Structured anisotropic deposits on plasma facing surfaces of fusion devices

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Modification of plasma facing components (PFCs) in contact with edge plasmas in fusion devices is an unresolved problem. Understanding of different factors influencing structure of the deposits is important for control of their growth and prediction of possible consequences for machine operation. Redeposition of eroded first wall materials in remote regions leads to formation of mixed layers with reduced thermal conductivity, lower density and specific heat in comparison with that of the original plasma facing components (PFC). Poor attachment and thermal contact with the substrate make spalling deposits a likely source of in-vessel dust which harmfulness for plasma purity and tokamak operation is well recognized. In net deposition zones accumulation of radio- and chemically active fuel and impurities along with degradation of the PFC's physical properties may be responsible for limited availability of future larger scale machines such as ITER and DEMO.

Morphology of the deposits depends on substrate temperature, composition of the incoming flow, energy and angular distribution of impacting atoms. Such results were obtained both in tokamak experiments and in laboratory tests. Earlier works experimentally demonstrated development of columnar structures under a collimated flux of atomic particles [1] and provided its explanation in the framework of the ballistic aggregation theory [2]. In magnetized plasmas regular aligned structures have been found in net erosion zones on C targets exposed in plasma simulators [3]. Also columnar structures in deposition zones have been observed in recent nanotechnology-relevant laboratory experiments, e.g. [4].

In fusion-relevant laboratory studies most attention is attracted to PFC's erosion limiting their lifetime. The redeposition is understood as inevitable evil but less critical for PFC's lifetime than the erosion. Recently the effect of ion impact angle on anisotropic target erosion has been demonstrated in ASDEX Upgrade tokamak [5]. Since the most worrisome consequences for PFC's lifetime are expected from ELMs, delivering transient energy fluxes of the order of tens of MW/m^2, most laboratory simulators are aiming on achievement of the maximum ITER relevant target heat loads. Target plates are facing the plasma flow normally, which leads to isotropic (with respect to the surface normal) flux distribution at the target. Hence, some details of materials modification due to grazing magnetic field in real machines can be overlooked.

In this work we report on observation of ordered regular columnar deposits grown in strike point region of JET tokamak with C wall and anisotropic erosion of metallic dust particles in full metal reversed field pinch EXTRAP T2R (Alfvén laboratory, Sweden). Surface samples from JET carbon divertor were extracted by coring technique [6]. Cylindrical samples were marked to keep track of their initial orientation in the divertor. Geometry of JET divertor as well as the positions from where the samples were taken are shown in figure 1 a. The two studied samples from tile 3 and tile 6 were removed from the machine during tile exchange interventions respectively in 2009 and 2001. The geometry of JET divertor has changed several times during this period. Modified was the design of tile 5, while all other tiles remained the same made of bulk Dunlop-grade CFC. Another experiment that contributed to this work is a medium-sized reversed field pinch EXTRAP T2R. Figure 1 b shows a flat section of its liner and one of poloidal arrays of Mo limiters. T2R has operated for more than 10 years with the current
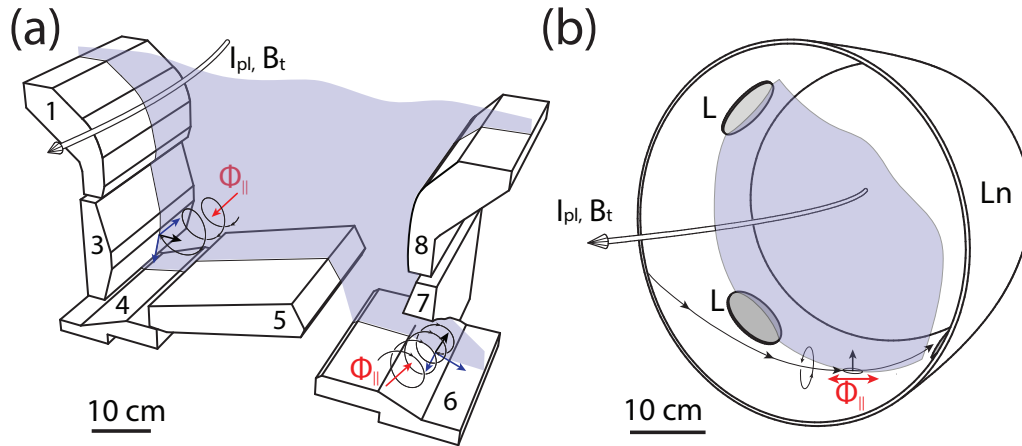
Figure 1: *(a) Geometry of JET Mk-II divertor and conventional tile numbering. The topology of magnetic field leads to the parallel diffusive flow $\Phi_{\parallel}$ towards the target directed CW in the inner divertor and CCW in the outer. Helix traces of ion trajectories (gyration radius is exaggerated) explain expected direction of ion impact onto the tile surface. Blue arrows indicate components of the column growth direction in toroidal and poloidal planes, as seen by SEM microscopy during analysis at both studied positions. A part of tile 7 is cut away in the image to show the analyzed spot on the sloping part of tile 6. (b) EXTRAP T2R flat SS liner section (Ln) and protecting Mo limiters (L). An approximate trace of B-field line at the edge (B_t is reversed with respect to that in the core) is shown, passing through the dust collection point. $\Phi_{\parallel}$ direction depends on whether or not the flux tube is connected to one of the nearby limiters.*

wall since the rebuilt in 2000. No major interventions or vessel cleaning was performed during this period, what provided an opportunity to study the surface conditions obtained after in total ~200 s of plasma accumulated in discharges ~30 ms each. In the recent years a newly introduced active magnetic feedback system for mode suppression made it possible to extend the discharges up to 90 ms [7]. Samples of loose surface material, mainly metallic dust, were collected from the flat liner section by the sticky tape method during recent service intervention [8]. The sticky collectors' positioning was tracked, therefore during the microscopy analysis it was possible to recover the original orientation of individual particles.

SEM images taken from the top of the deposited layers in JET divertor shown in figure 2 a-b reveal an anisotropic growth of regular columns. This may be expected in case of a grazing incidence of parallel incoming particle flux similar to that in experiments on ballistic aggregation [1]. Notably, the vector of column growth is not collinear with that of the diffusive flow towards the divertor target. Similarly, figure 2 c-d shows SEM images of two metallic particles non uniformly eroded by the impurity ions at the wall of T2R pinch. The inferred direction of the incoming ion flux is also deflected from the diffusive flow direction.

In both cases the observed angular distribution of incoming ion flux can be explained by considering the Larmor gyration of the impurity ions. Similar attempt has been made in [5] and led, in particular, to an estimated distribution of ion angles of incidence onto the target with respect to surface normal. We adopt the suggested recipe in order to numerically simulate ions trajectories through the magnetic pre-sheath and electrostatic sheath and estimate angular distribution of ion's speed both in the sample plane (as observed by SEM) and with respect to the surface normal. The former value can be directly compared to the direction of column growth in JET divertor and the direction of erosion flux at T2R edge deduced from the images in figure 2. The latter distribution can be useful if the angle of column growth with respect to the surface normal can be deduced from SEM images. This is done by focus variation of the
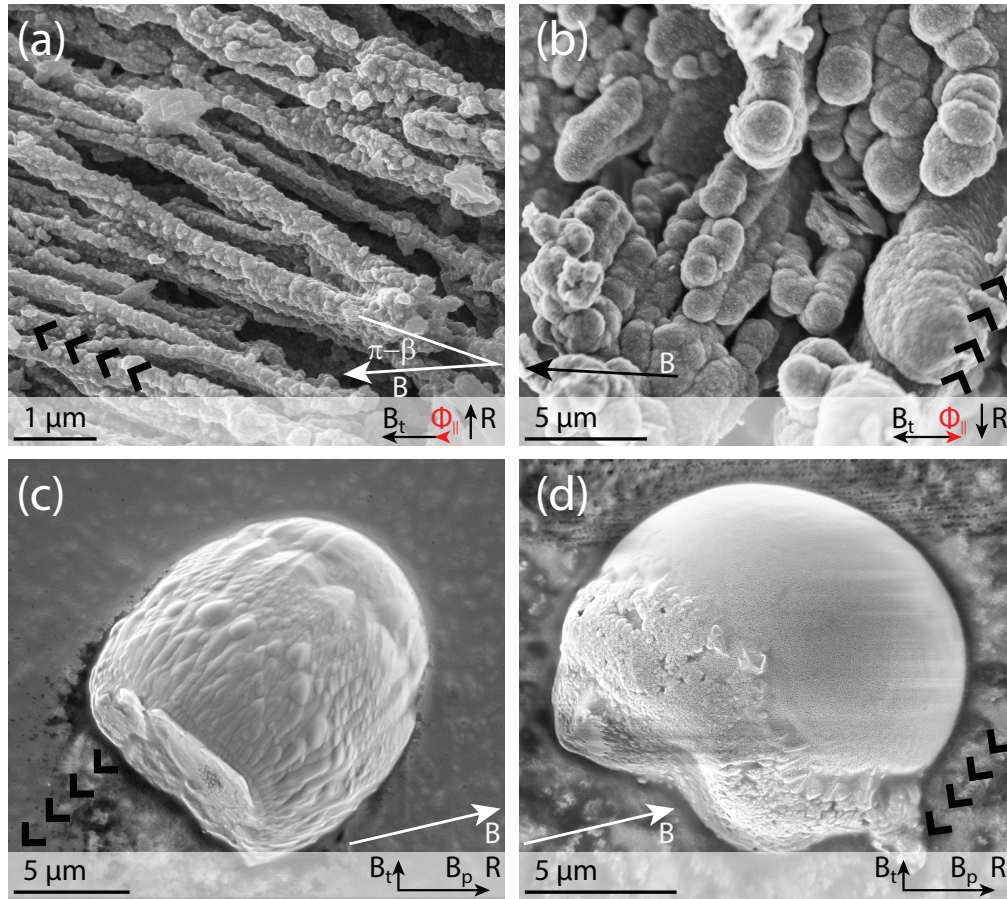
Figure 2: *(a,b) Columnar structures observed by SEM along the surface normal at samples from respectively the bottom part of tile 3 and sloping part of tile 6 in JET divertor, see figure 1. Arrows indicate the B-field direction projected onto the image plane, chevrons show the direction of ion impact opposite to the direction of column growth. Red arrows indicate the diffusive flow direction different in the inner and outer divertor. (c, d) Anisotropically eroded metal droplets collected at the bottom of the T2R vessel. All notations are similar to those in (a,b).*

SEM optics like it is described in [9] for optical microscopy.

For the simulation we use a simple model of the edge plasma consisting of one dimensional magnetic pre-sheath and electrostatic sheath regions, similar to [5], assuming T_e=10 eV and n_e=10^{18} m^{-3}. Test particles are followed from the entrance into the pre sheath until they collide with the wall. Original velocity distribution is Maxwellian. Necessary assumptions for such simple simulation to be relevant are that the ions approach the wall adiabatically with respect to the gyro motion and collisions are absent. The first condition is satisfied in JET due to grazing magnetic field incidence on the divertor targets achieved by divertor geometry, and in T2R with toroidal liner - due to small radial component of the field also resulting in grazing field line incidence.

Figure 3 shows calculated distributions of C^{3+} ion's angle of incidence α_i with respect to the surface normal and angle β between the ion impact speed and magnetic field projected at the surface of tile 3 in JET divertor, cf. also figure 2 a. Also indicated are the calculated means for the angles and their values measured with SEM. Mean angle $\alpha_i \simeq 70°$ of ion impact is estimated from the angle of column growth (both angles are measured with respect to the surface normal) using the empirical "tangent rule" $\tan\alpha_c$=0.5 $\tan\alpha_i$.

This rule is known to be only qualitatively correct [10], nevertheless the calculated mean α_i and measured using the tangent rule are close. Also a good agreement is observed between calculated mean value and the measurement is observed for angle β between ion incidence and B-field direction. This confirms the role of ion gyration in the formation of columnar deposits.

Similar correspondence has been observed between the direction of metal particle erosion and ion impact in T2R , figure 2 c-d, assuming its sputtering by heavy impurity ions: O, Mo and Stainless Steel components, which are the main wall materials in T2R. The observed structures do not carry information about distribution of ion's angles of incidence α_i, thus in this case such comparison with simulation was not possible. In agreement with the present observations, the effect of ion gyration on generation of edge flows by anisotropic momentum transfer to the wall has been previously observed in RFP configuration [11, 12]. The same anisotropic momentum transfer is responsible for the observed asymmetric erosion of dust particles.

Notably, the proposed simple model only including Larmor gyration and ExB drift in sheath and pre-sheath regions could explain asymmetries of the opposite processes of deposition and erosion in two different machines. More rigorous treatment would require calculation of modified plasma parameters in the vicinity of developing rough target surface and taking into account other types of ion drifts.
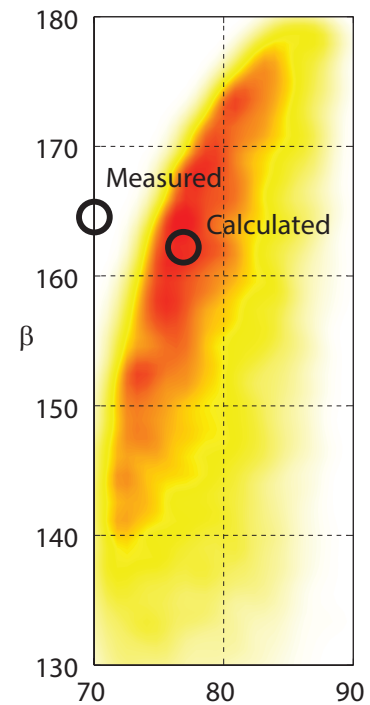

Figure 3: *Calculated angular distribution and mean values for ion angle of incidence α_i and angle β with respect to magnetic field at the bottom of tile 3 of JET divertor. The mean angles are also measured (see figure 2 a).*

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