

# Table of Contents

|                                                                                  |           |
|----------------------------------------------------------------------------------|-----------|
| <b>1. Non-linear Plasma Kinetics in Modern Physics</b>                           | <b>1</b>  |
| 1.1 Introduction                                                                 | 1         |
| 1.2 Controlled Fusion Research<br>and Non-linear Plasma Physics                  | 4         |
| 1.3 Laser Plasmas; Laser-Matter Interactions<br>and Collective Plasma Processes  | 5         |
| 1.4 Powerful Relativistic Electron Beams                                         | 7         |
| 1.5 Powerful Accelerators<br>and Collective Acceleration Methods                 | 8         |
| 1.6 Dynamic Chaos, Self-organisation, and Turbulence                             | 9         |
| 1.7 Vortex Turbulence and Self-organisation                                      | 12        |
| 1.8 Self-organisation in a Gas Discharge Plasma                                  | 13        |
| 1.9 Non-linear Processes in Dusty Plasmas                                        | 14        |
| 1.10 Non-linearities of the Ionospheric Plasma                                   | 15        |
| 1.11 Space Physics Research                                                      | 15        |
| 1.12 Plasma Astrophysics                                                         | 17        |
| 1.13 Cosmic-Ray Physics. Gravitational Fields                                    | 18        |
| 1.14 Outline of the Remainder of this Book                                       | 19        |
| 1.15 Recommended Literature                                                      | 21        |
| <b>2. Collective Plasma Oscillations</b>                                         | <b>23</b> |
| 2.1 Elementary Description of Collective Plasma Oscillations                     | 23        |
| 2.2 Some Definitions. Debye Screening                                            | 27        |
| 2.3 Number of Particles in the Debye Sphere<br>as a Fundamental Plasma Parameter | 31        |
| 2.4 Kinetic Theory of Linear Collective Plasma Oscillations                      | 36        |
| 2.5 Kinetic Theory of Langmuir<br>and Ion-Sound Plasma Oscillations              | 40        |
| 2.6 Landau Damping                                                               | 47        |
| 2.7 Beam-Plasma Instability                                                      | 51        |
| Problems                                                                         | 53        |

|                                                                                                                 |     |
|-----------------------------------------------------------------------------------------------------------------|-----|
| <b>3. Kinetics of Random Collective Excitations.</b>                                                            |     |
| <b>Quasi-linear Interactions</b> .....                                                                          | 55  |
| 3.1 Introduction. Distribution Function<br>for Plasma Oscillations .....                                        | 55  |
| 3.2 Correlation Functions for Random Fields .....                                                               | 57  |
| 3.3 Energy Density of Random Oscillations .....                                                                 | 61  |
| 3.4 Stimulated Vavilov-Cherenkov Emission<br>and Landau Damping .....                                           | 63  |
| 3.5 Quasi-linear Equation for the Particle Distribution .....                                                   | 65  |
| 3.6 Quasi-linear Relaxation of Beams in a Plasma .....                                                          | 68  |
| 3.7 Quasi-linear Description and Fluctuating Fields .....                                                       | 72  |
| Problems .....                                                                                                  | 74  |
| <b>4. Fluctuations and Particle Collisions</b> .....                                                            | 75  |
| 4.1 Introduction. Averaged Distributions and Fluctuations ...                                                   | 75  |
| 4.2 Fluctuations of Independent Particles .....                                                                 | 79  |
| 4.3 Fluctuations of Charged Particles .....                                                                     | 81  |
| 4.4 Landau-Balescu Collision Integral .....                                                                     | 83  |
| 4.5 Structure of the Collision Integral. Examples .....                                                         | 86  |
| 4.6 Conservation Laws.<br>Kinetic and Hydrodynamic Descriptions .....                                           | 92  |
| 4.7 Probabilities for Particle Collisions in a Plasma .....                                                     | 96  |
| Appendix: Belyaev-Budker Collision Integral .....                                                               | 104 |
| Problems .....                                                                                                  | 106 |
| <b>5. General Theory of Non-linear Interactions</b> .....                                                       | 107 |
| 5.1 Classification of Interactions .....                                                                        | 107 |
| 5.2 General Theory of Weak Non-linear Interactions .....                                                        | 113 |
| 5.3 Non-linear Plasma Responses .....                                                                           | 119 |
| 5.4 Approximate Expressions for the Non-linear Responses<br>for Langmuir Waves .....                            | 122 |
| 5.5 Approximate Expressions for the Non-linear Responses<br>for Ion-Sound Waves .....                           | 125 |
| 5.6 Non-linear Changes in the Particle Distributions .....                                                      | 129 |
| 5.7 Non-linear Changes in the Particle Distributions<br>for the Case of Random Fields .....                     | 134 |
| Problems .....                                                                                                  | 135 |
| <b>6. Stimulated Scattering of Waves by Particles</b> .....                                                     | 137 |
| 6.1 A Simple Physical Picture of the Scattering Process .....                                                   | 137 |
| 6.2 Description of the Stimulated Scattering Processes<br>of Waves in a Plasma. Non-linear Landau Damping ..... | 142 |
| 6.3 Conservation Laws in an Elementary Scattering Process ..                                                    | 146 |
| 6.4 Scattering Probabilities for Langmuir Waves .....                                                           | 150 |

|            |                                                                                                            |            |
|------------|------------------------------------------------------------------------------------------------------------|------------|
| 6.5        | Scattering Probabilities for Ion-Sound Waves .....                                                         | 156        |
| 6.6        | Transition Scattering .....                                                                                | 162        |
| 6.7        | Change in the Particle Distribution<br>Due to Stimulated Wave Scattering .....                             | 165        |
|            | Appendix: Scattering Processes Involving Transverse Waves ....                                             | 169        |
|            | Problems .....                                                                                             | 171        |
| <b>7.</b>  | <b>Plasma Turbulence .....</b>                                                                             | <b>173</b> |
| 7.1        | The General Concept of Turbulence .....                                                                    | 173        |
| 7.2        | Langmuir Turbulence .....                                                                                  | 178        |
| 7.3        | Non-linear Stabilisation of a Beam-Plasma Instability ....                                                 | 184        |
| 7.4        | Solar Radio Bursts .....                                                                                   | 186        |
| 7.5        | Ion-Sound Turbulence .....                                                                                 | 187        |
| 7.6        | Anomalous Plasma Resistivity .....                                                                         | 192        |
| 7.7        | Turbulent Shock Waves<br>and Turbulent Magnetic Reconnection .....                                         | 195        |
|            | Problems .....                                                                                             | 198        |
| <b>8.</b>  | <b>Non-linear Decay Interactions .....</b>                                                                 | <b>201</b> |
| 8.1        | General Concepts .....                                                                                     | 201        |
| 8.2        | The Balance Equation; the Conservation Laws .....                                                          | 204        |
| 8.3        | Probabilities of the Decay Interactions .....                                                              | 206        |
| 8.4        | Decay Processes and the Turbulent Spectrum .....                                                           | 209        |
| 8.5        | Decay Processes and Plasma Diagnostics .....                                                               | 211        |
| 8.6        | Scattering in a Strongly Turbulent Plasma .....                                                            | 213        |
| 8.7        | Decay Processes and Emission in a Turbulent Plasma.<br>Interaction of Strong Radiation with a Plasma ..... | 215        |
|            | Problems .....                                                                                             | 218        |
| <b>9.</b>  | <b>Non-linear Modulational Interactions .....</b>                                                          | <b>219</b> |
| 9.1        | Non-linear Frequency Shift and Modulational Interactions                                                   | 219        |
| 9.2        | Kinetic and Hydrodynamic Linear Instabilities .....                                                        | 222        |
| 9.3        | General Theory of Modulational Interactions .....                                                          | 225        |
| 9.4        | Averaging over the Plasma Frequency .....                                                                  | 229        |
| 9.5        | Modulational Instability .....                                                                             | 231        |
| 9.6        | Conservation Laws .....                                                                                    | 235        |
| 9.7        | Solitons. Self-contracting Cavitons .....                                                                  | 239        |
|            | Appendix: Non-linear Frequency Shifts<br>Produced by Ion-Sound Waves .....                                 | 243        |
|            | Problems .....                                                                                             | 244        |
| <b>10.</b> | <b>Dissipative Structures and Strong Langmuir Turbulence</b>                                               | <b>247</b> |
| 10.1       | Introduction. Self-organisation and Strong Turbulence ....                                                 | 247        |

|            |                                                                                                          |            |
|------------|----------------------------------------------------------------------------------------------------------|------------|
| 10.2       | Resonant Interactions of Strong Regular Fields<br>with Uniformly Distributed Particles .....             | 250        |
| 10.3       | Self-consistent Description of the Interaction<br>Between Structures and Resonant Particles .....        | 253        |
| 10.4       | Excitation and Damping of Structures<br>in Beam-Plasma Interactions .....                                | 257        |
| 10.5       | Non-linear Landau Damping of Structures .....                                                            | 263        |
| 10.6       | Coherent Landau Damping. Arrest of the Self-contraction ..                                               | 266        |
| 10.7       | Coherent Transition Damping of Cavitons .....                                                            | 269        |
| 10.8       | Interaction Between Structures and Random Fields .....                                                   | 272        |
| 10.9       | General Theory of the Interaction Between Regular<br>and Random Fields .....                             | 274        |
| 10.10      | Interactions Between Regular Structures<br>and Inhomogeneous Turbulence .....                            | 276        |
| 10.11      | Inhomogeneity of the Turbulence<br>Excited by Interactions with Regular Structures .....                 | 277        |
| 10.12      | Development of Self-organisation .....                                                                   | 278        |
| 10.13      | Some General Statements<br>About Strong Langmuir Turbulence .....                                        | 281        |
| 10.14      | Collective Laser-Plasma Interaction Processes .....                                                      | 282        |
|            | Problems .....                                                                                           | 282        |
| <b>11.</b> | <b>Plasma Maser Effect and Adiabatic Invariants<br/>in Non-linear Interactions .....</b>                 | <b>285</b> |
| 11.1       | Introduction .....                                                                                       | 285        |
| 11.2       | Damping Due to Inhomogeneities<br>Created by External Sources .....                                      | 289        |
| 11.3       | Non-linear Permittivity in the Presence<br>of Random Resonant Waves .....                                | 292        |
| 11.4       | Non-linear Interactions of Resonant<br>and Non-resonant Random Waves .....                               | 293        |
| 11.5       | Adiabatic Invariants in the Interaction of Resonant<br>and Non-resonant Waves .....                      | 294        |
| 11.6       | The Plasma Maser Effect for Weak Turbulence .....                                                        | 299        |
| 11.7       | The Plasma Maser Effect for Strong Turbulence .....                                                      | 301        |
|            | Problems .....                                                                                           | 305        |
| <b>12.</b> | <b>Non-linear Interactions of Collective Oscillations<br/>and Waves with Particle Fluctuations .....</b> | <b>307</b> |
| 12.1       | Introduction .....                                                                                       | 307        |
| 12.2       | General Relations .....                                                                                  | 309        |
| 12.3       | Interactions Unconnected with Fluctuations<br>in the Particle Distribution .....                         | 311        |
| 12.4       | Virtual Field Fluctuations .....                                                                         | 313        |

|            |                                                            |            |
|------------|------------------------------------------------------------|------------|
| 12.5       | Interactions Produced by Particle Fluctuations.            |            |
|            | Contribution from Virtual Fields .....                     | 314        |
| 12.6       | Direct Interactions with Particle Fluctuations .....       | 315        |
| 12.7       | Spontaneous Scattering Processes .....                     | 316        |
|            | Problems .....                                             | 320        |
| <b>13.</b> | <b>Collective Effects in Bremsstrahlung</b>                |            |
|            | <b>of Plasma Particles .....</b>                           | <b>321</b> |
| 13.1       | Introduction. Elementary Concepts of Bremsstrahlung        |            |
|            | of Colliding Particles .....                               | 321        |
| 13.2       | Qualitative Description of Collective Effects              |            |
|            | in Bremsstrahlung of Particles in a Plasma .....           | 324        |
| 13.3       | Bremsstrahlung of Longitudinal Waves by Bare Particles .   | 326        |
| 13.4       | Bremsstrahlung Probabilities and Balance Equations .....   | 329        |
| 13.5       | Bremsstrahlung Probabilities for Particles in a Plasma     |            |
|            | Including Collective Effects .....                         | 331        |
| 13.6       | Analysis of the Bremsstrahlung Cross-Sections              |            |
|            | for Particles in a Plasma .....                            | 339        |
| 13.7       | Collective Effects in Bremsstrahlung in Electron-Electron, |            |
|            | Ion-Ion, and Electron-Ion Collisions .....                 | 341        |
|            | Problems .....                                             | 344        |
| <b>14.</b> | <b>Some Remarks on Plasma Non-linear Kinetics</b>          |            |
|            | <b>in External Magnetic Fields. Conclusion .....</b>       | <b>347</b> |
| 14.1       | Summary of Problems Considered .....                       | 347        |
| 14.2       | External Magnetic Fields .....                             | 349        |
| 14.3       | Plasma Inhomogeneities .....                               | 353        |
| 14.4       | Electromagnetic Effects .....                              | 354        |
| 14.5       | Relativistic Effects .....                                 | 356        |
| 14.6       | Quantum Effects .....                                      | 357        |
| 14.7       | Conclusion. Acknowledgements .....                         | 358        |
|            | <b>Glossary .....</b>                                      | <b>359</b> |
|            | <b>Index .....</b>                                         | <b>365</b> |