Chapter X. Conclusions and outlook

Over the whole book, we were emphasizing the complexity and multifaceted nature of the processes and phenomena in edge plasma. To unravel the physics of these processes and phenomena one needs to involve: i) Classical and anomalous (often highly intermittent) transport of multispecies plasma including impurities which are either released due to erosion of plasma-facing components or introduced into the edge plasma to radiate the high power coming from the core (see Ch. VI and Ch. VII); ii) Different issues of atomic physics, including ionization, recombination and radiation processes involving different species, which often occur in optically opaque media (see Ch. II); iii) Sheath physics and plasma interactions with the materials of the plasma-facing components, including material erosion and deposition, saturation with hydrogenic species and impurities, which can result in modification of the surface morphology and material properties, as well as an impact of the eroded material, including dust particles, on edge plasma performance (see Ch. III, Ch. IV, and Ch. V).

We notice that all these processes have strongly nonlinear behavior and in many cases exhibit strong synergistic effects. Therefore, it is very difficult to build simplified analytic or semi-analytic models that can properly describe the edge plasma phenomena. In most cases, the outcome of such models needs to be verified with more sophisticated numerical simulations (e.g. see Ch. IX).

However, because of the complexity of the edge plasma and a large span of spatiotemporal scales which need to be covered, the numerical codes are capable of treating only some “patches” of the necessary spatiotemporal domain. In addition, they often do not work smoothly even though some significant compromises in the physics embedded in these codes are usually made. For example, edge plasma turbulence and edge plasma transport are usually described with different models and even though the relative turbulent fluctuations of the edge plasma parameters in many cases exceed 100%, edge plasma transport is described with “laminar” models where the impact of these fluctuations is ignored (see Ch. VIII). Also, most of the codes (e.g. the edge plasma transport codes such as SOLPS) are based on a combination of the discrete (e.g. complex 3D3V neutral transport Monte-Carlo codes treating a vast body of atomic physics) and continuous (e.g. plasma transport based on the fluid approximation) parts, which complicates convergence and forces implementation of different algorithms for their numerical solution (see Ch. VIII).

Various experimental tools are used in the edge plasma studies, including different Langmuir probes, Thomson scattering, visible and UV spectroscopy, postmortem analysis of the plasma-facing components (including the nuclear reaction analysis) and *in situ* surface temperature measurements with infrared radiation, etc. However, the spatiotemporal resolution of all these experimental techniques is rather limited and the raw data obtained in the experiments do often require post-processing (e.g. conversion of the spectroscopic data obtained by integration of the signal along the viewing chords into the distributions over the magnetic flux coordinates).

Nonetheless, in spite of all these issues with both the experimental and theoretical/computational studies, in the last two decades, substantial progress has been made in our understanding of the physics of the edge plasma phenomena. In particular, i) The main ingredients governing the divertor plasma detachment process have been identified and confirmed by both numerical simulations and experimental data. ii) The impact of sheared plasma flow on suppression of anomalous cross-field plasma transport has been clearly shown theoretically and confirmed by both the results of numerical simulations and the experimental data. Moreover, it was demonstrated that such a flow can be generated by the plasma turbulence itself. iii) It was shown that anomalous plasma cross-field transport can not always be described by diffusion type equations and in many cases, it can have a much more complex and nonlocal nature. In particular, it can be associated with large intermittent bursts of the plasma particle and energy fluxes. iv) Dust particles, under some conditions, can play an important role in plasma contamination with impurity. v) Erosion and re-deposition of the materials of the plasma-facing components can result in the formation of rather thick layers of the co-deposited material. Such loose co-deposits can cause the formation of hot spots and emission of dust particles and impurity atoms/molecules, severely limiting the operational window of fusion devices. In addition, they can retain a large amount of hazardous tritium. vi) Both the fluid-based and gyro-kinetics-based codes capable of describing edge plasma turbulence have been developed. They are more and more frequently used for the understanding of anomalous transport of the edge plasma and in many cases produce the experiment-relevant results, etc.

However, there are still many things that can be improved. Here we outline only the most important gaps in our understanding of the edge plasma phenomena. Obviously, this list reflects just the view of the authors and it is pretty much possible that other researches working in the field of the physics of edge plasma in magnetic confinement devices would alter it.

We think that one of the most important showstoppers on the way to a better understanding of the edge plasma phenomena is related to our poor apprehension of edge plasma turbulence. Edge plasma turbulence has an overarching impact on the processes in the edge plasma. It can govern the heat loading on and erosion of the plasma-facing components including the divertor targets and main chamber wall. These issues are crucial for both the feasibility of fusion reactor design and the reactor lifetime. We also notice that cross-field plasma transport in the SOL and divertor regions plays an important role in divertor plasma detachment which seems to be the only plausible solution for the mitigation of large divertor heat load in the future reactors. In particular, today it is not clear if the plasma turbulence observed in the SOL is driven by the SOL plasma itself or is originated inside the separatrix and then spreads into the SOL. It is also not clear, through what mechanisms the divertor plasma conditions (e.g. the attached or detached states) affect edge plasma turbulence, as seems to be observed in experiments.

Another issue, which is closely related to the study of edge plasma turbulence, is how to incorporate it into the codes simulating the edge plasma. It is clear that without the use of comprehensive numerical simulations, no progress in edge plasma studies is possible. However, today, edge plasma transport and turbulence are mostly simulated with, correspondingly, 2D and 3D codes (the limitations associated with such an approach were discussed above). Taking into account the multifaceted nature of the physics of the edge plasma and strong synergy between the different processes in it, we believe that both edge plasma turbulence and transport should be described simultaneously by 3D codes. This is a very challenging task combining different ranges of the timescales, which requires incorporation into the turbulence codes of both the physics of multispecies plasma and the atomic physics effects. Obviously, the development and real application of such codes require close collaboration of physicists and computer scientists as well as a new generation of computers.

A further issue in the edge plasma physics is related to the interactions of the plasma and neutral particles with the materials of the plasma-facing components. In the past, such interactions were described by some particle and energy reflection coefficients for the impinging species and sputtering coefficients for the surface material. However, nowadays it is well recognized that these interactions are more complex. They involve not only reflection of the impinging species and erosion and re-deposition of the wall material, but also the modification of subsurface layers of the wall material due to complex phenomena associated, in particular, with the penetration if the impinging particles into the lattice of the wall material (see Ch. III). As a result, the wall response to the impact of the charged and neutral particles of the edge plasma becomes very complex and nonlinear. Since all these processes determine such crucial parameters of a magnetic fusion reactor as the lifetime of the plasma-facing components and tritium retention, the topic of the plasma-material interactions becomes one of the top priorities in the edge plasma physics. We notice that the neutron damage of the lattice of the plasma-facing materials, inevitable in fusion reactors, brings additional complication to this issue.

Because of the synergy among edge plasma transport, plasma recycling, impurity radiation and transport, plasma-material interactions, physics of strongly modified subsurface layers and wall material erosion, etc., it seems that it is inevitable that more and more integrated models and codes of different sophistication, describing the edge plasma in fusion devices, will be developed in the future. As a matter of fact, such a development is already underway.