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Summary and Outlook

Enclosing a plasma simply in a vessel results in extremely large energy and particle fluxes on the wall. These losses are reduced considerably by confining the plasma within a magnetic field. However, the magnetic confinement of a hot plasma is not perfect. Particles can still leave the plasma and hit the surfaces. The wall components act as a sink for energy and particles, and at the same time they are a source of particles. Once the wall surfaces are saturated, the recycling of particles comes close to the possible maximum: for every two incoming ions (D^+), one particle, usually a neutral molecule (D_2) with thermal energy, is released from the surface. The electrons hitting the wall take part in the recombination process of the incoming ions. Electrons can leave the solid, if the temperature of the surface is sufficiently high, or by processes such as secondary electron emission and field emission. Most of the incoming energy, however, is absorbed by the solid material. Only a fraction of backscattered particles are able to bring a considerable amount of energy back into the plasma. Processes such as diffusion, trapping in the material, and the release of gas atoms depend on many parameters including the history of the solid wall and its temperature.

The energy and particle transfer from the plasma to the wall is governed by the electric sheath, which is established just near the surface to ensure zero charge transfer to the solid. The solid walls are negatively charged with respect to the plasma in order to repel the fast electrons and to attract the ions. It was shown, via a new derivation of the Bohm criterion, that the potential differences in the sheath and in the presheath obey an energy minimum criterion. The ions are accelerated in the electric field of the sheath and may cause, after impact, significant erosion.

The history of emitted target atoms in fusion experiments based on the concept of magnetic confinement can be described within the cycle of erosion, transport, and deposition (Fig. 14.1). After a target atom is emitted, for example, by physical sputtering, chemical erosion, or thermal sublimation, it is going to be ionized at a position not far away from the surface. Once ionized, electric and magnetic forces are exerted on the particle, now called an

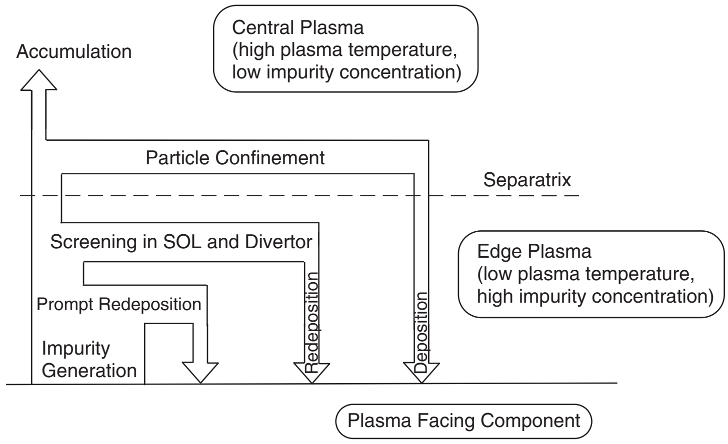

Fig. 14.1. The impurity cycle in fusion experiments. The pumping out of volatile impurities is not included here

impurity ion. If the ionization length is smaller than its gyro-radius, then it has a good chance to be promptly redeposited very close to the place of emission. Otherwise, it changes momentum and energy in collisions with plasma ions and other impurity ions. It may be subjected, besides multiple ionization and recombination, to a large number of different reactions in the plasma, in particular charge exchange. As long as the impurity ion stays in the plasma of the scrape-off layer, it will be efficiently transported along the magnetic field lines until it strikes a divertor or limiter plate. This process is called redeposition.

A small fraction of the impurities is able to penetrate deeply into the plasma core by crossing the separatrix. Now, the transport parallel to the magnetic field lines as well as transport in the poloidal direction (diamagnetic flows) do not play a role and only the cross-field transport matters; it is characterized by anomalously high diffusion coefficients. After a while, the particle confinement time, each impurity crosses the separatrix again, now from the plasma core into the SOL, and is deposited at one of the wall components. This process is called deposition and is characterized by the loss of information about the origin, where the particle originally came from.

For a burning fusion plasma, it is essential to keep the plasma in the central region hot enough to maintain the fusion reactions. In order to reduce the large cross-field transport of energy, so-called internal transport barriers have to be established. On the other hand, the impurity ions lead to dilution of the fuel and strong radiation losses. Hence, their concentration should be kept as small in a fusion reactor. Transient effects such as sawteeth in the core and ELMs in the edge plasma, used as “plasma cleaners”, may be helpful for efficient impurity and He ash control. ELM control by pellet injection is a topic of large relevance.

Impurity ions impinging on the surface of a wall component sticks with a certain probability. It may cause sputtering as well as defects in the material. In the case of hydrocarbons, the interaction process with the surface involves not only sticking but also transformation. Due to the impact of one certain hydrocarbon, one or more hydrocarbon radicals of a different type may be emitted.

The deposition of impurities determines the magnitude of the net effects, whether an area is dominated by net erosion or net deposition. The gross effects are usually much larger than the net ones. The erosion at the divertor plates in future fusion experiments such as ITER has to be reduced by redeposition in order to achieve an acceptable level of net erosion. The favorable effect of redeposition can be enhanced exploiting the $\boldsymbol{E} \times \boldsymbol{B}$ drift motion of the impurity ions in the electric sheath. By a suitable choice of the magnetic field direction and geometry the peak net erosion at the divertor plates can be minimized. A simple relation has been derived which allows for estimating the peak net erosion concerning all important effects: erosion by the plasma ions, self-sputtering, prompt redeposition, and redeposition due to friction with the plasma streaming towards the plates.

Along with erosion and deposition processes, surface modification occurs. The material composition changes as well as the surface profile, and the material roughness. Hence, erosion depending sensitively on the surface composition is affected too. Deposited impurities such as C or Be protect targets made from other materials efficiently by formation of layers on their surfaces.

The build-up of layers on the surface of wall components, even at very remote areas, is inherently connected to the tritium retention problem. Tritium ions arrive simultaneously with the impurities at the surface and are codeposited there. The concentration of radioactive tritium in such layers can reach high values, and the amount of collected tritium, being proportional to the layer thickness, can exceed the amount implanted (as well as the amount of tritium trapped deeply in the bulk material) by several orders of magnitude. The process of codeposition works very efficiently for carbon impurities, but has been also observed for Be and W deposition. Techniques for efficient tritium removal and recovering should be further developed in order to cope with the tritium retention problem.

The theoretical description of the involved processes will more and more rely upon computer simulations. They are based on reliable data on atomic and molecular processes, and material properties. It is not (yet) possible to follow a large number of representative particles in their motion through the whole plasma and further in the solid material. Though such a comprehensive analysis is today out of the reach of existing computer systems, computer simulations nevertheless provide a valuable tool to test theoretical models and assumptions. Such simulations act as a bridge between the different scales in space and time. In plasma–material interaction studies these scales cover several orders of magnitude: beginning from the fast scattering and sputtering processes up to the rather slow processes involved in changing the surface composition. Simulations dedicated to certain processes are usually restricted to a narrow range of space and time. Analyzing the results from such simulations, theoretical models can be derived, which provide simplifying assumptions (scaling rules) to be used in simulations of processes characterized by other scales.

Computer simulations should be used with great care, and the validation against experimental results is an indispensable part of the numerical analysis. Laboratory experiments should provide as much detailed knowledge as possible. The more parameters can be measured the less are left in the analysis, which otherwise could be used incorrectly as fitting parameters. Only by collecting the information obtained in different laboratory experiments can a successful analysis of the *big* fusion experiments, where all processes take place at the same time, be possible. Often, the output of computer simulations appears as incomprehensible as the experiments themselves. Only theoretical analysis can provide then the desired understanding by formulating the right questions. New results, new knowledge, and a better understanding of the real world can hardly be obtained without the trinity of experiment, theory, and simulation (Fig. 14.2).

The choice of plasma-facing materials is always a compromise, and is determined by a large number of different criteria and operation limits. In particular, a new plasma density limit (11.3) as well as a new impurity criterion (12.12) have been proposed. Unfortunately, this choice is based only on a very limited list of possible candidates. While for the next step devices such as ITER some compromise solutions can be found, there is at present no material available for a commercial fusion reactor. Either the heat loads are too large (for Be and W), or the build-up of a large tritium inventory by codeposition (in the case of C) prevents the use of materials under consideration.

The plasma-exposed materials in fusion experiments suffer from major erosion and destruction events. The emitted material is distributed via the plasma to all neighboring surfaces and deposited there. After some discharges, the surface composition shows significant concentration of all materials present

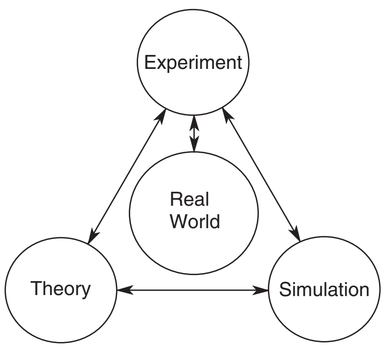

Fig. 14.2. The trinity of experiment, theory, and simulation

in the plasma chamber. Having more than one material in the device, will lead to a material mix and, thus, to a possible loss of the desired properties. The processes of material mixing need further investigations. It is expected that ITER will give the answers to this issue of concern.

Is it perhaps possible to use only one material for both the divertor and the first wall? Beryllium is not suitable for the divertor plates. It melts already at modest heat loads. Tungsten could be used, in principle, also for the strike zones at the divertor plate, but will survive only a limited number of major disruption events and ELMs. Tungsten can be used also as wall material in the main chamber, but should be protected from energetic charge-exchange neutrals. These neutrals have energies larger than the threshold energy for physical sputtering. The tungsten atoms emitted from the wall can penetrate deeply into the plasma and cause the serious problem of high-Z radiation losses. Carbon would be the ideal material applicable for all surfaces. It withstands high thermal loads and radiates, as desired, only in the plasma edge, but it is susceptible to chemical erosion. The threshold energy for chemical sputtering is rather low and the yields quite significant even at room temperature. Most of the tritium inventory would be collected in amorphous carbon–tritium layers.

The use of carbon as the only material would be possible if efficient tritium removal techniques could be developed, or if the formation of thick layers could be prevented. The use of tungsten as the only material appears possible if disruptions and ELMs could be mitigated. In addition, the recycling process should be localized in the divertor in order to prevent charge-exchange processes occurring outside the divertor. If tungsten is eroded in the divertor, redeposition and divertor retention reduce the outflux of tungsten into the main chamber. Tungsten should not be used as bulk material but rather as a thick plasma-sprayed coating on CFC material.

The use of CFC material covered by tungsten could be an option for a fusion reactor based on the stellarator concept. As mentioned, disruptions do not occur in stellarator configurations, and the possibility of continuous operation is an essential advantage from the engineering point of view. It must be shown whether high-Z accumulation as predicted by neoclassical transport theory is pertinent or can be avoided.

One may speculate whether the development of a new material system, where Li is continuously pressed through a CFC material with a rather loose composite of fibers (i.e., with reduced matrix material), can be successful. Under regular conditions, a very thin film of Li has to keep up on top of the target controlled by the pressure at the rear side of the material and the material temperature. Large thermal loads caused by disruptions or ELMs have to be absorbed by the Li vapor cloud formed immediately after impact of the plasma particles from the disrupted plasma. The CFC material should efficiently conduct the heat along the fibers toward the heat sink of the cooling system installed beneath the targets. The chemical erosion of graphite would be significantly reduced, and lithium would assist in effective wall pumping.

Once eroded, both materials—as low-Z elements—radiate almost completely in the plasma edge, where a significant conversion of the outflowing power into radiation is required. It may be possible to use the outstanding properties of both materials, while compensating for their handicaps.

In general, a reliable solution of the material problem can only be found in the joint development of new materials and suitable plasma scenarios. Fifteen years ago, the designed heat load at the strike point of the divertor plates reached values of 25–30 MW/m^2. Soon it became clear that there was no technical concept of target plates in sight that could handle more than 10 MW/m^2 under steady state operation. As a consequence, the new divertor concept using all available processes to spread the generated power over larger areas was developed resulting in much lower values of the power flux density onto the targets.

The development of adequate plasma solutions is a major task. A robust solution has to be found considering both aspects: the plasma conditions and operation scenarios on one side and the design of the plasma-facing components on the other. Establishing transport barriers inside the separatrix could help to reduce the power flux into the scrape-off layer, while reaching burn conditions in the core. The fluxes of particles and energy out of the confined region have to be distributed over larger areas to reduce the local power loads.

Despite all experience in plasma control that will be gathered during the next few years, one concern remains—the high flux of neutrons. Today, there is no solid material available which is able to withstand the expected fluence leading to several hundred displacements per atom without significant degradation. In particular, advanced materials such as carbon fiber enforced composites suffer from neutron bombardment and lose their advantageous properties such as heat conduction by disintegration of their optimized and complex structure. Future research must concentrate on this issue. If no satisfying solution can be found, there is still the pragmatic, but rather expensive alternative of regular replacements of divertor and wall elements.

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