Physics of near-wall plasma in tokamaks

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The review describes modern achievements of the physics of plasma—wall interactions in tokamaks. The main methods allowing a reduction of the energy of the particles incident on the first wall and, thus, important for the prevention of wall erosion, are described in an easily understandable form. The conditions required for the formation of strong near-wall material recycling are briefly considered. The heat and mass transport processes in the peripheral region of the plasma as well as electric arc discharges on walls of tokamaks are discussed.

CONTENTS

1. INTRODUCTION

In a thermonuclear reactor with magnetic confinement plasma with a temperature of approximately 10 keV must be surrounded by a vacuum shell the temperature of which is not more than several hundred degrees. The phenomena taking place near and on the walls are essential for the realization of the idea of controlled thermonuclear fusion (CTF), and it is not a coincidence that these phenomena have received proper attention already in the first (1951) publications on the theory of the thermonuclear reactor with magnetic confinement.[1–3]

Thermal flux towards the walls in a pure plasma is provided mainly by thermal conductivity, and the thermal flux directly to the wall is transmitted by ions and electrons incident and recombining on the wall:

$$q = \gamma \Gamma T_w; \qquad (1)$$

here q and Γ are the specific fluxes of heat and ions, T_w is the temperature of the edge plasma, γ is a coefficient weakly depending on T and equal to 5–7 for a wall which does not emit electrons. The temperature T_w turns out to be much higher than the temperature of the wall, i.e., there is a temperature discontinuity on the boundary between the plasma and the wall. The qualitative picture of processes taking place near the wall is shown in Fig. 1. Slow neutral hydrogen atoms formed on the wall undergo a charge exchange reaction at a small distance from the wall. This leads to the formation of fast neutrals having a significant mean free path before they become ionized by the plasma electrons. In Refs. 1, 2 it was shown that for $q = 10$ W/cm^2 and a plasma density near the wall of $n_w \approx 10^{15}$ cm^{-3}, the plasma temperature is equal to 10 eV. In these papers it was assumed that such large values of n_w, exceeding the density at the center of a reactor by factors of ten, would be achieved as a result of thermal diffusion if the transverse transport can be described classically. In fact, the density of the edge plasma in tokamaks is significantly less than the density in the central region, and the density profile can be approximately described by a parabolic law:

$$n(r) = n_0\left(1 - \frac{r^2}{d^2}\right),$$

where d slightly exceeds the small radius a of a plasma.[4] Additionally, it was assumed that the ratio of plasma pressure to the pressure of the magnetic field confining the plasma will be of the order of unity, and this does not hold for tokamaks because of the Kruskal-Shafranov stability criterion.

The value of q in future reactors must be several tens of W/cm^2, and $n_w \approx (1–5)\cdot 10^{13}$ cm^{-3}. The plasma temperature near the walls must be, according to formula (1) and the estimate given in Ref. 2, two orders of magnitude higher, $T_w \approx 1$ keV. A flux of particles with such energy creates a serious problem of the erosion of the first wall. The main mechanism of erosion is physical destruction, known for a long time in glow discharges as "cathode sputtering." The sputtering coefficient S, i.e., the ratio of the number of sputtered atoms to the number of ions incident on the surface, is a function of the energy of the incident particles (ε) and of the reduced mass for incident and sputtered particles. For

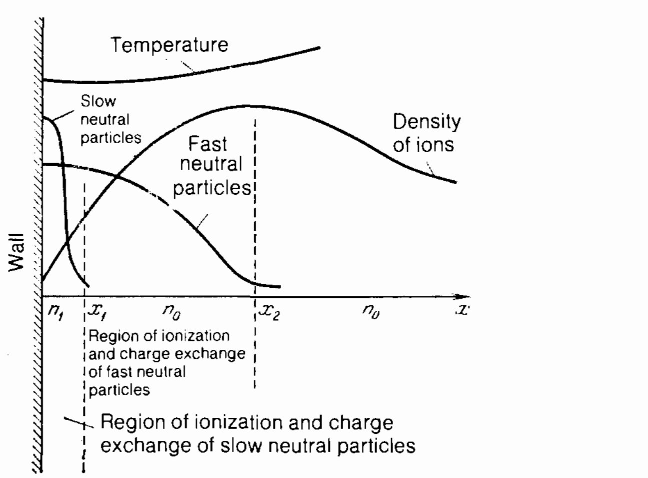

FIG. 1. Qualitative picture of the near-wall plasma in a thermonuclear reactor in a magnetic field.[1]

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$\varepsilon_t < \varepsilon < 20\varepsilon_t$, this function can be described rather well by the following expression:

$$S(\varepsilon) = 6{,}4\cdot 10^{-3}\frac{m_{\rm I}}{m_{\rm i}}\gamma_{\rm m}^{5/3}\left(\frac{\varepsilon}{\varepsilon_{\rm t}}\right)^{1/4}\left(1-\frac{\varepsilon_{\rm t}}{\varepsilon}\right)^{7/2}, \qquad (2)$$

where

$$\gamma_{\rm m} = \frac{4m_{\rm i}m_{\rm I}}{(m_{\rm i}+m_{\rm I})^2}, \quad \varepsilon_{\rm t} = \frac{E_{\rm B}}{\gamma_{\rm m}(1-\gamma_{\rm m})},$$

$E_{\rm B}$ is the sublimation energy, and the indices I and i refer, correspondingly, to the atoms of the target and the incident ions; for energies below the threshold energy (ε_t), the sputtering is negligibly small. However, for $T \approx 1$ keV the values of S are such that if the sputtering products will accumulate in the plasma, as predicted by classical transport theories, the burning time of a thermonuclear reaction will be unacceptably short.

Besides sputtering, there are some other types of destruction by fast particles, caused by a high pressure of hydrogen and helium which accumulate under the surface of a solid, i.e., the "blistering" and "flaking." In these cases, layers with thicknesses close to a penetration depth of incident ions (10^{-6}–10^{-5} cm) are destroyed mechanically. Unfortunately, these types of erosion turned out to be "childhood diseases"—they disappear with an increase in the radiation dose. After destruction of several layers, the surface becomes sufficiently porous, and gas escapes.

During the entire history of experimental work on magnetic confinement of hot plasmas, the struggle against contamination of plasma by wall impurities was always one of the main concerns of experimentalists.

First successes in that struggle in the case of tokamaks in the USSR and stellarators in the USA were due to the improvement in the wall heating in vacuum and the introduction of special limiters (diaphragms) restricting the transverse size of a plasma filament. The limiter being itself exposed to a strong and concentrated action by the plasma significantly restricts the access of charged particles to the walls of the main chamber. Subsequent steps were surface cleaning methods using special induction or glow discharges, and also the replacement of diaphragms made from high-melting-point metals by graphite ones, since plasma is less sensitive to impurities with smaller atomic numbers.

In recent years, "divertor" configurations of the magnetic field suggested by Spitzer[5] have been used in some tokamaks. In them the magnetic field lines in the peripheral region of a tokamak are brought "outside," i.e., to special areas of the walls, the divertor plates, which are placed at the greatest possible distance from the main plasma. Experiments with divertors have confirmed that these devices are effective in increasing plasma purity.

As a result of these developments, one can obtain in modern large tokamaks plasmas of rather high purity. Without this it would be impossible to approach plasma parameter values required for thermonuclear fusion. However, the problem of interaction of a hot plasma with a first wall is not solved by this, on the contrary, it becomes more urgent. Modern installations use additional high power sources for plasma heating, and this significantly increases the heat flux to the walls. The duration of discharge pulses increases. The seriousness of this problem for future reactors with quasi-steady-state burning has been shown convincingly in a presentation of Beresh and Kadomtsev[6] that played an important role in the consolidation of efforts of researchers working in that area. Since 1974, in addition to the regular annual international conferences on plasma physics and problems of controlled thermonuclear fusion, special conferences on the interaction of plasmas with the surfaces in thermonuclear installations began to be organized every other year. Extensive and detailed experimental information is available in the proceedings of these conferences.[7]

Without claiming to be complete, this article aims to familiarize the reader with the modern concepts concerning the near-wall plasma physics in tokamaks. The development of these concepts is an important achievement of the last decade in solving the problem of plasma-wall interactions in controlled thermonuclear fusion.

2. REGIMES WITH STRONG RECYCLING

From the foregoing one can see that it is possible to get rid of strong sputtering by lowering the temperature of the near-wall plasma. This, in turn, can be achieved by increasing the particle flux to the wall [see formula (1)] which, unlike the heat flux, is not a given quantity. By increasing the transverse diffusion near the walls, it is possible to increase the convective flux by a large factor:

$$\Gamma = D_\perp \frac{dn}{dx} \approx D_\perp \frac{n_{\rm w}}{l_{\rm a}};$$

here $l_{\rm a}$ is a typical distance over which fast neutrals get ionized. Since fast ions created during a charge exchange process acquire the temperature of the ions, and their trajectories have random walk character, their propagation follows the diffusion law with $D_{\rm a} \approx \lambda_{\rm a} v_{\rm i}$, where $v_{\rm i}$ is the thermal velocity of the ions, and $\lambda_{\rm a} = (\sigma_{\rm c} n)^{-1}$ ($\sigma_{\rm c}$ is the cross-section of a resonance charge exchange weakly dependent on temperature). Over the time period $t_{\rm i} = (k_{\rm i} n)^{-1}$ before ionization they are displaced by the distance

$$l_{\rm a} \approx (D_{\rm a} t_{\rm i})^{1/2} \approx n^{-1}\left(\frac{v_{\rm i}}{\sigma_{\rm c} k_{\rm i}}\right)^{1/2}$$

($k_{\rm i}$ is the ionization constant). From here, taking into account (1), we obtain $T_{\rm w} \sim D_\perp^{-1}$.

Therefore, if one forms near a wall a strong material exchange called recycling, so that the particles can participate many times in neutralization acts on the surface and ionization in a plasma, their average energy can be sufficiently small. For a strong recycling, the flux to the wall can significantly exceed the flux from the central region, and their ratio can serve as the quantitative characteristic (coefficient) of recycling.

2.1. Turbulent plasma blanket

If instead of using for $D_\perp$ its classical value, as was done in Refs. 1–3, one uses the quantity

$$D_{\rm B} = \frac{cT}{16eB},$$

introduced by Bohm for a turbulent plasma in a strong magnetic field and typical for the near-wall regions in tokamaks, the plasma and neutral profiles have the shapes shown in Fig. 2. These shapes correspond to a recycling coefficient of ~ 50. In that case, the density of a neutral particle flux is sufficient to cause the outflow of helium and unburned fuel through an opening in the first wall, which has relatively small dimensions. As one can see from the picture, for a concentration of fast neutrals of the order of 10^{11} cm^{-3}, the

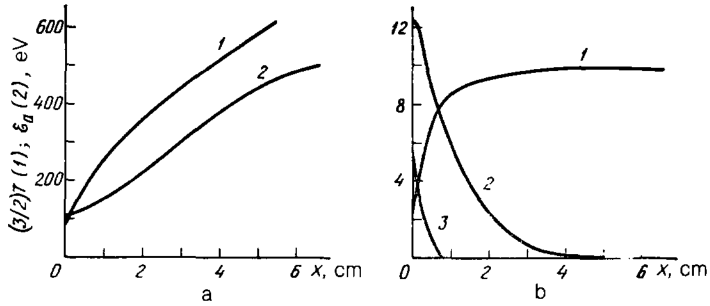

FIG. 2. The near-wall plasma profiles in a reactor with $q = 10^2$ W/cm^{-2} and $B = 5$ T (Ref. 8). a. Average energy of the plasma (1) and of the atoms after a charge exchange reaction (2); b. density of plasma in units of 10^{-13} cm^{-3} (1), of atoms after a charge exchange reaction in units of $5\cdot10^{-11}$ cm^{-3} (2) and of cold atoms in units of 10^{-12} cm^{-3} (3).

energy of particles incident on the wall is sufficiently low, however, the density of the near-wall plasma $n_w \approx 10^{14}$ cm^{-3} turns out to be of the same order of magnitude as in the internal regions of a tokamak.

Since the "Bohm" plasma turbulence alone is not sufficient, an effective diffusion can be increased by destroying magnetic surfaces by small spiral perturbations of the magnetic field. The resonance between the perturbation harmonics and the main helical field of a tokamak can lead to randomization of field lines in some layer.[8-10] Such a perturbation can be created, for example, by placing outside of a reactor helical coils carrying an electrical current flowing alternately in opposing directions and equidistant to the field lines of the main field. One of the possible configurations of the coils for randomization of a magnetic field over a limited area is shown in Fig. 3.

When it passes along a magnetic field in a randomized region, plasma "diffuses" in the transverse direction. The velocity of this diffusion can be regulated by the coil current; the required value of $D_\perp \approx (1\text{–}5)\cdot 10^4$ cm^2 sec^{-1} is achieved with a current representing only a small part of the total plasma current in a tokamak. The resonance coils must be placed in the immediate vicinity of the wall, and this can present some technical difficulties for a thermonuclear reactor.

It was suggested to denote a near-wall layer of a cold, dense plasma with nonclassical transport of heat and particles as a result of turbulization by instabilities or of destruction of magnetic surfaces, by the name of a turbulent plasma blanket.[11]

Experimental test of the idea of near-wall magnetic field randomization in a tokamak is under way now in Japan, USA, and FRG. The first results show that, as one could expect, when a spiral perturbation is imposed, the emission from impurities in the center decreases, and emission from the periphery of the discharge increases. Randomizing coils are provided in a large tokamak TORE-SUPRA under construction in France.

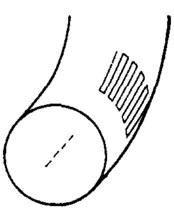

FIG. 3.

2.2. Recycling near divertor and limiter plates

Plasma flows along a magnetic field to the side walls of limiters or to the divertor plates, in the vicinity of which strong recycling also can be formed, if the thickness of the plasma layer δ is greater than the mean free path of a neutral atom before ionization λ_i, and if ions and electrons recombining on the wall return to this layer. In the steady-state regime (and for a wall which does not absorb particles) the plasma flux from the central areas to the layer still must be compensated by a flux of neutrals through its side surfaces.

Plasma reaches a plate with a speed close to the thermal velocity of ions. Then, the condition for the existence of a state with strong recycling can be written in the form of the inequality[12]:

$$Q > \gamma \frac{T v_i^2}{k_i} \sin\psi, \tag{3}$$

where Q is the heat flux per unit length of contact with a limiter, ψ is the angle between the field lines and the surface. To estimate k_i, we shall use the Thompson formula for the cross-section for ionization of hydrogen atoms by electrons:

$$k_i = \frac{\pi e^4}{I^2}\left(\frac{8T_e}{\pi m_e}\right)^{1/2} \exp\left(-\frac{I}{T_e}\right) \tag{4}$$

(I is the ionization energy).

The right-hand side of expression (3) is a function of the temperature, which at $T_e = 2I/3$ has a minimum equal to

$$Q_{cr} \approx \gamma \frac{I^{7/2}}{e^4}\frac{m_e^{1/2}}{m_i} \sin\psi \approx 3\,\frac{\text{kW}}{\text{cm}}\cdot\sin\psi. \tag{5}$$

For strong recycling, there exists a critical density of the current j, also per unit contact length, which corresponds to a minimal value of Q:

$$j_{cr} \approx \frac{m_e^{1/2}}{m_i}\frac{I^{5/2}}{e^4}\sin\psi \approx 3\cdot10^{20}\ \text{cm}^{-1}\,\text{s}^{-1}\cdot\sin\psi. \tag{6}$$

For values of Q and j larger than the critical ones, there can be two stable states near a limiter or in a divertor: with a hot and relatively low density plasma, and with a cold and dense plasma.[13,14] The transition between these states occurs abruptly with an increase in j. Intermediate states are unstable: an increase in the density of the plasma layer decreases the mean free path λ_i and even more shuts off the flux of neutrals from the surface until the temperature and, with it, the ionization constant, fall sufficiently low so that atoms can again leave the layer.

Figure 4 shows the calculated dependences of the linear density $N = \delta n$ and the plasma temperature near the plates for different values of Q.[15]

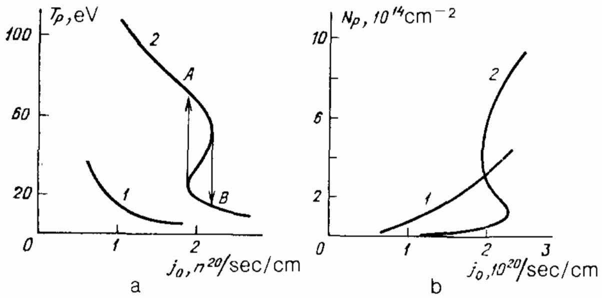

FIG. 4. Dependence of the temperature (a) and the linear density (b) of a plasma near the plate as a function of the particle flux into a divertor; 1—$Q = 2$ kW/cm; 2—$Q = 12$ kW/cm.

According to calculations, with the beginning of strong recycling the influx of impurities to the discharge decreases abruptly by 3–4 orders of magnitude! This is caused both by a strong decrease in sputtering, and by the high ionization probability of sputtered atoms and the carrying along of the formed ions by the counter flux of plasma back to the surface.[16] Ions incident on the surface are accelerated by a potential difference between the plasma and the wall, and acquire from thermal electrons the energy $\sim 3zT_e$, where z is the ion charge. Multiply charged ions penetrating from a hot cental area, can acquire a significant energy and cause strong sputtering. A decrease in T_e favors a sharp decrease in sputtering also by multiply charged ions.

In a number of tokamaks, an abrupt transition to the strong recycling regime in a divertor was observed at some fluxes of Q and j. For example, Fig. 5 shows how the plasma density in a divertor on the D-III installation changes with an increase of the average density of a discharge; the flux to a divertor is approximately proportional to it.[17]

Together with the function of protecting the first wall, the divertor in a reactor must also provide for the removal of helium formed during the fusion reaction, and of the unburned fuel. The gas pressure in the pumping chamber is determined by the efficiency of pumps and the mass exchange on its open surface, where the divertor plasma is confined by the magnetic field. Strong recycling increases the density of neutral atoms in the chamber and significantly simplifies the technical problems of pumping. The transition to strong recycling also changes the gasdynamics of the flow. If at low densities in a divertor the plasma is accelerated by the pressure gradient to a velocity close to the ion sound velicty v_s, then the "bottleneck" of the dense plasma blocks the flux and in front of it $v \ll v_s$.[18–20] More than that, it is possible to have a situation when the ionization of the gas

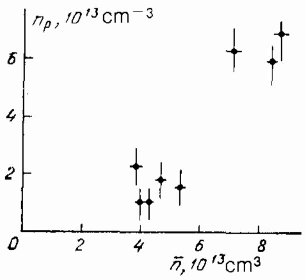

FIG. 5. Dependence of the plasma density in a divertor on the average density in the D-III tokamak.[17]

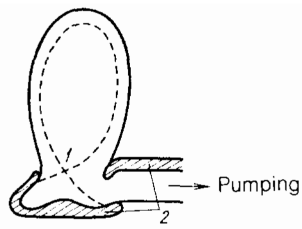

FIG. 6. Poloidal divertor INTOR. 1. Separatrix; 2. Plates.

coming from outside into the layer open towards the pumping chamber forces the plasma to flow back, i.e., from the divertor to the main volume of the tokamak.[21] The low subsound velocity of the plasma flow into a divertor was measured in the D-III, PDX, and ASDEX installations, and the oppositely directed flow was measured in the divertor of the British tokamak DITE.[22] For $v \ll v_s$, the plasma pressure along the magnetic field changes little, and large densities with $n > 10^{14}$ cm^{-3} correspond to low tempertures near the plates. Because of the relative remoteness of these areas, the divertor configuration allows these high densities to be compatible with the average density $(1–3) \cdot 10^{13}$ cm^{-3} at the periphery of the tokamak discharge.

Thermal flux into a divertor in the case of strong recycling is transported by a longitudinal thermal conductivity and is proportional to $T^{7/2}$. Even for an anomalous transverse thermal conductivity with $\lambda \sim D_B$, the thickness of the hot layer turns out to be narrow. For example, in the design of the INTOR reactor, developed by the international group at MAGATE, the thermal flux to the plates of a poloidal divertor (Fig. 6) is concentrated in a layer with a thickness of the order of 1 cm and reaches 1–2 kW/cm^2.

2.3. Gas target

A remarkable regime in the operation of the divertor called the "gas target" has been discovered on the ASDEX tokamak.[23] In this regime, only 20 percent of the heat flux entering a divertor reaches the plates; the remaining heat is dissipated in the gas and is transported to the wall of the pumping chamber (Fig. 7). The transition to the "gas target" regime takes place when the temperature near a plate goes below the temperature at which $\lambda_i = \delta$ (lower than 7 eV for ASDEX). The plasma becomes transparent for fast neutrals produced in charge exchange processes; the neutrals enter the pumping chamber and there transfer their energy to the gas. A transfer of energy comparable in magni-

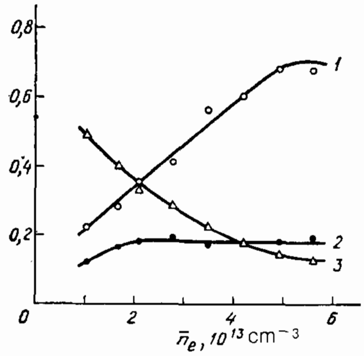

FIG. 7. The fraction of the power input into the discharge transported to the walls of the main chamber (2), to the divertor plates (3), and to the walls of the pumping chamber of the divertor (1) in ASDEX.

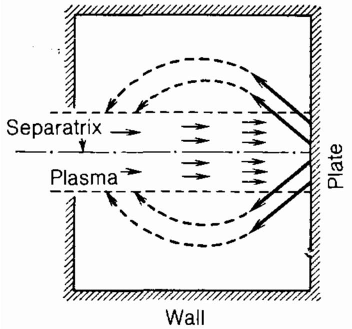

FIG. 8. Schematic diagram of the recycling of material in the "gas target" regime.

tude takes place by radiation. Together with recycling near a plate, the convective heat flux also decreases. A large portion of atoms returns from the pump chamber (mostly in molecular form) to the plasma, undergoes ionization and recombines on the plate. Thus, strong recycling takes place not in a narrow layer of the order of λ_i, but in the entire pumping chamber, as is shown schematically in Fig. 8. Theoretical models describe the experiments with "a gas target" sufficiently well.[24,25] In a future reactor such a regime could remove the concentrated thermal load to divertor plates; however, the possibility of its realization with parameters existing in reactors raises doubts of many researchers.

Thermal flux into the divertor of a reactor is much larger than in the case of ASDEX, and for its removal needs large concentrations of neutral gas in the pumping chamber. This creates the possibility of emergence of this gas into the main plasma, and this was probably observed in Ref. 26. The author holds the opinion, supported by calculations,[27] that the regime of a "gas target" in a reactor can, in principle, be realized. And it is the large thermal flux that is capable of providing the sufficiently high temperature and plasma density at the input to a divertor to ionize all the atoms that could penetrate into the main volume of the reactor. A low, of the order of 1 eV, temperature near the plates is reached at the transition of the plasma flux velocity through the ion sound velocity not far from the plate.

2.4. Pumped limiter

A divertor is technically a rather complicated device. For that reason, it is tempting to continue to use in reactors limiters which were used successfully until now in most tokamaks.

The problems with limiter sputtering, as was said earlier, can be overcome by forming a cold plasma near a limmiter. By arranging pumping in the vicinity of a limiter, it is also possible to remove helium and unburned fuel. Various constructions of limiters with pumping have acquired the name of pumped limiters. Since the pumping fittings are entered by atoms which have appeared at a distance from the boundary of the plasma layer smaller than $\lambda_i \sim (n_L k_i)^{-1}$, their flux is $\sim \exp(I/T_L)$. From the condition of pressure constancy, relating the density n_L and the temperature T_L near a limiter with the average values in a layer $\langle n \rangle$ and $\langle T \rangle$, $q = \gamma n_L T_L v_s \approx \gamma \langle T \rangle \langle n \rangle (2T_L/m_i)^{1/2}$. Therefore, the pressure of the pumped gas is

$$p \sim \exp\left(-\frac{\langle n \rangle^2}{n_*^2}\right), \text{ where } n_* = \frac{q}{\gamma \langle T \rangle}\left(\frac{m_i}{2I}\right)^{1/2} \qquad (7)$$

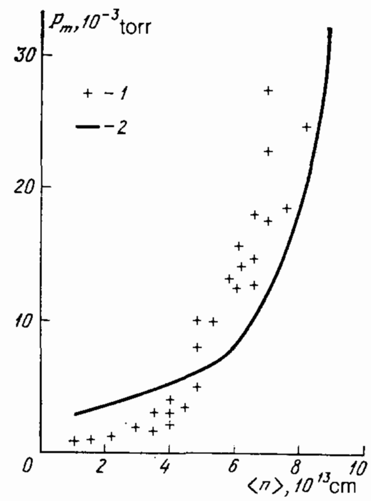

FIG. 9. Dependence of the pressure in a fitting of a pumped limiter on the average density of the plasma in the limiter layer; 1. experiment[29]; 2. theory.[28]

A comparison of the dependence (7) (Ref. 28) with an experiment carried out on the "Alcator" installation[29] is given in Fig. 9. Using the large increase in pressure, it is possible to provide the necessary pumping using available technical means. We note that an increase in the pumping rate above a certain limit decreasing the pressure of the pumped gas, can destroy the strong recycling regime in a divertor or in a pumped limiter.

Technical difficulties related to the presence of high specific heat fluxes make it necessary to enlarge the surface and to increase the number of pumped limiters, and this brings the idea of the use of limiters even closer to the concept of a turbulent plasma blanket. In particular, the high average density of the plasma on the periphery, comparable to the average density in a reactor, is a universal problem.

In recent years, a new phenomenon was discovered in a number of large tokamaks. It received the name MARFE (from the "Multifaceted Asymmetric Radiation From the Edge).[30–34] It consists in the appearance in a near-wall area of plasma formations with high density and low temperature, which are asymmetric, relative to the poloidal angle, and which become sources of intense emission of neutral hydrogen atoms and of light impurities. Its main cause is the instability described above, and the formation of areas with strong recycling, and their subsequent cooling by radiation. There is also another point of view on the nature of MARFE: the development of an instability in the heat balance within a volume of plasma related to radiation from impurities. We shall talk about that in the next section.

3. RADIATION FROM IMPURITIES

In the previous sections we assumed that the plasma is sufficiently clean, and neglected the radiation coming from it. This radiation, however, plays an important role in the energy balance of the near-wall plasma due to the presence of impurities in it. For typical temperatures of 10–100 eV, the largest contribution comes from the line emission of light impurity ions—oxygen and carbon. In the case of coronal equilibrium, i.e., when excitation and ionization by electron collisions are balanced by radiative transitions and radiative recombination, the intensity of radiation (L) has a maxi-

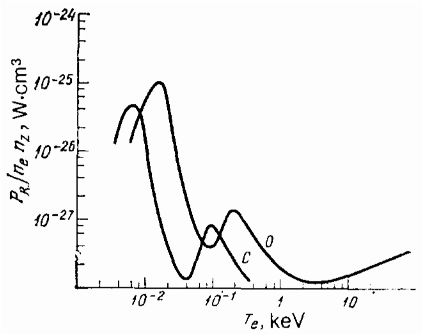

FIG. 10. Specific radiative losses P_R in the case of coronal equilibrium (n_e—concentration of impurity ions).

mum at $T_e \sim 10$–20 eV (Fig. 10).[35] In a certain interval of energies, radiation falls off rapidly with increasing temperature because of the growth of multiple ionization and the depletion of the line spectrum. Re-emission of a significant part of the energy supplied to the peripheral region decreases the convective flux to the walls. Correspondingly, the critical conditions for transition to strong recycling are changing.

The cooling of the edge plasma caused by radiation from light impurities prevents contamination of the discharge by metallic impurities, sputtered from the surfaces of the walls and the limiters.[4,36,37] For this reason, excessive cleaning of metallic surfaces from oxygen and carbon can be damaging to attempts to keep contamination at a minimum. There are suggestions to use regulated introduction of impurities for the creation of cold peripheral plasma.[38,39]

The presence of regions with $(dL/dT) < 0$ can create instability of the thermal balance. In an increase of radiative losses occurring with a temperature decrease is not compensated by the heat flux from central areas, the temperature will continue to fall. The existence of an upper limit on the average plasma density in tokamaks, above which a discharge collapse occurs, is related to such a "cooling" instability caused by impurities. The development of an instability cools the peripheral region; a narrowing of the current channel and a development of magnetohydrodynamic instabilities occur destabilizing the discharge.[40] The recent achievement of high density values can be explained by progress in obtaining plasma of higher purity.

In a number of experiments, it was possible to observe cold radiating layers. Their formation in the large TFTR tokamak is preceded by the appearance of MARFE.[41] Interaction of strong nonlinear effects, related to recycling and radiation from impurities, details of which are not yet well understood, takes place. Not sufficiently well understood

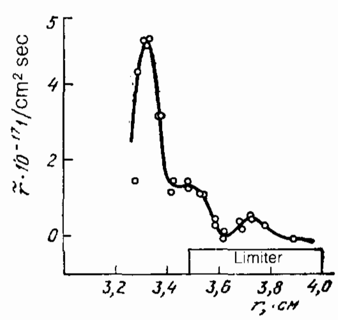

FIG. 11. Radial fluctuation flux near the limiter of the TB-1 tokamak.[46]

are also the kinetics of excitation, ionization, and wall-recombination of impurities, the state of which in the near-wall region is far from coronal equilibrium. The complexity of the described processes requries the development of two- and three-dimensional mathematical models of the near-wall plasma[42,43] which would take into account the hydrodynamics of plasma, and the kinetics of neutral hydrogen atoms and impurities. For these models, one needs to know the heat and particle transport coefficients, which themselves are not known sufficiently well.

4. TRANSPORT PROCESSES

4.1. Near-wall turbulence

The plasma parameters at the edge $(r = a)$ of various tokamak limiters with ohmic heating differ only slightly and are in the range $n(a) \approx (1\text{–}5)\cdot 10^{12}$ cm^{-3}; $T_e(a) \approx 10$–50 eV. Higher values of $n(a) \approx (4\text{–}10)\cdot 10^{13}$ cm^{-3} are achieved in tokamaks with a strong toroidal magnetic field of 6–8 T, while higher temperatures $T_e(a) \approx 30$–100 eV occur in the largest tokamaks JET and TFTR.[44] Deeper inside the limiter shadow the density falls off exponentially with the characteristic length d_n. An estimate by the formula $D_\perp = d_n^2/\tau_\parallel$, where $\tau_\parallel = \pi R/v_s$ is the time for the plasma to reach the limiter along the magnetic field, gives $D_\perp \approx D_B$, which means that the plasma has a turbulent character.

In recent years, this turbulent character has become an object of detailed investigation.[45–47] It was discovered that the relative level of plasma density fluctuations $\langle \tilde{n} \rangle / \langle n \rangle = 0.5$–0.6, i.e., its variations reach almost one order of magnitude. There are strong variations of the local poloidal electric field $\tilde{\mathbf{E}} \perp \mathbf{B}$ reaching tens of V/cm. The variations of $\tilde{n}$ and $\tilde{E}$ occur over a wide range of frequencies, in the interval 10^4–10^5 Hz. The inverse scale (the wave number) of the spatial correlation in the direction perpendicular to the magnetic field is $k_\perp \rho_i \approx 0.1$ (ρ_i is the ion Larmor radius). Since the fluctuations of n and $E_\perp$ are partially correlated, a turbulent drifting flux of plasma particles occurs

$$\tilde{\Gamma}_r = \int \tilde{n}(t)\, \tilde{v}_\perp(t)\, dt,$$

where $\tilde{v}_\perp = c[\tilde{\mathbf{E}} \times \mathbf{B}]/B^2$. Near the limiter edge, it reaches the magnitude $\sim 10^{17}$–10^{18} cm^{-2} sec^{-1}, and rapidly decreases towards the main plasma (Fig. 11).

The observed picture of turbulence leads to a suggestion that it is caused by the limiter. It is possible to indicate a simple instability mechanism in the limiter shadow, the channel instability of a homogeneous plasma in an inhomogeneous magnetic field when $\nabla n \uparrow\uparrow \nabla B$. A transverse "hump" in the density elongated along the magnetic lines of force because of the drift in the toroidal field $(B_\perp \sim 1/R)$, directed in opposite directions for ions and electrons becomes polarized, and, on the outside surface of the torus, moves in the direction of decrease of the density of the surrounding plasma. The transition layer between plasma and limiter has an increasing volt-ampere characteristic.

$$j_\parallel = en\left[v_s - \left(\frac{T_e}{2\pi m}\right)^{1/2} \exp\left(-\frac{e\varphi}{T_e}\right)\right], \qquad (8)$$

limiting the current to the limiter to the ion saturation current. For that reason, the flow of the current through the limiter cannot remove polarization completely and stabilize the growth of a perturbation. The plasma must be stable on the inner surface of the torus. A rough estimate of the turbulent diffusion coefficient as a function of the channel instability increment and the typical mixing scale gives a quantity which depends on the poloidal angle and is equal at the maximum to $\approx (cT/eB)(\rho_i\, q/a)^{1/3} \approx D_B$ (Ref. 48). The fact that the anomalous transport of plasma has a clear maximum near the outside surface of the torus was for the first time noticed by Mukhovatov already in 1966.[36]

At a distance approximately equal to the mixing length, the turbulence penetrates from the limiter shadow also into the main plasma.

The study of a detailed three-dimensional picture of a near-wall turbulence in tokamaks is the subject of future experiments. The fact that this picture is not one-dimensional, can be seen for example from Fig. 11. The divergence of the turbulent flux is greater than zero, and in the limited region, where measurements were performed, plasma flows in poloidal or toroidal direction. The concentration of neutral hydrogen atoms in that region is small, and their ionization cannot be an internal source of charged particles.

4.2. Plasma convection

The vertical drift of electrons and ions in a toroidal magnetic field is compensated in a tokamak by an additional electric field directed along the magnetic field. In the shadow of a limiter, this current comes into a contact with its surface, and has to pass through the limiter. As a result, a difference of potential, of the order of T_e [according to formula (8)], is formed between the plasma and the limiter, and, due to high longitudinal conductivity, plasma tubes located on different field lines are charged differently. On the side of the ionic toroidal drift a positive charge dominates, while on the side of the electron drift a negative charge dominates.[49]

Into a ring limiter obstructing the vertical cross-section near the wall, the sections of spiral field lines enter from different sides and rotated by some poloidal angle. On both sides of any sector of such a limiter, the plasma potential is different, and in the limiter shadow there is a poloidal electric field of the order of T_e/a, which significantly exceeds the field of the main plasma.

In the shadow of a limiter electrons and ions as a rule do not have time to exchange energy during the time spent at the side walls. The temperature of the ion gas changes but little, since ions leave it with their thermal energy. Electrons lose part of their thermal energy in the abrupt potential drop near the wall, and for that reason the electron gas cools down in penetrating into the limiter shadow. This cooling is also assisted by the radiation from impurities. The electron temperature falls off exponentially with a characteristic length d_T, which is usually several times larger than d_n. The appearance of the potential difference along the small radius and of the radial electric field is related to that decrease.

The resulting two-dimensional distribution of the electric field causes a convective motion of the plasma, which is superimposed on the process of turbulent diffusion. Over the lifetime $\tau_{\parallel}$, the plasma drifts over the small radius into the shadow of the limiter on the outer surface of the torus and simultaneously in the poloidal direction towards the inner surface.

There, entering the region of the opposite sign of the poloidal field, a part of the plasma can flow out again into the main volume of the tokamak. The convective flux into the working volume on the inner surface can lead to removal of impurities from the limiter shadow.[50,51]

Properties of the plasma turn out to be dependent on the poloidal angle, and this asymmetry becomes larger with penetration into the shadow. Plasma has a spiral structure, and its density falls off slower on the outside surface and on the side of the toroidal drift of ions. With that asymmetry is related the phenomenon of nonambipolarity of radial flux, i.e., near the limiter edge it is reached by a larger number of electrons, and further from it—of ions. The heat flux to the side walls of a limiter is also strongly asymmetrical, what unavoidably must lead to its nonuniform heating in large tokamaks.

The above description gives only an approximate qualitative picture of the complicated mass and thermal exchange processes taking place near the walls of tokamaks, particularly when the multitude of limiter configurations, used in different experimental installations, is taken into account. At the present time, an intense accumulation of experimental data is underway, and this picture is going to become more precise.

5. ELECTRIC ARC DISCHARGES

Concluding the review of physical processes taking place near the tokamak walls, we must mention one more phenomenon. At the end of the 50's it was discovered that the metal walls of installations for thermonuclear research have characteristic traces, similar to those left by the cathode spots in vacuum arcs.[52] Also now, a large number of such arc traces are being found on limiters and the main walls of operating tokamaks and stellarators. Electric discharges which do not require external power supplies and in which the current flows to the surface of a single electrode, are called unipolar arcs.

Without a magnetic field, such arcs can exist due to the contact potential difference between the plasma and the wall.[53] In the absence of current, the contact potential difference for sufficiently hot plasma is larger than the potential drop in a cathode spot ($\sim$ 15–20 V). During arc operation, electron emission reduces that difference in the area of the spot, and the electron current from the plasma exceeds the ion current, completing the circuit for the electric current.

In a magnetic field, the radial current which completes the circuit between the voltage source and the spot playing the role of a load, is possible only in the limited area near the spot where, because of the high vapor density of the wall material, the electrons are weakly magnetized. For that reason, the unipolar arcs must form "columns" of reduced potential, elongated along the field, based on the cathode spots. According to the estimates of Ref. 54 the radius of these "columns" is several millimeters.

Since cold electrons leave the surface, and the same number of hot electrons reaches the surface, the unipolar arcs increase (by more than an order of magnitude) the coefficient of thermal conductivity γ in expression (1). This method of lowering T_w by a strong recycling of electrons is not acceptable, however, for thermonuclear fusion installations because of arc erosion, which exceeds the usual cathode sputtering.

Although arc discharges caused by the contact potential are possible, in tokamaks they are caused by electromagnetic induction accompanying the magnetohydrodynamic activity of the plasma.[55] In quiet discharges one can observe arcs at the initial and the final stages. In unstable discharges, arcs are correlated with an increase of spiral perturbations of plasma, and there appear on the sides of limiters short voltage pulses of hundreds of volts, and the arc current changes from amperes to kiloamperes. In strongly unstable discharges, the total arc current reaches 5–7% of the total discharge current. If a limiter is isolated from the chamber, the direction of current between its sides coincides with the direction of the main current, and the traces of the spots remain predominantly on the side oriented towards ions of the main current.[54]

In reactors with cold near-wall plasma, the unipolar arcs should not be dangerous. But in unstable discharges they will become the main mechanism of interaction between the plasma and the walls and the source of impurities.

CONCLUSION

The plasma-wall interactions have become, and will remain for a long time, one of the main areas of research in the physics and technology of controlled thermonuclear fusion. This area has prominent physical effects which change the characteristics of processes by an order of magnitude and require detailed studies. Some of them, for example, strong regular vibrations in the near-wall plasma, which are natural for such a nonlinear system, are not mentioned in this article.[15,56] The conditions in the peripheral region largely determine also the processes in the main plasma. In the vivid expression of B. B. Kadomtsev, the peripheral plasma is just as essential for the high-temperature central area of a tokamak as skin is to an animal.

As the physics of the near-wall plasma is becoming better understood, we also begin to understand better how to solve the technical problems. The main features of such solutions are already visible today, although "the distant image of the free novel I could not yet clearly discern through the magic crystal."

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