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Tetsuo Tanabe

Plasma-Material Interactions in a Controlled Fusion Reactor

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Preface

Since the discovery that nuclear reactions produce energy, 90 years have already passed. Now fission reactors are well established as energy sources, while a fusion reactor seems to need still several decades to be realized. Even though the assembly of ITER (the International Tokamak Engineering Reactor) has started on July 28, 2020, it will not be used as an energy source. Why has such a long time been required to establish a fusion reactor as an energy source compared to fission reactors? The answer could be found in different energy conversion mechanism between the two.

In a fission reactor, the energy required to start nuclear chain reactions and to keep them in steady-state operation is quite small. Energy is used just for adjusting the position of control rods including neutron absorbers or the density of neutron absorber in cooling water to maintain steady operation and to stop the reactions by inserting control rods in the reactor core. In order to convert the output power produced by fission reactions, a massive flow of coolant, i.e. water in most operating fission reactors, should be circulated and this requires a significant amount of energy, similar to that required by normal power stations using oil or coal as a fuel and would be required by a fusion reactor as well.

Unlike the fission reactor, a huge power is required for starting and keeping the burning plasma in a fusion reactor. Accordingly, the power used is dissipated to plasma-facing surfaces (PFS). In particular, the power load to the divertor area is extremely high so that power exhaust is one of the critical issues to establish the fusion reactor. The power load to PFS appears as plasma–materials interactions (PMI), which are similar to what the surface of a rocket running into the sun would be exposed to and, at present, the physical and chemical phenomena expected in PMI in a fusion reactor would be very difficult to study directly.

Among presently operating plasma apparatus, only JET can realize similar or a little lower levels of power load. Therefore, understanding of PMI in a fusion reactor must be extrapolated from observations on the currently operating apparatus whose power load is still too low. Hence special apparatus such as linear plasma machines to realize a heat load like the divertor region of a fusion reactor are being constructed. Heat exhaust is also one of the most important technical issues in the development of a fusion reactor.

Thus, PMI is a critical scientific issue for the establishment of a fusion reactor as a power source, with major potential limitations on plasma core and edge operating parameters. Gaining understanding and predictive capability in this area will require simultaneously addressing complex and diverse physics and chemistry occurring over a wide range of lengths (angstroms to meters) and times (femtoseconds to days). Furthermore, the following key engineering issues remain: lifetime of plasma-facing components (PFC's) due to steady-state sputter erosion; erosion/damage by plasma transients; surface ultrastructure and mixed-material evolution; plasma contamination by eroded material and plasma operating limits due to these factors. Shortage of tritium fuel resources and radioactivity give additional issues for fuel self-sufficiency and nuclear safety in controlling PMI.

Although many books and reviews have already been published on PMI some of which are referred in Chap. 1, they are mostly standing on plasma physics, namely how plasma or plasma confinement is influenced by PMI. This book stands on the material side focusing on changes caused by heat and particle load, i.e. how plasma-facing materials (PFM) are modified by plasma exposure and then accordingly how the modified PFM responds to the plasmas.

After the introduction of PMI in Chap. 1, Chap. 2 describes what present tokamak discharges look like and Chap. 3 describes the power load on PFM. Then basic processes of PMI are described in Chaps. 4–7: "Responses of plasma-facing surfaces to heat and particle loads" in Chap. 4, "Erosion and deposition and their influence on plasma behavior" in Chap. 5, "Material modification by high-power load and its influence on plasma" in Chap. 6, and "Fundamentals of hydrogen recycling and retention" in Chap. 7. In Chap. 8, "PMI in large Tokamaks" is discussed and in Chap. 9, "Estimation of tritium retention in a reactor" is discussed.

In Chap. 10, "Selection of PFM" is discussed. Finally in Chap. 11, "Closing remarks, including future prospect" is given.

Hopefully, this book will help in the understanding of PMI and its impact on plasma confinement and will preview what kind of research and development will be required.

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* Throughout this book, the term "hydrogen" is used as the representative of all hydrogen isotopes including protium (H), deuterium (D), and tritium (T), if not specified.

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Part I Fusion Reactor and Plasma Material Interactions

Part II Basic Processes in PMI

Part III PMI, Observations in Present Large Tokamaks and Prospects in a Reactor

Part I

Fusion Reactor and Plasma Material Interactions

Chapter 1
Introduction

1.1 The Organization of This Book

There is one significant difference between plasma–material interactions (PMI) and other interactions between gas and solid or liquid, and liquid and solid. For the latter cases, one can think of chemical or thermo-dynamical equilibrium where no energy transfer occurs, while in PMI there is always energy or power flow from plasma to materials under a steep gradient of (potential) energy. The higher energy state of plasma than that of plasma-facing materials causes energy release or power flow from the plasma to the materials by radiation and kinetic energy of plasma particles (ions of fuels, He and impurities, and electrons motivated by the energy gradient). Such power release by the radiation and the kinetic energy of the particles results in PMI which includes so many different physical and chemical phenomena that it is hardly possible to introduce PMI phenomena in an orderly sequence but to introduce important subjects separately. (Please refer Fig. 1.3, which describes various physical and chemical phenomena occurring in a wide range of energy states together with energy ranges corresponding to fusion reaction, burning plasma, plasma–surface interactions, material responses to the power exhaust in a fusion reactor).

In addition, fuel losses by burning and flow-out from fusion plasma must be compensated by fueling, which is another important subject of PMI in a reactor. Different from most of the plasma apparatus, tritium (T) is used as a fuel of the reactor. Since T is hazardous due to its radioactivity and its resources are scarce, special care is required for safety handling and fuel self-sufficiency. Fuel recycling at plasma-facing surface (PFS) has often been discussed separately with the power load. However, as described above, the power is carried by fuel particles. Hence, the fuel recycling should be discussed considering the power flow.

This book tried to describe PMI phenomena referring basic physics and chemistry in them and their roles in the construction of a fusion reactor. To realize this, the total of 11 chapters are grouped into three parts which correlate with each other as shown in Fig. 1.1. Part I consists of three chapters. Following the present chapter (Chap. 1) which describes the concept of PMI, brief introduction of a D-T fusion

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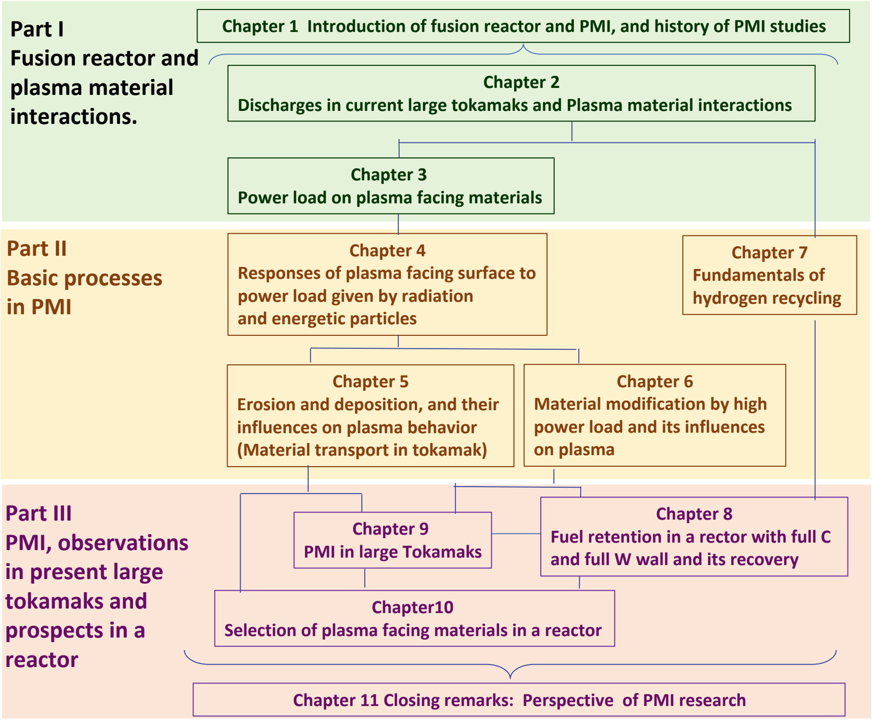

Fig. 1.1 The organization of this book

reactor and history of PMI studies, and required PMI studies in future. Chapter 2 describes the observation of discharges in a large tokamak, and Chap. 3 explains power load to plasma-facing surface as the main cause of PMI in a fusion reactor. In Part II, four basic processes in PMI are separately explained. They are “Responses of plasma-facing surface to power load” in Chap. 4, “Erosion and deposition, and their influences on plasma behavior” in Chap. 5, “Material modification by high-power load and its influences on plasma” in Chap. 6, and “Fundamentals of hydrogen (fuel) recycling” in Chap. 7. In Part III is described the present research status and future prospect of PMI in three chapters. Chapter 8 summarizes “PMI in large Tokamaks”. Chapter 9 describes “Fuel retention in a rector with full C and full W wall and its recovery” as one of the critical issues for the establishment of a fusion reactor as an energy source. Chapter 10 gives some ideas on the “Selection of plasma-facing materials” for which we do not have the solution yet. In Chap. 11, the final chapter, future prospects and research targets of PMI are suggested as the closing remarks.

1.2 Plasma–Material Interactions Caused by Power Load of Radiation and Energetic Particles

Nearly 90 years have passed after finding that nuclear reactions give energy. Now fission reactors are well established as energy sources, while a fusion reactor seems to need still a few decades to be realized. Why so much longer time has been required to establish a fusion reactor as an energy source compared to fission reactors?

There have been various difficulties in the research and development of a fusion reactor as an energy source. Although confinement of burning plasma has been the largest hurdle, it could be overcome in ITER. In engineering aspects, several problems are coming up, such as extremely high-power load to plasma-facing materials (PFM), conversion of neutron energy to heat, and management of radioactive T fuel to keep safety and fuel self-sufficiency. For consideration of the power load and energy conversion, principles of energy conversion in a fusion reactor system and a fission reactor system are quite different as compared in Table 1.1. Different from any other energy sources, the fusion reactor needs a significant amount of energy to start burning or ignition and also to continue burning, i.e. to make high-energy and high-density

Table 1.1 Comparison of energy conversion processes in fission and fusion reactors as energy sources

	Fission reactor	Fusion reactor
Characteristics	All of the energy conversion, fuel breeding, waste-confinement are done in a fuel pin of diameter of ~1 cm	An open tritium handling system with a huge volume
Power Input	Nearly zero	Huge power is required to sustain and to keep burning plasma Poor fueling efficiency requires huge fuel throughput
Energy conversion	Energy carried by fission products (FP, heavy ions) (~170 MeV) is deposited in fuel pins and converted to heat	Energy carried by a neutron (14 MeV) must be converted to heat in a large volume of the blanket system
Fuel breeding and recovery	One fission produces more than two neutrons, easy to keep chain reactions and to breed fuels Fuel pins contain both FPs and new fissile Spent fuels are reprocessed to remove/recover them	To keep breeding ratio more than 1, neutron multipliers (Be, Pb) are required Tritium breeding and energy conversion must be done simultaneously
Nuclear Waste	Long-life radioactive FPs and trans-uranium elements must be handled with special care and will be reposed deeply underground	Waste is limited to activated structure materials and could be recycled

plasma confined to satisfy the Lawson condition. The initial input power would be 1/3 to 1/4 of the fusion output power. Since a fusion reactor will be designed to produce the power of a few GW, each reactor may require a power station with the power of a few hundred MW to start up. In a fission reactor, no such high power is required, and only removing control rods from the reactor core starts fission reactions and continue steady-state burning.

Energy conversion systems for fission and fusion are also completely different. In a fission reactor, the energy produced by the fission reaction of an uranium atom (U) and a neutron is carried mainly by fission products (FPs) and transformed to thermal heat of coolant for electric power generation, while, in a fusion reactor, the energy carried by 14 MeV neutrons must be converted to the thermal heat of the coolant in the blanket. At the same time, the 14 MeV neutron is used to breed T to sustain fuel self-sufficiency as described below. Both fission and fusion leave nuclear wastes. Compared to long-life nuclear wastes in fission including FPs and trans-uranium elements like U, Np, and Pu, which are serious concerns for radiation safety, activated structure materials in a fusion reactor by neutron irradiation are less hazardous and even they could be re-used.

Any power sources require power removal through cooling system to convert their generated energy to heat or electricity. In a fusion reactor, nearly 1/4 of generated fusion power is used to sustain burning plasma (either initial heating power from outside and heating power given by He) and must be removed or recovered. Except energy carried by the 14 MeV neutrons, all power used for plasma heating is loaded to plasma-facing materials (PFM). Divertor is introduced to remove such high-power load and He ash. Still the tolerance of PFM to the power load is concerned. PFS of the main chamber is also exposed to the significant power load. Depending on the location of the plasma-facing components, power loads significantly differ. Mid-plane of the central pole (inner first wall) would be the highest except divertor target area.

Power load is given to PFM by radiation or energetic photons, and energetic particles including tritons, deuterons, neutrons, helium ions, and electrons escaping from boundary plasma in addition to neutrals produced by charge exchange. The radiation consists of the Bremsstrahlung emission from burning plasma, and radiation from impurities in plasma and seeded gas required for cooling the boundary plasma. The power load to PFM is so high that no simple material can tolerate without active cooling. Still there is a limit in the removal of the loaded power. Accordingly, the maximum of the power load to materials having a high melting point is limited to 10–20 MW m^{-2} under efficient cooling.

The main subjects of this book entitled “Plasma wall interactions in a fusion reactor” are to introduce/discuss responses of PFS to the power load and modification of PFM by the power load, both of which significantly influence the performance of burning plasma.

In the early days of PMI studies, when the first proceedings of the International Symposium on Plasma Wall Interaction were published in 1977 [1], the main interest was focused on material response to the injection of high-energy ions appearing as sputtering, and little works had done on high-power load, because confined energy in the plasma was too small to observe the effect of the heat load on PFS at that time. Since then, many books on PMI or plasma–surface interactions (PSI)* have been published. Some are given in references mostly focusing on sputtering and some atomic processes of sputtered atoms in boundary plasma [2–15]. Based on these PMI studies, plasma technologies are now widely used for the production of new materials and/or material modification [16], which are not discussed here.

* Plasma–material interaction (PMI) or plasma–surface interaction (PSI) are often used to represent the same meaning, so as plasma-facing surface (PFS) and plasma-facing materials (PFM). In this book, generally PMI and PFM are used, while PSI is used to represent phenomena in which only PFS is involved.

1.3 Energy Conversion from Nuclear to Thermal for Electric Power Generation

Figure 1.2 shows how energy released by a DT fusion reaction is converted to thermal energy. The D-T reaction produces 14 MeV neutron and 3.5 MeV He.

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}(3.5\mathrm{MeV}) + \mathrm{n}(14.1\mathrm{MeV}) \tag{1.1}$$

The main process to get electric power is energy conversion of the neutron energy (14 MeV) to thermal heat of coolant (Rotational and vibrational motions of atoms or molecules consisting of coolant or around 0.1 eV phonon) in the blanket. The 14 MeV neutron directly goes into the blanket and its energy is first lost by a nuclear collision

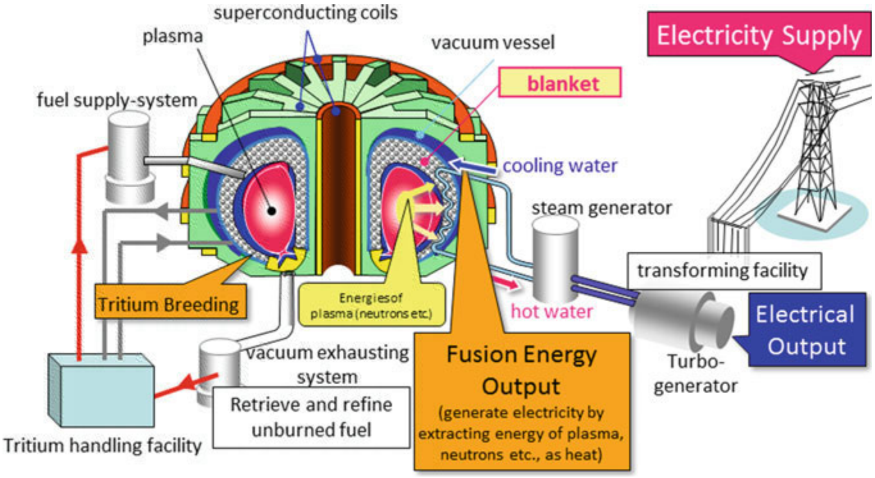

Fig. 1.2 Fusion reactor system and energy conversion. http://www.fusion.qst.go.jp/rokkasyo/en/project/blanket.html

with atoms consisting of the blanket. Neutron collision with Li in the blanket produces tritium (T). Both recoil atoms and produced T are in high-energy states (MeV to keV range). Succeedingly, they lose their energy with either electric or nuclear collision processes, and finally converted to heat (thermal energy) that is carried by vibration and rotation of atoms and molecules and collective motions of atoms consisting of the blanket, i.e. phonons with the energy of several tens meV (several hundred Kelvin). During the collision processes, secondary electrons and photons are produced by ionization and relaxation of atoms. The secondary particles lose their energy in a similar way until particle energy becomes smaller than the energy required for ionization or electron excitation. Most of these energy conversions are done in the blanket. According to the figure, the energy of 14 MeV neutron is converted into thermal energy consisting of around 10^8 phonons with an energy of meV range less than millisecond. The thermal energy is transferred to coolant for the generation of electricity through turbines. Understanding of the energy conversion processes will require simultaneous addressing of complex and diverse physics and chemistry occurring over a wide range of energy (MeV to meV), lengths (angstroms to meters), and times (femtoseconds to days) as shown in Fig. 1.3. In the figure are also given energy ranges corresponding to phenomena occurring in fusion reaction, burning plasma, boundary plasma, plasma-facing surface, and plasma-facing materials.

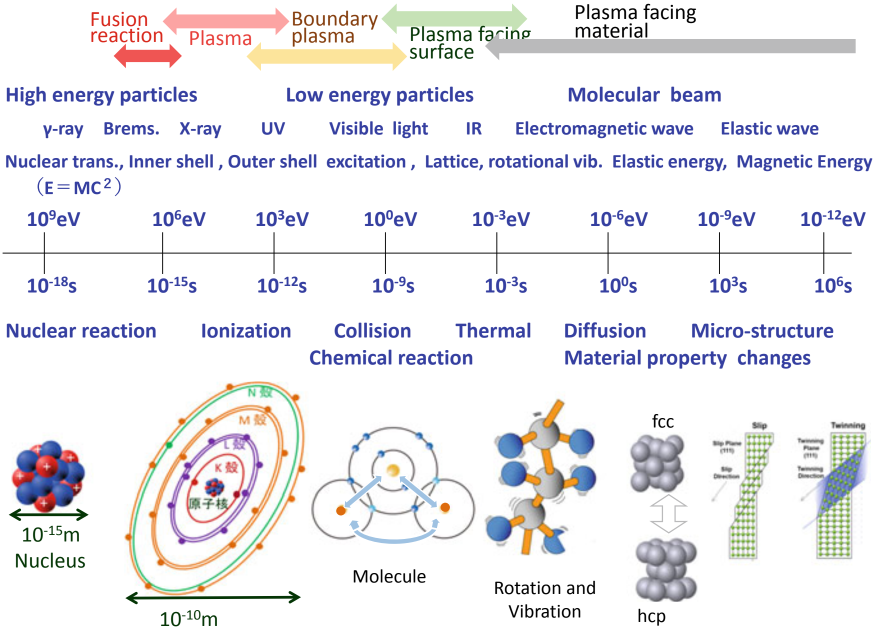

Fig. 1.3 Energy transfer/conversion and accompanied physical and chemical processes with characteristic times and their scales or sizes. Required energies to promote these processes correlate the times and sizes of the processes

There is one more important energy conversion process, which occurs at PFS. For sustaining burning plasma, fusion plasma shall be confined in the magnetic field. Confinement times of fuels and energy in the burning plasma are quite short, only a few seconds or less. That means fuels and energy are supplied and exhausted simultaneously to keep the input and output balance of fuel and power, which are quite hard to realize. The fuel balance has been discussed in a separate book [17] and will not be discussed here. To start up the burning plasma, energy is supplied from outside by various techniques, such as ohmic heating, neutral beam injection, electron cyclotron heating, ion cyclotron heating, and so on, while at the steady state, self-heating by 3.7 MeV He is expected in addition to the ohmic heating. Since plasma temperature is around 10–20 keV, 3.7 MeV He collides with fuel ions and electrons in plasma to give its energy to them through either the Coulomb collision or nuclear collisions. If the burning plasma does not contain impurity other than He, the Bremsstrahlung photon emission caused by motions of electrons, fuel ions, and He ions in the magnetic field gives energy loss from the plasma core.

Real plasma includes various impurities, in particular, atoms consisting of plasma-facing materials, and impurities included in them are easily released by collisions with plasma particles escaping from the plasma. Once these impurities enter in plasma, they are immediately ionized. Then they capture electrons and emit photons with energy corresponding to energy levels of binding electrons in impurity atoms. Together with the Bremsstrahlung emission, radiation from the impurities reduces plasma temperature. Depending on their atomic number, radiation power when they are in plasma changes significantly as shown in Fig. 1.4 [18]. It should be noted that depending on radiated energy which is proportional to the frequency or inversely proportional to the wavelength of radiated photons, the character of radiation or its

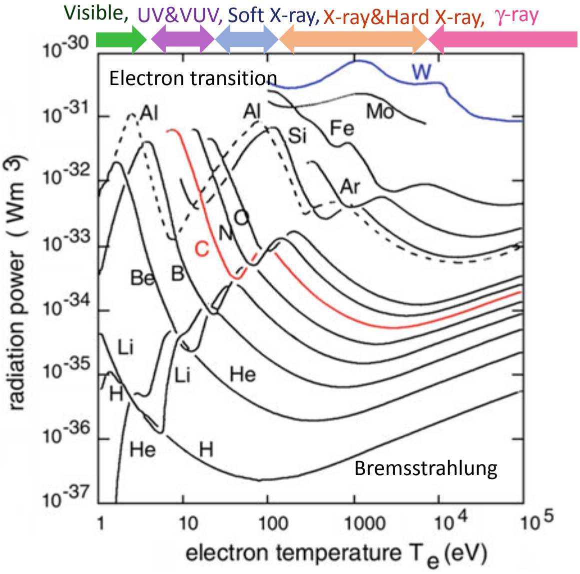

Fig. 1.4 Plasma (electron) temperature dependence of radiation power for various elements based on the Corona model. (reprinted with permission from [18]) On the upper horizontal scale, names of radiation are indicated

interactions with materials are different. Photons in the energy range of 1 eV to several eV are visible, 10 eV to several tens change from ultraviolet (UV) to vacuum ultraviolet (VUV), and above 100 eV changes from Soft X-rays to keV range X-rays as indicated in the figure. This means that depending on the atomic numbers of the elements, not only their radiation power but also the character of their radiation is different. Higher Z elements like Tungsten (W) are most probably used as PFM in a fusion reactor. When they are accumulated in the plasma center, they give stronger radiation as the X-rays and hence their concentration in core plasma should be suppressed to be below 10^{-5} to 10^{-6}.

Interactions of VUV and Soft X-ray with materials are so intense that they can penetrate the materials only in very short distances, in other words, their energy deposition on the material is so intense to exhibit strong PSI. Since the radiation for the high Z elements is in the X-ray region, PSI for the high Z wall must be dominated with the interaction with strong X-ray. However, no such high-intensity sources of Soft X-ray and X-rays emitted from burning plasma are available, the interaction of the strong radiation from the accumulated high Z elements in the plasma center with materials is not easy to study and lots of subjects remain, for examples, plasma opacity (radiation from plasma center does not come out to PFS to inhibit power exhaust), the effect of energy deposition limited within very thin surface layers, vapor shielding, and so on..

Particle confinement time in plasma is limited within a few seconds and they escape from the plasma with diffusion across the magnetic field. Since the surface temperature of the PFS should be below their melting temperature, injection of high-energy plasma particles to PSF should be avoided. To realize this, boundary plasma or scrape off layers are constructed with the installation of limiters or divertor outside of the last closed magnetic field lines. The energy conversion from 10 keV in core plasma to 100 eV in boundary plasma occurs with various processes together with complex mass transfer. Furthermore, boundary plasma with the energy of 10–100 eV contacts with PFS, resulting in plasma–material interactions (PMI) including complex physical and chemical processes. Studies of the physical and chemical processes occurring in the energy range of 1–100 eV are quite difficult mainly because atoms and molecules having these energies are in excited states. Moreover, emitted photons and electrons accompanied with energy loss process in this energy range have quite short escaping (penetration) depths in materials even in gases. This makes observation or monitoring of the occurring process in boundary plasma difficult. Thus, PMI has not been well diagnosed or understood yet.

1.4 Brief History of the Development of Plasma-Facing Materials

The first step in fusion research was to make plasma in vacuum, or to confine plasma in a vacuum system that was initially composed of glass and turned to stainless steel. Historically, improvement of plasma confinement relied on the improvement