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Sheath over a finely structured divertor plate

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Abstract

The surface of a divertor plate typically has fine structure. Depending on the material and the duration of exposure to the plasma, the characteristic size of the surface imperfections may vary over a broad range. In this paper, we consider the case where these structures have a scale height h that is greater than the electron gyroradius ρ_e. The magnetic field intersects the divertor plate at a shallow angle $\alpha \ll 1$. The present paper demonstrates that the combination of these two factors, fine surface structures and strongly tilted magnetic field, gives rise to many interesting new phenomena in the sheath. It is shown that the fraction of the surface 'wetted' by the plasma electrons is much less than that 'wetted' by the plasma ions. It is noted that, for $\alpha \ll 1$, secondary electron emission for a rough surface may be considerably larger than for a flat surface. A description of a dedicated experiment for the study of plasma interaction with structured surfaces in a tilted magnetic field is presented.

Keywords: Secondary electron; Sheath; Surface roughness

1. Introduction

The surface of a divertor plate typically has fine structure. Depending on the material and the duration of exposure to the plasma, the characteristic size of the surface imperfections may vary over a broad range. In this paper, we consider the case where these structures have a scale height h that is much smaller than the ion gyroradius ρ_i but greater than the electron gyroradius ρ_e:

$$\rho_e < h < \rho_i. \quad (1)$$

The magnetic field intersects the divertor plate at a shallow angle $\alpha \ll 1$. The present paper demonstrates that the combination of these two factors, fine surface structures and strongly tilted magnetic field, gives rise to many interesting new phenomena in the sheath (the case of smooth waviness of the surface was considered in Ref. [1]; the case of a rough surface with the features with sizes comparable with the ion gyroradius or greater was considered in Ref. [2]). We consider only the plasma part of the problem: given the presence of some structure, what are the consequences in terms of the plasma properties in the vicinity of the surface? We are not addressing the issue of what process has caused the appearance of the structure. However, once the plasma part of the problem is solved, one could return to the analysis of the wall erosion problem, based on the solution obtained. The analysis of the sputtering process for a finely structured surface was performed in Ref. [3].

For the environment of the divertor region of a medium-size tokamak (plasma density $n \sim 4 \times 10^{13}$ cm^{-3}, plasma temperature $T \sim 50$ eV, the magnetic field strength $B \sim 2$ T), one has: $\rho_i \sim 500$ μm (hydrogen), $\rho_e \sim 10$ μm. We, therefore, are going to analyze the scales of imperfections in the range 10 μm $< h <$ 500 μm. These scales are quite typical for a number of fusion devices [4]. For comparison, one can mention that the Debye radius ρ_D is $\sim$10 μm.

We will use the following model of the surface: we assume that it is formed by the randomly distributed cones of height h, with base radius and the distance between neighboring cones both also of order h (Fig. 1). This latter assumption means that the number of cones

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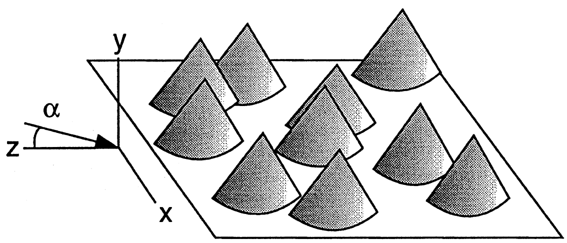

Fig. 1. A rough surface made of randomly distributed cones of the same height h. The arrow shows the direction of the magnetic field; in the divertor geometry, the axis x corresponds to the radial, the axis y to the poloidal, and the axis z to the toroidal directions.

per unit surface area is $\sim 1/h^2$. With minor modifications, the analysis can be extended to bumps with smooth tops (an example of such an analysis for $h > \rho_i$ can be found in Ref. [2]). The approach used in this paper is based on scaling arguments and order-of-magnitude estimates. Despite its simplicity, it allows one to obtain basic scaling relations and reveal some interesting phenomena.

After presenting a theoretical analysis of the plasma interaction with a finely structured surface, we present a brief description of a small-scale dedicated device for experimental studies of this problem.

2. Ion absorption

We will discuss the problem in two steps: first assume that the electric field does not have a significant effect on the particle motion, and then consider possible complications.

We first consider the case of very small hs, when the magnetic field does not directly affect the ion trajectories at a distance $\sim h$ from the wall. Even in this case, however, the presence of the magnetic field is important in that it causes the ions to approach the wall at a very shallow angle $\sim \alpha^{1/2}$ (we are talking of a 'typical' ion, with a pitch-angle ~ 1). This is so because the ion approaching the wall along a strongly tilted magnetic field, when making one full gyrocircle, moves closer to the wall by only a small distance $\sim \alpha\rho_i$. The ion velocity components near the wall are: $v_x \sim v_z \sim v_{Ti}$, $v_y \sim v_{Ti}\alpha^{1/2}$ (see Fig. 1 for the definition of the coordinate axes). The details of the corresponding analysis and the full ion distribution function near the wall can be found in Ref. [5]. The projection of a typical ion trajectory on the divertor plate forms an angle $\sim 45°$ with the projection of the magnetic field.

So, we consider a stream of ions with a density n moving with a velocity v along straight trajectories forming some small angle β with the plane. The problem is: how far below the level of the mountain tops will the ions penetrate? This is a problem similar to the problem of a mountain range during sunrise: what fraction of the mountain land is illuminated? Let us denote by Δh the corresponding distance from the mountain tops (here and below we mean by Δh a characteristic, statistically averaged quantity). The surface area of the illuminated mountain top is $\sim \Delta h^2$. Each mountain top collects $nv\Delta h^2$ ions per unit time. As the number of the mountain tops per unit area of the mountain land is $\sim 1/h^2$, the number of ions absorbed by the unit area of the plate per unit time is $\sim nv\Delta h^2/h^2$. On the other hand the number of the ions intersecting a unit surface element parallel to the plate at some distance from the plate is βnv. Equating the two expressions, we obtain

$$\Delta h \sim \beta^{1/2} h \,. \tag{2}$$

As we have mentioned above, in the problem under consideration $\beta \sim \alpha^{1/2}$. Therefore,

$$\Delta h \sim \alpha^{1/4} h \,. \tag{3}$$

Accordingly, the fraction ε_i of the surface wetted by the ions is

$$\varepsilon_i \sim \alpha^{1/2} \,. \tag{4}$$

Illuminated are southeast or northeast sides of the 'mountains' (where field lines from the plasma in the sunrise analogy are assumed to intersect the east side), depending on whether the magnetic field is directed towards or away from the plate. Note, Eq. (4) remains formally valid even for infinitesimally small bumps (the constraints will be discussed in Section 3).

Eq. (3) is valid so long as the height Δh is smaller than the distance $\alpha\rho_i$ by which the ion gyrocircle 'descends' to the wall during one gyroperiod (if Δh becomes formally larger, the ion motion at the scales of interest begins to be affected by the magnetic field). Therefore, the applicability condition for Eqs. (3) and (4) reads:

$$h < \rho_i \alpha^{3/4} \,. \tag{5}$$

When it breaks down, the following approach [2] can be used. From the kinematics of the gyromotion, it is clear that the characteristic vertical velocity of the ions whose gyrocenters have lowered by a distance Δh since the moment when the gyrocircle has just touched the mountain tops (Fig. 2), is $v_{Ti}\ (\Delta h/\rho_i)^{1/2}$. The other two velocity components are of the order of v_{Ti}. The phase-space density of ions moving in a magnetic field is constant and, therefore, their volume density is proportional to the volume occupied in the velocity space. At distances exceeding $\rho_i + h$ from the wall, this volume is $\sim v_{Ti}^3$, whereas in the layer of thickness Δh containing the mountain tops it is $\sim (\Delta h/\rho_i)^{1/2} v_{Ti}^3$. Accordingly, in the layer of thickness Δh, their density is $\sim n(\Delta h/\rho_i)^{1/2}$ (where n is now ion density in the bulk plasma). The number of ions absorbed by one mountain top per unit

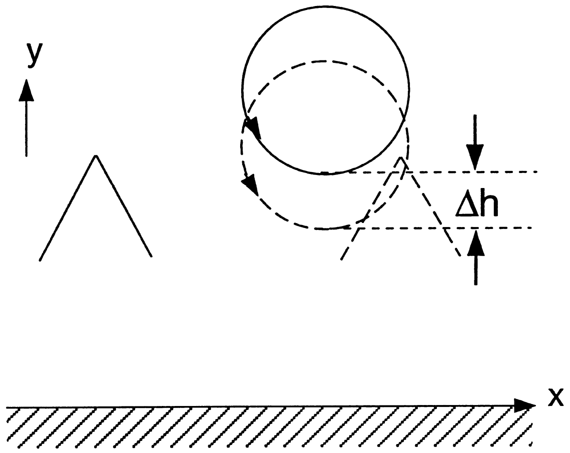

Fig. 2. The ion gyrocircle viewed in the direction of the magnetic field; the solid lines correspond to the instant when the lowest part of the circle is at the level of the mountain tops; the dashed lines correspond to some instant later in time, when the scraping-off of the ions begins.

time is $\sim n\Delta h^2(\Delta h/\rho_i)^{1/2}v_{Ti}$, and the number of ions absorbed per unit area of the divertor plate per unit time is $\sim n(\Delta h/h)^2(\Delta h/\rho_i)^{1/2}v_{Ti}$. On the other hand, the flux of ions approaching the divertor plate from the plasma is $\alpha n v_{Ti}$ (per unit surface). Equating the two quantities, one finds that

$$\Delta h/h \sim \alpha^{2/5}(\rho_i/h)^{1/5} . \tag{6}$$

The fraction of the surface wetted by the ions is

$$\varepsilon_i \sim \left(\frac{\Delta h}{h}\right)^2 \sim \alpha^{4/5}\left(\frac{\rho_i}{h}\right)^{2/5}. \tag{7}$$

The transition between Eqs. (3) and (6) [and Eqs. (4) and (7)] occurs at the point where inequality Eq. (5) becomes an equality.

Eqs. (6) and (7) remain valid so long as the illuminated height Δh remains smaller than ρ_i. This is so at

$$h < \rho_i/\alpha^{1/2}, \tag{8}$$

i.e., even at heights exceeding the ion gyroradius (the result was derived in [2] under the stated assumption that $\rho_i < h$). At even greater heights, when this inequality breaks down, the ion gyrocircles become small compared with the size of the illuminated mountain top, and the description of the gyrocircles as point particles moving strictly along the magnetic field becomes possible. This latter case was studied in detail in Ref. [2]. It corresponds to the case considered at the beginning of this section, but with $\beta = \alpha$. Accordingly, the fraction of the wetted surface was found to be

$$\varepsilon_i \sim \alpha . \tag{9}$$

3. Electron absorption and electric field effects

At equal electron and ion temperatures, the electron gyroradii are much smaller than the ion gyroradii. Therefore, in a number of cases of practical interest the electron absorption corresponds to the regime of an infinitesimal gyrocircle defined by inequality

$$h > \rho_e/\alpha^{1/2} . \tag{10}$$

In this regime, the fraction of the surface accessible to the electrons is determined by Eq. (9). In some cases, the regime defined by the inequality opposite to Eq. (10) may be realized. In such a regime the fraction of the surface accessible for electrons is determined from the estimate Eq. (7), but with ρ_i replaced by ρ_e . The division of the parameter space by these inequalities is shown in Fig. 3. Expressions for the fraction of the wetted surface are presented in the Table 1.

We have so far been ignoring the presence of the electric fields and the quasineutrality constraint. The first effect of this constraint is that the bulk plasma must be charged positively with respect to the wall, to provide equal electron and ion currents (for definiteness, we consider the situation where there is no current to the wall). The corresponding potential is of the order of (3–5)T/e. For

$$\alpha > \sqrt{m_e/m_i} , \tag{11}$$

a considerable fraction of this potential drop occurs within the Debye sheath immediately adjacent to the wall, whereas the rest of the drop occurs in a smooth fashion at distances of the order of the ion gyroradius (see, e.g., [5]). We will assume that inequality Eq. (11) is satisfied.

The second effect of the quasineutrality constraint is that, as we see from Table 1 and Fig. 3, in most regimes, if potentials are neglected, ions penetrate deeper beneath the mountain tops than the electrons (which are much more tightly tied to the magnetic field lines). Hence we

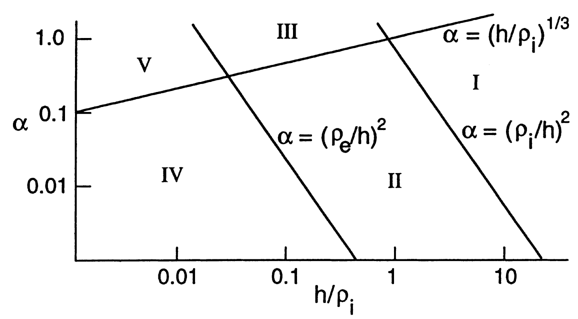

Fig. 3. The parameter domain of the problem. The lines correspond to deuterium. The line $\alpha = (h/\rho_e)^{4/3}$ is not shown because it does not fit the scale.

Table 1
Summary of wetted area vs. regime

Domain	Fraction of surface wetted by	
	Ions	Electrons
I	α	α
II	$\alpha^{4/5}(\rho_i/h)^{2/5}$	α
III	$\alpha^{1/2}$	α
IV	$\alpha^{4/5}(\rho_i/h)^{2/5}$	$\alpha^{4/5}(\rho_e/h)^{2/5}$
V	$\alpha^{1/2}$	$\alpha^{4/5}(\rho_e/h)^{2/5}$

see the second effect of the quasineutrality constraint: potentials must form to prevent ions from entering the spatial domain inaccessible for electrons in the shadows of the mountain tops. Therefore, with the quasineutrality constraint imposed, the area wetted by the ions will become equal to the area wetted by the electrons.

The transitional zone (that repels the ions) has a positive potential with respect to the walls. Therefore, if even a weak source of ionization acts on the corresponding field lines, the cold electrons produced there will be trapped electrostatically (whereas the cold ions will be expelled to the walls). The neutral atoms may arise as a result of surface recombination of the impinging ions. The ionization of neutral particles will gradually allow the plasma ions to penetrate deeper and deeper into the zone initially inaccessible for them (a manifestation of the Simon short-circuit effect [6]) and, eventually, will restore the situation where the ions will be 'wetting' a considerably greater surface than the electrons. It is interesting to note that, while the electrons 'illuminate' the surface from the 'east', the ions hit the cones from 'southeast' or 'northeast'. This may cause the appearance of a characteristic pattern of evolution of the surface relief.

The electric field present in the ion sub-sheath may also cause some changes of the overall picture in the case of non-uniformities which are smaller than the ion gyroradius. As was shown in [5], some ions (predominantly those with a small energy) may be accelerated to the walls from the middle of the ion sub-sheath, and approach the wall at an angle ~ 1. They will be wetting the surface almost uniformly. However, as was shown in [5], the majority of the thermal ions will still approach the wall in the same qualitative way as at no electric field at all. They will be wetting a small fraction of the surface determined by Eq. (4) or Eq. (7).

When surface non-uniformities become smaller than the Debye radius, the ions entering the Debye sheath experience a strong acceleration in the normal direction to the wall and, because of this, approach the wall at an angle ~ 1. This restores uniform wetting of the surface by the ions and sets the applicability limit for the estimate Eq. (4). It is interesting to note that the plasma electrons in the case of the non-uniformities with $h \ll \rho_e$ still reach the wall only near the mountain tops, and the fraction of the area wetted by the electrons follows Eq. (4) even for the infinitesimally small cones.

4. Secondary electron emission

It is well known that the secondary emission coefficient for a flat surface in a strongly tilted magnetic field may become much smaller than for a magnetic field intersecting the wall at an angle ~ 1 (see, e.g., Ref. [7] and references therein). Consider as an example a problem where the electron gyroradius is considerably smaller than the Debye radius and one can, therefore, neglect the effects of a normal electric field in the immediate vicinity of the surface. Then, the majority of the secondary electrons emitted from the wall will return to the wall because of their gyromotion. Only those secondary electrons whose velocity is directed almost parallel to the magnetic field will reach the bulk plasma. An estimate of the secondary emission coefficient S reads in this case

$$S \sim \alpha^{1/2} S_0 \, , \qquad (12)$$

(where S_0 is a secondary emission coefficient in the absence of the magnetic field, and the exact numerical factor depends on the angular distribution of the secondary electrons). In the case of a very strong magnetic field, where the electrons are strictly attached to field lines, transition to a rough surface would bring S close to S_0, because the magnetic field intersects the surface of the cones at an angle ~ 1. At weaker magnetic fields, S will tend to be smaller, because the surface wetted by relatively fast plasma electrons [satisfying condition Eq. (8)] would extend to a considerable distance beneath the mountain tips; hence the cold secondary electrons, which follow the field lines, will most often hit other mountain tops on their way from the surface.

5. The Bluebell device

We are constructing a small experimental facility, 'Bluebell', to explore the effects of surface roughness discussed here, as well as the larger-lateral-scale waviness discussed in Ref. [1]. The experiment uses a helicon plasma source [8] to create an argon plasma flow with ion kinetic energies in the range of a few eV. The plasma density is in the range of 2×10^{12} cm^{-3}, the axial magnetic field is in the range 100–200 G (in the zone of a free plasma stream outside the source region). The length of the free-flow zone is 50 cm, the diameter of the vacuum chamber is 30 cm. A $\sim$15 cm long metal cone (whence the name of the device) with its axis parallel to the magnetic field and a small angle at the apex (between 5 and 10°) will be installed in the plasma stream. The axial symmetry of this surface creates a well-defined initial state; installing bumps of various size, dielectric impregnations, and other structures, one will be able to compare the resulting potential distribution in the incoming plasma flow with a reference case and thereby evaluate the effect of the surface non-uniformities. Provisions will be made for electric biasing of the elements of the surface. An alternative method of creating the required geometry is using a funnel-shaped magnetic field structure, with a metal cylinder (with the axis coinciding with the magnetic axis) installed in it. Again, an axisymmetric surface forming a small angle with the magnetic field will be created. The test elements will be installed on this surface. The cone (or the cylinder) will have translational (along the axis) and rotational (around the axis) degrees of freedom, allowing one to move the structured elements of the surface relative to the fixed arrays of Langmuir probes.

A special set of experiments directed towards studying the 'shadowing' effect will be performed. Obstacles placed in the path of the flowing plasma would create shadows. If the size of the obstacles is much greater than the electron gyro-radius but much smaller than the ion gyro-radius, an electrostatic barrier will be formed near the surface of the shadowed flux-tube, preventing the ions from entering into the shadow (in the same way as it was discussed in Section 3). The plasma density and potential distribution near this surface will be measured, and possible plasma instabilities (causing anomalous penetration of the plasma into the shadows) will be studied. A first plasma has been obtained in the device and experiments directed towards its characterization are underway.

6. Summary and discussion

We have examined the plasma properties near a bumpy wall which is nearly tangent to the impinging magnetic field. We see that, for a wide range of feature heights, ranging from many ion gyroradii to of the order of the Debye length, only a small fraction of the surface is 'wetted' by the main plasma electrons and ions. When the scale height is not large compared to the ion gyroradius, the electron and ion wetted fractions are significantly different (though both small). This gives rise to potentials that lead to a filling in of the ion-rich region with cold neutralizing electrons from ionization of gas. After this filling in, the residual differences in electron and ion loss channels, as well as temperature variations between the illuminated and shadow plasmas, will leave potential variations of the order of the electron temperature on a cross-field scale of the order of the illuminated portion of the surface bumps, Δh. These potential structures should extend a considerable distance back into the impinging plasma.

Assuming that the heat is removed from the tips of the bumps by thermal conduction toward the body of the divertor plate (where cooling channels are situated at distance H below the nominal surface), one can relate the temperature difference ΔT^* between the tips and the bases of the bumps, and the temperature difference ΔT between the surface of the plate (if perfectly flat) and the cooling channels. One can show that for tightly packed conical summits with an apex angle $\sim 45°$, the following relationship holds in steady state:

$$\frac{\Delta T^*}{\Delta T} \sim \frac{h^2}{H \Delta h}.$$

For all realistic sets of parameters, the ratio $\Delta T^*/\Delta T$ is less than one. The temperature contrast is further reduced by radiation from the warmer tips. In a pulsed mode of operation the temperature contrast would increase, if the pulse duration were shorter than the thermal relaxation time.

We are constructing a small dedicated experimental facility, the 'Bluebell' device, to examine the phenomena discussed here as well as larger-lateral-scale surface waviness.

There are a number of consequences of the geometric relations and the shadowing that merit further exploration. One is secondary emission; as we noted above, a bumpy surface with scale height exceeding the electron gyroradius may not display the drop with angle of field-line incidence expected for a flat surface. Another question, which we plan to examine theoretically and in our experimental device, is whether a plasma boundary instability could also play a role in filling in the electron shadows.

There is also the challenge of closing the self-consistency loop to calculate the surface erosion. Certainly the restriction of the impinging plasma to the tips of the 'mountains' and the different wetted areas as well as different directions of approach of electrons and ions will have significant impact on the erosion process. On the other hand, it is worth emphasizing that a strong concentration of the heat and particle flux near the mountain tops does not necessarily mean a fast self-healing of the surface imperfections. It should be remembered that there are many other processes playing important role in establishing a steady state surface relief: (i) crack formation under the action of a cyclic heat load, with subsequent flaking; (ii) chemical sputtering that may favor lower temperatures than the temperatures of the 'mountain tops; (iii) cracking and blistering under the action of the absorbed neutral hydrogen; (iv) blistering and flaking under the action of the neutron flux in the fusion reactor conditions; (v) damage from disruption events. The enhanced sputtering of the tops of the bumps is just one more factor that affects the evolution of the surface relief.

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