Contents

Part I Introductory Systems and Plasma Fundamentals

1 Introduction to Systems Approaches to Nuclear Fusion 3
1.1 Fusion Physics and Systems Approaches 3
1.1.1 Fusion Reactors and Systems 3
1.1.2 Detailed Monograph Organization 5
1.1.3 A Simplified Description of Plasmas 7
1.1.4 Tokamak Magnetic Field Coils and Geometry 9
1.1.5 Plasma Current and MHD Fluid Equilibrium 11
1.1.6 Plasma Pressure and Confinement Time 12
1.1.7 Individual Particle Effects in Toroidal Systems 13
1.1.8 Auxiliary Heating and Current Drive 14
1.1.9 Elements of a Tokamak Fusion Reactor 14
1.2 Systems Engineering and Architecture Principles 16
1.2.1 Elements, Relationships and Systems Thinking 16
1.2.2 Hierarchy 16
1.2.3 Aspects 17
1.2.4 Models 17
1.2.5 Agility 19
1.3 Systems Engineering Process Model 19
1.3.1 Problem Solving Process, Systems Architecture and Design 21
1.3.2 Concept Development 21
1.3.3 Constraints 22
1.3.4 Metrics and Risk 22
1.4 Systems Emergent Properties, Robustness and Dynamics 23
1.4.1 Emergent Properties of Systems 23
1.4.2 Mechanisms for Robustness 24
1.4.3 Robustness Trade-Offs 24
1.4.4 Fragilities 25

1.4.5 Resource Demands 25
1.4.6 Performance 25
1.5 Examples of Systems Engineering, Architecture, and Emergent Properties 26
1.5.1 Building a House 26
1.5.2 Landing on the Moon and Returning 26
1.5.3 Guiding an Airplane in Flight 26
1.6 Systems Reverse Engineering 27
1.6.1 Identifying Elements and Relationships in Existing Devices 27
1.6.2 Analysing Metrics and Emergent Properties 27
1.6.3 Contributing Lessons Learned to the Design Space . . . 28
1.7 Systems Forward Engineering – From Concept to Architecture 28
1.7.1 Developing a Solution-Neutral Function 28
1.7.2 Developing and Implementing Concepts 28
1.7.3 Organization of Project Management 29
1.8 Summary Checklists of Systems Strategies for Fusion 30
1.8.1 Systems Concepts Summary – Checklist 1.1 30
1.8.2 Analyse Existing Plasma Physics and Nuclear Fusion Machines – Checklist 1.2 30
1.8.3 Design, Fund, Build and Commission New Fusion Machines – Checklists 1.3A and 1.3B 30
1.8.4 Design and Carry Out Fusion Experiments on Existing Machines – Checklist 1.4 31
1.8.5 Analyse Prototype Reactor Machines and Experiments – Checklist 1.5 32
1.8.6 Planning and Building Next-Step Fusion Reactor Machines – Checklist 1.6 32
1.8.7 Designing and Building a Fusion Reactor – Checklist 1.7 32
1.8.8 Comparing Approaches to Diverse Concept Fusion reactors – Checklist 1.8 33
1.8.9 Detailed Checklists 1.1 to 1.8 33
References 41

2 Systems Design Space for Tokamak Physics and Engineering 45
2.1 Developing a Design Space 45
2.2 Detailed Views of Tokamak Design Space 46
2.2.1 The Time View 46
2.2.2 Time Scales and Design Options 47
2.2.3 Plasma View 49
2.2.4 Spatial View of Form 50
2.3 Engineering and Interface Analysis 50
2.3.1 Engineering Aspects 50
2.3.2 Interface Analysis 51

2.4 Operational Scenarios from Tokamaks with Less Than 700 kA Plasma Current 53
2.4.1 Strategy for Developing a Catalogue of Operational Scenarios 53
2.4.2 TOSCA 55
2.4.3 TCABR, Formerly TCA 56
2.4.4 Neutral Beam Heating with PLT and COMPASS 57
2.4.5 Tokamak T-10, Successor to T-3 and T-4 58
2.4.6 HL-2A, Formerly ASDEX, and HL-2 M 59
2.4.7 START 61
2.4.8 GLOBUS-M and GLOBUS –M2 62
2.4.9 QUEST 63
2.4.10 General Fusion's Spector and SLiC 64
2.5 Design Space Catalogue of Tokamak Operational Scenarios . . . 65
2.5.1 Vacuum Vessel and Component Conditioning 65
2.5.2 Plasma Start-Up and Current Ramp 65
2.5.3 MHD Equilibrium and High Beta 66
2.5.4 Particle and Energy Confinement and H-Modes 66
2.5.5 Heating, Current Drive and Their Role in Controlling Instabilities and Disruptions 68
2.5.6 Divertor Radiation and Plasma-Wall Interaction 69
2.5.7 Plasma Diagnostics and Machine Control 70
2.5.8 High Power Tritium Burning and Alpha Particle Heating 70
2.5.9 Long Pulse and Steady-State Operation 71
2.6 Tokamak Simulation Codes 72
2.6.1 Plasma Simulation and Design Codes 72
2.6.2 Integrated Workflows of Simulation Codes 73
2.6.3 Systems Engineering Codes 74
2.7 Component Design Options 74
2.8 Integration of the Systems Design Space 78
References 78

Part II High-Current Tokamaks

3 Doublet III/DIII-D and 1–2 MA Tokamaks: Robustness and Adaptation 89
3.1 Systems Analysis Strategy for Doublet III/DIII-D 89
3.1.1 Overall Strategy 89
3.1.2 Application of Checklist 1.2 89
3.1.3 Doublet III Form and Function Choices 90
3.2 Doublet III Experiments and Scenarios 94
3.2.1 MHD Equilibrium 94

3.2.2 Plasma Energy Confinement in Different MHD Equilibria 94
3.2.3 Doublet III Scenarios 95
3.3 DIII-D Design and Results 98
3.3.1 Upgrade of Doublet III to DIII-D 98
3.3.2 DIII-D Scenarios 100
3.4 DIII-D Systems Analysis of Emergent Properties and Tradeoffs 104
3.4.1 Analysis of Emergent Properties 104
3.4.2 Systems Control 104
3.4.3 Fault-Tolerance 104
3.4.4 Modularity 105
3.4.5 Decoupling 105
3.4.6 Resistance 105
3.4.7 Avoidance 105
3.4.8 Resource Demands 106
3.4.9 Robustness 106
3.4.10 Fragility 106
3.4.11 Performance and Metrics 107
3.5 Asdex-Upgrade 107
3.5.1 Asdex-Upgrade Design 107
3.5.2 Asdex-Upgrade Scenarios 109
3.5.3 Robustness and Performance Analysis 110
3.6 Alcator C and C-Mod 111
3.6.1 Alcator and Alcator C-Mod Design 111
3.6.2 Alcator C and C-Mod Scenarios 112
3.6.3 Robustness and Performance Analysis 115
3.7 FTU 116
3.7.1 FTU Design 116
3.7.2 FTU Scenarios 116
3.7.3 Robustness and Performance Analysis 117
3.8 Spherical Tokamaks MAST, MAST-Upgrade and STEP 117
3.8.1 MAST Design and Results 117
3.8.2 Energy Confinement in MAST 118
3.8.3 Robustness and Performance Analysis 119
3.8.4 MAST Upgrade First Results 119
3.8.5 STEP 119
3.9 Spherical Tokamaks NSTX and NSTX-U 119
3.10 Low Aspect Ratio with High Vertical Elongation ST-40 120
3.11 Discussion of the Robustness and Performance of 1–2 MA Tokamaks 120
References 121

4 TCV: A Case Study in Systems Forward Engineering of a MA Tokamak 125
4.1 Systems Forward Engineering Strategy for TCV 125
4.1.1 Case Study Strategy 125
4.1.2 TCV Capabilities 126
4.2 Systems Approaches to the Design of TCV 128
4.2.1 Suitability of TCV as a Case Study in Systems Approaches 128
4.2.2 Systems Forward Engineering – Getting Started 128
4.2.3 Predecessor Tokamak TCA Design 129
4.2.4 TCA Technical Choices 129
4.2.5 TCV First Goals and Design Options 130
4.3 Review and Prioritize Goals and Evaluate Variants for TCV 132
4.3.1 Systems Review Process in Early Stages and Prioritizing Goals 132
4.3.2 Scenarios for TCV from the Tokamak Design Space and Revised Priorities 132
4.3.3 The Intermediate Design Research Areas for TCV 133
4.3.4 Tokamak Systems Basic Parameters for Further Design 133
4.3.5 TCV Systems Architecture 134
4.3.6 Scoping the Systems for Creating High Current and Highly Elongated Plasmas 136
4.3.7 Power supply Requirements for Shaping and Controlling Plasma 138
4.3.8 Phase I Proposal and Euratom Review 140
4.3.9 Phase II Proposal to Euratom 141
4.4 TCV Top Level Robustness Properties and Tradeoffs 142
4.4.1 Robustness 142
4.4.2 Fragility 143
4.5 TCV Final Design for Construction 144
4.5.1 Phase II Committee Review and Approval 144
4.5.2 Systems Level Considerations for Final Design and Construction 145
4.5.3 TCV System Level Final Design for Construction 145
4.5.4 Implementation 146
4.6 TCV Subsystem-Elements Descriptions and Robustness Analysis 146
4.6.1 Toroidal Field Coils, Power Supplies and Systems Analysis 146
4.6.2 Poloidal Field Coils, Power supplies and Systems Analysis 148
4.6.3 Flywheel Motor Generator and Systems Analysis 151

4.6.4 Vacuum Vessel and Vacuum Equipment Systems Analysis . . . 151
4.6.5 Management of Procurement, Construction and Initial Testing . . . 152
4.6.6 Auxiliary Heating Upgrades for TCV . . . 153
4.6.7 Machine and Plasma Control and Data Acquisition . . . 153
4.7 TCV Scenarios . . . 154
4.7.1 High Elongation Plasmas and Ohmic H-Modes . . . 154
4.7.2 Fully Digital Plasma Control . . . 154
4.7.3 Fully Non-inductive Steady-State Plasmas with Electron Cyclotron Current Drive . . . 155
4.7.4 Limits of Operating Space for High Plasma Elongation . . . 155
4.7.5 High Power Electron Cyclotron Heating and Bootstrap Current Drive . . . 155
4.7.6 Electron Internal Transport Barriers with EC Current Drive . . . 156
4.7.7 H-mode Regimes with Ohmic Heating in H, D and He . . . 156
4.7.8 Neutral Beam Current Drive and Heating . . . 156
4.7.9 Multi-machine ITER Scenario to Maximize Edge Pedestal Height . . . 156
4.7.10 Exhaust Control and Detachment in Snowflake and Super-X Divertors . . . 157
4.7.11 Vessel Wall Conditioning with ECRH . . . 157
4.7.12 Real Time Plasma Control Systems . . . 158
4.7.13 Disruption Avoidance by Real-Time Locked Mode Prevention with ECCD . . . 158
4.7.14 Elimination of Disruption Runaway Electron Current with Current Ramp Down . . . 158
4.7.15 High-βN Fully Noninductive Scenarios with Combined EC and NBI . . . 158
4.7.16 Reduced Heat Flux with Grassy ELM's at High Triangularity . . . 159
4.7.17 High-Shared-Flux Doublet Configuration with Separate Lobe ECRH . . . 159
4.7.18 Removable Gas Baffles Separating Main and Divertor Chambers . . . 159
4.8 Lessons Learned About Systems Forward Engineering . . . 160
References . . . 160

5 JET – World's Largest Tokamak and its d-t Fusion Experiments Plus TFTR's . . . 163
5.1 Systems Analysis Strategy for JET . . . 163
5.2 JET Goals, Machine Parameters and Systems Integration . . . 164

5.2.1 JET Design and Systems Architecting of Highest Level Systems . . . 164
5.2.2 Elements of Next Level Systems, Form Relationships and Design Choices . . . 166
5.3 Operational and Experimental Evidence of Success in Machine Operation . . . 168
5.3.1 Initial JET Operation Pre-1989 . . . 168
5.3.2 High Performance Plasmas in Preparation for Tritium Experiments . . . 169
5.3.3 Analysis of Emergent Properties of Systems and Robustness Against Faults . . . 171
5.4 Neutron and Fast Particle Diagnostics . . . 173
5.4.1 JET Plasma Diagnostics and the Role of Fusion Product Diagnostics . . . 173
5.4.2 Fusion Products and Diagnostics . . . 173
5.4.3 Measurements with Neutron and Fast Particle Diagnostics . . . 175
5.4.4 Robustness Analysis of Neutron and Fast Particle Diagnostics . . . 178
5.5 Preliminary Tritium Experiments (PTE) . . . 179
5.5.1 Systems Design of Preliminary Tritium Experiments (PTE) . . . 179
5.5.2 Preliminary Deuterium-Tritium Fusion Experiments (PTE) . . . 181
5.6 Full Power Deuterium-Tritium Experiments (DTE1) . . . 184
5.6.1 JET Optimization in Preparation for DTE1 . . . 184
5.6.2 Machine Upgrades . . . 184
5.6.3 Experimental Preparation for $Q = 1$ Energy Breakeven Experiments at High Power . . . 185
5.6.4 Systems Approaches to Planning Full Power Deuterium-Tritium Fusion Experiments . . . 186
5.6.5 Deuterium-Tritium High Power Nuclear Fusion Operational Scenarios and Results in JET . . . 193
5.7 Post-DTE1 Operation in JET – Preparation for DTE2 . . . 197
5.7.1 Planning for DTE2 Experiments in JET . . . 198
5.7.2 Extrapolated Baseline Scenario . . . 199
5.7.3 Extrapolated Hybrid Scenario at High Normalized Beta . . . 199
5.7.4 Completed Preparations for d-t Experiments . . . 199
5.7.5 Successful DTE2 Operation . . . 200
5.8 Fusion Power Experiments in TFTR . . . 200
5.8.1 Tokamak Fusion Test Reactor (TFTR) Design . . . 200
5.8.2 TFTR Experimental Results . . . 201
5.8.3 Robustness and Fragility Analysis . . . 201
References . . . 202

6 Superconducting and Long-Pulse Tokamaks for Prototyping Reactor Technology . . . 207
- 6.1 Systems Analysis Strategy for Prototyping Reactor Subsystems . . . 207
  - 6.1.1 Goals and Systems Architecture Choices for Superconducting and Steady-State Tokamaks . . . 208
  - 6.1.2 Key Elements and Constraints of Steady-State Operation . . . 210
- 6.2 Design Space for Superconducting and Long-Pulse Tokamaks . . . 210
  - 6.2.1 Goals for Using the Design Space . . . 210
  - 6.2.2 Technical Aspects of Superconducting Magnets . . . 211
  - 6.2.3 Systems Architecture of Choices and Trade-Offs . . . 212
- 6.3 HT-7 (Formerly T-7) . . . 215
  - 6.3.1 Design . . . 215
  - 6.3.2 Scenarios . . . 216
  - 6.3.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 216
- 6.4 TRIAM-1M . . . 216
  - 6.4.1 Design . . . 216
  - 6.4.2 Scenario: 5 h Fully Non-inductive Steady-State Operation with LHCD . . . 217
  - 6.4.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 218
- 6.5 T-15 . . . 218
  - 6.5.1 Design . . . 218
  - 6.5.2 Scenario: Ohmic Heating in T-15 and Test of Superconducting Windings . . . 218
  - 6.5.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 218
- 6.6 Tore-Supra, Later WEST, a Case Study of Prototyping a Superconducting Tokamak Reactor . . . 219
  - 6.6.1 Design . . . 219
  - 6.6.2 Scenarios . . . 221
  - 6.6.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 222
- 6.7 WEST (Tungsten {Symbol "W"} Environment in Steady-State Tokamak) . . . 222
  - 6.7.1 Design . . . 222
  - 6.7.2 Scenario: Plasma and Impurity Confinement in a Long Pulse, High Power, Tungsten Divertor Environment . . . 222
  - 6.7.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 224

- 6.8 SST-1 (Steady-State Superconducting Tokamak) . . . 224
  - 6.8.1 Design . . . 224
  - 6.8.2 Scenario: LHCD . . . 225
  - 6.8.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 225
- 6.9 EAST (Experimental Advanced Superconducting Tokamak) . . . 225
  - 6.9.1 Design . . . 225
  - 6.9.2 Scenarios . . . 227
  - 6.9.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 228
- 6.10 KSTAR (Korea Superconducting Tokamak Advanced Research) . . . 228
  - 6.10.1 Design . . . 228
  - 6.10.2 Scenarios . . . 229
  - 6.10.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 230
- 6.11 JT-60-U (Japan Tokamak 60 m^3 Plasma: Upgraded JT-60) . . . 230
  - 6.11.1 JT-60-U Design and Relevance to JT-60SA . . . 230
  - 6.11.2 Scenarios . . . 230
  - 6.11.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 232
- 6.12 JT-60SA (JT-60 Super Advanced) . . . 232
  - 6.12.1 Design . . . 233
  - 6.12.2 Commissioning Until Superconducting Coil Connector Fault . . . 234
  - 6.12.3 Robustness, Fragility and Relevance to Steady-State Operation . . . 234
- 6.13 Summary Evaluation of Robustness and Fragility in Prototyping Fusion Reactor Subsystems . . . 235
  - 6.13.1 Plasma Start-Up and Current Drive . . . 235
  - 6.13.2 Resistance to Disruptions . . . 235
  - 6.13.3 True Steady-State Operation . . . 235
  - 6.13.4 Long Term Gas Inventory . . . 235
  - 6.13.5 ITER . . . 236
- References . . . 236

Part III Prototype Tokamak Fusion Reactors

7 ITER: A Fusion Proto-Reactor and its Large Scale Systems Integration . . . 241
- 7.1 Systems Analysis Strategy for the ITER Tokamak . . . 241
  - 7.1.1 Overall Systems Analysis Strategy . . . 241
  - 7.1.2 ITER Goals . . . 241
  - 7.1.3 ITER Top Level Parameters and Scoping Comparisons . . . 242

7.1.4 Systems Engineering Approaches Used in ITER Design and Construction . . . 244
7.2 Review of Top Level Systems Architecture and Innovations . . . 246
7.2.1 Overall Systems Architecture . . . 246
7.2.2 Innovation . . . 247
7.3 Plasma with Heating and Current Drive . . . 248
7.3.1 Design Choices . . . 248
7.3.2 Robustness, Fragilities and Opportunities . . . 251
7.4 Detailed Subsystem Design and Emergent Properties . . . 252
7.4.1 Instability Coils . . . 252
7.4.2 In-Vessel Diagnostics . . . 254
7.4.3 Plasma Facing Components and Neutron Shield . . . 254
7.4.4 Test Tritium Breeding Modules (TBM) . . . 255
7.4.5 Divertor . . . 256
7.4.6 Vacuum Vessel and Disruption Mitigation . . . 258
7.4.7 Superconducting Magnetic Coils . . . 259
7.4.8 Auxiliary Heating and Current Drive . . . 260
7.4.9 Diagnostics and Control for Plasma and Neutrons . . . 261
7.4.10 Balance of Plant Including Power Systems, Cooling, Refrigeration and Tritium Processing . . . 264
7.5 Systems Aspects of Construction and Operation . . . 264
7.5.1 Systems Aspects of Machine Assembly and Commissioning . . . 264
7.5.2 Systems Integration of Construction and Operation . . . 265
7.5.3 Preparation for Assembly and Commissioning . . . 265
7.5.4 Robustness and Fragilities of the Construction Process . . . 266
7.5.5 Research Plans to Fulfil Goals . . . 266
7.5.6 Robustness and Fragilities of Physics Research Programme . . . 267
7.6 Conclusions and Lessons for Future Machines . . . 267
7.6.1 Conclusions on Systems Approaches . . . 267
7.6.2 Lessons for Future Machines . . . 267
References . . . 268

8 Demonstration Tokamak Fusion Reactors and Their Systems Approaches . . . 273
8.1 Systems Strategy for Demonstration Tokamak Reactors . . . 273
8.1.1 Identify Goals and Essential Elements of a Fusion Reactor . . . 274
8.1.2 Paths to an "ITER-based" Reactor . . . 275
8.1.3 Key Choices for Neutronics and Reactor Parameters . . . 276
8.1.4 Use Systems Codes to Develop Design Analysis Methods . . . 279

8.2 The EU DEMO and Planning Major Steps for Designing a Fusion Reactor – Case Study . . . 282
8.2.1 Use of Systems Approaches in the Staged Design Approach in Europe . . . 282
8.2.2 Application of Systems Codes . . . 284
8.2.3 Systems Design Point Studies, Sensitivities and Trade-Offs . . . 288
8.2.4 Systems Integration and Key Design Issues . . . 289
8.2.5 Fusion Blanket and Shield Thickness for DEMO . . . 289
8.2.6 Systems Management Structures . . . 292
8.2.7 Robustness and Fragilities . . . 292
8.3 Japan Demo and Fusion Reactor Designs and Their Variations . . . 293
8.3.1 Current Japan DEMO Design . . . 293
8.3.2 Robustness of Japan DEMO Current Design . . . 295
8.3.3 Japan DEMO Designs and Options in Systems Architecture . . . 295
8.3.4 Summary of Previous Design Variants . . . 297
8.4 China Fusion Engineering Test Reactor (CFETR) . . . 297
8.4.1 Two Phase Design . . . 297
8.4.2 Tritium Fuel Cycle Studies for CFETR . . . 297
8.4.3 Toroidal Field Coils . . . 298
8.5 Korea K-DEMO . . . 298
8.5.1 A High Field Reactor . . . 298
8.5.2 Fragility – Cyclotron/Synchrotron Radiation . . . 299
8.6 USA DEMO and Fusion Reactors . . . 299
8.6.1 A High Elongation Fusion Reactor . . . 299
8.6.2 Water or Liquid Nitrogen Cooled Toroidal Field Coil Reactors . . . 300
8.6.3 Advanced Tokamak Reactors . . . 300
8.7 Large Scale DEMOs – Robustness and Fragilities . . . 301
8.7.1 Common Features of Large Scale DEMOs . . . 301
8.7.2 Robustness Summary for Large DEMO Machines . . . 302
8.8 Very High Magnetic Field Reactors . . . 303
8.8.1 SPARC (Soonest/Smallest Private-Funded Affordable Robust Compact) . . . 303
8.8.2 ARC (Affordable Robust Compact) . . . 305
8.8.3 Innovations Required for Very High Field Reactor . . . 307
8.8.4 Fragilities of Very High Field Tokamaks . . . 308
8.9 Compact Spherical Tokamak Fusion Reactors . . . 310
8.9.1 ST-135 and STEP (Spherical Tokamak for Energy Production) . . . 310
8.9.2 USA Sustained High-Power Density (SHPD) Tokamak Facility . . . 312

8.9.3 Robustness of Spherical Tokamak Reactors 312
8.9.4 Fragilities of Spherical Tokamak Reactors 313
8.9.5 A Pulsed Reactor Concept Using Coaxial Helicity Injection 313
8.10 Summary 314
References 315

Part IV Helical, Linear and Inertial Fusion Reactor Concepts

9 Helical Fusion Reactor Concepts 321
9.1 Introduction to the Stellarator and Heliotron Families 321
9.1.1 Systems Analysis Strategy 321
9.1.2 Magnetic and Coil Configuration 322
9.1.3 Early History of Stellarator Development 323
9.1.4 Required Properties of Stellarator Fields 324
9.1.5 Main Stellarator Configurations and Design Space Options 324
9.1.6 MHD Equilibrium and Stability 325
9.1.7 Particle and Energy Transport 325
9.1.8 Symmetry and Stellarator Design Space Optimization Criteria 327
9.1.9 Coil Errors and Tolerances 328
9.2 Wendelstein7-AS (W7-AS) 329
9.2.1 W7-AS Systems Architecture and Technical Choices 329
9.2.2 W7-AS Stellarator Field Optimization 331
9.2.3 W7-AS Operational Scenarios 332
9.2.4 W7-AS Goals Achieved, Robustness and Fragilities 334
9.3 Wendelstein 7-X: A Case Study in Systems Forward Engineering of a Superconducting Helias 334
9.3.1 Systems Analysis Strategy for the Superconducting W7-X Helias as a Case Study 334
9.3.2 Systems Approaches to the Design and First Goals of W7-X 335
9.3.3 Review and Prioritize Goals and Evaluate Variants for W7X 337
9.3.4 W7-X Revised Proposal, Robustness and Tradeoffs 339
9.3.5 W7-X Final Design for Construction 340
9.3.6 Procurement, Construction, and Initial Testing of W7-X 340
9.3.7 W7-X Operational Scenarios 341
9.3.8 W7-X Metrics and Performance 343

9.4 Heliotron-E 343
9.4.1 Heliotron-E Systems Architecture and Technical Choices 343
9.4.2 Heliotron-E Operational Scenarios 344
9.5 Heliotron-J, a Helical Axis Configuration 344
9.5.1 Heliotron-J Systems Architecture and Technical Choices 344
9.5.2 Heliotron-J Operational Scenarios 345
9.6 Superconducting Large Helical Device (LHD) 345
9.6.1 LHD Goals, Systems Architecture and Technical Choices 346
9.6.2 LHD Operation Scenarios 348
9.6.3 LHD Robustness and Fragilities 349
9.7 Alternative Helical Configuration Systems Architecture and Operational Scenarios 350
9.7.1 TJ-II Heliac 350
9.7.2 Model Validation in Stellarators 352
9.7.3 Uragan-2 M and Uragan 3-M Torsatrons 352
9.7.4 H-1NF Heliac 352
9.7.5 HSX 353
9.7.6 WEGA/HIDRA 353
9.7.7 Scyllac 353
9.7.8 CTH 354
9.7.9 NCSX 354
9.7.10 Stellarator Robustness and Fragilities of Alternative Architectures 355
9.7.11 Comparison of Stellarators and Tokamaks 355
9.8 Helias Fusion Reactor Concept HELIAS 5-B 356
9.8.1 Basic Design Considerations 356
9.8.2 Updated Reactor Design 358
9.8.3 A Systems Approach to Optimization 359
9.8.4 Detailed Breeding Blanket Design 359
9.8.5 Balance of Plant 360
9.8.6 Robustness and Fragilities 360
9.9 Heliotron Fusion Reactor Concept FFHR-d1 360
9.9.1 Basic Design 360
9.9.2 A Systems Approach to Reactor Design and Optimization 361
9.9.3 Use of Joints and High Temperature Superconductors 362
9.9.4 Helical Divertor 362
9.9.5 A Liquid salt Breeding Blanket 363
9.9.6 Robustness and Fragilities 363
9.9.7 A Helical Volumetric Neutron Source FFHR-b2 364
9.10 Prospects for Stellarators 364
References 364

10 Linear Magnetic Traps, Field Reversal and Taylor-State Configurations 371
- 10.1 Linear Mirror Systems 371
  - 10.1.1 Basic Magnetic Mirror Machine 371
  - 10.1.2 Minimum-B Magnetic Wells 372
  - 10.1.3 Direct Conversion and Reactor Systems Analysis 373
  - 10.1.4 Tandem Mirror TMX and TMX-Upgrade 374
  - 10.1.5 Tandem Mirror PHAEDRUS-B 375
  - 10.1.6 Tandem Mirror GAMMA 10 375
  - 10.1.7 Tandem Mirror KMAX 376
- 10.2 Mirror Fusion Test Facility (MFTF) and MFTF-B – A Case Study of Systems Forward Engineering 377
  - 10.2.1 Systems Forward Engineering and Architecture in MFTF 377
  - 10.2.2 First Design Improvement of MFTF, One Year Later 378
  - 10.2.3 Systems Review Process in Early Stages 379
  - 10.2.4 Alteration of MFTF to Tandem Mirror MFTF-B 379
  - 10.2.5 Revised Goals of MFTF-B 383
  - 10.2.6 Final Construction Status Report and Project Cancellation 383
  - 10.2.7 Robustness, fragilities and Implications of Cancellation 383
- 10.3 Gas Traps, Multiple Mirrors, Cusps and Field Reversal 384
  - 10.3.1 Gas Dynamic Trap (GDT) 384
  - 10.3.2 Multiple Mirror GOL-3 and GOL-NB 385
  - 10.3.3 Cusps 386
  - 10.3.4 Tri Alpha Energy C-2U and C-2W Field Reversed Configuration 386
- 10.4 Linear Fusion Reactors and Systems Design Space 387
  - 10.4.1 Physics of the Systems Architecture Design Space 387
  - 10.4.2 Design-Space Building-Blocks for Systems Architecture of Linear Machines 388
  - 10.4.3 Linear Fusion Reactors 390
  - 10.4.4 Synthesis of Linear Mirror Design Space 391
- 10.5 Toroidal Versions of Linear Mirror Concepts 392
  - 10.5.1 ELMO Bumpy Torus (EBT) 392
  - 10.5.2 Nagoya Bumpy Torus (NBT-1 M) 392
  - 10.5.3 Auto-injection Mirror 392
- 10.6 Taylor State q < 1 Torus: Spheromak and Reversed Field Pinch 393
  - 10.6.1 Spheromak, Reversed Field Pinch and Taylor State 393
  - 10.6.2 SSPX Spheromak 394

  - 10.6.3 Reversed Field Experiment RFX-Mod and RFX-Mod2 395
  - 10.6.4 MST and Reactor Studies 395
  - 10.6.5 Review and Prospects for RFP 396
- References 397

11 Inertial Fusion and Magnetic Fast Pulsed Systems 401
- 11.1 Systems Analysis Strategy for Laser Inertial Confinement 401
  - 11.1.1 Introduction to Inertial Confinement 401
  - 11.1.2 Progress in Inertial Fusion Driver Concepts 402
  - 11.1.3 Challenges for Inertial Fusion Reactor Development 404
  - 11.1.4 Systems Analysis Strategy 404
- 11.2 Case Study of Architecture and Forward Engineering of NIF 405
  - 11.2.1 NIF Background 405
  - 11.2.2 NIF Systems Approach 405
  - 11.2.3 NIF Beamline Systems Architecture and Design Space 407
  - 11.2.4 Highly Modular and Robust Construction 409
  - 11.2.5 Operation and Control Systems 409
  - 11.2.6 NIF Physics Results 409
  - 11.2.7 Computer Simulations of Inertial Confinement Laser and Target Interactions 411
  - 11.2.8 Near Breakeven Production of 1.3 MJ of Fusion Energy 411
  - 11.2.9 Laser Inertial Fusion Energy (LIFE) Reactor 412
  - 11.2.10 Overall Fusion Efficiency 412
  - 11.2.11 Laser Mega-Joule (LMJ) and ShenGuang III (SG-III) Large Scale Indirect Drive Lasers 413
- 11.3 Direct Drive, Fast and Shock Heating and Alternate Laser Technologies 413
  - 11.3.1 PETAL 413
  - 11.3.2 Direct Drive Laser Fusion with OMEGA 414
  - 11.3.3 Gekko and LFEX Lasers for Fast Ignition Realization EXperiment (FIREX) 416
  - 11.3.4 The UK Central Laser Facility (CLF) and DiPOLE 418
  - 11.3.5 Petawatt and Exawatt Lasers 418
  - 11.3.6 Non-thermal p-^{11}B Fusion from Picosecond Lasers 419
- 11.4 Design Space and Systems Approaches for Laser Fusion 419
  - 11.4.1 Design Space for a Laser Inertial Confinement Fusion Reactor 419
  - 11.4.2 HiPER Laser Inertial Confinement Fusion Reactor Project 423
  - 11.4.3 Detailed Systems Modelling of HiPER 425
  - 11.4.4 The Future for Laser Fusion Reactors 426

11.5 Magnetic Fast Pulsed Systems 427
  11.5.1 Dense Plasma Focus 427
  11.5.2 Plasma-Jet-Driven Magneto-Inertial Fusion (PJMIF) 427
  11.5.3 MagLIF Z-pinch Experiments 427
  11.5.4 Z-pinch Fusion Reactor 429
11.6 Prospects and Systems Robustness of Inertial Fusion Reactors 429
References 430

Part V Synthesis and Conclusions

12 Synthesis and Conclusions on the Applications of Systems Approaches to Fusion Reactors 435
12.1 Methods Developed and Lessons Learned 435
12.2 Overall Systems Analysis Strategy for Comparing Concepts by Systems Architecture 438
  12.2.1 Methods 438
  12.2.2 Systems Strategy for Comparing Different Fusion Reactor Concepts 439
12.3 Progress in Existing and Planned Machines 439
  12.3.1 Systems Level Performance Metrics: Lawson Criterion and Triple Product 439
  12.3.2 The Cost Metric of Fusion Experiments and Reactors 440
  12.3.3 Metrics, Scaling Laws, Systems and Predictive Codes, Innovation and Breakthroughs 442
  12.3.4 The Central Role of ITER 443
12.4 Pathways Towards an Operating Fusion Reactor 444
  12.4.1 Pathways Towards a Working Fusion Reactor for Each Concept 444
  12.4.2 Robustness and Fragilities of Different Concepts 445
  12.4.3 Tokamak Reactors 445
  12.4.4 Stellarator, Helias and Heliotron 447
  12.4.5 Mirrors, Linear Traps and Field Reversal 447
  12.4.6 Inertial Fusion 449
12.5 Overall Conclusions: Optimization of Fusion Reactors by Systems Approaches 450
References 450

Glossary 453

Index 459