
| 3.1 Introduction | | | | | | 45 |
| 3.2 Law of Biot and Savart | | | | | | 45 |
| 3.3 Lorentz Force and Magnetic Pressure | | | | | | 46 |
| Problem 3.1: Uniform-current-density solenoids | | | | | | 48 |
| Bitter Magnet | | | | | | 53 |
| Problem 3.2: Bitter magnet | | | | | | 54 |
| Additional Comments on Water-Cooled Magnets | | | | | | 57 |
| Hybrid Magnet | | | | | | 58 |
| Parameters of Hybrid III Superconducting Magnet (SCM) . | | | | | | 59 |
| Problem 3.3: Hybrid Magnet | | | | | | 60 |
| Problem 3.4: Helmholtz coil | | | | | | 62 |
| Problem 3.5: Spatially homogeneous fields | | | | | | |
| Problem 3.6: Notched solenoid | | | | | | 67 |

x Contents

| Problem 3.7: | $Ideal\ dipole\ magnet\ \dots\dots\dots\dots$ | | | | | | | | 69 |
|----------------|--|---|---|---|---|---|---|---|-----|
| Problem 3.8: | $\it Ideal\ quadrupole\ magnet\ .\ .\ .\ .\ .\ .\ .$ | | | | | | | | 74 |
| Problem 3.9: | Magnet comprised of two ideal "racetracks" . | | | | | | | | 77 |
| Problem 3.10: | $\emph{Ideal toroidal magnet} \ldots \ldots \ldots \ldots$ | | | | | | | | 84 |
| Nuclear Fusio | n and Magnetic Confinement | | | | | | | | 86 |
| Problem 3.11: | Fringing field $\ldots \ldots \ldots \ldots$ | | | | | | | | 87 |
| Problem 3.12: | Circulating proton in an accelerator | | | | | | | | 89 |
| Particle Accel | lerators | | | | | | | | 89 |
| Problem 3.13: | Magnetic force on an iron sphere | | | | | | | | 91 |
| • | Fault condition in hybrid magnets 1. Fault-mode forces | | | | | | | | 95 |
| Vertical Magn | netic Force during Hybrid III Insert Burnout | | | | | | | | 97 |
| Problem 3.15: | Fault condition in hybrid magnets | | | | | | | | |
| | 2. Mechanical support requirements | | | | | | | | 98 |
| | Fault condition in hybrid magnets | | | | | | | | |
| | 3. Fault force transmission | | | | | | | | |
| | Stresses in an epoxy-impregnated solenoid. | | | | | | | | |
| Problem 3.18: | Stresses in a composite Nb_3Sn conductor . | • | • | • | ٠ | • | ٠ | ٠ | 105 |
| CHAPTER 4 CRY | YOGENICS | | | | | | | | 111 |
| 4.1 Introduct | | | | | | | | • | |
| • • | | | | | | | | | 111 |
| 4.3 Superfluid | • | | | | | | | | |
| Problem 4.1: | Carnot refrigerator | | | • | | • | | | 119 |
| Joule-Thomse | | | | | | | | | |
| • | Cooling modes of a magnet | | | | | | | | |
| Problem 4.3: | Optimum gas-cooled leads—Part 1 | | | • | • | | • | • | 125 |
| | Optimum gas-cooled leads—Part 2 | | | | | | | ٠ | 130 |
| Problem 4.4: | Optimum leads for a vacuum environment— | | | | | | | | |
| | | | | | | | | | 137 |
| | Franz-Lorenz Law and Lorenz Number | | | | | | | | |
| • | Gas-cooled support rods | | | | | | | | |
| | aterials for Cryogenic Applications | | | | | | | | |
| | Subcooled 1.8-K cryostat | | | | | | | | |
| | Residual gas heat transfer into a cryostat . | | | | | | | | |
| • • | y Residual Gas: "High" Pressure Limit | | | | | | | | |
| - | y Residual Gas: "Low" Pressure Limit | | | | | | | | |
| Vacuum Pum | | | | | | | | | |
| ` | ges | | | | | | | | |
| Problem 4.8: | Radiation heat transfer into a cryostat | | | | | | | | 151 |

| CONTENTS | хi | |
|----------|----|--|
| | | |

| Radiation Heat Transfer: Applications to a | Cryostat 151 |
|---|------------------------|
| Effect of Superinsulation Layers | |
| Practical Considerations of Emissivity | 153 |
| Problem 4.9: Laboratory-scale hydrogen (ne | con) condenser 155 |
| Problem 4.10: Carbon resistor thermometers | 3 159 |
| Effects of a Magnetic Field on Thermometer | ers 161 |
| CHAPTER 5 MAGNETIZATION OF HARD SUPP | ERCONDUCTORS 163 |
| 5.1 Introduction | 163 |
| 5.2 Bean's Critical State Model | 163 |
| 5.3 Experimental Confirmation of Bean's M | Model 168 |
| 5.4 A Magnetization Measurement Techniq | que 169 |
| Problem 5.1: Magnetization with transport of 1. Field and then transport cu | current |
| Problem 5.2: Magnetization with transport 2. Transport current and then | current a field 176 |
| Use of SQUID for Magnetization Measurem | |
| Problem 5.3: Magnetization with transport | |
| Magnetization Functions – Summary | |
| Problem 5.4: Critical current density from a | |
| Contact-Resistance Heating at Test Sample | - |
| | |
| | |
| | |
| | |
| | |
| Filament Twisting in Composite Supercond | |
| Problem 5.10: Flux jump criterion for HTS | |
| | |
| | |
| | 203 |
| | 203 |
| 6.3 Cable-in-Conduit (CIC) Conductors . | 206 |
| Problem 6.1: Cryostability 1. Circuit model | |
| Peak Nucleate Boiling Heat Transfer Flux: | Narrow Channels 211 |
| Problem 6.2: Cryostability | |
| Problem 6.3: Cryostability 3 Stekly criterion | 214 |

xii Contents

| Discussion of | Stekly Cryostability Criterion |
|------------------|---|
| Problem 6.4: | |
| | 4. Nonlinear cooling curves |
| $Composite\ Si$ | uperconductors: "Monolithic" and "Built-up" 217 |
| Problem 6.5: | Dynamic stability for tape conductors |
| | 1. Magnetic and thermal diffusion |
| Problem 6.6: | Dynamic stability for tape conductors |
| | 2. Criterion for edge-cooled tapes |
| Problem 6.7: | "Equal-area" criterion |
| Problem 6.8: | The MPZ concept |
| $Problem \ 6.9:$ | V vs I traces of a cooled composite conductor |
| | Stability analyses of Hybrid III SCM |
| Cryostable v | s Quasi-Adiabatic (QA) Magnets |
| Problem 6.11: | Stability of CIC conductors |
| Problem 6.12: | "Ramp-rate-limitation" in CIC conductors 245 |
| Problem 6.13: | MPZ for a composite tape conductor |
| Problem 6.14: | Stability of HTS magnets |
| CHAPTER 7 AC | C, SPLICE, AND MECHANICAL LOSSES 261 |
| 7.1 Introduct | |
| 7.2 AC Losse | |
| | esistance |
| | cal Disturbances |
| | Emission Technique |
| Problem 7.1: | Hysteresis loss—basic derivation |
| F100le111 1.1: | 1. Without transport current |
| Problem 7.2: | Hysteresis loss—basic derivation |
| 1 10000110 1.2. | 2. With transport current |
| Problem 7.3: | Hysteresis loss (no transport current) |
| | 1. "Small" amplitude cyclic field 280 |
| Problem 7.4: | Hysteresis loss (no transport current) |
| • | 2. "Large" amplitude cyclic field |
| Problem 7.5: | Coupling time constant |
| Problem 7.6: | Hysteresis loss of an Nb ₃ Sn strand |
| Problem 7.7: | AC losses in Hybrid III SCM |
| "Burst Disk" | and Diffuser for Hybrid III Cryostat |
| Problem 7.8: | AC losses in the US-DPC Coil |
| Problem 7.9: | Splice dissipation in Hybrid III Nb-Ti coil |
| Mechanical I | Properties of Tin-Lead Solders |
| | A splice for CIC conductors |
| | CIC Splice in a Time-Varying Magnetic Field 304 |

| CONTENTS | | | | | xiii |
|------------------------------|---|---|---|---|----------------|
| Experimenta Problem 7.12: | Loss due to "index" number | | | | . 307 . 309 |
| | ission Sensor for Cryogenic Environment | | | | |
| | Conductor-motion-induced voltage pulse | | | | |
| | Disturbances in HTS magnets | | | | |
| | ation Anisotropy in BiPbSrCaCuO (2223) Tapes | | | | |
| | , , <u>-</u> | | | | |
| 0121 | OTECTION | | | | |
| | tory Remarks | | | | |
| | n for Class 2 Magnets | | | | |
| | r Simulation | | | | |
| | Active protection | | | | |
| Comments or | a Z Functions for Magnet Protection | | | | . 332 |
| $Problem \ 8.2:$ | ${\it Hot\text{-}spot\ temperatures\ in\ Hybrid\ III\ SCM\ .\ .\ .}$ | | | | . 333 |
| Problem 8.3: | Quench-voltage detection (QVD) 1. Basic technique using a bridge circuit | | | | . 336 |
| Problem 8.4: | Quench-voltage detection (QVD) 2. An improved technique | | | | . 338 |
| Voltage Atter | nuation in Magnet Protection Circuit | | | | |
| | Quench-induced pressure in CIC conductors 1. Analytical approach | | | | |
| Problem 8.6: | Quench-induced pressure in CIC conductors 2. CIC coil for the NHMFL's 45-T hybrid | | | | |
| Problem 8.7: | Normal-zone propagation (NZP) | | | | |
| | 1. Velocity in the longitudinal direction | | | | . 347 |
| Problem 8.8: | Normal-zone propagation (NZP) 2. Transverse (turn-to-turn) velocity | | | | . 351 |
| Problem 8.9: | Passive Protection of "isolated" magnets 1. Basic concepts | | | | . 355 |
| Problem 8.10: | Passive Protection of "isolated" magnets 2. Two-section test coil | | | | . 358 |
| Problem 8.11: | Passive Protection of "isolated" magnets 3. Multi-coil NMR magnet | | | | . 362 |
| Problem 8.12: | NZP velocity in HTS magnets | | | | |
| | field HTS magnets operating at 20 K | | | | |
| | | • | • | ٠ | |
| | NCLUDING REMARKS | • | ٠ | • | . 375 |
| | Technology vs Replacing Technology | | | | |
| 9.2 Outlook | for the HTS | | | | . 376 |

| xiv | CONTENTS |
|-----|----------|
| | |

| APPENDIX I | PHYSICAL CONSTANTS AND CONVERSION FACTORS 3 | 77 |
|------------------------|---|-----------------|
| Table A1 | 1 Selected Physical Constants | 77 |
| Table A1 | 2 Selected Conversion Factors | 78 |
| APPENDIX I | THERMODYNAMIC PROPERTIES OF CRYOGENS 3 | 79 |
| Table A2 | 1 Helium at 1 Atm | 79 |
| Table A2 | 2 Helium at Saturation | 80 |
| Figure A2 | 1 Isochoric $P(T)$ curves for helium at two densities 3 | 81 |
| Figure A2 | 2 Isochoric $u(T)$ curves for helium at two densities 3 | 82 |
| Table A2 | 3 Selected Properties of Cryogens at 1 Atm | 83 |
| Table A2 | 4 Heat Transfer Properties of Cryogen Gases at 1 Atm 3 | 83 |
| APPENDIX I | I PHYSICAL PROPERTIES OF MATERIALS | 85 |
| Figure A3 | .1 Thermal conductivity vs temperature plots | 85 |
| Figure A3 | 2 Heat capacity vs temperature plots | 86 |
| Figure A3 | 3 Volumetric enthalpy vs temperature plots | 87 |
| Table A3 | .1 Mechanical Properties of Materials | 188 |
| Table A3 | 2 Mean Linear Thermal Expansion of Materials 3 | 189 |
| Appendix I | V ELECTRICAL PROPERTIES OF NORMAL METALS 3 | 191 |
| Figure A4 | .1 Normalized zero-field electrical resistivity vs temperature plots | 391 |
| Figure A4 | | |
| Figure A4 | .3 Copper Residual Resistivity Ratio (RRR) vs | |
| 775-1-1- A 4 | magnetic induction plots | |
| Table A4 Appendix V | | |
| | | |
| Table A5 | -02 | |
| Table A5 | · · | |
| Figure A5 | | |
| Figure A5 | | |
| Table A5 | • | |
| Figure A5 | - · · · · · · · · · · · · · · · · · · · | |
| Table A5 | .4 Selected Physical Properties of YBCO and BSCCO 3 | 399 |
| APPENDIX \ | I GLOSSARY | 1 01 |
| APPENDIX V | TI QUOTATION SOURCES AND CHARACTER IDENTIFICATION 4 | 113 |
| INDEX | | 115 |
| | | |