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# Fractal growth of deposited films in tokamaks

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**Abstract**

Surface topography of some amorphous films from the T-10 tokamak has been analyzed by using the scanning tunnel microscope. Film surfaces on the scale from ~10 nm to ~100 μm have stochastic topography and a hierarchy of granularity. Fractal geometry and statistical physics techniques have been used to study a variety of irregular films within a common framework of the invariance under scaling. Quantitative analysis of a local fracture surface has been made. Experimental probability density functions of surface height increments resemble the Cauchy distribution rather than the Gaussian function. Stochastic topography of the film surface is characterized by the Hurst exponent in the range of 0.68–0.85, indicating non-trivial self-similarity of the structure. A fractality (porosity) of deposited films has to be considered as a critical issue of the tritium inventory in fusion devices. The process of film growth on plasma-facing materials (PFMs) in tokamaks is considered in a frame of the surface growth problem.


*Keywords:* Deposited films; Carbon films; Turbulent plasma; Tokamak; Non-Gaussian diffusion; Hurst exponent; Fractals; Fractal growth of surface; Diffusion-limited aggregation

## 1. Introduction

In tokamak plasma experiments [1], intensive erosion of plasma-facing materials (PFMs) leads to a formation of amorphous films of irregular shape [2–11] on the plasma-facing components (PFCs) (vacuum chamber, divertor plates and limiters). The films are formed by surface processing (blistering, flaking, a reconstruction of the surface by the ion bombardment, etc.) or by a co-deposition on the PFMs. The co-deposition is defined as the re-deposition of the eroded and then transported material (i.e., plasma impurities) together with fuel species (usually, hydrogen isotopes). Material eroded from one place of the tokamak wall is redeposited to another location, unless it is pumped out [12]. Two basic microstructures of co-deposited films in tokamaks are classified: granular (“soft”) and stratified (laminar or “hard”) [10,11]. The structure of the “soft” films is irregular. Hydrogen isotopes of the plasma are trapped in the pores of the redeposited films. The enhanced content of hydrogen isotopes in the deposited films is regarded as critical issues related to the safety hazard such as tritium inventory in International Thermonuclear Experimental Reactor (ITER) [10].

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Roughness and porosity of co-deposited films inside the tokamaks are considered to be critical parameters for the performance of the ITER.

In the literature (see, e.g., Refs. [3,4,10]), the impact of the edge plasma property on the film's growth inside the tokamak chamber has been discussed. The plasma in tokamaks has very complicated features of a non-linear self-organized matter with a quite unusual behavior [13]. There is strong non-linear coupling in plasma-wall interaction. The strong plasma turbulence leads to the anomalous cross-field plasma diffusion and to a heat load on the PFM. This process leads to the erosion of materials having contact with a hot plasma and to the redeposition of the eroded materials on the PFCs (vacuum chamber, divertor plates and limiters).

In present-day tokamak experiments, graphite tiles are mainly used as the PFM. Erosion of the graphitic materials leads to the redeposition of carbon together with hydrogen (fuel of tokamak) on the PFCs of the tokamak. Amorphous carbonaceous (C–H) films are retained from a few to over 60 at% of hydrogen isotopes [14]. The amount of hydrogen isotopes retained in the films depends on the surface roughness as well as on the porosity of the deposited films. Accurate estimates of the long-term accumulation of hydrogen isotopes on the rough surfaces and in the bulk of porous materials of the PFC in a tokamak are still required for determining the tritium supply requirements and for assessing the radiological hazards in the ITER.

Many film samples found in tokamaks have a rough surface organized in a hierarchical structure shaped like a globe [2], cauliflower [2], ovoidal [3], stratified [11] and columnar [3]. The typical features of these films are its self-similarity of the rough surface, fractional dimension and dilatation symmetry: the invariance of major geometric features with a scale variation. The growth rate of such films is usually between 1.5 and 12 nm $s^{-1}$ [10,11]. Hydrogen isotopes are trapped in the pores and on the large area of the rough surface. Irregular films are easily disintegrated and thus a fuel-rich dust is produced. It can seriously alter the plasma property and the performance of a large tokamak.

In the literature (see, e.g., Refs. [3,10] and references therein), the problem of films in fusion devices is ordinary, considered in frame of concepts developed for material processing in low-temperature plasma devices, ion bombardment source devices or other non-fusion devices used for a surface treatment [15]. In these approaches, there were no treatments for non-equilibrium growth of self-similar rough surfaces. It is well known from condensed matter science [16] that there is a very sensitive and complex dependence of the deposited surface on growth conditions. In experiments, the evolution of the surface morphology is necessarily influenced by fluctuations of the deposition flux. So, inhomogeneous and non-equilibrium flux of deposited ions, molecules and atoms should be considered for the problems of film growth in realistic tokamak experiments.

In material science, numerous papers have been dedicated to the problem of growth and the dynamics of solid surface-displayed geometric self-similarity. The theoretical foundations of dynamic scaling phenomena in a surface growth suggest the roughness and scaling exponents to be universal. Experimental study of a film growth on different systems (molecular beam epitaxy (MBE), vapor deposition [16–18]) has shown that three-dimensional (3D) structures occur. The systems which show 3D growth have a common feature: power-law (time-depending) of a characteristic size $L$ of the structures is of $L \sim t^m$. From experiments, it was found that $m$ is between 0.16 and 0.33 [19]. In tokamaks, a typical flux of the deposited particles onto the PFCs is of $10^{15}$–$10^{16}$ particles $cm^2\,s^{-1}$, the temperature of the PFM surfaces is of ~300–1000 °C [10]. These conditions are similar to those treated by MBE [17] for a film growth. In such conditions, self-similar fractal roughness of thin films (a thickness of ~10–1000 nm) is observed in the MBE [17] and vapor deposition [18]. In the MBE, the deposited beam is typically perturbed by a "white" noise. Even relatively small fluctuations in the deposited flow lead to an instability of the surface growth. Therefore, the process generates rather rough surfaces. On the other hand, there are, of course, several mechanisms that allow the particles to move on the surface while it is generated. Such surface diffusion tends to smoothen the surface. These competing effects generate an actual roughness of the surface. In material science, numerous simulations have been performed and many numerical results reproducing a rough surface are known [16]. A large number of models of surface growth, of varying levels of sophistication, have been developed (see, e.g., Refs. [16,19] and the references therein). A universal mechanism behind the surface growth is suggested. It seems to be reasonable to investigate the problem of the amorphous film growth in tokamaks on the grounds of these results.

The goal of this paper is to analyze a surface structure of some amorphous film samples observed in the T-10 tokamak [2,20,21]. Film samples from the T-10 tokamak have been studied by using the scanning