Physics of Collisional Plasmas

Introduction to High-Frequency Discharges

Translation by Graeme Lister
Contents

1 The Plasma State: Definition and Orders of Magnitude of Principal Quantities ........................................... 1
  1.1 Definition and essential nature of plasma .................. 1
    1.1.1 A plasma behaves as a collective medium ............... 1
    1.1.2 A plasma is a macroscopically neutral medium ........... 2
    1.1.3 First examples of plasmas ................................ 3
  1.2 Areas of research and applications (examples) ............ 5
    1.2.1 Controlled thermonuclear fusion ...................... 5
    1.2.2 Astrophysics and environmental physics ................. 7
    1.2.3 Laser pumping .......................................... 8
    1.2.4 Plasma chemistry ....................................... 9
    1.2.5 Surface treatment ..................................... 10
    1.2.6 Sterilisation of medical devices ....................... 11
    1.2.7 Elemental analysis (analytical chemistry) .............. 12
    1.2.8 Lighting ................................................ 13
    1.2.9 Plasma display panels .................................. 13
    1.2.10 Ion sources ........................................... 14
    1.2.11 Ion propulsion thrusters ............................. 14
    1.2.12 Further applications ................................... 15
  1.3 Different types of laboratory plasmas ...................... 15
    1.3.1 Discharges with continuous current or alternative
          current at low frequency ..................................... 15
    1.3.2 High frequency (HF) discharges ........................ 16
    1.3.3 Laser induced discharges ................................ 16
  1.4 Electron density and temperature of a plasma .............. 17
    1.4.1 Range of electron density values in a plasma .......... 17
    1.4.2 Definition of plasma “temperature” and the concept
          of thermodynamic equilibrium (TE) ...................... 17
    1.4.3 Different levels of departure from complete
          thermodynamic equilibrium .............................. 21
  1.5 Natural oscillation frequency of electrons in a plasma ...... 23
1.5.1 Origin and description of the phenomenon .................. 23
1.5.2 Calculation of the electron plasma frequency .............. 24
1.6 Debye length: effect of screening in the plasma ............ 27
1.6.1 Description of the phenomenon .......................... 27
1.6.2 Calculation of the potential exerted by an ion in a
two-temperature plasma: definition of the Debye length 28
1.7 Collision phenomena in plasmas ................................ 32
1.7.1 Types of collision ........................................ 33
1.7.2 Momentum exchange and energy transfer during a
collision between two particles ............................ 36
1.7.3 Microscopic differential cross-section ..................... 44
1.7.4 Total (integrated) microscopic cross-section ............ 48
1.7.5 Total macroscopic cross-section .......................... 49
1.7.6 Expression for the temperature of a plasma in
electron-volt .................................................. 53
1.7.7 Collision frequency and mean free path between two
collisions ...................................................... 54
1.7.8 Average collision frequency and mean free path ......... 56
1.7.9 Examples of collision cross-sections ...................... 58
1.8 Mechanisms for creation and loss of charged particles in a
plasma and their conservation equation ....................... 64
1.8.1 Loss mechanisms ........................................ 64
1.8.2 Creation mechanisms ..................................... 66
1.8.3 Conservation equation for charged particles ............. 67
Problems .................................................................. 68

2 Individual Motion of a Charged Particle in Electric and
Magnetic Fields ....................................................... 101
2.1 The general equation of motion of a charged particle in \( E \)
and \( B \) fields and properties of that equation .............. 103
2.1.1 The equation of motion .................................... 103
2.1.2 The kinetic energy equation ............................... 104
2.2 Analysis of particular cases of \( E \) and \( B \) .................. 104
2.2.1 Electric field only \((B = 0)\) ............................... 105
2.2.2 Uniform static magnetic field .............................. 113
2.2.3 Magnetic field either (slightly) non uniform or
(slightly) varying in time ..................................... 135
Problems .................................................................. 155

3 Hydrodynamic Description of a Plasma .......................... 203
3.1 Fundamental aspects of the Boltzmann equation ............. 205
3.1.1 Formal derivation of the Boltzmann equation ............ 205
3.1.2 Approximation to the Boltzmann elastic collision
term: relaxation of the distribution function towards
an isotropic state ........................................... 208
3.1.3 Two classical methods to find an analytic solution to the Boltzmann equation ........................................ 210
3.2 Velocity distribution functions and the notion of correlation between particles ........................................ 211
  3.2.1 Probability density of finding a particle in phase space 211
  3.2.2 Single-point distribution function (the case of correlated particles) .................................................. 212
  3.2.3 Single-point distribution function (uncorrelated particles) ............................................................ 213
  3.2.4 Two-point distribution function (correlated particles) . 213
  3.2.5 Two-point distribution function (uncorrelated particles) 214
  3.2.6 N-point distribution functions ........................................ 215
3.3 Distribution functions and hydrodynamic quantities ........... 215
3.4 Kinetic and hydrodynamic conductivities of electrons in a plasma in the presence of a HF electromagnetic field .... 218
  3.4.1 Kinetic form of the electrical conductivity due to electrons in an HF field .............................. 219
  3.4.2 Hydrodynamic form of the electrical conductivity due to electrons in an HF field ....................... 221
3.5 Transport equations ........................................ 224
  3.5.1 The continuity equation (1st hydrodynamic moment, of zero order in \( w \)) ........................................ 226
  3.5.2 The momentum transport equation (2nd hydrodynamic moment, 1st order in \( w \)) ....................... 227
  3.5.3 Moment equations of second order in \( w \) .............. 234
  3.5.4 Higher order moment equations ................................. 239
3.6 Closure of the transport equations ............................ 240
3.7 The Lorentz electron plasma model ...................................... 243
3.8 Diffusion and mobility of charged particles ........................................ 245
  3.8.1 The concepts of diffusion and mobility ............................. 245
  3.8.2 Solution of the Langevin equation with zero total derivative ........................................ 246
3.9 Normal modes of diffusion and spatial density distribution of charged particles ................................... 253
  3.9.1 Concept of normal modes of diffusion: study of a time varying post-discharge .......................... 255
  3.9.2 Spatial distribution of charged particle density in the stationary diffusion regime ...................... 259
3.10 The ambipolar diffusion regime ........................................ 261
  3.10.1 Assumptions required for a completely analytic description of the ambipolar diffusion regime .......... 262
  3.10.2 Equations governing the ambipolar diffusion regime and the transition from the free diffusion to the ambipolar regime ........................................ 263
  3.10.3 The value of the space-charge electric field intensity . 265
3.10.4 The expression for the charge density $\rho_0$ on the axis:
limits to the validity of the analytic calculation .......... 267
3.10.5 Necessary conditions for a discharge to be in the
ambipolar regime ........................................ 268
3.11 Ambipolar diffusion in a static magnetic field .......... 271
3.12 Diffusion regime or free fall regime .................. 274
3.13 Electron temperature of a long plasma column governed by
ambipolar diffusion: scaling law $T_e(pR)$ ............... 275
3.13.1 Assumptions of the model .......................... 276
3.13.2 Derivation of the relation $T_e(p_0R)$ .............. 276
3.14 Formation and nature of sheaths at the plasma-wall
interface: particle flux to the walls and the Bohm criterion ... 282
3.14.1 Positive wall-potential with respect to the plasma
potential: electron sheath ................................ 283
3.14.2 Negative wall-potential with respect to the plasma
potential: ion sheath .................................... 284
3.14.3 Floating potential .................................. 288
Problems .................................................... 288

4 Introduction to the Physics of HF Discharges .......... 337
4.1 Preamble ................................................. 337
4.2 Power transfer from the electric field to the discharge .. 339
4.2.1 Direct current discharges .......................... 339
4.2.2 HF discharges ...................................... 343
4.2.3 HF discharges in the presence of a static magnetic field 345
4.2.4 Variation of the value of $\theta$ as a function of $n_e$ for
different plasma conditions ................................ 352
4.3 Influence of the frequency of the HF field on some plasma
properties and on particular processes ...................... 354
4.3.1 Posing of the problem ................................ 355
4.3.2 The EEDF in the non-stationary regime ............. 356
4.3.3 EEDF in the stationary regime ...................... 358
4.3.4 Three limit cases of the influence of $\omega$ on a stationary
EEDF ..................................................... 360
4.3.5 Influence of $\omega$ on the power $\theta$ ................ 362
4.3.6 Density of species produced per second for a constant
absorbed power density: energy efficiency of the
discharge .................................................. 363
4.3.7 Experimental and modelling results .................. 364
4.3.8 Summary of the properties of low-pressure HF plasmas 368
4.4 High-pressure HF sustained plasmas .................... 369
4.4.1 Experimental observation of contraction and
filamentation at atmospheric pressure ..................... 370
4.4.2 Modelling contraction at atmospheric pressure ...... 376
4.4.3 Validation of the basic assumptions of contraction at atmospheric pressure, using a self-consistent model ... 379
4.4.4 Kinetics of expanded discharges at atmospheric pressure as a result of adding traces of rare gases with a lower ionisation potential ........................................ 382
4.4.5 Summary of the properties of high-pressure HF plasmas ........................................ 385

I Properties of the Maxwell-Boltzman Velocity Distribution ........................................ 387
II The Complete Saha Equation ........................................ 393
III Partial Local Thermodynamic Equilibrium ........................................ 395
IV Representation of Binary Collisions in the Centre of Mass and Laboratory Frames ........................................ 397
V Limiting the Range of the Coulomb Collisional Interactions: the Coulomb Logarithm ........................................ 399
VI Stepwise Ionisation ........................................ 413
VII Basic Notions of Tensors ........................................ 417
VIII Operations on Tensors ........................................ 421
IX Orientation of $w_{2\perp}$ in the Reference Triad with Cartesian Axes $(E_{0\perp} \wedge B, E_{0\perp}, B)$ ........................................ 429
X Force Acting on a Charged Particle in the Direction of a Magnetic Field $B$ Weakly Non-uniform Axially ... 431
XI The Magnetic Moment ........................................ 433
XII Drift Velocity $w_d$ of a Charged Particle Subjected to an Arbitrary Force $F_d$ in a Field $B$: the Magnetic Field Drift ........................................ 435
XIII Magnetic-Field Drift Velocity $w_{dm}$ in the Frenet Frame Associated with the Lines of Force of a Magnetic Field with Weak Curvature ........................................ 437
XIV Spherical Harmonics ........................................ 441
XV Expressions for the Terms $M$ and $\mathcal{R}$ in the Kinetic Pressure Transport Equation ........................................ 443
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>XVI</td>
<td>Closure of the Hydrodynamic Transport Equation for Kinetic Pressure in the Case of Adiabatic Compression</td>
<td>445</td>
</tr>
<tr>
<td>XVII</td>
<td>Complementary Calculations to the Expression for $T_e(pR)$ (Sect. 3.13)</td>
<td>447</td>
</tr>
<tr>
<td>XVIII</td>
<td>Propagation of an Electromagnetic Plane Wave in a Plasma and the Skin Depth</td>
<td>451</td>
</tr>
<tr>
<td>XIX</td>
<td>Surface-Wave Plasmas (SWP)</td>
<td>455</td>
</tr>
<tr>
<td>XX</td>
<td>Useful Integrals and Expressions for the Differential Operators in Various Coordinate Systems</td>
<td>459</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>465</td>
</tr>
<tr>
<td>Recommended Reading</td>
<td></td>
<td>467</td>
</tr>
<tr>
<td>Index</td>
<td></td>
<td>471</td>
</tr>
</tbody>
</table>