An Introduction to Plasma Physics and its Space Applications, Volume 2

Basic equations and applications

An Introduction to Plasma Physics and its Space Applications, Volume 2

Basic equations and applications

Luis Conde
Universidad Politécnica de Madrid, Madrid, Spain

IOP Publishing, Bristol, UK

ISBN 978-0-7503-3543-0 (ebook)
ISBN 978-0-7503-3541-6 (print)
ISBN 978-0-7503-3544-7 (myPrint)
ISBN 978-0-7503-3542-3 (mobi)

DOI 10.1088/978-0-7503-3543-0

Version: 20200801

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, Temple Circus, Temple Way, Bristol, BS1 6HG, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

To my wife

Contents

Appendices

Preface

The physics of ionized gases and plasmas plays a relevant role in aerospace technology and requires that graduate students and professionals in the field understand their principles. For them, microwave electric discharges in telecommunication equipment testing or plasma propulsion of satellites are today familiar terms.

This book is the expanded version of the lectures and class notes I taught on this subject to students of aerospace engineering and physics and it is intended as a starting point. For this reason I left aside the conventional organization of plasma physics textbooks to make the subject more accessible to non-specialists.

In the first volume the fundamentals of plasma physics, the properties of molecular and atomic collisions and elementary plasma processes were introduced. This second volume is an introduction to the physical description of interacting particle systems where I tried do not leave the algebraic steps to obscure the physics and/or to be an additional difficulty for the reader. It starts from basic kinetic theory and the hydrodynamic transport equations for a plasma are derived next. The starting point is the velocity distribution function to make the subject more accesible to the beginner. The formal derivation of the kinetic plasma equation is discussed in appendix B. Finally, the readers will be introduced to microwave multipactor electric breakdown and the basis of in-space plasma propulsion.

This introductory book is limited in scope and missing relevant issues in plasma physics that I hope readers can address later. Each chapter concludes with a selection of recommended materials for further reading that are basically dictated by my personal choice. I apologize for the many books and papers that undoubtedly deserve the attention of readers and are inevitably not mentioned with this limiting criterion.

Finally, I made all efforts to make the text free of errors but this is a hopeless task. I will be grateful to readers who kindly inform me of misprints and errors, preferably by electronic mail.

Luis Conde
Madrid, November 2019
luis.conde@upm.es

Acknowledgements

I am grateful to my colleagues J M Donoso and J L Domenech-Garret who read the two volumes of this book and have made valuable commentaries and suggestions. I benefited from the helpful feedback and of early versions by S Tierno and J González and stimulating discussions with I M Tkachenko. I also appreciate the support and interest of Robert Trevelyan and David McDade from IOP Publishing. Finally, and most of all to my beloved wife for her patience while writing this book.

Author biography

Luis Conde

Luis Conde is Professor of Physics and the Polytechnic University of Madrid (Universidad Politcnica de Madrid, UPM). He received his PhD in Physics from the Open University of Madrid on Macromolecular Physics and has been with the Spanish National Research Council, the Complutense University of Madrid and he joined the UPM Faculty of Aerospace Engineering as a member of the Department of Applied Physics on1989. He has given lecture courses on plasma physics to master and undergraduate students of aerospace engineering and physics. He is Fellow of the European Physical Society and has authored/co-authored over 50 journal articles and 49 conference papers. In 2019 he received two patents (US 10172227B2 and EP3369294B1) of an innovative low electric power plasma thruster. His current interests are basic plasma physics, plasma diagnostics and plasma thrusters for space propulsion.

Acronyms

AC	alternating current.
AF-MPD	applied-field magnetoplasmadynamic thruster.
AIP	American Institute of Physics.
APS	American Physical Society.
AZ	anode zone.
BGK	Bathnagar–Gross–Krook relaxation model.
CEX	charge exchange collision.
CM	center of mass.
DC	discrete current.
ECR	electron cyclotron resonance.
CDS	cathode dark space.
EP	electric propulsion.
ESA	European Space Agency.
EWSK	east–west station keeping.
FDS	Faraday dark space.
FEEP	field emission electric propulsor.
GEO	geostationary Earth orbit.
GIE	gridded ion engine.
GOCE	gravity field and steady state ocean circulator Earth explorer.
GTO	geosynchronous transfer orbit.
HEMPT	highly efficient multistage plasma thruster.
HET	Hall effect thruster.
IOP	Institute of Physics.
IV	current–voltage curve of a DC electric discharge.
LEO	low Earth orbit.
LTE	local thermal equilibrium.
MB	Maxwell–Boltzmann.
MEO	medium Earth orbit.
mfp	mean free path.
MHD	magnetohydrodynamic equations.
MPD	magnetoplasmadynamic thruster.
NASA	National Aeronautics and Space Administration.
NG	negative glow.
NSSK	north–south station keeping.
PC	positive column.
PLE	partial local equilibrium.
RF	radio frequency.
RST	radioisotope thermoelectric generator.
SF-MPD	self-field magnetoplasmadynamic thruster.
SEY	secondary emission yield.
STP	standard temperature and pressure.
UV	ultraviolet electromagnetic radiation.

Symbols

Å	Ångstrom (length) 1 Å = 10^{-8} cm.
amu	atomic mass unit 1.66×10^{-27} kg.
α_g	ionization degree of a gas.
α_w	*specific power*; electric power to weight of power equipment in W kg^{-1}.
c_{is}	ion sound speed.
e	electron charge $e = 1.6021 \times 10^{-19}$ C.
$e_{i\alpha}$	internal energy per particle $\alpha = i, e, a$.
E_I, E_{II}	ionization energy of a neutral atom (*I* first level, *II* second, etc).
ε_o	permittivity of a vacuum $\varepsilon_o = 8.8542 \times 10^{-12}$ F m^{-1}.
eV	electron volt 1 eV = 1.602×10^{-19} J.
η_e	electric efficiency of a thruster.
η_m	mass utilization efficiency of a thruster.
η_T	total efficiency $\eta_T = \eta_m \times \eta_e$
f_{pe}	electron plasma frequency $f_{pe} = \omega_{pe}/2\pi$ in Hz.
$f_\alpha(\boldsymbol{r}, \boldsymbol{v}, t)$	non-equilibrium velocity distribution function.
$f_{mb}(\boldsymbol{v})$	Maxwell–Boltzmann velocity distribution function.
f_{pi}	ion plasma frequency $f_{pe} = \omega_{pi}/2\pi$ in Hz.
F	thrust $F = \dot{m}_p v_{ex}$.
$\phi_c(r)$	Coulomb potential $\phi_c(r) = q/(4\pi\varepsilon_o r)$.
$g_{mb}(E)$	Maxwell–Boltzmann energy distribution function.
g_o	Standard Earth's gravity $g_o = 9.8$ m s^{-1}.
Hz	Hertz (1 cycle/second).
GHz	giga Hertz (10^9 Hz).
I_{sp}	specific impulse in seconds.
I_t	total impulse in seconds.
$\boldsymbol{k}$	wave number $k = 2\pi/\lambda$.
k_B	Boltzmann's constant $k_B = 1.3805 \times 10^{-23}$ J K^{-1}.
K	Kelvin degree (temperature).
kHz	kHz (10^3 Hz).
keV	kilo electron-volts, 10^3 eV.
L_s	characteristic length scale (its meaning depends on the context).
λ	wavelength.
$\lambda_{D\alpha}$	Debye length for $\alpha = e, i$ charged particles.
λ_c	mean free path for collisions with neutral atoms.
mbar	millibar, gas pressure unit 1 atmosphere = 1013.25 mbar.
MHz	mega Hertz (10^6 Hz).
m_e	electron mass $m_e = 9.1091 \times 10^{-23}$ J K^{-1}.
MeV	mega electron-volt, 10^6 eV.
mN	milliNewton (10^{-3} N), unit of force.
N	Newton (force unit).
n_a	number density of neutrals. Number of neutral atoms or molecules by unit volume.
$N_{D\alpha}$	plasma parameter for $\alpha = e, i$ charged particles.
n_e	number density of electrons. Number of electrons by unit volume.
n_i	number density of ions. Number of ions by unit volume.
ν_c, ν_m	collision frequencies with neutral atoms.

ν_I	electron impact ionization frequency.
ω	wave angular frequency.
ω_{pe}	electron plasma frequency $\omega_{pe} = 2\pi f_{pe}$ in radians per second.
ω_{pi}	electron plasma frequency $\omega_{pi} = 2\pi f_{pi}$ in radians per second.
p_a	pressure of the neutral gas.
P_b	kinetic energy power (in watts) $P_b = \dot{m}_p v_{ex}^2/2$.
τ_b	burning time of a thruster.
τ_c	time elapsed between two successive atomic or molecular collisions.
τ_r	characteristic relaxation time.
τ_s	characteristic time scale (its meaning depends on the context).
τ_{ia}	time elapsed between two successive ion/atom collisions.
τ_{ea}	time elapsed between two successive ion/electron collisions.
$\bar{v}$	mean thermal speed $(8\, k_B\, T/\pi\, m)^{1/2}$.
v_{ex}	propellant exhaust velocity.
$v_f = \omega/k$	wave phase velocity.
$v_g = \partial\omega/\partial\mathbf{k}$	wave group velocity.
v_{th}	thermal speed $\sqrt{2\, k_B T_\alpha/m}$.