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Modeling of dust particle transport in tokamaks

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I. Introduction. Dust has been identified as having a potentially large impact on fusion plasmas and operation of magnetic-fusion reactors [1-3]. However, understanding of such crucial issues as: mechanisms and rates of dust production, dust dynamics in fusion plasma, impact of dust on performance of fusion devices, dust-wall interactions, is still in its infancy. Here we show that dust can grow in plasma volume under the detached divertor and afterglow conditions. The possibility of avalanche-like dust generation in a tokamak due to cascade dust-wall interactions is analyzed. Deeper penetration of carbon launched into the tokamak plasma as dust particles versus carbon originated from usual wall sputtering is demonstrated using the DUSTT-UEDGE codes for NSTX and ITER.

II. Volumetric dust growth in fusion plasmas. Under standard tokamak discharge conditions, dust particles in the plasma experience net erosion or sublimation. However, in some cases (e.g., detached divertor plasmas, afterglow plasmas after discharge termination or disruption, and parasitic plasmas that occur in "shadow" regions in some tokamaks), the dust particles can grow from net deposition when a low temperature plasma contains significant concentrations of intrinsic impurities.

To explore the conditions necessary for volumetric dust growth, we use a simple model where the carbon-dust particle is embedded in stationary plasma (density n_e and temperatures $T_e = T_i$. The deuterium plasma contains a fixed fraction γ_c of singly charge carbon ions $[C^+] = \gamma_c n_e$. The impact of neutrals is not considered here. The input parameters here are thus n_e, T_e, and γ_c. We solve a system of coupled equations describing: i) charging of dust particle (including secondary electron and thermionic emissions); ii) energy balance of dust including plasma energy flux, radiation loss, cooling by electron emission and evaporation/sublimation (dust material temperature T_d is assumed uniform within a grain); and iii) erosion/deposition rates that include sputtering, evaporation/sublimation, and sticking of Carbon to the dust. Hence, we find both the equilibrium T_d and the growth rate of dust particle dR_d/dt as functions of input plasma parameters (shown in Fig. 1,2). Since both chemical sputtering and evaporation-sublimation depend strongly on T_d, we find that dust temperatures in the range $700K < T_d < 2000K$ are favorable for deposition (chemical sputtering is suppressed while the sublimation rate remains small). But, beyond $T_d \sim 2000K$, evaporation and sublimation begin to dominate. Depending on Te, favorable T_d for growth correspond to

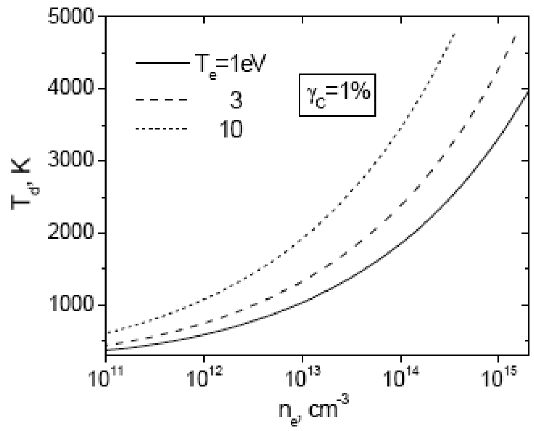


Fig. 1.

plasma densities: $10^{11}\text{cm}^{-3} < n_e < 10^{14}\text{cm}^{-3}$. However, the window of T_d and, therefore, n_e, favorable to the growth of dust is quite sensitive to electron temperature, which controls physical sputtering of dust. For $T_e \gtrsim 10\text{eV}$ and a relatively modest fraction of impurity, $\gamma_c \sim 1\%$, such window with growth rate $\sim 10\,\text{nm/s}$ barely exists for densities $10^{11}\text{cm}^{-3} < n_e < 10^{12}\text{cm}^{-3}$. However, for plasma temperatures typical of detached or afterglow plasmas, $T_e \lesssim 3\text{eV}$, the window extends up to $n_e \sim 10^{14}\text{cm}^{-3}$ where the dust growth rate reaches $\sim 1\,\mu\text{m/s}$. Note, carbon neutrals (whose density in the detached divertor and afterglow plasmas can be comparable to or exceed the carbon ion density) should increase the dust growth rate even further.

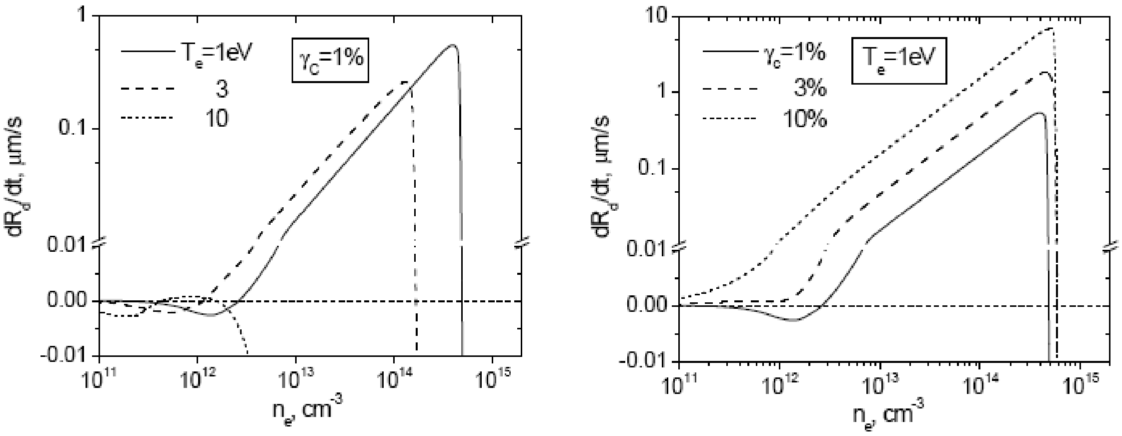


Fig. 2.

III. Avalanche-like production/destruction of dust due to dust-wall interactions. Being accelerated by plasma flow to the speed about few hundred m/s and hitting the wall, dust particle can chip off small bits of the wall material. Such avalanche-like generation of dust can be very dangerous for both plasma performance and safety of ITER. Here we briefly discuss this process from the energetic viewpoint. Most dust acceleration occurs within the rather dense part (thickness $\Delta \sim 1\,\text{cm}$) of divertor region adjacent to the separatrix [3]. Due to toroidal geometry, the dust particle is subjected to this strong acceleration over the length $\ell \sim \sqrt{2R\Delta} \sim 20\,\text{cm}$, where $R \sim 2\,\text{m}$ is the tokamak major radius. For a single passage through the acceleration region, a spherical dust particle of radius R_d gains kinetic energy $E_d \equiv (2\pi/3)\rho_d R_d^3 V_d^2 = M\xi P\pi R_d^2 \ell$, where V_d and $\rho_d \sim 2\,\text{g/cm}^3$ are the dust velocity and mass density, M is the Mach number of plasma flow, P is the plasma pressure, and ξ is a form factor for the effects of dust charging (for micron size particles in edge plasma, $\xi \sim 1$). For $n_e \sim 10^{14} cm^{-3}$, $T_e \sim T_i \sim 10\text{eV}$, $M \sim 1$, and $R_d \sim 1\,\mu\text{m}$, we find $V_d \sim 300\,\text{m/s}$ and $W_d \equiv (3/4\pi)E_d R_d^{-3} \sim 6\times10^8\,\text{erg/cm}^3$. The potential energy of charged dust particle, U_d, appears to be much smaller than E_d. Estimating dust charge as $Q_d \sim T_e R_d e^{-2}$, we find $U_d/E_d \sim \lambda_D^2/(R_d \ell)$, where λ_D is the Debye radius. For a tokamak edge plasma, where $\lambda_D \sim 1\,\mu\text{m}$, $U_d/E_d << 1$. Thus kinetic energy is the only source available for chirping off the wall surface or breaking the dust particle due to dust-wall collisions (or due to rapid dust particle rotation followed the collision). Typical dust particle speeds are much smaller than the sound speed for most of materials used for tokamak first walls (although modification due to erosion and re-deposition can significantly change material properties). Therefore, chipping off a new dust particles from the surface or breaking a particle is possible when W_d exceeds some critical level, W_{crit}, determined by the tensile strength of the material. For pyrolytic graphite, $W_{crit} \sim 10^9 erg/cm^3$ [4], and available collision energy is close to the critical value and both avalanche-like dust generation and break up of dust particles are possible.

IV. Modeling of dust dynamics and impurity sources. The DUSTT code is used to simulate the dust dynamics in the edge plasmas and to calculate impurity atom sources associated with dust ablation in both NSTX and ITER. An ensemble (10^5) of 1 μm carbon dust particles is launched into the plasma. The dust flux is the fixed fraction ξ_d of the carbon ion flux on walls from UEDGE. Compared to a previous version of DUSTT [5], thermionic and secondary electron emissions of dust particles are included affecting the dust particle charging, heating, and ion drag force. A revised model calculates kinetic and potential energy fluxes from absorbed plasma particles according to OML theory accounting for the equilibrium dust charge and relative velocity of dust in plasma. A correction to thermal radiation of small body for short wave lengths is also introduced.

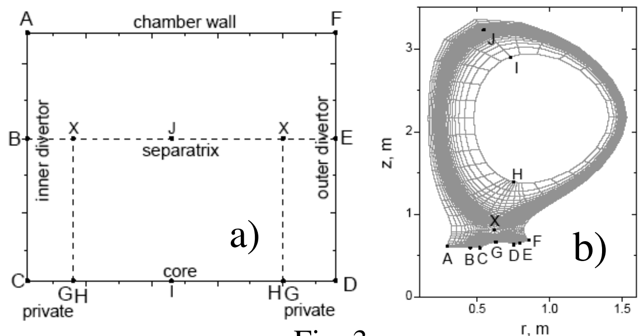


Fig. 3

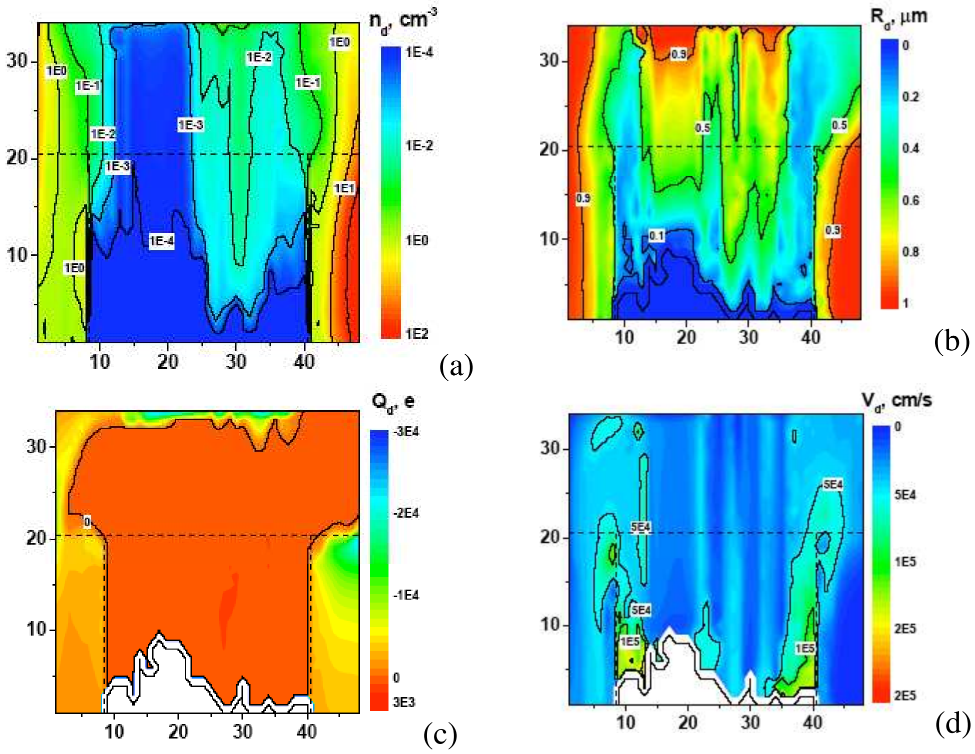


Fig. 4.

In Fig. 3, we show the 2D computational domain used in both DUSTT and UEDGE codes and its mapping to the mesh cell index space. On Fig. 4, we display the profiles of statistically averaged parameters of dust particles: density (a), radius (b), charge (c), and speed (d), obtained from the DUSTT/UEDGE modeling for NSTX discharge and $\xi_d = 1\%$. The profiles of carbon atom density calculated for two cases: carbon atoms originated from sputtering of plasma facing components (a) and from dust assuming

$\xi_d = 1\%$ (b), are shown in Fig. 5 for NSTX and in Fig. 6 for ITER. In Fig. 7, we display the radial profiles of carbon atom density at outer midplane of NSTX for different ξ_d. One clearly sees much deeper penetration of carbon atoms into the core plasma ($\rho<0$) when they are launched as dust. The carbon atom density at the separatrix from dust ablation is comparable to that from sputtering at very low conversion efficiency, $\xi_d = 0.01\%$.

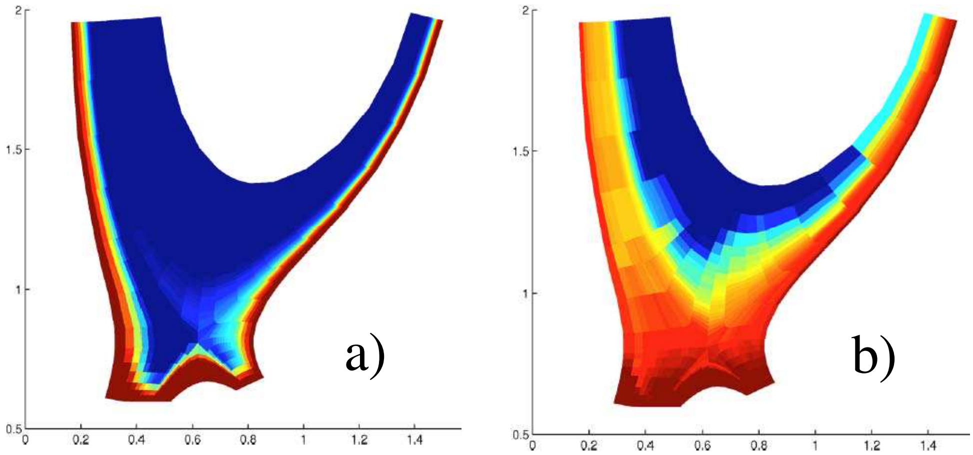
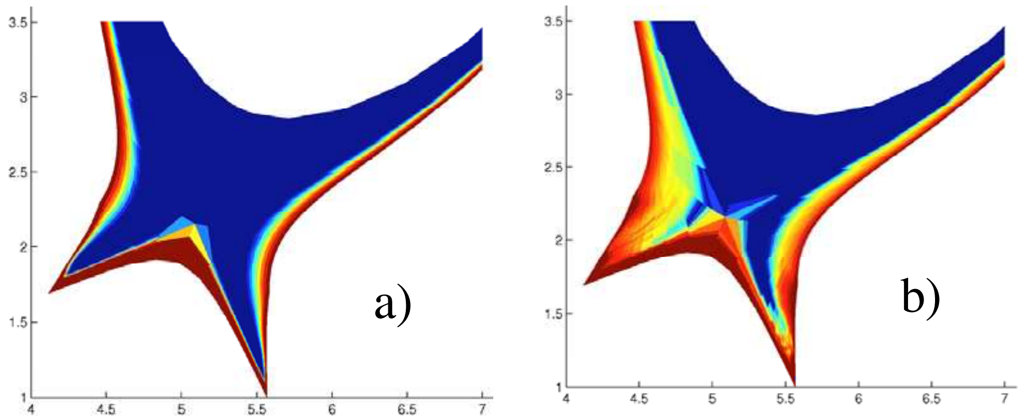


Fig. 5.



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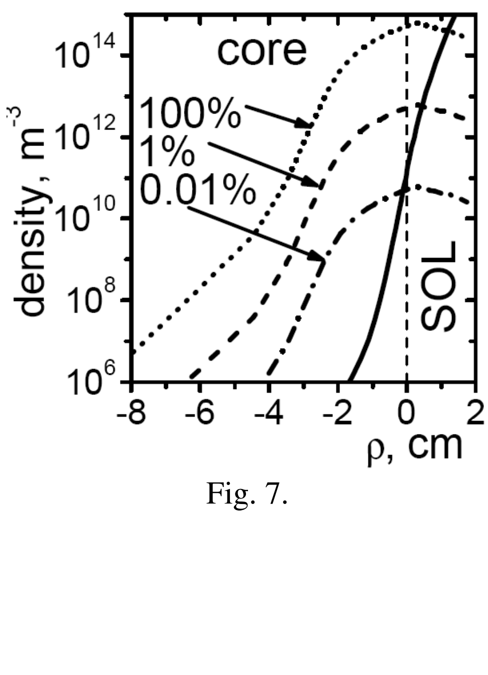

Fig. 7.

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