Preface to the English Edition

This book is devoted to the problem of confinement of energy and particles in tokamak plasmas. Although the first tokamaks were constructed more than half a century ago, large efforts will still be needed before a detailed description of transport in these devices will be a reality. So far, high hopes for a description of transport in tokamaks using huge multidimensional gyro-kinetic codes did not materialize. Growing attention is now focusing on the idea of self-organization in plasmas. The fusion community rejected a long ago the fundamental concept of a local connection between transport coefficients and plasma parameters. The idea that the fundamental nature of transport in fusion plasmas is dual, begins now to gain momentum: profiles of pressure and temperature are determined in main by the magnetic configuration and in a lesser extent by the energy and particle fluxes.

The English edition of this book is very close to the Russian edition. In the first five Chapters only editorial corrections were made. The only addition is Sect. 6.9 in Chap. 6, devoted to the analysis of temperature and pressure pedestals of JET ELMy H-mode discharges. The comparison of the experimental pedestal values with the canonical profile pedestals allowed us to establish simple relations to calculate temperature and density pedestals in general transport calculations. These relations are true for tokamaks with moderate aspect ratio $A = R/a \sim 2.5–4$.

I want to express my sincere appreciation to my colleagues S.E. Lysenko and I.S. Marchenko for their invaluable help with the translation. Without them it would have been a nearly insurmountable task to prepare the English version. First contacts with the Springer Publishing House were made by J. Ongena. He also made many suggestions to the translated text of this book. I want to express him my deep gratitude. Maria Bellantone and Mieke van der Fluit benevolently helped me during a long and tensional work with Springer. I bring them my hearty thanks.

I presented the Russian Edition of this book to many colleagues in the West and East. It is my hope that this English Edition will help them to provide an easier access to the ideas developed in the Russian version.

March 2014 Yu.N. Dnestrovskij
Moscow, Russia

Preface to the Russian Edition

Work on controlled thermonuclear fusion began in our country on the initiative of I.V. Kurchatov in the early 1950s. But the initial hope for a rapid realization of the final goal could not be fulfilled. The problem turned out to be much more difficult than originally thought, both in getting an understanding of the physical processes in the hot plasma and in surmounting the technological challenges inherent in the practical realization of heating and confining hot plasmas. The difficulties soon led to a united effort of scientists and engineers worldwide, culminating in the ITER project, a unique example of international cooperation. Confidence now grows that the first tokamak reactor could be built in the middle of the third decade of the twenty-first century.

However, the understanding of the physical processes underlying the energy and particles transport in a tokamak plasma is far from simple. Transport is mainly determined by turbulent processes in the plasma, and binary collisions between the particles play a secondary role. In principle one should be able to describe turbulent transport by solving numerically multi-dimensional kinetic equations using so-called gyro-kinetic codes. However, after more than two decades of huge efforts using the fastest computers in the world, one is far from a workable solution along this road. The main difficulty is the large difference in various characteristic times (6–7 orders of magnitude) and characteristic scales (4–5 orders of magnitude) inherent in the problem. In addition the experimentally observed large-scale self-organization of plasma (strong tendency to conserve pressure and temperature profiles), can still not be reproduced using gyro-kinetic codes.

The lack of a universal transport model forced scientists to look in other directions for the analysis of existing experiments and the extrapolation to future devices. A ‘brute force’ solution is the use of purely empirical scalings based on the analysis of a large database of experimental data obtained from a various fusion devices around the world. In this way work has continued over the last 25 years to determine scalings for the energy confinement time and other characteristic parameters in various plasma regimes. One of these scalings is the basis for the design of ITER.

It is clear that such scalings are only a first step towards a description of the transport processes in a thermonuclear plasma. The next step is to create one-dimensional (1D) models that are based on theoretical principles. The presentation and justification of such a model is the purpose of this book.

The earliest 1D models to describe the transport of energy and particles in fusion plasmas date back to the late 1960s. Transport coefficients were derived from experimental data and depended on local plasma parameters. This continued until the middle of 1980s, when it became clear that effects of self-organization play an important role in transport and must be incorporated into the model. First proposals for such 1D models were formulated by different authors, including ourselves, at the EPS Conference on Plasma Physics in Dubrovnik in 1988. In what follows, such models are called “critical gradient models”. In our model the critical gradient is closely linked to the self-organization of the plasma, and thus it is different from other similar models. We assume that the critical gradient is determined by the minimum of the magnetic energy of the toroidal plasma current with condition of the conservation of total current and total poloidal magnetic flux. The other models use usually the border of the instability of some drift waves as a condition for the critical gradient. The book first discusses the underlying theoretical hypotheses, based on a large number of experimental observations, that allow us to describe the phenomenon of self-organization and then the transport model is proposed using the concept of critical gradients. The transport coefficients in this model are determined by comparing the calculations with experimental results.

This book is organized as follows. In the Introduction basic concepts concerning self-organization of plasmas are discussed, and illustrated with examples from experiments. In the second chapter a variational formulation is presented for the so-called ‘canonical’ temperature and pressure profiles. Experimental profiles evolve towards canonical profiles and fluxes of heat and particles are determined by the difference (in some metric) between the experimental and canonical profiles. Since the plasma is an open system of particles and energy, and fluxes are always present in plasmas, the experimental profiles will never coincide with the canonical ones, but approximate them to a larger or lesser extent.

The third chapter extends the ideas on plasma self-organization to stellarators. Such a description for stellarators is more complex than for tokamaks, since the absence of axial symmetry in the plasma leads to large neoclassical fluxes that can compete with turbulent fluxes. We present experimental observations on the conservation of the pressure profile in stellarators and propose a variational formulation for canonical profiles in such devices.

The fourth chapter discusses scaling laws for the plasma energy confinement time. We discuss multi-machine scaling laws derived from a large multi-machine database (in particular ITER scaling) and one-machine scalings. The Taylor—Connor theory of invariants is presented, together with its conditions on the structure of scalings and transport coefficients.

The fifth chapter presents the linear version of the canonical profiles transport model. We discuss its application to the ohmic regime and L-mode regime in tokamak discharges. The plasma density, the electron and ion temperatures, the velocity of toroidal rotation and the toroidal current density are the required variables in this model. It can also be applied to the H-mode if the estimates for the pedestal values are known.

Finally, in the sixth chapter we discuss the non-linear version of the transport model, for the description of improved confinement regimes with external and internal transport barriers. H-mode plasmas with an external barrier at the plasma edge can be satisfactorily simulated. The same cannot yet be said about the description of plasma regimes with internal barriers, as the formation of such a barrier is linked to the position of resonant surfaces, and thus their position has to be determined by the discharge scenario, including the time evolution of the current profile. The chapter discusses also the not fully resolved issue of the impact of the toroidal rotation velocity on plasma confinement. Although we know experimentally that this effect is small, still more work is needed for a good quantitative description.

I started to work on transport models in the 1960s on the initiative of Academician L. A. Artsimovich together with D. P. Kostomarov, to whom I am deeply grateful. For several decades we worked together, discussing daily difficulties and progress. This close collaboration was extremely helpful to develop new ideas and improve the understanding of the main features of transport in tokamaks, resulting in the 1980s in several books on the modeling of fusion plasmas. The present book could not have been written without the lessons learned over many years working with him.

The basic theoretical ideas were developed by Academician B. B. Kadomtsev. As early as 1986–1987 he proposed to use a variational formulation as the basis for a self-consistent description of the plasma profiles observed in experiment. The main experimental background to this book is from the papers by B. Coppi (1980) and Y. V. Esipchuk and K. A. Razumova (1986). Fruitful and intense discussions with Ksenia Alexandrovna helped to crystallize many of the concepts presented in the subsequent chapters.

In preparing the book for publication I especially thank S. E. Lysenko for his invaluable assistance and hard work in the general plan and design of this book. Special thanks also go to my pupils and colleagues: A. Yu. Dnestrovskij, V. F. Andreev, A. V. Melnikov, A. V. Danilov, K. N. Tarasyan and S. V. Cherkasov. An especial gratitude to V. S. Mukhovatov for his patience and support in discussing the main ideas of this book, still not fully accepted by the scientific community. Thanks also to A. M. Stefanovskij for intensive discussions on the nature of variational problems.

For over 15 years our group is collaborating with scientists of the Culham Centre for Fusion Energy (CCFE), Culham, UK. Many of the ideas of this book were shaped during discussions with John Connor, Antony Field, Tim Hender, Colin Roach, Martin Valovich, Mikhail Gryaznevich, Irina Voitsekhovitch and Michele Romanelli. To all of them I am deeply grateful.

September 2012 Yu.N. Dnestrovskij
Moscow, Russia

http://www.springer.com/978-3-319-06801-5

Self-Organization of Hot Plasmas
The Canonical Profile Transport Model
Dnestrovskij, Y.N.
2015, XII, 134 p. 68 illus., 9 illus. in color., Hardcover
ISBN: 978-3-319-06801-5