Preface

This book is based on a series of lectures 'Elements of edge physics' given at JET in 1993, MIT in 1995 and the University of Toronto in 1998. The lectures were intended as an introduction to the basic ideas about the boundary or scrape-off layer, SOL, of magnetic fusion devices—particularly of tokamaks—for people with a plasma physics education. Concepts about the SOL have largely been developed during the 1980s and 1990s and, as yet, little of this has found its way into plasma texts. The first part of this book was written with the intention of filling this gap.

The book is divided in to three parts. Part I attempts to retain the spirit of the original lecture series, namely that of a quick review of the central ideas about the SOL. This would be appropriate for an introductory course on the subject. Derivations are heuristic and physical intuition is emphasized. The reader should be able to cover this material reasonably quickly, with little need to pause for careful derivations or to consult related texts.

In part I, problems have been included to aid the student. The problems are of two types. The first type is embedded in the text and has the character of a worked example intended to illuminate the point being discussed. The reader is encouraged to include these problems when reading the text, even if deciding not to actually work through the maths. Additional problems appear at the end of each chapter. Solutions, or hints, are included at the end of the book.

Part II provides an introduction to methods of modelling the plasma edge region of magnetically confined plasmas. A number of sophisticated computer codes have been developed during the last two decades to model the edge plasma in all its 2D or 3D glory, including time dependence and employing all the numerical power of modern computational fluid dynamics, CFD, techniques. As in other fields, this effort has resulted in creating what now constitutes a third basic line of attack on our ignorance of the physical world—additional, that is, to the two traditional lines of experiment and theory. The shear complexity of *code modelling*, however, requires that its output be subject to efforts aimed at interpretation and understanding—just as experiments always have required. The need for simpler modelling has been enhanced rather than diminished by the advent of computer code modelling.

Part II of this book is aimed at simple approaches to modelling the plasma edge—although the rudiments of 2D fluid code modelling are also touched on. Emphasis is therefore placed on 1D models of the edge, which often turn out to provide surprisingly close matches to the output of the sophisticated 2D computer code models. The modelling material of part II has been included for those envisaged readers who probably identify themselves as experimentalists, but with a penchant for interpreting their experimental results—as the best experimentalists always do. It is also for those who want to try to make sense of the output of their sophisticated code—i.e., to interpret code results—as the best code scientists always do. Even 1D modelling enterprises can reach the point that they require recourse to a computer—but simple numerical procedures such as Runge–Kutta quadrature are often adequate. Thus little maths need come between us and the physics in this type of modelling work.

Part III of the book is a collection of essays on currently active research topics in plasma edge physics. The selection of topics is inevitably arbitrary. The coverage is uneven. The topics tend to reflect the personal interests of the author. The sound of hobby-horses may be heard in the land. The material in Part III will undoubtedly date more quickly than that in parts I and II—and in the subsequent, numerous editions of the book, it is anticipated that some of this material may be revised, replaced or repudiated.

A distinction is made between the *plasma edge* and the scrape-off layer: the former includes the SOL, but also extends some distance inboard of the *last closed (magnetic) flux surface, LCFS*, or *separatrix*, into the *main* or *core* plasma. This region just inboard of the SOL is an important one in its own right and warrants separate treatment. Like the SOL, it is not a region of traditional magnetic confinement physics; atomic physics processes are also important. Effects such as the 'transport barrier', involved in H-mode confinement, are a feature of this region. This region is not the subject of this text. We take here the expression 'plasma boundary of a magnetic confinement device' to mean the *scrape-off layer*.

In the early decades of fusion energy research, the SOL was little considered, apparently in the hope that the edge would just sort itself out with little need for intervention or understanding. This hope was misplaced and by the 1980s it had been recognized that certain edge problems were sufficiently serious as to jeopardize the achievement of controlled fusion energy using magnetically confined plasmas. One of the most serious problems is that of high power handling or heat removal which results from the very small plasma-interaction areas characteristic of the SOL. Magnetic fields which are strong enough to provide adequate confinement of the main plasma are simply *too* effective for the SOL, where the characteristic cross-field scale length, i.e. the SOL width, ends up being only about 1 cm. The total exhaust power thus tends to be deposited on a total plasma-wetted area of solid surface of a few m^2 or less—an area far smaller than that which is in principle available, i.e. $\sim$1000 m^2, the internal wall area in a typical reactor design. It is turning out to be a challenge to keep the steady-state heat fluxes incident on the solid surfaces down to $\sim$5 MW m^{-2}, which is about the level briefly experienced by the nose cone of a space vehicle re-entering the

Earth's atmosphere.

In addition to this power-removal problem, impurities generated by plasma–surface interactions (PSI) have been the bane of fusion from the beginning and continue to be a serious problem. Their presence in the central fusion-producing plasma reduces power output by cooling the plasma radiatively and by diluting the hydrogenic fuel. The SOL is both the source and sink for most impurities and is the key to their control in magnetically confined devices. The one impurity that is produced in the core of fusion DT plasmas—helium—must be efficiently removed from the system to avoid poisoning the reaction. Helium removal is also largely a SOL issue.

In principle, all magnetically confined plasmas have scrape-off layers. While this text has been written in the context of tokamaks, much of the material applies directly to other magnetic configurations used in fusion or other applications.

The SOL is a very long and very thin plasma region aligned to the magnetic field $\boldsymbol{B}$. Not surprisingly, SOL modelling draws heavily on 1D, zero-$\boldsymbol{B}$ analysis. In most of the analysis in this book, in fact, $\boldsymbol{B}$ does not explicitly appear. Much of SOL analysis is thus applicable to non-magnetic plasmas, such as those used in plasma process applications, and students in such fields should also find material in this text helpful.