Comparison of Plasma Turbulence in the Low- and High-Field Scrape-off Layer in T-10.

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Abstract. Experimental investigation of the scrape-off layer (SOL) turbulence and associated transport in high density regime in the T-10 tokamak is presented. Comparison of the plasma parameters measured at low- (LFS) and high-field side (HFS) of the tokamak shows that inboard turbulence essentially differs from outboard one. Turbulence has intermittent character but fluctuation level of the inboard ion saturation current is about two times lower than at the LFS. A radial turbulent particle flux and an effective perpendicular diffusion coefficient measured at the LFS are about 3-5 times higher than ones observed at the HFS. Enhanced perpendicular particle flux at the LFS is defined by the high density plasma structures formed in the vicinity of the last close flux surface (LCFS). A radial velocity of the plasma structures is directed towards the vacuum vessel both at the low-field side and at the high-field side. Analysis of experimental data allows us to conclude that enhanced plasma turbulence originates on the outboard part of the plasma and then plasma propagates to the inboard side. These experiments support the hypothesis that SOL parallel flow might be caused by an additional mechanism such as "ballooning" transport which generates a larger flux of particles from the core into the SOL at the outer mid-plane.

1. Introduction.

It was shown recently that enhanced convective radial transport could be responsible for the SOL widening in tokamaks [1]. There is much evidence to show that density profiles in the SOL are non-exponential and are often flat far away from the LCFS [2-4]. Possible mechanism that could result in additional perpendicular transport in the plasma periphery is intermittency in the plasma fluctuations [5-10]. Intermittent convective transport leads to an essential increase of particle and energy flux reaching the wall of the vacuum chamber.

Experiments performed on different tokamaks [11-14] have shown that SOL is asymmetrical. Fluctuation level of the plasma parameters at the LFS substantially exceeds the level measured at the inboard side. Therefore one can assume that instabilities responsible for enhanced turbulent transport are excite at the low-field side of the tokamak. In the paper [15] it was proposed that poloidal asymmetry of the perpendicular particle flux is able to lead to the high parallel flows due to parallel plasma pressure formation. A high velocity parallel flow was observed in different tokamaks – JET [16], C-Mod [17], JT-60U [18]. The mechanisms underlying of the parallel plasma flow generation play a significant role in transport physics understanding [19]. Plasma flows are a key element to understanding of plasma recycling, impurity transport in the scrape-off layer (SOL) and divertor heat load asymmetry. Several mechanisms have been proposed to explain experimental values of the parallel plasma velocity including ExB, Bx∇B, diamagnetic drifts, Pfirsch-Schluter flows, momentum transfer. However, an application of the 2D divertor codes like EDGE2D [20], UEDGE [21] and SOLPS5.0 [22] including these mechanisms does not allow the high parallel flows to be reproduced. The measured parallel flows essentially differ from those defined in simulations. Therefore, it could be suggested that other mechanisms must be included to explain the parallel flow generation. One of them considered as driving force of the parallel flow is ballooning transport associated with enhanced turbulent level at the low field side of the tokamak [15].

In this paper, experimental investigation of the plasma turbulence and anomalous perpendicular transport in high density regime (an average electron density $\bar{n}_e > 0.5 \cdot n_G$, where n_G is the Greenwald density limit) in the T-10 tokamak is presented. Main aim of the experiments is a comparison of the plasma turbulence properties and perpendicular particle fluxes measured at low- and high-field sides of the plasma.

2. Experimental set-up, plasma parameters and diagnostics.

Experiments were performed on the T-10 tokamak (major radius R_0=1.5 m) which is equipped by a graphite rail limiter inserted in the vacuum chamber through the bottom port of the tokamak. For the experiments described below the minor plasma radius a_L determined by the rail limiter was 0.30 m. The experiments were performed in deuterium plasma. The average electron density $\bar{n}_e$ measured along a central chord was $6 \cdot 10^{19}$ m^{-3}, the toroidal magnetic field induction B_t = 2.4 T, the plasma current I_p = 0.3 MA.

Measurements of the SOL parameters were performed using two movable probe systems. Both systems consists of several tips (length 0.25 cm, diameter 0.1 cm) distributed in the poloidal direction. The poloidal distance between the tips is 0.3 cm. Probe tips can be combined in different measuring schemes for measurement of various plasma parameters. These probe systems were applied for measurements of the ion saturation current I_s, the floating potential U_{fl}, the electron temperature T_e using the triple probe scheme and the fluctuation of the ion saturation current and the poloidal electric field for calculation of the radial particle flux. Time resolution of the data acquisition system is 2 μs. Diagnostic systems are located in the same poloidal cross-section at the inboard and outboard sides of the tokamak about 30^0 below the mid-plane.

3. Experimental results.

Previous results [10] have shown an essential increase of the perpendicular anomalous particle flux in the low-field scrape-off layer in T-10 with an average plasma density rise. Langmuir probe measurements of SOL plasma parameters indicate that intermittent events can play a significant role in the cross-field transport. Intermittent behavior of the plasma parameters is associated with formation and propagation of the plasma structures with high density. The structures move in radial and poloidal directions. Radial movement is predominantly directed to the vacuum vessel wall in the SOL. Value of radial velocity of the high density plasma structures reaches 1000 m/s nearby of the last closed flux surface. Radial size of the structures is in a range of 0.5-3 cm. Poloidal velocity can exceed 2500 m/s and is directed towards an ion diamagnetic velocity; poloidal size of the plasma structures is 2-3 cm. Observed plasma structures can be responsible for more than 50 % of the total radial turbulent particle flux at the low field side.

Fig.1 shows time evolution of the ion saturation current for both LFS and HFS of the T-10 tokamak. As it can be seen from the figure amplitude of the positive bursts exceeds essentially the amplitude of the negative fluctuations. Positive fluctuations we associate with the high density plasma structures. However, the positive fluctuation level at the LFS is substantially higher that the HFS level. Radial profiles of relative level of the fluctuations $I_s^{rms} / \bar{I}_s$ (I_s^{rms} is the root-mean-square, $\bar{I}_s$ is the time average ion saturation current) are presented in fig.2. Δr is a distance from the LCFS (Δr=r-a_L). The profiles measured at both

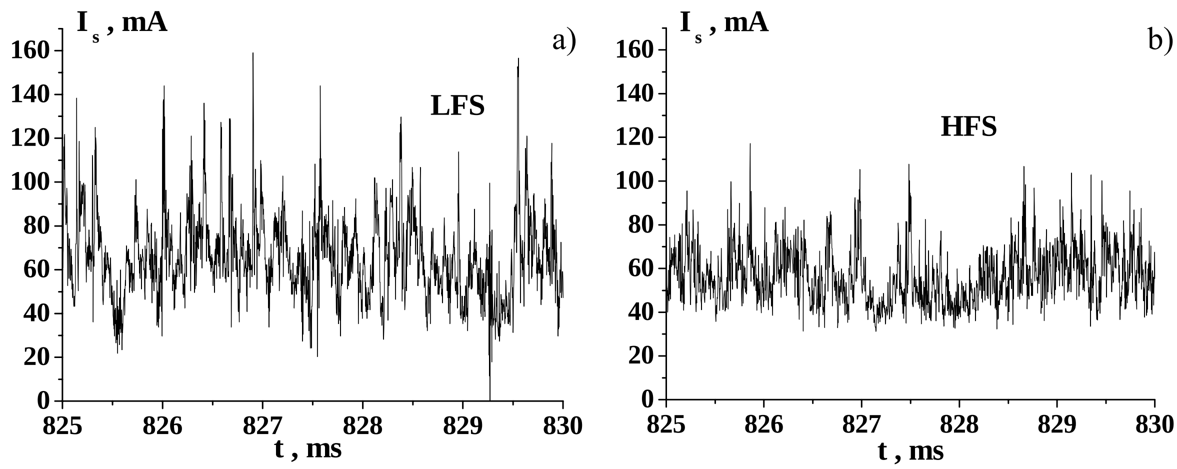

FIG. 1. Time evolution of the ion suturation current for inboard (a) and ouboard (b) parts of the plasma.

sides of the plasma are identical but the fluctuation level at the LFS is about 2 times higher than at the HFS. Moreover, the fluctuation level on the outboard part decreases sharply at the LCFS, the HFS level of the fluctuations begins to reduce at the distance of about 4 cm from LCFS. That is the profiles are shifted relatively one another by 4 cm.

High level of the fluctuations observed at the LFS leads to an increase of the perpendicular particle flux. Comparison of radial distributions of the total radial turbulent particle flux $\Gamma_\perp$ and effective perpendicular diffusion coefficient D_{eff} for inboard and outboard parts of the tokamak is shown in fig.3. Measurements of the turbulent flux were performed using of the triple probe methods. One probe tip was used for ion saturation current measurements, two other neighbouring tips were under floating potential and served for definition of the poloidal electric field E_θ. The perpendicular particle flow $\Gamma_\perp$ was calculated by using of the standard procedure [23]:

$$\Gamma_\perp = \langle n v_r \rangle = \gamma_{n.\Phi}(0)\tilde{n}\tilde{v}_r \qquad (1)$$

where $\tilde{n}$ и $\tilde{v}_r$ are the root-mean-square values of density and radial velocity, $\gamma_{n,\Phi}(0)$ is a coefficient of the cross correlation between fluctuations of the ion saturation current I_s and the floating potential Φ. Since the amplitude of the electron temperature fluctuations is less

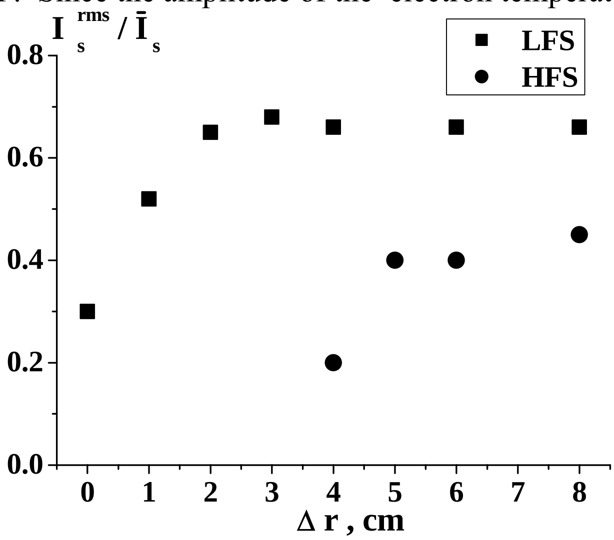

FIG. 2. Comparison of the relative fluctuation level of the ion saturation current.

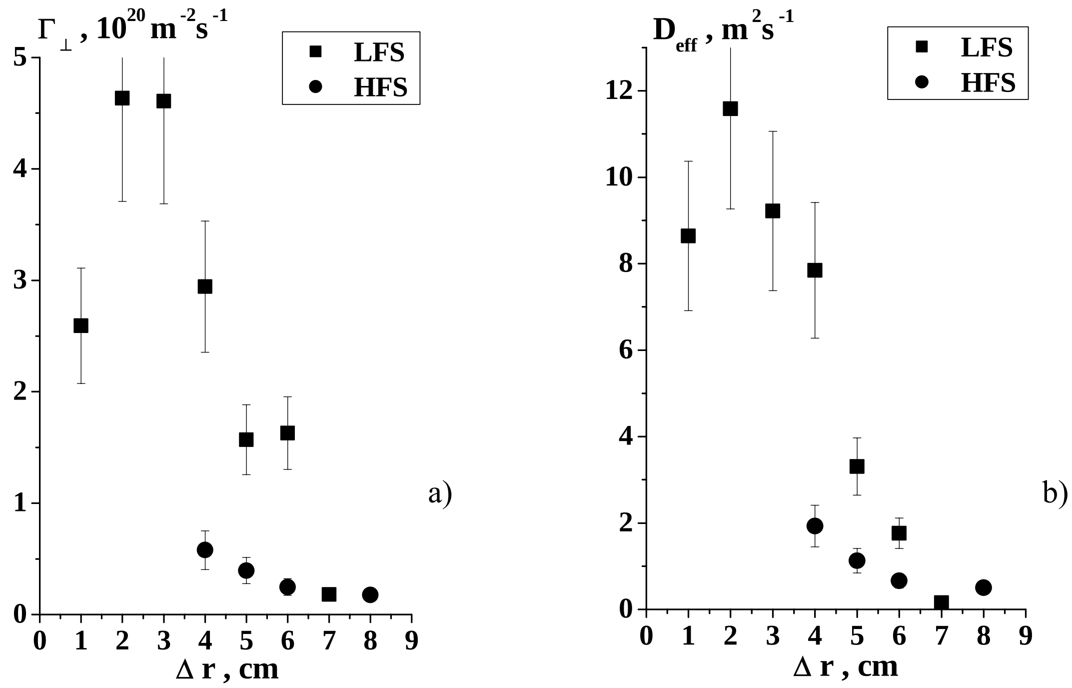

Fig. 3. Radial profiles of the perpendicular turbulent particle flux (a) and the effective diffusion coefficient.

than the amplitude of the ion saturation current fluctuations [10], fluctuations of T_e is neglected. The radial velocity is determined as $V_r = E_\theta/cB_t$. An effective diffusion coefficient D_{eff} was obtained as $D_{eff} = \Gamma_\perp/\nabla n$. As it is obviously seen from the figures the radial particle flux and diffusion coefficient at the LFS is about 3-5 times higher than analogous parameters measured at the HFS. An essential difference between perpendicular particle fluxes observed at both sides of the plasma could result in parallel plasma gradient formation and generation of the parallel plasma flow.

Using measurements of the poloidal electric field it is possible to estimate radial velocity of the plasma structures V_r and their radial size δr (Fig.4). The radial size was evaluated as $\delta r = V_r dt$ where dt is average duration of the poloidal field spike. The value of the radial velocity V_r is about 1000 m/s at the maximum and it reduces with radius at the LFS. The V_r decreases up to 200 m/s near the wall. The radial size of plasma structures also has a maximum at $\Delta r=+1$ cm and is equal to about 3 cm. The structure size is approximately 0.5 cm at the wall of vacuum chamber. Measurements of the V_r and δr at the HFS were performed in far scrap-off layer only. Velocity and size of the plasma structures in this part of the SOL are comparable with ones typical for the outboard side.

The time dependencies of the radial particle flow Γ_r calculated by using the plasma density n and the poloidal electric field E_θ (Γ_r=c/B nE_θ) are shown in figure 5 (the flux Γ_r is obtained according to equation 1, but without averaging). The bursts of the positive amplitude (positive amplitude means that the flux is directed to the wall) prevail on the dependencies. Analysing the adduced dependencies we can conclude that the plasma structures movement is directed from the LCFS to the wall at both inboard and outboard sides. Direction of the measured poloidal electric field in the plasma structures at the LFS coincides with direction of the electric field defined by charge separation due to gradient and centrifugal drifts. Similar charge separation is considered as a possible mechanism leading to the radial propagation of the plasma blobs [24]. However, the poloidal electric field changes direction at the HFS and consequently radial electric drift is towards the inner part of the wall.

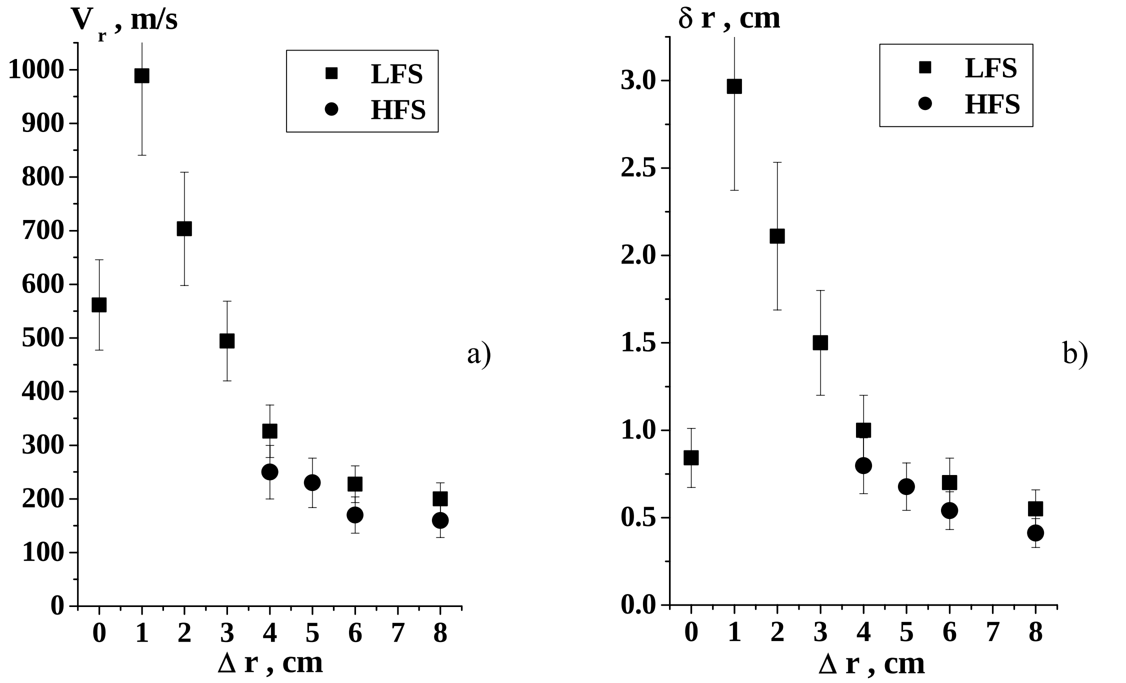

FIG. 4. Radial profiles of the radial velocity (a) and radial size (b) of the high density plasma structures.

Investigation of statistical properties of the turbulent fluctuations is often associated with a determination of probability distribution function (PDF) [25,26]. PDF of normal distribution is Gaussian. However, there are numerous experimental results [8,25,27] which show that PDFs of fluctuations measured in the SOL and edge plasmas of different type devices are non-Gaussian, i.e. the fluctuations are not randomly distributed in space and time. This suggests the existence of coherent structures formed in the plasma periphery. The deviation from Gauss distribution is quantified by definition of the third and fourth order central moments of the distribution. The normalised third and fourth order moments are often called the skewness S and flatness K factors respectively. The skewness is equal to zero and the flatness is equal to 3 for Gaussian distribution. Figure 6 shows the radial dependencies of the skewness of the radial particle flux Γ_r. The PDF of the Γ_r is positively skewed in the SOL. It means there are more positive bursts in Γ_r signal than negative ones. However a strong radial dependence of S is observed. The values of the third order moments verge towards zero at the LFS as LCFS is approached. At the high-field side, the skewness

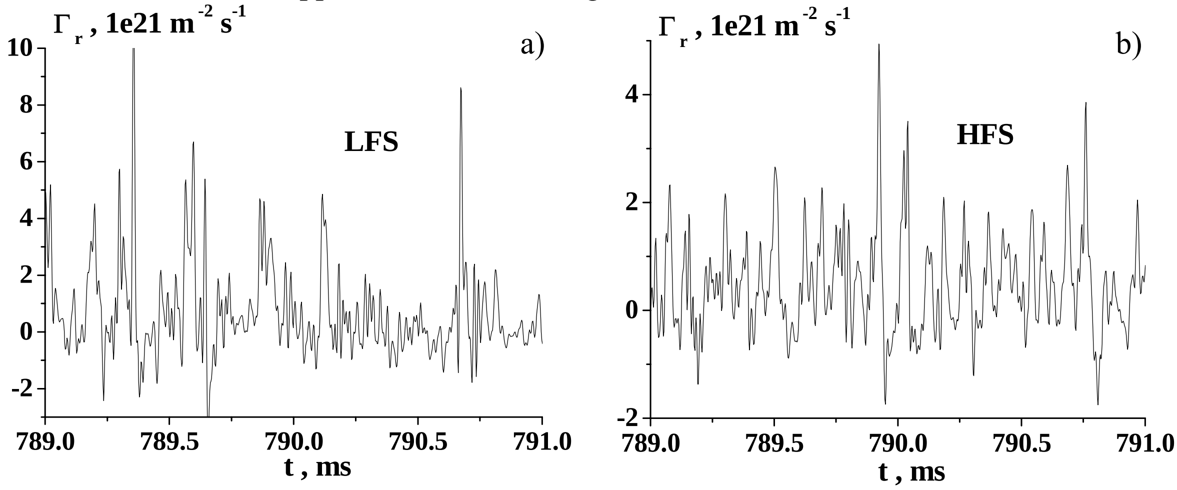

FIG. 5. Time evolution of the radial turbulent particle flux: a) – LFS, b) – HFS.

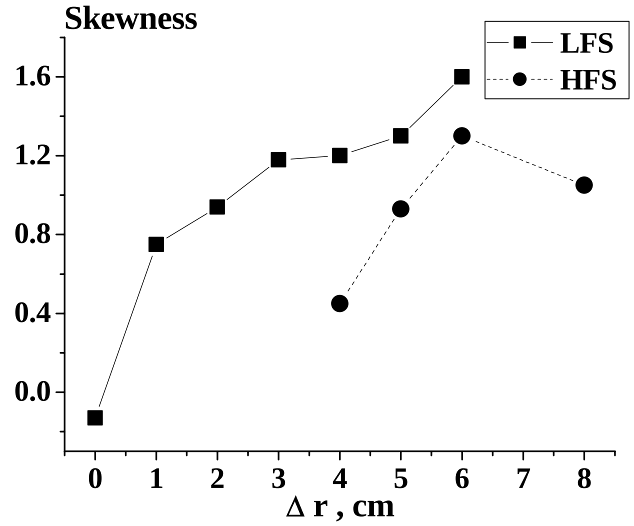

FIG. 6. Radial dependencies of the skewness of the radial particle flux.

of the PDF approaches to zero at a radius Δr≈4 cm. Thus behaviour of the skewness profiles is analogous to the fluctuation level profiles behaviour.

Analysis of the experimental data allow us to conclude that the plasma structures with high density leading to the enhanced perpendicular transport are formed most probably at the outboard part of the plasma and then plasma is extended towards the inboard side along magnetic field lines. At that a plasma density in the structures and correspondingly a fluctuation level decrease. Experimentally observed 4 cm shift of profiles of the fluctuation level and PDF skewness could be explained by radial moving of the plasma structures in a time of parallel plasma flow from the outboard to the inboard part.

4. Conclusions.

Experimental investigation of the scrape-off layer turbulence and associated transport in high density regime in the T-10 tokamak is presented. Comparison of the plasma parameters at low- and high-field sides of the tokamak shows that inboard turbulence essentially differs from outboard one. Turbulence has intermittent character but fluctuation level of the inboard ion saturation current is about two times lower than at the LFS. A radial turbulent particle flux and an effective perpendicular diffusion coefficient measured at the LFS are about 3-5 times higher than ones observed at the HFS. Enhanced perpendicular particle flux at LFS is defined by the high density plasma structures formed in the vicinity of LCFS. A radial velocity of the plasma structures is directed towards the vacuum vessel at both sides of the plasma. Analysis of the experimental data allow us to conclude that the plasma structures with high density leading to the enhanced perpendicular transport are formed at the outboard part of the plasma and then plasma is extended towards the inboard side along magnetic field lines. At that plasma density in the structures and correspondingly fluctuation level decrease. Experimentally observed 4 cm shift of profiles of the fluctuation level and PDF skewness measured at the HFS with respect to the LFS could be explained by radial moving of the plasma structures in a time of parallel plasma flow from the outboard to the inboard part.

These experiments support the hypothesis that SOL parallel flow might be caused by an additional mechanism such as "ballooning" transport which generates a larger flux of particles from the core into the SOL at the outer mid-plane.

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[1] LABOMBARD, B., et al., Nucl. Fusion **40** (2000) 2041.
[2] BOEDO, J.A., et al., Phys. Plasmas **8** (2001) 4826.
[3] ASAKURA, N., et al., J. Nucl. Mater. **241-243** (1997) 559.
[4] WADE, M.R., et al., J. Nucl. Mater. **266–269** (1999) 44.
[5] HIDALGO, C., et al., Plasma Phys. Control. Fusion **43** (2001) A313.
[6] BOEDO, J.A., et al., Phys. Plasmas **10** (2003) 1670.
[7] HIDALGO, C., et al., J. Nucl. Mater. **313-316** (2003) 863.
[8] RUDAKOV, D.L., et al., Plasma Phys. Control. Fusion **44** (2002) 717.
[9] NIELSEN, A.H., et al., Phys. Plasmas **3** (1996) 1530.
[10] KIRNEV, G.S., et al., Plasma Phys. Control. Fusion **46** (2004) 621.
[11] ENDLER, M., et al., Nucl. Fusion **35** (1995) 1307.
[12] LABOMBARD, B., LIPSCHULTZ, B., Nucl. Fusion **27** (1987) 81.
[13] TERRY, J.L., et al., Phys. Plasmas **10** (2003) 1739.
[14] VERSHKOV, V.A., et al., J. Nucl. Mater. **241-243** (1997) 873.
[15] HUGILL, J., J. Nucl. Mater. **196** (1992) 918.
[16] ERENTS, S.K., et al., Plasma Phys. Control. Fusion **46** (2004) 1757.
[17] GHOSH, J., et al., Phys. Plasmas **11** (2004) 1033.
[18] ASAKURA, N., et.al., Plasma Phys. Control. Fusion **44** (2002) 2101.
[19] CHANKIN A.V., STANGEBY P.C., Plasma Phys. Control. Fusion **36** (1994) 1485.
[20] RADFORD, G.J., et al., Contrib. Plasma Phys. **36** (1996) 187.
[21] ROGNLIEN, T.D., RYUTOV, D.D., Contrib. Plasma Phys. **38** (1998) 152.
[22] ROZHANSKY, V., et al., Nucl. Fusion **41** (2001) 387.
[23] ZWEBEN, S.J., et al., Nucl. Fusion **25** (1985) 171.
[24] KRASHENINNIKOV, S., Phys. Lett. **A 283** (2001) 368.
[25] HIDALGO, C., et al., Plasma Phys. Control. Fusion **44** (2002) 1557.
[26] CARRERAS, B.A., et al., Phys. Plasmas **8** (1998) 3702.
[27] ANTAR, G.Y., et al., Phys. Plasmas **8** (2001) 1612.