# Preface

During the 1960s, the public face of plasma physics was almost exclusively represented by plasma confinement, with the goal of developing a reactor to produce electricity by thermonuclear fusion. Such a reactor is still being developed, without any guarantee as to its successful achievement, but since then the applications of plasma physics have increased and diversified: one of the best known, besides lighting, is etching in the fabrication of microelectronic computer chips, for which plasma is indispensable. At present, the use of plasmas continues to expand and, from recent research publications, a seemingly limitless number of applications will eventually see the light of day. In this development, plasmas created by radiofrequency and microwave fields play a particularly important role.

The present text is basically concerned with plasma physics of interest for laboratory research and industrial applications, with emphasis on the understanding of the physical mechanisms involved, rather than on minute details and high-level theoretical analysis. At the introductory level to this discipline, it is very important to assimilate its characteristic physical phenomena, before addressing the ultimate formalism of kinetic theory, with its microscopic, statistical mechanics approach. In this textbook, the physical phenomena have been translated into more tractable equations, using the hydrodynamic model; this treats the plasma as a fluid, in which the macroscopic physical parameters are the statistical averages of the microscopic (individual) parameters. This textbook is intended for students in their early years at the graduate level, and for engineers who are interested in applications. Its level of difficulty lies somewhat below that of JL Delcroix and A Bers (from Université Paris XI, Orsay and Supélec, Gif-sur-Yvette, France, and MIT, Cambridge, MA, USA, respectively), which provides a series of complementary and interesting theoretical treatments.

This book is divided into four chapters.

**Chapter 1** is the introductory part of the textbook. It begins with a description of the plasma, an ionised gas, as a collective and electrically neutral gaseous medium, followed, for illustrative purposes, by a few selected scientific and industrial applications. Then, the fundamental concepts of plasma physics are introduced, with progressively increasing detail: the chapter aims to present the basic parameters required to reach a starting knowledge of the plasma medium, such as the Debye length, the electron plasma frequency, the various types of collision between particles and their description through specific cross-sections. The concepts presented in this introduction will be developed as a first approach, i.e. as the first step in an iterative process, to be completed by the detailed and quantitative presentations in the remaining chapters.

**Chapter 2** is a thorough examination of the trajectory of a single charged particle (assuming no interaction whatsoever with other particles), subject to an electric field $\boldsymbol{E}$, a magnetic field $\boldsymbol{B}$ or both. In the case of electric fields $\boldsymbol{E}$, special attention will be paid to those at RF and microwave frequencies, designated jointly as high-frequency (HF) fields, in preparation for the modelling of HF discharges developed in Chap. 4. The presence of a magnetic field $\boldsymbol{B}$ results in a cyclotron motion, encountered for example in electron cyclotron-resonance discharges (Chap. 4). The combination of $\boldsymbol{E}$ and $\boldsymbol{B}$ fields in different spatial configurations, and then the inclusion of the spatial inhomogeneity of the $\boldsymbol{B}$ field, reveals the so-called drift velocities, which have to be "tamed" for an efficient operation of Tokomaks, nowadays investigated as possible controlled-fusion reactors.

In contrast to Chap. 2, collisions between particles are taken into account in **Chapter 3**, to establish the hydrodynamic description of the plasma, considered as a fluid. Such a description is obtained from the macroscopic quantities calculated from the distribution function of the (microscopic) velocities of individual particles. The transport equations, i.e. the equations describing the space-time evolution of these quantities, are obtained from integration of the Boltzmann equation over the distribution function of velocities. The concepts of mobility (of charged particles) and diffusion of particles are then introduced, where free mobility and diffusion tensors are deduced from the (momentum transport) Langevin equation. Further, it is shown that, under sufficiently dense plasma conditions, the space-charge electric field makes electrons and ions diffuse together in the so-called ambipolar diffusion regime. Finally, toward the end of the chapter, a first example of a scaling law in plasmas is developed. Then, in the last section, the formation of sheaths located at the interface between the plasma and the walls is described, together with a straightforward and original derivation of the Bohm Criterion, which provides the velocity of the ions as they enter the sheath.

**Chapter 4**, the last chapter, is dedicated to the mechanisms involved in HF sustained discharges, which are developed based on an entirely new and original approach. The key element is $\theta_l$, the average power lost by an electron through its collision with heavy particles, in this way supplying power to the plasma. It is shown that $\theta_a$, the power taken on average per electron from the HF field, adjusts so that $\theta_l = \theta_a = \theta$, i.e. to compensate for the loss of charged particles. This implies, for instance, that the intensity of the

$\boldsymbol{E}$ field in the plasma is not set by the operator, but by this balance requirement. A further consequence is that, for given operating conditions and HF power density, whatever the means of supplying the HF field to achieve the discharge, the $\theta$ value should be the same in all cases. The parameter $\theta$ is also instrumental in demonstrating that, contrary to common belief, the $\boldsymbol{E}$-field intensity goes through a minimum at electron cyclotron resonance. The influence of varying the field frequency on the EEDF, and ultimately on plasma properties, is documented both theoretically and experimentally, in the case of low-pressure ($< 10\,\text{torr}$) plasmas. The case of high-pressure plasmas (including atmospheric pressure) is centred on the phenomena of discharge contraction and filamentation in rare gases with low thermal conductivity, emphasising the role of molecular ions in these monoatomic gas discharges. Interrupting the kinetic cycle leading to dissociative recombination (of molecular ions) by introducing traces of rare gases with an ionisation potential lower than that of the carrier gas leads to the disappearance of discharge contraction and filamentation.

In addition to the content of the main text, there are a large number of remarks and footnotes, for clarification, or to qualify certain points more precisely. Forty five problems, with detailed solutions, which are an indispensable complement to this book, are distributed at the end of the first three chapters. A set of Appendices provides clarifications of the subjects treated in the main text, together with a number of mathematical developments, and useful mathematical formulae. Finally, an alphabetic index of important terms is supplied, with a page reference to their first appearance in the text given in bold type.

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