Broadening of the Scrape-off-Layer by a Plasma Convection Induced by Toroidal Asymmetries of the Divertor Plates and the Gas-Puff+

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ABSTRACT

In the open field line region of the scrape-off layer (SOL), plasma potential is to a considerable degree determined by the boundary conditions on the divertor plates. By introducing toroidal asymmetries of the surface relief of the divertor plates or of their chemical composition, one can create toroidally asymmetric potential variations over the whole SOL and thereby induce convective plasma motion. This motion should lead to a broadening of the SOL and to reduction of heat load on the divertor plates. Convective motion can be induced also by a toroidally asymmetric gas-puff. In the present paper we consider all these techniques and evaluate the possible increase in the cross-field transport.

I. INTRODUCTION

The potential drop in the Debye sheath near the divertor plate is equal to $\Lambda T_e/e$, with T_e being electron temperature, e an electron charge, and Λ some logarithmic factor (Λ=2-4), weakly dependent on plasma parameters [1]. Potential variation along the field line in the bulk of the SOL is, typically, less than sheath potential. Therefore, the potential distribution in the bulk of the SOL plasma is controlled mainly by the sheath potential distribution over the divertor plate surface. For a toroidally symmetric system, the plasma potential is, obviously, toroidally symmetric, and the electric field inside the plasma is perpendicular to magnetic surfaces, causing only poloidal and toroidal drift which don't contribute to radial plasma transport. As was noted in paper [2], by making divertor plates "wavy" in the toroidal direction, one can produce considerable toroidal variation of the sheath potential and, thereby, induce convective motions with a large radial velocity component in the bulk of the SOL plasma.

Toroidal variation of the sheath potential can also be produced by varying the composition of the divertor plates in the toroidal direction, thereby creating toroidal variation of the secondary emission coefficient (which affects the sheath potential). Yet another approach, in a sense similar to the one just mentioned, is introduction of toroidally asymmetric gas-puff through slots in the divertor plates.

The present paper contains basic equations describing convective motion, discussion of the optimum amplitude and wave length of the perturbations , assessment of the effects caused by the presence of the X point, and comments concerning the possible (beneficial) role of instabilities set up by the convective flow pattern.

II. ESTIMATES OF CONVECTIVE TRANSPORT

Consider a piece of the poloidal (θ=const) cross-section of the SOL about half-way between the X-point and the upper point of plasma cross-section (Fig. 1a). In the unperturbed state, equipotentials almost coincide with magnetic flux surfaces (Fig.1,b).

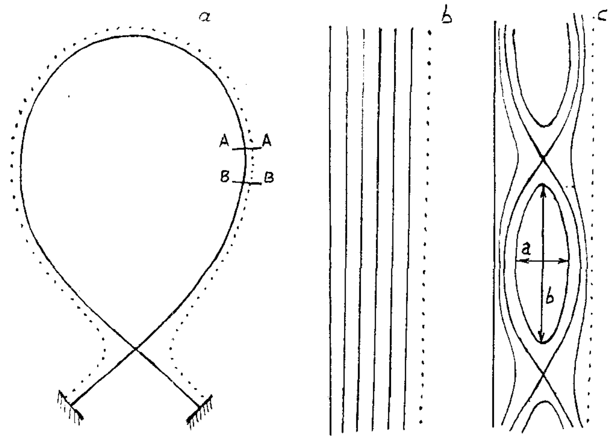

Fig.1 Basic geometry of the problem: (a) poloidal cross-section of the tokamak with a poloidal divertor; the solid line represents the separatrix, while the dotted line represents the outer side of the SOL; separated by lines A-A and B-B is the stretch of the SOL shown in (b) and (c); (b) blow-up of the stretch of the SOL with equipotentials coinciding with magnetic surfaces; (c) the same, with a strongly perturbed potential distribution forming a sequence of convective cells.

Unless T_e is almost uniform across the SOL, the radial potential variation is of order T_e/e. What we want to accomplish is to change equipotentials in such a way that the familiar structure of convection cells (Fig. 1c) appear. Electric drift trajectories lie within the surfaces φ=const.Clearly, in order to distort the potential structure of Fig.1b in the way shown in Fig. 1c, on has to produce potential variations $\delta\varphi \geq T_e/e$. As is clear from Fig. 1c, we must allow for the possibility that the poloidal extent of the convection cells is much larger than the SOL thickness Δ. In what follows, we denote the smaller dimension of the convection cell by a (Fig.2b corresponds to a~Δ) and the greater dimenson by b. We call the ratio

$$E \equiv b/a \qquad (1)$$

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the *elongation* of the convection cell. For a convection cell with elliptic cross-section and semi-axes a/2 and b/2, the time required for one full drift revolution is roughly

$$\tau=(\pi/4)Ea^2B/c\delta\varphi \qquad (2)$$

where B is a magnetic field strength and $\delta\varphi$ is the amplitude of potential variation. For the structure shown in Fig.1c, this time is also the characteristic time for the convective transport to mix the plasma over the thickness of the SOL. Introducing a dimensionless parameter

$$\Psi\equiv e\delta\varphi/T_e \qquad (3)$$

which characterizes the amplitude of the potential perturbations, one can rewrite the estimate (2) in the form:

$$\tau=(\pi E/64\Psi)(\Delta^2/D_B) \qquad (4)$$

where $D_B=(1/16)cT_e/eB$ is the Bohm diffusion coefficient (evaluated with the electron temperature). The estimate (4) is made under the assumption that a~Δ.

The parameter E can't be made smaller than about 20 (see below) but Ψ can reach values ~1. Therefore, we conclude that, potentially, electrostatic convection in the SOL could provide a radial loss rate comparable with or even exceeding the Bohm loss rate.

The convection which we have just described is laminar (see, e.g., [3]). It tends to make the temperature uniform inside every convection cell. Any additional small transport process then smooths discontinuities that appear in thin layers near the separatrices and allows efficient transport over many cell widths.

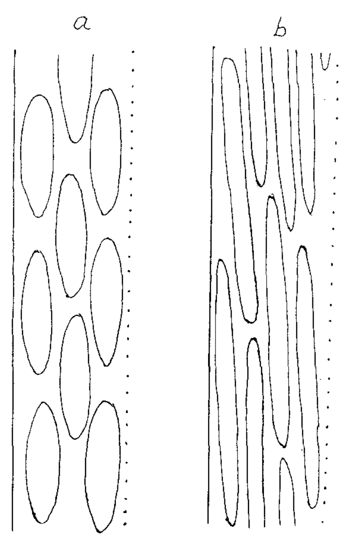

Fig.2 Convection pattern in the SOL for potential perturbations having a small radial extent a<Δ (a). Stretching of equipotentials by the shear effect (b).

For potential perturbations with a radial extent a considerably smaller than the SOL thickness Δ, the regular drift surfaces of Fig. 1b get replaced by convective structures of the type shown in Fig.2a if the potential perturbations satisfy condition

$$\delta\varphi>a(\partial\varphi_0/\partial r) \qquad (5)$$

where φ_0 is the unperturbed potential distribution, with equipotentials of the type shown in Fig. 1a. For $\varphi_0 \sim \Lambda T_e/e$ convection sets in at

$$\Psi>(a/\Delta)\Lambda \qquad (6)$$

If condition (6) is satisfied, then the plasma experiences a random walk with a characteristic radial step ~a and a characteristic time step (2). This estimate assumes that there is another transport process which can carry particles and/or heat across the boundary between convection cells in a time short compared to the cell convection time. Such transport can be provided by the turbulence which naturally exists in the SOL, perhaps by Kelvin-Helmholtz turbulence spawned by the convection pattern, and probably even by collisional diffusion. The total diffusion time across the SOL is still given by estimate (4) (though now it consists of a number of random steps).

III. EFFECT OF MAGNETIC SHEAR ON THE POTENTIAL DISTRIBUTION

Assume that potential variation in the poloidal cross-section near the divertor plate has the form shown in Fig. 2a. When projected along the field-lines to the tokamak median plane this distribution will experience strong stretching in the poloidal direction because of a very strong shear existing near the X-point (this effect, in the context of SOL physics, was pointed out in Ref. [3] where a simple linear model of the magnetic field was assumed; the study of the mapping properties of flux-tubes in general case was carried out in Ref. [4]). We will characterize the stretching by the parameter S which is defined by relationship

$$S\equiv\delta\ell/\delta r \qquad (7)$$

where δr is radial distance between two neighboring field lines on the divertor plate while $\delta\ell$ is the poloidal distance between the same lines at the point where we are making evaluations of the cross-field transport. For a typical divertor configuration S lies in the range of 20-30. Stretching converts a configuration of the type shown in Fig. 2a into a different one, shown in Fig. 2b. As the mapping of the flux tube does not change the area of the flux-tube cross section [3,4], the product ab, which determines the time of one full cycle of convective motion, remains the same as on the divertor plate. However, the "thickness" of the convection cell may become too small, approaching the ion gyroradius ρ_i. As soon as this happens, the potential perturbations get smeared out and the desired effect of enhanced convective transport disappears.

In order to avoid such a situation, one should keep the toroidal scale-length of the potential variations large enough. The "thickness" a of the convective cell in the bulk of the SOL (far above the X-point) can be expressed in terms of its thickness a_d and (poloidal) length b_d at the divertor plate as:

$$a=b_d/(b_d+Sa_d) \quad (8)$$

If one wishes that the "thickness" a should remain more or less the same as on the divertor plate, one shoud produce a strongly elongated potential perturbation. This is why we indicated, following Eq. (4), that *E* should be no smaller than about 20.

Assuming $a=\Delta/3$, $E=20$ and taking $\Delta=2$cm, we find that characteristic poloidal extent of the perturbations should be ~15 cm. Assuming that the poloidal magnetic field is equal to 0.1 of the total field, we find that the toroidal length of the non-uniformities on the divertor plates should be approximately 150 cm.

As was pointed out in Refs.[3,4], the strongest stretching of the flux-tube cross-section occurs near the X-point. This provides an interesting option for suppressing the turbulent transport beyond the X-point while maintaining it in the divertor legs. Indeed, if one chooses parameters of the potential perturbations on the divertor plate in such a way that the stretching makes the width of convective cells above the X-point smaller than the ion gyroradius, then the potential structures above the X-point get smeared out and no convective motions occur there. But the length of the field-line between the vicinity of the X-point and the divertor plate can be made large enough for plasma to spread over a broad area on the divertor plate. Of course, the feasibility of this option for any particular experimental situation depends on the details of the divertor design.

Strong diffusion during the plasma flight from the X-point to the divertor plate may cause plasma penetration to the private flux region. Therefore, it is advisable in this case to create surface non-uniformities on the divertor plate in the private flux region, too.

If, on the contrary, the potential structures tend to maintain their identity all way around the tokamak, from one divertor plate to another, then one might choose to create the necessary surface perturbations on one divertor plate only: the plasma potential inside a flux tube is determined by the conditions on both plates and, if one is uniform, the potential variations will still follow the structure of perturbations on the other plate. By creating inhomogeneities on both divertor plates, one can achieve a situation when the structure of the convective cells will become highly irregular and time-dependent, because the mapping of a divertor plate to another divertor plate along the field lines is very sensitive to variations in the plasma current distribution.

IV. HOW TO CREATE REQUIRED POTENTIAL VARIATIONS

We begin this section by presenting the result of paper [2] on the amplitude of potential variations caused by the presence of wavyness of the divertor plate surface. As was shown in Ref. [2], when magnetic field lines intersect a divertor plate at a shallow angle, the presence of diamagnetic currents and electric drifts in the SOL make the sheath potential quite sensitive to the intersection angle. Using Eqs. (33) and (40) of paper [2] and making an assumption that the inequality (39) is marginal, we find that potential variations correspond to $\psi\approx 1/\Lambda$ (see Eq.(3) of the present paper for the definition of ψ). This means that, according to (6), the width a of the potential structures should be of the order of or smaller than $\Delta/3$. A possible surface structure of the divertor plate corresponding to this case is shown in Fig.3a.

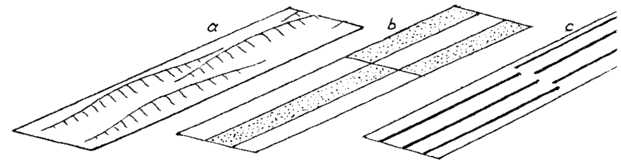

Fig.3 Three possible structures of divertor plates: a) surface "wavyness" in the form of "ridges" stretched along the toroidal direction; b) divertor plate assembled from tiles with different secondary emission coefficients; c) slots for controlled gas-puff. The scale in the toroidal direction is reduced.

The other way of effecting the sheath potential is to use materials with varying secondary emission coefficient σ. In practical terms, this can be done by assembling the divertor plate from tiles of two materials whose secondary emission coefficient is very different from each other (small for one and large for the other). One could distribute these tiles in a chess-board order, as shown in Fig. 3b. The plasma potential in the SOL would then acquire the shape shown in Fig. 2c, with very high potential gradients on the borders between neighboring regions and almost constant potential within each region.

For the case when the unperturbed current density on the divertor plates is a couple of times less than the ion saturation current, a relatively modest variation of the secondary emission coefficient from 0.2 to 0.7 would already cause a variation of the sheath potential corresponding to $\psi\approx 1$.

The presence of a large electric field in the boundary layers will cause very intense shear flows which should be hydrodynamically unstable. One can expect that the corresponding instabilities would then, by virtue of the turbulent viscosity, set also the inner parts of the cells into convective rotational motion.

A drawback of using tiles of two different materials is that, in the course of long experimental runs, the sputtering of the divertor plate surface could cause strong cross-contamination of the surfaces of the tiles and gradual disappearance of the necessary contrast in the secondary emission coefficient.

V. GAS-PUFF SCHEME

Assume that the divertor plate has slots in the toroidal direction distributed as shown in Fig. 3b. If plasma density is such that the gas gets ionized at a distance less than the radial distance between neighboring slots, then the plasma flow from the upper parts of the device meets with the gas clouds concentrated near the slots. Between the slots, plasma flow impinges on the bare surface of the divertor plate. If the divertor plate is made of a material with a low secondary emission coefficient, then additional ionization of gas in the regions near the slots would effectively create a varying secondary emission coefficient.

The main problem for this approach is the penetration distance of gas into the SOL plasma. This problem becomes relatively less significant if the divertor plates are situated close to the X-point (like in some experiments on DIID tokamak, [5]), because the SOL thickness is largest there.

VI. DISCUSSION

Gas puff is probably the most convenient scheme for present-day experimental devices as it provides flexibility in modifying experimental conditions without any need for mechanical changes in the divertor plates. On the other hand, the feasibility of this technique for devices of modest dimensions and plasma paramters is not yet clear: the relatively high ratio of neutral mean free path to SOL dimensions may prove to be insufficient to sustain considerable neutral density variation over the divertor plate. For reactors larger dimensions and higher plasma density and temperature should ameliorate the mean-free-path problem, but the compatibility of the gas distribution system with the overall design of the divertor plate may be an issue.

We think that the next in experimental convenience is the scheme with tiles of varying secondary emission coefficient. For devices with long experimental runs and for future reactors the problem of cross-contamination of the plates by the sputtered material may cause some problems.

The most robust and most insensitive to a hostile environment of a fusion reactor chamber is possibly the scheme based on using the "wavy" divertor plates.

Physics issues which should be addressed by further analyses include the interaction of the induced convection with (possibly) pre-existing plasma turbulence and with shear-flow turbulence produced by the convective motions themselves. Detailed calculations of interaction of gas injected through the slots in the divertor plates with the flow of incoming plasma are required to obtain reliable estimates of plasma potential variations.

An important issue is also possible "shielding" of any non-uniformities of the divertor plates by cold dense plasma whose presence near the divertor plates is envisaged in some designs. If this plasma is indeed present, it would be interesting to know whether one coud create nonuniformities in the transition region between cold and hot plasma and still induce convection in the hot plasma region.

An attractive feature of the scheme suggested in the present paper consists in that it induces a strong convection only on the open field lines, without causing an enhanced transport inside the separatrix. There exists even the possibility of limiting the enhanced transport to the region of the divertor legs, without producing any appreciable plasma perturbations in the SOL beyond the X-point. All in all, we believe that the possibility of inducing plasma convection in the SOL by relatively simple experimental techniques is an issue deserving some attention from theorists, experimentalists and design engineers.

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