Power laws in a problem of plasma-surface interaction

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In magnetic fusion devices the edge plasma and the wall are a strongly coupled system [1]. Intensive erosion of materials is observed in tokamak plasma experiments leading to the formation of hydrocarbon films. Co-deposition remains the major tritium repository for ITER. Effects of plasma-surface interaction (PSI) profoundly influences the conditions in the core plasma. Controlling PSI is critical to achieving high performance in present day tokamaks and ITER [1]. To treat PSI problem a lot of models [1] consider particle flux deposited on the wall as normal diffusion. In some cases such approach can be applicable to real experimental situations in tokamaks. But it is an extremely simplified picture of the process, because it neglects several features which can have a profound effect under certain conditions. Example of such feature is the self-similarity in the rough relief and porosity of deposited films [2,3]. Such roughness is believed to result from long-range correlation in deposited turbulent flow of particle and self-organization in a process of surface growth. When it is important more sophisticated dynamical models are required to describe PSI and films deposited on plasma facing materials (PFM). To develop and verify such models analysis of experimental data by statistical physics techniques should be performed. Such analysis cannot replace a detailed study of the underlying physics, but it can provide quantitative measures that models of PSI have to satisfy.

In this work, experimental study of scrape-off layer (SOL) plasma by Langmuir probes and relief of deposited films on PFM in T-10 tokamak [2,4] are presented. Analysis of ion saturation current (Isat) and particle flux Γ toward the wall has shown that the turbulence is highly intermittent (fig.1), spectra, correlation functions (fig.2) and probability density function (PDF) demonstrates long-range dependence with non-trivial power laws and multi-scale property. The process is said to exhibit long-range dependence (or to be a long-memory process) if there is a fat algebraic tail in the correlation function [5]. For a continuous, stationary stochastic process, a fat algebraic tail in the correlation function implies a power-law spectrum; $S(f)\sim f^{\nu}$. In T-10 experiments,

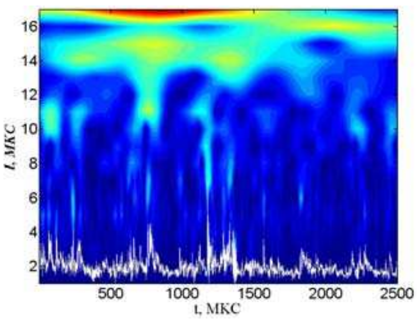

Fig. 1.Isat (white line) and its wavelet decomposition .SOL, r=34 cm.

several scaling ranges with respect to the frequency are registered in the frequency spectra $S(f)=|\Gamma(f)|^2$, (fig.2) with no $1/f$ behaviour. Typical value of scaling exponent of the power spectra in the high frequency range above ~100 kHz is in the range of $\gamma\approx1.2\div2.5$. The behavior of the spectra illustrates non-trivial self-similarity of the process which should be studied by statistical and fractal analysis. The signals of I_{sat} and Γ are studied by comparing PDF of the fluctuations with a Gaussian to measure how the signal deviates from trivial random process (”white noise”). PDF of particle flux increments (fig.3) resembles Cauchy (power law) function rather not Gaussian law indicating self-organizing in the process. Self-similarity of the signals are investigated by wavelet technique [6] and R/S analysis to estimate Hurst exponent as a measure of self-similarity and scale-dependence property. In edge plasma turbulence of T-10 tokamak, Hurst exponent is in the range from 0.6 to 0.8 with a tendency to increase toward the tokamak’s wall (fig.7). Persistent value of Hurst exponent H>1/2 is a signature of a long-memory process that is typical for the edge plasma in fusion devices [6]. Plasma edge turbulence possesses multifractal statistics, i.e. scaling behaviour of absolute moments is described by convex power-law function with non-trivial self-similarity and long-range correlations[6]. Long-range correlations as a result of power-laws in edge turbulent plasma regards a problem of films deposited on the plasma facing surfaces from turbulent plasma flow.

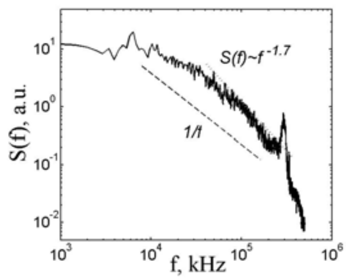

Fig .2. Power spectrum of the particle flux fluctuations,SOL, r=34 cm.

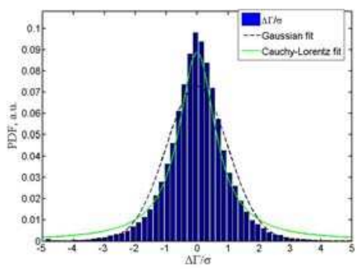

Fig. 3. PDF of the increments of particle flux fluctuations (bars). Gaussian fit (dashed) and Cauchy fit (dased-dot) .

By using scanning probe (tunnel) microscope (STM) and scanning electron microscope (SEM), we have analyzed topography relief of some amorphous hydrocarbon (so-cold “soft”) films deposited on graphite limiter, test limiter in far SOL and on the stainless steel elements of chamber in far scrape-off layer (SOL)[2]. In fig.4,5, Typical SEM and STM images exhibit hierarchy of the granularities. Self-similarity (rather not disordering) of such hierarchy is observed on 4 order of magnitude, from ~0.01 μm up to ~100 μm. Such self-similarity have been observed for many film samples from T-10

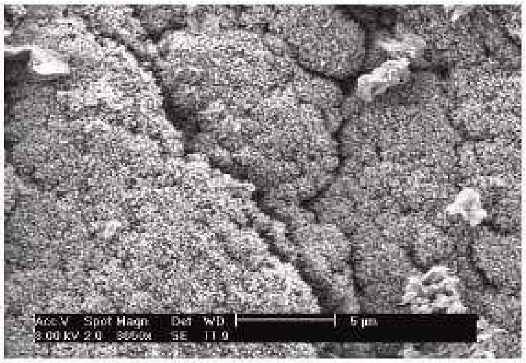

Fig.4 *SEM micrograph of cauliflower-shape hydrocarbon film.*

tokamak [2] and other tokamaks [3,4] Height's variations of the film's surfaces are distributed over power-law (Cauchy) rather not Gaussian function (fig.6) suggesting a self-organizing in a system. We study a variety of observed irregular films within a common framework of invariance under scaling. In fig.7, radial profile of Hurst exponent of the edge plasma turbulence in the

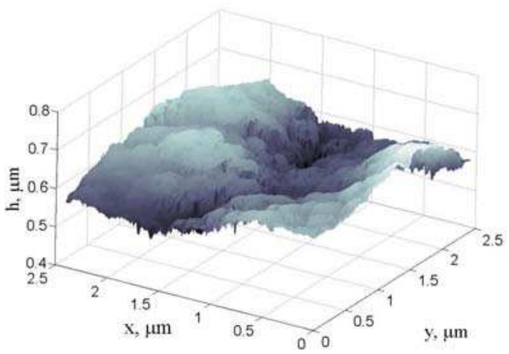

Fig.5 . STM image of hydrocarbon film's surface deposited on the vacuum chamber.

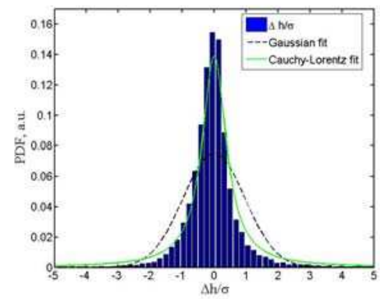

Fig.6. *Probability density function (bars) of height's increments (normalized by standard deviation) shown in Fig. 5. Gaussian fit (dashed) and Cauchy fit (dased-dot).*

T-10 is shown together with that of fractal film's surface. We stress that both plasma flux toward the surface and film's surface could be described by stochastic function (f.e., fractional Brownian function) with persistent Hurst exponent $H > 1/2$. The process of film's growth from turbulent plasma flow in tokamak edge can be considered quite generally in frame of surface growth problem [7]. Theoretical treatment and numerical simulations have shown that the noise in deposition flow can play a dominant role in the coarsening dynamics of growth process. In a problem of films growth in tokamak, we stress the importance of non-Gaussian statistics and long-range correlation of turbulent plasma flow on plasma facing materials that may generate roughness of the deposited films with self-similar porous structure. In the vicinity

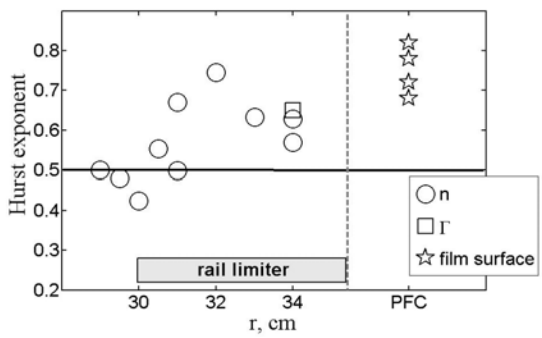

Fig.7. Radial profile of H for SOL plasma turbulence and the surface relief of films deposited on PFM.

of the wall, non-Gaussian statistics of electric field fluctuations drives not a standard Brownian motion (classic diffusion), rather superdiffusion with long-range correlation and flights of deposited particles. In fig.8, it is schematically illustrated importance of superdiffusion in film fractal growth. Gaussian statistics generates a tendency to stick of particles to the tops of cluster brunches; non-Gaussian statistics with"flights" leads to a penetration of deposited particles into the gaps of cluster. To reproduce self-similarity of rough films observed in tokamak, discrete diffusion limited aggregation model (DLA) [8] of fractal growth from turbulent flow is used for numerical simulations. The result of diffusion limited aggregation is a fractal geometry whose dimension is linked to the dynamics of particles which diffuse to surface. Main features of investigated films, such as fractality of surface and cauliflower-shape, are exhibited in the computer simulation (fig.9).Taking into account instability (probably universal) of surface growth from turbulent flow, irregular redeposited films are expected in the tokamaks with other then graphite (i.e. tungsten and berillium) plasma facing materials. Fractality (porocity) of the irregular deposited films has to be considered as one of the critical issue related to the tritium inventory in ITER.

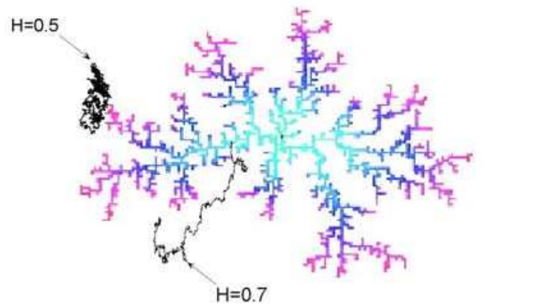

Fig.8 .Demonstration of statistics importance in fractal growth of cluster(colour). Particle's trajectories (black lines) possessed Gaussian (H=0.5) and non-Gaussian (H=0.7) statistics.

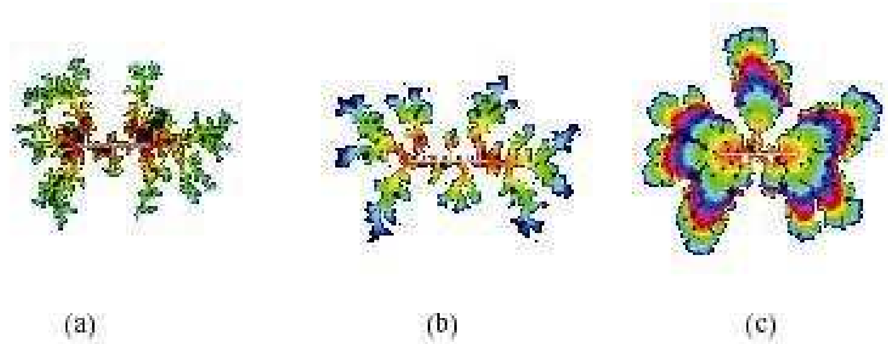

Fig.9 Diffusion limited aggregation with a variation in statistics of deposited particle diffusion. Simulation with Hurst exponent of diffusion: (a) H=0.5, (b) H=0.6, (c) H=0.8. Generations of the deposited particles are shown in different color.

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