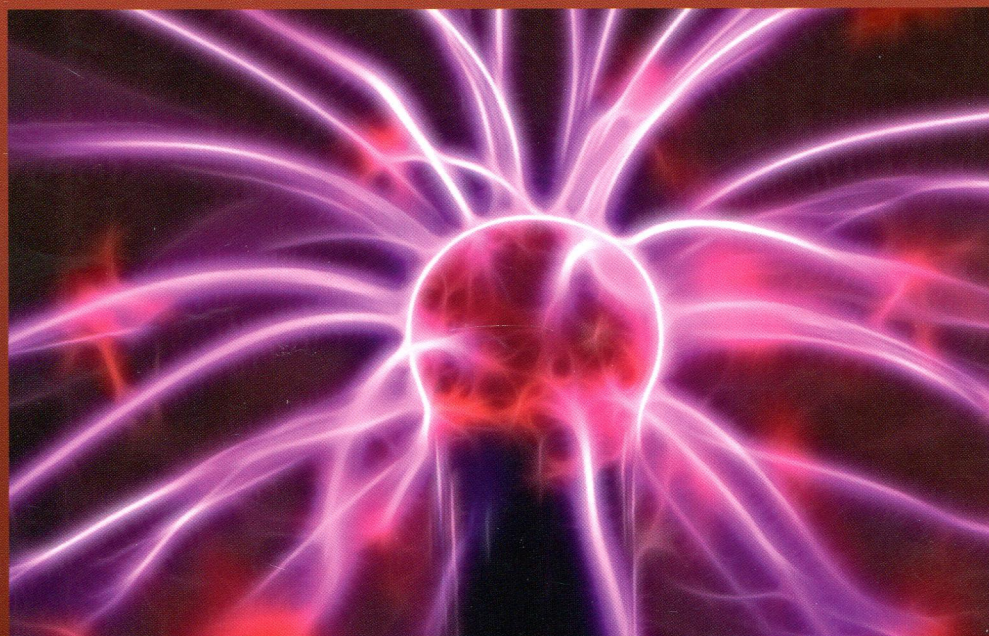




— SELECTED BY GRENOBLE SCIENCES —

Physics of Collisional Plasmas

Introduction to High-Frequency Discharges



Michel Moisan - Jacques Pelletier

 Springer

Michel Moisan • Jacques Pelletier

Physics of Collisional Plasmas

Introduction to High-Frequency Discharges

Translation by Graeme Lister

 Springer

Prof. Michel Moisan
Département de Physique
Université de Montréal
Montreal, Québec, Canada

Dr. Jacques Pelletier
Centre de Recherche
Plasmas-Matériaux-Nanostructures
LPSC
Grenoble, France

Translator

Dr. Graeme Lister
OSRAM Sylvania Inc.
Beverly, MA, USA

Original title: "Physique des plasmas collisionnels, application aux décharges haute fréquence",
Michel Moisan et Jacques Pelletier, Collection Grenoble Sciences - EDP Sciences, 2006

ISBN 978-94-007-4557-5

ISBN 978-94-007-4558-2 (eBook)

DOI 10.1007/978-94-007-4558-2

Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012941402

© Springer Science+Business Media Dordrecht 2012

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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 \mathbf{E} and \mathbf{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 \mathbf{E} and \mathbf{B}	104
2.2.1	Electric field only ($\mathbf{B} = \mathbf{0}$)	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 (1 st hydrodynamic moment, of zero order in w)	226
3.5.2	The momentum transport equation (2 nd hydrodynamic moment, 1 st 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 ρ_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 θ as a function of \bar{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 ω on a stationary EEDF	360
4.3.5	Influence of ω on the power θ	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 \underline{M} and \underline{R} in the Kinetic Pressure Transport Equation 443

XVI	Closure of the Hydrodynamic Transport Equation for Kinetic Pressure in the Case of Adiabatic Compression	445
XVII	Complementary Calculations to the Expression for $T_e(pR)$ (Sect. 3.13)	447
XVIII	Propagation of an Electromagnetic Plane Wave in a Plasma and the Skin Depth	451
XIX	Surface-Wave Plasmas (SWP)	455
XX	Useful Integrals and Expressions for the Differential Operators in Various Coordinate Systems	459
	References	465
	Recommended Reading	467
	Index	471